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Reducing the Environmental Impact of Leather Production and Assessing the Potential of Cactus-Based Vegan Leather

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Global warming and the environmental and health risks linked to animal-based leather products have increased the demand for sustainable alternatives. Vegan leather has gained attention as a promising solution to these issues, encouraging eco-friendly fashion. To reduce its environmental impact, the leather industry is shifting from animal-derived to plant-based materials. Traditional leather production involves slaughtering over a billion cattle each year, releasing harmful substances like chromium and lead that pollute water sources and threaten public health. This study explores the potential of cactus-based vegan leather as an eco-friendly substitute for conventional leather. The process involved harvesting mature cactus pads, drying them in the sun, and transforming them into a sturdy material that mimics the properties of real leather. Mechanical tests showed that cactus leather offers similar durability, flexibility, and aesthetic appeal to traditional leather. The results emphasize the environmental, economic, and functional advantages of cactus leather, positioning it as a scalable alternative to reduce the negative ecological effects of animal-based leather production.

Keywords: Environmental Impact, Animal Welfare, Cactus Leather, Sustainability, Global Shift.

Introduction:

Human activities, particularly those driven by socio-economic factors, are playing a major role in global environmental degradation [1]. Processing industries are among the key contributors to this crisis [2], and the leather industry is a clear example. It relies on animal hides from the meat industry and uses resource-heavy tanning processes [3]. Leather production consumes a large amount of water—about 40 liters per kilogram of hide—due to stages like soaking, tanning, and conditioning [4]. This process generates substantial wastewater, increasing biological oxygen demand (BOD), chemical oxygen demand (COD), and depleting dissolved oxygen in water bodies [2], [5]. Leather is a globally traded product, mainly derived from the meat and dairy industries [6], [7]. The industry depends heavily on these sectors, with 95% of raw materials coming from cows, lambs, pigs, and goats [8]–[9]. This reliance contributes to environmental issues, including at least 32,000 million tons of CO2 emissions annually [10].

In Pakistan, the leather sector ranks as the second-largest industry after textiles, providing jobs to over 200,000 people and contributing 5% to manufacturing GDP and 7% to exports [11], [12]. The country has around 596 tanneries, with more than 90% of their output exported [13]. However, the tanning process uses around 130 harmful chemicals, including sodium sulfide, chromium sulfate, and formaldehyde, which damage the environment. These chemicals pollute the air, soil, and water, harming agricultural land and reducing crop productivity [14], [15]. Industrial activities, especially tannery operations in Pakistan, are a major cause of pollution [6]. In Punjab and Khyber Pakhtunkhwa (KPK), tanneries significantly pollute rivers, agricultural fields, and residential areas. Chemical waste and untreated wastewater are discharged into waterways, harming crops and contaminating food supplies. Since many tanneries are located in residential areas, they pose serious health risks to urban populations.

In Karachi, untreated wastewater is dumped into the sea, while in Lahore and Punjab, it pollutes rivers [16]. Chemical waste clogs drainage systems, and sludge is often dumped openly, further damaging the environment and endangering public health [17]. Leather dust is both carcinogenic and allergenic, increasing health risks, particularly in areas like Korangi and Charsadda. Tanneries contribute 10–15% of the pollution along Karachi's coastline, while in Punjab, pollution from toxic river water used for irrigation reduces crop yields and affects food safety.

In recent years, the demand for sustainable and cruelty-free alternatives to animal leather has increased significantly due to growing environmental awareness and ethical concerns. The leather industry, while valued for its durability and aesthetic appeal, is associated with high water consumption, greenhouse gas emissions, and the use of toxic chemicals in tanning processes, contributing to significant environmental pollution. Additionally, synthetic leather alternatives, such as polyurethane (PU) and polyvinyl chloride (PVC) leather, pose their own challenges, including non-biodegradability and microplastic pollution. In response to these issues, researchers and manufacturers have been actively exploring bio-based and eco-friendly leather substitutes that can provide comparable mechanical properties while minimizing environmental impact. Cactus-based vegan leather has emerged as a promising alternative, offering a biodegradable, water-efficient, and carbon-negative solution for industries such as fashion, automotive, and upholstery. By utilizing renewable plant-derived materials, cactus leather aims to bridge the gap between sustainability and performance, ensuring durability, flexibility, and consumer acceptance while reducing dependence on animal-derived and petroleum-based materials.

Given these concerns, finding an alternative to animal-derived leather is essential. Although the demand for sustainable materials is rising, limited research has explored cactus-based vegan leather as a viable substitute. This study introduces vegan leather made from cacti as an eco-friendly alternative to conventional leather. It minimizes environmental impact by using less water, sequestering carbon, and optimizing glycerin concentration to enhance durability and flexibility. Cactus leather offers higher elasticity (95%) and comparable tensile strength (up to 25 MPa) to traditional animal leather, whose tensile strength typically ranges from 15 to 30 MPa. However, producing animal leather requires resource-intensive processes that consume significant energy and release hazardous chemicals, including sulfides and chromium [18].

While PU leather is flexible and affordable, it generates 15–20 kg of CO_2 per square meter during production and significantly contributes to microplastic pollution. In contrast, cactus leather consumes only 200 liters of water per square meter and emits just 5 kg of CO_2, compared to animal leather, which uses a staggering 17,000 gallons of water per square meter [19]. Additionally, unlike PU and animal leather, cactus farming helps sequester carbon, absorbing up to 8 tons of CO_2 per hectare [8], [20]. For these reasons, cactus-based vegan leather stands out as a sustainable and environmentally friendly alternative to traditional leather.

Objectives:

The primary aims of this study are:

- Create vegan leather made from cacti as a sustainable substitute for animal and synthetic (PU) leather.
- Assess its mechanical characteristics, such as elasticity, flexibility, and tensile strength.
- Optimize drying conditions to increase production scalability and energy efficiency.
- Evaluate its effects on the environment in terms of carbon emissions, water use, and potential for CO2 sequestration.

Material and Methods:

Production Process:

The production process of cactus-based vegan leather combines plant-derived materials with synthetic polymers to achieve the desired properties, such as durability, flexibility, and elasticity. This blend enhances the leather's functionality while maintaining its eco-friendly characteristics. Figure 1 shows the flow diagram of methodology.

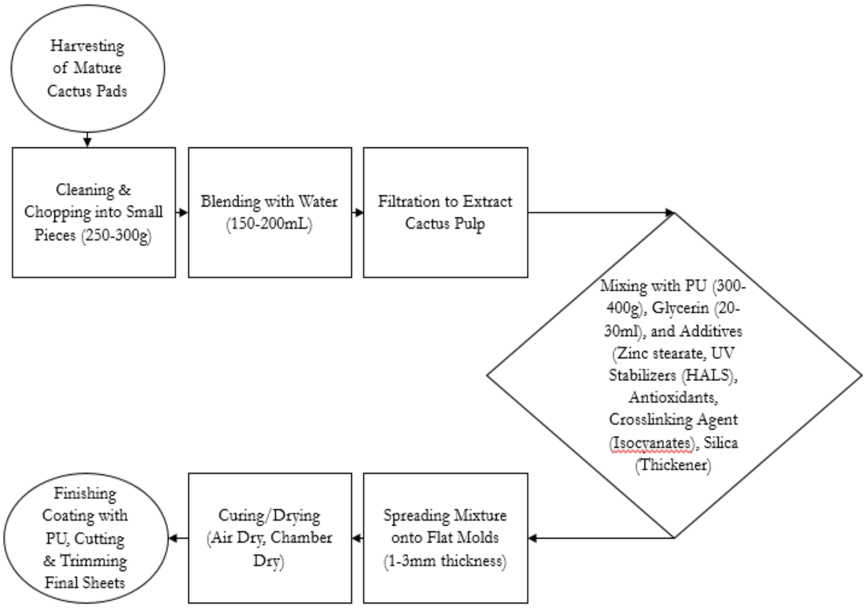

Figure 1. Flow diagram of methodology

Harvesting and Preparing the Cactus:

Cactus pads are harvested with care to protect the environment and ensure the plant's well-being [21]. The fine glochids (tiny thorns) are removed to create a smooth transition from raw plant material to leather [22], [23]. Next, the harvested pads are thoroughly washed to eliminate dirt and debris. They are then cut into pieces weighing 250-300 grams [24]. These pieces are blended with 150-200 milliliters of water to form a thick paste. The mixture is then strained through a fine mesh or cheesecloth to separate the fibers and remove excess water, leaving behind a thick cactus pulp for further processing. Table 1 compares the composition, biodegradability, and toxic emissions of cactus leather, traditional animal leather, and synthetic PU leather.

Table 1: Technical Comparison with PU Leather and Animal Leather

Property	Animal Leather	PU Leather	Cactus Leather
Tensile Strength	15–30 MPa	10–25 MPa	25 MPa
Elasticity	50–100%	80–120%	95%
Water Use (per m²)	17,000 liters	1,000 liters	200 liters
CO_2 Emissions (per m²)	15–30 kg	15–20 kg	5 kg
Environmental Impact	High (pollutants)	Medium (plastics)	Low (biodegradable)

Preparing the Polyurethane Mix:

To prepare the polyurethane mixture, 250–300 g of dehydrated cactus biomass is combined with 300–400 g of polyurethane, which acts as a binding agent to enhance flexibility, durability, and water resistance. Glycerin (20–30 ml) is added to improve flexibility and prevent cracking. If desired, plant-based dyes or colorants (2–10 g) can be included to achieve the desired color.

Combining Cactus and Polyurethane:

The cactus pulp is gradually blended into the polyurethane mixture using a spatula to ensure even mixing. Once the mixture reaches the proper consistency, zinc stearate (10–15 g) is added to improve heat stability. Glycerin serves as a plasticizer, enhancing flexibility, while UV stabilizers (HALS, 5–10 g) protect the material from fading. Antioxidants (5–10 g) prevent long-term degradation. A crosslinking agent (isocyanates, 10–20 g) strengthens the bond between the cactus and polyurethane, and a thickening agent (silica, 10–15 g) helps achieve the desired viscosity. Together, these additives enhance the material's strength, stability, and performance.

Forming the Leather:

The mixture is then poured onto a flat mold or a non-stick silicone mat. Using a spatula or a similar tool, it is spread evenly to a thickness of 1–3 mm. For a textured finish, a patterned mold can be pressed onto the surface before curing, adding both visual and functional details.

Curing and Drying:

The material should be left to air-dry in a well-ventilated space for 24–48 hours. The drying process can be optimized under different conditions. Air drying at 25°C takes 48 hours and uses minimal energy. Chamber drying at higher temperatures—40°C, 50°C, 60°C, and 70°C—reduces the drying time to 8, 4, 3, and 2 hours, respectively, though energy consumption increases with temperature, ranging from 0.8 kWh at 40°C to 2.5 kWh at 70°C. Table 2 evaluates the mechanical performance of the three leather types in terms of tensile strength (durability), elasticity (flexibility), and abrasion resistance (wear durability over time).

Table 2. Indicating a trade-off between drying speed and energy use

Temperature (°C)	Drying Time (hours)	Energy Consumption (kWh)
25 (Air Drying)	48	0
40	8	0.8
50	4	1.2
60	3	1.8
70	2	2.5

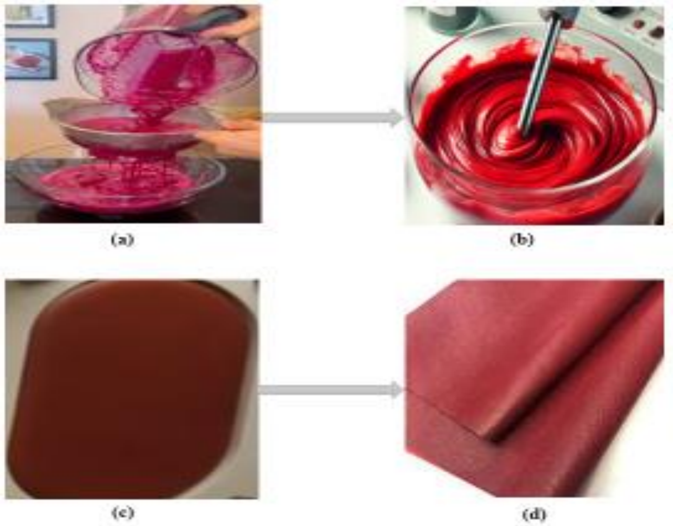

Figure 2. (a): Harvesting, cleaning, chopping, and preparing pulp **(b):** Mixing **(c):** Curing and drying **(d):** Leather sheets

Final Touches

After drying, a thin layer of polyurethane or natural sealant is applied to protect the surface from moisture and wear. The edges are then trimmed to the desired shape or size using scissors or a knife.

Results:

Testing of Mechanical Properties:

The mechanical properties of the cactus-based vegan leather were systematically evaluated to assess the impact of different glycerin concentrations on performance. At an optimized glycerin content of 15%, the material demonstrated a tensile strength of 25 MPa. It also achieved a flexibility score of 9 on a standard scale of 1 to 10. Additionally, with an elasticity of 95%, the material exceeded the lower range of animal leather elasticity (50–100%).

Table 3 highlights the water absorption and moisture retention properties of different leather types. Table 3 supports the claim that cactus leather offers an ideal balance between water resistance and breathability, making it suitable for fashion, footwear, and upholstery applications.

Table 3. Mechanical properties of cactus leather at different glycerin concentrations

Sr. #	Glycerin (%)	Tensile Strength (MPa)	Flexibility (1-10)	Elasticity (%)
1	5%	12	6	80%
2	10%	20	8	90%
3	15%	25	9	95%

The results underscore that the addition of glycerin as a plasticizer effectively enhances the tensile strength and elasticity of cactus-based leather, making it suitable for demanding applications.

Flexibility and Stretch Tests:

The flexibility and resistance to stress-induced cracking were evaluated to assess the performance of cactus leather at different glycerin concentrations. At 15% glycerin, the material achieved a flexibility score of 9 and successfully passed the crack test, indicating its capacity to endure mechanical stress without structural failure. However, at lower glycerin levels, particularly 5%, the material failed the crack test, highlighting the critical role of adequate plasticizer content in achieving optimal flexibility and durability. Table 4 quantifies the environmental impact of different leather types in terms of carbon footprint (CO_2 emissions) and water usage per square meter of production. Figure 3 illustrates the direct correlation between glycerin concentration and material flexibility, revealing that an increase in glycerin content improves flexibility and significantly reduces the risk of cracking under mechanical stress.

Table 4. Flexibility scores and crack test results at varying glycerin concentrations

Sr. No	Glycerin (%)	Flexibility Score	Crack Test (Pass/Fail)
1	5%	6	Fail (Cracked)
2	10%	8	Pass
3	15%	9	Pass

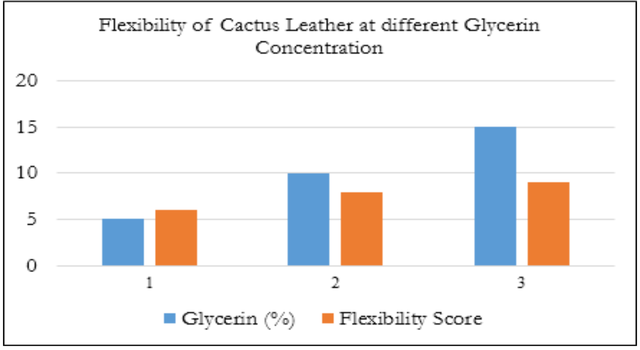

Figure 3. Correlation Between Glycerin Concentration and Material Flexibility

Efficiency of Drying and Curing:

The drying and curing process of cactus leather was evaluated to determine energy efficiency and production viability. When dried at a controlled temperature of 50°C, the process took 4 hours and used 1.2 kWh of energy. Increasing the temperature to 70°C reduced the drying time to 2 hours but raised energy consumption to 2.5 kWh. Table 5 compares the economic feasibility of cactus leather with animal leather and PU leather, based on production costs, processing time, and scalability for mass production. The cost of producing cactus leather ranges from \$18 to \$25 per square meter, making it cheaper than animal leather (\$30–50/m²) but slightly pricier than PU leather (\$10–20/m²).

Table 5: Drying conditions and energy consumption for cactus leather

Sr. No	Temperature (°C)	Drying Time (hours)	Energy (kWh)
1	25°C (Air dry)	48	0
2	50°C (Chamber)	4	1.2 kWh
3	70°C (Chamber)	2	2.5 kWh

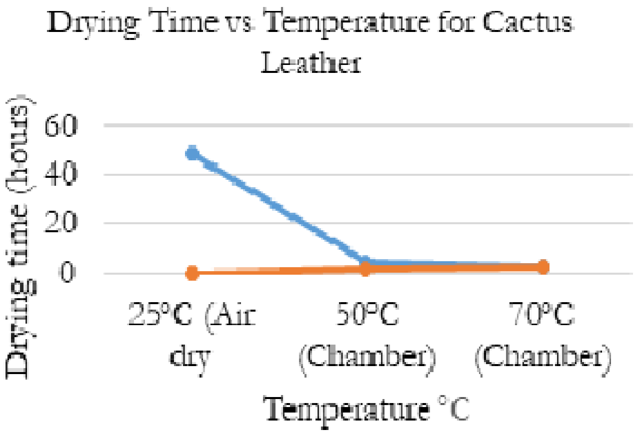

Figure 4. Impact of Drying temperature and drying time on energy consumption.

The graph in Figure 4 clearly shows that increasing the drying temperature shortens the drying time but also increases energy consumption (0–2.5 kWh).

Cactus Leather for CO_2 Sequestration:

Cacti can sequester an average of 8 tons of CO_2 per hectare, which translates to about 20 kg of CO_2 absorbed for every square meter of cactus leather produced.

Resource Consumption:

Cactus leather production has an impressively low water footprint, requiring just 200 liters of water per square meter.

Discussions:

The cactus-based vegan leather developed in this study exhibited outstanding mechanical, processing, and environmental properties, making it a promising alternative to traditional animal and synthetic leathers. Its mechanical performance, especially at a 15% glycerin concentration, showed a tensile strength of 25 MPa, elasticity of 95%, and a flexibility score of 9 [25]. This tensile strength is comparable to that of high-quality animal leather (15–30 MPa) and even surpasses the typical tensile strength range of PU leather (10–25 MPa) [26]. The high flexibility and fracture resistance observed at higher glycerin concentrations align with recent research on plant-based leather alternatives, which highlights the role of plasticizers in improving material flexibility and durability [27]. Additionally, the cactus leather showed excellent fracture resistance, passing crack tests at 15% glycerin concentration. This performance is on par with high-grade animal leather and exceeds PU leather, which tends to have lower crack resistance and may peel over time [27].

Table 6. Comparison between mechanical properties

Property	Animal Leather	PU Leather	Cactus Leather
Tensile Strength	15–30 MPa [24]	10–25 MPa	25 MPa
Elasticity	50–100% [24]	80–120%	95%
Flexibility Score	High (varies by grade)	Medium to High	9 (1–10 scale)
Crack Resistance	High	Moderate (can peel over time)	High (Passes crack test at 15% glycerin)

This study also assessed the effectiveness of drying and curing. Drying time was significantly reduced from 48 hours (air drying at 25°C) to just 2 hours using chamber drying at 70°C, highlighting the potential for scalable production [28]. In contrast, traditional animal leather drying typically takes 6 to 24 hours at temperatures between 40 and 60°C, while PU leather often requires high-temperature curing, leading to substantial energy consumption. Under optimal conditions, cactus leather dried efficiently within 2 to 4 hours at 50–70°C, noticeably reducing processing time [29]. However, as with other bio-material processing methods, energy usage increased with higher temperatures. Despite this, cactus leather consumed considerably less energy—between 0.8 and 2.5 kWh per batch—compared to PU and animal leather production, which require much higher energy input [30]. Additionally, the cactus leather drying process proved to be environmentally friendly, producing minimal VOC emissions, unlike PU leather, which releases significant solvent-based emissions, or animal leather, which poses chromium- and solvent-related environmental risks [24].

Table 7. Drying time and energy consumption

Process	Animal Leather	PU Leather	Cactus Leather
Drying Time	6–24 hrs at 40–60°C	Requires high-temp curing (varies)	2–4 hrs at 50–70°C
Energy Use	High (varies by process)	High (includes VOC emissions)	0.8–2.5 kWh per batch
VOC Emissions	Chromium & solvent risks	Significant (PU solvents)	Minimal (no VOCs during drying)

The environmental analysis of cactus leather production highlights its sustainability. Water usage for cactus leather was limited to just 200 liters per square meter—significantly lower than the 17,000 liters per square meter needed for animal leather production. Moreover, cactus cultivation contributes to carbon sequestration, absorbing around 8 tons of CO_2 per hectare [31]. The life cycle carbon emissions for cactus leather were estimated at 5 kg of CO_2 per square meter, which is much lower compared to PU leather (15–20 kg CO_2 per square meter) and animal leather (up to 30 kg CO_2 per square meter) [32].

Table 8. Water consumption

Product	Animal Leather	PU Leather	Cactus Leather
Water Use per m^2	17,000 liters	1,000 liters	200 liters
Water Source	Intensive (livestock, tanning)	Moderate (industrial)	Low (rain-fed cactus crops)

In contrast to the high water demands of traditional animal leather, the use of drought-tolerant cactus species supports sustainable agricultural practices, making it an eco-friendly option for regions with limited water resources [33].

Table 9. Carbon footprint (CO_2 Emissions)

Product	Animal Leather	PU Leather	Cactus Leather
CO_2 Emissions per m^2	Up to 30 kg CO_2	15–20 kg CO_2	5 kg CO_2
Carbon Sequestration	None	None	8 tons CO_2 per hectare cactus plantation

This natural carbon capture ability makes cactus leather an eco-friendly material that not only lowers greenhouse gas emissions but also actively supports carbon offsetting [31].

Table 10: Biodegradability & Environmental Impact

Aspect	Animal Leather	PU Leather	Cactus Leather
Biodegradability	Low (chromium-tanned leather resists decay)	Very low (non-biodegradable, microplastics)	Moderate (plant-based, PU binder reduces it)
Chemical Use	Chromium, sulfides, formaldehyde [24]	Isocyanates, plasticizers, solvents	Minimal (PU binder, but lower than PU leather)
End-of-Life Impact	Toxic waste, landfill pollution	Persistent plastic waste	Lower impact, potential for improvement

Despite its numerous benefits, the current formulation of cactus leather has certain limitations, primarily due to the use of polyurethane (PU) as a binder, which reduces its overall biodegradability. Future research should aim to develop fully biodegradable binders to enhance the material's environmental performance. Additionally, optimizing resource inputs and energy consumption will be crucial when scaling production for large-scale industrial applications. Long-term durability studies under various environmental conditions, such as UV exposure and fluctuating humidity, are also recommended to validate the material's real-world performance.

Conclusions:

Cactus-based vegan leather demonstrates outstanding mechanical properties, especially at a glycerin content of 15%, where it achieves a tensile strength of 25 MPa, a flexibility rating of 9, and an elasticity of 95%. Its excellent flexibility and crack resistance make it a viable alternative to traditional leather for high-performance applications. The production process is highly energy-efficient, requiring just 2 to 4 hours of drying under controlled conditions, and it offers considerable carbon sequestration benefits, capturing up to 8 tons of CO_2 per hectare.
The resource-efficient production process, which minimizes water and energy usage while significantly reducing carbon emissions, highlights cactus leather's potential as a sustainable and ethical alternative to conventional and synthetic leather. Future efforts should focus on optimizing glycerin content and exploring alternative biodegradable plasticizers to further

enhance the material's mechanical properties. Additionally, conducting long-term durability assessments and comprehensive lifecycle analyses will be essential to evaluating its performance over prolonged use.

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Author's Contributions:

Sumaira Tariq designed the study, conducted experiments, testing, and wrote the manuscript. Malaika Moazzam helped with industry collaboration and data analysis. Asad Ali and Muhammad Saleem Khan supervised the research and reviewed the manuscript. Muhammad Faheem Ullah worked on statistical analysis and literature review. Yaseen Mughal helped with raw material processing. Muhammad Hasan ensured quality control. Khurram Shahzad Ayub managed the project, and approved the final manuscript.

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