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Development of Sustainable Myco-material from Fungi: Current Trends and Future Scope

Dr Ajay Kumar Singh , Akhilesh Kumar Pandey*

Mycological Research Laboratory, Department of Biological Science, Rani Durgawati University, Jabalpur-482001 (Madhya Pradesh), India
*Corresponding Author: Dr Ajay Kumar Singh email-drajay2009@gmail.com

ABSTRACT

Filamentous fungi are known as production organisms in biotechnology and have become indispensable in research and industry. Today, fungi are not only used for human consumption, but also fungal enzymes are widely used in the food, biofuels and detergent industries and fungal bioactive compounds are applied in agriculture for pest management (insect, weed and plant disease), veterinary and human medicine. The metabolic products of fungal organisms are interesting for research and industry, and also the mycelial structure of filamentous fungi is moving into the focus of new areas of application. Fungal mycelium is vegetative parts of fungus consisting of massive branching thread like hyphae which is also known as “shiro” which appears like “ferry ring” fungi. Given the experience to farm edible fungi on plant or animal waste material that is utilized by the fungus as the substrate, one extension that became attractive was the fabrication of structures that contain biomass material as a filler that is glued together by fungal mycelium. The use of mycelium-based products is regarded as biodegradable and sustainable and contributes to the transformation to sustainable economy, which is one of our challenges in society today. In contrast to today’s fossil-based economy, which uses linear streams that lead to the depletion of fossil resources, circular economy approaches allow cycles to be closed by novel recyclable materials that can be generated from waste and secondary streams. Fungal mycelium packaging products were developed with an intent to replace plastic packaging options such as polystyrene. These petroleum-based products are increasingly facing scrutiny as petroleum prices come from conflict-ridden and unstable regions, creating uncertainties in the supply chain. Furthermore, plastic products take several years to decompose and some never do so. Hence, cost-efficiency and growing consumer response can drive the fungal mycelium packaging market in the near future. Fungal mycelium materials are widely gaining increased attention due to their biodegradable and renewable nature. This will make way for widespread industrial commercialization. Moreover, fungal mycelium materials are not just running away with packaging products but are used in various applications such as thermal insulation, building materials, protective packaging, and panels.The aim of this review to evaluate researched information that consider the production and processing of fungal mycelium for novel applications as biomaterial.

Introduction

Fungi based bio-composites are produced by combining fungal mycelium with a natural reinforcement or filler. These materials are renewable and recyclable, and are slowly starting to replace various plastics, packaging and insulating materials on Earth(Lelivelt, 2015). The fungi-based bio-composite is also being discovered by artist, designers and architects who have been successful in using these materials in many new ways like Bricks and new architectural structures have been produced with fungi. As well as various fungi-based products (Saporta et al., 2015). The combination of 3D printing with living organisms has been studied using 3D printing technique with organic waste, which then formed the basis for the mycelium growth. The mycelium grew through the organic waste, forming a network of interwoven roots, which then bound the material into cohesive and strong bio-composite structure (Saporta et al., 2015).From a large group of fungi, Ascomycota and Basidiomycota are known to be the best type of fungi to create mycelium-based materials as they can construct larger and more complex organic structures than other fungi (Lelivelt, 2015). From the two, Basidiomycota have two importantproperties which can make them more suitable for producing biocomposites: Septa and Anastomosis. Septa, special transverse cell walls, have an opening that can be closed in order to block the draining of a cytoplasma through the rapture when hypha becomes damaged. This will decrease the damage of the colony and therefore will lead to faster colonization of a substrate. Also anastomosis increases the growth speed of mycelium by fusing two different hyphae together when they meet. In addition, it creates a more homogeneous network of mycelium which promotes a fast transport of nutrients.

In general the mycelium materials are produced in six steps. The production starts by creating a suitable substrate for the fungus. The choice of a substrate depends on the function and required properties of the final product, but is also connected to the type of fungi used as every fungi has its specific needs for the growth environment. The substrate can be any cellulose rich material as fungi are special in that they can break cellulose down into glucose as opposed to other organisms. It is therefore also smart to use cellulose- rich materials in order to prevent contamination by other organisms. When the substrate is selected it needs to be sterilized in order to prevent contamination by other organisms. The sterilization can be done in three ways: by pasteurization, hydrogen-peroxide solution or natural composting. After sterilization the substrate is inoculated with the spawn and the colonization of the substrate can start. It is important, however, that the right growth conditions for the specific fungi is met. In average, it takes about two weeks for the mycelium to fully colonize the substrate. When the substrate is fully grown, the growth of the mycelium has to be stopped in order to prevent the total consumption of the substrate and production of fruiting bodies. The growth can be stopped by heating. After the growth has been stopped the material can be treated with a surface finishing if needed(Lelivelt, 2015)

Fungi as Biomaterial

Buildings keep growing every year for demanding of people's lifestyle, but they also produce construction wastes such as glasses, woods, concretes, steels, bricks, or plastic materials, etc. They become influential factors to environmental sanitation and people. Scientists try to find solutions to innovate the use of biological resources to replace non-renewable resources. Because of the increasing demand for "green" materials and productive processing, scientists have been developed the new method and product called bio-composite and bio-based materials (Girometta et al., 2019). Such biomaterials are made from fungi, and they are progressively used to produce different bio-based innovations nowadays (Karana et al., 2018).

The usefulness of agriculture wastes has been acknowledged by researchers and scientists in different science fields (Nguyen et al., 2019). Bio-composites from agriculture wastes for growing mushrooms are coconut husk, rice husk, rice straws, or coffee husk. Rice husk composts with soil mixture to improve the yield of many crops effectively as a good fertilizer to rice under diverse irrigation periods (Aliyu et al., 2011).

Most people have general knowledge mushrooms can be food and medicines, but they do not know fungi play important roles in bioproduction. A mycelium-based composite is a combination of natural fibers and mycelium which is used as a binding compound, and it has successfully replaced nonrenewable materials (Travaglini et al., 2013).

Mycelium is from fungi including mushroom. Various types of mushrooms have been used to produce composites. For instance, Pleurotusostreatus was cultured with supplements for cultivating the mycelium on wheat bran to produce materials as masonry in construction and this mycelium-based composite was tested for compressive strength (Ghazvinian et al., 2019). Due to these effective promising properties of agriculture wastes and mushrooms, therefore the preparation of bio-composites obtained from local mushrooms mycelia, *Pleurotusostreatus*, *Ganoderma* sp. and agricultural wastes (rice husks and coconut husks) as growth substrates.

The construction sector becomes the main factor to develop the country and earn benefits, but construction wastes are harmful to the environment and human society. Researchers and scientists take this challenge and innovate bio-composites from fungi as biomaterials in order to reduce the environmental impacts.

Construction Wastes

The construction sector has become a key role for countries all over the world for development. It also reflects their countries economic growth based on this sector. However, it leads to an increase in the number of construction wastes and landfills for disposal too. Material wastes consist of glasses, concretes, ceramics, roof tiles, steels, soil, woods, bricks, or plastic materials, etc. Construction materials will become wastes when they are no longer considered of value to retain, and they are also difficult to be recycled. Construction wastes are considered as solid pollution harmful to the environment. Moreover, fossil fuel-based materials which are known as nonrenewable resources, also serve as building materials. If people use them until they reach the limitation, those resources can be lost infinitely because they take a million years to restore themselves again. In the EU, the construction waste quantities were caused by more than 700 million tons per year (Iacoboaea et al., 2019). Malaysian government reported that Hulu Selangor district was found about 39.3% of construction wastes (Nagapan et al., 2012). In 2005, construction wastes in the UK about 28 million tons were thrown into landfills and Australia disposed of about 7 million tons of construction wastes from 2006 to 2007 (Fadiya et al., 2014)

Alternative biodegradable materials

Scientists produce biomaterials from bio-composite processing to replace petroleum and plastic products in the construction sector to reduce wastes. In this research, four biodegradable materials are taken to describe what they are, and how to produce them. Nowadays, scientists start to replace nonrenewable materials with these biomaterials.

Mycelium-based materials

There is another new technology called mycelium-based material to innovate bioproduct to replace the nonrenewable product and reduce wastes too. Mycelium-based composite is the result of the structure of filamentous fungi or mushrooms species grow on different natural fibers to produce bio-materials or 3-D structure mushroom (Appels et al., 2019).Mycelium-based materials can be applied for industrial materials as biodegradable alternative resource to develop a broad scope of production in the fields of architectures and industrial design such as bricks to walls (Attias et al., 2017)

Mushrooms

Mushroom are classified in Kingdom Fungi, and they have a part functioning as a reproductive structure which springs up from the ground like plants, and roughly equivalent like flowers (Nicolas &Ogamé, 2006). They are neither plant nor vegetation, but they either single-cell, multi-cellular, or spores outgrowth structure including molds, yeasts, and mushrooms which are fed on natural fibers (Jones et al., 2017). Mycelium is an association of interwoven and sting-like fungal hyphae which composes the vegetation part of mushroom growth by stretching and splitting their hyphae into substrates (Karana et al., 2018).

Culturing and growth

The growth of mushrooms is associated with different factors including temperature, moisture, and media. Potato Dextrose Agar (PDA) is common for culturing fungi. The ingredients of PDA were followed: potato 200 g, dextrose 200 g, agar 20 g, and distilled water 1,000 ml. Media and Petri dishes were autoclaved at 1210C for 30 min. Mushroom's inner parts were placed in PDA Petri dishes and incubated at a temperature dark room. Substrates were autoclaved for 30 min at 1210C before inoculating. The water content was measured at the beginning of the experiment to test whether the substrate contained about 65% of water for fungal growth (Attias et al., 2017). Jones et al., (2017) reported inoculation conditions had an important consequence to increase fungi growth rate on substrates from 5 to 14 days. Also, the temperature was important for the initial growth rate between 18 to 220C. Mycelium of mushrooms were maintained in these different media including Potato Dextrose Agar (PDA), Sweet Potato Dextrose Agar Medium (SPDA), Yam Dextrose Agar Medium (YDA), and Malt Extract Agar Medium (MEA) to measure for 8 days. PDA and YDA were suitable for the mycelium growth of mushrooms (Hoa& Wang, 2015).

Mycelium bio-composites

Bio-composite is classified as green material consisting of natural fibers which are biodegradable (Dicker et al., 2014). Scientists have used bio-composites and investigated their properties e.g. density, modulus, natural fiber composites, toughness, thermal conductivity, high temperature, and so on (Nusyirwan et al., 2019). A mycelium brick as one of the bio-composites is formed from agriculture waste with the mycelium to produce 3D structure (Santhosh et al., 2018). They can be used as materials with strong flexure and non-flammable building materials which can release less smoke and CO_2 (Jones et al., 2018). Nowadays, the architectural and construction industry has recently taken interest in using mycelium bricks to replace clay bricks. They are known as environmentally friendly material while clay bricks are produced from muddy clay which is the result of deforestation and harmful to the environment and human (Kishan et al., 2018)

Agriculture waste for mycelium growth

Agriculture waste is defined as the non-product output of production from cultivating and agricultural activities such as grains, vegetables, or crops (Obi et al., 2016). Agriculture has expanded three times over the past 50 years due to the development of land, agricultural needs, mechanical improvement, and population expansion which approximately result in 23.7 million tons of agriculture products per day globally (Duque-Acevedo et al., 2020).

Around 80% of solid wastes are from farms in form of organic decay, so agricultural wastes such as straw, coconut shells, and others are contributing varieties of helpful materials for many purposes (Nguyen et al., 2019).

The current baseline estimate for the process of manufacturing fungi structures is:

1. Collecting material for the production of substrate (any cellulose-rich organic waste,possibly agricultural waste from, for example, greenhouses, or some combination of soil)
2. Sterilizing the substrate by pasteurization or natural composting
3. Creating suitable conditions for the growth of fungi (possibly inflating a temporary shelter of air thigh thermal control layer (MLI of inflatables) for the environmental control, depends on the type of fungus but in general: humidity >90%, temperature <30°C, no light, high CO2, O2 for growth
4. Using additive manufacturing technique to print the structure and inoculate the substrate (by 6-axis robotic arm)
5. Removing the shelter to heat up the structure in the UV light and stop the mycelium growth
6. Treating the structure with surface finishing if needed

It is possible to create suitable growing conditions for fungi regarding temperature, humidityand atmosphere in a space environment. An important question, however, is whether fungi areable to survive in environments with a high radiation level. Due to weak or inexistent magneticfield, the Moon and Mars are exposed to galactic cosmic radiation (GCR), solar winds andsolar particle events (SPEs). There is, however, evidence that a specific type of fungi cansurvive the simulated cold conditions (Scalzi et al., 2012; Onofri et al., 2015) and that the ionizing radiation can evenenhance the growth of melanised black fungi (Zhdanova et al 2004; Dadachova et al. 2007; Robertson et al., 2012). Onofri et al., 2015 proved in their Lichens and Fungi Experiment (LIFE) that *Cryomycesantarcticus* and*Cryomycesminteri* are able to survive the simulated cold conditions aboard the International Space Station for 18 months. They found that more than 60% of the cells and rock communitiesdid not undergo any change due to the exposure (Onofri et al., 2015). Dadachova et al., (2007) studiedmelanised microorganisms, such as*Cryptococcus neoformans, Wangiella dermatitidis* and*Cladosporium sphaerospermum* and found that ionizing radiation changes the electronicproperties of the organisms and enhances their growth. In another study, researchers wereable to provide clues how melanised black yeast *Wangiella dermatitidis* has adapted the abilityto survive or even benefit from exposure to ionizing radiation(Robertson et al 2012) These studies suggest thatmelanin pigments play a crucial role in the survival of fungi when exposed to radiation, whichcould mean that it is necessary to choose, either melanin containing fungal species whendeveloping the architectural structures for space environment, or add melanin pigments to thespecies which does not contain them yet.

Advantage of Myco-materials

Fungi based biomaterials could offer the following advantages over other in situ manufacturing technologies:

1. Costs: Lower manufacturing and energy costs due to excluding the costs of (a)prospecting to locate and validate the accessibility of indigenous resources, (b)developing and demonstrating capabilities to extract indigenous resources and (c)developing capabilities for processing indigenous resources to convert them to neededproducts
2. Manufacturing: Full manufacturing loop following a cradle-to-cradle principle: the waste of another process (eg. greenhouse) can be used as a basis for building structures, which at the end of their service period can be used biodegrade
3. Mass: Light weigh, therefore easy to handle. Can be used for complex shapes
4. Known to hold compressive and tension stresses. Non-flammable, waterproof, good insulation properties.
5. Strength: Forms a fibrous composite with a substrate, which enhances the material strength. Can be used for complex shape
6. Diversity of applications and products: Enables to produce a variety of different fungi based materials: from transparent films to concrete/ brick like materials
7. Speed: Grows relatively fast (in general two weeks)

Drawbacks of Myco-material

The main weaknesses include:

1. Needs special environment during the growth period (humidity >90%, temperature <30°C, no light, high CO2, O2, so energy is needed to sustain that environment)
2. Due to autonomous growing process there is a factor of uncontrollability and uncertainty of the final material properties

Future Scope

1. To date the mycelium was not so normal but rather on future premise there is part of utilization of mycelium in numerous development materials.
2. Like it can supplant the thermomould that are utilized for protection and numerous different works Additionally it can supplant wood since the mycelium can utilized to develop engineered wood and that wood is considerably more grounded than ordinary wood
3. Furthermore, it will supplant cowhide as the calfskin which we develop from mycelium is substantially more grounded and no longer is creature skin required to develop calfskin.
4. Many things can be made of the mycelium. In future there is immense utilization of mycelium in development and in different things.
5. When mycelium bricks are place together, in a few hours, the material fuses together. The growth can be stopped when the substance is dried, creating a rigid material which can be sanded and painted. The mycelium bricks are bulletproof and absorb carbon dioxide, making them a sustainable material for the construction of our future buildings.
6. The process of producing with mycelium brings a huge reduction in using fossil fuels. The energy required for fabrication is small and there is a massive reduction in construction waste as the product is 100 percent biodegradable and can be used as soil
7. The final result is a mushroom brick that can be 200,000 times softer than steel, 10,000 times less stiff than a typical housing brick, but capable of holding the equivalent of 50 cars.
8. Construction applications for mycelium include a composite board (Myco-board) which can be used much like Medium-density fiberboard/particle board without the extremely dangerous formaldehyde used in the glue.
9. Mycelium can be used to grow furniture and/or the bricks which are easily recycled at the end of their life. Depending on how the mycelium brick was made its compressive strength may be around 30 psi in comparison to the 4000 psi compressive strength of concrete. However, relative to its weight a mycelium brick is stronger than concrete with a cubic meters of mycelium brick weighing 43 kg and a cubic meters of concrete weighing 2400 kg.
10. More areas where people are developing applications for mycelium are Renovation, Restoration and building with mycelium wood, smart concrete, and wall reinforcement material for restoration.

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