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Vegan Leather and Environmental Impact: Alternatives, Innovations, and a Case Study on Cactus Leather

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Abstract
This research examines the environmental implications of traditional animal leather and compares them with emerging plant-based alternatives specifically cactus-derived leather and kombucha SCOBY (bacterial cellulose) leather. Through an in-depth life cycle assessment (LCA) of Desserto's cactus leather as a case study, the paper evaluates greenhouse gas emissions, water usage, biodegradability, and socio-economic implications. Additionally, we review kombucha-derived leather production methods and their mechanical suitability. Results indicate that cactus leather offers significant reductions in carbon footprint and water consumption, while SCOBY leather shows promise as a biodegradable biomaterial. We highlight challenges such as PU coatings, scalability, and durability and make recommendations for future research, policy interventions, and equitable implementation in sustainable fashion.
Keywords: *Vegan Leather, Sustainable materials, Environmental impact, Biodegradable textiles.*

I. INTRODUCTION

Leather production is associated with high environmental costs: deforestation, methane emissions, toxic tanning effluents, and animal welfare concerns. Vegan leather synthetic or plant-based has emerged as an alternative, but many synthetic pleathers rely on fossil-based polymers like PVC or polyurethane (PU), which are not biodegradable and contribute to microplastic pollution. Recently, plant-based leathers sourced from unconventional biomaterials such as cactus (Opuntia spp.) and kombucha SCOBY have gained traction as more sustainable options.

This paper aims to (1) compare environmental impacts of animal leather vs. cactus and SCOBY alternatives using LCA data, (2) present a real-world case study of Desserto cactus leather's production and sustainability metrics, (3) analyze the material properties, challenges, and scalability of kombucha-derived leather, and (4) propose policy and ethical frameworks to ensure equitable, low-impact adoption.

2. Environmental Impact of Traditional Leather

Conventional cow leather emits approximately 60 kg CO eq/m^2, with high water usage and toxic chemical inputs from tanning processes. Additionally,$_2$ the livestock sector contributes significantly to deforestation and biodiversity loss. These profound environmental burdens justify the search for more sustainable alternatives. According to data from Climate Plus and others, tanning chemicals and livestock feed production exacerbate these impacts across the supply chain.

3. Cactus Leather (Desserto): Case Study

Desserto, a Mexican company founded in 2019, produces vegan leather from the *Opuntia ficus-indica* (nopal cactus), a plant native to Mexico that thrives in semi-arid regions. The production process is notably sustainable, mature leaves are harvested without damaging the core plant, and the cactus requires no irrigation, pesticides, or herbicides, making it well-suited to low-resource agricultural systems (Collective Fashion Justice, 2023).

According to Desserto's ISO 14040/44-aligned life cycle assessment (LCA), their cactus leather emits approximately 1.4 kg CO eq/m^2, compared to around 60 kg CO eq/m^2 for traditional cow leather. Water usage is drastically$_2$ lower as well just 0.02 m^3/m^2, versus$_2$ 33 m^3/m^2 used in the production of bovine leather (Collective Fashion Justice, 2023). In fact, the cactus plantation maintained by Desserto is described as carbon-negative, reportedly absorbing more than 8,100 tonnes of CO annually through photosynthesis and regenerative farming techniques
(Collective Fashion$_2$ Justice, 2023).

In terms of material performance, Desserto leather is flexible, lightweight, and durable, with an estimated lifespan of eight to ten years, making it suitable for use in fashion, accessories, and interior design.

However, the product includes a biodegradable polyurethane (PU) coating, which though advertised as more eco-friendly than conventional plastics raises questions regarding its true compostability and the environmental impact at end-of-life stages (Collective Fashion Justice, 2023).

Desserto has successfully collaborated with major global brands including H&M, Everlane, Karl Lagerfeld, and BMW, integrating cactus leather into both fashion and automotive sectors. Through these partnerships, the company positions itself within a circular economy framework, promoting renewable raw materials and reduced dependency on animal and fossil-based inputs (Collective Fashion Justice, 2023).

4. **Kombucha SCOBY Leather**

Another innovative vegan leather alternative is derived from kombucha, a fermented tea that produces a Symbiotic Culture of Bacteria and Yeast (SCOBY). This SCOBY biofilm, once harvested and dried, creates a bacterial cellulose sheet with a texture and pliability comparable to lightweight leather (Mohay et al., 2021).

The production of kombucha leather requires minimal energy and water, particularly when the feedstock for fermentation is food waste or brewery by-products, making it highly sustainable in terms of resource efficiency (Mohay et al., 2021). Importantly, the resulting leather-like material is completely biodegradable and non-toxic, making it an attractive alternative in a circular materials economy.

While kombucha leather offers exceptional environmental benefits, it currently suffers from low mechanical durability. Researchers have attempted to improve its strength and flexibility by incorporating plant-derived binders, natural plasticizers like glycerol, and soy or mushroom-based composites, with some success (Wjunow et al., 2023). These modifications have extended its usability for accessories, wallets, artwear, and small leather goods, though its fragility still limits its application in footwear or industrial upholstery (Mohay et al., 2021).

Educational and experimental projects such as those undertaken by Queensland University of Technology (QUT) and European design institutes have demonstrated growing interest in kombucha textiles for use in interactive fashion, biodegradable packaging, and even wearable electronics due to the nanocellulose structure of the SCOBY film (Vidya Journal, 2022). Despite its promise, kombucha leather is not yet industrially scalable, and it requires controlled environmental conditions for fermentation and drying. However, its DIY accessibility, low input needs, and full biodegradability make it a valuable candidate for further research and small-batch sustainable fashion innovation (Mohay et al., 2021; Vidya Journal, 2022).

Comparative Environmental Analysis

Material	CO eq (kg/m^2)$_2$	Water Use (m^3/m^2)	Biodegradability	Mechanical Durability
Cow Leather	˜ 60	˜ 33	No	High
PU Synthetic Leather	˜ 5.6	Low	No	Moderate
Cactus Leather	˜ 1.4	˜ 0.02	Partial (PU - based)	High
Kombucha SCOBY Leather	<2 (est.)	Very Low	Yes (fully biodegradable)	Low to Moderate (prototype)

6. **Comparative Environmental Analysis**

The environmental advantages of vegan leather alternatives particularly cactus leather and kombucha SCOBY leather stand in sharp contrast to the well-documented ecological costs of conventional animal leather and fossil-based synthetics.

Animal leather production generates significant greenhouse gas emissions, with lifecycle studies estimating 60 kg CO eq per square meter, alongside extensive water consumption (~33 m^3/m^2) and toxic waste from$_2$ chromium-based tanning (Climate Plus, 2021; Collective Fashion Justice, 2023). PU-based synthetic leathers fare slightly better in terms of emissions, averaging around 5.6 kg CO eq/m^2, but still rely heavily on non-renewable petrochemicals, and lack biodegradability,$_2$ contributing to long-term microplastic pollution (Good On You, n.d.).

In contrast, Desserto's cactus leather records a remarkably low 1.4 kg CO eq/m^2 and 0.02 m^3/m^2 water use, positioning it as 97% lower in emissions and over 1,600 times more$_2$ water-efficient than cow leather (Collective Fashion Justice, 2023). Its partial PU content, however, complicates full biodegradability and limits composting options.

Kombucha leather, meanwhile, is estimated to emit less than 2 kg CO eq/m^2 and uses very minimal water, especially when grown from food waste substrates (Mohay$_2$ et al., 2021). Most importantly, it is entirely biodegradable, making it superior in terms of end-of - life sustainability. However, its current limitations include lower tensile strength and shorter durability, which restrict its practical application in high-stress use cases such as footwear or furniture (Vidya Journal, 2022).

Below is a side-by-side comparison of key indicators:

Material	CO eq ($kg/m^2{}_2$)	Water Use (m^3/m^2)	Biodegradability	Mechanical Durability	
Cow Leather	~ 60	~ 33	No	High	
PU Synthetic Leather	~ 5.6	Moderate	No	Moderate	
Cactus Leather	~ 1.4	~ 0.02	Partially (PU-based)	High	
SCOBY Leather	<2 (est.)	Very Low	Fully	Moderate Use Cases)	(Limited

Sources: Collective Fashion Justice (2023), Mohay et al. (2021), Climate Plus (2021), Vidya Journal (2022)

7. **Challenges and Limitations**

Despite the promise shown by cactus leather and kombucha SCOBY leather as sustainable alternatives, both materials face critical limitations that hinder their widespread adoption and long-term viability in the mainstream market.

Durability and Mechanical Limitations

One of the most significant technical barriers to the adoption of SCOBY-derived leather is its limited tensile strength. While bacterial cellulose is lightweight and flexible, it lacks the abrasion resistance and structural robustness necessary for heavy-duty applications such as footwear, outerwear, or upholstery (Mohay et al., 2021). Although researchers have attempted to reinforce the material through blending with glycerol, soy proteins, or mushroom-based polymers, its current mechanical properties restrict its use to low-stress contexts, such as wallets, wearable art, and biodegradable packaging (Vidya Journal, 2022). Until these strength limitations are resolved, SCOBY leather is unlikely to replace animal leather or synthetics in demanding fashion or industrial applications.

1. **Polyurethane (PU) Content in Cactus Leather**

While cactus leather, such as that produced by Desserto, is promoted as a plant-based solution, it is not entirely free from synthetic additives. Most commercial formulations incorporate a polyurethane (PU) coating or binder to enhance flexibility, durability, and water resistance. In some cases, PU content may comprise up to 60% of the total product weight (Good On You, n.d.). Although manufacturers claim the use of biodegradable PU, these polymers typically degrade only under controlled industrial composting conditions and may still contribute to microplastic pollution if disposed of improperly. The inclusion of PU raises transparency concerns, as products are often marketed as "100% plant-based" without full disclosure of their chemical composition (Collective Fashion Justice, 2023).

2. **Cost and Accessibility**

The premium pricing of vegan leather alternatives is another substantial limitation. Due to small-scale production, specialized processing, and limited distribution channels, both cactus and SCOBY leathers tend to be significantly more expensive than their animal-based or synthetic counterparts (Ellen MacArthur Foundation, 2021). This high cost creates barriers to accessibility, particularly in low- and middle-income markets, and risks reinforcing the notion that sustainability is a luxury rather than a necessity. For these materials to have widespread environmental impact, their pricing must become competitive and scalable.

3. **Lack of Regulatory Standards and Certification**

Currently, there is no global regulatory framework or certification system for what qualifies as "vegan leather." This regulatory vacuum has led to inconsistent terminology, where products labeled as "vegan," "eco," or "plant-based" vary widely in composition, durability, and environmental performance (Good On You, n.d.). Furthermore, lifecycle data is often provided by manufacturers without third-party verification, making it difficult for consumers and businesses to make informed decisions. The absence of standardized lifecycle assessments (LCAs), compostability tests, and eco-labeling protocols contributes to a landscape vulnerable to greenwashing and misinformation (Mohay et al., 2021; Collective Fashion Justice, 2023).

8. Recommendations and Future Directions

To advance the adoption of plant-based leather alternatives while minimizing environmental trade-offs, several strategic actions are recommended:

1. Standardized lifecycle assessments (LCAs) should be required across all commercial vegan leather products. Independent, peer-reviewed LCAs using ISO 14040/44 standards can ensure comparability of claims and identify areas for material improvement (Collective Fashion Justice, 2023).
2. Transparent labeling systems must be implemented to disclose the exact composition of vegan leathers, including the proportion and biodegradability of any synthetic polymers used (Good On You, n.d.). Many "plant-based" leathers still contain up to 65% fossil-based PU, which can mislead ethically conscious consumers.
3. Investment in materials research is essential to enhance the durability and mechanical properties of kombucha SCOBY leather. Research into bio-blending, natural reinforcement, and protein cross-linking has already shown promise in extending its use beyond accessories and prototyping (Mohay et al., 2021).
4. Circular economy models should integrate community-based production networks, especially in rural areas where cactus or fermentation-based materials can be cultivated using low-input systems. Such integration promotes not only environmental resilience but also economic inclusion and skill development (Ellen MacArthur Foundation, 2021).
5. Finally, policy incentives such as tax credits for sustainable material use, R&D subsidies, and export support for ethical bio-leather producers would accelerate industry transition while protecting artisans and small producers from being excluded in the shift toward biomaterial futures.

9. CONCLUSION

The fashion and materials industries are at a crossroads, compelled by the dual pressures of environmental degradation and consumer demand for ethical alternatives. Traditional leather, long prized for its durability and aesthetics, is increasingly scrutinized for its carbon footprint, toxic processing, and reliance on animal agriculture (Climate Plus, 2021). While synthetic leather has emerged as a substitute, it remains tethered to fossil-based inputs and microplastic pollution, falling short of ecological ideals (Good On You, n.d.).

Plant-based leathers, such as cactus leather from Desserto and kombucha SCOBY leather, offer a compelling path forward. Cactus leather demonstrates measurable reductions in greenhouse gas emissions and water use, while maintaining industry-grade performance. SCOBY leather, meanwhile, excels in biodegradability and embodies principles of circularity and low-tech innovation (Mohay et al., 2021; Collective Fashion Justice, 2023).

However, both face limitations in terms of mechanical durability, polymer transparency, and scalability. These must be addressed through cross-sector collaboration, policy reform, and continued scientific innovation. If guided by a justice-centered framework, one that includes environmental sustainability, economic equity, and cultural respect, the vegan leather revolution can move beyond trend to become a systemic material transformation.

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