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Review

Fungi-based Biomimetic Approach to Address Plastic Pollution: A Developing Nation's Perspective

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Abstract: Plastic waste management has become a major problem in the present times, and many countries are struggling to deal with it. The situation has become a crisis in developing nations due to a lack of proper waste management, resources, technology, and political will. The extensive usage of foam-based packaging materials such as Styrofoam as a secondary packaging material has led to environmental pollution both in land and water, in developing countries. It is important to address this problem using a sustainable approach such as biomimetic manufacturing. One such solution that is present in developed nations is mycelium-based packaging, wherein the agricultural and industrial-based cellulose waste is converted into a biocomposite with the help of a fungi root network. Such a process has the potential to convert biomass into useful products but also has an indirect effect on pollution reduction by eliminating stubble burning in nations like India. In this review, we examine the details of the manufacturing process, properties, advantages, and limitations of such composite materials. A comparison of the present status of such materials produced in the market by some of the companies across the world is presented. Finally, the challenges involved with such materials and the future directions are discussed.

Keywords: waste management; plastic pollution; biomimetics; mycelium materials; developing nations

1. Introduction

In a global analysis study, it was found that we have accumulated 4977Mt of plastic waste in landfills or the natural environment and it is expected to increase to ~12000 Mt by 2050 [1]. Plastic waste management is a bigger menace in developing nations because of the lack of integrated waste management systems. For example, in India, waste disposal and management of packaging materials is a growing problem with the rise in e-commerce platforms and commodities being shipped across the country to consumers. Current methods for waste disposal and management include at-source segregation of material followed by recycling. Most of the waste is simply sent to large landfills and buried which has a devastating impact on the environment (Figure 1). India's growth in manufacturing is going to increase the demand for expanded polystyrene. The push by the Government in Appliances and Consumer electronics will add to the demand for Extended PolyStyrene (EPS) and other foams. The market surveys forecast the global demand to be at 8.5 million tons in 2021 and the packaging industry contributes to almost half of the volume. In India, the PolyStyrene market is forecast at 0.34 million tonnes and expected to reach 0.5 million tonnes by 2030. It is observed that most of the consumption is from the construction and packaging industries. There are incidences of EPS burning that result in the release of toxic chemicals into the air and also instances of discarded EPS blocking drains in big cities [2]. Also, there is a company in India that has developed a machine that can be primarily used for recycling EPS, but it appears to be less percolated across the nation because of its specificity and low economic feasibility aspect of the EPS segregation by the local waste collection systems.

A. B.

Figure 1. EPS foam waste was found **A.** clogging the water canals [3], **B.** huge amounts found in a waste collection site.

To address this plastic pollution problem in the current times, it is of utmost importance to rethink the process of innovation and industrialization systems through learning from nature, instead of imposing them on nature. Thus, one can look at nature as a model, a measure, and a mentor, thereby enabling one to solve some human problems [4]. Living organisms can provide immense inspiration to develop novel materials because of their ability to adapt and regenerate. By specifically looking at some organisms from a technological perspective, we can decipher their intricacies of them and try to create novel technologies that mimic them. Specifically, there has been a lot of interest in creating novel materials termed " Engineering Living Materials" [5]. This approach needs novel ways of thinking to create materials and processes, with strong interdisciplinary interactions [6]. Biomimetics brings in scientists from various disciplines in combination with business people to develop products with functional and economic viability [7].

The most challenging aspect of 21st century is to develop models that sustain the livelihoods of people without harming the environment. Through a biomimetic approach, we can develop such models and in the past, there has been a significant interest observed around a 12-fold increase in the number of patents, research articles, and grants [8]. According to Fermaninan, biomimetics has the potential to contribute to the global economy in the order of 1.6 trillion dollars. Thus the pursuit of biomimetics is not only useful for economic benefits but also for use in the integration of innovation and development strategies in biodiverse developing countries [8]. The biomimetics process can either use single or multi-organisms. There is a significant amount of research where biomimetic processes/materials are developed using single organisms. Also, there is a rise in interest in the direction of using multiple organisms. For example, NASA has created the Center for the Utilization of Biological Engineering in Space (CUBES) to research integrated multi-organism biomanufacturing systems that will enable humans to produce materials, fuel, pharmaceuticals, and food [9]. In addition, working with multi-organisms may provide us with enhanced and multifunctional materials.

One of the prominent biomimetic processes based on fungi that had caught attention in the last 5-10 years, is the conversion of cellulose-based materials into useful forms such as nano papers, foams, panels, leather alternatives, and other flexible forms [10]–[15]. This process offers the unique ability to convert the cellulose waste streams coming from agricultural, industrial wood processing, and even roadside weeds, through a circular economy approach [16]–[20]. In addition, polysaccharides from the plants are the most abundant biomass making it a viable process [21], and cellulose itself accounts for 30% of the plant biomass [22]. Also, it is important to focus on issues like air pollution in countries like India, where 17.8 % of all deaths were solely attributed to air pollution [23]. It is reported that crop residue burning accounts for 15% of the air pollution in 2020, based on an analysis from the government's environment ministry. The real reason for crop residue burning in countries like India is primarily based on socioeconomic roots [24]. Earlier, technologies such as chemical treatments and mechanical methods, and their combination

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was used to convert agricultural biomass to biodegradable packaging but they were not successful due to some inherent challenges related to storage and transportation [25]. The research based on the fungi platform has resulted in the incubation of various biotechnology companies based in countries like the United States, Netherlands, Italy, and Indonesia, that have successfully produced products that are available for consumers. Overall, this fungi-based process offers enormous potential to impact the environment, economy, and livelihood of poor farmers. Thus, the development and expansion of such biomimetic processes are significant not only because of the economic and environmental prospects but also because it holds tremendous potential for the biodiverse developing countries to enable them to integrate such methods in their innovation and development strategies. In this review, a brief analysis is presented on fungi-based processes and their advantages, various materials produced using them, their commercial viability, and the present challenges to making them mainstream materials, specifically in the context of developing nations.

2. Fungi-based process and materials

Fungi are a species that are known to play significant roles in the environment and the world economy [26], such as environmental and food science, health, soil mineral weathering, and element cycling [27]. Fungi are an incredibly diverse kingdom of organisms and their ability to degrade organic matter like agricultural waste (paddy straw, hay) or industrial wood waste (sawdust, wood chips, etc.) makes them an attractive candidate for biodegradation and biotransformation of organic materials [28]. This can be attributed in great part to the biochemical characteristics such as producing a range of enzymes from the growing hyphal cells of fungi which form a tightly interwoven complex tissue called mycelium that has large surface area [29]. So far, the widely used fungi are *Ganoderma lucidum* and *Pleurotus ostreatus*, which belong to the white-rot fungus and have the ability to digest hard plant components such as lignin while simultaneously forming the woven network that binds the substrate [30]. Mycelium grows into the substrate through the application of physical pressure [31] and acts as a binding agent for the material it is incorporated within, thereby giving rise to stable and solid structures [32]. The hyphal cells are responsible for the conversion of substrate material around them into sugars which are used for fungal metabolism and it occurs in a selective manner or simultaneous process [33]. The branching and networking of mycelium occur through a highly polarized process called tip extension [34]. Mycelium growth is sensitive to environmental conditions and the underlying substrate, hence making it an attractive candidate to produce biocomposites with tunable properties [35]–[37]. With the increasing constraints or regulations from the authorities on the use of plastic-based materials, fungi also have the advantage of being an environmentally friendly material [38].

The process of fabrication using mycelium is relatively inexpensive and does not require sophisticated processing methods as compared to other biopolymer sources [16]. The process involves inoculating the prepared substrate material with the fungus followed by a growth period to allow the fungus to colonize the substrate material and form a biocomposite [39], as shown in Figure 2. Once the desired growth levels are achieved, the biocomposite is then incubated at an elevated temperature to reduce moisture content and prevent further growth of the mycelium [40]. The biocomposites produced are generally considered foam-grade materials and can thus be used to replace conventional plastic-based foams used in various forms of packaging. They are known to show good shape retention properties in a wet state which broadens the application of their use [41]. Such composites can also be post-treated in the form of hot pressing or cold pressing to achieve desirable properties that are usually better than the simply grown composites [13], [42].

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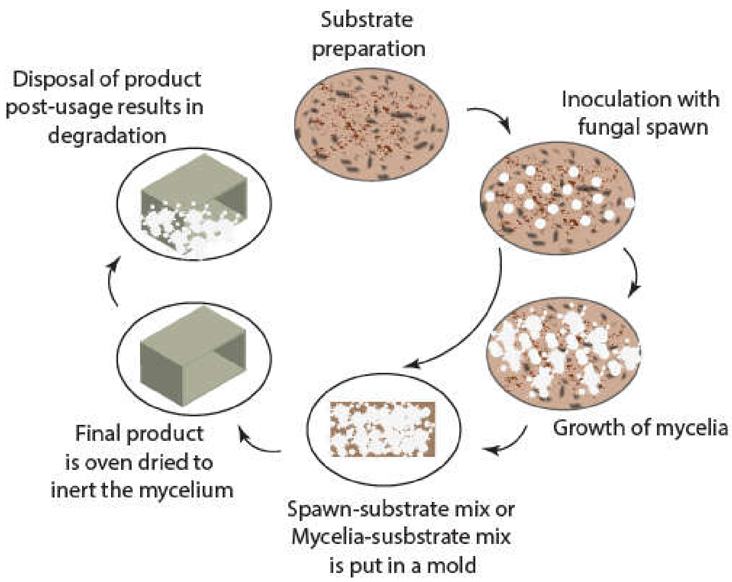

Figure 2. Fabrication steps of mycelium composite from cellulose-based waste.

Table 1. Comparison between a mycelium composite and similar materials available in the market.

	Mycelium composite	Extruded PolyStyrene	Bubble wrap	Shredded cardboard
Base material	Cellulose-based waste + mycelium	Polystyrene	Polyethylene	Cellulose
Degradability	30-60 days, under ambient conditions	Non-biodegradable	500-1000 years	5 years
Sustainability	Renewable source	Non-renewable resource	Non-renewable resource	Renewable source
Disposal	Even in your vegetable garden	Proper waste collection	Local waste recycling	Local waste recycling
Mechanical properties	Good (E=0.12-0.67 MPa) *[39] (0.1-1.5 MPa)*[43] High shock absorption	Good (E= 0.4 MPa, *[28]) Good shock absorption *[44]	Good E= 0.04 MPa * [45] High shock absorption[46]	Moderate Low compressive resilience Low shock absorption
Fire retardant	Yes [47]	No	No	No
Recyclability	Free of cost/cheap	Expensive	Expensive	Relatively less expensive

Studies based on the fabrication of leather-like materials as an alternative to the existing animal-based leather show that such alternatives can be cost-effective and environmentally friendly [48]. Unlike the growth process of fungal biocomposites materials, the sheet-like materials are produced by growing hyphal filaments either by using liquid or soil substrate medium, where the growth of the hyphae is controlled to form sheet-like materials [12], as shown in Figure 3. Also, this process involves stringent control of the growth conditions in terms of the carbon dioxide levels and humidity inside the chamber that will allow hyphae to grow directionally in search of oxygen [49]. More importantly, the production of these fungal leather-like materials also involves the usage of chemicals to alter the properties such as strength and elasticity [12]. Unlike fungal biocomposite materials process which is similar across various suggested methods, the production of leather-like materials made from pure mycelium can be produced through different production routes, specifically fermentation technologies [50]. The bioreactor technologies were present for long enough time which enable the scaling up process relatively easier as compared to the fungal biocomposites production.

A. B.

Figure 3. Materials produced from fungal platform **A**. Composite and **B**. Sheet-like. (Acquired from Naturewrks Technologies Pvt. Ltd.).

3. Advantages of mycelium-based materials

The mycelium-based products are a good alternative to the present plastic packaging as they are lightweight, relatively less expensive, and can be molded into the required shape. Based on the estimates from an earlier study, the mycelium-based composites are found to be 6 to 12 times cheaper in the cost of production as compared to Extended PolyStyrene [10]. The above estimates are primarily applicable to developed nations and this might not be the case for developing nations. Conventional biodegradable packaging derived from bioresources is deemed unsuitable for sending to landfills because of its propensity to release methane in the process of degradation [51]. Because of the biodegradable nature of the mycelium composites and their nutritional content, they might improve the soil quality after composting [52]. Thus, mycelium-based packaging can be a substitute for avoiding the above-mentioned methane problem. If agricultural waste is used to create fungal biocomposites to replace plastic, the benefits can be quadrupled by reducing pollution from crop burning, and be able to create large-scale manufacturing, and help farmers earn a little extra income.

The fabrication process of fungal biocomposites or pure mycelium materials allows us to modify them at different microscopic and macroscopic levels, along with various possible additives and even chemical alternations of the organism's cell wall. Thus these materials present a platform that can offer us a wide range of tunability and thereby find suitability in numerous applications [50]. One such example is the usage of mycelium composite as an alternative to DIY project electronic circuits [53].

4. Present market

The market for these products is primarily driven by the need to have biodegradable materials, quick adoption, and sustainable technologies in combination with initiatives from the governments. Presently, there are very few companies that were able to bring mycelium-based products into the market (Table 2). Ecovative is the first company to come up with the biocomposite idea and now they have ventured into making leather and foams. Mycoworks is another company that primarily focuses on making its trademark leather product Reishi™ and has received $125 million in funding to expand its manufacturing facilities. Based on the above-mentioned products, companies like IKEA and Dell have decided to use mycelium-based materials in some of their packaging [54].

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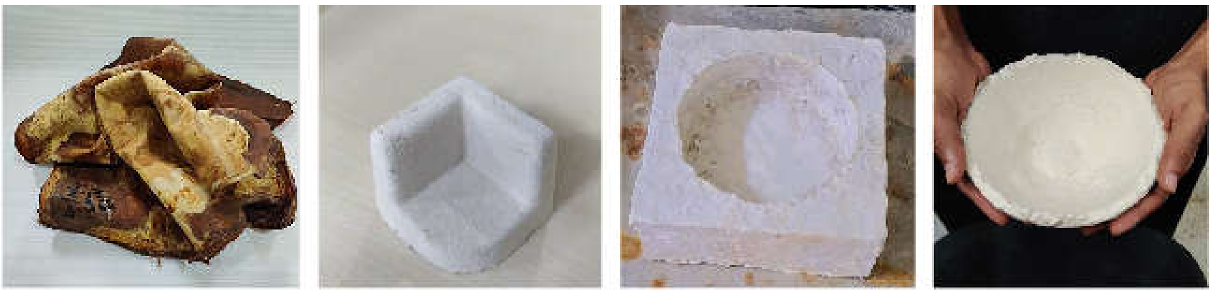
Table 2. List of prominent companies that are manufacturing mycelial materials.

Company	Location	Products (™)
Ecovative LLC	USA	Packaging (Mycocomposite) Foams (Air mycelium)
Mycoworks	USA	Leather (Reshi)
Bolt Threads	USA	Leather (Mylo)
Grown Bio	Netherlands	Packaging
Mogu Srl	Italy	Acoustic and floor panels
Mycotech Lab	Indonesia	Composite (BIOBO) Leather (Mylea)

In developing nations such as India, there has been a significant rise in the number of startups trying to work in mycelium materials (Table 3). Most of these startups are still in the process of validating their products and are in the very early phase of adoption by environmentally conscious consumers/companies (Figure 4). India being a strong agriculturally based economy, there is abundant access to cellulose and lignocellulosic raw materials that can be sourced from the local farmers and corporations that own large farms. The main challenge for these startups will be in coming up with cost-efficient upscaling for manufacturing and dealing with the complexities involved in that process.



A. B. C. D.

Figure 4. Samples images from the corresponding startups **A**. Fleather from *Phool* **B**. Corner support from *Dharaksha* **C.** Bottle support from *Kinoko Biotech* **D.** Lamp shade prototype from *Naturewrks.*

Table 3. Indian startups working on mycelium-based materials.

Company	Year founded	Products	Main raw material
Phool	2017	Packaging, Leather	Flower waste
Dharaksha Eco solutions	2020	Packaging	Agricultural waste (Hay)
Kinoko Biotech	2020	Packaging	Agricultural waste
NatureWrks Technologies	2022	Packaging	Agricultural waste and Industrial waste

5. Challenges of mycelium materials to penetrate mainstream market

One of the latest reports indicates that the economic feasibility of mycelium composites is not good enough compared to that of conventional plastic-based materials. To address this concern, the fabrication process needs industrialization and optimization based on various locally available fungi strains and raw materials. Also, 90% of this production cost is found to be incurred in labor costs during the manufacturing of fungal biocomposites [55]. Thus, there is ample amount of scope to increase employment in developing countries, but it might be at the cost of slight inconsistency in terms of the product quality due to the variation coming from human errors. The main source of carbon footprint in these composites are the plastic molds that are used in the process and this can be reduced by using the locally available resources [56]. Alternatively, bioplastics or novel materials can be used to fabricate these molds. Another main challenge is the storage of mycelium composites because the main component is cellulose which is prone to infestation by insects and rodents. Some studies suggest genetic modification could be route to improve the resistance to infestation [57]. This can also be solved by using biobased ingredients or coating that can act as deterrent to these infesting animals. There are very few studies that tested the longevity of these composite materials to determine the structural integrity and lifespan, in practical weather conditions [58].

Fungal biocomposite manufacturing is based on a growth process that is in contrast with conventional manufacturing which transforms the raw materials into the desired product using various techniques. Thus, it is crucial to integrate all the influencing factors in the initial phase of design conception [55]. Additionally, unconventional raw materials such as cardboard and newspaper were also used in mycelium composite fabrication, making it a more lucrative process [59]. In such cases the substrate preparation process may need additional treatment step to standardize the process. Even the biodegradability testing of mycelium composites needs to be standardized to have a comparison across studies and the environments used [60]. Overall, it is challenging to develop fit for purpose composite material that meets the industry standards in terms of cost-effectiveness, functionality, durability, and biodegradability [61]. Additionally, from a consumer perspective, eco-friendly packaging is based on the aspects such as the packaging material, manufacturing technology, and market appeal [62]. So, targeting consumers is challenging as they need to be educated on the perception of mycelium-based packaging because of the negative association they have the fungi in the form of molds.

6. Conclusion and future directions

Fungi play key role in nature, medicine, food production, alternative materials, and bioremediation. Based on the earlier studies, only 150000 out of the ~6 million species of fungi are discovered to date. Thus, fungi present enormous scope for the discovery and development of novel materials with unique properties to suit the desired application. Specifically, developing nations present a huge opportunity in terms of the agricultural, wood waste being and municipal waste, that can be used for the fabrication of fungal biocomposites. In addition to the usage of raw materials from agricultural cellulose-based materials, studies have also reported the usage of waste materials like egg cartons, cardboard, newspaper, and paper cups [63]. Lately in India, there is a significant increase in the cultivation of hemp which has relatively less water requirement. Cultivation of such crops will not only increase the use of arid land use and provide the necessary raw material for usage in fabrication of mycelium composites [64]. The latest report based on the study carried out in the Netherlands shows that there is a possibility of using even the weed residues in making these composites [20].

Looking at the present ban on single plastic based on policy changes and their execution, it still appears impossible to eliminate EPS foam usage drastically. Thus, a gradual shift to novel packaging materials that substitute EPS will enable nations to reach their goals. Even if 5% of the current packaging industry is targeted to be replaced by mycelium-based biocomposite, we can reduce the consumption of EPS of the order of 0.016 million tonnes by 2023. More importantly, the biocomposite can facilitate the degradation properties of other materials when it reaches landfill because it aids in the development of microorganisms and eventually biodegrades. There is also significant interest in extracting chitin from mycelium and creating films that can be used as an alternative to paper and some plastics [65].

Novel ways of producing mycelium-based composites have also been proposed in the form of extrusion-based additive manufacturing that uses gelling agents which are proven to improve the mycelium growth without interfering [63], [66], [67]. This process

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also offers the advantages of less usage of the inorganic molds such as plastic that are currently being used. Thus, integrating additive manufacturing into biomimetic methods, this process presents an opportunity to create ecological metamaterials that can have superior structural properties [55]. Incorporation of reinforcements in fungal biocomposites is also a less explored area of research and provides a unique opportunity for startups to come up with novel composites that can be used to create insulation panels with improved characteristics. Recently, the discovery of plastic degrading fungi species has increased the significance of fungi's role in reducing plastic pollution [68]. The process of degradation of plastic by fungi is also in the nascent stage and it needs to be standardized before it becomes a tangible solution [69].

In the scientific literature, the current analysis of the fungal materials with intended use in various applications shows that they pose a low risk to the workers, consumers, and the environment [57]. With the expected scenario of a steep rise in the development of mycelial materials the focus should be on the risk assessment of these materials when they are brought back into the soil or other composting methods. This might present an additional challenge to the developing nations due to the lack of widespread testing facilities to ensure the safe usage of these materials. Overall, increased efforts in research and development by the startups in developing nations might result in novel fungal platform-based materials that can substitute a wider range of plastic-based packaging materials to help them transition into adapting to more circular economy-based models.

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