Analysis of plant-based leather as a sustainable alternative to traditional animal leather

Analiza biljne kože kao održive alternative tradicionalnoj životinjskoj koži

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Abstract

The leather industry faces numerous challenges, including significant environmental consequences from deforestation, water pollution from chemical tanning, and waste generation, as well as social and human rights concerns such as animal welfare, worker exploitation, and the psychological toll on slaughterhouse workers. Plant-based leather is a cruelty-free, environmentally friendly alternative to traditional leather created from a variety of plant sources such as pineapple leaves, mushrooms, cactus, and coconuts, usually utilizing agricultural waste products. The aim of this study is to analyze the manufacturing processes, sustainability, ethical aspects, and innovative properties of various plant-based leathers. This study provides information on the manufacturing, benefits, limitations, and market growth of various plant-based leathers as sustainable alternatives to traditional animal leather. Plant-based leathers have several benefits, including reduced water and energy use, fewer CO_2 emissions, reuse of agricultural leftovers, and partial or full biodegradability, which supports circular economy principles. Leading fashion and automotive firms are increasingly using these materials. Despite their environmental and ethical benefits, plant-based leathers have limitations, such as lesser durability and sensitivity to water, heat, and humidity, which may limit their use in high-demand applications. Overall, plant-based leathers are a viable, environmentally friendly, and ethical alternative to traditional animal leather, with potential for further innovation and market expansion.

Keywords: leather industry; plant-based leather; leather alternative; environmental impact

Sažetak

Kožarska industrija suočava se s brojnim izazovima, uključujući ozbiljne ekološke posljedice poput krčenja šuma, onečišćenja voda uzrokovanog kemijskim štavljenjem te značajnog stvaranja otpada. Osim toga, otvara i važne društvene i ljudskopravaške probleme, uključujući pitanja dobrobiti životinja, iskorištavanja radnika te psihološkog opterećenja zaposlenih u klaonicama. Kao odgovor na to, koža biljnog podrijetla pojavila se kao alternativa bez okrutnosti i s ekološki osviještenim pristupom u odnosu na konvencionalnu kožu. Proizvodi se iz različitih biljnih izvora – poput listova ananasa, gljiva, kaktusa i kokosa – često korištenjem poljoprivrednog otpada. Cilj ovog istraživanja jest ispitati proizvodne procese, implikacije održivosti, etičke aspekte i inovativna svojstva različitih vrsta kože biljnog podrijetla. Ova studija pruža informacije o proizvodnji, prednostima, ograničenjima i rastu tržišta različitih koža na biljnoj bazi kao održivih alternativa tradicionalnoj životinjskoj koži. Kože na biljnoj bazi imaju nekoliko prednosti, uključujući smanjenu potrošnju vode i energije, manje emisija CO_2, ponovnu upotrebu poljoprivrednih ostataka te djelomičnu ili potpunu biorazgradivost, što podržava načela kružnog gospodarstva. Vodeće modne i automobilske tvrtke sve više koriste ove materijale. Unatoč ekološkim i etičkim prednostima, biljne kože imaju nedostatke, poput manje izdržljivosti i osjetljivosti na vodu, toplinu i vlagu, što može ograničiti njihovu upotrebu u zahtjevnim primjenama. Sveukupno gledano, biljne kože su održiva, ekološki prihvatljiva i etička alternativa tradicionalnoj životinjskoj koži, s potencijalom za daljnje inovacije i širenje tržišta.

Ključne riječi: kožarska industrija; koža biljnog podrijetla; alternativa za kožu; utjecaj na životnu sredinu

1. Introduction

Unsustainable practices have led to global issues such as climate change, lack of resources, and environmental damage. A circular economy prioritizes reusing materials and extending product cycles [1].

The leather industry faces significant challenges regarding sustainability, ethical concerns, and minimizing environmental impact. Traditional leather, as one of the most widely used materials in the clothing, footwear, furniture, and automotive industries, harms the environment through high water consumption, toxic chemical use in tanning, and greenhouse gas emissions from livestock farming [2, 3].

With the increasing demand for sustainable materials within the fashion industry, plant-based leather has appeared as an innovative alternative to traditional animal leather. Recently, various types of plant-based biodegradable leather have appeared as alternatives, opening the possibility of producing high-quality leather products with minimal environmental impact [4]. Plant-based leather, made from waste generated by the fruit industry and agricultural fields, offers ecological and ethical advantages [5]. The plant-based leather market is experiencing significant growth, with spending expected to increase year after year. In 2023, the global market was valued at 73.38 billion dollars, and by 2030, it is predicted to reach 139.02 billion [6].

In this study are presented manufacturing processes, sustainability, ethical aspects, and innovative properties of various plant-based leathers, including those derived from pineapple, apple, coconut, mushroom, cactus, and kombucha.

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2. Plant-based leather sourcing and processing

Plant-based leather is made from various sources of organic waste, such as pineapple, apple, cactus, mushrooms, coconut, banana, and other plant fibers [7, 8].

Pineapple leather (Piñatex) is an innovative alternative to traditional animal leather that utilizes waste from the pineapple industry. The manufacturing process starts with collecting the pineapple leaves left in the fields as waste after the pineapple harvest. After the pineapple harvest, the long fibers are extracted from them by mechanical processing. Between 2.5 and 3.5% of a pineapple leaf is fiber [9]. The obtained fibers are washed and dried, usually in the sun [10]. These fibers are mixed with a polylactic acid (PLA) and converted into a nonwoven textile, creating a material that possesses leather-like characteristics. The next phase includes treatment with certified pigment dyes and non-toxic resin coatings to achieve the mechanical strength, durability, and water resistance of leather. The pineapple leather is 85-90% biodegradable; the remaining 10-15% is the coating material, which is not biodegradable [11].

The pads harvested from nopal cactuses provide the raw material for the production of alternative leather, named Desserto. The manufacturing of cactus leather starts with the growing of the plant, which is extremely drought-tolerant and grows without pesticides [12]. As a result of these characteristics, the manufacturing of cactus leather has a lower ecological impact in comparison with traditional leather. When the cactus pads are gathered, they go through a mechanical processing followed by a soaking phase to form a homogeneous pulp. This pulp is mixed with either natural or synthetically derived polymers, then coated onto backing material, resulting in an elastic but resilient composite that mimics the characteristics of leather. The composite is then dried and subjected to a brief thermal conditioning that brings the intended surface feel and rigidity. The last phase consists of dyeing and treating with non-toxic coatings, producing leather appropriate for use in the fashion industry [13,14].

Apple-based leather, known as Appleskin, is another sustainable and environmentally friendly alternative to traditional leather [15]. The manufacturing process starts with the collection of residual apple parts from the fruit industry; then they are dried and converted into apple pulp, which is combined with water-based polyurethane (PU) and coated onto a fabric base, generally cotton or polyester canvas. The material undergoes further processing, including washing, heating, and embossing, to achieve desired qualities like flexibility, durability, and texture [16].

Mushroom leathers (mycelium leather) are made from the root-like structure (mycelium) of fungi grown in controlled environments. The mycelium is grown under controlled conditions of temperature, humidity, and nutrients. By growing on agricultural waste like wood chips, grains, or crop residues, the mycelium promotes a circular economy and facilitates reuse of biological waste. Once the mycelium reaches a certain density and structure, it is harvested and processed through pressing, drying, and treatment with non-toxic coatings to produce essentially leather-like material. Additionally, the material can be dyed with natural pigments and treated to achieve various visual and tactile properties [17, 18].

Coconut leather, with the name Malai, is produced using bacterial cellulose grown on coconut water. The first phase of the manufacturing process is coconut water sterilization to create conditions for bacterial growth. The coconut water is collected as a byproduct of coconut processing. The next phase is permitting a bacterial culture to ferment and produce jelly-like cellulose. This cellulose is further refined with natural fibers and resins to produce a material that is flexible and durable. From this material, sheets are formed and dyed with natural dyes [13, 19, 20].

Kombucha leather is a symbiotic culture of bacteria and yeast (SCOBY) as a probiotic. Yeast provides the bacteria with nutrition, and they grow a protective mass of single-fiber cellulose. The end result is a flexible skin sheet that may be cut and sewn into a fashion product [21, 22].

In the context of the increasing calls for sustainable and eco-friendly materials in the fashion industry, Nova Milan utilizes a process of creating plant-based leather derived from agricultural waste, primarily from pineapple, banana, and coconut waste. The manufacturing process starts with the collection of agri-waste from the fields, such as pineapple leaves, banana peels, and coconut husks. The second phase is extracting fibers and transforming them into a liquid paste, which is then coated onto a base material like recycled polyester or cotton. Then, the coated material is subjected to finishing processes to improve its appearance, texture, and durability. This approach aims to create a more earth-friendly and fully biodegradable alternative to traditional leather while also handling agricultural waste management [13].
Plant waste, such as fruit peels, seeds, stems, leaves, and pulp, can be combined to produce materials with enhanced strength, flexibility, and durability. Saha et al. developed a prospective leather alternative by mixing waste maple leaves and apple fruit pulp with kombucha biomass cellulose, biodegradable polyesters, and plasticizers. The received biocomposites are breathable and flexible with considerable mechanical strength. This leather can be used for leather accessories production, such as handbags and upper shoe soles [23]. Duangsuwan et al. developed an alternative PALF leather from natural rubber and pineapple leaf fiber. PALF leather has a higher tensile strength, tear strength, and hardness than synthetic polyurethane (PU) leather. This artificial leather was used to make shoes [24].

The general manufacturing process typically involves the extraction and processing of plant fibers to develop a material that resembles the appearance and texture of traditional animal leather. This procedure frequently includes the selection of plant sources such as pineapple leaves, cactus, mushrooms, or agricultural byproducts, followed by the preparation and mixing of these materials with binding agents to create a sheet-like substance. Subsequently, finishing processes such as dyeing and coating are implemented to improve both durability and visual appeal.

3. Benefits of using a plant-based leather

Sustainability: Plant-based leathers are significantly more sustainable compared to animal leathers. They are produced from waste products from the agricultural fields or food industry and do not necessitate the same level of resources, including water and land, as animal leathers [1-24].

Environmental impact: In comparison to traditional leather production, plant-based leathers have a lower environmental impact, especially when the materials are obtained sustainably and the manufacturing process is environmentally earth-friendly [1-24].
Ethics: Plant-based leathers do not entail the exploitation of animals, in contrast to animal leathers. [1-24].
Cost: Some types of plant-based leathers are more economical than animal leather [25,26]. This is because plants like pineapples, and cactus require less space, water, and plant-based leathers are frequently generated from the waste sections of plants.

Biodegradability: Many plant-based leathers are engineered to be biodegradable, which means they will degrade naturally over time [27].
Plant-based leathers offer a promising and sustainable alternative to traditional animal leather, but they are not without restrictions. Common difficulties across diverse types—such as pineapple, cactus, apple, mushroom, coconut, kombucha, and Nova Milan—include lower durability, sensitivity to water, heat, and humidity, and limited flexibility and softness [28]. Expectations for the future development of plant-based leather are linked to increased innovation and improved technological processes. It is anticipated that materials with greater durability and better resistance to water, heat, and moisture will be created, as well as complete biodegradability without the need for synthetic coatings. Research is focused on combining plant fibers with new biopolymers, as well as using nanotechnology and bioengineering to achieve materials with characteristics that approach or even surpass those of traditional leather [29].

In Table 1 are shown the data of the manufacturing process, benefits, and limitations of using plant-based leather.

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Table 1. Data of the manufacturing process, benefits and limitations of using plant-based leather

Plant-based leather	Raw material	Manufactoring process	Sustainability notes	Ethical/ Biodegradability notes
Pineapple Leather (Piñatex®)	Pineapple leaves (agro weaste)	Collect leaves → extract fibers →combine with biodegradable polymers → drying → coating/dyeing	Uses agricultural waste, low water/energy consumption, reduces CO_2 emissions	Vegan, cruelty-free, partially biodegradable (polymer coating slows full breakdown), sensitivity to moisture and heat
Cactus Leather (Desserto)	Cactus pads	Harvest pads → mechanical processing → hydration → mix with natural/ synthetic polymers → drying → thermal treatment → dyeing/coating	Low water usage, drought-resistant crop, minimal pesticides, lower CO_2 emissions	Vegan, cruelty-free, partially biodegradable (synthetic polymers reduce full biodegradability), limited flexibility and softness, sensitivity to moisture and heat
Apple Leather (Appleskin)	Apple pomace and peels	Collect industrial apple waste → dry & grind → combine with biodegradable polymers → drying → rolling → coating/ dyeing	Reduces agricultural waste, low water/energy use, lower greenhouse gases	Vegan, cruelty-free, partially biodegradable, water and heat sensitivity,
Mushroom Leather (Mycelium Leather)	Fungal mycelium	Cultivate mycelium on agricultural waste → grow to desired density → harvest → press, dry, coat with non-toxic materials	Minimal water and chemical usage, reuses biomass waste, low CO_2 emissions	Vegan, cruelty-free, generally fully biodegradable, moisture and heat sensitivity
Coconut Leather	Coconut water	Collect and sterilize water → produce jelly-like cellulose → shaping → dying and treating	Uses agro-waste, low water consumption, eco-friendly	Vegan, cruelty-free, partially biodegradable, moisture sensitivity
Kombucha leather (SCOBY leather)	Symbiotic culture of bacteria and yeast (SCOBY) grown in sweetened tea	Fermentation of sweetened tea → bacterial cellulose film formation → harvested, dried, and treated with oils/ waxes	Very low resource input (tea, sugar, water); fermentation-based and chemical-free; mainly small-scale	100% biodegradable and compostable; vegan; limited durability and water resistance
Nova Milan Leather	Organic plant waste: banana, coconut, yucca, pineapple	Collect plant waste → extract fibers → combine with biodegradable polymers → drying → thermal treatment → non-toxic coating	Fully uses organic waste, minimal water/ energy consumption, low CO_2 emissions	Vegan, cruelty-free, fully biodegradable under natural conditions, water sensitivity

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4. Brands that use plant-based leather

Many fashion brands use plant-based leathers in their products. For example, Gucci uses 77% plant-based leather for the creation of their bags and shoes. McCartney uses mycelium-based and apple-based leathers in her collections. Vivienne Westwood uses plant-based leathers that include bamboo and apple fibers in her collections of handbags, accessories, and footwear. Adidas and Nike have produced sneakers made from plant-based leather [30].

From the automotive industry, BMW uses Desserto for car interiors [31], Mercedes-Benz uses mushroom and cactus leather [32], and Volkswagen is partnering with Revoltech to create a hemp-based leather known as LOVR™ [33].

5. Plant-based leather market

The global market for plant-based leather is experiencing steady and significant growth, supported by ethical, environmental, and technological factors. The statistical overview and forecast for the global market of several types of plant-based leather are as follows:

- In 2024, the global sustainable apple leather market was estimated at 100 million USD, with a projection of up to 300 million USD by 2033 [34].
- The global pineapple-based leather market in 2024 is estimated at USD 200 million, with a projection to grow to USD 600 million by 2033 [35].
- The mushroom leather market was valued at around USD 85 million in 2024 and is projected to reach USD 312 million by 2033 [36].
- The market for vegan cactus leather was worth USD 67.8 million and is expected to grow to USD 394.1 million by 2033 [37].
- The worldwide coconut leather market was estimated at USD 412 million in 2024 and is expected to grow to USD 910 million by 2033 [38].

6. Conclusions

Plant-based leathers being developed from fibers are significantly more sustainable compared to traditional cowhide leather because they are obtained from renewable sources with minimal water and energy utilization during processing. This plant-based leather is a new category of ethical and earth-friendly natural materials that are increasingly meeting customer aesthetic and functional demands as alternatives to animal and synthetic leathers. Additionally, plant-based leather production doesn't involve animal exploitation, which makes this leather a vegan product. These alternative leathers are produced from bacterial cellulose, mycelium, leaves, and agro-waste, applying eco-friendly methods. These leathers provide significant benefits, such as decreasing water and energy utilization, lowering CO_2 gas emissions, reusing agricultural waste, and providing partial or full biodegradability. Leading fashion and car brands are using plant-based leathers, which indicates that people are becoming more aware about using eco-friendly and sustainable materials. The global market for plant-based leather is experiencing robust growth across various types, including apple, pineapple, mushroom, cactus, and coconut leathers.

Due to the limitations of plant-based leather, current research is focused on developing materials with improved durability and resistance to water, heat, and moisture, as well as complete biodegradability without the use of synthetic coatings.

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