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Plant-based leather production: An update

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Abstract

Plant based leather has pretty extraordinary potential to contribute to a climate-friendly, eco-friendly, cruelty-free sustainable fashion industry. Plant-based leather is proving to be a versatile and high-quality material that can be used to create beautiful and fashionable garments. Plant-based leather available in the market can be made using a variety of plants and plant materials for example, Cactus- (Desserto; Mexican), sugarcane bagasse, pineapple (Piñatex; Thailand), mushroom (Mylo), corn leather - Veja (Italian), coconut water (Malai) (Kerala, India), Industrial *Cannabis sativa* (Fiber): Hemp leather, mango, tomato (Bio-leather), dried waist flowers, oak tree bark and leaf, apple, teak leaf, banana leaf (Banafi), grape, orange peel waste, cork oak trees, (Portugal), jute fibre, brittle leaves of the Areca betel nut tree (palm leather) and coffee husk. Chromium tanning is the most common method, but this produces wastewater with high concentrations of toxic chromium and sulphide, as well as the pesticides that are often used to protect the hide before tanning. These chemicals are harmful as they increase the chemical oxygen demand (COD), biological oxygen demand (BOD) and total dissolved solid (TDS) level of water. This hexavalent chrome, Cr^{6+} 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. Now a days, consumers have become more aware of these issues, leading to a rising demand for eco-friendly and sustainable materials. Bio-based leather is made from renewable and natural resources such as plants.

Keywords: Animal leather; Bioleather; Banafi; Chromium; Cactus; Desserto; Plant leather; Malai; Vegan leather

1. Introduction

Plant-based leather is a type of material that is made using plant materials, rather than animal hide [1-85, 97]. It is often used as a cruelty-free and environmentally-friendly alternative to traditional leather [1-85]. Plant-based leather can be made using a variety of plants and plant materials, such as cork, bark, sugarcane bagasse, fungi, cactus, coconut, banana leaf, oranges, tomato, mango, pineapple leaf, waist flower materials, and even mushrooms [1-85, 97-101]. The specific process for making plant-based leather varies depending on the type of plant material being used, but it typically involves breaking down the plant fibres and then combining them with a binding agent to create a material that is similar in appearance and texture to animal leather [1-85-101]. The growth for plant-based leather is in the luxury market [1-85]. Further, plant-based leather is proving to be a versatile and high-quality material that can be used to create beautiful and fashionable garments [1-85-101]. As more designers and fashion houses incorporate plant-based leather into their collections, it will become increasingly popular and mainstream for use in furniture, automotive sectors, garments, and footwear [1-85-101]. Plant-based vegan leathers have been developed from pineapple leaves, mushrooms, sugarcane bagasse, jute fibers, grape, olive tree bark, bananas, grapes, and coffee [1-85-101]. Leather is a

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flexible, hard-wearing material for many common products such as furniture and clothing, and fancy shoes production [1-85].

Animal skin production causes damage to the environment due to the herders stripping the agricultural lands with the purpose of raising animals [1-85]. It also harms humans; as toxic chemicals are utilized during the tanning process [1-85-101]. These issues have spurred the expansion of leather-like materials that are not derived from animals [1-85]. Tannery effluents are harmful to human health as well as to the natural environment [101]. They have a long term impact on ground water and the environment [101]. In the tannery, raw hides/skins undergo several chemical and mechanical operations, among which tanning is the most important process [101]. Tanning agents are considered as the paramount chemicals in the leather manufacturing [101]. Among all tanning agents, basic chromium sulphate is the most popular as it provides unique properties and good hydrothermal stability to tanned leather [101]. About 90% of the tanneries use basic chromium sulfate (BCS) during tanning [101]. However, studies reported that only 60-70% of used chromium is consumed by the pectin, the traditional chrome tanning process and the rest is discharged into the chrome tanning effluent, causing a great waste of chrome and severe environmental pollution [101]. Effluent comes from tannery operations, containing huge amounts of pollutants and heavy metals [101]. These pollutants may cause serious environmental pollution and may be considered as one of the biggest challenges for the sustainability of the leather industry [101].

The harmful effects of animal-based leather on human health and the environment are driving the market [1-85-101]. Traditional leather products consist of chemicals that cause sensitivities and allergies in some people [1-85]. The contact of chemicals with the skin can cause rashes and other skin disorders [1-85]. The health risks associated with chemicals in traditional leather products have led many countries to impose bans or restrictions on animal leather products due to a rising number of health issues [1-85]. Nowadays, consumers have become more aware of these issues, leading to a rising demand for eco-friendly and sustainable materials [1-85-101]. Bio-based leather is made from renewable and natural resources [1-50-101]. Hence, it offers a viable solution by conserving resources, reducing pollution, and providing safer options for people and the planet [1-85-101]. This shift toward bio-based materials reflects a growing demand for ethical consumption and sustainability in the fashion industry and beyond [1-85].

Leather is a strong, flexible and durable material obtained from the tanning, or chemical treatment of animal skins and hides to prevent decay [1-85]. The most common leathers come from cow, camel, buffalo, elk, zebra, pig, sheep, goat, kangrooves, deer, emu, eel, stingray, lambs, calves and oxen, crocodile, equine animals including horses, mules, zebras, ostrich, and aquatic animals seals, walrus, whales, and alligators [78, 79-101]. The most common leathers come from sheep, cattle, goats, and hogs [1-85]. The production of animal leather often involves inhumane treatment of animals, including dehorning, branding, and tail docking [1-85]. Furthermore, many animals used for leather are raised in cramped and unsanitary conditions, leading to significant animal suffering [1-85-101]. Animal skin is not the leading source of leather, but there are multiple other sources like synthetic leather [1-85-101]. In the commercial market, there are 3 types of leather are available, one is synthetic, natural animal and plant based leather [1-85]. In contrast, the production of plant-based leather does not required the killing or mistreatment of animals [1-85]. By choosing plant-based leather, consumers can support a more compassionate and ethical industry [1-85]. In addition to its environmental and durability benefits, plant-based leather is also a more humane option than animal leather [1-85].

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 [1-85-101].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 [1-85-10].

Another challenge of plant-based leather is its availability [1-85]. Unlike animal leather, which is widely produced and sold, plant-based leather is still a relatively niche market [1-85]. As a result, consumers may have difficulty finding a wide range of plant-based leather products, such as shoes and clothing, in mainstream stores [1-85]. Another problem is that plant based leather even if it is available in the market, is found very expensive and people can not afford to buy the plant based leather product [1-85]. This can make it difficult for consumers to fully incorporate plant-based leather into their wardrobe, limiting its potential impact on the market [1-85-101]. Despite these challenges, the plant-based leather is a valuable and important alternative to traditional animal leather [1-85-101]. Its environmental, durability, and humane benefits make it a compelling choice for those looking to reduce their impact on the planet and support more ethical practices [1-85]. As awareness of these issues grows, there is a shift towards greater adoption of plant-based leather, leading to a more sustainable and compassionate fashion industry [1-85-101].

2. Advantages of Plant- Based Leather

Some of the advantages of plant based leather are

- **Sustainability**: Plant-based leathers are much more sustainable than animal leathers. They are made from renewable resources, such as cork or mushroom, and do not require the same amount of resources, such as water and land, as animal leathers [1-85].
- **Ethics**: Plant-based leathers do not involve the exploitation of animals, unlike animal leathers. The production of animal leather often involves cruel practices, such as dehorning and branding, which are not necessary for the production of plant-based leathers [1-85].
- **Cost**: Plant-based leathers are often more affordable than animal leather [1-85].
- **Environmental impact**: Plant-based leathers have a much lower environmental impact than animal leathers. They do not require the same amount of land, water, and energy, and do not contribute to pollution and waste in the same way as animal leathers [1-85].
- **Health**: Plant-based leathers are often healthier for the user and the environment than animal leathers. They are hypoallergenic and do not contain chemicals, such as chromium, which are often used in the production of animal leathers [1-85]. This is because they do not require the same level of resources and labour, and are not subject to the same market fluctuations as animal leathers [1-85].
- **Durability**: Plant-based leathers are often just as durable as animal leathers [1-85]. They are resistant to water, stains, and other environmental factors, and do not require the same level of care and maintenance as animal leathers [1-85].
- **Appearance**: Plant-based leathers can be just as beautiful and stylish as animal leathers. They come in a wide range of colors and textures, and can be designed to mimic the appearance of animal leathers [1-85].
- **Comfort**: Plant-based leathers are often more comfortable to wear than animal leathers. They are breathable, lightweight, and do not retain heat, making them ideal for use in shoes, bags, and other accessories [1-85].
- **Versatility**: Plant-based leathers can be used in a wide range of applications, from fashion to furniture. They are versatile and can be moulded into a variety of shapes and sizes, making them suitable for a wide range of products [1-85].
- **Performance**: Plant-based leathers often outperform animal leathers in terms of durability, comfort, and style. They are often more flexible and breathable, and do not required the same level of care and maintenance as animal leathers [1-85].

Hence plant-based leathers are a better choice than animal leathers for those who value sustainability, ethics, and performance [1-85]. They are more sustainable, affordable, and versatile, and do not involve the exploitation of animals. They also have a lower environmental impact and are healthier for both the user and the environment [1-85].

One of the main advantages of plant-based leather is its environmental friendliness. The production of animal leather is a highly polluting industry, with toxic chemicals such as chromium and formaldehyde commonly used in the tanning process [1-85]. These chemicals can contaminate soil and water, leading to negative impacts on the environment and human health [1-85]. In contrast, the production of plant-based leather uses a fewer toxic chemicals and produces less waste [1-85]. Furthermore, some plant-based materials used to make plant-based leather, such as cork and pineapple leaves, are considered waste products from other industries and would otherwise be discarded [1-85]. Cork is a sustainable, renewable resource that can be harvested from trees without damaging them [1-85]. It is then processed into a material that resembles leather, and can be used to make a wide range of products, such as bags, shoes, and accessories [1-85]. By repurposing these materials, plant-based leather production helps to reduce waste and conserve resources [1-85].

Another advantage of plant-based leather is its durability [1-85]. Many people are skeptical about the durability of plant-based leather, believing that it is not as strong or long-lasting as animal leather [1-85]. However, this is not the case. In fact, plant-based leather can be just as durable as animal leather, with some types even more so [1-85]. For example, cork leather is extremely resistant to water and scratches, making it a great choice for shoes and bags that will be exposed to the elements [1-85].

3. Some Luxury Brands using Plant Based Leather

Bio-based materials can be derived from various sources, including mushrooms, agricultural waste, and other plant-based substances, offering a lower environmental footprint compared to traditional leather production [1-85-101]. The

growing demand for sustainable alternatives is reflected in people's lifestyle choices and their purchasing behaviors, particularly in sectors such as automotive and fashion, where leather is extensively used [1-85-101].

Some luxury brands that use vegetable-based leather in their products include:

- **Stella McCartney** – uses a vegetable-based leather alternative called "Alter-Nappa" in their bags and shoes.
- **Gucci** – uses a vegetable-based leather alternative called "Eco-Vegetable Tanned Leather" in their bags and accessories.
- **Hermes** – uses a vegetable-based leather alternative called "Veau Trade" in their bags and accessories.
- **Tod's** – uses a vegetable-based leather alternative called "Tod's Vegetable Tanned Leather" in their bags and shoes.
- **Vivienne Westwood** – uses a vegetable-based leather alternative called "Vegetable Tanned Leather" in their bags and accessories [1-85]. Leading car brands that use vegetable-based leather in their products.
- **BMW & Minis**: As of the 2023 model year, most BMW and Mini Cooper cars are available with primarily vegan materials [51].
- **Ford**: The Ford Mustang Mach-E comes standard with all-vegan interiors, including a vegan steering wheel.
- **Mercedes**: The EQXX is an all-electric car with a vegan interior featuring cutting-edge renewable materials made from mushrooms, bamboo, cactus, and vegan silk.
- **Tesla**: The company's Model 3 originally included a leather-wrapped steering wheel by default, but no longer. All new Model 3 and Model Y cars now ship with premium synthetic seats and a vegan steering wheel.
- **Toyota**: While Toyota does offer leather seats and steering wheels in some models, it is easy to find a vegan Toyota. Look for Softex, Toyota's vegan leather alternative, in premium or upgraded Toyota models. Base model Toyotas generally come with cloth seats.
- **Volvo**: The company wants to make all cars leather-free by 2030, although it intends to continue offering wool blends. Edmunds reports that the model year 2022 C40 Recharge and all future electric vehicles will be leather-free. The plant-based leather will continue to develop and improve in the coming years [1-85-101].

As demand for sustainable and cruelty-free fashion grows, companies will invest more in research and development to create new and innovative plant-based materials [1-85-101]. There are exciting advances in this field of plant based leather production such as the development of cork leather, which has the potential to be even more durable and water-resistant than traditional animal leather [1-85]. The future of plant-based leather looks bright. As consumers become more aware of the environmental and ethical implications of their fashion choices, plant-based leather will become an increasingly attractive option [1-85]. With its cruelty-free, sustainable, and stylish benefits, plant-based leather has the potential to revolutionize the fashion industry and create a more compassionate and environmentally friendly future [1-85]. Even luxury cars are going vegan. For its 100 year anniversary, Bentley designed an electric car with an all-plant leather interior. It chose **grape leather**, collaborating with Italian company Vegea. Many other brands, including Tesla, Renault Twizy and Volvo, have launched vegan-friendly cars, ditching animal leather completely in favor of plant-based alternatives [1-85].

4. Plants used in Leather Production

Additionally, plant-based leather can be treated with protective coatings to further enhance its durability and longevity [1-85]. Plant-based leather is a type of leather made from plant or other biological materials. It offers the same appearance and properties as traditional animal leather [1-85]. The leather is a more ethical and sustainable alternative to animal leather, which reduces the environmental impact associated with traditional leather manufacturing processes such as the use of water, land, and chemicals [1-85]. Factors such as the increasing adoption of vegan products, rising awareness of environmental issues, and the fashion industry's shift toward more sustainable practices primarily drive the demand for plant-based leather [1-85]. Following are the some of the examples of plant based leather in the market.

- **Pineapple Leather - *Ananas anam***

Pineapple leather, also known as "pineapple leaf fiber" or "Piñatex," is made from the leaves of the pineapple plant [5, 6-85]. The leaves are harvested, dried, and then processed into a material that is similar in appearance and texture to leather [5, 6,35]. Pineapple leather is durable, flexible, and sustainable, making it a popular choice for a variety of leather material [5, 6-85]. In a significant breakthrough in sustainable materials science, researchers have developed a plant-based leather alternative using pineapple leaf fiber (PALF) and natural rubber (NR) [5, 6]. This eco-friendly material is promised to revolutionize the leather industry with its impressive strength and sustainability [5, 6]. The process begins with the extraction of pineapple leaf fiber from waste pineapple leaves through a mechanical method, showcasing a

clever use of agricultural waste [5, 6]. The extracted fibers are then divided into two categories: untreated (UPALF) and sodium hydroxide-treated (TPALF) to widen the leather properties [5, 6]. These fibers are formed into non-woven sheets using a paper-making process, which are then coated with compounded natural rubber latex in various NR/PALF ratios [5, 6]. To enhance the material's properties, an adhesion promoter could be added [5, 6]. The resulting leather-like materials were rigorously tested for tensile properties, tear strength, and hardness, with their internal structures examined using a scanning electron microscope [5, 6].

According to the study conducted by Duangsuwan et al., (2023) [6] at Mahidol University, Thailand , a plant-based leather substitute material or leather alternative was developed from natural rubber (NR) and pineapple leaf fiber (PALF) using a simple process [6]. Pineapple leaf fiber was extracted from waste pineapple leaves using a mechanical method [5, 6]. Untreated PALF (UPALF) and sodium hydroxide-treated PALF (TPALF) were then formed into non-woven sheets using a paper making process [6]. PALF non-woven sheets were then coated with compounded natural rubber latex at three different NR/PALF ratios, i.e., 60/40, 50/50, and 40/60 [6]. Epoxidized natural rubber with an epoxidation level of 10% (ENR) was used as an adhesion promoter, and its content was varied at 5, 10, and 15% by weight of the total rubber [6]. The obtained leathers were characterized in terms of tensile properties, tear strength, and hardness [6]. The internal structure of the leathers was observed with a scanning electron microscope [6]. Comparison of these properties was made against those reported in the literature [6]. It was found that the leather with NR/PALF equal to 50/50 was the most satisfactory; that prepared from TPALF was softer and had greater extension at break [6]. With the addition of ENR at 5%, the stress-strain curve of each respective leather increased significantly, and as the amount of ENR was increased to 10 and 15%, the stresses at corresponding strains dropped to lower values but remained higher than that without ENR [6]. Pineapple leaf fiber (PALF) leather prepared in this study has comparable or better properties than other alternative leathers reported in the literature and is much stronger than that made from mushrooms [6]. Thus, this type of leather alternative offers unique characteristics of being bio-based and having a lower carbon footprint [6].

The pineapple segment will register a significant growth during the forecast period [6]. Pineapple leather, such as Pinatex, is increasing in demand due to its cruelty-free and environmentally friendly nature [5, 6, 35]. It is a by product of the fruit industry and is made from the fibers of pineapple leaves [5, 6]. It has recorded an increasing demand in the fashion industry [6]. In terms of application, the market is segmented into footwear, garments & accessories, and others [5, 6, 35].

- **Mushroom Leather - Mylo**

Mushroom leather is very famous and is made from the stems of mushrooms [7-13,86]. The stems are processed into a material that has a leather-like appearance and feel, and can be used to make a range of products, such as shoes, bags, and accessories [7-13, 86]. Sustainable leather substitutes are made from mushroom-based material, an eco-friendly alternative to bovine leather [7-13, 86]. Mycelium-based leather was derived from the fruiting body of *Fomitella* spp. and *Phellinus ellipsoideus* [7-13]. Mushroom mycelium is whitish brown, leathery, resistant to puncture, and exhibits different physical and mechanical characteristics [7-13, 86]. Also, these manufactured leathers are durable and can be reinforced with some materials leading to increase tear strength and flex resistance [7-13-86]. Industrially prepared fungi-derived leather substitutes display similar resistance to fading or running like bovine leather [7-13]. In addition, fungal-derived leather has exhibited thermal degradation at 250 ℃ [7-13, 86].

The mushroom segment held the highest share of the global market in 2023 and is estimated to record a significant growth rate during the forecast period [7-13-86]. Mushrooms contain a fibrous material called mycelium [7-13, 86]. Rising consumer preference for eco-friendly and sustainable products contributes to the segment growth. Mushroom leather offers innovative design opportunities and allows for unique colors, textures, and patterns that appeal to both designers and consumers [7-13-86]. The product's versatility makes it suitable for various footwear applications [7-13].

Mycelia-based leather can be produced utilizing agro-waste substrates and lignocellulosic materials [7-13-86]. It may be low-cost, eco-friendly, and free from toxic reagents and chemical 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 [7-13]. Fungal chitin is found within the cell walls of hyphae, which are extended tubular arrangements that grow to form a mycelium of hyphal filaments [7-13-86]. Leather substitutes derived from mushrooms are supposed to be an ethical and eco-friendly choice for traditional bovine leather [7-13]. Leather substitute materials derived from fungi typically consist of fully biodegradable chitin and other polysaccharides such as glucans [7-13]. Mushroom leather is an eco-friendly material because it can be produced without using toxic substances [7-13]. At the end of its life, the material is biodegradable and compostable [7-13]. It is especially weightless and adjustable, which makes it useful for

a wide range of products [7-13-86]. The current growth and interest in mycelium directly link to biotechnical companies that use mycelium to produce leather substitute materials [7-13]. 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) [7-13]. Reishi™ is a new category of the material brand name made from fine mycelium and use to develop fashion and luxury items [7-13]. MycoWorks is a biotechnology company linked with Reishi™ (https://www.mycoworks.com/) [7-13]. 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/) [7-13-86].

Mycelium composites are generated using edible mushroom species together with other natural materials [7-13]. 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) [7-13]. Fungi-derived leather is an emerging green and sustainable material with a low environmental impact and can replace synthetic and bovine leather [7-13-86]. This new method can lower the environmental and health risks caused by the production of bovine leather and petroleum-based polymers [7-13-86]. It is enabled and thanks to the development of biomaterial engineering which causes zero pollution and renewability during the preparation and treatment processes [7-13]. Fungi are aerobic organisms and exhibit carbon-neutral growth since it facilitates the capture and repository of carbon [7-13]. Mushroom leather does not require harmful chemicals, and post-consumer waste can be recycled [7-13]. 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 [7-13-86]. 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 [7-13]. Companies are now trying to produce larger quantities of mushroom leather at a lower cost than other synthetic leathers [7-13-86]. 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 [7-13].

Mycelium-based leather offers a promising solution as a 'green material' for environmental problems [7-13]. Mushroom mycelium-biomass-based leather substitutes are eco-friendly, biodegradable, and inexpensive to manufacturers [7-13-86]. The vegan community also likes fungi-derived leather substitutes because they are more satisfactory than other leather products [7-13]. Microorganisms in general and especially fungi (Mushrooms) are capable of degrading sawdust and pistachio shells and producing leather-like materials [7-13]. Leather alternatives are derived from mushroom mycelium (the vegetative growth of filamentous fungi) [7-13]. Therefore, the mushroom leather production process does not need toxic chemicals [7-13]. As a result, these new, greener products will play a substantial role in the future development of environmentally responsible fabrics [7-13].

- **Cactus Leather - Desserto (Mexican)**

Cactus belongs to the family *Cactaceae* and botanical name is *Pachycereus pringlei*, a giant Mexican cactus [19-22, 48, 54-56, 57, 58, 81]. The *Cactaceae,* a broad group of plants, are primarily found in regions characterized by arid and semi-arid climates [19-22, 48, 54-56, 57, 58, 81]. There are more than 5000 cactus species, most of which are found on the American continent. In addition, they are widespread in the arid regions of Mexico (e.g., Chihuahuan Desert), Brazil (e.g., Caatinga region), and Argentina (e.g.,Jujuy province) [19-22, 48, 54-56, 57, 58, 81]. Cacti inhabit tropical forests, grasslands, semi-deserts, and deserts. Argentina is a country with a great diversity of cactus species, with some 200 to 300 native species [19-22, 48, 54-56, 57, 58, 81]. Typically, cacti thrive in dry regions, where their lifestyle is dictated by the limited availability of water [19-22, 48, 54-56, 57, 58, 81]. They must gradually and consistently accumulate biomass to survive, relying on water to absorb nutrients [19-22, 48, 54-56, 57, 58, 81]. During the winter, like many other plants, cacti require a period of rest. For example, inside the Opuntia cladodes, a fiber net serves as a reinforcing and cushioning skeleton [19-22, 48, 54-56, 57, 58, 81]. The fibers can be obtained through different techniques such as water retting , burying, or using dried cladodes that only have the fiber net remaining [19-22, 48, 54-56, 57, 58, 81]. Cutting back cactus plants to control growth or processing the fruit produces large amounts of waste, but this can be a sustainable resource, as it can be used to produce fibers [19-22, 48, 54-56, 57, 58, 81]. These fibers can be used as reinforcements in a variety of applications, including the manufacturing of protective clothing, shoes, and accessories, as well as for technical purposes, such as water purification or the filtration of heavy metals from waste water in the textile industry [19-22, 48, 54-56, 57, 58, 81].

The number of animal leather alternatives continues to grow, with many more examples emerging. The use of cactus leather in fashion has become increasingly significant in recent times, with numerous companies and brands partnering with Desserto®, a prominent cactus leather producer [19-22, 48, 54-56, 57, 58, 81]. In March 2021, the major fashion retailer H&M released The Science Story collection, which incorporated cactus leather and castor oil threads [45]. The collection featured a pair of high-heel sandals crafted from Desserto® cactus leather. Renowned car brands like

Mercedes-Benz and BMW are incorporating Desserto®'s cactus leather into their car interiors [19-22, 48, 54-56, 57, 58, 81]. This is because consumers are now seeking alternative options to real leather, and sustainable trends, including eco-friendly textiles and clothing, are becoming increasingly important. As a result, luxury fashion brands such as Givenchy, Karl Lagerfeld, Adidas, and Fossil are introducing collections made of Desserto®'s cactus leather to cater to this demand [19-22, 48, 54-56, 57, 58, 81].

Nopales (pronounced no-PAHles) are fleshy, arboreal cactus plants which grow between one and five meters high [19-22, 48, 54-56, 57, 58, 81]. They have oblong green stalks or branches (pencas) that are flat with thorns. Cactus leather is a bio-based material known for its breathability, an area in which other vegan leathers fall short [19-22, 48, 54-56, 57, 58, 81]. This unique material is used for handbags, shoes, apparel, and furniture. Even car companies are jumping on the bandwagon; Mercedes-Benz applied leather alternatives, including cactus, to the interior of a concept electric car in January 2022 [19-22, 48, 54-56, 57, 58, 81]. Desserto is another big name in the emerging field of leather made from plants [19-22, 48, 54-56, 57, 58, 81]. The Mexican brand has pioneered a way of making eco friendly leather made from prickly pear cactus [19-22, 48, 54-56, 57, 58, 81]. Desserto leather is another sustainability winner, too, employing less carbon-intensive practices and generating less waste during the production process than real leather. Desserto cactus leather offers a whole host of benefits for the environment, from enriching the soil and increasing biodiversity to saving water (very important in the desert!) and energy [19-22, 48, 54-56, 57, 58, 81]. Their afforestation program (planting prickly pear cactus) also reverts land use change, one of the main drivers of terrestrial CO_2 emissions and soil degradation [19-22, 48, 54-56, 57, 58, 81]. Cacti are left to grow and regenerate, so material can be harvested continually from the same plant, and no chemical fertilizers or pesticides are used [19-22, 48, 54-56, 57, 58, 81]. The harvested plant matter is also dried in a solarium – not in energy-sucking dryers – significantly reducing their carbon footprint. American fashion brand Fossil is one of the early adopters of Desserto leather, having just launched their stylish line of cactus leather tote bags [19-22, 48, 54-56, 57, 58, 81].

Cactus leather comes straight from the prickly pear cactus, automatically making it a fairly sustainable material. Cactus leather is made from the nopal cactus (*Opuntia ficus-indica)* also known as the prickly pear or Indian fig optunia [19-22, 48, 54-56, 57, 58, 81]. The cactus is harvested twice a year by cutting off only mature pads (cactus leaves) so that the cactus is not harmed and can continue to grow [19-22, 48, 54-56, 57, 58, 81]. The pads are then cleaned, smashed into smaller pieces, and left out in the sun to dry for at least three days. The drying process, which is dependent on humidity levels, can take up to five days. Fibers are separated from the dried mulch [19-22, 48, 54-56, 57, 58, 81]. Then, a powdered protein is extracted, taken to a laboratory, and mixed with varying formulas that include dyes to form a liquid bio-resin [19-22, 48, 54-56, 57, 58, 81]. The resin is then poured on top of a carrier material to form cactus leather. The type of material used is dependent on the future application of the textile, but recycled cotton, polyester, or blends of both are what is typically used [19-22, 48, 54-56, 57, 58, 81]. The prickly pear cactus used to make cactus leather is a fast-growing plant that does not need much water or pesticides [19-22, 48, 54-56, 57, 58, 81]. It is easily grown in arid conditions and is considered drought tolerant, an important quality for water conservation. Its hardiness also makes it ideal in an industry that is reliant on weather and climate conditions, creating a good income source for farmers [19-22, 48, 54-56, 57, 58, 81]. The cactus has proven to be adaptable and hard to kill, which makes it great for cultivation. However, these same characteristics have caused it to become an invasive species in some areas [19-22, 48, 54-56, 57, 58, 81]. For instance, in Ethiopia, the species is hedging out grazing and cultivable areas. This means the land could soon be useless for farming other crops [19-22, 48, 54-56, 57, 58, 81]. Despite this, one of the most promising parts of farming cacti is its ability to sequester carbon, allowing it to play a part in climate change mitigation [19-22, 48, 54-56, 57, 58, 81].

Cactus leather is a type of plant-based leather that is made from the fibres of the cactus plant [19-22, 48, 54-56, 57, 58, 81]. It is considered to be a sustainable and environmentally-friendly alternative to traditional animal leather, as it can be produced without harming animals and requires less water and other resources to produce [19-22, 48, 54-56, 57, 58, 81]. Cactus leather is also durable and flexible, making it a good material for use in a variety of applications [19-22, 48, 54-56, 57, 58, 81]. Cactus leather is a sustainable material made from Opuntia ficus-indica, which is also famously known as prickly pear or Nopal, a raw substance [19-22, 48, 54-56, 57, 58, 81]. It does dry well in low-water environments and is native to Mexico [19-22, 48, 54-56, 57, 58, 81].The process of deriving leather from cactus requires less water consumption [19-22, 48, 54-56, 57, 58, 81]. Nopal cacti naturally adjust to desert environments and require little water. The water-intensive methods used to raise cattle for traditional leather production stand in stark contrast to this sustainable use of water [19-22, 48, 54-56, 57, 58, 81]. Cactus leather can reduce plastic waste by 32%- 42% **[**19-22, 48, 54-56, 57, 58, 81]. It is a more eco-friendly substitute for manufactured leathers made from plastic-based materials like PVC, as it often reduces the requirement for oil-based treatments [19-22, 48, 54-56, 57, 58, 81]. **Since it is made to last at least 10 years,** it is a good long-term alternative to animal leather. Due to its durability, cactus leather products last longer and require less upkeep over time [19-22, 48, 54-56, 57, 58, 81]. The tanning of traditional leather involves the utilization of up to 250 different chemicals, most of which are harmful to the environment and human

beings [19-22, 48, 54-56, 57, 58, 81]. The negative effects of breeding cattle for traditional leather are reduced by the use of cactus leather, which provides a more effective ecological substitute [19-22, 48, 54-56, 57, 58, 81].

Cactus leather is an adaptable material that can be utilized for interior vehicle design, accessories, and apparel. It is a great material to employ in the production of a variety of items due to its adaptability and appealing look, including: **:** Cactus leather shoes and belts are not only fashionable but also robust and flexible, which makes them a more environmentally friendly choice than traditional leather goods [19-22, 48, 54-56, 57, 58, 81]. These products blend elegance and dedication to minimizing environmental effects. They are produced from cacti that have been ethically harvested [19-22, 48, 54-56, 57, 58, 81]. Customers can now select from a diverse range of environmentally friendly clothing styles, which include coats, and other things made of cactus leather. This modern material encourages eco-friendly design choices while providing a modern substitute for traditional leather [19-22, 48, 54-56, 57, 58, 81]. As eco-friendly interior design gains popularity, cactus leather becomes a stylish and robust substitute for couch coverings. It is also a sustainable solution [19-22, 48, 54-56, 57, 58, 81]. Because of its distinct texture and adaptability, it stands out as a great alternative for modern interiors. Although leather made from cacti has immense potential, several concerns and challenges with its production and composition still need to be addressed [19-22, 48, 54-56, 57, 58, 81].

The use of **polyurethane (PU)** in cactus leather goods has drawn criticism from certain places. PU is a synthetic polymer that is often used to improve flexibility and durability in vegan leather. Its presence helps to reduce the overall sustainability of cactus leather, even if it is not as harmful as PVC [19-22, 48, 54-56, 57, 58, 81]. Producers must pursue openness and reduce their use of artificial additives. Like any new technology, it might be difficult to scale up manufacturing to satisfy demand around the world. It will take investments in infrastructure and sustainable cultivation methods to guarantee a steady supply of high-quality cactus leather [19-22, 48, 54-56, 57, 58, 81]. Customers need to be made aware of the benefits of cactus leather over other synthetic leathers to ensure its widespread use [19-22, 48, 54-56, 57, 58, 81]. Clear labeling and marketing are effective ways to boost demand for sustainable alternatives and promote trust. Cactus leathers are a significant advancement in environmentally conscious design. Their manufacturing without cruelty and smaller environmental impact, when compared to traditional leather, might ause a significant change in the leather business [19-22, 48, 54-56, 57, 58, 81]. But for cactus leather to be a true success, it needs to be continuously innovative, transparent and consumer-focused [19-22, 48, 54-56, 57, 58, 81]. As an innovative and environmentally beneficial alternative to traditional animal leather, *Desserto* or cactus leathers are recommended [19-22, 48, 54-56, 57, 58, 81]. Cactus leathers have many positive environmental effects since they are made without chemicals, are long-lasting, require little water, and produce less plastic waste [19-22, 48, 54-56, 57, 58, 81]. Although issues like scalability and polyurethane content must be resolved, cactus leathers have the unquestionable potential to transform the fashion business completely. Plant-based substitutes like cactus leathers will greatly influence future sustainable fashion as customers grow more aware of their impact on the environment [19-22, 48, 54-56, 57, 58, 81].

- **Corn Leather - Veja (Italian)**

Corn leather is made from the fibers of corn stalks, which are processed into a material that resembles leather [23-32]. It is a sustainable and eco-friendly alternative to traditional leather, and can be used to make a variety of products, such as shoes, bags, and accessories [23-32]. Researched and developed by Italian company Veja, corn leather utilizes corn waste to create this leather alternative, and is sustainable due to the use of water and energy for the regrowth of corn being protected [23-32-85]. This research was conducted over five years with Veja's team undergoing tasks such as visiting dozens of innovative suppliers, attending conferences, employing a biologist and running numerous tests on fabrics [23-32]. This semi-natural material is composed of 50% corn waste and approximately 47% to 82% polyurethane which is then coated onto a canvas [23-32]. The number percentiles are dependent on which brand is making the products. Corn leather is a resistant and durable material which in fact is tougher than animal hide [23-32]. This material obtains leather characteristics in terms of its touch and elasticity and is 63% biodegradable [23-32]. Corn leather is a vegan leather that does not contain any animal materials, and is therefore much more ethical and sustainable than animal leather [23-32]. It is often seen as one of the next-generation vegan leathers because it includes organic plant-based material (from corn) but still has the look and feel of animal leather, and is high performing (it's durable and wears well) [23-32]. Corn leather uses both corn husks and vegetable oils from corn, which tend to be waste products [23-32]. The corn used for making the base material is a non-food grade crop, so it does not divert food resources from human or animal supply chains [23-32]. The non-edible parts of corn can also be used to produce leather, making this a creative way to salvage and re-use waste [23-32].

Corn leather is the latest one in a long line of naturally derived materials that are rivaling animal leather as consumers move away from what has repeatedly been found to be one of the most harmful materials for the planet [23-32]. Cow leather – the most commonly used type of animal-derived leather in particular has been found to have a devastating

environmental impact, due to animal agriculture's contributions to pollution, deforestation, and climate change among others [1-23-32-86]. Leather also kills over one billion animals every year. But likewise, consumers are reluctant to opt for petroleum-derived synthetics, whose impact, while not as alarming as that of leather, is still significant [1-23-32-86]. Solutions like corn leather offer durability and style while setting consumers' minds at ease with the use of these innovative textiles, no animal deaths are involved, and the impact on the planet is greatly diminished [23-32]. Other environmental benefits of corn leather include the fact that it is free from chromium – one of the substances that makes animal-derived leather so harmful [23-32]. Chromium, which is frequently used in the tanning process, is a highly toxic substance that is harmful not only to workers but also to communities located near tanneries [23-32-86].

Corn leather is also GM-free. The corn vegan leather is a bio-based alternative leather that with the corn as main raw material [23-32]. It is a new eco-friendly material, more and more brands start using the corn leather to replace the traditional animal leather or synthetic leather [23-32]. The corn vegan leather is eco-friendly leather, which is corn as the base material [23-32]. The corn vegan leather is made from the corn by products (such as the corncob, corn starch or corn protein) and combination with other renewable source(such as the bio based fiber or synthetic material) [23-32]. Comparing with the traditional leather, the corn leather production has less impact to the environment, for example reduce agriculture production waste, prevent these by-products from entering the garbage heap, improve the recycling efficiency of the resources [23-32]. Corn vegan leather is very light and flexible makes it very comfortable [23-32]. The corn leather as the sustainable leather is very light and with very good flexibility, it is used to all kinds of lightweight products, like corn vegan leather bags, corn leather shoes, corn vegan leather jacket, corn leather vegan belt etc [23-32]. The corn vegan leather usually has good durability and can resist wear, tear and dirt in daily use [23-32]. However, the specific durability depends on the manufacturing process and the quality of the product [23-32]. Corn leather is non-toxic and healthy [23-32]. Corn leather is often produced without the use of harmful chemicals, unlike the traditional leather, which has some heavy metal content, and the corn leather is used natural component of the plant origin, so it is more safe, no toxic and no health risks [23-32]. Corn leather waterproof performance is better, can deal with a certain degree of water stains [23-32]. However, long-term exposure to water may affect its appearance and durability, so it needs to pay attention to daily maintenance [23-32]. As a plant-based material, corn leather has good biodegradability and can theoretically be decomposed through natural processes at the end of its life cycle, helping to reduce the burden of waste on the environment [23-32].

- **Coconut Leather - Malai (Kerala, India)**

Coconut leather is made from the fibers of the coconut husk, which are processed into a material that resembles leather [33-34, 87-93]. It is a sustainable and durable alternative to traditional leather, and can be used to make a range of products, such as shoes, bags, and accessories. (www.malai.eco) [33-34, 87-93]. Malai is a plant-based leather grown on coconut waste [33-34, 87-93]. The material has a feel comparable with paper or leather and repels water. The leather can be formed using innovative molding, allowing it to make three-dimensional shapes. The vegan leather is produced by feeding organisms from the waste coconut water from coconut production, which creates bacterial cellulose [33-34, 87-93]. The Malai Biomaterials start up company in Kerala, India, has developed an innovative material made from organic and sustainable bacterial cellulose, grown on agricultural waste sourced from the coconut industry [33-34, 87-93]. It can serve as an alternative to animal leather in applications such as cases, bags, light footwear and different accessories. The Malai coconut leather is strong, durable, water resistant, flexible, breathable and 100% biodegradable [33-34, 87-93]. Malai is PETA certified vegan material that does not contain anything of animal origin [33-34, 87-93].

The whole study, design and production process was developed by Susmith C Suseelan (product designer and mechanical engineer) from India and Zuzana Gombosova (material designer and researcher) from Slovakia [33-34, 87-93]. The aim of these researchers is to develop a material that is circular in nature, does not harm the environment, and can be used in product design as a new sustainable solution for the fashion industry, the second most polluting in the world [33-34, 87-93]. In 2018, they founded the Malai Biomaterials start-up company and began the production in a small-scale pilot manufacturing unit based in Kochi, Kerala, a region where the coconut cultivation is an important sector of the local economy [33-34, 87-93].

The Malai company works with coconut farmers and their processing units where they generate ‘waste’ coconut water after having removed the harvest of white flesh from inside the mature coconuts. Normally this waste water would be released into the drainage system, causing pollution of water and of soil that becomes acid [33-34, 87-93]. Every day a small coconut processing unit disposes of almost 4000 liters of this water per day, which can be used to grow 25kg of cellulose and to make 320 sq. meters of the Malai material [33-34, 87-93].

The company rescues this coconut water, which is placed into vats and sterilized, resulting in an energy-rich, entirely natural nutrient upon which the bacterial culture can feed [33-34, 87-93]. They combine the nutrient and the culture and then let the bacteria grow and reproduce. The fermentation period takes between twelve to fourteen days. The material is then enriched with natural fibers (from Banana stems, Sisal and Hemp plants) for strength, gums and resins to bound together, to produce a more durable and flexible product which may be formed into flat sheets with a range of thicknesses and textures [33-34, 87-93]. The selection of the base ingredients has been researched and tested over hundreds of trials to ensure the final properties of Malai. The company is committed not to add anything oil-based in order to maintain the disposal of materials hassle-free at the end of use [33-34, 87-93].

Malai is a flexible and durable material, comparable to leather. It is water resistant and because it contains absolutely no artificial components. It will not cause any allergies, intolerances or illness. It is a completely vegan product [33-34, 87-93]. It consumes less resources in terms of energy and water during manufacturing, and uses no toxic chemicals in any stage of its production cycle. It is available in a range of beautiful earthy colors achieved through the use of mordant-free natural dyes [33-34, 87-93]. The company uses natural dyes extracted from the finest plants from all over India. No extra energy is used in their dyeing process unlike during other traditional dyeing production and a patented cold batch dyeing method is used for this process [33-34, 87-93]. A product from Malai will last from 4-8 years if properly cared for and it is designed to remain in good condition for many years [33-34, 87-93]. If the product becomes dirty it can be wiped with a damp cloth and then left to air-dry and when it has dried, applying beeswax or coconut oil will help restore it to its original condition [33-34]. At the end of their life all the Malai products and materials are biodegradable and home compostable [33-34, 87-93]. Removing metal trimmings which can be recycled, the materials can be shred in smaller pieces and inserted in home compost where they will decompose within 90-120 days [33-34, 87-93].

In 2019, to expand operations, they launched a crowd funding campaign in collaboration with the Fueladream.com platform in India, proposing for purchase some unique products made from Malai leather, including laptop cases, backpacks, foot wears and more [33-34, 87-93]. These products offer an idea of the wide range of possible applications of the innovative material created by the company [33-34, 87-93]. In 2021 ten products, bags and accessories included, are in production [33-34, 87-93]. The company is working on up-scaling the activity in the most sustainable way, collecting and validating the data from each step of the production [33-34, 87-93]. They are also developing a process to create seamless three-dimensional vessels or objects using a molding technique [33-34]. They also intend to introduce the Malai material everywhere in India, working with Indian manufacturers [33-34, 87-93]. However, their main focus is on material development, by growing other bio-based materials that can replace leather in all its applications [33-34]. The growing emphasis on environmental responsibility and sustainability across industries creates an opportunity for manufacturers to capture more share in the market by introducing plant-based leather products [33-34, 87-93].

- **Industrial *Cannabis sativa* (Fiber): Hemp Leather**

In one of the recent study by **Basak et al.,** (2024) [37] hemp fiber [102-139] was extracted from hemp plant, normally available in the Uttarakhand region of Northern India [37, 102-139]. Extracted fibers were degummed, bleached and physico-mechanical properties of the extracted fibers was examined [37]. Bleached fiber was used to prepare non-woven based fibrous structure and used as reinforcement material for making vegan leather [37-44, 48, 50, 51]. Natural rubber based formulation was used as matrix for making flexible composite like material. For developing such unique product, primarily, hemp fibre was extracted from the *Canabinus sativa* L., i.e., industrial hemp plant [37-44, 48, 50, 51, 102-139]. The structure and physico-mechanical properties of extracted hemp fibre used for making leather alternative were thoroughly studied [37-44, 48, 50, 51]. Characterization analysis has underscored that the fibre has crystallinity of around 78 % and composed of mainly cellulose, hemicellulose and lignin [37-44, 48, 50, 51]. Physical properties of fiber denote that hemp is longer, finer, stronger, higher elongation%, than widely available ligno-cellulosic jute fibre [37]. Natural rubber (latex) biomolecule-based formulation was used as matrices, allowing the hemp fiber content in the flexible composite approximately 38–40 % [37]. Developed flexible composite was then hot-pressed and colored for mimicking with natural leather [37]. Natural fiber-reinforced-leather with areal density of 250–550 g/m^2 were fabricated and were characterized in detail in terms of physical, structural, mechanical, and chemical properties [37]. Tensile and tear strength of the developed leather material lies in between 8 and 9 N/mm^2 and 90–110 N, respectively [37]. Moreover, different integral parts of natural rubber based engineered leather were examined by Fourier-Transform-Infrared-Spectroscopy (FTIR), X-ray diffraction (XRD), surface roughness, chemical composition analysis and scanning-electron-microscopy (SEM) techniques to understand the mechanical of interaction among the different component were studied [37]. This study suggested the possible chemical reaction among the different macro-molecules, responsible towards good stability of the natural fibre-reinforced-leather structure [37].

Animal leather industries consume a larger quantity of toxic chemicals, acid, alkali, salt, heavy metal, etc [37]. It generates large quantum of liquid effluent that pollutes surrounding atmosphere [37]. Indeed, chemicals used in leather processing have detrimental effect on skin of work-force and cause of associated hazardous risk [1-37-86]. Moreover, most of the artificial leather products, available in the market, are also not eco-friendly due to usage of polyurethane, poly vinyl chloride like petroleum products in their manufacturing formulations [1-37-86]. Most of the cases, synthetic leather available in the market, are manufactured using polyester, nylon, etc., as reinforcement fiber matrix [1-37-86]. They are neither biodegradable not their physical properties are similar to the natural leather in term of tensile, weight, thickness and performance [1-37-86]. As the world R & D is moving towards sustainable direction, therefore nowadays development of fiber-based leather or natural-fiber-reinforced-leather (NFRL) is truly a promising area of research and product development [1-37-86]. Very few research findings have been registered in the literature on the domain of leather alternative engineered using on ligno-cellulosic plant fibers like pineapple, flax, wool and ramie, and biopolymer [1-37-86].

Another work reported by YORGANCIOGLU et al., (2019) [38] in Turkey evaluated the potential applications of fiber-type industrial hemp for leather industry [38]. According to this study of YORGANCIOGLU et al., (2019) [38], the root, stem and fiber parts of the hemp plant were investigated in terms of tannin content as the residues of the hemp [38]. The results of this study by YORGANCIOGLU et al., (2019) [38] showed that root and stem parts have low phenolic content, but fibers of the plant have a great potential in the use of leather production and can be evaluated in different processing steps such as tanning and retanning [38]. Besides, the antimicrobial activity of the hemp fabrics was determined with five different microorganisms due to the demonstration of potential antimicrobial effect of the hemp extracts that will be used in the leather production [38]. Additionally, fabrics of hemp can be also used in leather products as auxiliary material by means of the promising properties in literature and clothing hygiene and will be evaluated in the manufacturing of lining materials for footwear [38].

Fatliquors are very important in the manufacture of leather [40]. Leather treated with fatliquor become more flexible and softer by the separation of leather fibers in the wet state so that they do not stick too much during drying, also the physical properties, such as tensile strength, softness, tear strength and stability of the leather become influenced simultaneously [40]. The step of fatliquoring is carried out during leather processing operation after tanning [40]. Variety of fatliquors is synthesized so far from various vegetable oils [40]. In one of the study reported by Mahboob et al., (2022) [40] for the first time, fat-liquor, named as, “Hempfat” is synthesized from oil extracted from hemp seeds [40]. As hemp oil consists of high amount of omega-6, omega-3 fatty acids possessing antioxidant activities, so accepted as beneficial to health for public, also possess high kinetic stability and increased protective effect during increase or decrease of temperature[40]. On high temperatures, trans-fatty acids are not formed [40]. So, the developed fatliquor, “Hempfat” and the leather developed from it were evaluated on physical and chemical grounds, both found to possess the excellent properties of a fatliquor as leather fatliquoring agent in making good quality finished natural leather [40]. “Hempfat”, it is claimed that for the first time, fat-liquor is synthesized from the oil extracted from hemp seeds, which possesses the excellent properties of a fatliquor as leather fatliquoring agent in making good quality finished natural leather carrying better properties of tensile strength, tear strength, stability and softness of the leather [40].

Volkswagen has entered into a cooperation with the German start-up Revoltech GmbH from Darmstadt [36, 39, 41, 42, 51]. The aim is to research and develop sustainable materials based on industrial hemp [36, 39, 41, 42, 51]. These could be used as a sustainable surface material in Volkswagen models from 2028 [36, 39, 41, 42, 51]. The material made from 100% bio-based hemp uses residues of the regional hemp industry. It can be produced on existing industrial plants and recycled or composted at the end of its service life in an automobile [36, 39, 41, 42, 51]. The first presentations of the innovative material have already received a very positive response and feedback from customers [36, 39, 41, 42, 51]. 100% bio-based leather alternative from industrial hemp**:** Together with the Revoltech GmbH start-up, the predevelopment team at the Volkswagen brand is working on a material innovation as a substitute for imitation leather [36, 39, 41, 42, 51]. This material made from what is known as industrial hemp cultivated for the food industry is an all-natural, 100% biological single-layer surface material called **LOVR™** (the letters stand for leather-free, oil-free, vegan and residue-based) that is being developed specifically with the automotive industry in mind [36, 39, 41, 42, 51]. The hemp fibers and a fully bio-based adhesive are combined using a special technology and processed to become a surface material [36, 39, 41, 42, 43, 51]. This truly circular material is sourced from regional hemp fields and is fully recyclable or compostable once it has reached the end of its service life [36, 39, 41, 42, 51]. It is produced from residues of the hemp industry that have no further use [36, 39, 41, 42, 51]. In addition, it can be manufactured on existing industrial plants, thus enabling swift scalability – and is therefore, also suitable for use in large-scale production [36, 39, 41, 42, 51].

One of the study reported by HULTKRANTZ (2018) [43] covered a preliminary life cycle assessment (LCA) on imitation leather made from hemp fiber (hemp leather) and a comparison to bovine leather [43]. Further examined whether hemp

leather is an environmentally sustainable alternative[43]. The bovine leather industry is responsible for heavy chemical use and emissions, detrimental effects to the environment as well as to human health [43]. The United Nations (UN) and other organizations call for immediate action against the animal product industry sector to greatly reduce emissions and protect the environment [1-43-85]. Hemp is a versatile plant that can be used for many things, including paper, composites, textiles, food and medicine, and is probably a suitable material for imitation leather [36, 39, 41, 42, 43, 51]. The comparison showed that hemp leather is superior to bovine leather in all compared categories except for water consumption and hazardous waste [36, 39, 41, 42, 43, 51]. Bovine leather had 99% more energy use, 78% higher acidification potential (AP), 99,9% higher eutrophication potential (EP) and 83% higher global warming potential (GWP) than hemp leather [36, 39, 41, 42, 43, 51]. The large water consumption in the manufacturing phase of hemp leather is possible to be explained by over dimensioning of inputs [36, 39, 41, 42, 43, 51]. This report of HULTKRANTZ (2018) [43] concludes that hemp leather would be the environmentally and ethically admirable choice between the two leathers [36, 39, 41, 42, 43, 51].

- **Apple Leather**

Apple leather is the plant leather of choice for funky Paris-based brand Good Guys Don't Wear Leather [52]. At GG, they take vegan fashion very seriously, and in their opinion, apple leather is the best. According to them, apple leather looks good, wears well and meets their high standards for sustainability [1-52-86]. It is another Italian-based company that is behind this vegetable leather alternative. It goes by the name AppleSkin™ and also makes use of a food waste product – a mushy pulp left over from industrial-scale apple juicing [52]. AppleSkin™ leather is not 100% plant-based, though; it's only about 20-30% apple waste, mixed with polyester [52-85]. The manufacturers are, however, working on a version that uses recycled polyester, which they hope to launch in 2026 [52].

Fruit leathers are dehydrated, restructured fruit-based products prepared by the acid - sugar - high methoxyl pectin gelation [1-52-86]. They are eaten as candy or snacks, and presented as flexible strips or sheets [52]. Due to their novel and attractive appearance, and because they do not normally require cold storage to avoid microbial growth, fruit leathers constitute a practical way to increase fruit solids consumption, especially for children and young people [52]. In recent years, their popularity has increased: they are becoming an industrial product, evolving from their origins as a homemade preparation produced by enthusiasts [1-52-85].

Fruit leathers, a dehydrated snack, have the potential to increase fruit solids consumption especially in the young [1-52]. Two apple puree formulations containing sugar and citric acid and one containing potassium metabisulphite (100 mg SO_2/kg final product) were prepared by hot-air drying at 60 ^{o}C to a water activity of 0.7 (moisture content ¼ 25 kg water/100 kg of final product) [52]. The fruit leathers were then subjected to a storage trial and remained stable for a period of 7 months at 20 ^{o} C [52]. Changes in organoleptic and nutritional parameters such as Browning Index (BI) and antioxidant activity (AA), respectively, were evaluated [52]. The effect of temperature was studied by accelerated storage tests at 30^{o} C [52]. Using the kinetic constants at both temperatures, a Q10 coefficient was calculated as 2.55 for BI and 16.26 for AA, leading to estimated activation energies of 68.9 and 206.1 kJ mol^{-}1 , respectively [52]. A potassium metabisulphite (KMBS)-added formulation, satisfactorily maintained the quality characteristics of apple leathers without microbial development over a 7 month storage period [52].

Frumat, based in the Tyrol region of northern Italy, an area known for its apple production, addresses the issue of significant apple waste generated each year by creating eco-friendly alternatives to leather [52]. This innovative material is made from cellulose and offers various textures, thicknesses, embossing, and laser-printed designs. Frumat operates two production lines [52].

First uses softened apple skin fibers, which are ideal for textile applications, particularly in the fashion and furnishing industries [52-86]. The second line produces a sturdier version of the material, made from 50% recycled apple fibers and 50% polyurethane, creating a thicker version suitable for making shoes, luggage, and items for furnishing and upholstery [52]. This approach helps reduce waste while offering sustainable solutions for various industries [52].

- **Teak Leaf Leather**

One of the most intriguing of all the plant based leathers is leaf leather which uses traditional Thai production methods [1-52-85]. To make leaf leather, people harvest fallen teak leaves, soak them in water and then leave them to dry. The soaked and dried teak leaves are then arranged in large sheets which results in a sturdy and waterproof leather-like product [1-52-85].

- **Tomato-based Leather**

Being conscious of the negative impact that the industries are causing to the environment by using animal and faux leather, the lack of sustainable material alternatives available to satisfy an ever-growing industrial demand, Tomato Leather [71]**,** a sustainable tomato-based biomaterial that is PU free and landfill biodegradable has been developed [71]. Bioleather has its headquarters in Mumbai, India, Since its official launch, it has received an important award like Best Innovation in textile award by PETA India 2021 [1-71-86]. Bioleather is committed to create new sustainable solutions and promoting ethical practices through the industry value chains to help build a better world through the fashion industry [1-71-86].

- Leather from flower waist material.
- Jute fiber and Coffee husk.
- Leather from banana plant material [98].
- Coconut water waist material.
- Cellulose is an essential component of the cell walls of green plants which is a linear polysaccharide [1-71-90]. The strength and stiffness of the plant is mainly due to micro fibrils of cellulose arranged in cell walls [1-71-90]. The cellulose is the most common organic polymer on earth and has a regenerative nature [1-71-90]. In order to provide the finished product stiffness, plant-driven bio-leathers rely on the cellulose found in plant biomass [1-71-90]. The production techniques for developing these kinds of leathers vary depending on the source of cellulose utilized due to the surrounding the businesses[1-71-90]. PiatexR, one of the most popular plant-based bio-leathers, is created from the fibers of pineapple leaves, a leftover from the pineapple industry [1-71-90]. To generate a nonwoven mesh, the fibers from the leaves are removed, cleaned, dried, and combined with polylactic acid (PLA) from maize [1-71-90]. The mesh is then coated to create the finished product called PiatexR. DessertoR is the other kind of plant-based bioleather made of cactus leaves [1-71-90]. A compact layer, a foam layer, and a woven base consisting of either polyester, cotton, or a mix of the two make up DessertoR [1-71-90]. This type of bio-leather is sustainable since it is manufactured from cactus that is grown and collected twice annually [1-71-90]. 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 DessertoR leather [1-71-90].

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 [1-71-90]. The photosynthesis carried out by the cactus plantings reduces the overall emissions from this material, further enhancing its sustainability [1-71-90]. Being a plant-based bioleather substitute, mango leather is made by mechanically separating the mesh from the seed and pulping the mesh afterward [1-71-90]. Binding agents are then included, and the mixture is cooked in an oven [1-71-90]. A leather finisher takes sheets of material out of the oven and coats them [1-71-90]. The mango leather is positioned on top of an organic cotton foundation and has satisfactory mechanical properties [1-71-90].

- **Orange Peel waste Leather**

One of the study conducted by Rimantho et al., (2024) [80] promotes the utilization of novel substances for repurposing orange peel waste as a component in vegan leather production [80]. The results of this study by Rimantho et al., (2024) [80] indicated that the test specimen that utilizes Pomelo dressing as reinforcement has the most pronounced influence [80]. It exhibits an elongation value of approximately 67.28 %, the greatest among sweet oranges using dressing as reinforcement [80]. Additionally, the tear resistance of grapefruit with dressing as reinforcement is approximately 14.28 N/cm2 [80]. These findings showed that recycling organic orange peel waste as vegan leather material has the potential for further development [80]. There is an increasing demand to emphasize the use of natural materials and replace non-renewable resources in all sectors of industrial production, motivated by concerns about sustainability [1-80]. Although leather is biologically derived and can be refilled, these characteristics have not led to a revival of the leather industry [80]. However, the leather industry is being closely scrutinized due to the ongoing debate surrounding the greenhouse gas emissions associated with cattle farming, the sustainability of leather production, and the ethical treatment of animals [80]. The wide range of requirements presents unique obstacles regarding culture and concrete progress [80]. The search for alternative raw materials has been driven by the need to minimize environmental harm and enhance efficiency [80]. Orange peel waste can be an alternative to humanity's main challenges, especially in finding environmentally friendly alternative materials in the leather industry [80]. However, it has been found that not many researchers have researched vegan leather [1-80].

- **Corkor (Bark of cork Oak trees)**

Natália and Vitor, a couple from Portugal, were the first to introduce vegetable leather made from the bark of cork oak trees, offering an eco-friendly and cruelty-free alternative to traditional leather in the fashion industry [1-80]. They discovered that cork possesses remarkable qualities, making it an ideal material for vegan fashion [1-80]. As a natural and renewable resource, cork can be harvested without harming the trees, which continue to thrive and grow after the bark is removed [1-80]. Once harvested, the cork undergoes a six-month air-drying process [1-80]. It is then boiled and steamed to increase its elasticity [1-80]. Heat and pressure are applied to compress the cork into blocks, which are sliced into thin sheets, ready to be crafted into a wide range of beautiful cork leather accessories [1-80]. This process is completely chemical-free [1-80]. Cork leather offers several benefits: it is lightweight, resistant to water, soft, and highly durable, without cracking or crumbling over time [1-80]. Natália and Vitor named their brand "Corkor," and their production facility in Portugal employs local artisans to create various accessories such as bags, belts, and wallets, all from this sustainable material [1-80].

- **Palm Leather**

Palm leather is produced by soaking the dry, brittle leaves of the Areca betel nut tree in a biologically softening solution [1-80]. Over the course of a few days, the material transforms, becoming permanently soft, flexible, and acquiring impressive aesthetic properties. It can then be processed using standard machinery [1-80].

- **Sugarcane Bagasse Leather**

In a significant development for the sugar industry and sugarcane farmers, bagasse, a by-product of sugar production, is now being utilized to produce vegan leather [100, 101]. This innovative approach not only addresses environmental concerns but also opens up new avenues for revenue generation [100]. India's vast sugarcane production could effectively utilize sugarcane waste through technology developed by PA Footwear P Ltd, a company specializing in vegan leather alternatives [100]. "In sugar mills, bagasse is occasionally used to generate electricity [100]. Farmers use it when producing jaggery in temporary crushing units installed in their fields [100]. In both scenarios, excess bagasse is often burned in the fields, leading to waste [100]. By purchasing a portion of this surplus material, one can prevent it from being burned and provide farmers with an additional source of income, resulting in a marginal increase in their earnings [100].

In one of the study reported by Ariram and Madhan (2020) [96] *Saccharum officinarum* L. (*Gramineae*), sugarcane bagasse, a by-product of the sugarcane industry is used as a tanning agent after converting the cellulose and hemicellulose content into di-aldehyde polysaccharides from hydrolyzed bagasse (DAPB) by oxidation process [96, 100]. Leather from goats skins after conventional pre-tanning process (Soaking to Deliming), tanned by developed di-aldehyde polysaccharides [96]. The developed leather provided resistance to collagenase degradation, which reflects the tanning efficiency of di-aldehyde polysaccharides [96, 100]. Additionally, tanned leather also provided reasonable mechanical strength [96,100]. The leathers made from di-aldehyde polysaccharides were observed to have properties comparable to conventional chrome tanned leathers [96, 100]. This study focused on the development of a di-aldehyde tanning agent from *Gramineae***,** *Saccharum officinarum* **L.** (sugarcane bagasse) as a cleaner alternative tanning system suitable for making different types of leather [96]. Additionally, it also paves the way for better biodegradation after the indented usage of the leather [96, 100]. Cellulose and hemicellulose were extracted through hydrolysis of sugarcane bagasse and oxidized using sodium meta periodate to produce di-aldehyde polysaccharide and used them as a tanning agent [96]. Leathers made using the developed tanning agent di-aldehyde polysaccharide (DAPB) is further tested for its leather properties and bio-acceptance characteristics for creating a model for a circular economy in leather and leather products [96, 100]. From hydrolyzed bagasse solution, fungal strains are isolated and tested for the degradation of the crust di-aldehyde polysaccharides tanned leather, where delimed pelt (untanned), chrome tanned, and vegetable tanned crust leathers were set as control [96, 100]. In comparison to delimed (untanned) pelt, the newly developed tanning system showed significant resistance to degradation [96, 100]. However, compared to chrome and vegetable tanned leathers, the di-aldehyde polysaccharides tanned leather showed better biodegradation [96, 100]. The developed bagasse tanning system paves the way for a cradle to cradle approach in creating a circular economy and sustainable development in leather manufacture [96, 100].

5. Animal Leather

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 [1-85-93-101]. Animal leather used in clothes, shoes, upholstery, and accessories and its longevity along with its natural taxtile and visual qualities, including color, softness, and warmth [74]. It is a common commodity with a market share predicted to reach about US$360 billion by 2025 [74]. Due to toxic chemical involvement and large amounts of sludge waste discharge, while treating raw hides and skins, leather production is not ecologically sound [1-74-101]. Those problems have led to the creation of leather-like materials that are not made from animal products [1-74-101]. 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 [1-74-101]. However, these synthetic leather substitutes often entail the use of risky ingredients in their manufacturing as they are made from fossil fuels, making them non-biodegradable, and experience the same constrained end-of-life possibilities as most plastics [1-74-93-101].

Generally natural leather is a collagen based animal hide, has been obtained after various chemical based processing of the skins of cattle, pig, goat, dog, horse, aviator etc [49-93-101]. It is composed of keratin, other amino acids like alanine, glycine, arginine, proline etc. These amino acids are joined by peptide linkages among themselves [49]. Natural leather has variety of end usage as it is well commercialized in the market for manufacturing of jacket, wallet, belt, seat cover, footwear parts, watch strap etc [1-74]. Main advantages of using the natural leather are its breathable, partly water proof, crease free, resistance to fire, resistance to dry abrasion nature [49-93-101]. However, in recent days, exploration of natural leather is gradually going down because of the involvement of unethical issue of animal killing [1-74-101]. Besides, conventional leather processing required larger quantity of toxic chemicals like salt, quick lime, sodium sulphide (for liming process, removing hair from raw hide and skin), strong acids (for pickling), chrome metal salt (for tanning), etc [1-74-93-101]. These chemicals are harmful as they increase the chemical oxygen demand (COD), biological oxygen demand (BOD) and total dissolved solid (TDS) level of water [1-74-86-93-101]. Moreover, high cost, some few fixed colours in the finished products, bad odour, not easy to cut or sew, batch to batch quality variation etc., are adding newer challenges in the field of leather technology [1-74-93-101].

Leather is a durable and flexible material created by tanning the animal raw hide. The main used raw material is cattle hide and skin [1-74-93]. Leather usage has come under criticism in the 20th and 21st centuries by Animal Rights groups [1-74]. These groups claim that buying or wearing leather is unethical because producing leather requires animals to be killed [1-74-101]. However, according to the LCA report for the United Nations Industrial Development Organization, most of the raw hides and skins used in the production of leather were derived from animals that are raised for meat and/or dairy production [1-74-93-101]. The skin and hide from the meat industry may create a major pollution. It can be either burnt or buried in landfill [1-74-93]. Leather production utilizes the non-usable part of dead animals, so that, there will no waste of animals' skin [1-74-93]. It helps to decrease dead animal waste and improves economic growth of India by maximizing export of leather goods [1-74-93-101]. It is widely known that the production of animal leather is very harmful to the environment, but leather is a staple of many industries [1-74-93-101]. Secondly, the animal hide must undergo the tanning process to become leather [1-74-86-101].Tanning treats the hide with chemicals to slow its decomposition and make it tough and flexible [1-74-86-93-101]. Chromium tanning is the most common method, but this produces wastewater with high concentrations of toxic chromium and sulphide, as well as the pesticides that are often used to protect the hide before tanning [1-74-86-93-101]. It is estimated 300kg of chemicals are used to treat each 900kg of leather [1-74-86-101]. Production of animal (usually bovine) leather is environmentally harmful in many ways. Firstly, the management of livestock demands extensive resources [1-74-86-93-101]. Therefore, development of artificial leather is getting attention for the industries and researchers [1-74-86-93-101].

6. Faux or Artificial Leather

The most common faux leathers are made with polyurethane or polyvinyl chloride – plastics [1-74-86-94, 97].These materials are manufactured from fossil fuels and do not biodegrade, and they usually have a short lifespan and need to be replaced regularly [1-74-86-93]. Different researches are going on for the improvement of the quality of artificial leather so that it can meet all the standards of natural leather based compound [1-74-86-93]. Most of the artificial leathers composed of one natural or synthetic fiber based base fabric, coated with polyurethane (PU) or polyvinyl chloride (PVC) or other elastomeric synthetic polymer having long chain linear molecule arrangement [1-74-86-94]. This kind of leather popularly used for making shoes, bags, wallets, upholstery, automobile, seat cover and in other applications [1-74-86-93, 94, 97]. Basic reinforcing material of artificial leather could be non-woven or knitted synthetic or natural woven textile structure [1-74-86-93]. Apart from popular PVC and PU, some other chemicals like butyl rubber (isobutene isoprene copolymers), hypalon (chlorosulfonated polyethylene), neoprene (polychloroprene), nitrile rubber

(acrylonitrile butadiene copolymer), styrene butadiene rubber, poly tetra fluoroethylene also have been used for coating purposes [1-74-86-93]. Each of the coated chemical has different advantage and disadvantages [1-74-86]. Butyl rubber is a copolymer of isobutylene, shows excellent property against heat ageing, chemical resistance and oxidation [1-74-86]. Poly Tetra Fluoro Ethylene (PTFE) showed good resistance against heat and chemical and also having good mechanical properties [1-74-86]. Both PVC and PU showed good mechanical and chemical properties, coated material shows rigid behavior and excellent strength [1-74-86-93]. It is reported that the artificial leather could be engineered by coating of natural fibre based woven canvas cloth with rubber based formulation [1-74-86-93].

However, the major part of synthetic leather is made from polyvinyl chloride (PVC), polyurethane (PU), and polyolefin (PO) mixed with a base material of plant and/or synthetic fibers, which are made from carbon-based materials that also need special care for recycling [17]. Therefore, replacing these materials with the bio-degradable fibrous materials can be a better choice [17]. Natural fibers are soft, flexible material. On the other hand, the polymeric resin PVA is water soluble and biodegradable that can form flexible film [17]. The combination of these natural fibers with the polymer PVA can form the flexible planar composite to be applied where flexibility is essential like leather based merchandise [17]. Natural fibre reinforced composites are a lightweight, affordable, and environmentally friendly replacement for many problematic applications [17]. These natural fibers could be constructed into flexible planar materials with the aid of composite phenomena that can be used for a variety of applications where flexibility is important like as artificial leather. In one of the work by Shahid et al., (2023) [17] nonwoven matt made from spinning wastes of jute fiber was used to reinforce the biodegradable polyvinyl alcohol (PVA) matrix [17].

One of the research group has developed multiple wood pulp made sheet into the form of artificial leather by using mixed formulation of 18–22 % rubber solid (latex), 4–7 % albumin based gum, 60–65 % water, 6–8 % ethyl alcohol, ethyl acetate and 1–3 % formaldehyde with very minor quantity (1 %) of ammonia [1-74-86-93]. Ammonia has been added into the formulation for stabilization of latex and formaldehyde removes the odour and assists in the tanning process of the engineered product [1-74-86-93]. This method has also proposed a method of preparation of artificial leather by using different composition of polyester and nylon blend as non-woven base material having g/m^2 range from 180 to 280 and free air volume range 70–90 % [1-74-86-93]. Different other techniques are also developed for making artificial leather by using plant leaf, paper, pineapple fiber etc. with synthetic rubber based formulations [1-74-86-93]. However, very few researches have been identified on the usage of natural rubber as coating material for the development of flexible composite material [1-74-86-93].

7. Natural Rubber leather

Natural rubber is latex, a milky liquid present in the cells of the rubber producing plants. Isoprene is the primary chemical constituent of natural rubber and it is made up of solid particles suspended in a milky white liquid, very much resistance to alkali [1-74-86-93]. It has been used as a coating ingredient due to its high elasticity, toughness, impermeability and adhesiveness [1-74-86-93]. Natural rubber showed a good tensile strength, tear strength and flexibility [1-74-86]. As per current market demand and also based on sustainability issues, manufacturing of vegan leather is very promising area of research [1-74-86-93]. However, most of the research work accomplished in this field indicated the exploration of synthetic rubber, elastomeric synthetic polymer, synthetic fibers like nylon, polyester, polypropylene polyurethane, poly vinyl chloride etc [1-74-86-93]. Therefore, for minimizing hazardous effluent problem of leather industries, minimizing animal killing issues and for lowering the usage of non-sustainable synthetic leathers made from polyurethane, polyvinyl chloride, synthetic rubber etc., a leather like flexible composite has been developed by using natural fibre and natural rubber (plant product) based formulations [1-74-86-93]. Very few research works are reported on the exploration of natural ligno-cellulosic fibers (paper, pineapple fiber, hemp fibre etc) for making flexible composite material and no systematic scientific data has been reported in this regard [1-74-86-93].

Bio-based surface material made from industrial hemp is being developed and tested for possible use in Volkswagen vehicles from 2028 onward [1-74-86-93]. Volkswagen (Wolfsburg, Germany) has entered into a cooperation with the textiles manufacturer startup Revoltech GmbH (Darmstadt, Germany) to research and develop sustainable materials based on industrial hemp, specifically, a substitute for imitation leather [1-74-86-93]. These could be used as surface materials in Volkswagen models starting in 2028 [1-74-86-93]. The leather alternative is made from 100% bio-based hemp cultivated for the food industry [1-74-86-93]. It is an all-natural, single-layer surface material called **LOVR** ("leather-free, oil-free, vegan and residue-based") that is being developed specifically with the automotive industry [1-74-86-93]. It can reportedly be produced in existing industrial plants and recycled or composted at the end of its service life [1-74-86-93]. The hemp fibers and a fully bio-based adhesive are combined using a distinctive technology and processed to become a surface material [1-74-86-93].

8. Tanning Pollution chemicals

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 [1-74-86-93, 95, 99]. 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 [1-74-86-93, 95, 99-101]. Hexavalent chromium (Cr^{6+}) and other toxic compounds are discharged via industrial wastewater to the environment [1-74-86, 95, 99]. 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 [1-74-86-93-101]. The toxicity occurs in humans because of environmental pollution through soil and water contamination or due to occupational and nonoccupational exposure to heavy metals [1-74-86-93]. Additionally, while Cr^{3+} is more chemically stable and relatively inert [1-74-86]. Cr^{6+} is highly mobile and soluble in water making it 1000 times more mutagenic and nearly 100 times more toxic than Cr^{3+} [1-74-86-93, 99-101]. Metal toxicity results in serious morbidity and mortality [1-74-86-93, 99]. 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 [1-74-86-93]. Soluble Cr^{6+} poses a significant carcinogenic risk if ingested [1-74-86-101]. This will attributed to the low pH of the stomach as particulate chromate dissolves at low pH [1-74-86-93]. Chromium is toxic and mutagenic to microorganisms at concentrations between 10 and 12 mgl^{-1} which are inhibitory to the majority of soil bacteria in liquid media [1-74-86-93, 99-101].

Tanneries are using an ample amount of harmful chemicals that may impose a huge negative impact on human health and the environment [98, 101]. Therefore, it is an emerging requirement for the removal of pollutants from effluents before discharging them to the environment [101]. For this, the development of an adsorbent from agricultural waste is significant for removing pollutants from the tanning effluent and greening the environment [101]. In one of the study by Sultana et al., (2021) [101] a low-cost adsorbent is developed and used to remove pollutants from the chrome tanning effluent [101]. The developed adsorbent is prepared from sugarcane bagasse and activated by using NaOH [101]. The study was performed at pH 4, with an adsorption time of 1 hour, and the adsorbent doses of 2.5 g/L [101]. The findings of the study by Sultana et al., (2021) [101] revealed that a considerable amount of pollution was mitigated with the reduction in BOD (42.17%), COD (75.00%), Cr_2O_3 (41.91%), TSS (81.85%), and TDS (84.24%) [101]. This investigation proved that the adsorption technique is one of the efficient modes of physico-chemical treatment of the tannery wastewater [101]. In this study, the level of pollutants i.e., BOD_5, COD, Cr_2O_3, TSS and TDS were investigated [101]. The findings of the study revealed that BOD_5 value was reduced to 42%. It is also noticed that, after the adsorption, the COD value, the Cr_2O_3 content, TSS and TDS were reduced to 75%, 41.91%, 81.85% and 84.24% respectively [101]. Therefore, it is stated that sugarcane bagasse can be used as an effective adsorbent for the treatment of the chrome tanning effluent [101]. In the future, this study can be extended by taking various samples from multiple tanneries. Furthermore, sugarcane bagasse can be activated by using various chemicals to investigate its efficiency [101].

9. Plant based Leather Market

The global bio-based leather market size was valued at USD 122.6 million in 2023 and is projected to grow from USD 139.2 million in 2024 to USD 394.9 million by 2032 at a CAGR of 13.9% during the forecast period [1-74-86-93]. North America dominated the bio-based leather market with a market share of 38.66% in 2023 [1-74-86]. The COVID-19 pandemic impacted several key areas of the market, such as supply chain disruptions, economic uncertainties, and changes in consumer behaviour [1-74-86]. Supply chain disruptions affected the availability of raw materials necessary for the manufacturing of bio-based leather [1-74-86-101]. Similarly, economic uncertainties resulted in fluctuations in development and investment within the sector, impacting growth projections [1-74-86]. However, after COVID-19, consumers' heightened focus on sustainability and ethical consumption has potentially increased interest in bio-based alternatives to traditional leather [1-74-86-93].

Bio-based leather is gaining popularity in the fashion industry due to its ability to replace traditional leather materials in footwear, garments, and accessories [1-74-86-93-101]. Based on the source, the market is classified into mushroom, pineapple, apple, and others. The footwear segment held the largest bio-based leather market share in 2023 [1-74-86]. The leather records a major demand in footwear applications due to the fashion industry's growing commitment to reducing its carbon footprint and increasing interest in sustainable materials [1-74-86-93-101]. Bio-based leathers are increasingly adopted by a range of footwear manufacturers, from luxury brands to more affordable, mass-market producers [1-74-86-93-101]. These materials also offer unique aesthetic qualities, durability, and comfort [1-74-86-93]. Similarly, technological advancements and material science have greatly improved the performance and quality of bio-based leathers, making them a viable alternative for a wide array of footwear applications from athletic shoes to high-end fashion boots [1-74-86-93-101]. The garments and accessories segment is predicted to witness a notable growth over the coming years [1-74-86-93-101]. As technology advances, the durability, quality, and appearance of bio-based

leathers continue to improve, making them a usable choice for various garments, ranging from shoes to jackets and accessories [1-74-86-93-101].

North America holds the dominant share of the global market. Advances in the bio-based leather industry, economic conditions, industry regulations, and increasing adoption of lightweight and sustainable materials are factors propelling the bio-based leather market growth in the region [1-74-83-101]. The U.S. government's focus on environmentally sustainable product renovation and carbon-free projects is driving the need for bio-based leather in the country's footwear and automotive industries [1-74-86]. Developed and developing countries such as India, Japan, and China are raising their investments to produce and use sustainable products in various end-use industries [1-74-86-93]. Such growing investment and innovation in the leather industry drive the demand for bio-based leather products [1-74-86-93-101]. In addition, a growing trend in the footwear industry to use sustainable footwear materials as they are sustainable, eco-friendly materials, and durable is expected to drive the growth for sustainable leather products [1-74-86-93]. Such factors propel the demand for products in the regional market. Europe registers a notable growth in the global market [1-74-86-93-101]. The growing automotive and footwear industry in Europe due to innovations in mobility, production excellence, and rising consumer spending capacity drives market growth during the forecast period [1-74-86-93-101]. Italy is registered as one of the key countries in the use of leather [1-74-86]. The market in the rest of the world is projected to grow significantly over the forecast period. The growing adoption of plant-based leather in furniture and the automotive industry positively impacted the market expansion in the region [1-74-86-93-101].

In recent years, the development and application of coffee grounds have become a new hot spot for research and exploration in the field of sustainability [14]. The preparation method of water-based synthetic leather by reusing solid waste coffee grounds as fillers and developing a new environmentally friendly production process of water-based synthetic leather, testing its properties, such as color fastness to dry and wet rubbing, and designing applications of sustainable coffee grounds [14]. Synthetic leather in garments and apparel products is analyzed [14]. The experimental results showed that the material fully achieves the performance of waterborne garments and luggage synthetic leather and can provide breathability close to that of genuine leather [14]. This makes the whole production process energy-saving and environmentally friendly, which is an innovative and sustainable product that can be applied to the apparel industry in the future [14]. Of course, this method is not limited to the application of coffee grounds but can also be extended to the recycling and reuse of more solid waste impurities, as research continues, it will be more widely developed and applied in the field of textiles, turning environmental problems into opportunities [14].

10. Brand Names of Plant based Leather

Muskin is produced using a specific type of non-edible mushroom called *Phellinus ellipsoideus* [1-74-86]. It is native to subtropical forests where it is considered a pest for feeding on certain tree trunks, and causing them to rot [1-74-86-93]. This is another plus for mycelium leather – finding solutions for not one but *two* ecological problems [1-74-86]. The end result is a surprisingly suede-like leather that is durable, water-repellent and lightweight [1-74-86]. "Fungi fashion" (the new buzz word for mycelium leather) is also soft enough to be worn against the skin without causing irritation (no surprise there since mushrooms are a key ingredient in some ancient Chinese skin remedies!) [1-74-86-93]. In addition to Grado Zero, German brand nat-2™ produces their own mushroom-based vegetable leather [1-74-86]. It similarly uses a parasitic fungus, making it another environmental win-win [1-74-86-93]. Unlike Muskin, nat-2™ combines mycelium leather with organic cotton and recycled water bottles to produce their faux leather shoes [1-74-86-93].

Mycelium leather has been popularized by Italian textile company Grado Zero Espace who have been producing it under the brand name Muskin [1-74-86]. Not only this leather is made from plants, but Grado Zero uses all natural products during the manufacture of Muskin [1-74-86].

Another popular plant based leather alternative is Piñatex (also known by the anglicized name, Pinatex) a plant-based leather made out of pineapple leaf fibers [1-74-86-101]. One of the great things about pineapple leather is that it makes use of what would otherwise be an agricultural waste product [1-74-86]. First designed by Dr Carmen Hijosa and manufactured under the brand name, Ananas Anam, pineapple leather supports farming communities in the Philippines by providing extra income for materials that they previously just threw away [1-74-86].

Pinatex also follows a circular economy model and cradle to cradle principles [1-74-86]. This means that their product was designed with its full lifecycle in mind – from cradle to cradle [1-74-86-93]. The Muskin, this vegetable leather is also killing two birds with one stone, by producing a more sustainable leather alternative out of an industry by-product that would otherwise just go to waste [1-74-86-93]. The discarded pineapple leaves left in the fields following the pineapple harvest are collected and the long fibres extracted from them [1-74-86-93]. These fibres are then washed,

purified and dried – often in the sun [1-74-86]. The resulting fluff-like pineapple leaf fibre is mixed with a corn-based polylactic acid and transformed through mechanical processes into a non-woven mesh [1-74-86]. A resin top coating gives it additional strength, durability and water resistance, and colour is added using GOTS certified organic pigments [1-74-86]. The German fashion label Hugo Boss was one of the earlier brands to launch shoes made of Pinatex, part of its collection of responsible designs with low environmental impact [1-74-86-101]. Other brands working with Piñatex include Maravillas, Portuguese shoe brand Nae, and Altiir, a popular Italian fashion brand with a line of custom pineapple leather jackets [1-74-86].

Nova Milan is another fashion-forward company making vegetable leather based on discarded pineapple leaves and other agricultural waste [1-74-86]. Based in Costa Rica, they claim to be the "first full supply chain ecosystem creating petroleum-free, plant based vegan leather at scale," and it is their mission to turn Costa Rica into the world leader of the emerging plant based leather economy [1-74-86]. Costa Rica is the world's largest exporter of pineapples, leaving behind a lot of plant fibre waste up to 5 million tonnes per year that could be used to make vegan leather [1-74-86-101]. Clearly, vegetable leather is an innovative new realm in the faux leather industry, with heaps of potential and lots to get excited about pineapple leather's journey started way back in the 1990s, but brands are only just starting to use the leather alternative in their products [1-74-86-93-101]. Mycelium leather can only currently be produced in small quantities, making it hard for brands to incorporate it into their designs on a large scale [1-74-86-101]. But even with all these ifs, ands or buts, plant based leather has pretty extraordinary potential to contribute to a climate-friendly, cruelty-free sustainable fashion industry [1-74-86-101]. And like other plant leathers, Nova Milan's vegan alternative leather is 100% biodegradable [1-74-86-93-101].

Desserto® was developed by Adrián López Velarde and Marte Cázarez, from Mexico, and was first commercially available in 2019 [1-74-86-93-101]. They were inspired to develop an alternative after working with leather for furniture, car interiors, and fashion. Desserto® can be produced in a range of colors and thicknesses, and is very similar to animal leather in its appearance and texture [1-74-86-93-101]. This leather alternative is made from the nopal (prickly pear) cactus. The leaves are harvested and then sun-dried until they have the perfect moisture level. A patented and organic process transforms the leaves into Desserto® [1-74-86-93-101].

11. Vegan Leather

The collective term of "vegan leather" includes both synthetic materials made from petroleum, such as polyurethane (PU) and polyvinyl chloride (PVC), as well as natural, plant-based materials such as pineapple fibers, mushroom mycelium, apple peels, cactus leaves, or plants and minerals [1-74-86-93-101]. Plant-based leather alternatives are a growing market, with innovators turning to pineapple, olives, and coconuts to produce eco-friendly materials [1-74-86-101]. Earlier this year one of the leading brands unveiled a vegan jacket made from pineapple leather, while another launched a product of leather shoes made from olive leaves [1-74-86-101]. Further another local South India, Kerala, manufacturer came out with leather and accessories made from coconuts [1-74-86-101]. Home grown labels in India have also been taking the initiative of making sustainable leather from plant waste (such as extracts of coconuts, sugarcane bagasse, leaves of pineapple plants, cacti, and more) or blending the same with synthetic material to lessen green washing [1-74-86-101]. Various studies have shown that vegan leather alternatives are particularly suitable because they mimic the properties of real leather, and the qualities of the bio-based materials combined with textile substrates are relatively close to real leather [1-74-86-93-101]. In addition, cactus plants required less water and can completely replace real leather. The use of cactus as a source of sustainable textiles and leather offers numerous environmental benefits [1-74-86-93-101]. This is due to the fact that harvesting the cactus does not harm the plant or its roots, allowing it to keep growing and sequestering carbon dioxide [1-74-86].

With growing awareness of the effects of the leather industry on the environment and animals, the market for cruelty-free alternatives will keep growing [1-74-86-93-101]. So many brands are out there, trying to make vegan leather as low impact as possible by using plants to create leather-like fabrics [1-74-86-101]. Two factories in Mexico have developed durable vegan leather from cactus, and it could very well replace animal leather [1-74-86-101]. Initially, all vegan leather was made of plastic-based materials [1-74-86-101]. Later on due to further research in the last few years, textile scientists have discovered many ways to make vegan leather out of everything easily available from pineapples to cactus leaves to flowers [1-74-86-101]. The vegan leather industry has come up now leaving aside the good old leather and coming out with some exciting plant-based leathers on the market [1-74-86-101]. Very interesting fact is that every vegan leather is made from a plant, but unfortunately, none of them are fully biodegradable [1-74-86-101]. That is because each material is either made with a mixture of plants and polyurethane or is plant-based and coated with a plastic-based resin [1-74-86-101]. While there are a few brands already selling fully compostable sneakers, no one has been able to come out with compostable vegan leather shoes [1-74-86-101]. But the good news is that the most of the brands are fine tuning towards perfecting their respective vegan leathers to make their shoes biodegradable [1-

74-86-101]. It is well known that vegan leather has always a lower impact than animal based leather, whether it is plant-based or completely synthetic [1-74-86-101]. Not only does vegan leather leave animals out of the picture, but the process of manufacturing like breeding, raising, and killing animals and tanning leather has a high environmental impact [1-74-86-101]. To raise animals (typically cows) for leather requires large amounts of land, water, and cattle feed, the animals emit methane into the atmosphere; and the excrement from cattle bodies and factory farms pollutes the nearby waterways, soil, and air, which becomes a public health risk for people who live nearby [1-74-86-101]. The manufacturers had previously made vegan leather from a mix of polyurethane and bio-oil [1-74-86-101]. The bio-oil is sourced from cereal crops that were organically grown in northern Europe in a carbon-neutral process [1-74-86-101]. The manufacturer is trying to stop using polyurethane to make its vegan leather and recently planning to come out with a new product using viscose made from eucalyptus bark [1-74-86-93-101]. It has been found that all the major vegan leather manufacturers make vegan leathers made from plants but also contain polyurethane in their composition, usually in their finishing or as the backing material [1-74-86-101]. It was a required component in the production [1-74-86-93].

Later on, people are thinking of a 100 percent biodegradable vegan leather technology that does not exist to exclude polyurethane totally [1-74-86-101]. However, time is not far the researchers which have developed a vegan leather made from nopal cactus leaves which are organic, partially biodegradable, soft, and durable [1-74-86-101]. This can be used to make furniture and car interiors in addition to fashion items like wallets, purses, and shoes [1-74-86-101]. The scientists named **Adrian** Lopez Velarde and Marte Cazarez came together to create a cruelty-free alternative to animal leather, and , they developed the first time an organic leather made entirely from nopal or prickly pear cactus which they name as " Dessert [1-74-86-101]. These nopal cactus grow in abundance across Mexico without requiring any water called a low impact crop [1-74-86]. Cactus leather is a sustainable leather alternative made from Opuntia cactus (also known as Nopal) that has been developed in Mexico [1-74-86-101]. It is called Desserto and is a highly sustainable plant based vegan leather made from cactus having superior softness to touch and great performance for a wide variety of applications and complying with the most rigorous quality and environmental standards [1-74-86-101]. This vegan leather aims to offer a cruel-free and sustainable alternative, without toxic chemicals, phthalates, and PVC [1-74-86-93]. It is one of the world's most popular and heavy demand products where leather is part of an overwhelming $80 billion industry [1-74-86]. They have named their cactus vegan leather Desserto, and it is made from cactus grown on their plantation in the city of Zacatecas situated in Mexico [1-74-86-93-101]. The cactus as a plant is having rugged, thick skin, which makes it the perfect texture to have a similar appearance to animal leather [1-74-86-101].

12. Vegan Leather Industry in India

The Indian vegan leather industry, also known as plant-based leather, has experienced remarkable growth in recent years [1-74-86-93]. In 2023, it was valued at USD 73.38 billion, and projections indicated that by 2030, it will soar to USD 139.02 billion, boasting an impressive compound annual growth rate (CAGR) of 9.58%1 [1-74-86-93]. This eco-conscious sector provides cruelty-free alternatives to traditional animal-derived leather, catering to consumers who prioritize ethics and sustainability [1-74-86-93]. Following are the few Indian vegan industries involved in the plant based leather production.

12.1. Winner Nippon Leatherette Private Limited

Winner Nippon Leatherette Private Limited, an Indian company based in Solan, Himachal Pradesh established in 2006, specializes in manufacturing a wide range of synthetic leather products including 100% vegan leather options like Featherette, WinNamo (cactus-based), Flora (plant-based), and Relive (recycled) [1-74-86-93]. Their products cater to various sectors such as footwear, fashion accessories, automotive, furniture, and healthcare [1-74-86-93]. With a strong focus on sustainability and innovation, the company has earned its place among India's top 10 vegan leather manufacturers due to its diverse product range, eco-friendly initiatives, and commitment to quality [1-74-86-93].

12.2. Malai Eco

Malai Eco, founded in 2017 in Kerala India, is a pioneer in sustainable vegan leather made from upcycled coconut waste [1-74-86-93, 98]. They collaborate with local coconut farmers and processors to collect leftover **coconut water**, which is then used to cultivate bacterial cellulose which is Malai's core material [1-74-86-93, 98]. This bio-based material is not only earth-friendly but also versatile and durable, making it a popular choice among sustainable fashion brands [1-74-86-93].

Malai Biomaterials, co-founded by **Susmith from Kerala and Zuzana from Slovakia**, is an innovative venture that epitomises the future of sustainable material development [1-74-86-93]. Their groundbreaking project transforms organic bacterial cellulose into Malai, a versatile material derived from agricultural waste of the coconut industry in

Southern Kerala, India [1-74-86-93]. This development marks a significant advancement in eco-friendly material innovation [1-74-86-93]. Malai stands out for its sustainability, adaptability, and successfully being used in fashion accessories [1-74-86-93]. It emulates leather's texture and durability, offering a biodegradable and vegan alternative to conventional leather widely used in fashion [1-74-86-93]. This innovation is a part of the founders' broader commitment to sustainability, incorporating natural fibres like banana stem, hemp, and sisal into Malai, fostering a circular economy through compostable materials [1-74-86-93, 98]. Since 2018, Malai Biomaterials has been renowned for its ecological approach, addressing environmental and ethical concerns in various industries [1-74-86-93]. Their use of coconut water to create a material comparable to leather in functionality and aesthetic appeal has set a new standard in sustainable solutions [1-74-86-93]. As a PETA-approved entity, Malai's notable feature is its quick decomposition, breaking down within 90-150 days [1-74-86-93]. This attribute highlights the multifaceted benefits of coconut, well-known for its healing and nutritional properties [1-74-86-93]. Malai Biomaterials has ingeniously tapped into coconut water's potential to create an eco-friendly leather substitute [1-74-86-93]. The material is produced through a fermentation process involving waste coconut and other natural resources, resulting in a biodegradable, vegan product [1-74-86-93]. This initiative reflects the founders' passion for sustainable fashion and environmental care, culminating in a product development phase funded by personal savings and conducted in a collaborative manufacturing unit in Karnataka, India [1-74-86-93]. The manufacturing process of Malai involves collecting and sterilising coconut water from Kerala farms [1-74-86-93]. The cellulose produced is mixed with banana fiber or gum, forming sheets or 3D shapes [1-74-86-93]. These are then treated with natural dyes and water-resistant coatings, offering various textures and hues [1-74-86-93]. Despite challenges like the COVID-19 pandemic, Malai Biomaterials aims to expand into the Indian market, exploring new applications in furniture and interior design [1-74-86-93]. With a monthly production capacity of 200 square meters, the company is poised to make a significant impact in sustainable material development [1-74-86-93]. Malai Biomaterials represents a paradigm shift in material innovation, blending traditional resources with modern research to offer eco-friendly alternatives [1-74-86-93]. Their commitment to environmental and ethical manufacturing sets a precedent in the industry, heralding a future where sustainable choices are not only viable but also preferred [1-74-86-93].

12.3. Aulive

Aulive, an Indian company founded in 2017, is a leading manufacturer of vegan leather crafted from innovative plant-based materials like pineapple leaf fibre and cork [1-74-86-93]. They cater to environmentally conscious consumers seeking stylish and cruelty-free alternatives to traditional leather, making them one of the top 10 vegan leather manufacturers in India [1-74-86-93].

12.4. Vortex Flex Private Limited

Vortex Flex Private Limited is an Indian manufacturer established in 2017, specializing in high-quality PVC products with a focus on innovative vegan leather [1-74-86-93]. Catering to the burgeoning demand for sustainable materials, the company offers a diverse range of vegan leather options for the fashion, automotive, upholstery, and footwear industries [1-74-86-91]. With a strong commitment to quality and customer satisfaction, Vortex Flex has earned a reputation as a leading provider of vegan leather solutions in India, trusted by both domestic and international brands [1-74-86-93]. The company is located at Chikhli, Navsari, Gujarat, India.

12.5. Zaibunco Industries Private Limited

Zaibunco Industries Private Limited is an Indian manufacturer established in 2010, specializing in high-quality faux leather products [1-74-91]. The company offers a diverse range of vinyl fabrics, faux leather, and microfiber leather catering to the furniture, automotive, and fashion industries [1-74-86-93]. Renowned for its durable, anti-microbial, and eco-friendly vegan leather alternatives, Zaibunco has gained a strong reputation among furniture manufacturers, fashion brands, and automotive interiors for its sustainable and cost-effective products. Website**:** www.zaibunco.co.in. Kanpur, UP, India [1-74-86-93].

12.6. Responsive Industries Limited

Responsive Industries Limited is a leading Indian manufacturer established in 1982, specializing in PVC-based products [1-74-86-93]. The company is renowned for its high-quality vinyl flooring and synthetic leather, including a wide range of plant-based alternatives [1-74-86-93]. Serving diverse sectors such as healthcare, transportation, real estate, and fashion [1-74-86-93]. Responsive Industries is a preferred choice for both domestic and international markets. Through a steadfast commitment to innovation, quality, and sustainability, the company has positioned itself as a major player in the Indian vegan leather industry [1-74-86-93].

12.7. Response Fabrics India Private Limited

Response Fabrics, an ISO 9001-certified company at Ghaziabad, UP established in 2004 in India, is a leading manufacturer of various fabrics including vegan leatherette (polyester leatherette) [1-74-86-93]. They cater to a wide range of clients in the corporate, commercial, and hospitality sectors, offering a variety of materials like crepes, recycled cotton, mesh, and jute for use in office furniture, wall panels, and seating [1-74-86-93]. Their commitment to quality and innovation has placed them among the top 10 vegan leather manufacturers in India. Website**:** www.responsefabrics.com [1-74-86-93].

12.8. Giriraj Coated Fab Private Limited

Giriraj Coated Fab Private Limited is a prominent Indian manufacturer of artificial leather, established in 2008 [1-74-86-93]. Specializing in high-quality PVC and PU vegan leather, the company serves the automotive, footwear, furniture, and fashion industries. Committed to innovation and sustainability, Giriraj Coated Fab offers durable, stylish, and eco-friendly alternatives to real leather [1-74-86-93]. **Website:** www.girirajcoated.com. Giriraj Coated Fab Pvt Ltd KH NO 55 47, KM MILE STONE, Rohtak - Delhi Rd, near TOLL PLAZA, Bahadurgarh, Haryana, 124501, India [1-74-86-93].

12.9. Bioleather

Bioleather, an Indian company founded in 2021, is a prominent manufacturer of innovative vegan leather products particularly leather from tomato [1-74-86-93]. They offer Eori™, a unique bio-based material derived from microbes and tomato plant waste, known for its luxurious feel, sustainability, and biodegradability [1-74-86-93]. Targeting manufacturers in the fashion industry, Bioleather provides high-performance, eco-friendly alternatives to traditional leather for textiles, lifestyle accessories, footwear, and furniture [1-74-86-93]. Their commitment to sustainable practices and the development of novel vegan materials has positioned them as a key player in India's vegan leather market. Website**:** www.bioleather.in. Address (India**):** B 16 102 Neelkanth CHS ,Evershine City , Vasai East . Palghar 401208. Maharashtra state, India [1-74-86-93].

12.10. Banofi

Banofi is a leading Indian company founded in 2022 that specializes in creating sustainable, plant-based leather from **banana crop** waste [1-74-86-93, 98]. By transforming abundant banana stem waste into high-quality vegan leather, Banofi offers a cruelty-free and eco-friendly alternative to traditional leather for the fashion, automotive, and furniture industries [1-74-86-93, 98]. With a significant reduction in environmental impact compared to traditional leather production, Banofi is at the forefront of India's growing vegan leather market, appealing to both ethically-minded consumers and businesses seeking sustainable materials. Website**:** www.banofileather.com [1-74-86-93, 98]. This Indian start up specializes in creating plant-based leather from banana crop waste [1-74-86-93]. Founded by Jinali Mody, has experience at McKinsey & Co., the brand was inspired by the lack of sustainable alternatives, particularly those relying on petrochemical sources [1-74-86-93]. Recognizing this gap, she assembled a team of experts in leather, textiles, design, agriculture, and material science [1-74-86-93, 98-101]. India is an ideal location for their operations, producing 4 tons of waste for every ton of fruit, leading to an estimated annual generation of 80 million tons of waste [1-74-86-93-101]. Banofi focuses on up-cycling banana crop waste into high-quality leather products. Their process incorporates 50% banana stem waste, 30% natural additives, and 20% mainly recycled polymers to create the fibre [1-74-86-93]. Banofi produces luxury, sustainable fashion items for brands like Rashki, Misfit Panda, and Beej etc [1-74-86-93, 98-101].

13. Conclusion

Bio-based leather alternatives are eco-friendly, non-toxic, sustainable and ultimately can substitute natural leather made by conventional processing. 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. 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. Hide Biotech in London creates conventional leather substitutes using isolated collagen proteins. Bio-leather, which is derived from mycelia 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.

However, tanning leather also adversely impacts the environment and human health. Chromium agents have the potential to be very toxic and detrimental to the environment, with the degree of harm dependent on their present condition. Chrome tanning harms the environment, and the final product frequently releases noxious chemical scents. An essential concern in the leather industry is the management of chromium waste, which arises when the treatment procedure results in the creation of sludge contaminated with chromium.

Recently, there are more natural, environmentally friendly, and cruelty-free alternatives have experienced a shift rise in popularity within the various industries especially in fashion, textile, and automotive sectors. Today, consumers increasingly demanding eco-friendly options, and seeking brands that prioritize sustainable and ethical practices. With the growing demand in the market, these alternatives are becoming more accessible to consumers. However, many more eco-friendly alternatives are available and gaining popularity. Plant-based vegan leathers have been developed from pineapple leaves, sugarcane bagasse, mushrooms (*Phellinus ellipsoideus*), bananas, grapes, and coffee husks, and jute fibre. Other alternatives include cork, wood, and even stone. But perhaps the most promising so far is Desserto®, a vegan leather made from cactus.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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