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MYCELIUM-BASED MATERIALS FOR THE ECODESIGN OF BIOECONOMY

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The exceptional organic recycling ability of fungi is attracting attention in the bioeconomy, being exploited in industrial processes. Mushroom mycelium has been classified as the largest living organism on earth, being capable of growth through its symbiotic relationship with the substrate components. The ability of fungal mycelium to decompose lignocellulosic materials makes it usable for the fabrication of packaging materials, as isolation material or for bio-textile products. This paper presents an up-to-date overview of the current state of the art regarding mycelium biostructures. Thus, we described the development of research over the years, the most tested fungal species, the most used substrates and the up-to-date findings regarding technological challenges.

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1. Introduction

The global sustainable development strategy is targeted towards reducing the non-renewable materials by replacing them with bio-based materials, Bio-based materials will challenge traditional processes in many industrial sectors, for a successful transition from a linear economy model to a sustainable bioeconomy. The biocomposites, biopolymers and natural fiber composites (NFC) may replace fossil-based plastics and other unsustainable materials.

According to recent available studies, it was demonstrated that mycelium bio-composites mixed with other materials derived from biological processes, such as plant extracts or agricultural residues, represent an alternative option in order to produce different materials that could be useful in construction industry [1], design materials [2] or food industry. Fungal mycelium is able to decompose lignocellulosic materials and form complex networks [3], with various properties such as higher mechanical strength, insulation or non-flammability, hydrophobicity [4]. This capability makes it usable for the fabrication of packaging materials, as isolation material or for bio-textile products.

The exceptional organic recycling ability of fungi is attracting attention in the bioeconomy, being exploited in industrial processes. Mushroom mycelium has been classified as the largest living organism on earth, being capable of growth through its symbiotic relationship with the substrate components; it might be useful to take advantage of its properties to manufacture various products. It has been proved that mushrooms are economically important biotechnological products, representing a good source of protein, vitamins, minerals, and biologically active substances.

In order to produce mycelium-based biostructures, an individual strain of fungi is inoculated in a substrate of organic substances. The vegetative mycelium degrades and colonizes the organic substrate, using the products of degradation as feeding elements to extend its hyphae from the tip and branching new hyphae and fusing them together to form an abundant network [5]. The substrate matrix is penetrated by the hyphae, which develops inside as an increasingly tight network. Over time, the substrate is replaced partially by the fungal biomass and the resulting mycelium is able to strongly cement the substrate itself, resulting in a bio-composites material (Fig. 1).

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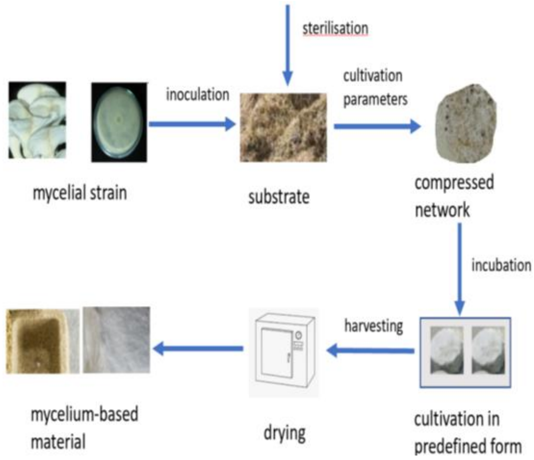

Fig. 1. Technological flow for fabrication mycelium-based materials.

2. Knowledge gaps

The need of this study resides in the identification of several knowledge gaps on mycelium -based biostructures, as follows:

Knowledge gap: Are end-of-life mycelium composites suitable for agricultural purposes?

Even mycelium-based products have an end-of-life, and although they are not widely used yet, researchers may already think about the reutilization of waste myco-composites. Depending on their composition, mycelium biocomposites mainly contain organic matter that may be suitable for agricultural purposes, enhancing the level of nutrients in soil. There is no study referring to this possibility or even their reintegration in the manufacture of other composites. Research has to explain if the spent composites reintegrated in the manufacturing process may lead to the production of composites with the same properties. The materials that are used for myco-composites production are naturally compostable. However, some studies explored the possibility of including industrial waste as glass fines [6] or plastic waste in myco-composites [7], or other additives that enhance their properties [8], making their dismantling more difficult and their impact unpredictable.

Knowledge gap: Are myco-composites safe for the environment? Are myco-composites better than traditional building materials in facing with the external factors?

Engaging myco-composites in agricultural activities means that these materials are compostable, but no one explored that. However, if they are compostable, they are more or less affected by external factors and so not suitable for outer spaces in building and architecture. We have to know how natural factors as climate conditions or natural deteriorators can affect myco-composites. Some studies tried to make fire and termite resistant mycelium panels [7, 8, 9], but there are other deteriorators that have to be considered.

3. Materials and methods

This paper is based on a bibliographic research carried out mainly on Web of Science (WoS) and Scopus databases, including information from all years up to May 2020. The specific keyword ”mycelium” combined with ”composites” and ”foams” was used. Besides keywords, papers were selected based on a series of different criteria. There have been identified studies exploring the possibility to use mycelium as a binding agent for different types of waste. Papers that referred to the manufacturing, properties, applications and sustainability of mycelium biostructures were also taken into consideration. For a clear overview of the current state of the art regarding mycelium biocomposites, we described the development of research over the years, the most tested fungal species, the most used substrates and the up to date findings regarding technological challenges.

4. Fungal species and cultivation substrates

Since the variability of the degradative processes in fungi is enormous, lignocellulosic substrates are colonized by a large number of species. It was demonstrated that the most efficient degradation of the lignocellulosic compound is well-known to be carried out by wood-decay fungi, mostly belonging to Basidiomycota. There are about 40 species in the *Pleurotus* genus. These mushrooms grow on various lignocellulosic substrates and form shell-shaped fruiting bodies of high nutritional value as they are rich in proteins, vitamins and minerals.

According to Golak-Siwulska et al. (2018) at the moment, *Pleurotus sp.* are the world's third most common species of cultivated mushroom after button mushrooms. *Pleurotus ostreatus* and *Pleurotus pulmonarius* are the most economically significant species of oyster mushrooms [10]. The fruiting bodies of oyster mushroom present high nutritional and health-promoting value. In addition, many species belonging to the *Pleurotus* genus have been used as sources of substances based on their medicinal properties, such as high-molecular weight bioactive compounds like polysaccharides, peptides, proteins, and low-molecular weight compounds [11,12,13].

The bioactive substances contained in the mycelium and fruiting bodies of *Pleurotus sp.* species exhibit immunostimulatory, anti-diabetic, anti-inflammatory, antibacterial and anti-oxidative properties. Their positive influence on the human organism is the result of interaction of their bioactive substances. Extracts from individual *Pleurotus* species can be used for the production of dietary supplements, increasing the organism's immunity. Moreover, they are also used for the production of cosmetics, can be added in foods as probiotics, or used as natural preservatives [13].

Pleurotus ostreatus, known as the oyster mushroom, is a white-rot edible fungus, which is strongly saprophytic and highly adaptable. It is easy to cultivate and has the ability to fruit on various agro-industrial wastes and its production continues to increase rapidly worldwide [11, 13,14].

Genus *Pleurotus* includes several taxa and species-complexes with a world-wide distribution many of which are of high economic interest. However, their study was repeatedly hindered by problems related to ambiguous initial identifications, mistaken use of taxonomic names, and conclusions based on fragmentary and incomplete data. *Pleurotus sp.* is a popular mushroom due to its stability of cap and stem, its cooking qualities and longer shelf life. Its good growth can be achieved by using as cultivation substrate various components such as basic plant substrates, saw dust, wheat straw, mango, rice rind, jackfruit, coconut, straw, corn cobs and waste cotton. Fungi are organisms able to merge with materials due to the production of hyphae, a mass of microscopic filaments that form the mycelium.

Table 1. Fungal species and substrates tested for producing mycelium-based materials.

Source	***Fungal species***	***Substrate main components***
[15]	*Ganoderma sp.*	cotton waste
[16]	not mentioned	rice husk; wheat grain
[17]	not mentioned	rice straw, hemp pith, kenaf fiber, switch grass, sorghum fiber, cotton bur fiber, flax shive
[7]	*Trametes villosa*, *Pycnoporus sanguineus*, *Coriolopsis rigida*	post-consumer waste from bottle caps of PP and EVA, eucalyptus, pine wood flour
[18]	*Coriolus versicolor*, *Pleurotus ostreatus*	wood chips, hemp hurd, loose hemp fiber and non-woven mats of hemp fiber
[19]	not mentioned	coconut pith
[20]	not mentioned	cotton burs, switch-grass, rice straw,

Source	***Fungal species***	***Substrate main components***
		sorghum stalks, corn stalks, kenaf
[21]	*Ceriporia lacerata*	soybean straw, wheat bran, gypsum
[22]	not mentioned	cotton byproduct (ginning waste) and hemp pith
[1,23]	*Pleurotus pulmonarius*, *Pleurotus ostreatus*, *Pleurotus salmoneo-stramineus*, *Aaegerita agrocibe*	woodchips of eucalyptus, oak, pine, apple and vine
[8]	*Daedaleopsis confragosa*, *Ganoderma resinaceum*, *Trametes versicolor*	kenaf, hemp and corn fibers
[24]	*Ganoderma lucidum*, *Pleurotus ostreatus*	cellulose, PDB-cellulose
[25]	*Trametes versicolor*	rice hulls
[26]	not mentioned	corn stover
[27]	not mentioned	birch sawdust, millet grain, wheat bran
]28]	*Trametes versicolor*	rice hulls, glass fines
[29]	not mentioned	corn stover particles
[30]	*Trametes versicolor*	wheat grain
[31]	*Trametes versicolor*	rice hulls, glass fines, wheat grains
[32]	*Pleurotus ostreatus*, *Pleurotus eryngii*, *Pycnoporus sanguineus*	coconut powder, wheat bran
[33]	*Oxyporus latermarginatus*, *Megasporoporia minor*, *Ganoderma resinaceum*	wheat straw
[34]	*Ganoderma lucidum*	palm sugar fiber, cassava bagasse
[35]	*Trametes multicolor*, *Pleurotus ostreatus*	beech sawdust, rapeseed straw, cotton fiber
[36]	*Colorius sp.*, *Trametes sp.*, *Ganoderma sp.*	woodchips (pruning residues) apple, vine crops
[37]	*Pycnoporus sanguineus*, *Pleurotus albidus*, *Lentinus velutinus*	sawdust, wheat bran
[38]	*Trametes versicolor*	hemp, flax, flax waste, softwood, straw fibers
[39]	*Pleurotus ostreatus*	sawdust, straw
[40]	*Polyporus brumalis*, *Trametes versicolor*, *Agaricus bisphorus*	wheat straw, rice hulls, sugarcane bagasse, blackstrap molasses
[41]	*Ganoderma lucidum*	cotton stalk
[42]	*Ganoderma sp.*	ground corn stover, grain spawn
[3]	not mentioned	mixture of spruce, pine, fir wood particles
[43]	*Fomitopsis pinicola*, *Gloeophyllum sepiarium*, *Laetiporus sulphureus*, *Phaeolus schweinitzii*, *Piptoporus betulinus*, *Pleurotus ostreatus*, *Polyporus arcularius*, *Trametes pubescens*, *Trametes suaveolens*, *Trichaptum abietinum*	sawdust - paper birch, aspen, lodgepole pine, subalpine fir, white spruce
[44]	*Ganoderma lucidum*	D-Glucose, alkali lignin
[45]	*Pleurotus ostreatus*	wheat bran, sugarcane, sawdust
[46]	*Ganoderma lucidum*	cotton stalk
[47]	*Ganoderma lucidum*	bamboo fibers
[48]	*Pleurotus ostreatus*	rubberwood sawdust, corn grain
[2]	*Pleurotus ostreatus*, *Pleurotus citrinopileatus*, *Pleurotus eryngii*, *G. lucidum*	husk psyllium, chicken feathers, flour, textile
[49]	*Trichoderma asperellum*, *Agaricus bisphorus*, *Lentinula edodes*, *Pleurotus ostreatus*, *Ganoderma lucidum*, *Kuehneromyces mutabilis*, *Flammulina velutipes*	oat husk, rapeseed cake

Hyphae can display different types and specializations related to substrate degradation and the development of reproductive structures. In structure of bio-composites, mycelium, is coupled with other non-fossil materials derived from biological processes, such as plant materials, to exploit the natural growth of the fungal organism on these substrates compounds [11]. There is great scientific interest in *Pleurotus sp.* due to the important phytochemicals in its structure, but the most important aspect is that it can secrete enzymes, thus is capable to decompose the substrates, developing interwoven filamentous structures, or can decompose plant components difficult to be hydrolyzed, like lignin.

In a recent research study, Girometta et al. (2019) demonstrated that mycelium of *Pleurotus sp.* can be shaped in order to produce insulating panels, packaging materials, bricks and a variety of design objects like vases, flower pots, office products, LED lighting, shoes made of bacterial cellulose or a water bottle made from algae and furniture [13].

Pleurotus sp. mycelia penetrate into their feeding substrates by physical pressure and enzymatic secretion in order to break down biological polymers into easily absorbed and transported nutrient, as glucose [24].

Haneef et al. (2016) have used in their research study two types of edible and also medicinal fungi species, *Ganoderma lucidum* and *Pleurotus ostreatus*, and have chosen as a nutrient substrates biopolymers from pure cellulose and cellulose-potato dextrose broth cellulose based on the idea that cellulose is the most abundant natural polymer and PDB is the most common medium that promotes fungal growth since it is rich in simple sugars easily digestible by mycelium. The final result should be a uniform material since the mycelium growth process occurs on an invariable nutrition platform and the two substrates are very homogeneous, having regular surfaces, and the polysaccharide nature of the two feeding substrates similar fungal enzymes are expected to be used by mycelium for their hydrolysis, guaranteeing the uniform absorption of the nutrients by the mycelia throughout the growing process. At the end of their growing period, the mycelium films obtained were heat treated in order to stop their grown and to obtain the final fibrous membranes [24].

Trametes and *Ganoderma* were investigated as well (Table1). However, the whole diversity of fungi is vaster and there are fungal species that may present advantages as the ones that can increase in volume. Mycelium is an essential network capable of secreting enzymes that convert polymers in the substrate and breakdown products that can be later added as source of nutrients and minerals. Therefore, fungal organism produces biomass by using the nutrients degraded from substrate resulting a compact layer of fungal organism covering the substrate. Substrates used in mushrooms cultivation have effect on chemical, functional and sensorial characteristics of macromycetes [35,50]. Mycelium degrades and colonizes the organic substrate, using the products of degradation as feeding elements to extend its hyphae from the tip, while branching new hyphae and fusing them together to form a denser network. The substrate must provide the necessary nutrients for the mycelium to grow, such as carbon, nitrogen, minerals, vitamins and water. Depending on the species, fungi can degrade the cellulose or lignin compound of plant biomass in a preferential manner, whereas hemicellulose is usually attacked by all species. Most fungi are selective and degrade both cellulose and lignin, despite being shifted toward a cellulose preference or lignin preference. Such a preference is both species-specific and environmentally determined. The choice of substrate is closely linked to the choice of fungus as each species grows on completely different substrates or matter and a thorough study of the choice of this component is required for the development of the composite.

The substrate, as already mentioned, needs to have the appropriate nutrients for the growth of the fungus, but not only to improve its growth, but also to influence the mechanical capacities that the mycelium compound acquires after its growth.

A large number of substrates have been used for the cultivation of the mycelium *Pleurotus ostreatus*, the most commonly used materials as a source of carbon are wheat straw, oats, rye and cotton, coffee waste and wood shavings in particular birch wood (the tree where the mushroom is in the natural state) [5, 10, 12, 20, 23, 27, 34, 37].

The variety of methods in the productive process of fungal bio-composites relies on the colonization of a substrate that is shaped contemporarily or subsequently to the mycelial growth. Once the colonization is carried out, the bio composites material is pressed and dried by different protocols of pressure and temperature.

For solid biocomposites, the most used substrates are represented by common agricultural wastes of vegetal origin, except one study which involved chicken feathers in the biocomposite [2]. Another major category is represented by forestry waste, ranging from economically important woods to fruit tree and bamboo fibers. Some studies included glass fines and plastic waste; however, these may represent a problem for the recycle and reuse of end-of-life myco-composites. In patent applications, wool and silk are also considered besides the vegetal substrates [51].

5. Properties of mycelial biostructures

Some preliminary studies on mycelium-based composites development direction have been performed since 2006, but most of the available studies were published after 2015. The research is quite recent and develops progressively, however knowledge is still lacking and there is need for further improvement. The mechanical performance, density and compression behaviour were extensively studied and research, also focused on the optimization of growth rate, economic cost and finding a correlation between manufacturing variables and the properties obtained. Other studies explored the flammability, water absorption and termite resistance of myco-composites.

Studies indicate that properties of the mycelium composites depend on the fungus, substrate, growth conditions, and processing of the material, as well as its additives. For instance, densely packed substrate resulted in higher dry density and compressive strength when compared to loosely packed substrate. According to a study realized by Karana et al. (2018) mycelium-based materials could be produced by exploiting the abilities of mycelium to interlock other substances within its network to form a thick material representing mycelium-based biostructures [35, 52].

Drying or heating of the substrate at some stage during colonization will result in mycelium-based biostructures. The mycelium matrix in the composite dominates the soft compression at small strain, while the organic substrate particles cause rapid stiffening at higher strain.

The fungal biomass coexists with the residual substrate and form together a biocomposite placed in the foam category. Although their key properties comprise high porosity and rigidity tested for very competitive mechanical properties as compared to expanded polystyrene (EPS), mycelium-based foams are often referred in literature as ‘mycelium bricks’ or ‘panels’. Despite the very restrictive industrial secrecy and the competitive know-how of the manufacturing process, companies all over the world are thriving to offer as quick as possible a highly sustainable alternative for small packaging, all at reasonable costs [53].

Optimized mycelium-based materials are characterized by enhanced insulation properties and low density that provide light weight, comprising a very promising future material in a wide range of industries.

A. Density

The low density of MBFs is not only emerging in light-weight properties for mycelium panels, but also into mechanical and thermodynamic properties of the biocomposites. The low density is highly related to substrate composition and structure.

(1) The higher the fraction of grains in the substrate, the higher the final density. Density is lowered when particles over 2 mm in diameter are avoided in substrate composition and liquid cultures are used for inoculum [15].

(2) The decrease in density of MBFs is strongly dependent of porosity (Pelletier et al., 2013). The replacement of plant biomass by fungal biomass decreases the density of the composite material, making MBFs competitive with EPS density [29].

(3) MBFs are shaped by pressure of about 30 kN, which increases the density in comparison to non-pressed materials, thus decreasing the porosity [35].

B. Insulation

The most cited parameter in literature regards the enhanced thermal and acoustic insulation properties of MBF panels placed intra-wall or extra-wall. Intra-wall panels might be applied for joint thermal-acoustic insulation

(1) The cementing action of mycelial growth provides inter-layer cohesion. In order to increase the cohesion, the need for a complete drying emerges in order to improve the thermal insulation properties (the residual moisture fraction can decrease thermal conductivity)

(2) The surface roughness in panels increases acoustic absorption. Panels from different substrates were tested by Pelletier et al. (2013). The acoustic absorption was reported over 75% at 1000 Hz, even by the worst performing samples

Mycelium-based foams are low-density materials growing from the colonization of a lignocellulosic substrate by the fungus. The result is a fibrous structure where the fungal biomass and residual substrate coexist in a unique matrix. Mycelium-based biostructures are often placed in the foam category due to their high porosity and slight rigidity [52,13].

Besides low density, mycelium - based foams show good insulation properties, making them usable to produce panels placed in a wall core for thermal and acoustic isolation (13, 35, 52, 53].

Foams are generally regarded as good insulators and have a great specific heat capacity. In order to produce mycelium-based materials the researchers developed a scaffolded structure by reiterated layer deposition, each layer being constituted by a colonized substrate. Inter-layer unity is provided by the cementing action of the mycelium [13].

Some investors and companies focus on insulation products and they introduce compostable mycelium-based packaging material as a replacement for traditional extruded polystyrene foam insulation. In 2009, a tea-house constructed from mycelium bricks was created. Likewise, it was created a new type of leather grown from mycelium and agricultural products in a carbon negative-process. On the other hand, other experts in growing mycelium-based materials for design have transformed the material into artistic furniture, emphasizing its freedom of shaping by incorporating advanced technologies such as 3D printing [52].

Karana et al. (2018) realized a research study, using six mushroom samples, regarding the use of mycelium as a component to produce bio based-materials. To acquire a better insight into the actual performance of the mycelium samples, materials included were namely, Medium-density fibreboard, Palm leaf, Cork, and Styrofoam, in these technical tests. According to the test results, the researchers concluded that the main difference between the technical performances of the six mycelium samples were due to the processing techniques. When not compressed, the material was not strong but had good insulating properties. When the material was compressed with heat, the material became much stronger, though less appropriate for insulation [52].

An important feature of mycelium bio-composites is that allows a diversity of technical properties that can be achieved through variations in the fabrication process, such as enriching the culture with different minerals such as selenium and zinc or by modifying the level of temperature or pH [54-57].

Recently, mycelium-based biopolymer composites have been commercialized. Mycelia of filamentous fungi digest and bond to the surface of lignocellulosic materials form networks and provide mechanical strength to panels with fire resistance and acoustical absorption properties. These composites achieved five levels of density and also had acoustic absorption properties. This technology can be applied to traditional wood-based composites as fiber board manufacturing and will be an additional application for this natural material. Bio-based materials are defined as materials containing at least one component that is biologically produced and completely biodegradable [3], but it does not exclude the presence of other synthetic components [13, 18, 58].

Cultivation conditions are essential to produce a good quality mycelium-based bio-structure. In a research study made by Appels et al. (2018), it was shown that the mycelium material grown on cellulose is stiffer, while addition of dextrose to the cellulose based substrate makes both fungal materials more elastic. During colonization of the substrate, fungal growth can be stopped by drying or heating the material. If the fungus is wanted to be preserved in a latency state than it is dried, allowing the fungus to restart growth when conditions become favorable again [35].

According to Dicker et al. (2014), biocomposites represents green composites, a bio-derived polymer reinforced by natural fibers which have the property of biodegrability - an essential quality since it prevents accumulation of solid waste, which is a major consideration for composite materials in products with a limited service [59]. Bio-composites allow exploiting biological wastes and residue, such as bark, waste fibers, and residual stems; thus, waste and residues are valorized and are not simply thrown away into the natural environment. Its production involves low energy, the resulting materials are biodegradable and they have a potential for cost-effectiveness [59, 60].

Also, the beneficial properties of mushroom mycelium were used since the 1990s in Japan for the production of paper and buildings materials. Recent studies have demonstrated the effective performance of foam-like mycelium-based biostructures, compared to conventional materials used in construction industry which can replace synthetic petroleum products such as polystyrene. Thus, mycelium bio-composites have successfully demonstrated their potential to replace plastics or wood composites with less environmentally threatening materials [37, 59].

6. Technological challenges

According to a study realized by Karana et al. (2018), mycelium-based materials could be produced by two grown alternative methods: either exploiting the abilities of mycelium to interlock other substances within its network to form a thick material representing mycelium-based biostructures or harvesting a liquid culture of mycelium [52].

The production of mycelia can be performed in the basal medium such as mineral salt medium. The necessary nutrients should be provided by the substrate for the mycelium to grow. For instance, the substrate should be enriched with growth factors, carbon, nitrogen, minerals, and vitamins. As an alternative of culture medium, the waste streams of agriculture may be used, like wheat or rice straw, from wood sawdust or from other fibers like flax and cotton. The type of substrate chosen significantly influences the technical and experiential qualities of the resulting material. A liquid culture of mycelium was used to obtain pure mycelium materials. The liquid fermentation of fungal microorganisms can be performed in static or machine-shaken containers. When mycelium is grown in a static liquid culture, filamentous fungi form a mat of hyphae at the surface of the liquid. On the other hand, when dried, the resulting material can vary in properties and resembles to leather, paper or plastic. Depending on the additives provided to the mycelium at the end of its cultivation, the outcome can vary in color, translucency and firmness [52, 53].

In order to ensure the growth of the mycelium and to obtain positive results it is necessary to fine-tune several parameters during the fabrication flow (Figure 2). The fabrication of mycelium-based materials requires proper sterilization to achieve appropriate results and prevent contamination by other organisms [61].

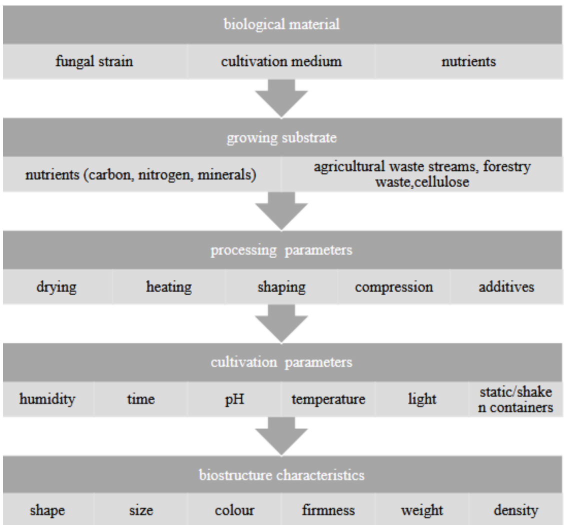

Fig. 2. Technological challenges in fabrication of mycelium-based materials.

The substrate on which the mycelium will grow should be maintained at controlled environmental conditions of light, temperature and moisture to ensure stable growth within two to three weeks. The optimal conditions of temperature and moisture vary depending on the strain of fungi used in the experiment, however the optimum temperature is around 25-35°C, which ensures a uniform growth. Regarding the humidity, it should be maintained around 60-65% in order to prevent the substrate from drying as well as conditions of darkness are also preferable, not only to prevent the formation of fruiting bodies, but also to favor the rapid growth of mycelium. When the growing process is over, the mycelium is dehydrated to stop further growth by drying the material at a 60ºC or leaving it at room temperature to be preserved. The material is grown in a mold which allows designers to reach the shape of the final object. Besides that process, a technique to achieve the required shape and structure for the grown material is laser cutting or cold and heat compression [25, 53].

7. Practical applications within circular economy

A global sustainable development strategy is reducing the non-renewable materials by replacing them with bio-based materials. Besides bio-based materials such as bio-plastics like poly-lactic acid, materials made by bacteria, algae, or fungi are increasingly used as innovative bio-based alternatives [62]. For instance, these bio-based alternatives are used in fashion industry in order to develop new materials such as leather by modifying and controlling the growth condition of organisms and then shaping them into a specific manner [52].

Due to its unique structure and composition could be possible a production of large amounts of mycelium-based materials. In structural terms mycelium is mainly composed of natural polymers as chitin, protein, cellulose, so it is a natural polymeric composite fibrous material. According to Haneef et al. (2016) so far mycelium have been exploited mainly by an American company that uses unprocessed biomass with mycelia resulting into foamy structures which is a combination of mycelium with polysaccharide-based substrates of different compositions [24]. Moreover, a car company (Ford) has decided to use mushroom-based foam as a key component in their automobile parts like bumpers, side doors and dashboards. Ikea, a furniture company, is determined to reduce its use of fossil fuel-based materials and has been looking for alternatives to polystyrene for its packaging foam [53].

In a research study Karana et al. (2018) emphasized that in the clothing industry designers do not exclude the possibility of collaboration with biological organisms guiding their growth in order to produce a useful product. It has been found that designers are concerned on the development of novel materials what led to exploring the biological properties of organisms.

Consequently, by controlling the growth conditions of some macromycetes or by experimenting with different shape possibilities by directly growing materials into a desired product idea it was possible to produce a bio-fabricated leather. In recent years was observed the rising number of design exhibition towards the production of materials made of living organisms. The aim is to introduce a new material as a sustainable solution to a wider audience [24].

Sun et al. (2019) conducted a study about a novel hybrid panel composites based on wood, fungal mycelium, and cellulose nano-fibrils. Mycelium was grown on softwood particles to produce mycelium-modified wood which was then hybridized with various levels of cellulose nano-fibrils as binder [3]. Another sets of experiments made by Sun et al. (2019) were conducted on unmodified wood particles mixed with cellulose nano-fibrils and pure mycelium tissues. The result was that the composites made of mycelium-modified wood and cellulose nano-fibrils presented an improvement regarding physical and mechanical properties compared to the ones made by physically mixing wood, mycelium and cellulose nano-fibrils. Mycelium had an effect on reducing water absorbtion and thickness swelling of the hybrid composites and cellulose nano-fibrils increased the elasticity properties [3].

The technologies of producing self-binding composites were based on chemical or enzymatic pretreatment. Sun et al. (2019) investigated the hybrid systems of wood, mycelium and cellulose nano-fibrils in the production of fully bio-based composite panels. Two systems of applying fungal biomass were compared and growing mycelia on the wood resulted in better properties than physically mixing pure wood particles and mycelium. Growing mycelium on wood did not change the particle dimensions and shape but well covered on the surface of the particles which had positive effects on bonding. The added cellulose nano-fibrils formed a uniform film over the particles and improved the physical and mechanical properties of the composites. The researchers conclude that this novel composite systems showed good physical and mechanical properties and has potential to replace formaldehyde-based composites [3]. Thus, the better dimensional stability of composites produced from mycelium-treated wood was promising in terms of potential to produce outdoor-type composites using water-resistant resins.

As stated before, an advantage of using mycelium-based biostructures is because of its low density viewed as a major factor in the competitiveness. Besides the low weight for packaging purposes, density affects important material properties, both from a physical-mechanical and a thermodynamic point of view. The control of density and its homogeneity within the material are still problematic aspects in mycelium-based foams, as it is related to substrate composition and structure. However, density can be lowered by using liquid cultures for inoculum instead of grain spawn and by avoiding particles over 2 mm in diameter in the substrate [13].

8. Conclusions

Mycelium-based composites are materials capable of replacing foam, wood, and plastics in acoustic, insulation, fireproof, and mechanical applications. Given its low conductivity index and high sound absorption and flame-retardant index, this material could replace traditional materials used in construction, and given its sustainable characteristics, this material could also play an important role in the future of sustainable construction.

Mycelium-based biostructures result from the growth of filamentous fungi on organic materials such as agricultural waste streams. These bio-composites have been explored to produce new materials for packaging.

Renewable mycelium bio-composites have the potential to reduce and even replace plastic and petroleum-based materials which represent a new form to sustain the economy and the natural environment. Since now mycelium-based materials have been produced from mushroom forming fungi.

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