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A review on synthesis, properties and applications of mycelium biocomposite

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Abstract
This review study gives a general overview of the characteristics of mycelium-based biodegradable packaging materials. mycelium-based materials provide a sustainable substitute for conventional plastics derived from petroleum, which customers are demanding more eco-friendly packaging solutions. The tensile strength, elasticity, and fire reaction properties of mycelium-based materials, as well as their thermal, mechanical, and barrier characteristics are all reviewed in this paper. The adaptability of mycelium-based packaging materials and uses of mycelium biocomposites in a variety of sectors are highlighted in this study. Mycelium composites offers a sustainable, cost effective and biodegradable replacement to traditional synthetic materials, minimising waste and environmental impact. This paper reviews the achievement and current status of technology based on fungal mycelia for bio remediation of agro-industrial wastes and also emphasizes on mycelium-based material for packaging and other applications as a sustainable alternative for polystyrene.

Keywords: Mycelium, biocomposite, packaging, fungi

1. Introduction

Foods can be protected, preserved, marketed, merchandised and distributed using packaging materials. The two primary categories of packing materials are stiff and flexible. The first group includes rigid containers such as Plastic bottles, Glass, cans, tins, pottery, plastic pots and wood boxes. They create a reliable barrier that protects the food from harm from the outside, which flexible packaging may not always do (Raheem, 2013) [34]. Environmental contamination concerns have been raised as a result of the usage of non-biodegradable materials in a variety of packaging applications. The synthetic plastic packaging industry in particular, the food packaging sector is expanding rapidly (Ncube *et al*., 2020) [31].

The greatest consumer of plastics is the packaging industry, where plastics account for more than 90% of flexible packaging and just 17% of rigid packaging (Raheem, 2013) [34]. The burning of polystyrene will release harmful combustion products, making it an ecologically dangerous synthetic polymer. Some plastic materials never degrade while others take several years to do so. Taking into account these considerations, a biodegradable substitute for polystyrene that may function just as well as polystyrene will show to be a significant step towards a sustainable future (Jose *et al*., 2021) [24]. since fungal mycelium can break down lignocellulosic materials, It can be used for creating packaging materials (Butu *et al*., 2020) [10]. Packaging made of fungal mycelium can take the place of polystyrene and other plastic packaging. The usage of mycelium biocomposite is considered to be sustainable, biodegradable, and it helps the economy transition to a sustainable one (Singh & Pandey, 2022) [36].

The best fungi for producing mycelium-based products are known to be Ascomycota and Basidiomycota since they can build more and bigger intricate organic structures than others. Septa and anastomosis are two crucial characteristics that basidiomycota possess that might make them more appropriate for making biocomposites. When a hypha sustains damage, the septa, distinctive transverse cell walls, contain an aperture that may be closed to prevent cytoplasma from draining through the rupture (Lelivelt, 2015) [28].

The rapidly growing vegetative portion of a fungus known as mycelium is an inert, safe, renewable substance that may be grown mostly from biological and agricultural wastes. It grows as a mass of branching filaments that attaches to the substrate on which it is developing (Abhijith *et al*., 2018) [1]. Mycelium functions as a natural binder, feeding on any nearby organic materials to bind together a superdense network of threads. Materials made by mycelium have several benefits over synthetic materials that are widely utilised.

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mycelium based materials are more affordable, biodegradable, less dense and can be produce with less energy (Alemu *et al*., 2022) [3].

The study offers a thorough analysis of the state of mycelium-based materials research and their prospective uses in packaging and composite materials. This review study is unique in that it concentrates on mycelium-based materials especially for packaging and composite applications. While there has been an increase in interest in mycelium-based materials for a variety of applications, such as textiles, building materials, and even food product packaging, this report offers a detailed analysis of their potential as polystyrene replacements.

2. Mycelium composite synthesis

The vegetative portion of a fungus, known as mycelium, has a variety of possible uses when grown on natural fibres because it may produce a strong, sustainable materials. A specific strain of fungus is inoculated into an organic substrate to create mycelium-based composites. In order to spread its hyphae from the tip and create a denser network, mycelium disintegrates and colonises the organic cellulosic substrate, utilising the biproducts of disintegration as feeding substrate. The substrate gives the mycelium the nutrition it needs for growth. Agricultural wastes can be utilised as suitable substrate medium (Karana *et al*., 2018) [26]. The capacity of the digestive enzymes generated from tips of hyphae for breaking down organic waste to a form with a simpler body structure enables hyphae to develop on a substrate. The term "colonisation" refers to the process of degrading the substrate in which mycelium attaches to substrate and replaces it partially with a robust fungal biomass (Aiduang *et al*., 2022) [2]. Iordache *et al*., (2018) [16] used *Fusarium oxysporum* to produce a unique mycelium composite based on substrate made of crushed recycled paper and used coffee. The fungal stain effectively grown on a new nutritive substrate that allowed for the growth of biofilm of 64.23µm on the substrate's exterior and a uniform hyphal grid inside the aerial structure of the substrate, producing a material with a high degree of stiffness. The material demonstrated excellent flame resistance, withstanding near flame contact for 80 seconds. Jose *et al*., (2021) [24] constructed a packaging material by growing *Pleurotus ostreatus* on sawdust in a container. Container was kept at 80% relative humidity and 25 °C. The mycelium composite material was characterised using a variety of methods, and the outcomes were compared with those of polystyrene. A combustion test utilising a respirable dust sampler was used to determine the amount of hazardous combustion products emitted during the burning of polystyrene samples. Gases such carbon monoxide, sulphur dioxide and nitrogen dioxide were detected and quantified. The development of mycelium without contamination has been guaranteed by observation of scanning electron microscope pictures. Mycelium-sawdust biocomposite was found to have an average bulk density of 0.1785 g/cm3, while polystyrene had a bulk density of 1.04 g/cm3. The mycelium biocomposite samples had a moisture content of about 30%, whereas polystyrene retained almost zero moisture even after being submerged in water for 24 hours. Mycelium biocomposite packaging material was made using rice husk, wheat grain and mushroom mycelia and the characterization of the composite was also done. Three composites of distinct percentage, 70% rice husk 30% wheat grain, 50% rice husk 50% wheat grain and 30% rice husk 70% wheat grain was made and the test of apparent porosity on mycelia has been done. Each specimens showed average apparent porosity of 55%, 66% and 58.7%. In comparison to the specimen 70% rice husk 30% wheat grain, the specimen 30% rice husk 70% wheat grain has a higher density (Arifin & Yusuf, 2013) [5].

A mycelium biocomposite was made using a substrate of sawdust and coir pith. The composite is made by choosing an appropriate substrate ratio and integrating *Pleurotus ostreatus* mycelia. The biocomposite material has a big potential to replace expanded polystyrene (EPS) in packaging applications, according to the observation made. Compression test results showed that biocomposite material is capable of withstanding greater compressive stresses than EPS. This quality may make it possible to utilise less expensive, thinner packing material. The sound absorption coefficient shows that the mycelium biocomposite's sound-absorbing abilities are superior to those of EPS. Composite has a coefficient that is higher than 0.2, while EPS has a coefficient less than 0.2. Mycelium biocomposite can therefore be used as a soundproofing material (Sivaprasad *et al*., 2021) [37]. Yang *et al*., (2017) [41] demonstrated the remarkable potential of fungal mycelium-based biofoam as an eco-friendly and enduring building material developed by using fungal mycelium integrating with different substrate materials including millet grain, calcium sulfate, wheat bran, wood pulp and natural fiber. Physical and Mechanical Properties of the constructed Biofoam were tested and compared. Shear failure was noted in samples that were tightly packed having no natural fibre. After the compression test, loosely packed samples showed noticeably more plastic strain than more dense samples. The Young's moduli were much greater than the shear moduli for each set of samples. Thermal conductivity values for live samples ranged from 0.13–0.40 W/(m · K), whereas those for dried samples had a considerably narrower range, 0.05 to 0.07 W/(m · K). With an average value of 350–570 kPa, biofoam showed good compressive strength. It was also discovered that biofoam has substantially lower weight than water, soils, or most other materials utilised in the civil engineering industry. Jiang *et al*., (2016) [18] introduced a novel method for producing sandwich constructions made of biocomposite materials. He concentrated on the subsequent steps: filling prestamped textile shells with the core mixture, letting it grow to link the textile skins and reinforcing particles into a unified preform, and then drying this preform to eliminate moisture and inactivate mycelium. Organic waste is employed as the core material in sandwich constructions, and layers of natural fibre reinforcement are bound together by fungal network to create laminates. After being thermally pressed to help establish the general brick dimensions, fully grown bricks undergo a lengthy convection drying cycle in a traditional thermal oven to totally deactivate the mycelium and reduce core moisture to appropriate levels. Discovered that core strength dominated stiffness and Strength was substrate-dependent and correlated with the level of skin colonisation and skin-to-core bonding. Zimele *et al*., (2020) [43] built mycelium biocomposite from hemp shives and wood chips and also investigated it’s the mechanical properties. The basidiomycete fungi, *Trametes versicolor* was used and the mechanical properties of mycelium biocomposites were compared with some reference materials. Depending on the density and particle size of the substance, the mycelium-based biocomposites had compressive strengths from 0.36 to 0.52 MPa. The biocomposite's bending strengths varied from 0.11 to 0.16 MPa, with samples with bigger particle sizes and lower densities showing the strongest bending properties. After 24 hours, the biocomposite's water absorption varied from 400% to 550%, showing that they had a high water-holding capacity. Fig. 1 showed the representation of mycelium biocomposite synthesis

3. Properties of mycelium packaging material

Mycelium-based packaging materials provide a variety of advantages that make them a desirable choice for both consumers and enterprises. For instance, because it is lightweight, shipping expenses and transportation-related carbon emissions are reduced. A durable, adaptable, and environmentally beneficial substitute for conventional packaging materials is mycelium-based packaging (Alemu *et al*., 2022) [3]. Additionally, it resists fire, giving products an additional measure of safety and defence. Natural antibacterial properties make mycelium-based packaging materials the best option for use in the packaging of food and medical items. Packaging made of mycelium is a great illustration of the circular economy, which turns waste goods into useful resources while minimising environmental effect and fostering sustainability (Javadian *et al*., 2020) [17].

3.1 Density of the material

The mass of a unit volume of a material substance is referred to as the density, which is an important feature of packing material. Numerous characteristics of the packaging, such as its weight, strength, and durability, can be impacted by the density of the packaging material. Depending on the lignocellulosic residue type and fungus species utilised in their synthesis, mycelium-based composite's (MBC's) densities can change. A denser material, for instance, is often stronger and more durable than a less dense one, making it more suited for safeguarding goods during transit. Denser materials are heavier as well, which can drive up transportation prices and carbon emissions (Attias *et al*., 2017) [7]. The quality of the composite materials is impacted by the incubation period's duration. With longer incubation times, fungal-based composite's density increased from 195 kg/m^3 to 280 kg/m^3. This is because as the mycelium develops and the substrate becomes more tightly connected to one another, the gaps between fibres are filled, increasing the density (Ayele *et al*., 2021) [9]. Coffee husk had the largest water absorption capacity of any composite created from substrates, whereas sawdust had the lowest, which is directly connected to mycelium growth and material density. The size and chemistry of the substrate might be to blame. Mycelium based board developed from sawdust composite had maximum compressive strength and density of 570 kPa and 280 kg/m3, respectively, and water absorption of 200% (Attias *et al*., 2020) [6].

3.2 Thermal insulation

When compared to common materials like extruded polystyrene, rock wool, and glass wool, MBCs exhibit similar or lower thermal conductivities and have a generally good insulation behaviour. A layer of insulation that helps control the product's internal temperature is provided by the mycelium, which is made up of a thick network of interwoven fibres that generate air pockets. This characteristic is particularly helpful for goods that must be maintained within a certain temperature range, such as food, medications, and electronics (Robertson *et al*., 2020) [35]. The kind of lignocellulosic waste and fungi species employed in the manufacturing of MBCs might affect the thermal conductivity of such materials. Due to their ability to act as thermal insulators, MBCs are excellent for usage in the building sector and other fields that need for insulation (Yang *et al*., 2017) [41]. Lower thermal conductivity is a characteristic of superior insulating materials, which is mostly a function of the material's density. The thermal conductivity of dry air is quite low (26.2 10-3 W/mK at 0.1 MPa, 300 K), and there is a strong association between the thermal conductivity and the material density (Jones *et al*., 2018) [19]. The comparatively low thermal conductivity of mycelium-based composites is 0.05 Wm^{-1} K^{-1} makes them an intriguing option for thermal insulation. Thermal conductivity, on the other hand, can vary widely depending on the raw material and fungus strain used (Butu *et al*., 2020) [10]. (Sivaprasad *et al*., 2021) [37] has developed an innovative mycelium biocomposite material to replace polystyrene in various applications such as packaging. The heat conductivity of biocomposite is a much bigger than the Expanded Polystyrene (EPS) samples. While the thermal conductivity of the EPS sample is 0.053984 W/m-k, that of the mycelium composite is approximately 0.069950 W/m-k. The conclusion drawn from the results is that myco-composite would transfer more heat than EPS.

3.3 Fire resistance

The behaviour of the resulted myco-composites towards combustion, pyrolysis or fire, is the subject of just a few research. Jones *et al*. (2018) [19] found that MBFs have a time to ignition that is comparable to that of EPS foam but substantially less than that of particleboard. Interesting enough, mycelium does not exhibit intrinsic flame-retardant qualities and only functions as a cement at temperatures known to range from 200 °C to 400 °C (M. Jones, Bhat, Huynh, *et al*., 2018). According to several research, chitosan is a potential flame-retardant addition that primarily relies on the stabilisation of materials at high temperatures. Materials that have limitation oxygen index (LOI) values under 21% are categorised as combustible, whereas materials that have LOI values above 21% are categorised as self-extinguishing because they cannot maintain burning in ambient conditions without the need of external energy. Materials with a high LOI value have the capacity to withstand fire. The biocomposite's LOI is larger than 21% (24%) compared to EPS's LOI of less than 21%, making it self-extinguishing and fire-resistant (Jones *et al*., 2017) [21]. According to investigations, mycelium-bound composite materials lack any natural fire-retardant properties. Chitosan and hydrophobins, a class of proteins that can coat the surface of mycelium with a hydrophobic layer, are its main components and have shown to have fire-retardant properties; however, it has been demonstrated that their effect on fire resistance in mycelium-bound composite materials is insufficient (Palumbo, 2015) [32]. To improve the fire resistance of mycelium-bound composite materials, a substrate rich in phenolic natural polymers and naturally occurring silica (SiO2), both of which are found in abundance in many agricultural by-products or forest residues, such as rice hulls or bamboo fibres and leaves, can be used. It has been demonstrated that these kinds of substrates improve the performance of mycelium-bound composite materials in fire (M. Jones *et al*., 2018) [19]. It has also been extensively researched how to incorporate flame retardants into lignocellulosic materials. Diammonium phosphate (DAP), a phosphorus-based retardant, and salts of sulfamic acid, such ammonium sultamate, are examples of this type of retardant. (Jones *et al*., 2020) [22].

3.4 Mechanical properties

Strength, toughness, and elasticity are three mechanical qualities of packing materials that are essential for safeguarding goods during handling and transit. Because of the tight network of interwoven fibres in the mycelium-based packaging material, it offers outstanding mechanical qualities. Mycelium packaging is extremely strong and long-lasting because to this network, which also makes it resilient to compression and impact pressures (Yang *et al*., 2017) [41].

3.5 Compressive strength: Recent research concentrated on improving the microstructure of material to raise its elastic modulus and compressive strength, primarily to survive the compressive pressures created by the structure. The biocomposite material is stronger in compression as compared to EPS since it has a greater compression modulus and compression strength (Sivaprasad *et al*., 2021) [37]. (Sydor *et al*., 2022) [38] studied the elastic and strength characteristics of mycelium biofoam in both tension and compression and discovered that the compressive strength is nearly three times the tensile strength and the strength of the biofoam declines with increasing moisture content. (Yang *et al*., 2017) [41] observed that compressive strength can be increased by adding sawdust-based composites to natural fibres. With a longer incubation period, the compressive strength can be raised. Mycelium-based composites achieved compressive strengths that were up to three times greater than those of expanded polystyrene. (Haneef *et al*., 2017) [14] investigated on the mechanical and physical properties focusing on *Pleurotus ostreatus* and *Ganoderma lucidum*. The authors claim that substrate has significant impact on the composition of mycelial by lipids, polysaccharides, and chitin as well as the final shape and mechanical characteristics. When compared to its composite, mycelium exhibited seemingly and unexpected incongruent properties. Particularly, it was discovered that *P. ostreatus* is harder and stiffer than *G. lucidum*, which was attributed to its greater content in polysaccharide.

3.6 Tensile strength: The ability of a material to resist deformation when subjected to tension or stretching forces is measured by its tensile strength. A material is characterised by the highest tensile stress that it can withstand before failing or breaking. Because brittle materials have no yield point, the ultimate tensile strength is a crucial engineering parameter when designing members made of such materials. Typically, testing entails applying a consistent strain rate to a tiny sample with a set cross-sectional area using a tensometer until the material breaks (Fairus *et al*., 2022) [11]. When compared to cold-pressed composites, the tensile, flexural, and elastic modulus of *P. osteratus* biocomposite grown in cotton seed hull and rapeseed straw was significantly higher when hot-pressed. Increases in tensile strength of 0.03 to 0.13 MPa and elastic modulus of tensile of 6 to 35 MPa were seen in *P. osteratus* composite grown on cotton seed shell (Appels *et al*., 2019) [4]. (López Nava *et al*., 2016) [30], myco-composite developed on *Pleurotus* and wheat straw reported high values compared to every EPS types. When tested parallel to the surface, the biocomposites' average tensile modulus ranged from 3.65 to 7.13 MPa and their average tensile strength ranged from 0.096 MPa for K treatment to 0.197 MPa for P treatment. Furthermore, there were noticeable changes in the strain at maximum tensile stress, which varied from 8.13% for hemp pith with a nonwoven mat (K treatment) to 41.8% for cotton fibre with a woven mat (P treatment). While polystyrene had a maximum tensile strength of 0.20 MPa, comparable products like fibre cotton composites had tensile strengths that were much lower than those of biocomposites made with hemp pith (Ziegler *et al*., 2016) [42].

3.7 Flexural strength: A material's flexural strength is determined by its capacity to withstand bending forces that are applied perpendicular to its longitudinal axis. As much bending stress as a material can withstand before yielding is what is meant by this term. The peak stress that the material was under at the time of yield is represented by the flexural strength. Flexural strength is sometimes referred to as bend strength, transverse rupture strength, and rupture modulus. The flexural modulus of mycelium biocomposite is approximately five times of EPS. As a result, myco-composite takes more power to bend or buckle than EPS (Sivaprasad *et al*., 2021) [37]. Densification is a technique for stiffening the composite by making the substrate denser by dense packing, cold or hot pressing, or both. According to reports, increasing a specimen's density from 100-130 kg/m^3 to 350-390 kg/m^3 results in an increase in flexural strength of 4 to 14.5fold and a flexural modulus rise of 27 to 72-fold. Mycelium composite material produced by heat pressing has characteristics including elastic modulus, density, and flexural strength that are similar to those of natural materials like cork and wood. Flexural strength increased when the material was cold- and hot-pressed. Flexural strength ranged from 0.05 to 0.29 MPa, while flexural moduli ranged from 1 to 9 MPa for the non-pressed materials. Non-pressed Ganoderma-cotton plant biomass composites were having bending strengths in range of 7-26 kPa, whereas hemp-based or cotton-based mycelium materials were discovered to have flexural moduli of 66 to 72 MPa (Appels *et al*., 2019) [4].

3.8 Elastic deformation: Elastic deformation is a brief alteration in length, volume, or shape caused by a stress that is below the material's elastic limit. It is a kind of deformation when a material changes shape in response to tension but returns to its initial condition once the stress is removed. Stretching, twisting, compression, and bending are just a few of the things that can cause elastic deformation. When the external factors that caused the change and the tension connected with it are removed, the deformation goes away (Gironetta *et al*., 2019) [13]. When compared to equivalent non-pressed and cold-pressed materials, the heat-pressed materials' elasticity modulus was greater. During three-point bending, a comparable pattern was seen. Unfilled mycelium in uniaxial tension displays a linear elastic regime upto 8% strain, after which there is a linear regime of strain hardening until rupture at 25–30% strain. Elastic modulus swings as a quadratic function of network density, and strength is proportional to network density to the power 3/2. Mycelium under compression exhibits an elastic regime at low loads, followed by a regime of strain localization where the effective tangent stiffness is dramatically lowered due to the elastic-plastic buckling of fibres (Pohl *et al*., 2022) [33]. When dextrose is added to the cellulose-based substrate, *Pleurotus ostreatus* and *Ganoderma lucidum* mycelium become more elastic. *Pleurotus ostreatus* mycelium is stiffer than *Ganoderma lucidum* (Javadian *et al*., 2020) [14]. The elastic modulus describes the linear, reversible connection between stress and strain that occurs during elastic deformation. Above a yield point, further loading causes a product to deform permanently even after the force has been released because it breaks or becomes plastically distorted. All myco-composites showed plastic-elastic deformation behaviour when subjected to compression loading upto 1.8 kN (i.e., a force generated by 180 kg of weight). Following unloading from the compression tests, the elastic deformation is largely recovered, but some plastic deformation is left behind (Pohl *et al*., 2022) [33].

4. Applications

Mycelium biocomposites are a durable and adaptable material that have applications in several industries. These materials are easily mouldable into a variety of forms appropriate for the production of shock-resistant materials for packaging. Moreover, it can be utilised as a building material or an insulator. They create the biocomposite using cheaper raw materials and the finished product is a greener alternative to expanded polystyrene. Mycelium-based packaging materials for a typical server may typically be developed in one to two weeks in the mould (Aiduang *et al*., 2022) [2]. The use of typical synthetic materials, conventional production methods, and the tendency towards disposable items have all contributed to the addition of millions of pounds' worth of fashion products to the waste stream. To make the fashion business more sustainable, eco-friendly and renewable, respective materials must be developed that will decompose at the end of their useful life. shoe parts where mycelium biocomposites might take the place of foam-like sneaker or other shoe soles. A mycelium-based shoe sole would be safe to wear, biodegradable after its useful life, and ecologically friendly (Fallis, 2013) [12]. Mycelium biocomposites replaces wood, foams, and plastics in applications including, door cores, insulation panelling, cabinets, flooring, and other furniture because they have adaptable material qualities dependent on their composition and production technique. They exhibit great potential as acoustic and thermal foams for insulation since they surpass conservative building materials like engineered woods and synthetic foams in terms of low thermal conductivity, high acoustic absorption, and fire safety. While the hydrophobicity of the mycelium material itself can lead to the development of mycelium based films to textile applications or coating, the water absorption capabilities of mycelium composites are also garnering interest as superabsorbent materials (Jones *et al*., 2020) [22]. Mycelium-based foam will be used by Ford Motor Company in dashboards, side doors, and bumpers for automobiles. A new generation of vehicles with more biodegradable parts will be available in the near future. Currently, each car produced contains roughly 15 kg of synthetic foam, which Ford is expected to replace, at least a part of it with environmentally friendly alternatives (Aiduang *et al*., 2022) [2].

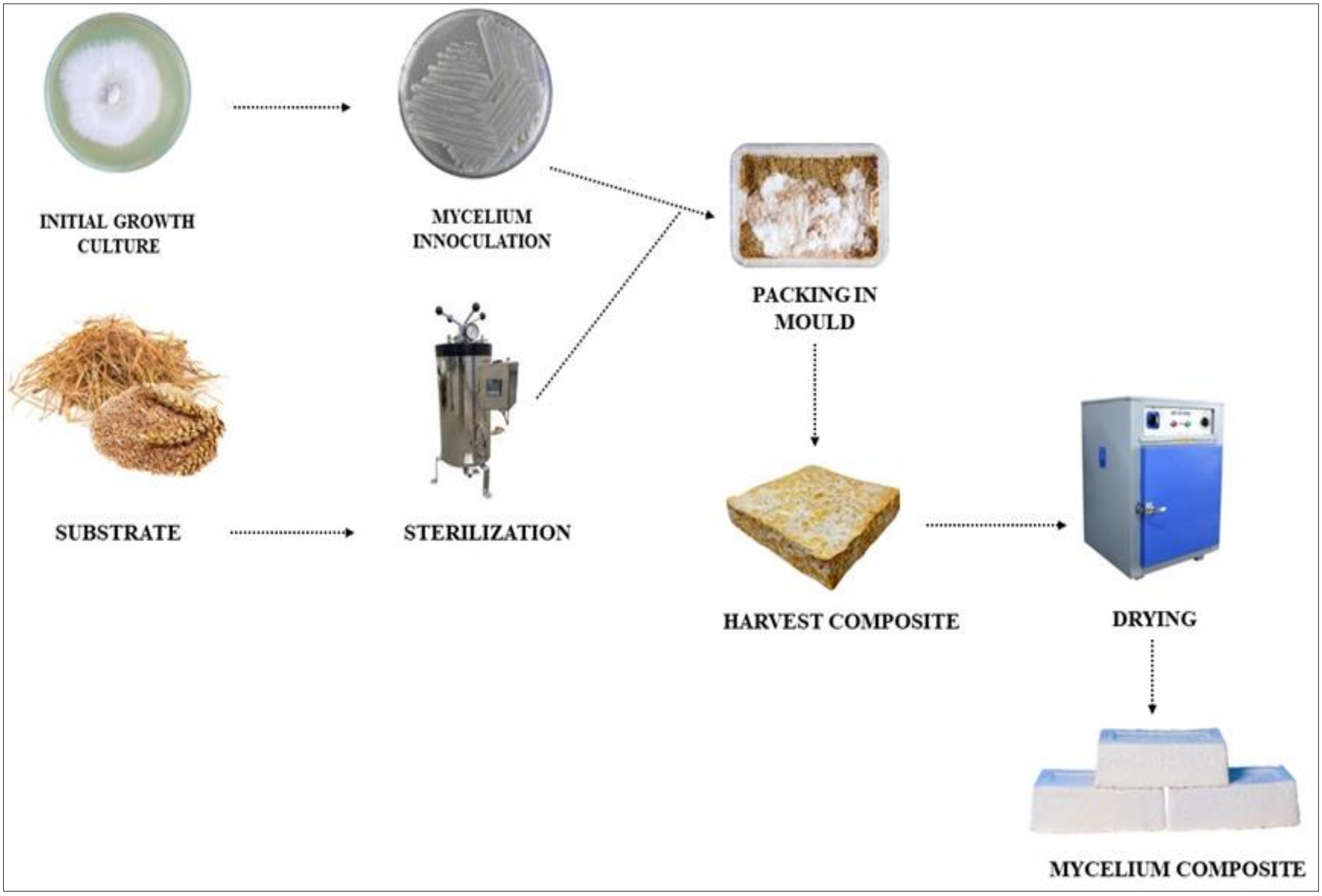

Fig 1: Diagrammatic representation of mycelium composite synthesis

Table 1: Applications of mycelium biocomposite

Mycelium biocomposite	Fungal sp.	Process temperature	result	reference
Packaging material	*Ganoderma sp.*	Sterilization: 115 °C Incubation: 21 °C Oven drying: 60 °C	Density similar to polystyrene packaging, high compressive strength	(Holt *et al.*, 2012) [15]
	Pleurotus ostreatus	Sterilization: 121 °C Incubation: 25 °C Oven drying: 90 °C	Mycelium fibers obtained are uniform and thermally stable, better thermal resistance properties than polystyrene packaging.	(Joshi *et al.*, 2020) [25]
	Pleurotus ostreatus, P. eryngii, Pycnoporus sanguineus	Sterilization: 120 °C Incubation: Room temperature Oven drying: 60 °C for 24 hrs.	Pleurotus eryngii composite showed a plastic behaviour after 15 days of complete colonization, elastic behaviour due to high density of composite.	(Teixeira *et al.*, 2018) [39]
Architectural material	*Colorius versicolor*	Sterilization: 100 °C Incubation: 23 °C Oven drying: 60 °C	Composite pH dropped to a very low level. Average density of mycelium foams was 10-fold higher than polystyrene foam.	(Attias *et al.*, 2020) [6]
	Pleurotus pulmonarius, Pleurotus ostreatus, Pleurotus salmoneostramineus, Aaegerita agrocibe	Sterilization: 121 °C Incubation: 25 °C Oven drying: 105 °C	Composite with great quality was formed, Dense mycelium formed and good water absorption found with apple wood chips rather than vine.	(Attias *et al.*, 2017) [7]
biofilm	*Ganoderma lucidum, Pleurotus ostreatus*	Sterilization: 120 °C Incubation: 25 °C Oven drying: 60 °C	Composites are stiffer and elastic, composite becomes thicker when feeding substrate is difficult to digest	(Haneef *et al.*, 2017) [14]
Foam	*Coriolus versicolor*	Sterilization: 115 °C Incubation: 100 °C Oven drying: 125 °C	*C. versicolor* and non-woven hemp mats displayed the densest mycelial development, stiffness is higher for hemp mat composite	(Lelivelt *et al.*, 2015) [28]
Insulation material	*Trametes versicolor*	Sterilization: 121 °C Incubation: 28 °C Oven drying: 70 °C	Poor growth for dust straw and dust flax. Well-developed composite obtained from hemp and flax. The Young's modulus is greater for chopped fibre.	(Wösten *et al.*, 2018) [40]
Construction material	*Trametes versicolor*	Sterilization: 121 °C Incubation: 25 °C Oven drying: 95 °C	Increased water absorption. Composite was completely biodegradable	(Zimele *et al.*, 2020) [43]
	Trametes versicolor	Sterilization: 121 °C Incubation: 25 °C Oven drying: 50 °C for 48 hrs.	Composite released significantly less smoke and CO2. The composites with the best fire performance contained glass fines.	(Jones *et al.*, 2018) [19]
Atmospheric particulate matter adsorption panel	*Pleurotus ostreatus*	Sterilization: 121 °C Incubation: 20-22 °C Oven drying: 60 °C	Particulate Matter Adsorption increases with Water Absorption capacity of composite. Nitrate adsorption was the highest in panels made of hemp.	(Lee & Choi, 2021) [27]
Nanofibers	*Trametes versicolor, Polyporus brumalis*	Sterilization: 121 °C Incubation: 25 °C Freeze dried	Very high biomass produced by blackstrap molasses, higher hyphal extension rate for *Trametes versicolor* in blackstrap molasses than in malt extract	(Jones *et al.*, 2019) [23]

5. Conclusion

The environmental issues connected to the manufacture and disposal of polystyrene have drawn a lot of interest to the use of mycelium composites as an alternative in packaging and other industries. Mycelium composites have a lot of potential as a sustainable and environmentally friendly alternative. Physical and mechanical characteristics of mycelium biocomposite have been the subject to detailed study. The composites have demonstrated remarkable mechanical qualities, including high strength, low cost, low density, and excellent thermal insulation, making them appropriate for use in a variety of packaging, architectural, and construction applications. Mycelium composites are biodegradable so that they will disintegrate spontaneously without leaving any unwanted residues behind. Because of this characteristic, they are a far more environmentally friendly choice than polystyrene, which takes hundreds of years to degrade. The characterisation of mycelium composites has demonstrated that the fungi's growth parameters, such as temperature, humidity, and nutrient availability, can be changed to optimise the composite's qualities. This makes it possible to create composites with specialised qualities that suit a variety of applications. further study is required to optimise their characteristics for various applications and assess their economic feasibility, but the promise of mycelium composites for a sustainable future is clear.

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