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Fungi-derived leather (Mushroom leather)

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Abstract
This review represents an overview of leather substitutes derived from mushrooms. Mushrooms are raw materials for leather substitutes and provide a cost-effective, socially and environmentally friendly option for natural (bovine) and synthetic leather (Muskin). Companies and consumers (such as the vegan community) are increasingly interested in mushroom leather substitutes.

Keywords – Bovine leather; Leather fungi; Mushrooms mycelium; Muskin; Natural leather; Synthetic leather.

Introduction

Mushrooms include both higher Basidiomycetes and Ascomycetes, and contain secondary metabolites in their cultured mycelium, fruiting bodies, and broth. For many years, they have been utilized in several fields related to human activities (Elkhateeb et al. 2019a, b, c, d, 2020a, b, c, 2021c, El-Hagrassi et al. 2020, Elkhateeb 2020, Elkhateeb & Daba 2020c, 2021d, 2021e, Daba et al. 2020). Some of them have been identified as medicinal mushrooms due to their various morphological, physiological, and ecological aspects that are also responsible for their diversity (Daba et al. 2020, Elkhateeb et al. 2020d, Elkhateeb and Daba 2020a, Thomas et al. 2020, 2021).

A lot of research has been done on the applications of mushrooms such as food and medicinal values. Some mushrooms and fruiting bodies of filamentous fungi are edible and considered a good source of protein. Other mushrooms induce a narcotic effect and are used as medicine. Mushrooms consist of many valuable secondary metabolites such as polysaccharides, fatty acids, terpenoids, and phenolic compounds. Secondary metabolites of mushrooms display various biological activities, including anti-oxidant, anti-viral, anti-inflammatory, anti-coagulate, anti-cholesterol, anti-cancer, antimicrobial, and other activities (Elkhateeb & Daba 2021a, c, Elkhateeb et al. 2021a, b, d). In addition, bioactive compounds in mushrooms can be applied as therapeutic agents such as anti-aging and skin-whitening agents. Many cosmetic products available in the market containing mushrooms have replaced synthetic compounds with long-term adverse effects. Today, mushrooms are considered a popular and valuable food because they are low in carbohydrates, calories, fat, and sodium and they are also cholesterol-free. Finally, mushrooms provide important nutrients, including selenium, potassium, riboflavin, niacin, vitamin D, proteins, and fiber (Thomas et al. 2019, Elkhateeb & Daba 2019, 2021b, ALKolaibe et al. 2021).

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Leather

Leather is a long-lasting natural product that is made by changing the protein structure of animal hides through physical and chemical treatment (tanning). There is a growing market for a natural leather (cow skin) thanks to its toughness, softness, and beauty (Jones et al. 2020). The most common leathers come from sheep, cattle, goats, and hogs. Leather is a flexible, hard-wearing material for many common products such as furniture and clothing. Animal skin is not the leading source of leather, but there are multiple other sources like synthetic leather.

Synthetic leather substitutes made from polyvinyl chloride and polyurethane have captured a wide market and largely mitigate the environmental and social problems associated with leather production. These synthetic leather alternatives also need toxic chemicals in their production and are derived from fossil fuels, resulting in a lack of biodegradability and having the same limited end-of-life options as most plastics (Jones et al. 2020). Animal skin production causes damage to the environment due to the herders stripping the agricultural lands with the purpose of raising animals. It also harms humans; as toxic chemicals are utilized during the tanning process. These issues have spurred the expansion of leather-like materials that are not derived from animals (Jones et al. 2020).

Development of fungi-derived leather

Several artificial types of leather such as polyurethane (PU) and polyvinyl chloride (PVC) are more environmentally friendly than bovine leather. The investigation of sustainable leather materials is increasing in recent years thus lab-based, waste-derived cellulose or collagen for manufacturing leather-based substitutes is concentrated by researchers (Jones et al. 2020).

Fungi are a renewable and natural source of beneficial structural polymers, such as chitin, which is also the main element of most insects and other arthropod exoskeletons. Fungal chitin is found within the cell walls of hyphae, which are extended tubular arrangements that grow to form a mycelium of hyphal filaments (Kavanagh 2005, Webster & Weber 2007). Leather substitutes derived from mushrooms are supposed to be an ethical and eco-friendly choice for traditional bovine leather (Jones et al. 2020).

Fungal biomass is used to produce fabric traces, and its origins go back to papermaking in the 1950s (Van Horn et al. 1957). The use of fungal mycelium filaments in traditional papermaking enhances the fire resistivity of paper. This concept was extended in the 1970s (Carlson et al. 1972, Johnson & Carlson 1978) and continued until the 1990s before chitin-β-glucan sheets were discovered (Jones et al. 2020). Also, fungal biomass has been used for wound treatment which was based on the fibrous structure of the chitin-β-glucan filaments. During the 1990s, mycelium pulp was used for several applications, such as adhesive coatings, food wrapping, disposable diapers, and fibreboard construction materials (Dschida 1998).

Mycelium is the vegetative part of a fungus that consists of a grid of fine white filaments. It can be grown in basically any kind of agricultural waste such as sawdust and pistachio shells. The fungal biomass can be gathered within a couple of weeks, and physically and chemically treated. As a result, these sheets of fungal biomass become a leather-like material with tactile properties. Leather substitute materials derived from fungi typically consist of fully biodegradable chitin and other polysaccharides such as glucans. Mushroom leather is an eco-friendly material because it can be produced without using toxic substances. At the end of its life, the material is biodegradable and compostable. It is especially weightless and adjustable, which makes it useful for a wide range of products (Webster & Weber 2007).

The current growth and interest in mycelium directly link to biotechnical companies that use mycelium to produce leather substitute materials. For example, an Indonesian biotechnical company named MycoTech Lab has introduced several products to the market such as sandals, handbags, shoes, watch bands, and wallets produced from mycelium-derived leather substitutes (https://www.mycote.ch). Reishi™ is a new category of the material brand name made from fine mycelium and use to develop fashion and luxury items. MycoWorks is a biotechnology company linked with Reishi™ (https://www.mycoworks.com/). In addition, Bolt Threads Company in the

United States is producing Mylo™ material from mycelium and is supported by pioneering brands such as Adidas, lululemon, Stella McCartney (https://boltthreads.com/technology/mylo/).

Manufacturing fungi-derived leather

Recently, the growing demand for alternative products and materials that are biodegradable and derived from renewable sources has led researchers from various fields to search for more sustainable alternatives and generate natural biocomposites (such as packaging, building and insulation materials, leather-like, textile, and transparent edible films) in order to decrease environmental stress (Elkhateeb & Daba 2019). Sustainable leather substitutes are made from mushroom-based material, an eco-friendly alternative to bovine leather. Mycelium-based leather was derived from the fruiting body of *Fomitella* spp. and *Phellinus ellipsoideus* (Figs. 1, 2).

Figure 1. Fruit bodies of *Fomitella* sp. Cited in: https://www.inaturalist.org/observations/121660189; photographed by Jennifer Clifford in Flathead County, MT, USA.

Figure 2. Fruit bodies of *Phellinus* sp. Cited in: https://www.inaturalist.org/observations/129877658; photographed by Crisgiraovieira in Kouvola, Finlândia.

Recently, mushroom mycelial has shown promising characteristics for the evolution of sustainable biomaterials (Elkhateeb & Daba 2019, Jillian et al. 2020). These include mycelial bio-composites, mushroom leather, foams, mycoboard, and mycoflex. Mushroom mycelium is whitish brown, leathery, resistant to puncture, and exhibits different physical and mechanical characteristics. Also, these manufactured leathers are durable and can be reinforced with some materials leading to increase tear strength and flex resistance. Industrially prepared fungi-derived leather substitutes display similar resistance to fading or running like bovine leather. In addition, fungal-derived leather has exhibited thermal degradation at 250 °C (Jones et al. 2020). However, Mycelia-based leather can be produced utilizing agro-waste substrates and lignocellulosic materials. It may be low-cost, eco-friendly, and free from toxic reagents and chemicals (Attias et al. 2017, Elsacker et al. 2019, Bustillos et al. 2020, Raman et al. 2021).

Mushroom mycelium ties together substrate materials as it grows, offering options for composite development. Mycelium composites are generated using edible mushroom species together with other natural materials. Four mushroom species (Reishi [*Ganoderma lucidum*], Oyster [*Pleurotus ostreatus*], King oyster [*P. eryngii*], and Yellow oyster [*P. citrinopileatus*]) have been applied on two fabric levels (with or without a natural fabric mat). Scanning electron microscopy images showed that mycelium grows within the composite and around the substrates. The two-way ANOVA revealed that both species and fabric significantly affected the density and compressive strength. A positive and significant linear relationship was found between density and compressive strength, with higher density leading to higher compressive strength. The compressive strength of mushroom mycelium composites, especially those made from king oyster mycelium, provides options for renewable and biodegradable non-toxic materials (Kavanagh 2005).

Mushroom mycelium spores are fed in a mixture of sawdust and other organic materials that support mycelium growth into a thick sheet. Environmental conditions such as temperature and humidity contribute to mycelium's growth, which accelerates when these factors are maintained. Spores of mycelia and the nutrient-rich sawdust mixture are positioned on a large mat, where it grows into a thick, foam-like substance (Fig. 3). Once the mycelium is harvested, the remaining by-products are composted. The resulting sheet of mycelium is then processed and stained to become Mylo™ material for use in the textile industry as an alternative to animal or synthetic leather (Kavanagh 2005).

Figure 3. Mushroom mycelium fibers. Cited in: https//www.watsonwolfe.com20200208what-is-mushroom-leather.

During the manufacturing process (Fig. 4), different chemical and physical treatments are required to obtain the outcome. During the pre-treatment process, mushroom mycelium may be treated with a moisturizing/hydrating agent (glycerol or sorbitol) to increase the sectioned and water content. The tissue is then dipped in, vacuum infused, or injected with alcohol, sodium hydroxide, and acid from five seconds to six months. This chemical treatment helps to remove carbohydrates and proteins and causes deproteination while deacetylating the chitin and creating crosslinking sites. The physical treatment is the third step, during which the thickness of the fungal biomass is reduced through hot or cold pressing using rollers, and manual or hydraulic pressing. The resultant product is dried in a convection oven. Then plasticizer (glycerol, sorbitol) is added to increase the flexibility and stretchability of the product. During the post-treatment step, we can apply the desired color or pattern before the final drying (Jones et al. 2020).

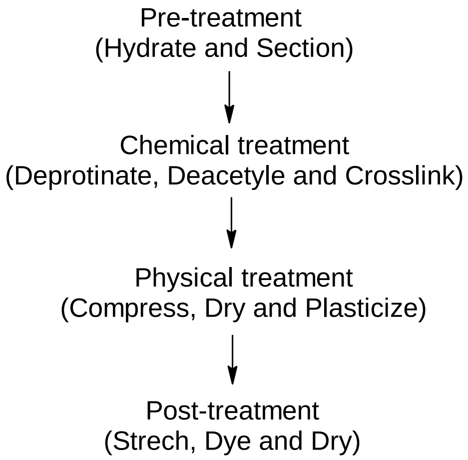

Figure 4. Flow diagram of manufacturing processes of fungi-derived leather.

Several patents have been achieved for the production of mycelium-derived leather by US-based companies such as Ecovative Design LLC and MycoWorks Inc. (Greetham et al. 2015, Kaplan-Bie 2018, Ross et al. 2018). These patents used pure mycelium mats developed on a solid sawdust substrate to produce biopolymer material (Fig. 5). During the manufacturing process, the strength, density, and elasticity of the tissue are increased and provide a well-finished outcome (Kaplan-Bie 2018).

Figure 5. Leather-like Mushroom (Muskin) and some products. Cited in: https://www.thecivilengineer.org/news-center/latest-news/item/1600-this-leather-substitute-ismade-entirely-out-of-mushroom-caps. https://www.pinterest.com/pin/190558627974010485/.

Environmental and economic benefits of fungi-derived leather

Fungi-derived leather is an emerging green and sustainable material with a low environmental impact and can replace synthetic and bovine leather (Raman et al. 2022). This new method can lower the environmental and health risks caused by the production of bovine leather and petroleum-based polymers. It is enabled thanks to the development of biomaterial engineering and causes zero pollution and renewability during the preparation and treatment processes (Attias et al. 2017). Fungi are aerobic organisms and exhibit carbon-neutral growth since it facilitates the capture and repository of carbon (Malyan et al. 2019). This process continues through symbiotic relationships with plants while causing the removal of atmospheric carbon dioxide (Kavanagh 2005, Juan-Ovejero et al. 2020). In addition, leather substitutes can be made from mushrooms by upcycling low-cost agricultural and forestry by-products. These serve as feedstock for the growth of fungal mycelium, which includes a mass of elongated tubular structures and represents the vegetative growth of filamentous fungi (Jones et al. 2017, 2019, Elsacker et. al. 2019, Malyan et al. 2019).

Mushroom leather does not require harmful chemicals, and post-consumer waste can be recycled. It takes more than two years to raise cattle to the right size to obtain the skin, while mushrooms grow at an exponential rate, so it takes weeks for the mushrooms to completely consume their substrate (Jones et al. 2020). Mushroom leather is also very flexible, and it is possible to make its surface look like animal skin and create different patterns, colors, and textures that regular leather would not allow to. Companies are now trying to produce larger quantities of mushroom leather at a lower cost than other synthetic leathers (Jones et al. 2020).

According to Jones et al. (2020), the precise manufacturing costs of fungi-derived leather are hard to estimate. However, fungi-derived leather is cheaper to manufacture than synthetic or bovine leather.

Conclusion

The future strategy is to reduce health and environmental risks. Mycelium-based leather offers a promising solution as a 'green material' for environmental problems. Mushroom mycelium-biomass-based leather substitutes are eco-friendly, biodegradable, and inexpensive to manufacturers. The vegan community also likes fungi-derived leather substitutes because they are more satisfactory than other leather products. Microorganisms in general and especially fungi (Mushrooms) are capable of degrading sawdust and pistachio shells and producing leather-like materials. Leather alternatives are derived from mushroom mycelium (the vegetative growth of filamentous fungi). In conclusion, the mushroom leather production process does not need toxic chemicals. As a result, these new, greener products will play a substantial role in the future development of environmentally responsible fabrics.

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