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Leather-like material biofabrication using fungi

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Fungi-derived leather substitutes are an emerging class of ethically and environmentally responsible fabrics that are increasingly meeting consumer aesthetic and functional expectations and winning favour as an alternative to bovine and synthetic leathers. While traditional leather and its alternatives are sourced from animals and synthetic polymers, these renewable sustainable leather substitutes are obtained through the upcycling of low-cost agricultural and forestry by-products into chitinous polymers and other polysaccharides using a natural and carbon-neutral biological fungal growth process. Following physical and chemical treatment, these sheets of fungal biomass visually resemble leather and exhibit comparable material and tactile properties.

Leather is a durable and flexible natural product that is produced by physically and chemically treating (tanning) animal skins and hides to alter their protein structure[1]. It is a common commodity with a market value estimated to reach almost US$360 billion by 2025 and a popular material in clothing, footwear, furniture and accessories due to its durability coupled with its natural aesthetic and tactile properties, such as its colour, soft feel and warmth[1,2]. However, with shifting social standards and increasing emphasis on environmental sustainability, the use of leather, which would typically be characterized as a co-product of meat production[3], has been criticized by some as socially irresponsible and environmentally unsustainable[4,5]. After all, livestock farming is associated with deforestation for grazing, considerable greenhouse gas emissions and environmental damage attributed to animal waste[6]. Leather processing is also not environmentally friendly, utilizing hazardous chemicals and generating substantial quantities of sludge waste when treating raw hides[6,7].

These issues have prompted the development of leather-like materials that are not derived from animals. Synthetic leather substitutes produced from polyvinyl chloride (PVC) and polyurethane (PU) have found a wide market and largely mitigate the social and environmental concerns typically associated with leather production[8]. However, these synthetic leather alternatives also require the use of hazardous chemicals in their production[9] and are derived from fossil fuels, resulting in a lack of biodegradability and have the same limited end-of-life options as most plastics[10,11].

A new competitor in the artificial leather market derived from fungal biomass is now emerging, promising to be a cost effective, socially and environmentally responsible alternative to both bovine and synthetic leather alternatives for use in upholstery, apparel, footwear and athletic gear[2]. Chitinous leather-like materials extracted from fungal mycelium, the elongated tubular structures that constitute the vegetative growth of filamentous fungi[12], are rapidly gaining commercial traction, with several biotechnology companies around the world now marketing fungi-derived leather-like materials. Fungal mycelium is grown on low-cost forestry by-products, such as sawdust, before being physically and chemically treated to produce leather-like materials with comparable appearance and materials properties to both bovine and synthetic leathers[13]. Primarily comprising chitin and other polysaccharides, such as glucans, proteins, chitosan, polyglucuronic acid or cellulose[14,15], these new leather-like materials are also fully biodegradable at the end of their useful service life, unless hybridized with other fabrics or polymeric materials, such as polyester and polylactic acid, in which case biodegradability is correlated with the least-easily degraded constituent.

This Review examines the sustainability of bovine and synthetic leathers before providing the first glimpses into the development and commercialization of fungi-derived leather substitutes and their current applications. The manufacturing processes associated with these new materials are comprehensively described and their environmental sustainability and cost discussed for prospective manufacturers. A comparison of the material properties of bovine, synthetic PU leathers and fungi-derived leather-like material is then provided to quantitatively characterize the similarities and differences between these fabrics for consumers. Finally, the market outlook and future challenges of this new leather substitute are discussed.

Sustainability of bovine and synthetic leathers

Several social and environmental issues surround leather production, ranging from the obvious ethical concerns associated with any animal product to the considerable impact of livestock and leather processing industries on the environment. The livestock sector is estimated to be responsible for 12–14.5% of global greenhouse gas emissions, with approximately 65% of this value attributed to cattle[2,8]. Cattle farming generates substantial quantities of methane, which is produced during digestion of grass by ruminant digestive systems and released through belching[16]. Deforestation for livestock grazing areas also results in loss of animal habitats, carbon capture and storage[17]. However, since the majority (91%) of the environmental impact associated with bovine leather can be attributed to livestock rearing, the proportion of this impact for which the leather industry is responsible depends on whether leather is considered a co-product or by-product of meat production[2,3]. This is a matter of debate but the value of bovine skins, accounting for 5–10% of the market value of the entire animal, would suggest that they are a co-product rather than a by-product, which by convention is not inventoried or assigned a resalable value due to its lack of industrial or commercial worth. Hides are among the principal co-products of meat generation, accounting for ~7 wt%

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Table 1 | Environmental impact of bovine and synthetic leather (Higg Materials Sustainability Index)

Category	Bovine leather	Synthetic leather
Global warming	36.3	10.1
Eutrophication	73.5	4.8
Water scarcity	25.0	1.7
Abiotic resource depletion	14.4	13.0
Fossil fuels and chemistry	13.8	13.4
Total	**163**	**43**

Data from The Sustainable Apparel Coalition (https://msi.higg.org).

of the animal mass in cows and ~16 wt% of cow co-products[18]. Other principal co-products include bones (10–13 wt% of animal mass and 25–30 wt% of co-products) and feet (~2 wt% of animal mass and ~5 wt% of co-products). These co-products are primarily used in glue, gelatine and mineral production often requiring energy-intensive heating processes and use of lime. Other bovine co-products include meat products consumed by humans or used as animal feed, such as the blood, head, lungs and trachea, rumen and reticulum, omasum, liver, abomasum, heart, tongue and kidneys, which are considered by some people to be delicacies. Since many of these bovine co-products are consumed with minimal processing, the environmental impact associated with leather is comparatively quite high. Additionally, the tanning process itself utilizes chemicals, such as chromium salts, which have the potential to endanger worker safety during leather manufacture and can even leach from the finished leather products resulting in allergic reactions in some consumers[7,19,20]. The tanning process is also associated with substantial quantities of waste; the processing of 1,000 kg of raw hide generates 600 kg of sludge waste[6]. Interested readers can find further details relating to the sustainability of bovine leather in refs. [4,21,22].

Many of the social and environmental issues associated with leather can be mitigated using artificial leather, produced from PVC or PU. These synthetic leather alternatives do not require livestock farming and traditional tanning processes making them more environmentally friendly than bovine leather[2]. However, it should be noted that elements of the manufacturing and end-of-life processes of these synthetic materials do affect the environment. Both PU and PVC are derived from fossil fuels. In the case of PU, hazardous substances, such as methylene diphenyl isocyanate and toluene diisocyanate, are required during fabrication[9,23]. The end-of-life options for synthetic leathers are also problematic as they are not biodegradable and take centuries to break down in the natural environment[10,11]. Incinerating these synthetic materials is associated with production of toxic gases, such as hydrogen cyanide from PU, and hydrogen chloride and carbon monoxide from PVC[24].

The sometimes-ambiguous importance, applicability and impact of the supply chains, raw materials and processes that are used to manufacture bovine and synthetic leathers make the environmental sustainability of these materials difficult to assess. However, the Higg Materials Sustainability Index developed by The Sustainable Apparel Coalition can help to provide some insight into the full environmental impact loading of bovine and synthetic leather based on their contribution to global warming, eutrophication, water scarcity and abiotic resource depletion (Table 1) (https://msi.higg.org). The index value for bovine leather is weighted for co-product status, constituting the environmental impact associated with cow hides, a chrome-based tanning process, single drum operation leather finishing (dyeing, waterproofing or fatliquoring), hang drying and polyurethane coating. The index value for synthetic leather includes the environmental impact associated with polyethylene terephthalate (PET), continuous filament extrusion and melt spinning with texturing, knitting, scouring and heat setting of synthetic fibres and batch dyeing using disperse or cationic dyes. According to the index, synthetic leathers have a quarter of the environmental impact of bovine leather (43 compared to 163) with the most notable reduction in environmental damage associated with reduced eutrophication (4.8 compared to 73.5) since synthetic leather does not require animal farming, the runoff of which is a major source of water pollution[25,26]. Large reductions in the global warming (10.1 compared to 36.3) and water scarcity (1.7 compared to 25.0) components of the total impact are achieved in PU manufacturing, again due to the absence of cattle rearing, although bovine and synthetic leather contribute almost equally to abiotic resource depletion (14.4 and 13.0, respectively).

It should, however, be noted that the widespread adoption of non-animal-related manufacturing processes for the production of leather-like materials is not likely to substantially affect meat production dynamics with demand for red meat effectively independent of leather demand[27]. With the decline of per capita meat consumption in developed countries, over half of the world supply of skin and hides for leather production is sourced from developing countries[28,29], such as Ethiopia, where the low value of the hides compared to meat is perhaps illustrated by the prevalence of pre-slaughter, slaughter and post-slaughter defects, resulting in hide rejection rates as high as 83%[30].

Development of fungi-derived fabrics

Although PU and PVC artificial leathers are more environmentally friendly than traditional bovine leather, the search for increasingly sustainable leather alternatives continues with recent research focused on the potential of lab-grown or waste-derived collagen or cellulose for production of leather substitutes (Table 2)[2]. Bacterial cellulose is producible within seven days in industrial quantities and can be fashioned to resemble leather[31], while companies, such as Piñatex, utilize abundant wastes, such as pineapple leaf fibres, to produce other cellulosic leather substitutes (https://www.ananas-anam.com). Collagen, which is the structural protein present in bovine leather, can also be grown in labs using genetically modified yeast cells and is the basis for the leather substitute Zoa (http://www.modernmeadow.com). However, among a growing number of renewable natural sources for production of leather-like materials, the newcomer is the humble fungus.

Fungi are a natural and renewable source of valuable structural polymers, such as chitin, which is also the main component of most insect and other arthropod exoskeletons[12,32]. Fungal chitin is located within the cell walls of hyphae, which are elongated tubular structures that grow to form a mycelium (collective noun) of hyphal filaments. Providing the structural attributes of the cell wall, this linear macromolecule composed of *N*-acetylglucosamine units is strong with a nanofibril tensile strength of ~1.6–3.0 GPa (ref. [33]) resulting from hydrogen bonding between the chains of the macromolecules[12]. Chitin has a similar molecular structure to cellulose, which is the structural component of the primary cell wall of green plants, algae and oomycetes[34]. This structural similarity to cellulose has long since resulted in suggestions that fungal pulp could find industrial applications as an alternative to wood pulp in the paper, clothing and biomedical fields[35–38].

The use of fungal biomass to produce fabrics traces its origins back to the related field of papermaking in the 1950s, where the similarity between cellulose and chitin was exploited to produce writing paper using combinations of these fibres[35]. Inclusion of fungal mycelium filaments in traditional papermaking processes improved the fire resistance of paper without adversely affecting its bursting strength. This concept was further expanded in the 1970s when researchers considered the resource recovery potential of fungi for pulp mill effluents, growing hyphal chitin-β-glucan fibres on papermill waste by-streams and then pressing the biomass into

Table 2 | Raw material, advantages and disadvantages of bovine leather, synthetic and renewable leather substitutes

Parameter	Bovine leather	Synthetic leather	Renewable leather
Raw material	• Animal skins or hides	• Polyurethane • Polyvinyl chloride	• Cellulosic material • Yeast-derived collagen • Fungal biomass
Advantages	• Attractive mechanical and tactile properties • Derived from nature • Renewable • Upcycles waste • Biodegradable	• Animal-free • Leather-like material properties	• Animal-free • Upcycles waste • Derived from nature • Renewable • Biodegradable • Leather-like material properties
Disadvantages	• Cattle farming emissions • Animal welfare concerns • Chromium-based tanning	• Fossil-fuel-based • Not renewable • Not biodegradable	• Limited biodegradability (composite leathers) • Achieving uniformity is challenging

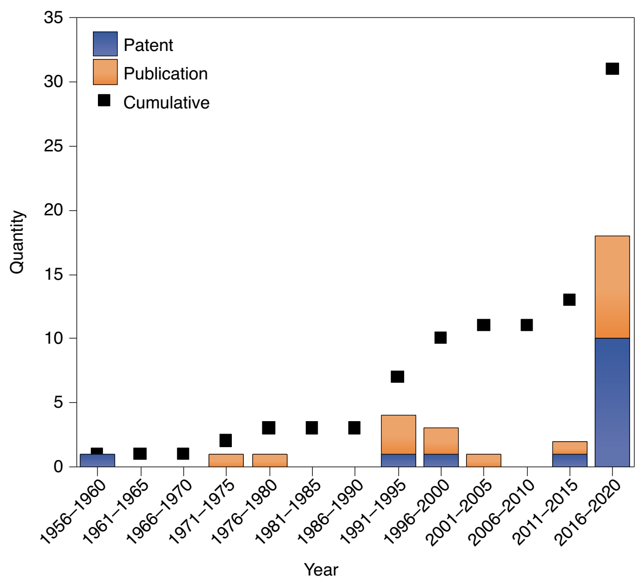

Fig. 1 | Commercialization (patent) and research trends (publication) relating to the production of paper and other fabrics derived from fungi from 1950–2020. Data are from refs. [13,35–45,47–49,51,53–65].

sheets to form mycelium-derived paper[39,40]. Use of mycelium for papermaking continued into the 1990s[37,41–43] before chitin-β-glucan sheets found their next application as a skin substitute and wound healing agent[38,44–46]. The success of fungal biomass in wound treatment was based on the fibrous structure of the chitin-β-glucan filaments, which facilitated simple construction of dressing materials, and the biomedical properties of chitin and chitosan. During the same period, the use of mycelium pulp for applications, such as food wrapping, disposable diapers, fibreboard construction materials and adhesive coatings, was also proposed[36]. However, it is only in the last five years that the use of mycelium has really generated substantial interest for the generation of fabrics, such as paper[47–53], filtration membranes[54] and biopolymer sheets from which clothing fabrics can be derived (Fig. 1)[13,55–65].

This recent expansion of commercial and academic interest in mycelium correlates with the rapidly growing number of biotechnology companies utilizing fungal mycelium to produce leather-like materials, with companies in Indonesia, Italy and the United States having already released promotional material and prototypes in fundraising campaigns (Fig. 2). The Indonesian biotechnology company MycoTech released a range of products including shoes, sandals, handbags, wallets and watch bands made from its mycelium-derived leather substitute Mylea in 2019 (https://www.mycote.ch). Limited-edition fundraiser prototypes sold for US$33 (wallet) to US$93 (watch with Mylea band) with forecasted retail prices of US$52 (wallet) to US$149 (watch). In the United States, prototype driver bags designed by Chester Wallace, puzzle pouches and keychain fobs, made from a product called Mylo, have also been released by Bolt Threads Inc. (https://boltthreads.com). These limited-edition products sold in 2019 fundraising campaigns for US$25 (fob) to US$500 (custom embossed driver bag). Rival Italian and US-based companies Mogu S.r.l. and MycoWorks Inc. (Reishi) have also released promotional material for their leather-like materials exhibiting various textures and colours (https://www.madewithreishi.com).

Manufacturing fungi-derived leather substitutes

Fungi-derived leather-like materials most commonly constitute either a pressed fibre pulp derived from masses of hyphal filaments grown in a nutritious liquid medium (liquid fermentation) or a physically and chemically treated mycelium mat grown on a bed of nutritious lignocellulosic solid particles (solid state fermentation)[13,53,56,66,67]. Liquid state fermentation typically utilizes laboratory media or even low-cost agricultural by-products, such as blackstrap molasses, to grow fungal biomass which can then be separated into fibres and processed using traditional papermaking techniques involving fibre suspension, filtration, pressing and drying[49,50,68,69]. Conversely, solid-state fermentation typically utilizes a bed of forestry by-products, such as sawdust, high concentrations of carbon dioxide and controlled humidity and temperature to force the aerial hyphae to grow outwards in search of oxygen, avoiding stipe, cap and spore production[13]. The continuous mat formed on top of the particle bed is then dehydrated to render the fungus inert, chemically treated to improve material properties, compressed to a desired thickness and imprinted with a selected pattern[56].

Patents for the production of mycelium-derived foams and fabrics using solid-state fermentation have been registered by the US-based companies Ecovative Design LLC[13,55] and MycoWorks Inc.[56]. The fungi-derived materials described in these patents utilize pure mycelium mats grown on a solid sawdust substrate composed of crude protein, non-fibre carbohydrates, lignin and crude fat[13]. This foam-like mycelium mat is referred to as precursor tissue for mycological biopolymer material and is manufactured within 4–9 days[13,56]. Physical and chemical processing is then completed to increase the density, strength and elasticity of the tissue and provide the final fungi-derived leather-like material (Fig. 3).

Initially, the precursor tissue may be treated with lipids, moisturizing or hydrating agents, such as glycerol or sorbitol, to increase its water content, and sectioned. The tissue is then immersed in,

Fig. 2 | Leather-like products produced from fungal mycelium. a–d, Watch band (**a**), designer bag (**b**) and shoes (**c**) produced from post-processed leather-like material (**d**), using Mylea (**a**,**c**) and Mylo (**b**,**d**) fungi-derived leather substitute. Credit: Images reproduced with permission from MycoTech (Bandung, Indonesia) (**a**,**c**) and Bolt Threads Inc. (Emeryville, United States) (**b**,**d**).

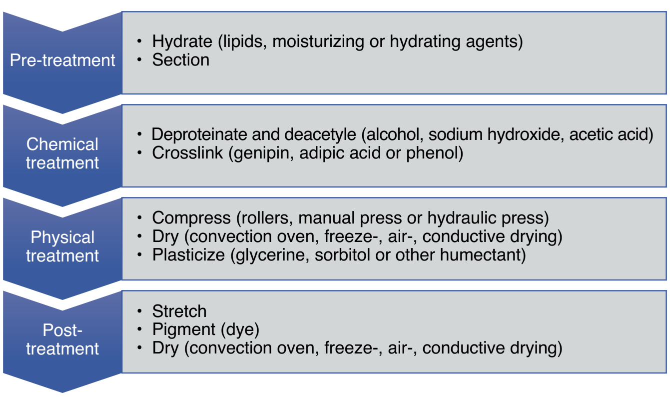

Fig. 3 | Manufacturing processes. Physical and chemical processes required to convert mycelium mats (precursor tissue for mycological biopolymer material) grown on sawdust using solid-state fermentation techniques into fungi-derived leather-like material.

vacuum infused or injected with sodium hydroxide, acetic acid or alcohol, such as isopropanol, ethanol or methanol, for periods potentially ranging from five seconds to six months[13]. This chemical treatment removes soluble extra cellular matrix components, such as carbohydrates and proteins, in addition to denaturing proteins and deacetylating the chitin, which creates sites for crosslinking[13,56,70]. This process also fixes the precursor tissue so that it does not embrittle when dried, makes the tissue more resistant to fatigue, microbial decay and shear stress (tearing) in addition to bleaching the mycelium and eliminating its odour[13]. Crosslinking treatments using genipin, a chemical compound found in gardenia fruit extract, adipic acid, a common food additive and gelling agent, or phenol, an aromatic organic compound derived from petroleum, can also be incorporated at this stage if desired[13,56,71–73]. These crosslinking agents react with the chitin fibrils, forming covalent bonds, such as amide bonds between fibrils[56] or covalent bonds between the primary amine of chitin and the amine and hydroxyl groups of amino acid residues[13], which improves tensile strength, tear strength, abrasion resistance and dye fixation while reducing decay tendencies.

Following chemical treatment, the fungal biomass is hot or cold pressed to less than half of its original thickness using rollers, manual or hydraulic pressing and is dried using convection ovens, freeze-, air- or conductive drying[13,56]. Moisture is then returned to the material to increase its flexibility utilizing glycerol, sorbitol or another humectant to plasticize the material, which may then be stretched[13]. It can be dyed using a pigment treatment and mechanically imprinted with a pattern if desired, before a final drying step is completed. The final leather-like material can be produced in sizes up to 2.5 m^2.

Inherent biological variation in fungal growth makes uniform thickness and surface texture difficult to achieve in mycelium-derived leather-like materials. Many strategies attempt to overcome this problem using growth manipulation to facilitate directionally organized and highly compacted hyphal morphologies or include perforated membranes or grids at the interface between substrates and mycelial sheets to ease separation during harvest and avoid substrate debris[56,61]. Woven and non-woven (felted) fabrics are also sometimes intertwined with mycelium to increase tensile and tear strength[59], while post-treatments, such as pressing and mechanical abrasion, are often used to obtain smooth and uniform mats[63]. Other post-treatments, such as chemical deacetylation and crosslinking with chitin nanowhiskers via genipin[60], and the less sustainable but also common application of polymeric coating products, such as polylactic acid (PLA), can also enhance durability and hydrophobicity in mycelium-derived leather-like materials[62]. However, the latest candidates in ongoing research to improve mycelium mat uniformity are utilization of monokaryotic strains, chemical fruiting inhibitors, or genetic modifications promoting vegetative growth over sporocarp formation[64,65,74,75]. Papermaking techniques constituting fibre suspension, filtration, pressing and drying could also be used to improve material homogeneity[49,51].

Boutique leather-like products are also sometimes produced from the polypore fungi *Fomes fomentarius* and *Phellinus ellipsoideus* in small hand-processed batches[76]. The flexible material termed Amadou leather is created by finely slicing and boiling the fungal fruiting bodies in an alkaline bath before manual stretching to form sheets[77]. Amadou leather resembles animal-derived leather in colour but has a texture closer to wool or fur felt. The use of fruiting bodies, rather than the mycelium sheets used in the patented processes described, also results in a protracted growth period (months). The limited supply of these fruiting bodies in nature and the time-consuming manufacturing process limits scalability and industrial viability.

Fungi-derived material sustainability and cost

Fungi-derived leather-like materials have a low environmental impact since natural biological growth is used to produce chitinous polymers and other polysaccharides that make up this leather-like material[48,78–80]. Although fungi are aerobic organisms, their growth is effectively carbon neutral since it enables the capture and storage of carbon that would otherwise be emitted to or remain in the atmosphere[81]. This is achieved through symbiotic relationships with plants that result in more rapid removal of atmospheric carbon dioxide, through its conversion into plant biomass, and carbon cycling[32,82]. In fact, carbon sequestration in soil directly depends on the volume and hyphal biomass of the fungi that it contains[83,84]. Fungi are heterotrophic and subsequently require no exposure to light to facilitate growth. There is in fact no direct energy input required during manufacturing other than that associated with sterilizing raw materials to neutralize any microbial competition, such

Table 3 | Tear, abrasion, flex and colourfastness durability properties of bovine leather, black emboss and brown natural Reishi fungi-derived leather substitute

Parameter		Bovine leather	Reishi leather substitute	
			Black emboss	Brown natural
Tongue tear strength (N)		>20	9.9	6.7 (normal) 52.6 (high strength)
Stroll abrasion (cycles, 1 lb)		>1,300		>1,300
Bally flex (cycles)		>10,000		>20,000
Colourfastness: 1 (low) – 5 (high)	Distilled water	4.5–5	4	4.5
	Salt water	4.5–5	4	4.5
	Perspiration	4.5–5	4.5	4.5
	Water spotting	4.5–5	5 (dry)	5 (dry)
	Solvent wicking	4.5–5	3.5–5	5
	Crocking	4.5–5	4 (dry)	5 (dry)
	UV exposure	5	4.5	1.5

Data from MycoWorks Inc. (https://www.madewithreishi.com/stories/performance-results).

as existing parasites, bacteria or other fungi, that might affect the growth dynamics of the desired fungal species[79,80], with common pasteurization techniques developed by the mushroom cultivation industry able to dramatically reduce the costs associated with substrate preparation. Growth substrates are typically forestry or agricultural by-products, such as sawdust or blackstrap molasses, which facilitate by-product upcycling and circular economy[78–80]. Fungal growth itself can be facilitated at ambient conditions, although growth rates increase at elevated temperatures (25–30 °C) allowing for expediated manufacturing[12,78].

Life-cycle assessments for other industrially produced mycelium-based products, such as the meat substitute Quorn, indicate that it has half of the embedded carbon associated with beef[85] although considerable energy is required for medium cultivation[86]. Mycelium composites have an embodied energy of 38.1 MJ kg^{-1} based on the water use, oven sterilization and drying used during manufacture, resulting in a moderate environmental impact compared to other material classes[53,87]. This embodied energy value can be reduced by up to 80% if air drying is used[87,88]. The environmental impact associated with tanning depends heavily on the sustainability of the electricity used to rotate drums and how wastewaters containing nitrates that affect marine eutrophication are disposed, with reduction, reuse, recycling and recovery of solid waste and tannery effluents closely correlated with more sustainable life-cycle assessment results[89]. Pure mycelium is also readily biodegradable (~94%)[90] and precursor tissue used in the production of mycelium-derived leather-like materials is described as having similar biodegradability to mycelium composites, which break down in the natural environment within a matter of months[91]. However, inclusion of reinforcement or post-treatment coatings that hybridize mycelium-derived leather-like materials with polymeric materials, such as polyester and polylactic acid, to improve their material properties, may compromise the biodegradability of the material, with overall biodegradability limited to the least readily degraded constituent of composite leather substitutes.

The exact manufacturing costs of fungi-derived leather are difficult to estimate; however, Ecovative Design LLC projected costs of less than US\$142 m^{-3} for manufacturing 0.7 m^3 mycelium composite blocks, which also use solid-state fermentation technology, in production volumes >42,000 m^3 yr^{-1} (ref. [92]). Based on a fungi-derived leather thickness resembling bovine leather (0.9–1.4 mm), this would suggest a manufacturing cost of US\$0.18–0.28 m^{-2}, excluding the costs associated with chemical post treatment. In contrast, the wholesale value of unprocessed raw hide in 2019 was US\$5.38–6.24 m^{-2} (https://thejacobsen.com/2019/10/24/international-hide-report) and the raw materials required to make polyurethane synthetic leather are valued at US\$4.43–23.30 m^{-2}, based on a price of US\$8.2–10.4 kg^{-1} (ref. [93]), a density of 600–1,600 kg m^{-3} and an assumed thickness resembling bovine leather (0.9–1.4 mm). None of these values include processing costs; however, as fungi-derived leather would not be expected to cost any more to process than bovine or synthetic leather, it can be assumed that it is substantially cheaper to manufacture than these other materials.

Properties of fungi-derived leather substitutes

Ecovative Design LLCs MycoFex platform, which is the foundation of Bolt Thread's Mylo, is the best characterized precursor tissue for mycological biopolymer materials. This foam-like mycelium material has densities described in patents as ranging from 13–48 kg m^{-3} and a tensile strength and elastic modulus of 0.1–0.3 MPa and 0.6–2.0 MPa, respectively[13,53,94]. The post-processed leather-like material is distinguished from the precursor tissue by a higher moisture content (>15% compared to <12%), density (240–800 kg m^{-3}) and elastic modulus (13–55 MPa)[13]. Although the tensile strength of post-processed materials based on MycoFlex are unknown, the tensile strength of MycoWork's Reishi and MycoTech's Mylea leather-like materials are quoted to be 5.6–12.5 MPa and ~14 MPa, respectively, with elongations at break of 16–80% and 57%, respectively (https://www.madewithreishi.com/stories/performance-results). These tensile properties are typical for mycelium biomass, which generally has tensile strengths up to 9.6 MPa with values peaking at 40.4 MPa for genetically modified solid material[95]. Chemically treated and hot-pressed nanopapers produced using treated mycelium also have tensile strengths of up to 24.7 MPa (ref. [49]), although studies utilizing chitin-β-glucan nanopapers produced from the fungal biomass of white button mushroom (*Agaricus bisporus*) fruiting bodies had tensile strengths of up to 204 MPa (ref. [51]). These physical and mechanical properties make fungi-derived leather-like materials lighter than bovine and synthetic leathers, which have densities of 570–1,170 kg m^{-3} and 600–1,600 kg m^{-3}, respectively, and comparable in terms of tensile properties. Bovine leather has tensile strengths <25 MPa and elongations at break <56%[96], and PU synthetic leather alternatives have tensile strengths <15.5 MPa and elongations at break <60%[97].

Fungi-derived leather-like materials are also durable, with MycoWork's Reishi high-strength brown natural composite variant, which incorporates a non-woven felted polyester reinforcement and a polylactic acid surface coating, exhibiting considerably higher tongue tear strength (52.6 N) than bovine leather (>20 N), greater flex resistance (>20,000 cycles compared to >10,000 cycles for bovine leather) and similar stroll abrasion resistance (both >1,300 cycles) (Table 3). These fungi-derived leather substitutes also exhibit comparable colourfastness (resistance to fading or running) to bovine leather for perspiration, water spotting, solvent wicking, crocking, ultraviolet (UV) exposure, distilled and salt water, with a rating of 4.5–5 for all parameters, except Reishi natural brown, which is susceptible to UV exposure (1.5). Thermal degradation data for fungi-derived leather substitutes also indicate an onset of thermal decomposition at 250 °C, which is typical for mycelium-based materials[98–100].

Adoption of fungi-derived leather substitutes

Incredible market potential exists for fungi-derived leather-like materials, with growing social and environmental concerns driving the demand for leather substitutes that are not animal derived. The value of the global PU and PVC artificial leather market was estimated at US$22.13 billion in 2015 and is expected to grow to a revenue of US$28.03 billion by 2025, with the predominant use of artificial leather being in footwear[8]. As an arguably more sustainable material than synthetic polymer (PU and PVC) leather substitutes, and with comparable material properties, fungi-derived leather-like materials could expect to win favour with sustainability-conscious consumers.

Given that the raw material costs associated with fungi-derived leather-like materials are also likely to be lower than those associated with bovine and synthetic leather alternatives and that the manufacturing process is no more complicated or resource intensive than those associated with leather or synthetic leather substitutes, with only a basic understanding of mycology required, it is also probable that these materials would be profitable to produce and easily adopted by businesses and industry. The material is particularly accessible to smaller businesses, designers and artisans who lack the capital to invest in expensive industrial manufacturing equipment, with a range of manufacturing options available from small-scale to mass production and very limited equipment requirements. Specifically, owner-operator boutique businesses could benefit from the potentially high sale value of luxury tailored leather-like products and low manufacturing costs to keep them profitable and commercial mushroom cultivators could diversify their product lines by simply modifying and adapting their existing production processes to grow these high-end fungal mats.

Some of the greatest challenges surrounding the progression and development of fungi-derived leather substitutes are associated with attaining homogeneous and consistent mycelium mats exhibiting uniform growth and consistent thickness, colour and mechanical properties. Orientated hyphal growth and fungal cell morphology is an area of ongoing research and substantial investigation into the use of crosslinkers, plasticizers and biological nanocomposite architectures to enhance mechanical performance is necessary. Research into optimal substrates and growth media, controlled growth conditions, 4D bioprinting techniques, genetic engineering and post-processing of mycelium tissue could also allow the mechanical properties of these materials to be tailored to resemble rubber, which would expand the possible applications of fungi-derived flexible materials to heavy-duty products. Hydrophobicity and flexural fatigue resistance will also be critical aspects of research if these new leather substitutes are to compete with leather in terms of durability and water resistance.

Conclusions

Leather substitutes can be derived from mycelium, the vegetative growth of filamentous fungi, which upcycles low-cost agricultural and forestry by-products into chitinous polymers and other polysaccharides in a carbon-neutral biological growth process. These chitinous polymer mats can then be physically and chemically treated to produce fabrics that visually and to the touch resemble both bovine and synthetic leather and exhibit comparable mechanical and tactile material properties. In addition to being more environmentally sustainable to produce than leather and its synthetic alternatives, as they do not rely on livestock farming or the use of fossil resources, pure fungi-biomass-based leather substitutes are also biodegradable at the end of their service life and cheap to manufacture. These attributes provide this new leather substitute with considerable potential to win favour with sustainability-conscious consumers and businesses, with commercial traction rapidly increasing across the globe. The vegan community is also likely to find fungi-derived leather alternatives to be more acceptable than other leather products. Substantial advances in this technology and the growing number of companies that are producing fungi-biomass-based leather alternatives that appear to meet the aesthetic and functional expectations of consumers suggests that this new material will play a considerable role in the future of ethically and environmentally responsible fabrics.

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Author contributions

M.J. contributed to the conceptualization, investigation, formal analysis and writing of the original draft. A.G., S.J. and A.B. edited the manuscript. A.B. supervised the project.

Competing interests

A.G. has been gainfully employed by Ecovative Design LLC and Mogu S.r.l. The other authors declare no competing interests.

Additional information

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