Packaging Applications of Fungal Mycelium-Based Biodegradable Composites

Rejeesh C. Rajendran

Abstract In a world that demands the use of sustainable practices for producing more eco-friendly products, the idea of a circular economy prevails through the gradual reduction in consumption of finite resources. Mycelium is that collection of filamentous fibers extending out from the hyphae of any fungus. Mycelium is a biomaterial that is renewable in nature and has the capability to grow quickly on agricultural wastes. Thin fibers grown from the fungus can bind the matrix material to form biocomposite materials that are strong as well as biodegradable. These bio composite materials can be easily molded into various shapes suitable for the manufacturing of shock resistant packaging materials, and can also be used as a construction material or as an insulation material. They use cost-effective raw materials to form the biocomposite and the developed material is a sustainable substitute to synthetic materials like expanded polystyrene (EPS). These attributes make the mycelia-based bio composite material to have every chance of becoming a material of choice in packaging applications. This chapter gives an overview of the current state of the art technologies and the challenges ahead in the development of mycelium-based bio composite materials regenerating from agro-industrial waste. While the main focus is on the packaging applications of fungal mycelium-based biodegradable composites, the chapter also focuses on a variety of applications as a viable substitute for synthetic polymer materials like expanded polystyrene.

Keywords Biocomposites · Biodegradation · Expanded polystyrene · Green material · Insulation foam · Mycelium · Mushroom · Sustainable packaging

---

R. C. Rajendran (✉)
Department of Mechanical Engineering, Federal Institute of Science and Technology, Angamaly, Kerala, India
e-mail: rejeeshcr@fisat.ac.in

S. K. Deshmukh et al. (eds.), *Fungal Biopolymers and Biocomposites*,
https://doi.org/10.1007/978-981-19-1000-5_11

1 Introduction

One of the few sectors that saw an exponential growth during the COVID-19 pandemic is the e-commerce sector with millions of people opting for a home delivery through online shopping/teleshopping for retail essential goods and even groceries. The pandemic has essentially changed the way people used to shop retail goods. According to recent reports from Salesforce, digital sales have ballooned 71% in the second quarter of 2020 and 55% in the third, which created a surge in the use of packages and packaging materials that are bound to end up in landfill sites, and incineration chambers, or worse in water bodies and the natural environment. The amount of plastic waste generated as a part and parcel of packaging is at a staggering level and is growing at a frightening rate. The excellent versatility and manufacturability of plastic materials have made tremendous improvements to the economic well-being of society; however, a price has to be paid in the form of depleting resources and environmental deterioration (Ashok et al. 2018).

Packaging materials do serve a purpose which is mostly dedicated to protecting things, improving usability and allows safe handling (Ashok et al. 2016). The recyclability of packaging materials like polystyrene or polypropylene is often oversold and it is estimated that only less than 14% of the global annual production of nearly 86 million tons of plastic packaging gets recycled. Instead of getting recycled, a considerable portion of the packaging waste that have been generated is destined for landfill, or to the incineration chamber. It may also end up in the natural environment which unfortunately includes our waterbodies and oceans, where they turn harmful to marine life (Ellen MacArthur Foundation 2017). However, a recent market survey indicates that with increasing awareness about the environment among the customers, they have an affinity towards plastic-free alternatives which drives the companies to adopt alternative materials and strategies to reduce their plastic footprint. In an attempt to minimize the undesirable consequences of packaging waste, research has been in place all over the world that focuses on the development of alternative materials that are sustainable and biodegradable which are mostly derived from renewable agricultural sources (Ashok et al. 2016, Abhijith et al. 2018, Ellen MacArthur Foundation 2017, Ashok et al. 2018).

Expanded Polystyrene or Styrofoam is a lightweight material that is safe for use with food. It is a preferable packaging material for food, electronics and other fragile products all the while being a less eco-friendly petroleum derivative (Rosato and Rosato 2012). While considering factors like emission of greenhouse gases or energy consumption, production of polystyrene leaves a very serious negative impact on the environment. Expanded Polystyrene has become a major constituent in municipal solid waste and marine debris and it is also detrimental to wildlife since they are extensively used for manufacturing disposable products like food plates or food containers. These products made from polystyrene are neither biodegradable nor recycled and are mostly used only once before it turns out to be waste after their useful life (Rosato and Rosato 2012; Arifin and Yusuf 2013).

Fungus is considered as dreadful but they have a major role in the decomposition of biological wastes and thus makes it vital in our ecosystem (Miles and Chang 2004). Manufacturing of biodegradable materials through Bio-design practices is an important leap in this area of research recently. Moist media and living organisms like fungi and algae, are the essential building blocks to grow these designs rather than manufacturing them (Ghazvinian et al. 2019). The fungi-based packaging materials developed from mushroom mycelium have been extensively studied and reported in the past decade. Mycelium based foams developed from agricultural residues or materials like sawdust can be considered as a cost competitive alternative with comparable properties to conventional Styrofoam. Incorporation of mycelium composite materials for packaging applications could reduce the consumption of Styrofoam, and will enhance sustainability through eco-friendly packaging (Vilaplana et al. 2010; Cooper 2013).

Mycelium is a natural glue that binds onto surrounding particles like sawdust, coir pith, hay, or rice husk to create a dense network of hyphae (Miles and Chang 2004). Mycelium biocomposite materials are grown in molds with different shapes as per the final requirement, where they grow quickly into a dense compact material. The material is dehydrated to prevent further growth after it has been grown to the required shape and density. Mycelium-based materials are completely biodegradable and it will decompose within a few weeks without the help of external stimulus. The cost of these materials can be reduced when it is processed on a mass scale in batches and it is easier to biodegrade after its useful life than recycling (Jiang et al. 2013).

This chapter reviews the current state of technology and achievements that have been made on utilizing mycelia for bioremediation of agro wastes. It also reveals the various mycelium packaging materials that have been developed and discusses their characteristics for being projected as a sustainable alternative for conventional packaging materials like Expanded Polystyrene.

2 Demand for Sustainable Materials in Packaging

According to a report, it is estimated that approximately 9.15 billion tons of plastic materials have been manufactured worldwide since the 1950s, of which around 30% are currently in use, only 9% have been reused, and more than 60% are in landfills after their useful life. At this rate of production, it is expected to have around 28.6 billion metric tons of plastic in the world by 2050 (Geyer et al. 2017). Packaging materials made from plastic are non-biodegradable but can be shredded to small fragments. The polymer chain of these fragments gets weakened when they are exposed to sunlight, but the environmental impact caused by these milli fragments is not yet conclusive (Tudryn et al. 2018).

Different materials have different processes suitable for their recycling and the conversion rates also may vary with respect to the plastic (Hopewell et al. 2009). Polyethylene terephthalate (PET) allows repeated recycling with a restoration rate of about 19.5% by weight, while polystyrene plastics like extruded polystyrene or expanded polystyrene can be recycled only with a recovery rate of just 0.9% by its weight which places them amongst the least recycled plastics. Moreover, freight companies usually charge their services after considering factors like weight and volume of the goods to be transported. Considering that, the transportation cost of the EPS will be relatively very high as it requires a large volume to weight ratio and the light weight structure really makes it a poor choice of material for primary and secondary recycling. For each ton of plastic being turned into waste, the energy consumption required for transportation is approximately 0.49 million BTU all the while emitting 0.04 metric tons of carbon dioxide (Containers and Good 2016; Mojumdar et al. 2021).

Disposing plastic waste through combustion is a common practice which adopts the waste-to-energy (WTE) approach to generate energy. Though the combustion of plastic wastes can release exorbitant amounts of carcinogenic pollutants and heavy metals, other recycling options that involves collection of plastic wastes and their transportation are also harmful to human health and the environment, just like WTE incineration (Rigamonti et al. 2014).

During the 1980s, manufacturers introduced starch-based polymers to polyethylene blends and begin to market them as “ecofriendly” (Iles and Martin 2013). Biodegradable plastic materials from renewable sources are considered as a substitute for synthetic polymers and were extensively studied and used (Ashok et al. 2016). The different types of bioplastic materials that were suitable for packaging application included the

1. Polysaccharides like starch or cellulose extracted from biomass
2. Polymers like Polylactic Acid (PLA) or polyacrylates from chemical synthesis of renewable bio-based monomers
3. Polymers like Polyhydroxyalkanoates (PHA) from microorganisms or genetically modified bacteria (Ashok et al. 2016).

   With the growing awareness of environment and sustainability issues caused by packaging materials, there is an increasing demand to find ecofriendly materials derived from renewable sources with comparable properties to substitute traditional packaging materials. Suitability of packaging materials depends on their mechanical and thermal properties which can be improved through steps like using a plasticizer, blending of polymers or reinforcement with nano-materials. More research that focuses on developing environmentally benign and competent alternative materials that are also economical, needs to be investigated in order to fulfill the demand for plastic-based packaging materials.

3 Role of Mycelium in Biocomposite Materials

Mushrooms are unique organisms with body structures and reproductive modes that may look like plants but are in fact fungi. Mushrooms are heterotrophs that must digest food to live, unlike autotrophs like plants that make their own food through photosynthesis. Mycelium (collection of hyphae), fruiting body and spores are the essential parts of fungi anatomy. Hyphae are long, branched filamentous structures that help in absorbing nutrients from decaying organic matter. While mycelia forms the vegetative part of the fungus and thereby is a growth agent, the fruiting body is a reproductive structure that produces spores. Fungal spores are haploids (carry only one chromosome for each gene) involved in fungal reproduction as they can germinate on damp soil (Mojumdar et al. 2021).

Mycelium gets attached to the medium on which it is grown. The digestive enzymes secreted from hyphae tips have the ability to break down organic waste material to a matter of less complex body plan which allows the hyphae to grow on a substrate. This process of degradation of the substrate materials during which mycelium grows on the substrate by bonding and partially replacing the substrate with a strong biomass of the fungus is called colonization (Appels et al. 2019). Once the mycelium-based bio composite material grows into the required shape and density, further growth of mycelium has to be arrested. Heating and drying are the two ways that can be used to cease the growth of mycelium based bio composite materials. Drying process can temporarily cease the growth of fungi leading to hibernation. It also means that by providing favorable environmental conditions like moisture, the mycelium can grow again. However, heating of mycelium arrests any further growth by permanently destroying them.

A large variety of mycelium based bio composite materials can be developed by varying the fungal species used for inoculation or by changing the type of substrates or additives used. Properties of mycelium bio composite materials can be influenced through optimizing the factors like growing conditions or processing techniques. Several studies have reported the properties of different mycelium biocomposites compared against the conventional plastics like polystyrene (Attias et al. 2017; Haneef et al. 2017; Jones et al. 2017).

Mycelium bio composite materials are made by growing them into the required shapes in customized moulds. Mycelium grows around substrates like sawdust or coir pith by binding them together and the result is a compostable material which is an environmentally benign substitute to expanded polystyrene and other polymers used for cushioning of packaging goods. However, their ability to compete with synthetic materials as a protective packaging material in terms of cost and performance is yet to be established (Ellen MacArthur Foundation 2017).

Fungi grows with a filament like structure to form branches and this architecture helps them to grow quick in soil. Elongation of fungal hyphae is strictly due to the deposition of polysaccharides (Gooday 1995). The forward movement of vesicles with new cell membranes causes the hyphal tips to extend. The excretion of lytic enzymes enables the hyphae to grow through the substrates allowing them to receive nutrients in the form of solutes. The redistribution of internal metabolites throughout the structure is done through translocation. (Olsson 1995). Active hyphae are involved in activities like nutrient uptake, branching and translocation while inactive hyphae are no longer directly involved in those activities. Hyphal tips are the ends of those active hyphae which are extended by using the nutrients inside the fungus. Thus, a hyphal tip extends to become hyphae as it begins to form branches and receive nutrients from adjacent material. Whatever be the environment, fungus needs the presence of certain elements or their combination for their steady growth. Elements like carbon, hydrogen, nitrogen, sulphur, phosphorus, oxygen and several others including metals are of special interest in this context (Boswell et al. 2003).

4 Potential of Mycelium Biocomposite Materials for Packaging Applications

Labelling of green products and marketing them as such had an appeal only with a smaller customer base until recently, however, an increase in awareness about the positive effects of using sustainable and renewable materials has brought in positive changes in perception to a larger customer base. There has been an increase in purchase power among the eco-conscious consumers who happen to be mostly the younger generation which has made a shift in the sales and marketing landscape and has inspired the manufacturers to focus more on sustainable materials. Consumers are now more inclined towards greener products that advertise sustainability and towards the companies that are keen on corporate social responsibility. The combined effect of these value based thinking has made it look like a viable proposition and has encouraged the manufacturers to incorporate sustainable business practices to their manufacturing chain that consists of stakeholders like suppliers, consumers and employees (Matthews and Rawlings 1999. Mohanty et al. 2005, Kazmierski 2012).

If this increased customer affinity can be channelized to a growth in sales, the companies that switch to sustainable packaging materials from conventional materials like polystyrene could benefit from increased sales revenue. They might also enjoy a young dedicated customer base who is keen on purchasing eco labeled products even after paying a slight premium in price for sustainability. Consumers are now aware of the waste generated as a result of e-commerce and buying consumable goods and they are the more interested to minimize the packaging waste than ever (Abhijith et al. 2018).

Corporates who advertise their commitment to ecological and socially responsible business practices are more likely to get a considerable boost in sales and revenue. Retail sales data of selected goods across several brands in different countries suggests that the products marked with a green labelling on its packaging has experienced an annual increase in average sales by 2%, in comparison with the brands without a green labelling that showed a meager 1% increase in sales. Products having environmental benefits experienced a whooping increase in annual sales by 5%, but obviously with the help of marketing promotions. The increase in sales and revenue of products will help to quickly overtake whatsoever the additional costs are associated with redesigning of their packaging (Abhijith et al. 2018).

Bio design and growing of fungal mycelia in suitable moulds use living organisms to create a viable substitute for polystyrene based foam in conventional packaging. The development and use of mycelium based biocomposite foam

Fig. 1 Mycelium composite material molded for packaging applications

supports a commitment to use renewable materials for better sustainability. Figure 1 shows Mushroom based foam being used for some of the several applications in packaging. At the time when these materials can be developed cost effective, it could change the status quo for good and would reduce the use of non-biodegradable petroleum derived synthetic waste materials that adds to the pollution. Also, the agricultural wastes for growing mycelium biocomposite material could derive additional value from this increased demand. This could very well turn as an added income to the farmers who could utilize these as raw materials instead of incinerating it.

These materials are designed for single use and after its useful life, it will biodegrade either in a compost pit or in landfills instead of remaining there without decomposition forever. Mycelium biocomposite materials are capable of creating an impact in the area of sustainable packaging and will make oil-based plastic materials obsolete and radically change the way the environment has been affected due to non-biodegradable packaging materials. Mycelium based packaging materials have the potential and will make those persistent oil-based plastic materials obsolete and radically change the way industry impacts the environment. Raw materials to be used as substrate to grow mycelium can be any feedstock material (agricultural by-products) that are locally available in abundance, which makes it suitable for manufacturing the biocomposite foam from anywhere in the world. Minimal logistics and transportation is sufficient if the raw materials and finished products are produced locally, using local feed stocks (Abhijith et al. 2018; Jiang et al. 2013).

These shifts in customer behaviour has an impact in global economy and it is being noticed by the corporate giants like Coca Cola and Unilever and they have included sustainability as a core value of their brand. Customers around the world are vocal on local and sustainable products more than ever. The use of mycelium biocomposite materials in packaging will offer the businesses a new way to tap into the values of potential customers and a reduction in environmental impact.

5 Early Adopters of Mushroom-Based Packaging

Any change in business practices in order to transform the present methods to sustainable packaging might seem like an unnecessary cost, especially for smaller firms with tight margins. However, despite the size of the business, a radical rethinking of the packaging process can be done in order to reduce the harm it does to the environment and focus more on sustainability. While packaging is an important entity in the marketing of any product, a large part of it turns as disposable waste once the item has been unpacked. Mycelia is a natural binder that can grow on agricultural by products like corn, coir pith or oat husks to make sufficiently durable cushioning materials that could substitute expanded polystyrene in practically every application. More and more firms have declared their commitment to reduce dependency on Styrofoam during the past few years and they are actively looking for alternative materials for their products.

Ecovative design is a New York based biotech company and is a pioneer in manufacturing of mushroom based foam. They have gone a long way in making the process efficient, all the while maintaining the key properties of material intact. Corporates like Dell is one of the early adopters that has announced their decision to use the eco-friendly fungal mycelium based foam for shipping their servers in its packing cases. They have extensively tested these material in their labs to ensure that the same amount of safety is provided to their products when compared to traditional expanded polystyrene foam. While they satisfy the necessary requirements, cushioning from mycelium materials are found to be more suited for heavy goods like servers. Mycelium based packaging materials for a standard server can be grown in the mold usually in one to 2 weeks' time. The use of ecofriendly packaging materials comes as a part of the firm's plan for a more sustainable shipping strategy. Not only that mycelium is renewable which makes it a green solution, the organic based mycelium foams can be composted easily after its useful life (Abhijith et al. 2018, Mojumdar et al. 2021).

Ford motor company has decided to make use of mycelium-based foam in automotive parts like bumpers, side doors, and dashboards. The immediate future will see a new generation of cars with more biodegradable components while at present, about 15 kg of synthetic foam is present in each car being manufactured and Ford is likely to replace at least a part of it with eco-conscious alternatives. These materials can be decomposed in a short period after its useful life unlike petroleum derived synthetic foam. The furniture giant Ikea, is also determined to reduce its use of petroleum-based synthetic packaging materials and is keen to substitute polystyrene. Mycelium based cushioning materials is one among the few alternative materials under consideration (Abhijith et al. 2018; Mojumdar et al. 2021).

6 Production of Mycelium Biocomposite Materials

The production of the mycelium biocomposite samples can be divided into two phases. In the first phase, the mycelium/mushroom roots of *Pleurotus ostreatus* species of oyster mushroom are grown and the biocomposite samples are prepared in the second phase.

6.1 Phase 1: Growing of Mycelium

Mycelia is usually grown in a basal medium such as mineral salt, and is supplemented with nutrients like sources of carbon, nitrogen and inorganic compounds (Zhu et al. 2015). Factors like initial pH, carbon source, nitrogen source and presence of inorganic compounds has a heavy influence on the process of microbial mycelia production under submerged fermentation conditions. While factors like fermentation temperature, time, rotation speed and inoculum size affect the fermentation process. A few organic compounds that influences the production of mycelium are $ZnSO_4$, $MgSO_4$, $CuSO_4$, $CaCO_3$, K_2HPO_4, KH_2PO_4, and $Zn(CH_3COO)_2$ (Zhu et al. 2015).

The *Pleurotus ostreatus* species oyster mushroom has been reported as a most favorable choice used for the development of mycelium (Sivaprasad et al. 2021; Hoa and Wang 2015). Oyster mushroom spawns have more life and can endure higher temperatures when compared to other species of mushrooms (Zhu et al. 2015). The growth of mycelium is enhanced by using a medium of potato dextrose agar (PDA), (HI media MH096). The bio composite material has been reported to be prepared in a matrix of growth promoting materials like sawdust or coir pith. Fine particles of the substrate are more suitable for growth of mycelium as the size of particles have a direct impact on binding. Once the required growth of the sample is achieved then it is chemically sterilized and the excess moisture is driven out.

The fruiting body of the mushroom was sliced into tiny parts and was kept at the base of a mixture of steam sterilized Potato dextrose agar (PDA) medium and distilled water. An incubation temperature between 24 °C and 27 °C is important for growth of mycelium and the samples were kept at 25 °C for about 5–7 days. (Islam et al. 2017; Bruscato et al. 2019). Figure 2 shows the various samples of fungal mycelium.

The microscopic images of mycelium under different stages of its growth are shown in Fig. 3. These pictures are captured at an interval of 7 days. The first image is captured on the seventh day just after the mushroom is moved to dextrose agar. The image has been contaminated with the presence of external fungi. Mycelium was again freshly sub cultivated and a second image showing development of mycelia was captured on 14th day. The third image captured on the 21st day shows mycelium growing without contamination (Jose et al. 2021).

.

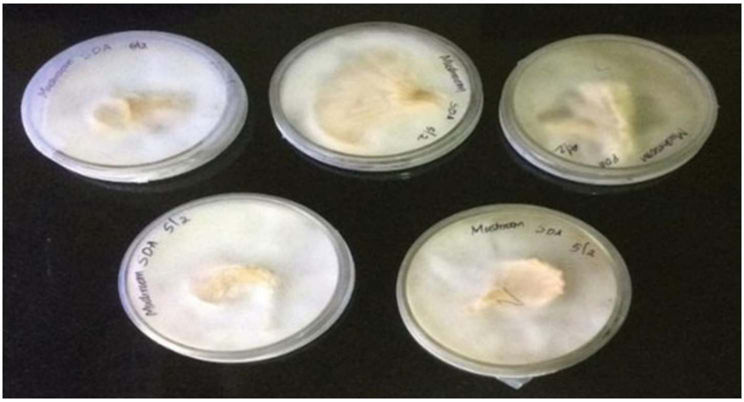


Fig. 2 Mycelium fungus

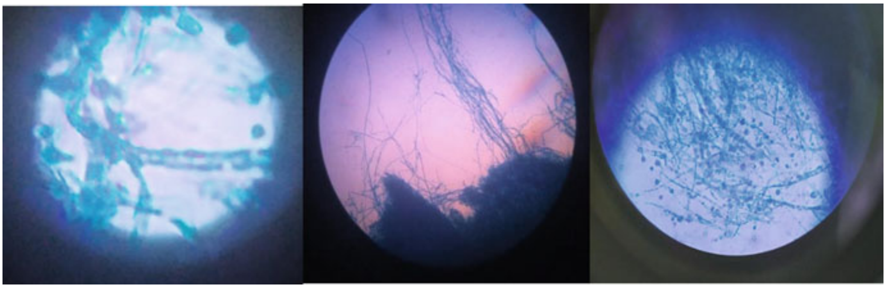


Fig. 3 Microscopic images of growing mycelium

6.2 Phase 2: Preparation of the Biocomposite Materials

Mycelium formed in the first phase is placed in the sterilized substrate at a temperature of 25 °C and relative humidity of 80% and provide a source of nutrition for further growth of mycelium. Sterilization process will kill the microbes present inside the mixture and will cease the growth of mycelia and it takes at least a week for the mycelium to attach entirely to the substrate. It is then transferred to the mold so that the bonds become closer and form a stable structure (Jose et al. 2021). Figure 4 show the biocomposite sample developed from sterilized sawdust and mycelium fungus.

The shelf life of the material is a priority as these bio composite materials can only be a viable substitute to polystyrene if their shelf life is also good as they mainly find their application in the packaging industry, where it might also have to be stored for extended periods. Fungal mycelium-based biocomposite materials are reported to have a lower shelf life and attempts have been made to improve their shelf life by adding coir pith as a substrate material along with saw-dust in the ratio 2:3 (Sivaprasad et al. 2021). The presence of lignin in coir-pith makes it difficult for

Fig. 4 Mycelium-sawdust bio composite foam

the microbes to digest them. Hence the presence of coir-pith can significantly increase the shelf life of mycelium composite materials than when they are prepared alone with sawdust as the substrate. However, any reduction in the amount of saw-dust has led to a reduced growth rate as it is the main nutrient supplier for mycelia in and a decrease in the amount of coir-pith can lead to a decrease in shelf life as the lignin content is reduced (Bruscato et al. 2019; Shashirekha and Rajarathnam 2007; Islam et al. 2018).

Figure 5 shows the process of preparing the mycelium composite material samples. The spawns are evenly distributed in the mold initially before the mold is filled with matrix (saw-dust coir-pith mixture) material. Once the inoculant and substrate are placed in the mold, the mold is fully wrapped but with sufficient holes punctured to maintain enough ventilation and humidity. The molds filled with saw-dust coir-pith mixture and spawns are kept in a laminar airflow cabinet for around 2 weeks and during which, their growth is monitored and water is sprayed every 2 days to ensure the required humidity. On completion of the growth period, the sample is dried in a hot air oven at a temperature of 140 °C for 20 mins (Sivaprasad et al. 2021). Drying of the samples drive out the moisture in it and in the process makes it light in weight. It also inhibits the further growth of mycelium Fig. 6 shows the various samples fabricated with different shapes and size.

Fig. 5 Process of preparing the samples

Fig. 6 Mycelium bio composite samples fabricated in different shapes and size

7 Properties of Mycelium Biocomposite Materials

Promising results were observed when the dense mycelium bio composite samples were subjected to various characterization tests. Tests like thermogravimetric analysis (TGA) and Differential Scanning Calorimetry (DSC) analysis indicated that the thermal stability of mycelium-sawdust bio composite specimens are far more superior when compared to that of expanded polystyrene (Jose et al. 2021). Mycelium bio composites are made of biodegradable raw materials like mushroom roots and sawdust, and this biodegradable nature of mycelium composite materials is a significant influence for its selection as an alternative material to replace expanded polystyrene in packaging applications. Sustainable materials have been an important player in the strategy to reduce environmental pollution. Mycelium bio composite materials require only minimum energy for their production and thus is a strong competitor to expanded polystyrene in packaging applications.

7.1 Toxicity Test

Incineration is not the best way of waste disposal for either EPS or mycelium bio composite materials. However, the non-biodegradable polystyrene waste is more susceptible to accidental fires in waste landfill sites especially if they are not wholly covered with soil as they are meant to be. Mycelium based bio composite material will quickly biodegrade in outdoor environmental conditions so that the instances involving their burning in a landfill site will be rare (Bruscato et al. 2019; Girometta et al. 2019). When polystyrene is burned, it emits hazardous gases and releases particulate matter to the atmosphere. A toxicity test was performed using a Respirable dust sampler (Envirotech, APM 460 NL) in order to find the extent up to which the amount of particulate matter concentration and hazardous gases has been emitted when polystyrene and mycelium composites were burned. Combustion products contained traces of gases like nitrogen dioxide, carbon monoxide, and sulfur dioxide. The amount of particulate matter released into the atmosphere is shown in Table 1 (Jose et al. 2021).

Results of toxicity tests suggests that burning of expanded polystyrene releases more toxic substances than mycelium bio composite samples. The results are in agreement with the previous results reporting the flame-resistant nature of mycelium-based composites due to high char residue and release of water vapour (Jones et al. 2018).

The burning of mycelium bio composite materials release more carbon monoxide and Sulfur dioxide than when EPS is burned. This is due to the presence of saw dust material as substrate in the bio composite. However, the amount of particulate matter released is very less for the bio composite than that of EPS. Nitrogen dioxide emissions from bio composite material is nearly half that of EPS. Even though mycelium bio composite materials release significant amounts of Sulfur dioxide and carbon monoxide when burned, the instances of mycelium bio composite material catching a fire is very rare as they degrade very quickly leaving little chances of an accidental fire.

Table 1 Combustion products of mycelium sawdust composite material

Sl. No.	Combustion products in μg/m^3	Expanded Polystyrene	Mycelium bio composite
1	Sulfur dioxide	95.59	167.87
2	Nitrogen dioxide	89.78	43.80
3	Particulate matter	1643.0	153.31
4	Carbon monoxide	49	92

7.2 Scanning Electron Microscopy and Energy Dispersive Spectrum Analysis

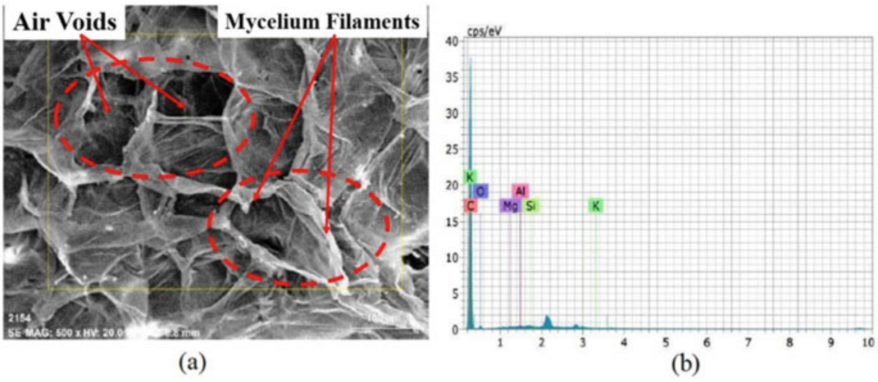
The Scanning Electron Microscopy (SEM) image of mycelium composite materials clearly indicate the presence of a network-like microstructure with fine filament distribution in the matrix while polystyrene is reported to have a plate-like structure. It is evident that the mycelium composite also has a well-defined structure when compared to EPS with long polymeric chain structures The open cell structure of mycelium composite material is responsible or the cushioning effect of the foam material which enables it as a suitable alternative for packaging applications (Jose et al. 2021).

The SEM image of mycelium composite (see Fig. 7(a)) at a magnification of 500X shows mycelium filaments binding loosely packed sawdust matrix. The air voids present in the structure is responsible for the lightweight characteristics of the mycelium composite material. Figure 7(b) shows the Energy Dispersive Spectrum (EDS) which reveals the elements present in the sample and they are potassium (K), carbon (C), oxygen (O), magnesium (Mg), Aluminium (Al), and Silicon (Si) (Jose et al. 2021).

The matrix of mycelium bio composite materials has a continuous orientation throughout the material which indicated that their physical properties are consistent throughout the material. (Girometta et al. 2019).

7.3 Density and Moisture Content

The average bulk density for mycelium - sawdust composites were found to be 178.5 kg/m^3 when polystyrene has a density of 1040 kg/m^3. Mycelium composite materials are biologically grown without applying any compressive forces. Samples



(a) (b)

Fig. 7 Mycelium bio composite specimens (**a**) SEM image (**b**) EDS spectrum with a higher density can be achieved through compressing and densifying of the material. However, this densification can bring out radical changes in other properties of the material. The effect of densification in mycelium based materials is sparsely studied or reported. (Jose et al. 2021).

The moisture content in mycelium composite samples were around 30% while EPS has nearly zero water retention. Moisture retention is a serious determining factor especially when the primary application is in the field of packaging. Applying a thin film of lamination over the surface can greatly increase the moisture resistance of mycelium composites which also increases the shelf life but it comes at the cost of reducing the biodegradability.

7.4 Water Absorption Test

The average density of mycelium-based material after water absorption is about 318.309 kg/m^3. Biocomposite samples remained afloat despite gaining 120–185% mass as shown in Table 2 (Sivaprasad et al. 2021; Attias et al. 2020). The mycelium composite was able to retain its dimensions without any deformation, decomposition or warping even after absorbing water. This indicates that the composite material is a suitable substitute for packaging applications where the product needs to be stored for a limited amount of time.

A biocomposite material that absorbs water is definitely not an ideal feature for a packaging material. However, the mycelium composite material can be considered when the items packed are dry and free from liquids.

7.5 Acoustic Impedance Test

Mycelium composites have superior sound absorbing properties than EPS as evident from Table 3. Mycelium biocomposite material has a higher sound absorption coefficient compared to EPS. Sound waves are either absorbed or reflected and are only partially transmitted through the bio composite (Sivaprasad et al. 2021).

Table 2 Water absorption of mycelium composite material

Sl No.	Time (h)	Weight (kg)	Volume (cm^3)
1	0.5	0.065	157.0796
2	1	0.095	171.5969
3	2	0.115	171.5980
4	4	0.135	181.8390
5	24	0.15	158.319
6	48	0.155	188.832
7	96	0.160	188.832

Table 3 Sound absorption coefficient of mycelium composite

Sl.no	Frequency (Hz)	EPS	Mycelium biocomposite
1	250	0.04	0.17
2	500	0.05	0.19
3	1000	0.10	0.33
4	1600	0.33	0.22

The average sound absorption coefficient for mycelium composite is 0.2275 while that of EPS is 0.13. The average sound absorption coefficient of 0.2 is kept as a standard benchmark for categorizing material as a sound insulator or not. Since the average sound absorption coefficient of composite is above 0.2, mycelium composites have a great potential in the field of sound insulation of walls, doors, and ceilings of concert halls, cinema, auditorium, and broadcasting studio (Girometta et al. 2019; Li and Ren 2011).

7.6 Mechanical Strength of Mycelium Composites

It is observed that the average value of compressive strength and compression modulus of biocomposite material is superior to that of EPS. The flexural modulus of mycelium biocomposite is about five times the flexural modulus of EPS. Since the biocomposite material has a higher compression modulus and compressive strength than EPS, it is safe to assume that the biocomposite material is stronger in compression than EPS. The biocomposite material is capable of taking higher compressive loads when compared to EPS, which will help to reduce the thickness of material to be used for packaging which in turn reduces cost. (Sivaprasad et al. 2021).

7.7 Thermal Conductivity and Limiting Oxygen Index

The thermal conductivity of mycelium biocomposite is a little greater than that of the EPS samples. The mycelium composite has a thermal conductivity of about 0.069950 W/m-k whereas the EPS sample has 0.053984 W/m-k. For the same temperature difference, mycelium biocomposite can transfer more heat compared to EPS, hence expanded polystyrene is marginally a better insulator (Sivaprasad et al. 2021).

The observations from Table 4 indicate that the LOI of EPS is less than 21% and that of the biocomposite is greater than 21%, therefore the biocomposite is self-extinguishing and has fire-retardant properties (Rejeesh and Saju 2017). The LOI of mycelium biocomposite is 23% which is classified as a fire-retardant material whereas EPS has an LOI of 19% which can be classified as a flammable material.

Table 4 Thermal conductivity and LOI

Sample	Material		Thermal conductivity (W/m-K)	LOI (O_2%)
1	Expanded polystyrene (EPS)		0.053984	19
2	Mycelium biocomposite		0.069950	23

8 Application of Mushroom Biocomposites

It was in the 1980s, where Shigeru Yamanka a Japanese scientist reported the gluing power of mycelium to be effective in the paper industry and in manufacture of building materials (Mojumdar et al. 2021). Recently, mycelium is being used in many industries like design, fashion, packaging, architectural design, etc.

The possibility of using mycelium bricks were also exploited to find new applications including the construction sector. Mycelium bricks were used to build a tower as tall as 40 feet and it is the largest structure reported to be made from mushroom materials. Over the past few years, mycelium has been used in building a few architectural projects like Hy-Fi Tower, the Mycotecture alpha, MycoTree (Abhijith et al. 2018; Mojumdar et al. 2021). David Benjamin designed a temporary structure of the Hy-Fi tower in the form of three 13-m tall intersecting cylinders built with 10,000 blocks of mycelium and the tower remained for 3 months in summer (Mojumdar et al. 2021). Phill Ross, the cofounder of MycoWorks designed a small-scale pavilion Mycotecture Alpha. (Karana et al. 2018).

It has also been tried as an insulation material similar to insulation boards, leading to a more energy efficient building It also achieved class A fire rating without using toxic fire retardants. According to Ecovative, their product can be used in many more applications than just packing cases. (Abhijith et al. 2018).

Myco Board is an engineered wood substitute that has the potential to replace wood, plywood or similar engineered wood products (Fig. 8). Engineered wood products that use formaldehyde resins can be substitute by a resin less technology where particles are bonded together with naturally occurring mycelium

Fig. 8 Myco-boards made from mycelia

Myco-boards are expected to substitute popular fabricated wood substitutes like medium density fiber boards and particle boards (Abhijith et al. 2018).

Greensulate is a trade mark fire-retardant board from Ecovative Design that is primarily used for sustainable insulation (Abhijith et al. 2018; Casini 2016). MycoWorks and MOGU Inc. have been successful in producing synthetic leather from mycelium. The product is durable, flexible, sustainable and waterproof. “Future of Plastics” is a project started by OFFICINA CORPUSCOLI that focuses on the development of kitchenware and substitutes to disposable plastics (Mojumdar et al. 2021).

MOGU have been developing mycelium-based wall and ceiling panels (Mojumdar et al. 2021). A Shell Mycelium domed building has been constructed in India for Kochi Muziris Biennale 2016 (Mojumdar et al. 2021).

Various investigations to find newer applications for mycelium composites especially in the field of architecture arein place world wide. The objective is to improve the mechanical, thermal and chemical properties of mycelium-based bio composites and find a way for affordable, and durable, structures which can challenge environmental threats and weather.

9 Conclusion

Fungal mycelium-based bio composites are a centre of attraction not just because it is a sustainable choice instead of the conventional non-biodegradable packaging material, but they are also researched into newer applications like air purification filters or as insulation panels. The manufactured mushroom based packaging material has to maintain a consistent density with a binding material that is a microbe. The real challenge also lies in the scaling up of the production of mycelium composite. In general, factors like reproducibility, or mechanical and thermodynamic properties of mycelium bio composites are still inferior to synthetic materials. These synthetic materials have been in use under extreme conditions for a long time now and are found useful in a variety of applications. However, the investigation on mycelium composites has only recently gained momentum and thus it is safe to conclude that these materials have all the potential to substitute the conventional packaging materials which are mostly petroleum derived synthetic materials. Mycelium bio composite materials as an alternative to expanded polystyrene could largely change the way how packaging industry works currently but it is expected to happen silently than as a radical shift.

References

Abhijith R, Ashok A, Rejeesh CR (2018) Sustainable packaging applications from mycelium to substitute polystyrene: a review. Mater Today Proc 5(1):2139–2145

Appels FV, Camere S, Montalti M, Karana E, Jansen KM, Dijksterhuis J, Krijgsheld P, Wösten HA (2019) Fabrication factors influencing mechanical, moisture-and water-related properties of mycelium-based composites. Mater Des 161:64–71

Arifin YH, Yusuf Y (2013) Mycelium fibers as new resource for environmental sustainability. Procedia Eng 53:504–508

Ashok A, Abhijith R, Rejeesh CR (2018) Material characterization of starch derived bio degradable plastics and its mechanical property estimation. Mater Today Proc 5(1):2163–2170

Ashok A, Rejeesh CR, Renjith R (2016) Biodegradable polymers for sustainable packaging applications: a review. IJBB 2(2):1–11

Attias N, Danai O, Abitbol T, Tarazi E, Ezov N, Pereman I, Grobman YJ (2020) Mycelium biocomposites in industrial design and architecture: comparative review and experimental analysis. J Clean Prod 246:119037

Attias N, Danai O, Ezov N, Tarazi E, Grobman YJ (2017) Developing novel applications of mycelium based biocomposite materials for design and architecture. In: Proceedings of Building with Biobased Materials: Best practice and Performance Specification, 6th–7th September, pp 76–77

Boswell GP, Jacobs H, Davidson FA, Gadd GM, Ritz K (2003) Growth and function of fungal mycelia in heterogeneous environments. Bull Math Biol 65(3):447–477

Bruscato C, Malvessi E, Brandalise RN, Camassola M (2019) High performance of macrofungi in the production of mycelium-based biofoams using sawdust—sustainable technology for waste reduction. J Clean Prod 234:225–232

Casini M (2016) Smart buildings: advanced materials and nanotechnology to improve energy-efficiency and environmental performance. Woodhead Publishing, Sawston

Containers P, Good ND (2016) Documentation for greenhouse gas emission and energy factors used in the waste reduction model (WARM)

Cooper TA (2013) Developments in bioplastic materials for packaging food, beverages and other fast-moving consumer goods. Trends in Packaging of Food Beverages and Other Fast-Moving Consumer Goods (FMCG) 5:108–152

Ellen MacArthur Foundation (2017) The new plastics economy: Rethinking the future of plastics and catalysing action. http://www.ellenmacarthurfoundation.org/publications

Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. Sci Adv 3(7):e1700782

Ghazvinian A, Farrokhsiar P, Vieira F, Pecchia J, Gursoy B (2019) Mycelium-based biocomposites for architecture: assessing the effects of cultivation factors on compressive strength. In: The eCAADe and SIGraDi Conference. University of Porto, Porto

Girometta C, Picco AM, Baiguera RM, Dondi D, Babbini S, Cartabia M, Pellegrini M, Savino E (2019) Physico-mechanical and thermodynamic properties of mycelium-based biocomposites: a review. Sustainability 11(1):281

Gooday GW (1995) The dynamics of hyphal growth. Mycol Res 99(4):385–394

Haneef M, Ceseracciu L, Canale C, Bayer IS, Heredia-Guerrero JA, Athanassiou A (2017) Advanced materials from fungal mycelium: fabrication and tuning of physical properties. Sci Rep 7(1):1–11

Hoa HT, Wang CL (2015) The effects of temperature and nutritional conditions on mycelium growth of two oyster mushrooms (*Pleurotus ostreatus* and *Pleurotus cystidiosus*). Mycobiology 43(1):14–23

Hopewell J, Dvorak R, Kosior E (2009) Plastics recycling: challenges and opportunities. Philos Trans R Soc Lond Ser B Biol Sci 364(1526):2115–2126

Iles A, Martin AN (2013) Expanding bioplastics production: sustainable business innovation in the chemical industry. J Clean Prod 45:38–49

Islam MR, Tudryn G, Bucinell R, Schadler L, Picu RC (2017) Morphology and mechanics of fungal mycelium. Sci Rep 7(1):1–12

Islam MR, Tudryn G, Bucinell R, Schadler L, Picu RC (2018) Mechanical behavior of mycelium-based particulate composites. J Mater Sci 53(24):16371–16382

Jiang L, Walczyk D, Mooney L, Putney S (2013) Manufacturing of mycelium-based biocomposites. In: Manufacturing of mycelium-based biocomposites. Proceedings of the International SAMPE Technical Conference, Long Beach, CA, pp 1944–1955

Jones M, Bhat T, Kandare E, Thomas A, Joseph P, Dekiwadia C, Yuen R, John S, Ma J, Wang CH (2018) Thermal degradation and fire properties of fungal mycelium and mycelium-biomass composite materials. Sci Rep 8(1):1–10

Jones M, Huynh T, Dekiwadia C, Daver F, John S (2017) Mycelium composites: a review of engineering characteristics and growth kinetics. J Bionanosci 11(4):241–257

Jose J, Uvais KN, Sreenadh TS, Deepak AV, Rejeesh CR (2021) Investigations into the development of a mycelium biocomposite to substitute polystyrene in packaging applications. Arab J Sci Eng Arab J Sci Eng 46(3):2975–2984

Karana E, Blauwhoff D, Hultink EJ, Camere S (2018) When the material grows: a case study on designing (with) mycelium-based materials. Int J Des 12(2):119–136

Kazmierski C (2012) Growth opportunities in global composites industry 2012–2017. Composites:21–23

Li Y, Ren S (2011) Acoustic and thermal insulating materials. In: Building decorative materials. Woodhead Publishing, pp 359–374. https://doi.org/10.1533/9780857092588.359

Matthews FL, Rawlings RD (1999) Composite materials: engineering and science. Elsevier

Miles PG, Chang ST (2004) Mushrooms: cultivation, nutritional value, medicinal effect, and environmental impact. CRC Press

Mohanty AK, Misra M, Drzal LT (2005) Natural fibers, biopolymers, and biocomposites. CRC Press

Mojumdar A, Behera HT, Ray L (2021) Mushroom mycelia-based material: an environmental friendly alternative to synthetic packaging. In: Vaishnav A, Choudhary DK (eds) Microbial polymers. Springer, Singapore, pp 131–141. https://doi.org/10.1007/978-981-16-0045-6_6

Olsson S (1995) Mycelial density profiles of fungi on heterogeneous media and their interpretation in terms of nutrient reallocation patterns. Mycol Res 99(2):143–153

Rejeesh CR, Saju KK (2017) Effect of chemical treatment on fire-retardant properties of medium density coir fiber boards. Wood Fiber Sci 49(3):332–337

Rigamonti L, Grosso M, Møller J, Sanchez VM, Magnani S, Christensen TH (2014) Environmental evaluation of plastic waste management scenarios. Resour Conserv Recycl 85:42–53

Rosato DV, Rosato MG (2012) Injection molding handbook. Springer Science & Business Media

Shashirekha MN, Rajarathnam S (2007) Bioconversion and biotransformation of coir pith for economic production of Pleurotus Florida: chemical and biochemical changes in coir pith during the mushroom growth and fructification. World J Microbiol Biotechnol 23(8):1107–1114

Sivaprasad S, Byju SK, Prajith C, Shaju J, Rejeesh CR (2021) Development of a novel mycelium biocomposite material to substitute for polystyrene in packaging applications. Mater Today Proc 47(15):5038–5044 https://doi.org/10.1016/j.matpr.2021.04.622

Tudryn GJ, Smith LC, Freitag J, Bucinell R, Schadler LS (2018) Processing and morphology impacts on mechanical properties of fungal based biopolymer composites. J Polym Environ 26(4):1473–1483

Vilaplana F, Strömberg E, Karlsson S (2010) Environmental and resource aspects of sustainable biocomposites. Polym Degrad Stab 95(11):2147–2161

Zhu W, Guo C, Luo F, Zhang C, Wang T, Wei Q (2015) Optimization of Calvatia gigantea mycelia production from distillery wastewater. J I Brewing 121(1):78–86