Hindawi
Journal of Engineering
Volume 2023, Article ID 1629174, 11 pages
https://doi.org/10.1155/2023/1629174

Review Article

A Systematic Review on Potential Bio Leather Substitute for Natural Leather

Girmaw Yeshanbel Kefale, Zerihun Teshome Kebede, and Alehegn Atalay Birlie

Leather Engineering Department, Ethiopian Institute of Textile and Fashion Technology, Bahir Dar University, Bahir Dar, Ethiopia

Correspondence should be addressed to Girmaw Yeshanbel Kefale; girmawyeshanbel83@gmail.com

Received 10 April 2023; Revised 22 July 2023; Accepted 22 September 2023; Published 13 November 2023

Academic Editor: Hans Kristianto

Bio-based leather substitutes are an emerging class of ethically and environmentally responsible natural fabrics that are increasingly exceeding consumer aesthetic and functional expectations as an alternative to bovine and synthetic leathers. This literature review creates a clear and elaborative overview of conventional leather processing along with innovative potential bio-leather substitutes. Plant-driven, fungal-origin, bacterial-driven, and animal-origin bio-leathers are the current innovative research advances addressed in this literature. While traditional leather and its alternatives are sourced from animals and synthetic polymers, these renewable and sustainable leather substitutes are gained from bacterial cellulose, mycelium, plant cellulose, and animal cells using tissue engineering and other eco-friendly techniques. In conclusion, bio-based leather alternatives are eco-friendly, non-toxic, and sustainable and ultimately can substitute natural leather made by conventional processing.

1. Introduction

When animal skins and hides are physically and chemically treated, their protein structures are changed to create a strong and flexible natural product called leather [1]. Due to its popularity in clothes, shoes, upholstery, and accessories and its longevity along with its natural tactile and visual qualities, including color, softness, and warmth [1, 2], it is a common commodity with a market share predicted to reach about US$360 billion by 2025. The usage of leather, which is traditionally considered as a byproduct of meat industry [3], has, however, come under fire from some reasons like being socially irresponsible and ecologically unsustainable [4, 5], given the changing societal norms and growing emphasis on ecological responsibility. After all, raising cattle results in significant emissions of greenhouse gases deforestation by grazing, and environmental devastation from animal waste are among the challenges that the leather industry must tackle [6].

Due to toxic chemical involvement and large amounts of sludge waste discharge, while treating raw hides and skins, leather production is not ecologically sound. Those problems have led to the creation of leather-like materials that are not made from animal products. On the other hand, faux leather alternatives made of polyvinyl chloride (PVC) and polyurethane (PU) have found a substantial market and significantly lessen the social and environmental issues traditionally connected to leather manufacturing [7]. However, these synthetic leather substitutes often entail the use of risky ingredients in their manufacturing [8], as they are made from fossil fuels, making them nonbiodegradable, and experience the same constrained end-of-life possibilities as most plastics [9].

In the past few decades, research efforts have been made to substitute natural leather with bio-leather alternatives. Hide Biotech in London creates conventional leather substitutes using isolated collagen proteins. Bio-leather, which is derived from mycelial growth, is another newly emerging material that holds promise as a financially advantageous, socially conscious, and ecologically sustainable potential substitute to both natural and artificial leather alternatives for use in furniture, garments, and footwear [9].

An eco-friendly coffee-dyed bacterial cellulose bio-leather [10] has also been developed as a sole substitute for conventional animal-driven leather.

Although several academic and industrial studies on alternatives to natural leather have been carried out, there is a gap on the systematic compilation of research developments on potential bio-based leather alternatives for natural leather. Therefore, the sole aim of this review is to assess and compile research advances in bio leather as an alternative to natural leather.

2. Overview of Conventional Leather Processing

2.1. Beamhouse Operations. Being the initial stage of leather processing, soaking aims to wash away curing salt from the salted skin, clear off surface dirt, and remove blood stains. It also rehydrates the skin structure which leads to the opening up of the fibers for further chemical processing. Glycosaminoglycans, nonstructural proteins, and lipids are removed from the skin during this process, and the fibril bundles in the fiber structure are separated to split the fibers [11]. The float (200–300%), temperature (30°C), pH (8.5–9.5/10), duration (24–48 hours), and mechanical action (3-4 rpm) should all be met for the soaking process [11, 12]. The rehydrated hide/skin is then soaked with sulphides and an alkaline solution to get rid of hairs and other keratinous material in hair burning unhairing. The pelt swells as a result of the alkaline solution, which eventually allows the fiber structure to open up at a pH of 12–12.5 [9]. This enables more efficient chemical reactions and improved chemical penetration in the next stage of leather making. The lime chemicals present in the lime liquor react with the hair root or base of the hair shaft and cause the hair to become looser. This thinning of the hair is caused by the amino acid cysteine's disulfide bond breakage, a process known as hair burning [11]. To detach adherent flesh that was left after flaying, the fleshy side of the pelt undergoes a mechanical procedure known as fleshing after the liming process [13].

Deliming lowers the pH of liquor from 12–12.5 to 8-9 by removing lime as well as other alkalis from the limed pelt, either through continuous water cleansing or chemical processing. While the lime found in the pelt cross-section can be eliminated using chemicals like ammonium chloride and ammonium sulphate, surface lime may be removed by repeated water washing [11]. On the other hand, the bating procedure contributes to the manufacture of supple, stretchable, pliable, and flat finished leather. The fibrous structure of the pelt is opened by proteolytic enzymes as they are added as part of the process. Besides, the leftover lime in the pelt is also removed during batting. The procedure is carried out between 35 and 40°C, which is the ideal range for the enzymes [11].

The basic goal of the pickling process is to modify the collagen to the specifications needed by the tanning chemicals during the process of tanning. The pH of pickle liquor is adjusted through the addition of an acid and salt [14]. Common salt (5–10%) and sulfuric acid (0.6–1.5%) are the two pickling agents that are most often employed. While the purpose of the salt used is to inhibit acid swelling, the collagen matrix is protonated with the application of acids since the chrome tanning process exclusively uses ionized carboxyl groups [15].

2.2. Tanning Operation. The collagen protein of the pelt which is stabilized by this process does not putrefy and is thermal resistant [16]. During this procedure, extra cross-links are added to the collagen including bonding the protein's functional group with the active groups of the tanning chemicals. The stability of the collagen matrix is evaluated by measuring the shrinkage temperature of the tanned leather. Adequate uptake and even dispersion of the tanning ingredients are characteristics of a desirable tanning outcome [17]. There are various tanning materials and techniques, and the decision is mostly influenced by the characteristics of the final leather, the price of the tanning material, and the abundance of plants used as tanning material. Among numerous tanning techniques employed to convert putrescible pelt to a material-resistant putrefaction vegetable tanning and nonmineral tanning techniques like chrome tanning methods are widely used. Following tanning, basification is carried out with sodium bicarbonate to raise the pH to support subsequent procedures including retanning, dying, and fat liquoring [18]. The basification procedure bonds the tanning substance to the leather, and the more tanning substance that is bound, the better the leather's thermal.

2.3. Post-tanning Operation. After basification chrome-tanned and semichrome leathers are piled up for the night. The pH then lowers, indicating the release of acid. The ionization of neutral carboxyls, the ionization of positively charged amino ($-NH^{3+}$) groups, or even the hydrolysis of chrome itself may be the sources of this acid [19]. Neutralization, a crucial step in the production of leather, eliminates the leather's acidity and helps dyes penetrate the leather matrix. Sodium carbonate and sodium bicarbonate are among the chemicals used to assist the neutralization process and the pH of the float is adjusted between 5.4 and 6.5 [19, 20].

Retanning chemicals are used to prevent the possibility of loose grain and to make the finished leather level out, full, and elastic [20]. The sole purpose of this process is to fill any loose areas of the tanned leather, reduce shrinkage while drying, increase the penetration of anionic type fat liquors, dyestuffs, and finish adhesion, enhance some specialized attributes like sweat resistance, and flame retardancy. Syntans, inorganic mineral compounds like chromium, resins, and vegetable extracts are among the chemicals widely utilized for retanning. While vegetable retanning raises the thickness of the leather and enhances its useable surface area, acrylic resins are frequently employed as they offer an excellent selective filling property to increase the leather's cutting value [21].

Fat liquoring process of leather making prevents fibers from adhering during drying resulted from the interaction between the fatty substance and the collagen's fibrous structure. The water that is trapped between the smaller fibrils and the bundles of fibers thoroughly lubricates the leather. The main aim of fat liquoring is to regulate the leather's level of softness and suppleness and ultimately to improve its strength attributes [8]. Additionally, this aids in giving the leather's physical qualities including tensile strength, extensibility, wetting capabilities, waterproofness, and permeability to water vapor and air. On the other hand, leather dyeing introduces coloring agents to the leather matrix. To impart a deep, opaque color, dyes may be applied to the surface of the leather in the form of a solution or pigment, which may then be sprayed or distributed by hand. Scientists have discovered a wide variety of natural dyes as a result of growing environmental concerns, which led to a decrease in the usage of azo dyes causing potential risks to human beings through prolonged exposure to their potential colon carcinogens [22].

2.4. Finishing Operation. To reduce the water content of wet-processed leather and make it ready for final finishing, leathers are often dried after prior finishing. The process of drying is regarded as one of the most crucial mechanical steps in the production of leather since the final texture and elasticity of the leather are obtained by drying. When preparing leather, many drying techniques including overhead dryers, vacuum dryers, and toggle dryers are employed [23]. Due to the moderate drying temperature during toggle drying, the area yield is increased as well as the mechanical properties. Surface finishes are applied after mechanical treatment in the finishing process. This serves to both emphasize the inherent features of leather and conceal any surface flaws that may have existed in the leather. Finishing may be accomplished using a variety of ingredients, including casein, nitrocellulose, polyurethane, acrylic, and other resin and polymer components combined with organic elements including oils, waxes, albumins, and cellulose esters. Shade coating, roller coating, and spraying are a few of the several finishing techniques [21].

Pretanning and tanning procedures are in charge of raising the effluent's biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), and other parameters. As a result, they are ultimately responsible for 80% to 90% of the pollution [23] generated by the leather industry. Both hazardous wastes like lime and chrome sludge as well as hazardous gases like hydrogen sulfide are produced during these operations. Furthermore, according to [24], posttanning operation of leather making is accountable for (6–11), (24–40), and (8–15) kg/weight of rawhide suspended solids, COD, and BOD, respectively, making it the other pain in leather production that the tanners have to deal with. Industrial experts and academic researchers have created alternative bio-leather substitutes to address these and other environmental and human health issues associated with natural leather and synthetic leather made of polyvinyl chloride and polyurethane. These substitutes can offer insights for environmentally friendly materials and aspects for sustainability.

3. Ecological and Health Impacts of Chrome Tanning

Tanneries are among the polluting industries mainly causing chromium pollution, and its effect is highly pronounced on regions where high concentrations of tanneries are located. For instance, it has been reported that more than 2500 tanneries were operating in India by 2009, of which 80% of them were engaged in the chrome tanning process [25]. Hexavalent chromium (Cr^{6+}) and other toxic compounds are discharged via industrial wastewater to the environment. This hexavalent chrome is soluble, toxic, mutagenic, tetragenic, and known to have a number of negative effects on human health as a result of its high oxidizing potential. The toxicity occurs in humans because of environmental pollution through soil and water contamination or due to occupational and nonoccupational exposure to heavy metals [26]. Additionally, while Cr^{3+} is more chemically stable and relatively inert, Cr^{6+} is highly mobile and soluble in water [27], making it 1000 times more mutagenic and nearly 100 times more toxic than Cr^{3+}. Metal toxicity results in serious morbidity and mortality. Because of its high toxicity, mutagenicity, and carcinogenicity, Cr^{6+} can have negative effects on the environment and human health at even very low levels [28]. Soluble Cr^{6+} poses a significant carcinogenic risk if ingested. This is attributed to the low pH of the stomach as particulate chromate dissolves at low pH [29]. Chromium is toxic and mutagenic to microorganisms at concentrations between 10 and 12 $mg{\cdot}l^{-1}$, which are inhibitory to the majority of soil bacteria in liquid media.

4. Bio Leather Alternatives for Natural Leather

4.1. Fungal Origin Bio-Leathers. Fungi are aerobic creatures that display carbon-neutral growth [30]. Scholars from several fields are looking for more viable ways to mitigate environmental stress as a result of the increased demand for sustainable alternatives that are biodegradable and made from renewable sources [31]. A network of tiny white filaments known as mycelium makes up the vegetative portion of a fungus. The diameter of these hyphae ranges from 1 to 30 m, and they can branch and merge to form networks that cover kilometers [32, 33] making them the biggest creatures on Earth. The majority of agricultural waste, including sawdust and pistachio shells, is suitable for growing mushrooms. The fruiting bodies of Fomitella species and Phellinus ellipsoideus were used to create mycelium-based leather. Fungi-based leather substitutes are ethically and environmentally responsible alternatives to natural leather [34].

As mycelia-based leather can be produced utilizing agro-waste substrates and lignocellulosic materials, it is more eco-friendly and sustainable than conventionally processed bovine, polyurethane, and PVC-based leather materials. Cattle require more than two years before they reach the optimum size to extract the skin while mushrooms grow exponentially and take weeks to entirely eat their substrate [34]. The current growth and advances in fungal-driven bio-leather substitutes are directly linked to biotechnological companies such as MycoTech, Reishi™, MycoWorks, Bolt Threads Company, and so on that have developed sandals, handbags, shoes, watch bands, and wallets (Figure 1(a)). Industrially produced alternatives for leather made from fungus exhibit a comparable resistance to fading or running as does leather made from animals. Additionally, leather made from fungi has revealed heat degradation at 250°C [34]. Mushroom's mycelium binds substrate materials together as it develops, providing opportunities for composite growth. Several edible mushroom species and other natural materials can potentially create mycelium composites. According to [36], four different mushroom species Reishi (Ganoderma lucidum), Oyster (Pleurotus ostreatus), King oyster (P. eryngii), and Yellow oyster (P. citrinopileatus) have been applied on two fabric levels.

The relation between density and compressive strength was presented to be linearly significant as increased density resulted in higher mechanical properties [36]. The growth of mycelium depends on environmental elements including temperature and humidity, which accelerates when these circumstances are maintained. As far as the production of mycelium is concerned, first mycelia spores and the nutrient-rich sawdust combination are spread out across a sizable mat, where they develop into a thick, foamy mass. The leftover residues are composted once the mycelium has been collected. The resultant mycelium sheet is subsequently treated and colored to create Mylo™ material, a bio-leather substitute used in the leather industry [36]. To get the desired result, different physical and chemical treatments are employed during the production process. To enhance the amount of sections and water in the mushroom mycelium, a moisturizing/hydrating chemical (glycerol or sorbitol) can be used during the pretreatment stage. Then, between five seconds and six months, the tissue is immersed in alcohol, sodium hydroxide, and acid by vacuum infusion or injection. Then, through deacetylating the chitin, crosslinking sites can be produced as this chemical process helps remove proteins from the body. The third phase is physical treatment involving manual, hydraulic, hot, or cold pressing utilizing rollers to minimize the thickness of the fungal biomass. The finished product is then dried in a convection oven. After all, a plasticizer such as glycerol is added to the product to improve its flexibility and stretchability. The required shade or patterns can be applied during the posttreatment phase before the final drying [34].

4.2. Bacterial Origin Bio-Leathers. Bacterial cellulose (BC) is a substance naturally present in some bacteria [37]. It could provide an alternative to plant cellulose if produced in large amounts via biotechnology. Microorganisms such as Acetobacter xylinus and Komagataeibacter are potential sources of BC, a pure cellulose biomaterial [38]. It has the appearance of a gelatinous pellicle and exhibits good resilience. It is made up of three-dimensional interwoven nanofibers [39], which result in high porosity, strong water-holding capacity, and high crystallinity [40]. The perception of BC as a potential leather alternative is based on the industrial synthesis of cellulose fibers from bacteria belonging to the genus Komagataeibacter, which are consumed as part of the fermentation process for kombucha tea and other products [41]. These microbes create cellulose pellicles that build up in the extracellular media by respiring aerobically, either by themselves or in cooperation with other bacteria and yeasts.

These can potentially be produced at the necessary thicknesses and, when dried, provide a flexible leather-likematerial with comparable characteristics to those of animal leathers. Through the industrial-scale fermentation of basic nutrients, large amounts of these pellicles might be produced. The tactile characteristics of BC are comparable to those of high-end, stretchy, fine-finished leather. A study conducted by [42] reported a bio-leather alternative from kombucha-derived bacterial cellulose formulated with sour whey, apple juice, and brewer's spent grain composites. The resultant bio-based composites showed good shape stability and considerable flexibility with an average tensile strength and elastic modulus of 1.69 MPa and 100 MPa, respectively.

4.3. Plant-Driven Bio-Leathers. Cellulose is an essential component of the cell walls of green plants which is a linear polysaccharide. The strength and stiffness of the plant is mainly due to microfibrils of cellulose arranged in cell walls [43]. According to [44], cellulose is the most common organic polymer on earth and has a regenerative nature. In order to provide the finished product stiffness, plant-driven bio-leathers rely on the cellulose found in plant biomass.

The production techniques for developing these kinds of leathers vary depending on the source of cellulose utilized due to the confidentiality surrounding the businesses. Piatex®, one of the most popular plant-based bio-leathers, is created from the fibers of pineapple leaves, a leftover from the pineapple industry. To generate a nonwoven mesh, the fibers from the leaves are removed, cleaned, dried, and combined with polylactic acid (PLA) from maize [45]. This mesh is then coated to create the finished product called Piatex®. Desserto® is the other kind of plant-based bio-leather made of cactus leaves. A compact layer, a foam layer, and a woven base consisting of either polyester, cotton, or a mix of the two make up Desserto® [46, 47]. This type of bio-leather is sustainable since it is manufactured from cactus that is grown and collected twice annually. After being washed and powdered, the cactus leaves are sun-dried for three days. After that, fibers and proteins are extracted from leaves to make a combination that is later transformed into Desserto® leather [48].

As it is said to be PVC-free and contains about 28% bio polyurethane, this cactus-based leather has a lower environmental effect than conventional and synthetic leather [46, 49]. The photosynthesis carried out by the cactus plantings reduces the overall emissions from this material, further enhancing its sustainability. Being a plant-based bio-leather substitute, mango leather is made by mechanically separating the flesh from the seed and pulping the flesh afterward. Binding agents are then included, and the mixture is cooked in an oven. A leather finisher takes sheets of material out of the oven and coats them [50]. The mango

Figure 1: Process and product overview of bio-based leathers. (a) Products made of leather like mushroom bio-material. Photo credit: (MycoTech (Bandung, Indonesia) and Bolt Threads Inc. (Emeryville, United States)) (b) production process of leather-like bio-material by tissue engineering [35].

leather is positioned on top of an organic cotton foundation and has satisfactory mechanical properties [51].

4.4. Animal Origin Bio-Leathers. The collagenous matrix found in animal skins can be customized to serve a variety of purposes as it is incredibly durable. Nowadays, there has been a great deal of attempts to create collagen matrix without using animal products. A discovery of laboratory-cultured bio-leather announced by Modern Meadow is made from cow cells that are removed without adversely injuring the animal. In order to encourage collagen creation, these cells are multiplied in a lab and placed on the proper medium. Although the collagen structure obtained is extremely different from that of skin [35], findings revealed that a bio-leather may still be created using this tissue-engineering technique (Figure 1(b)). On the other hand, hide Biotech in London makes leather alternatives out of isolated collagen proteins obtained from scales and other fish debris [52]. The company's exclusive enzymatic and chemical procedure aids in the development of a transparent material by strengthening and constructing a protein network. There is no need for a separate dyeing or tanning process because dyes and fat liquors may be applied to the material as it is being created.

5. Global Production, Fermentation Media/Biomass, and Market Size of Bio-Based Leathers

The global leather industry is expected to grow significantly in the coming years. In light of this, the leather industry's

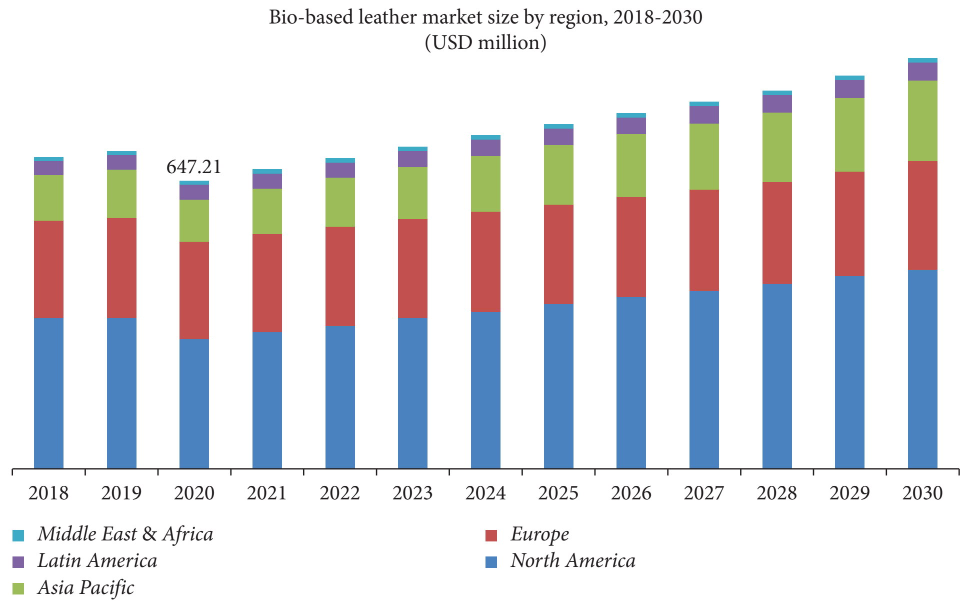


Figure 2: Global bio-based leather market size (source: Polaris market research analysis).

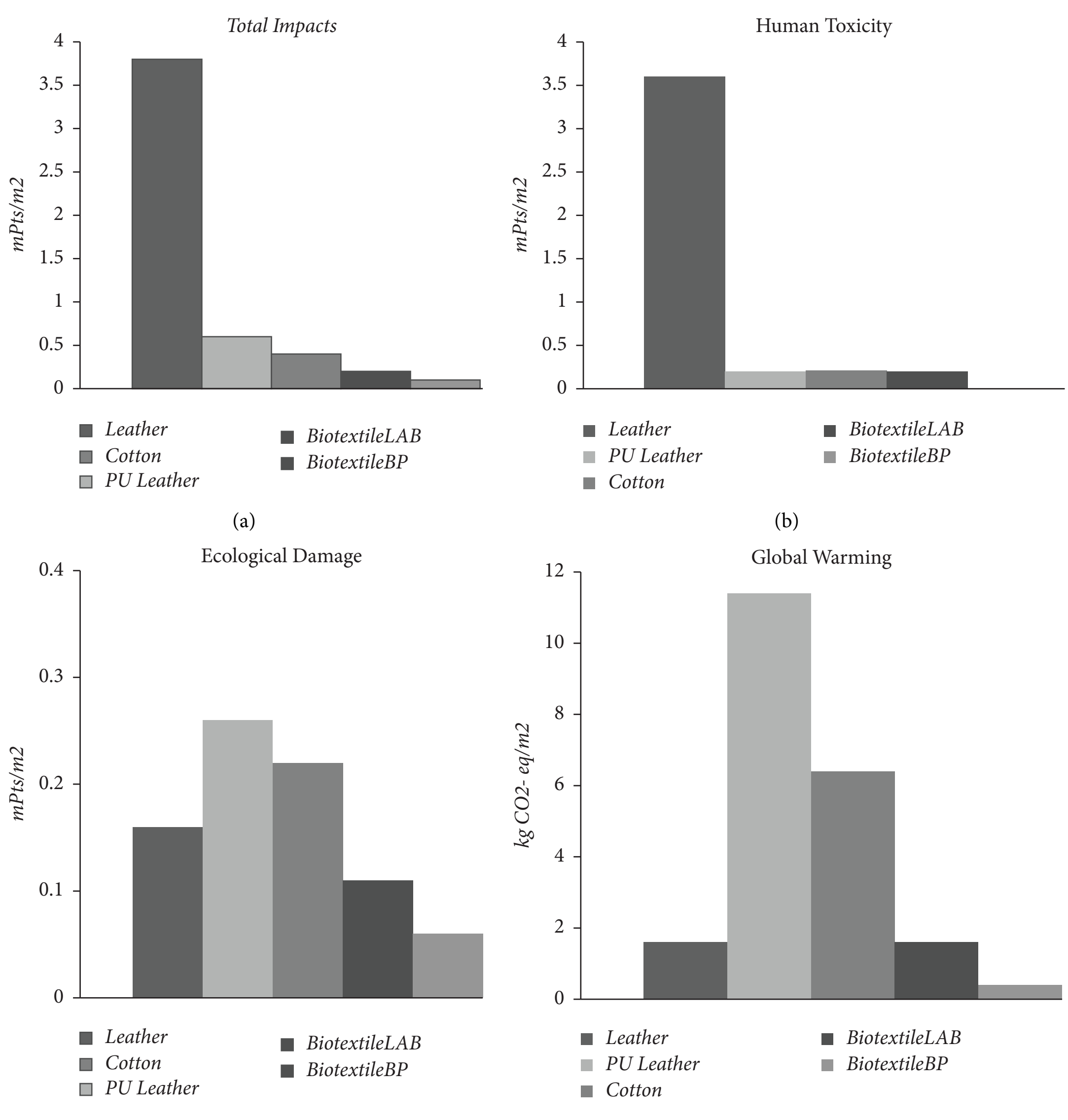
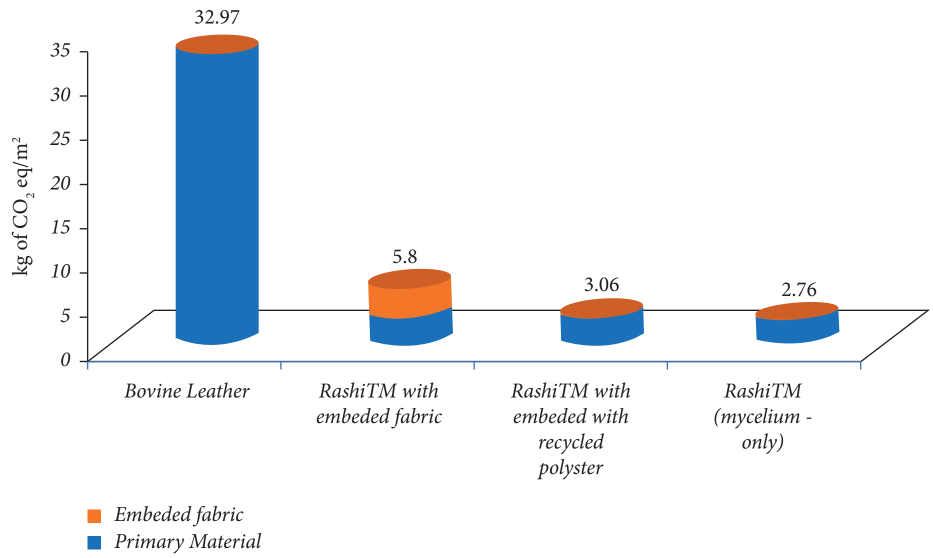


Figure 3: Continued.



(e)

Figure 3: Life cycle impact assessment (LCA) comparison for conventionally manufactured leather and leather alternatives (each 1 m^2) [54]. (a–d) Comparison with respect to environmental impact categories (e) carbon footprint of Reish™ [57].

market size is anticipated to reach USD 708.7 billion to USD 738.61 billion by 2030, displaying a CAGR of 5.76% to 6.7% over the predicted timeframe. The development can be attributed to the rising demand for luxury items, shifting fashion tastes, and expanding domestic and international tourism [53]. On the other hand, as described in Figure 2, the global bio-based leather market was valued at USD 647.21 million in 2021 taking its share from the leather industry and is expected to grow at an alarming rate with a CAGR of 6.2% during the forecast period of 2030.

This progress can be directly attributed to the significant growth in the global production of bio-based leathers signifying their pronounced scalability in the coming years though specific details regarding the current production of bio-leathers have not been quantified yet in the current literature. The most crucial nutrients for the fermentation of bio-leathers, on the other hand, have been identified by various scholars as being carbon sources, nitrogen sources, water, salts, and micronutrients [54].

It is important to note that the specific composition of fermentation media for bio-leather production can vary depending on the desired properties of the final product and the microorganisms used. In a study aimed to develop eco-friendly bacterial cellulose bio-leather with improved durability using plant-based proteins, soy protein isolate, glucose, and yeast extract were used by researchers as the fermentation medium [55]. However, the amount of biomass or fermentation media required for bio-leathers has not been quantified yet based on the currently available literature. The amount will generally depend on the specific process and the type of material used for bio-leather manufacturing.

6. Biodegradation Studies and Life Cycle Assessment for Different Leather Categories

The biodegradation of microbial cellulose and lecithin-tanned fabricated microbial bio-textiles has been studied in natural terrestrial environments for the amount of mass lost after 60 days in soil. The results revealed that microbial cellulose and lecithin-tanned bio-leathers possessed an average mass loss of 74.45 ± 2.94 and 76.3 ± 4.3 percent, respectively, after 60 days [54]. Another study has been conducted to develop an eco-friendly BC bio-leather with improved durability using plant-based proteins. The researchers found that BC could undergo rapid and eco-friendly biodegradation without leaching toxic compounds into groundwater [55]. Besides, a bio-leather produced by extracting cellulose fibers from tomato plant waste has been developed by an Indian alt-leather producer. This material is biodegradable and offers a sustainable alternative to traditional leather.

Strategies to improve the mechanical and moisture stability of bio-leather typically involve heavy metals and/or synthetic plasticizers and coatings, which can compromise biodegradability and introduce human and ecological toxicity [54]. Synthetic polymers used in bioleathers such as polyurethane, poly (butylene adipate-co-terephthalate) may contain chemicals that can be harmful to humans and the environment [56]. These chemicals can leach out of the material and have negative effects on living organisms. Moreover, these polymers are not easily broken down by natural processes, leading to their accumulation in the environment. This can contribute to pollution and long-term environmental damage. To address these issues, researchers

Table 1: Comparison on mechanical properties of leather and various leather alternatives.

Material type	Material name	TS (N/mm^2) ISO 3376	E (%) ISO 3376	TrS (N/mm) ISO 3377	FR (cycles) ISO 32100	WVP (mg/(cm^2 * h)) ISO 14268	WVA (mg/cm^2) ISO 17229	Reference
Animal leather	Bovine shoe upper	39.5	30–80	82.9	>200,000	4.6	8.4	Meyer et al. [47]
Synthetic leather	PU-coated textile	10.2	—	17	200,000	1.1	1.4	
Plant-based leather	Fruit leather	7.74	49.2	19.38	10,000	—	—	[51]
	Pinatex®	4.5	—	31	150,000	2.5	3.8	Meyer et al. [47]
	Desserto®	20.8	—	37.2	30,000	0.5	2.5	
	Appleskin™	14	—	18.4	50,000	0.4	1.7	
Mycelium leather	Reishi™ high strength	8.8–12.5	55–80	52.6	100,000	—	—	[60]
	Muskin®	0.2	—	0.5	10,000	10.4	6.0	Meyer et al. [47]
	Mylea™	8–11	22–35	24	—	—	—	[61]
Microbial cellulose	Kombucha	9.7	—	5.1	10,000	0.1	9.2	Meyer et al. [47]
Tissue engineered collagen	Chrome tanned bio fabricated leather	19.03	11.43	—	—	—	—	Jakab et al. [35]
	Veg. tanned bio fabricated leather	12.18	1.9	—	—	—	—	

TS: tensile strength, E: elongation at break, TrS: tongue tear strength FR: flex resistance, WVP: water vapour permeability, WVA: water vapour absorption.

are exploring alternative materials and production methods for bio-leathers. One approach is the use of microbial nanocellulose biotextiles, which offer renewability, low toxicity, and functional properties. These biotextiles are made from natural materials and have the potential to be more biodegradable compared to synthetic polymers [54]. By exploring these alternative materials and production methods, it is possible to reduce toxicity and improve the biodegradability of bio-leathers, making them more environmentally friendly.

Life cycle assessment and key performance indicators have been employed as a standard and a valid evaluation metric to evaluate the environmental impact of bio-leathers in some scholarly published research [57]. Life cycle assessment is a practical tool used to evaluate the life cycle environmental impacts of a product. The global warming contributors in the life cycle of different leather and leather alternatives are quantified and expressed as a carbon footprint. As stated in Figures 3(a)–3(d), the environmental impact of bio-leather production compared to traditional leather is generally considered to be more sustainable and less harmful since reduced use of harsh chemicals is involved which results in a reduced carbon footprint. In a study conducted to analyze the carbon footprint of finished bovine leather in the cradle-to-gate scenario, leather thickness has been found to have a major impact on the carbon footprint of the finished leather.

Accordingly, finished bovine leather has been found to have 64.8, 74.5, and 79.6 kg of CO_2 equivalents per square meter carbon footprint for 1.5 ± 0.1 mm, 1.7 ± 0.1 mm, and 1.9 ± 0.1 mm leather thicknesses, respectively [58]. On the other hand, the carbon footprint of bio-leather (Figure 3(e)) is generally much lower than conventional leather production. The carbon footprint of bio-leather is 100 times lower than leather modeled as a coproduct. When compared to synthetic leather made from polyurethane-coated polyester and cotton, the carbon footprint of bio-leather is reduced by 96.8% and 94.3%, respectively. In addition, life-cycle assessment studies showed that bio-leather reduces greenhouse gas emissions by nearly 80% compared to conventional leather [59].

7. Mechanical Properties of Leather and Different Leather Alternatives

In a study, conducted by [42], different compositions of leather-like materials were fabricated using waste maple leaves and apple fruit pulp, mixed with additives such as kombucha biomass cellulose biodegradable polyesters and plasticizers. Scanning electron analysis of the result showed that the bio-fabricated materials were porous and breathable. However, the water absorptivity evaluation indicated that the values obtained were slightly higher compared to the required value (max. 25%) for upper shoe soles by BASF. In another study, the durability of bacterial cellulose bio-leather was improved using soy protein isolate and mushroom plant-based proteins via a physical entrapment. Accordingly, the tensile strength of the resultant bio-leather was approximately 13 N/mm^2 which was better than that of cowhide leather. The flexibility and crease recovery of BC bio-leathers were also improved after the entrapment of plant-based proteins [55]. In an attempt to alleviate food waste and fashion pollution environmental issues, a textile material with leather-like properties from fungal biomass cultivated on bread waste was investigated. The resulting leather-like material with only glycerol posttreatment showed a tensile strength of 7.7 MPa and an elongation at a break of 5%. The physical properties of bovine and various leather alternatives have been stated in Table 1.

8. Concluding Remarks and Gaps for Future Work

This review attempts to highlight recent advances in bio-based leather research that could eventually replace natural leather. The goal of these bio-leather alternatives is to lessen the negative effects that the manufacture of natural and artificial leathers has on human health and the environment. Since many chemicals used in the processing of natural leather have a negative influence on human health and the environment, researchers and inventors have been more interested in the sustainability of the leather processing industry. According to the literature, bio-based leather substitutes can be derived from bacteria, fungi, plants, animals, and so on which can offer a viable answer for problems related to the ecological and commercial sustainability of the industry. Because they do not need the use of hazardous chemicals in their synthesis, bio-leather alternatives are produced in a manner that is ecologically sound, biodegradable, and economical for producers.

To sum up, these new, greener, and bio-based natural leather alternatives will play a substantial role in the future development of ecologically responsible and sustainable leather manufacturing. Despite their priceless ecological and sustainability importance, most bio-driven leathers have low mechanical properties when we compare them with the properties of conventionally obtained natural leather. So, to fill the gap, researchers in this area should put their efforts into improving the mechanical properties of innovative bio-based leathers.

Data Availability

All the data used to support the findings of this review are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] C. R. China, M. M. Maguta, S. S. Nyandoro, A. Hilonga, S. V. Kanth, and K. N. Njau, "Alternative tanning technologies and their suitability in curbing environmental pollution from the leather industry: a comprehensive review," *Chemosphere*, vol. 254, Article ID 126804, 2020.

[2] F. J. S. Qua, *(Im) Material: A Qualitative Study on Sustainable Materials for Design through a Comparative Review of Leather*

and its Modern Alternatives, Massachusetts Institute of Technology, Cambridge, MA, USA, 2019.

[3] A. Gac, C. Lapasin, P. T. Laspière et al., "Co-products from meat processing: the allocation issue," in *Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014)*, American Center for Life Cycle Assessment, San Francisco, CA, USA, October 2014.

[4] S. Dixit, A. Yadav, P. D. Dwivedi, and M. Das, "Toxic hazards of leather industry and technologies to combat threat: a review," *Journal of Cleaner Production*, vol. 87, pp. 39–49, 2015.

[5] J. Kanagaraj, T. Senthilvelan, R. Panda, and S. Kavitha, "Eco-friendly waste management strategies for greener environment towards sustainable development in leather industry: a comprehensive review," *Journal of Cleaner Production*, vol. 89, pp. 1–17, 2015.

[6] H. J. Gibb, P. S. Lees, P. F. Pinsky, and B. C. Rooney, "Lung cancer among workers in chromium chemical production," *American Journal of Industrial Medicine*, vol. 38, no. 5, pp. 606–126, 2000.

[7] UNIDO, *Future Trends in the World Leather and Leather Products Industry and Trade*, United Nations Industrial Development Organization, Vienna, Austria, 2010.

[8] X. Baur, W. Marek, J. Ammon et al., "Respiratory and other hazards of isocyanates," *International Archives of Occupational and Environmental Health*, vol. 66, no. 3, pp. 141–152, 1994.

[9] Y. Otake, T. Kobayashi, H. Asabe, N. Murakami, and K. Ono, "Biodegradation of low-density polyethylene, polystyrene, polyvinyl chloride, and urea formaldehyde resin buried under soil for over 32 years," *Journal of Applied Polymer Science*, vol. 56, no. 13, pp. 1789–1796, 1995.

[10] H. Kim and H. R. Kim, "Production of coffee-dyed bacterial cellulose as a bio-leather and using it as a dye adsorbent," *PLoS One*, vol. 17, no. 3, 2022.

[11] A. D. Covington, *Tanning Chemistry: The Science of Leather*, Royal Society of Chemistry, London, UK, 2009.

[12] A. Orlita, "Microbial biodeterioration of leather and its control: a review," *International Biodeterioration & Biodegradation*, vol. 53, no. 3, pp. 157–163, 2004.

[13] P. Thanikaivelan, J. R. Rao, B. U. Nair, and T. Ramasami, "Progress and recent trends in biotechnological methods for leather processing," *Trends in Biotechnology*, vol. 22, no. 4, pp. 181–188, 2004.

[14] V. Suresh, M. Kanthimathi, P. Thanikaivelan, J. Raghava Rao, and B. Unni Nair, "An improved product-process for cleaner chrome tanning in leather processing," *Journal of Cleaner Production*, vol. 9, no. 6, pp. 483–491, 2001.

[15] K. Li, H. Chen, Y. Wang, Z. Shan, J. Yang, and P. Brutto, "A salt-free pickling regime for hides and skins using oxazolidine," *Journal of Cleaner Production*, vol. 17, no. 17, pp. 1603–1606, 2009.

[16] P. Kesarwani, S. Jahan, and K. Kesarwani, "A review on leather processing," *International Journal of Applied Research*, vol. 1, no. 9, pp. 977–982, 2015.

[17] H. Mahdi, K. Palmina, A. Gurshi, and D. Covington, "Potential of vegetable tanning materials and basic aluminum sulphate in Sudanese leather industry," *Journal of Engineering Science & Technology*, vol. 4, no. 1, pp. 20–31, 2009.

[18] J. R. Rao, M. Kanthimathi, P. Thanikaivelan et al., "Pickle-free chrome tanning using a polymeric synthetic tanning agent for cleaner leather processing," *Clean Technologies and Environmental Policy*, vol. 6, no. 4, pp. 243–249, 2004.

[19] V. Beghetto, Z. Aurora, A. Scrivanti, U. Matteoli, and P. Giorgio, "The leather industry: a chemistry insight Part I: an overview of the industrial process," *Sciences At Ca Foscari*, vol. 1, pp. 12–22, 2013.

[20] Q. Taotao, B. Qiaoqiao, and R. Longfang, "Tanning technique of sturgeon skin," *Journal of the Society of Leather Technologists and Chemists*, vol. 98, no. 5, pp. 229–235, 2014.

[21] A. Adigüzel Zengin, N. Oglakcioglu, and B. Bitlisli, "The Effects of leather finishing types on foot wear comfort properties," in *Proceedings of the 7th International Conference of Textile*, Tirana, Albania, November 2016.

[22] V. Sivakumar, J. L. Anna, J. Vijayeeswarri, and G. Swaminathan, "Ultrasound assisted enhancement in natural dye extraction from beetroot for industrial applications and natural dyeing of leather," *Ultrasonics Sonochemistry*, vol. 16, no. 6, pp. 782–789, 2009.

[23] I. S. Arvanitoyannis and A. Kassaveti, "Fish industry waste: treatments, environmental impacts, current and potential uses," *International Journal of Food Science and Technology*, vol. 43, no. 4, pp. 726–745, 2008.

[24] J. Ludvik and J. Buljan, *The Scope for Decreasing Pollution Load in Leather Processing*, UNIDO–United Nations Industrial Development Organization, Vienna, Austria, 2000.

[25] M. Pandi, V. Shashirekha, and M. Swamy, "Bioabsorption of chromium from retan chrome liquor by cyanobacteria," *Microbiological Research*, vol. 164, no. 4, pp. 420–428, 2009.

[26] M. Tripathi, P. Singh, R. Singh et al., "Microbial biosorbent for remediation of dyes and heavy metals pollution: a green strategy for sustainable environment," *Frontiers in Microbiology*, vol. 14, Article ID 1168954, 2023.

[27] I. W. Almanassra, T. Al-Ansari, I. Ihsanullah et al., "Carbide-derived carbon as an extraordinary material for the removal of chromium from an aqueous solution," *Chemosphere*, vol. 307, Article ID 135953, 2022.

[28] M. Tripathi, S. K Upadhyay, M. Kaur, and K. Kaur, "Toxicity concerns of hexavalent chromium from tannery waste," *J Biotechnol Bioeng*, vol. 2, no. 2, pp. 40–44, 2018.

[29] A. L. Holmes, S. Wise, and J. Wise, "Carcinogenicity of hexavalent chromium," *Indian Journal of Medical Research*, vol. 128, no. 4, pp. 353–372, 2008.

[30] S. K. Malyan, A. Kumar, S. Baram et al., "Role of fungi in climate change abatement through carbon sequestration," *Recent Advancement in White Biotechnology through Fungi: Perspective for Sustainable Environments*, vol. 3, pp. 283–295, Springer, Berlin, Germany, 2019.

[31] W. A. Elkhateeb and G. M. Daba, "The amazing potential of fungi in human life," *ARC Journal of Pharmaceutical Sciences*, vol. 5, no. 3, pp. 12–16, 2019.

[32] F. V. Appels and H. A. Wösten, "Mycelium materials," *Encyclopedie Mycologique*, vol. 2, pp. 710–718, 2021.

[33] M. R. Islam, G. Tudryn, R. Bucinell, L. Schadler, and R. C. Picu, "Morphology and mechanics of fungal mycelium," *Scientific Reports*, vol. 7, no. 1, pp. 13070–13112, 2017.

[34] M. Jones, A. Gandia, S. John, and A. Bismarck, "Leather-like material biofabrication using fungi," *Nature Sustainability*, vol. 4, no. 1, pp. 9–16, 2020.

[35] K. Jakab, F. Marga, R. Kaesser et al., "Non-medical applications of tissue engineering: biofabrication of a leather-like material," *Materials Today Sustainability*, vol. 5, Article ID 100018, 2019.

[36] W. A. Elkhateeb, M. C. A. Galappaththi, H. M. Wariss, K. V. Haesendonck, and G. M. Daba, "Fungi-derived leather (mushroom leather)," *MycoKing*, vol. 1, pp. 1–5, 2022.

[37] C. García and M. A. Prieto, "Bacterial cellulose as a potential bioleather substitute for the footwear industry," *Microbial Biotechnology*, vol. 12, no. 4, pp. 582–585, 2019.

[38] S. Chen, Y. Zou, Z. Yan et al., "Carboxymethylated-bacterial cellulose for copper and lead ion removal," *Journal of Hazardous Materials*, vol. 161, no. 2-3, pp. 1355–1359, 2009.

[39] M. Fernandes, M. Gama, F. Dourado, and A. P. Souto, "Development of novel bacterial cellulose composites for the textile and shoe industry," *Microbial Biotechnology*, vol. 12, no. 4, pp. 650–661, 2019.

[40] S. Gorgieva and J. Trček, "Bacterial cellulose: production, modification and perspectives in biomedical applications," *Nanomaterials*, vol. 9, no. 10, p. 1352, 2019.

[41] K. Kubiak, M. Kurzawa, M. Jędrzejczak-Krzepkowska et al., "Complete genome sequence of Gluconacetobacter xylinus E25 strain—valuable and effective producer of bacterial nanocellulose," *Journal of Biotechnology*, vol. 176, pp. 18-19, 2014.

[42] H. T. Nguyen, N. Saha, F. A. Ngwabebhoh, O. Zandraa, T. Saha, and P. Saha, "Kombucha-derived bacterial cellulose from diverse wastes: a prudent leather alternative," *Cellulose*, vol. 28, no. 14, pp. 9335–9353, 2021.

[43] J. K. Polko and J. J. Kieber, "The regulation of cellulose biosynthesis in plants," *The Plant Cell*, vol. 31, no. 2, pp. 282–296, 2019.

[44] D. Klemm, B. Heublein, H. P. Fink, and A. Bohn, "Cellulose: fascinating biopolymer and sustainable raw material," *Angewandte Chemie*, vol. 44, no. 22, pp. 3358–3393, 2005.

[45] A. Anam, *The Manufacturing Propcess*, 2023,https://www.ananas-anam.com/about-us/.

[46] Desserto, *Early Life Cycle Assessment*, 2023,https://desserto.com.mx/e-lca.

[47] M. Meyer, S. Dietrich, H. Schulz, and A. Mondschein, "Comparison of the technical performance of leather, artificial leather, and trendy alternatives," *Coatings*, vol. 11, no. 2, p. 226, 2021.

[48] A. D. Marti, *Cactus Vegan Leather Process*, 2021,https://www.youtube.com/watch?v=xuvBGtajBJw.

[49] MoEa, *Cactus Full green*, 2021,https://moea.io/en-int/products/gen1-cactus-full-green.

[50] B. Insider, *How Vegan Leather Is Made From Mangoes | World Wide Waste*, 2021,https://www.youtube.com/watch?v=rcieZYwyEiA.

[51] Fruitleather, "Technical test results for fruitleather rotterdam," 2019, https://fruitleather.nl/wp-content/uploads/2019/01/Technical-textile-test-results-for-Fruitleather-Rotterdam-1-1.pdf.

[52] E. Waltz, "Bio-leather gears up to wow fashion industry," *Nature Biotechnology*, vol. 40, no. 3, pp. 287–289, 2022.

[53] J. Strasser, P. Dannenberg, and E. Kulke, "Temporary resource availability and quality constraints in the global leather value chain–the impact of the festival of sacrifice on the leather industry in Bangladesh," *Applied Geography*, vol. 45, pp. 410–419, 2013.

[54] T. N. Schiros, R. Antrobus, D. Farías et al., "Microbial nanocellulose biotextiles for a circular materials economy," *Environmental Sciences: Advances*, vol. 1, no. 3, pp. 276–284, 2022.

[55] H. Kim, J. E. Song, and H. R. Kim, "Comparative study on the physical entrapment of soy and mushroom proteins on the durability of bacterial cellulose bio-leather," *Cellulose*, vol. 28, no. 5, pp. 3183–3200, 2021.

[56] L. Raksaksri, Y. Ruksakulpiwat, and T. Udomkitpanya, "The properties of tannery waste addition as a filler based on two types of polymer matrices: poly (butylene adipate-Co-terephthalate)(PBAT) and poly (butylene succinate)(PBS)," *Advances in Polymer Technology*, vol. 2023, Article ID 8301108, 16 pages, 2023.

[57] E. Williams, K. Cenian, L. Golsteijn, B. Morris, and M. L. Scullin, "Life cycle assessment of MycoWorks' Reishi™: the first low-carbon and biodegradable alternative leather," *Environmental Sciences Europe*, vol. 34, no. 1, p. 120, 2022.

[58] K.-W. Chen, L.-C. Lin, and W.-S. Lee, "Analyzing the carbon footprint of the finished bovine leather: a case study of aniline leather," *Energy Procedia*, vol. 61, pp. 1063–1066, 2014.

[59] C. R. Locker and R. Theregowda, "Life-cycle assessment of Bioleather1," *Cleaner and Circular Bioeconomy*, vol. 1, Article ID 100003, 2022.

[60] J. Raman, D.-S. Kim, H.-S. Kim, D.-S. Oh, and H.-J. Shin, "Mycofabrication of mycelium-based leather from brown-rot fungi," *Journal of Fungi*, vol. 8, no. 3, p. 317, 2022.

[61] P. Viniani, S. Abdurrahman, and H. Azhar, "Reduce mycelium leather (Mylea) waste from Mycotech Lab Indonesia into fashion accessories," *Embracing the Future: Creative Industries for Environment and Advanced Society 5.0 in a Post-Pandemic Era*, Routledge, London, UKpp. 193–198, 2022.