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Sustainable packaging applications from mycelium to substitute polystyrene: a review

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Abstract

Mycelium is a fast growing vegetative part of a fungus which is a safe, inert, renewable, natural and green material which grows in a mass of branched fibres, attaching to the medium on which it is growing and can be originated from mainly biological wastes and agricultural wastes. The self-assembling bonds formed by mycelium grows quickly and produces miles of tiny white fibres which envelopes and digest the seed husks, binding them into a strong and biodegradable material. Mycelium based materials have the potential to become the material of choice for a wide variety of applications, with the advantage of low cost of raw materials and disposal of polystyrene posing an environmental issue. This paper reviews the achievement and current status of technology based on mushroom cultivation for bio remediation of agro-industrial wastes and also emphasizes on mycelium based material for packaging and insulation applications as a sustainable alternative for polystyrene.

Keywords: Mycelium; Sustainable Packaging; Mushroom; Biodegradation; Insulation foam

1. Introduction

A few years ago, mushrooms were only considered as an edible vegetable for culinary garnishes or used as a hallucinogenic but now, its derivatives made from agricultural wastes like stalks or seed husks with fungal mycelium which acts as a self-assembling glue can be used for a more noble purpose. Fungus is, almost universally, not accepted a good thing to have but Mycelium is a natural glue, where it latches onto whatever around it which is

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usually any low value organic matter like plant stalks or cotton hulls to create a super-dense network of threads [1]. The fungi based mushroom packaging material can be considered as an alternative to conventional plastic and are cost competitive to any other standard foams. Polystyrene foam whose main component is derived from petroleum or natural gas is a prominent packaging material which is neither biodegradable nor compostable. Incorporating mycelium based materials for packaging could help in reduced polystyrene foam consumption, and will eventually lead the way for eco-friendly packaging, thus enhancing sustainability, without any compromise on cost or performance [2-4].

The mycelium (mushroom roots) can be grown in a mold to form different shapes for different items and they grow quickly into a dense material. Once reaching the desired density and shape, the material is dehydrated, to stop further growth. After its useful life as a packaging material, mycelium based materials can be left out in your backyard and it decomposes within a few weeks. The material is much cheaper when made on a grand scale and is a lot easier to biodegrade than recycling [5-7].

Polystyrene or Styrofoam is a less eco-friendly petroleum derivative but is safe for use with food, which justifies its wide spread use. Being a light material, it also makes quiet a good packaging option for electronics and other fragile products [8]. Production of polystyrene creates the worst impact on environment, in terms of energy consumption and greenhouse gas emissions; second only to production of aluminium. Polystyrene has been a main component in urban litter and marine debris since when used excessively for single-use products like food plates or food takeout containers. They are non-recyclable and non-biodegradable, which makes it also detrimental to wildlife [8, 9].

Mushrooms are a major source of proteins, amino acids and several biological active molecules which could not only provide nutrition but also have wide applicability in use for therapeutic purposes. They are agricultural products of biological origin and can be grown on agricultural wastes and agro-industrial wastes or even industrial wastes. Mushroom is considered as protein rich food and the source of a single cell protein, which is comparable to eggs, milk or meat [10]. They possess high quantities of fibers, amino acids, phenylalanine, threonine and tyrosine but few sugars and low calories. Mushrooms are also used for industrial processes like bio pulping and bio bleaching [6,10].

Fungi play major roles in decomposition, nutrient cycling, plant symbiosis and pathogenesis of bio wastes and thus make it an element of fundamental importance in terrestrial ecosystems. They are also used as a tool for biological control against pests and diseases of plants on the other hand it has the ability to transform toxic metals in the context of bioremediation. As nutrient recyclers, bio control agents and bioremediation agents, fungi are growing in environments exhibiting spatio-temporal nutritional and structural heterogeneity. Mycelia growth and function can be influenced by simulated environments like homogeneous and heterogeneous conditions, which include porous media like soil [11].

The usage of polypropylene instead of polystyrene has also been advocated based on the fact that polypropylene being a resin-based material is more recyclable. But the use of polypropylene is also not justified when accounted to sustainability or environment friendliness. This paper reviews the current scenario of technology and achievements made on utilization of mushroom for bio remediation of agro-industrial wastes and also emphasizes on mycelium based material for packaging and insulation applications as a sustainable alternative for polystyrene foam.

2. Potential of mushroom based foam to substitute Polystyrene

Until recently, advertising of products pin pointing on their eco-friendliness was effective only with a small, dedicated set of buyers but increasing awareness of human impact on our fragile ecological system has made some change in perceptions. The increased buying power of eco-conscious consumers, particularly among the younger generation, has augmented the sales and marketing landscape, inspiring both local businesses and multinational companies to emphasize on sustainability. Consumers now have stronger affinity towards products that proclaim sustainability along with corporate social responsibility. A combination of these values encourages companies to implement viable business practices throughout the entire process. That includes suppliers, consumers and employees [12-14]. Research from a variety of sources suggests that switching to sustainable packaging could impart benefits from increased sales revenue to having a dedicated and youthful consumer base that cares more about the green labeling than the actual cost and is true for businesses of all kinds. Buyers are deeply interested in minimizing the waste involved in buying consumable goods. About one-third of the consumers favour environmentally labeled packaging as an important criterion in their choice which can furthermore be asserted as an increasing awareness about the importance of ethical and environmental dimension in product choices.

Companies who market their dedication to ecological and social positive business practices get a considerable boost at the sales. Using retail sales data from a cross-section of consumable and non-consumable goods across several brands in different countries, products with sustainability claims on the packaging showed an average annual sales increase of 2 percent, compared to a meager 1 percent increase for the brands without sustainability claims. Products whose environmental efforts were simultaneously promoted through marketing promotions saw an annual sales increase of 5 percent for the duration. Considering young generation is now the largest generation in the labor force, this is quite a monumental finding for business owners looking to get an edge over competitors.

Fig. 1. Mushroom based foam for various purposes

In line with the commitment to advocate changes through a robust design, the material uses the power of living organisms to create an alternative to conventional packaging. Figure 1 shows some of the several applications in packaging. The cost-competitive technology could disrupt the status quo of unpredictable and irresponsible waste streams that pollute the environment. The feedstock for the mushroom material can serve as an additional source of income for cultivators as it paves way to utilize their agricultural waste. Intended for temporary use, the material breaks down in compost and landfills instead of persisting for generations. With the help of mycelium, the efforts to make a real, positive impact in the area of packaging, will have the potential to make toxic and persistent oil-based materials obsolete and radically change the way industry impacts the environment. The feed that the mushrooms grow on can differ according to locally available materials, which makes the product ideal for manufacturing all over the world: The raw material inputs of the material are selected based on regionally available agricultural by-products. By manufacturing regionally, and using local feed stocks, transportation of raw and finished materials could be minimized [5,6].

And these trends are being noticed by big players in the global economy. Companies like Coca Cola and Unilever have announced of making sustainability central to their brand's core values. World consumers are looking for local and sustainable products more than ever. Sustainable practices in packaging will offer businesses a way to tap into the values of buyers. Reducing the impact on environment goes beyond making a difference in your business practices and it can lead a whole new market of engaged buyers to your firm.

3. Production of mushroom based foam

Ecovative, a New York based start-up used mushrooms to create a heat and fire-resistant, energy-absorbing, biodegradable, and low-energy material called Myco-bond. It requires just one eighth the energy and one tenth the carbon dioxide of traditional foam packing material to produce. The product is made by working together the mycelium of mushrooms which is the mass of a filament like fibre of the fungus that invades organic material such as any agricultural waste to feed on it [7]. There is a process of growth and breaking down and more growth and forming into blocks, and the result is a material that functions more or less as polystyrene does, except that it breaks down when exposed to the atmospheric conditions favouring decomposition. As long as the material is kept dry, it lasts and serves the purpose; dumping it outside exposed to atmosphere will make it to degrade. Being all organic, the material can be composted easily [7].

A combination of mushroom roots as binders and agricultural sources like corn or oat husks are placed in trays of various sizes. These are then left to fester and furl in a dark warehouse for a minimum of five days, after which the mix emerges glued together to form a new packaging material which is biodegradable, fire proof and water resistant, making it an excellent substitute for polystyrene and Styrofoam [15]. Figure 2 shows a production facility for manufacturing mushroom based foam materials.

Fig. 2. Production facility for mushroom based foam

The process is transformative in two ways. First, there are the unique biological properties of Mycelium, which can grow miles of thread-like roots in days. The organism grows incredibly fast, to fit any mold, almost like dense foam. They grow everything from finely detailed packaging for laptops, to wide panels of insulation for homes. It is also possible to control the density of each product, by stopping the growth process sooner or later. Before mushrooms are grown the source material is to be disinfected to kill competing spores in order to hold its final shape, but that's a natural process too. A more energy-intensive steam-treatment sterilization process can replace the one that uses the natural organism killing properties of cinnamon-bark oil, thyme oil, oregano oil and lemongrass oil, which are often used for natural disinfection in herbal remedies. The biological disinfection process simply emulates nature, in that it uses compounds that plants have evolved over centuries to inhibit microbial growth.

Ecovative makes its packaging foam by placing organic waste like cotton hulls or wood fiber in a mold, which is then inoculated with mushroom spores. The mushrooms could digest the waste and grow into the shape of mold, utilizing the carbohydrates present in the waste for the energy needed to make the material. After attaining sufficient growth they are subjected to heat to stop it from flowering spores. Since the mycelium is not grown for long enough to fruit to form a mushroom, there are never any spores or allergen concerns with the process [7].

4. Early adopters of mushroom packaging

For small companies with tight margins, changing business practices or packaging can seem like an unnecessary or unattainable cost. No matter the size of the business, there are several things that could be done to minimize environmental impact and emphasize on sustainability such as radical rethinking of packing process. While packaging is certainly important for marketing a product, nearly all of it goes in the garbage once the sale is made. A little consideration on the ways on using less material during packaging could help especially when it comes to shipping. Mycelia are natural binding agents that can work with agricultural products such as corn and oat husks to make an incredibly durable material that could replace Styrofoam and polystyrene in practically every application. Several companies from a number of industries are looking to cook up alternative materials for their products as well so that the dependency on polystyrene and Styrofoam can be ended.

Ecovative has pioneered the idea of using mushroom based foam and has gone a long way to make the process efficient, all at the time maintaining the key properties of material intact. Dell has decided to use mushroom materials in its packing cases. They have announced that they will begin shipping their servers using the eco-friendly fungi foam. Dell has extensively tested the material in their labs to ensure that it provided the same safety to their products as traditional foam and they conformed to the requirements set. The mushroom cushioning is found to be more suited for heavier products like servers. The packaging for Dell grows in five to ten days. The use of green packaging materials is part of Dell's larger plan for a more sustainable shipping strategy. Mushroom cushioning makes for a super green solution and best of all the organic based mushroom cushions are easily composted after use [7].

Ushering in a new generation of partially compostable cars, Ford has decided to use mushroom based foam as a key component in their automotive parts like bumpers, side doors, and dashboards. The best part is that the material will decompose in a short period after being buried. Each car currently contains about thirty pounds of petroleum-based foams, and the company would like to replace them with environmentally friendly alternatives. And Ikea, the giant flat-pack furniture maker from Sweden, is determined to reduce its use of fossil fuel-based materials and has been looking for alternatives to polystyrene for its packaging foam. One alternative being considered is mushroom based foam [7].

5. Production of Mycelium

The production of mycelia can be performed in the basal medium such as mineral salt medium, and it is supplemented with various nutrients including carbon sources, nitrogen sources and inorganic compounds. The suspension is sterilized by autoclaving at 121^0C for 30 minutes and is allowed to cool, and then the flasks were inoculate with a 10% inoculum (v/v) and incubated at 28 °C for 6 days with shaking at 150 rpm. At the end of the incubation period, the mycelia can be recovered by centrifugation at 2500g for 10 min, and wash repeatedly with distilled water. The mycelia were weighed after drying to a constant weight at 80°C [16].

In the process of microbial mycelia production under submerged fermentation conditions, parameters like initial pH, carbon source, nitrogen source and presence of inorganic compounds influences heavily. On the other hand, the parameters that affect fermentation process are, fermentation temperature, time, rotation speed and inoculum size. Some of the common organic compounds used in the production of mycelium are $MgSO_4$, K_2HPO_4, KH_2PO_4, $CaCO_3$, $Zn(CH_3COO)_2$, $ZnSO_4$ and $CuSO_4$ [16].

5.1. Spatial development of mycelium

Mycelium is spatially developed by growing them into custom shapes and the self assembling bonds formed by mycelium produce this material as it grows around a substrate of regionally sourced agro waste. They are bonded together by the fungal mycelium and the final material is home compostable. It is an environmentally responsible alternative to expanded polystyrene and other plastics. They competes directly with petrochemical foams in terms of performance and cost, with low embodied-energy, compostable, protective packaging material.

Modelling the fungus and growth-promoting substrates as continuous variables is a common approach to model large-scale spatio-temporal properties of fungal mycelia. There are commonly five (continuous) variables used to define a model; active hyphal density, inactive hyphal density, hyphal tip density, internal substrate concentration and external substrate concentration. This modelling strategy allowed translocation to be explicitly modelled in a variety of habitat configurations as well as certain functional consequences of fungal growth, such as acid production [17]. This approach is ideal when modelling dense mycelia, surfaces of solid substrates such as foodstuffs and plant surfaces.

Due to their branching architecture and filamentous growth habit fungi are well adapted for growth in soils. Fungal hyphae elongate strictly by deposition of wall skeletal polysaccharides [18]. Underlying this growth process is the forward movement of a variety of types of vesicles that provide new cell membrane material and thus generate the extension of hyphal tips. As a result of this hyphal tip movement, hyphae are able to penetrate solid substrata such as chitin and, by the excretion of lytic enzymes, are able to uptake various nutrients in the form of solutes.

Translocation is an important process that allows the redistribution of internal metabolites throughout the fungal mycelium [19]. Active hyphae refer to those hyphae involved in nutrient uptake, branching and translocation while hyphal tips denote the ends of these hyphae. Inactive hyphae denote hyphae that are no longer directly involved in translocation, branching or uptake. Internally-located nutrients within the fungus is used to extend hyphal tips and thus a hyphea may be regarded as a trail left behind a hyphal tip as it moves, initiate branching and drives nutrient uptake. In all environments, a combination of elements are required for growth; some elements of particular importance are carbon, hydrogen, nitrogen, sulphur, phosphorus, oxygen and other elements including metals [20].

6. Applications of mushroom materials

Mycelium is not just used as a packaging material, its applicability ranges from manufacturing lamp shades, flower pots to even surfboards. Application since has expanded into the building sector also where mushroom bricks were also made and tested to build a 40 foot tower that makes it the largest structure made of mushroom materials. It can also be used as an insulation material similar to rigid board insulation, and provides a tight envelope with thermal bridges, leading to a more energy efficient building. It also achieved class A fire rating without using toxic fire retardants [7]. According to Ecovative, their product can be used in many more applications than just packing cases. They list industrial equipments like pumps and compressors, LED lighting, printers, furniture, office products and a lot more as applications for the product. Other potential applications for their products include cosmetics and computer parts [7].

A Myco Board is an engineered product that has every potential to replace wood and other engineered wood products. Many engineered wood products that use known carcinogen agents like Urea-formaldehyde is obviously over run by a technology where particles are bonded together with naturally occurring mycelium instead of resins. Potentially, this could outperform medium density fiber boards and particle boards. Figure 3 shows Myco-boards manufactured from mushrooms.

Fig. 3. Myco boards

Greensulate is a fire-retardant board made out of water, flour, perlite and mushroom spores primarily used as a form of sustainable insulation. The insulation material is grown by pouring the ingredients into moulds of suitable size with hydrogen peroxide. The mushroom oyster cells start to grow into a thick panel, when the mixture is placed in a dark environment, which is then dried to prevent fungus from growing [21].

7. Conclusion

There is a caveat; the producer of mushroom based foam has to overcome the challenge of maintaining a consistent density with a raw material that is a living organism. The biggest challenge with scaling the burgeoning fungus operation is likely the public perception of its products. Organically grown packaging is usually seen as coup for companies marketing teams, but it's less so for those on the logistics side of things which is rapidly changing. Several electronics manufacturers are potential users for growing mycelium based packaging for products such as laptops and tablets. These materials have been tested in environmental chambers under extreme conditions and were found fit to be deemed in use. Mushroom based foam replacing polystyrene could mark an important milestone in the history though much of it is expected to be a silent change.

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