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Fungal mycelium as leather alternative: A sustainable biogenic material for the fashion industry

Ayodeji Amobonye [a], Japareng Lalung [b], Mukesh Kumar Awasthi [c], Santhosh Pillai [a,*]

[a] *Department of Biotechnology and Food Science, Faculty of Applied Sciences, Durban University of Technology, Durban 4000, South Africa*
[b] *School of Industrial Technology, Universiti Sains Malaysia, 11800 Penang, Malaysia*
[c] *College of Natural Resources and Environment, Northwest A&F University, Yangling, Shaanxi Province 712100, PR China*

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ABSTRACT

The global leather industry has been at the receiving end of various environmental and ethical backlash as it mainly relies on animal agriculture which contributes to deforestation, greenhouse gas emissions, and animal welfare concerns. In addition, the processing of animal hides into leather generates a huge amount of toxic chemicals, which ultimately get released into the environment. Thus, growing concern for environmental sustainability has led to the exploration of alternative materials to conventional animal- based leather. In this regard, the application of fungal leather alternatives in material technology is gaining traction because of its high biodegradability, biocompatibility, renewability, as well as its affordable and carbon-neutral growth processes. Fungal leather alternatives have been found to possess significant mechanical and physical properties, thanks to the interwoven hyphal network of the fungal mycelium, as well as antimicrobial activities which have been ascribed to their bioactive metabolites. Various fungal species, including those from the *Agaricus, Fomes, Ganoderma, Phellinus,* and *Pleutorus* genera, are currently being investigated for their potential in this area. This review, therefore, attempts to gain insights into the recent advances in scientific research and real-world applications of fungal-derived leather like materials. It makes a compelling case for this sustainable alternative and discusses the morphology-property relationship of the fungal mycelium driving this innovation. Additionally, the current processing methods and major players in the fungal leather substitute industry are presented. The paper also brings attention to the challenges facing the full deployment of fungal leather substitutes and proposes solutions with the aim of encouraging further research and resource mobilization for the acceptance of this renewable leather substitute.

1. Introduction

According to the United Nations Environment Programme (UNEP), the application of sustainable environmental strategies to processes, products and services is expected to lead to increased efficiency in resource utilization and consequently a reduced risk to human life and the general environment [76]. This notion is clearly in tandem with many of the 17 UN sustainable development goals 2030 (SDG 2030), especially SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible consumption and production). Unfortunately, leather and its derivatives are one of the highest consumer products whose production processes have since been identified to be detrimental to human health and the ecosystem [27]. Recent trends, however, have indicated an increasing consumer awareness, especially in the Global North, with regard to the leather industry and the sustainability of its processing. Being almost as old as the earliest human civilization, animal-derived leather is one of the most durable and malleable materials with a wide range of material properties. According to recent statistics, the global leather goods market was valued at approximately USD 400 billion in 2021, and it is expected to grow at a compound annual growth rate of 6% in the next eight years (Grand View [48]). This sustained rise in the leather market is believed to be motivated by improved living standards, increasing consumer disposable income and evolving fashion trends, among other important factors [31].

It was observed that while the processing of animal skin and hide to the intermediate material leather is a predominant enterprise in many

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* Corresponding author at: Department of Biotechnology and Food Science, Faculty of Applied Sciences, Durban University of Technology, Durban 4000, South Africa.

E-mail address: santhoshk@dut.ac.za (S. Pillai).

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developing countries, the conversion of the leather to tangible consumer products such as apparel, accessories and furniture is usually done by companies in industrialized countries along with their outsourced partners in the developing world. Basically, the leather value chain can be divided into three stages. The first stage starts at the slaughterhouse, where the hides and skins are sourced; the next stage is the processing and tanning of the raw skin and hides into the leather, while the third stage involves the manufacture of different consumer products from leather [91]. However, the huge amount of toxic waste released during these processes as well as the enormous amount of energy and water inputs have become a source of environmental concern and public outcry [1]. For example, the second stage, tannery, is notorious as the most environmental degrading step due to its huge water consumption and its release of hazardous chemicals including chromium salts, chlorides, sulphides, tannins, oils, resins, and detergents, into the surrounding ecosystem [25].

As a result of the immeasurable environmental damage caused by animal leather processing as well as advancement in material science, different alternatives have been developed to imitate animal-based leather. Top among these alternatives are synthetic leathers, also commonly referred to as faux leather, which are usually plastic-based and are majorly derived from polyurethane, polyvinyl chloride and silicone [83]. Unfortunately, being derived from non-renewable fossil fuels, these synthetic leather alternatives pose new challenges, which include their non-biodegradability and the release of various hazardous chemicals which is synonymous with their production processes [5]. For example, the raw ingredients of polyurethane fabrics are mainly derived from petroleum; the processing of this resource has been noted for its huge energy consumption, as well as its negative effects on climate change and the general environment [65].

Recently, more natural, and environmentally friendly alternatives to animal leather have been developed and these include materials from bacterial cellulose, banana trunk fibre, cactus leaves, mango fibres, pineapple leaves, lab-grown collagen, and fungal mycelium. It must be noted that these alternative materials currently do not match leather in the desirable properties, as animal-derived leather is a naturally designed multi-scale material which is optimized for load transferring and its various biological functions [82]. Generally, these alternative materials have been observed with various limitations, especially their undesirably high hydrophilicity [32,64]. In the same vein, leather substitutes from pure fungal mycelium are also noted to be limited due to their low tensile strength, poor handling properties, and lack of uniformity in thickness [103]. Therefore, a lot of efforts are currently being invested into circumventing these challenges; consequently, it is believed by many that leather alternatives derived from fungal biomass are one of the most viable and feasible options. Filamentous fungi exhibit a natural growth pattern which generates a near-infinite amount of microscopically interconnected tubular cells eventually adding up to form the mycelium (the vast macroscopic network of fungal biomass). Fungal mycelium is made up of chitin, glucans and proteins [43] and these biomaterials are now the toast of various start-ups and established companies in the world as a result of their sustainability potential, low combustibility potential, low production cost, fast growth rate as well as their relatively low carbon footprint and carbon turnover [112].

According to Williams et al. [115], the carbon footprint of bovine leather is 1250% that of Reishi – a trademarked fungal leather substitute – which had an estimated carbon footprint of 2.76 kg CO_2-eq per m^2t. Furthermore, the impact of the alternative material was recorded to be significantly lower in comparison to that of bovine leather under the impact categories, such as ecotoxicity, eutrophication, and damage to human health [115]. Interestingly, historical evidence has confirmed the centuries-old usage of fungal mycelium as raw materials for textiles and fabrics. These include Amadou, a traditional felt indigenous to some European countries and the mycelium derived pouches crafted by indigenous North Americans [17]. Recent developments have shown the contemporary adoption of fungal mycelium derived materials by fashion and sportswear brands such as Adidas and Hermes; in the same vein, several start-up companies have also sprung up in different parts of the world and these include Bolt Threads, Ecovative Design, Grado Zero Espace, Mugo, MycoTech, and MycoWorks. Initially, fungal utilization in material science was focused on their use as components of composite materials, however, recent industrial trends have now shifted their use to pure mycelium materials [82]. Currently, 36 patents related to the use of fungal-derived materials as leather substitutes or textiles have been recorded with more than three-quarters of the patents originating in the Global North [41].

However, despite the commercial progress made in the development of fungal leather alternatives, there is still a lacuna in scientific knowledge in this regard [103]. Thus, this paper presents a comprehensive and critical analysis of the latest scientific findings as well as the industrial progress made in the field of fungal-based leather alternatives. For a start, the biological basis for the utilization of fungal mycelia as leather substitutes is highlighted, followed by an exposition on the fungal species that are currently at the centre of focus of this innovative technology. Furthermore, the chemical and physical processes involved in the conversion of raw mycelium into wearable fungal leather substitutes are discussed, while special emphasis is placed on the remarkable industrial players in this field. Finally, the challenges preventing the significant deployment of this technology together with developmental approaches to surmount these challenges are highlighted.

2. The biological basis for the use of fungal mycelium in leather alternatives production

Historically, the industrial utilization of fungal biomass to create fabrics can be traced back to 1950s, when the similarities between the structural properties of chitin (in fungal biomass) and cellulose (wood) were exploited to create writing paper made of composites of the two polymers [58]. It was recorded that the inclusion of fungal biomass into conventional papermaking processes resulted in a significant increase in the paper's fire resistance without a compromise in the bursting strength [16,58]. Subsequently, the application of fungi in papermaking was expanded to the growth of fungal biomass on papermill wastes and the compression of the biomass to create mycelium-derived papers [60]. More recently, fungal biomass has found diverse applications in adhesive coatings, construction of wood dressings, disposable diapers, food wrapping, fibreboard construction materials, filtration membranes and biopolymer sheets from which clothing fabrics and leather-substitutes can be derived [21]. In all, the fibrous nature of the mycelial filaments serves as the basis for the applicability of fungal biomass in many of these industrial applications. It was observed that the physicochemical, mechanical and thermodynamic properties of mycelium derived biomaterials are competitive with many conventional polymers, thus allowing their successful usage in leather, construction, architecture, textiles, and packaging among others [7].

Generally, the mycelium is the vegetative part of fungi is built on an interwoven network of fine tubular filaments commonly referred to as hypha. The porous mycelial structure has been noted to possess remarkable properties which include low density, biodegradability, safety for human use, and remarkable growth rates of approximately 12–245 mm^2/day depending on the fungal strain or species [18]. Furthermore, similar to their mother structures, filaments also vary in size, ranging from ~1 μm to 30 μm in diameter and a few microns to several meters in length, depending on the strains, species and prevailing growth conditions [55]. Basically, the mechanics of a particular mycelium are based on the biochemical nature of its hyphal filaments as well as the topological organization of the filaments within the network. Thus, the hierarchical cellular structure in the hyphal filament is majorly composed of a well-balanced combination of chitin, proteins and glucans which confers their significant mechanical and structural characteristics, desirable in sustainable material science. According to Lew [69], the stress mechanics of fungal hyphae can be attributed to their elasticity, stiffness (or rigidity), and plasticity, which are the various intrinsic responses of their cell walls to stress. While the chitin-glucan structures are responsible for the strength of the structure, the plasticity can be ascribed to the protein component.

In general, the hyphal cell wall is a hardy network that is made up of an inner highly cross-linked chitin-glucan matrix followed by an outer layer that is rich in proteins (Fig. 1). It is believed that the chitin microfibril chains are connected to each other via intra-molecular hydrogen bonds and thus adopt crystalline conformations [11]. The chitins are then cross-linked to branched β-1,3-glucans to form a stronger complex which may further covalently attach to other polysaccharides, depending on the fungal species. In many fungi, the glycosylated proteins in the filaments are connected to β-1,6-glucan through a glycosylphosphatidyl-inositol anchor and these proteins include structural proteins, proteins involved in cell adhesion and cell wall remodelling enzymes [11]. The individual filaments, however, spin and deform in response to far-field loading in a way that depends on their elastic characteristics, orientation, and connectivity within the network, resulting in a complex overall reaction of the network [55]. Although not many studies have been carried out on the mechanical properties and the structure-property relationships, which are relevant to a variety of applications of fungal mycelium, it was noted that tuning of mechanical properties of mycelium-based materials can be attributed to the interchangeable content of chitin, glucans, and proteins within its hyphal walls [18].

Research has shown that the morphology and the mechanical characteristics of fungal mycelium can be manipulated to the desired structure by changing and optimizing their feed substrates, as their growth response has been shown to vary and depend largely on the medium of cultivation [18]. This could also be achieved by genetic manipulation tools, especially by gene editing. Another major reason identified for the utilization of various fungi as cell factories and workhouses in industrial applications is their ability to grow and proliferate on inexpensive growth substrates, both simple and complex, thus remarkably reducing cost while also ensuring environmental sustainability. Being majorly saprophytes, they have developed efficient cellular machinery to degrade complex materials and subsequently retrieve nutrients from these materials [84]. It is common knowledge that their saprophytic lifestyle is largely responsible for organic matter recycling and the maintenance of various biogeochemical cycles of mineral nutrients [13]. It has since been asserted that the remarkable ability of fungi to degrade complex substrates such as lignocellulosic biomass, even under low moisture conditions, is mainly dependent on their highly effective enzymatic system [84]. However, the final material property of the fungal biomaterials is highly dependent on the starting growth substrates. For example, Jones et al. [60] highlighted that pressed fibre pulp derived from masses of hyphal filaments would be most likely obtained from fungal growth under submerged conditions (liquid fermentation) while mycelium mat would be obtained from lignocellulosic particles under solid-state fermentation conditions. However, it is noteworthy that the affordability and low operation cost of using fungi are still covered under both fermentation conditions. While fungal growth under submerged conditions typically makes use of common laboratory media as well as low-cost agricultural by-products such as blackstrap molasses and blended food wastes [95], growth under solid state conditions mainly involves the use of agricultural residues such as wheat bran, wheat straw, sugarcane bagasse, etc. [6].

3. Fungi for leather substitute production

Currently, white-rot fungi are considered among the most viable candidates for the production of leather substitutes and other biocomposite materials, which is a result of their inherent colonization abilities as well as their ability to utilize various biomass for growth [77]. These white rot fungi comprise mainly filamentous fungal species of the Basidiomycota and the Ascomycota phyla, which are both from the fungal subkingdom Dikarya (higher fungi). Although Ascomycetes and Basidiomycetes are the two largest groups of fungi with more than 40,000 and 30,000 species, respectively, a few numbers of these species have been described with the potential to be utilized as leather-substitute materials, giving a large space yet to be researched. In this regard, members of these groups which include *Agaricus bisporus*, Ganoderma *lucidum, Pleurotus ostreatus*, *Phellinus ellipsoideus* and *Trametes versicolor*, have been identified for their significant potential in the production of leather-substitute both in the pure mycelial form or as biocomposites [45,60]. However, some studies have demonstrated the feasibility of other fungal species as base materials for leather substitutes, and these include *Fomitopsis iberica*, *F. pinicola*, *Stereum hirsutum*, *Terana caerulea* [20], *Rhizopus delemar* [114] and *Schizophyllum commune* [10], among many others.

The recent study by Elsacker et al. [40] enumerated 69 fungi involved in different patents related to fungal leather substitutes, with the majority of them belonging to the genus *Ganoderma,* followed by *Trametes, Fomes, Fusarium, Pleurotus,* and *Schizophyllum,* genera. It is believed that materials derived from these classes of fungi are easily biodegradable and can also be composted subsequent to their cycle of use, thus encouraging a circular bioeconomy and minimizing waste generation [7]. As single materials, the aim is to adapt their inherent fibrous networks to materials that are closely related to the fibrous structural units of animal skins, while as composites, they serve as supports for coating layers, thus, giving additional plasticity to the other components [81]. Fortunately, the assessment of the pathogenicity and toxicity of many of these highlighted fungi have shown that they are low-risk species, hence they can be worked upon with no need for extra-

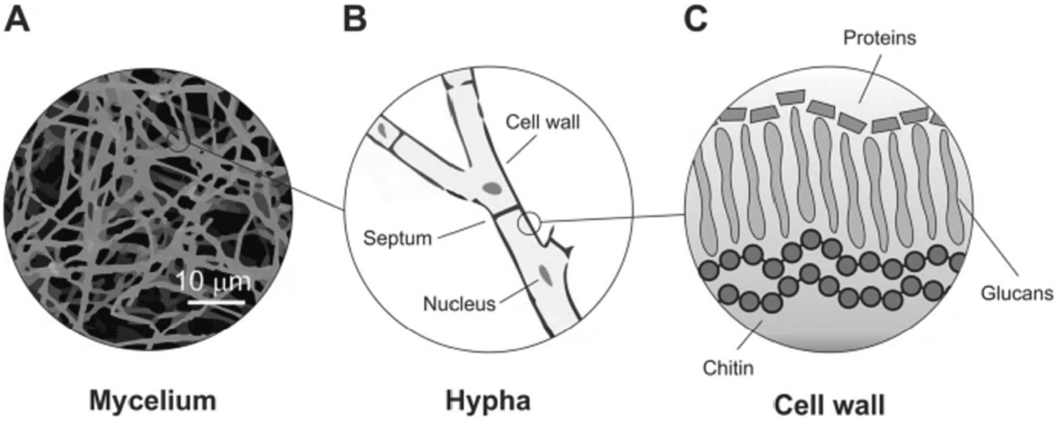

Fig. 1. Visual characteristics of the structure and arrangement of fungal filaments in mycelium (A) optical morphology of mycelium fibre (B) schematic representation of hyphae (C) a conceptual image of the fungal cell wall (Adapted from [113] and licensed under CC BY 4.0).

containment [111]. Supporting the previous assertion is the fact that *Agaricus bisporus* and Pleurotus *ostreatus* are edible mushrooms that are popular in different parts of the world, while *Fomes fomentarius* and Ganoderma lucidum are popular as medicines and dietary supplements. Thus, this section discusses in more detail selected fungal species that have been highlighted in previous studies for their potential in the production of vegan leather substitutes (Fig. 2).

3.1. *Agaricus bisporus*

Agaricus bisporus, commonly referred to as button mushroom is an edible basidiomycete mushroom that is considered to be the most cultivated and consumed mushroom species due to its high organoleptic, nutritional, and therapeutic properties [72]. It is extensively cultivated in the Americas and Europe, second only to *Saccharomyces cerevisiae* as the most consumed fungal species and holds approximately 40% of total global mushroom production [102]. Besides its application as a leather substitute, the fungus has also been utilized in the fabrication of various materials including nanopapers which have immense applications in filtration, energy storage, and sensing. *A. bisporus* pileus has a diameter between 5 and 10 cm, while the stipe could be as tall as 8 cm long and 3 cm wide, thus allowing for enough surface area for material processing [98]. Like most macroscopic fungi, *A. bisporus* mycelia are made up mainly of β-D-glucans, chitin, and some other heteropolysaccharides in lower quantities, as well as structural proteins that are complexed with the polysaccharide and lipid components [102]. Most importantly, biomaterials derived from the fungus' chitin-glucan complex have been demonstrated to possess the highest rigidity and tensile strength of any fungus, as they possessed Young's modulus (*E*) and ultimate tensile strength (σ) of approximately 7 GPa and 100–200 MPa, respectively [42]. In addition, their ease of cultivation, ability to utilize inexpensive lignocellulosic biomass as growth substrates and remarkable mechanical characteristics highlight their potential as future starting materials for leather-substitute materials and other sustainable wearables.

3.2. *Fomes fomentarius*

Fomes fomentarius (tinder fungus) is a basidiomycete white-rot fungus belonging to the Polyporaceae order; it is considered an important forest parasite and is typically found on hardwoods such as birch, poplar, etc. [118]. The fungus is ubiquitous being found in Africa, Asia, Europe and North America, with records showing its use in ancient traditional medicine for the management of inflammation, gastroenteric disorder, hepatocirrhosis, ulcers, etc. [63]. The mycelia of *F. fomentarius, which* are shaped like horse nails, range from 5 to 45 cm in diameter and 2 to 25 cm in height [38]. The fungus has been identified as a promising cell factory for the production of fungal based biomaterials including mycelium-based composites judging from its remarkable mechanical properties which were noted to be close to that of polystyrene [96]. It is also believed that the structural and mechanical properties of *F. fomentarius* biomaterials can be tuned at the micro-scale through the manipulation of its growth conditions, which has been shown to have a significant effect on its cell wall composition [96]. Like many wood rot fungi, the tinder fungus has been grown effectively using waste biomass

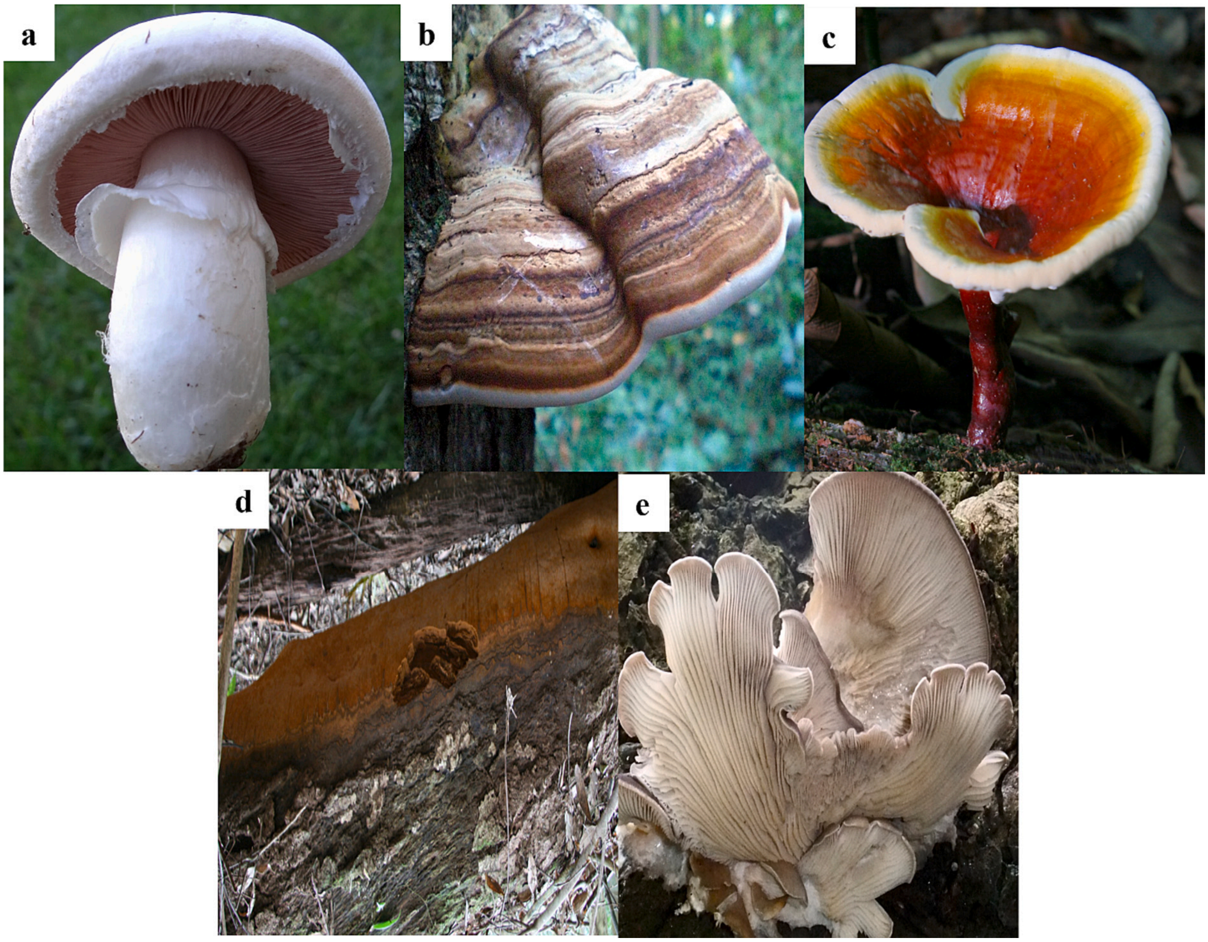

Fig. 2. Macroscopic images of (a) *Agaricus bisporus* by Jerzy Opioła is licensed under CC BY-SA 3.0 (b*) Fomes fomentarius* by Onnola is licensed under CC BY-SA 2.0 (c) *Ganoderma lucidum* by Caspar is licensed under CC BY 2.0 (d) *Pleurotus ostreatus* by Martin Cooper Ipswich is licensed under CC BY 2.0 (e) *Phellinus ellipsoideus* by *Bao-Kai Cui* is licensed under CC BY-SA 2.0.

and its potential for the production of lightweight biomaterials has been elucidated [26]. The fruiting body of *F. fomentarius* is historically popular for its use as a leathery material called Amadou, and it is currently being explored for the production of various fashionable leather-like products in artisanal batches [92]. Furthermore, Amadou leather substitute has been widely proclaimed to be similar to animal-derived leather in colour and close to wool or fur felt in texture [92]. It is a spongy material derived after the thin slicing and boiling of *F. fomentarius* trama in an alkaline bath, after which it is manually stretched [45]. The bulk densities, Young's modulus and compressive strength (at 10% strain) of dried *F. fomentarius* mycelium were recorded to be 0.12 ± 0.01 g/cm^3, 22.21 ± 3.38 kPa and 0.51 ± 0.12 MPa respectively [26]. The *F. fomentarius* fruiting body has been described to possess remarkable viscoelastic recovery properties in the presence of moisture, hence it is a suitable candidate for the development of materials that may require anisotropic loading conditions, such as leather [86].

3.3. *Ganoderma lucidum*

Ganoderma lucidum is a tropical fungal species of the industrially important mushroom family known as the Polyporales, commonly referred to as the shelf or bracket fungi. The Ganoderma genus and other genera belonging to the Polypore family, such as the *Coriolus*, *Trametes*, *Pycnoporus*, and *Formitella* have been described to have immense potential in the production of alternative sustainable materials mainly because of their perennial growth and notable mycelial growth characteristics [101]. Though highly genetically diversified, this family of fungi is important in traditional oriental medicines; however, *Ganoderma* species are different from other polypores because of their double-walled basidiospore [51]. The pileus has been shown to have a width of 2 to 8 cm and a length of 3 to 12 cm, thus, providing a large surface area for processing [52,74]. The basidiocarp has an intricately layered and spongy structure which confers mechanical toughness and lightweightedness, which are well-sought material properties [97]. For instance, the fruiting body of *Ganoderma* cultivated on oak sawdust and walnut shells was recorded to have a whitish velvety appearance with an average density, high tensile strength, and maximum deformation percentage of 0.511 g/cm^{-3}, 0.392 MPa, and 26% respectively [110]. Like many other higher fungi, *G. lucidum* can bio-convert agro-residue and forest waste, under both natural and controlled fermentation conditions, to produce various bioproducts ensuring both economy of scale as well as environmental sustainability [108]. In addition, *the high chitin content of G. lucidum* basidiocarp has been described as one of the main factors which project it as a choice fungus in the development of novel and sustainable biomaterial design [106]. Earlier, Sacchachitin, a skin-like biomaterial used for wound dressing was developed from *Ganoderma* basiodocarp [109]. The utilization of *Ganoderma* has now entered a commercial scale as it is being used to make different fashion items including caps, bags, and shoes which are highly durable and of high performance [89].

3.4. *Phellinus ellipsoideus*

Phellinus ellipsoideus, first identified in Hainan Province, China, is a polypore fungus which produces large and perennial fruiting bodies on dead wood [59]. The fungus (formerly referred to as *Fomitiporia ellipsoidea*) was reported with the largest fungal fruiting body ever recorded with an approximated length, weight and volume of 1000 cm, 460 kg and 467,000 cm^3, respectively [30]. Thus, it is believed that its large size, together with the antimicrobial properties of its constituent compounds have raised the possibilities of its utilization as a leather-like substitute [81]. This potential has since been exploited in different studies with significant results [18,37,81]. For example, Muskin, one of the most popular vegan leather substitutes, was derived from *P. ellipsoideus* and its aesthetics and strength were noted to be quite remarkable [37]. The strength of the biomaterial was noted to be impressive judging from its remarkable heat stability as well as its tensile strength, which were estimated at 1.2 MPa and 101% strain at break, respectively [18]. These remarkable structural properties of muskin have been attributed to its well-balanced ratio of chitin and proteins which was calculated at 3:7 [18]. Furthermore, the notable resistance of the biomaterial to bacterial and fungal attacks is believed to be due to the antimicrobial actions of its bioactive components which have been found to include protocatechuic acid, protocatechualdehyde, hispidin, hispolon, phelligridin, inoscavin etc. [70]. Though smaller in size and unexplored, many other *Phellinus* species including *P. populicola, P. nigricans, P. igniarius, P. tremulae, P. pachyphloeus* may also be valuable bioresources for fungal leather substitute production due to their close structural similarity to *P. ellipsoideus*.

3.5. *Pleurotus ostreatus*

P. ostreatus (oyster mushrooms) is one of the notable members of the Pleurotus genus, which has been identified to be adaptable to different environmental conditions and to possess highly nutritional, medicinal and bioremediative properties [94]. The genus has been noted to be the second most grown edible mushroom after *A. bisporus*, being cultivated in both tropical and temperate regions [100]. P. ostreatus is naturally found on both dead and living trees including popular trees such as beech, hornbeam, poplar, walnut and willow [94]. The fruiting body has colours ranging from grey to dark brown, and from 4 to 15 cm in width, and expectedly, its structural and biochemical properties are dependent on the type of growth substrate used [29,35]. Some studies have cultivated P. ostreatus for applications as mycelium-bound composites, however, it was asserted that the structural properties of the biomaterial, in its original form, were more suited to be used as leather-substitutes and other wearable materials [47]. The fungus is believed to be an attractive low-cost biotechnological tool because of its inherent tolerance and its complex enzymatic system which ensures that it can proliferate within a short period on waste biomass such as cotton cake, corn cobs, coffee residue, grape pomace, wheat straw, wheat bran, as well as various straw, shavings and sawdust [80].

4. Biomass cultivation for fungal leather substitute production

The characteristic of the final leather substitutes derived from fungi depends on several factors, including the type of fungal strain used, the type of growth substrates and other growth conditions, the mode of fermentation as well as the subsequent downstream processing [61]. The previous sections have highlighted various fungi with potential in this regard while identifying the white-rot fungi with the most desirable properties required of the starting materials for fungal-based leather substitutes. Subsequently, the fungal inoculum can be cultivated under submerged, solid state or liquid-state surface for efficient product recovery [15]. Being xylophagous in nature, higher fungi practically utilize a wide variety of materials for their propagation, ranging from simple defined media to complex lignocellulosic biomass (that are readily available), and it has been noted that in addition to the fermentation mode, the choice of the nutrient substrates can be used to tailor the mycelium materials' properties for their use in various applications [8]. For example, there was a significant variation in the moisture level of *Trametes multicolor*-derived biomaterials with different agricultural residues as the feed substrates; average moisture levels of 6.5% and 8.6% were recorded when grown on cotton and rapeseed straw, respectively [8].

4.1.1. Solid state fermentation (SSF)

SSF has been recognized as a sustainable fungal cultivation mode, especially when the production of biomass or secondary metabolites is to be optimized. Compared to its main alternative i.e., submerged fermentation, SSF tends to be more attractive due to its higher productivity, lower water and energy consumption, minimized risk of contamination, and reduced generation of wastewater [3]. According to Chilakamarry et al. [28], fungal growth demands less water activity (~0.5) when compared to bacteria (~ 0.9), thus, the natural growth of fungi is better simulated under SSF conditions leading to increased efficiency. Despite the low water activity of the SSF approach, the growth substrates usually possess adequate moisture to support microbial metabolism, and this could be in the range of the maximum water-holding capacity of the solid substrate [68]. It has been observed that the purpose of producing pure mycelial mats which is the starting material for fungal leather substitutes, is better served under SSF [45]. This is important because fungi typically require direct contact with their growth substrate, thus, they tend to be intimately tethered to their nutrient source [112], however, the production of fungal leather substitutes demands the use of nonwoven fungal mycelial mats which can only be harvested from the top surface of SSF or LSSF trays [45]. Basically, a mat of fungal mycelium grows on top of a solid substrate, after which the top pure mycelium layer is carefully separated from the substrate [49]. Furthermore, the chemical and mechanical properties of the mycelial layer can also be tailored by varying the type of solid substrate used for the fermentation. For instance, the solid-state cultivation of *P. ostreatus* on potato dextrose broth (PDB) resulted in a higher rate of hyphal collapse, reduced hyphal size and showed different relative concentrations in chitin, polysaccharides, lipids, and proteins when compared with the growth on cellulose, thus suggesting that the harder the substrate used, the stronger the mycelium produced [50]. In the same study, it was shown that the fungus grown on PDB had lower Young's modulus, higher water absorption as well as a higher rate of elongation relative to the latter. SSF has been noted to be the preferred mode of mass mycelium production and is currently used by companies such as Ecovative, Mycoworks, and Mycotech, for commercial purposes [40].

4.1.2. Liquid-state surface fermentation (LSSF)

LSSF involves the cultivation of microorganisms in a liquid medium using simple culture medium or lignocellulosic substrates or both under static conditions; as a result, the microbe grows on a surface of a static liquid medium that contains up to 95% free water [88]. This fermentation mode has been widely used in the production of organic acids and many other volatile compounds and was preferred to submerged fermentation due to its economic advantage and ease of product recovery [119]. Similar to SSF, utilizing LSSF is also effective for producing pure mycelial mats [45]. It is believed that this approach of mycelial cultivation also gives room for tunability of the material property of the mycelium. According to Elsacker et al. [41], the material properties of biomass can be enhanced by the addition of porous materials - such as linen, or cotton- on top of the surface, allowing the mat to into the layer. Variations of this method have been demonstrated in the works of Dschida [33] and Gandia et al. [44]. However, the major limitation identified with this cultivation method is the poor availability of dissolved oxygen within the static liquid medium which affects biomass proliferation [44].

4.1.3. Submerged fermentation (SmF)

Submerged fermentation (SmF) process, also referred to as liquid fermentation is the cultivation of microbes in liquid media containing all the nutrients necessary for the growth and metabolism of the microorganisms. SmF is considered more advantageous than SSF as it allows for easier control and flexibility of process parameters especially in the bioreactor scale [34]. Although this cultivation mode has been used severally for growing fungi, including mushrooms, the majority of these were done to produce other bioproducts, besides fungal biomass [14]. It is believed that the cultivation of fungal biomass under submerged conditions will result in the production of slurry or pelletized biomass that would demand laborious processing before a coherent piece of material can be obtained [40]. Expectedly, the material obtained under SmF has been noted to possess different tactile properties in comparison to fungal leather substitutes during SSF which have more spongy morphology [114]. For instance, in a study aimed at producing engineered living materials from *G. lucidum*, cell pellets produced from SmF were blended, homogenized and plasticized to finally form a flat leather-like material [41]. Such processing was also carried out successfully in the production of fungal materials with leather-like properties under submerged conditions using bread waste as the substrate [114].

5. Overview of the processing of fungal mycelium to leather substitute

Subsequent to the harvesting process, the mycelial mats are made to undergo a series of physical and chemical treatments to get them in the right aesthetics, shape, texture and mechanical conditions required for various applications (Fig. 3). Furthermore, the different combinations and variations of treatments currently in use are mainly aimed at improving pliability over rigidity, as well as increasing the durability and absorbent properties [112]. According to Gandia et al. [45], these treatments vary in scale, and may include adjustments of mechanical properties through techniques such as deacetylation and crosslinking of chitin, protein denaturation, material densification, and moisture content control. However, the treatment processes are still undergoing intensive research; hence, there is currently no "one size fits all" procedure. It is also important to note that the different processing methods of the various companies involved in the development of fungal leather-substitute is their trade secret, hence an authoritative comparison will be difficult to make. Despite this, a general overview of the currently reported processing methods of fungal mycelium to the final leather substitute is presented in this section and illustrated in Fig. 3.

The chemical pretreatment process has been noted to either be a mild alkali or acid treatment and these are both synonymous with the liming pretreatment in animal skin leather, which serves to remove extraneous materials, while enhancing the subsequent penetration of the tanning agents [62]. The modification of the chitin content of the fungal mycelium has also been identified as a viable avenue for the introduction of chemical modifications, thereby enabling new properties. Deacetylation of the chitin, which is also achieved during alkali treatment, is expected to release amino groups which will facilitate additional crosslinking sites on the chitosan backbone structure in the mycelium [36]. In addition, the deacetylation process has also been noted to improve the antibacterial properties of fungal chitin, making the deacetylated fungus-derived materials more suited for applications such as bioactive wound dressing materials [36].

Crosslinking of the hyphal filaments in the mycelial mats is a treatment method that is expected to enhance the stiffness and strength of the alternative material as well as improve its durability. According to Elsacker et al. [40], crosslinking can be achieved chemically by using acids (citric acid, dicarboxylic acid, polycarboxylic acid, and tricarboxylic acid) and tannins (glutaraldehyde and pyrogallols). For example, citric acid was found to be effective in crosslinking the cell walls of the adjacent hyphae crosslink via its reaction with the glucan hydroxyl groups present in the cell wall [107]. The tanning process of fungal mycelial mats is another major treatment process which is closely related to crosslinking; it stabilizes the structure of the biomaterial, giving it a texture, which might mimic that of actual leather [41]. Tanning of fungal mats has been done using vegetable tannin at mild temperatures for prolonged periods, such as eight days at 25 °C [114]. The tanning of fungal biomass in Reishi production was noted to be achieved using environmentally friendly fatliquors, which are chemically modified animal and vegetable oil [115]. Subsequent to tanning, the fungal sheets may be further flattened using the wet-laid technique [36,67]. Hot pressing can also be introduced as the mechanical,

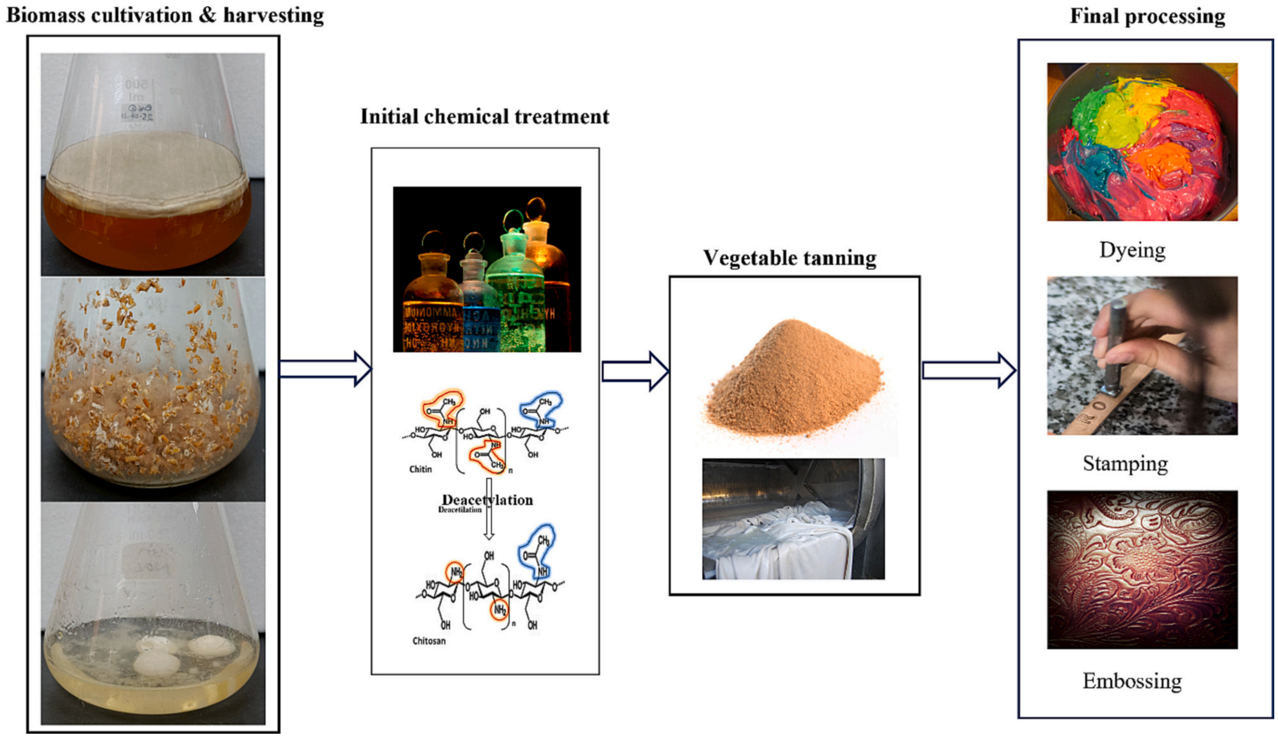

Fig. 3. Brief overview of the processing of fungal leather substitute (Tie-dye cake batter by moonlightbulb is licensed under CC BY 2.0; Young girl stamping leather" by Ivan Radic is licensed under CC BY 2.0; EasyWhite Tan leather in drum by Mirko Müller is licensed under CC BY-SA 3.0; Tannin heap by Simon A. Eugster is licensed under CC BY 3.0., Flasks by Skycaptaintwo is licensed under CC BY 2.0.; Chitin and Chitosan by Vicente Neto is licensed under CC BY 4.0.; Embossed leather by Elineart is licensed under CC BY 2.0).

physical, and thermal properties of the biomaterials are noted to be improved by the post-synthesis pressing temperature [77]. It is also believed that heat pressing will facilitate the homogeneity and isotropy of the biomaterial for better functionality. In a previous research, cold and hot pressing were used separately in the treatment of a fungal biocomposite, however, the material property- especially the elastic modulus- of the biocomposite was recorded to be improved with hot pressing than cold pressing [8].

Majorly, the other treatment process of the fungal biopolymer has been identified to be mainly chemical treatments which serve to further enhance the strength of the materials. For instance, treatment with glycerol (plasticizer) and a hydrophobic biobased binder was observed to increase the flexibility, tensile strength, and water-repellence ability of a fungal-based leather substitute [114]. In addition, the wearability, and resilience of the biogenic leather substitute to perspiration, water spotting, solvent wicking, crocking, UV exposure and salty water have also been noted to be enhanced by hybridization with other natural or synthetic materials such as felted polyester reinforcement or polylactic acid surface coating [24,104]. The post-treatment processes are mainly to improve the aesthetics of the material, and they involve large-scale modifications of appearance, which can be achieved through techniques such as carving, imprinting, embossing, stamping, and dyeing of the mats.

6. Global scenario of fungal-based leather-alternative industry

Fungal based leather substitutes and other biobased leather substitutes such as those derived from apple, bacterial cellulose, cactus, pineapple and kombucha have been found useful in diverse industries such as footwear, clothing, automotive, fashion accessories, furniture, interior decoration, etc. In the biobased leather substitute market, the current key players are Ananas Anam Ltd., Bolt Threads Inc., DuPont Tate & Lyle Bio Products, ECO Leather, Ecovative Design, Flokser A.S., Fruitleather Rotterdam, Modern Meadows, MycoWorks, Nat-2, Natural Fibre Welding Inc., Tjeerd Veenhoven Studio, Toray Industries Inc., Ultrafabrics, and Vegea. Although the current market size for biobased/plant-based leather substitutes is insignificant compared to conventional animal skin leather, various growth projections have indicated that it is an emerging market with significant growth potential. For instance, Grand View Research estimated the global market for biobased leather substitutes to be USD 710.3 million in 2020, a value which is projected to increase at a CAGR of 48.5% from 2021 to 2028. Similarly, in a different estimate by Mordor Intelligence, the market for biobased leather substitutes is expected to reach approximately USD 2.89 billion by 2026, expanding at a CAGR of 52.6% over the projected period [85]. According to MarketandMarket [79], fungal-based leather substitutes had a leading share of 26.6% of the total biobased/plant-based market in 2021 and is estimated to increase at a CAGR of 7.7% between 2022 and 2027.

From an industrial perspective, the advantages of the fungi derived material over the other leather alternatives have been noted to include the ease of biomass cultivation - as fungi can be grown under controlled fermentation conditions - the shorter growth period of fungi as well as the lower carbon footprint. Currently, the major companies in this fast-emerging fungi-based leather substitute industry have been identified to include BioFabrics, Ecovative, Kering, Bolt Threads, Mogu, Muskin, Grado Zero Espace, MycoTech and MycoWorks. Many of these companies are start-ups, while some of them are currently diversifying from other forms of biobased leather alternatives to mycelium leather alternatives. The estimated values of these companies range from approximately 5 million to 50 million USD and majority of themas well as their consumers, are concentrated in the US, Europe and Asia (Table 2). The acceptance and popularity of fungal-based leather alternatives in these parts of the world have been ascribed to the gradual shift to sustainable materials, technological innovation, as well as the relatively higher purchasing power of people in these regions compared to the rest of the world [19]. Furthermore, the increased patronization of vegan and cruelty-free goods as well as the collaboration between fungal-based

Table 2
Major fungal leather substitute companies and products.

Company name	Country of origin	Trademarked /Brand name	Range of products	Value (USD)*	Website
Bolt Threads	USA	Mylo	Shoes, Bags, Jackets	472.1	https://boltthreads.com/technology/mylo/
Ecovative	USA	MycoComposite AirMycelium	Shoes, Bags, Jackets	91	https://www.ecovative.com
Grado Zero Espace	Italy	Muskin	Bulk leather material	5	https://www.gzespace.com/
Mogu	Italy	Ephea	Shoes, Bags, Jackets	5.7	https://mogu.bio/
MycoWorks	USA	Reishi	Bags	187	https://www.mycoworks.com/
MycoTech	Indonesia	Mylea	Shoes, Bags, Jackets, Watch straps	1.4	https://www.mycl.bio

[*] Financial information obtained from Yahoo finance and ZoomInfo data.

leather substitute companies and internationally recognized fashion brands, are additional factors encouraging the growth of this emerging industry [112]. For instance, Bolt Threads, a mycelium leather substitute company in the United States, is in a manufacturing partnership with three established fashion brands: Adidas, Kering, Lululemon, and Stella McCartney. In addition, General Motors, besides being a collaborator with MycoWorks, a leading mushroom leather substitute company, is also one of the leading shareholders of the company.

Environmental pressure groups such as Ethical Fashion Initiative, Fashion Revolution, Greenpeace and People for the Ethical Treatment of Animals (PETA) have been at the forefront of the campaign against environmental impacts of leather production, animal cruelty and in the campaign for ethical and sustainable fashion practices. Many of the fashion products derived from fungal mycelium are currently displayed on the shelves of major fashion outlets across the world, while a large chunk of sales is achieved through direct-to-consumer sales via various e-commerce websites (Figs. 4 & 5). However, it should be noted that the manufacturing processes of fungal leather alternatives are relatively higher as it involves a huge investment in research and development. Furthermore, a lot of resources are required by the companies to attain the necessary certifications from regulatory organizations such as the United States Department of Agriculture (USDA), PETA, European Bioplastics, Biobased Industries Consortium, etc. All of these culminate into a significantly increased overall price of the products compared to conventional materials of the same or even better quality, thus drastically reducing their competitive edge. Presently, international standards have been developed for fungal based leather substitutes as well as other similar alternatives with the two most notable ones being the ASTM D6866 of the American Society for Testing and Materials International and the ISO 16620-2 which was developed by the International Organization for Standardization [56].

7. Challenges of the fungal-based leather industry

In view of the foregoing, the potential of fungal-based leather substitutes in various industries cannot be overestimated, however, the mushroom leather substitute industry is not immune to the various challenges facing such emerging industries. Although these materials possess some physical and mechanical properties that allow their use as substitutes for conventional leather, a critical review of currently available data indicates that they fall short of the minimum requirements for many important material properties expected of leather-like materials. For instance, despite the remarkable strength of *Schizophyllum commune* mycelium, it was noted that the biomaterial lacked dimensional stability, flexibility and resistance to biological and chemical degradation when compared with conventional materials [9]. Furthermore, the modification of mycelium to achieve the desired material properties such as comfort, durability, flexibility and cleanability

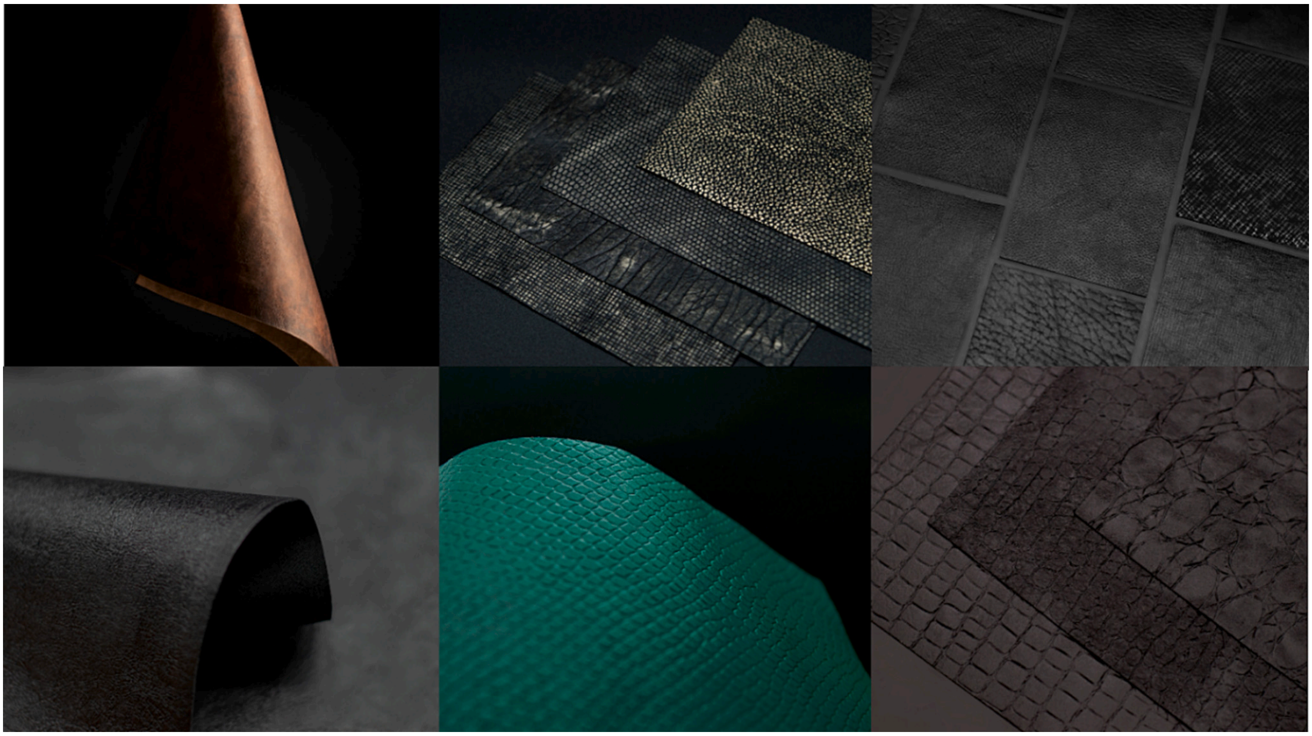

Fig. 4. Textured Ephea leather alternative samples made from mushrooms developed by Mogu (https://mogu.bio/).

Fig. 5. Finished fashion products from mushroom leather alternatives from Muskin developed by Grado Zero Espace (https://www.gzespace.com/).

would most probably be achieved via chemical processing [12]. This chemical finishing will affect the environment, both directly and indirectly, decreasing the sustainability of the new biomaterials, thus, defeating the main objective of their invention. According to Hildebrandt et al. [53], water usage and the energy consumption required for manufacturing these bio-based leather can also result in negative environmental impact. Thus, approaches that integrate environmental sustainability, biodegradability, increased circularity, and end-of-life recyclability are required to mitigate these attendant challenges. The most environmentally sustainable of these solutions have been identified to include the selection of appropriate fungal species and strains, genetic modification, standardization, process optimization and upscaling. In addition, the utilization of smart design practice which involves the development of composite materials from fungal mycelium with other biodegradable materials (e.g., fruit remains, cellulose, chitosan, proteins, lignocellulosic biomass) as well as synthetic materials (such as polyurethane), have also been proposed.

7.1. Fungal strain selection

Although various fungal species have been demonstrated for the remarkable applicability of their mycelium in material technology, especially of the Ascomycetes and the Basidiomycetes group, however, it is believed that these strains represent a tiny fraction of the approximately 12 million fungal species in existence [117]. In recent times, however, some significant progress has been made in the amount of catalogued fungal species; despite this, more than 90% of fungal species are still yet to be curated [54]. Thus, the selection of the right fungal species is an onerous task for researchers and manufacturers alike for effective biomaterial production. According to Alemu et al. [2], some of the eligibility criteria in this regard include mycelium density, growth rate, ease of cultivation, cost of the growth substrate, pathogenicity profile, and the structure of the mycelium. The cell wall composition of the fungal strain is also important as the compositional ratio of structural polymers (such as chitin/protein content) has a significant effect on the post-processing efficiency through the amount of available chemical crosslinking sites and consequently material properties [46]. It is believed that the efficiency of strain selection might be significantly enhanced by an improved understanding of the biology of the already curated fungal strains, which comprise industrially exploited strains, ecologically relevant species as well as reference laboratory strains [82]. It is also believed that the application of high-throughput technologies and approaches, such as the “omic” tools, would be instrumental in revealing the dynamics of fungal growth, product formation, as well as their plasticity under varying environmental conditions [105].

The mode of the fermentation process or the downstream processing of the mycelium has also been identified as another determining factor. For example, fungi belonging to the Agaricales and Polyporales order have been identified as potential candidates to successfully develop mycelium materials on lignocellulosic substrates especially those belonging to the *Fomes, Ganoderma, Pleurotus, Schizophyllum* and *Trametes* genera [39,112]. On the other hand, species of the *Aspergillus*, *Penicillium*, and *Trichoderma* genera are noted to grow more efficiently in bioreactor conditions [87,112]. In summary, before considering further strain improvements, it is imperative to choose the most appropriate and feasible species based on the cost of the substrate, the fermentation approach and the desired material application by screening the existing fungal biodiversity. For instance, Ecovative was noted to have identified and maintained a collection of over 70 valuable strains for the development of mycelium-based biomaterials [120].

7.2. Genetic modification

Strain improvement of filamentous fungi for enhanced applicability in the industry has been made possible by recent advancements in genetic transformation systems. This basically involves a change in the natural genetic code of the fungi for a particular function, and has been mainly achieved via the gene knockout, gene silencing approach and/or overexpression of the gene of interest [66]. For example, gene knockout or silencing can be employed to hinder the expression of native genes responsible for the synthesis of unwanted secondary metabolites in a fungus, thereby circumventing its pathogenicity. In this regard, the functionality of *Schizophyllum commune* mycelium was shown to be significantly improved by the deletion of its hydrophobin gene, which resulted in improvement in tensile strength, water holding capacity and mycelial density [9]. In the same fungal species, deletion of some transcription factors responsible for early development, viz., Bri1 and Hom1, increased mycelial growth by 130%, compared to the native strain [93]. In another instance, the genome of a *Trametes* strain was manipulated to facilitate the overexpression of chlamydospore production and consequently its rapid proliferation, as well as the overexpression of its chitin deacetylase gene for increased material strength [122]. Similarly, Schaak (2019), also described the overexpression of a chitin deacetylase gene in a *Ganoderma* strain with altered chitin/chitosan ratio in the fungal cell wall, which could be used to tune the mechanical properties and final performance of the resultant material.

However, despite all these notable examples, the deployment of this approach is relatively slow with fungi compared to advancements made on bacterial organisms. One reason for this observation is the huge size of the genomes of filamentous fungi. Unlike *E. coli*, a model bacterium with approximately 4000 genes, filamentous fungi contain between 9000 and 14,000 genes [82]. However, the CRISPR/Cas (Clustered Regularly Interspaced Short Palindromic Repeat" and "CRISPR-associated protein 9) system has recently emerged as one of the most effective genome editing tools in filamentous fungi and other living systems [71]. The increased utilization of this tool in the manipulation of biosynthetic gene clusters in fungi of interest is expected to greatly enhance fungal product discovery and engineering and could also introduce some other important bioactive properties into these biomaterials besides improving the mechanical properties [116].

7.3. Upscaling of fungal leather substitute production

In the process of utilizing living cells as microbial factories, the optimization of key parameters is important to achieve a competitive economy of scale [23]. Optimization in bioprocessing is noted to be critical when there is the need to improve efficiency, productivity, and profitability and it can be achieved via many approaches, which include the age-long "one factor at a time approach" and the more recent computer-aided mathematical modelling [78]. Numerous studies have been devoted to the optimization of various bioprocess involving fungi. In the case of fungal leather substitute production, however, optimization can be employed both during the fungal cultivation stage and the mycelium processing stage. For example, in *Ganoderma lucidum*, the statistical optimization of process parameters - including media composition, pH, aeration, temperature, spawn materials - was demonstrated to have led more than 1000% increase in mycelial formation [22]. Similarly, in the *Pleurotus* genus, another model genus for fungal-based leather alternatives, the optimization of the cultivation conditions was observed to have caused a remarkable increase in the yield, the number of fruiting bodies and more importantly, the chemical composition of the mycelium [90].

Like all other emerging technologies, the efficient upscaling from lab trials to eventual commercialization is a difficult task with various challenges and complexities. Currently, there are different bioreactor designs, from simple static shake flasks to more advanced computerized bioreactions with huge volumes. However, studies have shown that upscaling is more feasible under submerged fermentation conditions than solid state conditions as there is no limit to the upscaling operations and the process parameters (such as the pH, incubation temperature, aeration, etc.) can be easily controlled [75]. A critical factor to be considered in upscaling mycelium production and processing for commercial purposes is the fermentation substrate, which should serve as a cost-effective source of energy and nutrients for the fungus. An increase in the production volume will necessitate an efficiency in the economy of scale, thus, a higher quantity of substrates would be needed for the upscaled plant. It is imperative that a suitable substrate be identified and sourced from the immediate environment, a deviation from this may lead to increased production cost and an increase in the carbon footprint of the final biogenic leather alternatives, as was previously highlighted by Zheng et al. [121].

7.4. Improvement and evaluation of material properties

Even though the development of leather alternatives has seen significant progress in the last decade, it has been observed that the material properties of these alternatives still leave much to desire. Leather, a multi-scale material, is derived from animal skin that has been biologically optimized for load transferring, protection against mechanical, thermal and physical stress, and acts as a barrier to excess moisture and UV radiation [18]. It was previously established that the mechanical stability of Muskin (a fungal-derived leather-alternative), measured in terms of its tensile strength and tear strength, was very low compared to the conventional material [82]. Although it has been suggested that the use of crosslinking agents may circumvent this drawback, it is believed that this might significantly affect the multiscale material concept, as well as the orientation of the components along the load direction [18]. Thus, there is a need for novel treatment approaches that will significantly improve the functionality of this fungal-based material.

Although in the study by [82], the moisture permeability and flexibility of fungal leather alternative were described to be within an acceptable range, there is currently no data to show the real-life comfortability of these materials using ergonomics and usability as fundamental variables. The evaluation of the comfort would be able to quantify the ergonomics, skin sensation, as well as physiological and thermophysiological response of the human body to the fungal-derived material while identifying future areas of improvement. Expectedly, there are complications with the testing and standardization process for fungal based leather substitutes due to the wide variety of starting materials and processing aids currently utilized to achieve the final leather-substitute materials. In this regard, it is imperative that there should be standardized material testing methods for fungal-based leather alternatives as testing standards were observed to vary among different countries and manufacturers [40].

8. Conclusion

Filamentous fungi have been identified as remarkably rich and diverse groups of species, that have established themselves as promising bioresources with a wide range of industrial applications. Products derived from this group of organisms are now considered essential building blocks for a transition towards a more sustainable future for our planet, as they facilitate a pollution-free environment while providing renewable alternatives for fossil-based resources. The production of leather-alternative materials from filamentous fungi via environmentally benign processes has been noted as one of these sustainable solutions. In this biogenic process, agricultural wastes are upcycled into cost-effective, environmentally sustainable, and highly versatile leather-like substitutes, thus contributing significantly to a circular bioeconomy which aims to increase resource use efficiency and reduce waste accumulation to the barest minimum. Although the monetary value of this circular economy is currently unquantifiable, the environmental benefits, including lower emissions and better land use, are undeniable. Consequently, many start-up companies have recently emerged in the fungal-based leather substitute industry. Many of these companies have partnered with renowned fashion companies to design and market consumer products from mycelium leather substitutes. Currently, this industry is estimated to have a market value of ~1 billion USD, and it is being led by innovative including Bolt Threads, Ecovative Design Grado Zero Espace, Mugo, MycoTech and MycoWorks. Many of the identified limitations of the fungal leather substitute technology can be circumvented by sustainable design practices that are specifically tailored to fungal materials and this involves process optimization, development of composite materials with other biodegradable materials, provision of growth substrate with little or no carbon footprint, as well as strain selection and improvement. For instance, the large natural repository of fungal species is still relatively unexplored when compared to other microbes like bacteria, as there are still a lot of fungi, especially from the

Ascomycota, Basidiomycota and Zygomycota families that can serve as starting materials in this regard. Similarly, the approach of strain improvement, especially through genetic modification, has become relatively more productive with the advent of CRISPR/Cas9 based systems, which has shown remarkable results with filamentous fungi.

There is no gainsaying in the fact that chemical modification is currently involved in the processing and fine tuning of the mycelium to final leather alternatives, and these chemical processes could affect the environment and negate the whole sustainability concept surrounding the new materials. In this regard, there is a need for suitable eco-friendly production pathways to ensure the materials meet up to their sustainable tag. Recent development has shown that besides the utilization of fungus as raw materials for animal leather-substitutes, the list of potential applications is exhaustive, and it includes the production of biomedical scaffolds, electronic wearables, composite construction materials, packaging, support material for electronic circuit boards, wound care material and even the manufacture of meat alternative products. However, the potential of fungal leather substitute materials in the consumer market is still undervalued as it is faced with a myriad of challenges, which vary from the dearth of knowledge in basic fungal biology to industrial challenges. In addition, one of the biggest challenges with deploying this technology is the inability of fungal-derived leather substitutes and other leather substitutes to attain the same material properties as animal leather. It is expected that more research and development efforts will be focused on increasing the versatility and durability of these fungal-derived products, which will consequently facilitate the introduction of mycelium materials to a wider range of consumers. In the long run, the expected development of the fungal leather- substitute industry based on utility values will be enhanced majorly by the global shift towards environmental sustainability, the availability of low-cost agricultural residues as fungal feedstock, responsible fashion trends as well as government policies and regulations.

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Ayodeji Amobonye: Conceptualization, Resources, Writing – original draft. **Japareng Lalung:** Resources, Writing – review & editing. **Mukesh Kumar Awasthi:** Writing – review & editing. **Santhosh Pillai:** Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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