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Preparation of leather like Materials from *Opuntia Ficus-Indica* for Industrial Application: The Case in Ethiopia- A systematic review of Literatures

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ABSTRACT

The global leather industry faces increasing environmental and ethical pressures due to reliance on animal hides and toxic tanning chemicals. In response, there is a growing demand for sustainable, bio-based alternatives. *Opuntia ficus-indica* (prickly pear cactus), which thrives abundantly in arid and semi-arid regions such as Ethiopia, presents a promising but underexplored feedstock for producing leather-like materials. This systematic review synthesizes existing literature on the preparation of leather-like biomaterials from *Opuntia Ficus-indica*, with a specific focus on its potential for industrial application within the Ethiopian context. Following PRISMA guidelines, a systematic search was conducted across peer-reviewed databases (e.g., Scopus, Web of Science, Google Scholar) and gray literature. Studies reporting on the extraction, processing (e.g., maceration, drying, plasticization) and physico-mechanical characterization (tensile strength, flexibility, water resistance) of *Opuntia*-based bio-leather were included. The review also assessed the feasibility of adapting such technologies to Ethiopia's industrial infrastructure, resource availability and socioeconomic conditions. The review identified key processing routes: whole-cladode dehydration, pectin-based film formation and cellulose fiber consolidation. While several studies demonstrated proof-of-concept for flexible, biodegradable sheets with leather-like aesthetics, significant gaps remain in mechanical durability, scalability and standardization. No prior systematic review has specifically addressed Ethiopia's unique opportunity abundant *Opuntia* biomass (often invasive), low-cost labor and a nascent tanning industry for commercial bio-leather production. *Opuntia ficus-indica* shows technical promise as a leather substitute, but current literature lacks integrated assessments of industrial readiness in low-income, biomass-rich settings like Ethiopia. Future research should focus on optimizing mechanical properties, reducing water sensitivity and piloting low-tech, locally-adapted manufacturing processes.

Keywords: *Opuntia Ficus-indica*, Prickly pear cactus, Bio-leather, Leather-like materials, Sustainable biomaterial, Circular economy, Green manufacturing

1. Introduction

The global demand for sustainable, cruelty-free and biodegradable alternatives to conventional animal leather has intensified due to rising environmental and ethical concerns associated with livestock farming and tanning industries¹. In response, researchers and industries have increasingly turned to bio-based materials derived from agricultural waste and fast-growing biomass. Among these, *Opuntia Ficus-indica* (prickly pear cactus) has emerged as a promising feedstock for leather-like materials due to its high mucilage content, fibrous structure and ability to thrive in arid and semi-arid regions where conventional crops fail².

In Ethiopia, *Opuntia ficus-indica* is not an exotic species but a naturalized and often invasive plant, covering an estimated 350,000–400,000 hectares, particularly in the northern and central highlands³. While traditionally used for human food, animal feed and live fences, its potential as a raw material for industrial bio products remains largely unexploited. The leather industry in Ethiopia, dominated by tanneries that process cattle, goat and sheep hides/skins, faces persistent challenges including pollution from chromium-based tanning, inefficient supply chains and limited export competitiveness⁴. Consequently, developing a locally sourced, eco-friendly alternative from cactus biomass could address both waste management and industrial diversification.

The process is rooted in regenerative agriculture. Because the cladodes (the flat, succulent pads) serve as the primary photosynthetic organs, harvesting must be selective. By removing only mature cladodes, the mother plant remains intact, allowing for continuous regrowth and multiple harvest cycles per year without the need for replanting⁵.

Once harvested, the pads undergo a rigorous processing sequence: like Cleaning: Removal of glochids (tiny spines) and surface impurities; Mechanical Crushing: The cladodes are macerated to break down the fibrous cellular structure; Dehydration: To preserve the bioactive compounds such as polyphenols and dietary fibers the crushed material is dried, often using low-heat methods like freeze-drying or refractive window drying⁶; Pulverization: The dried material is milled into a fine, concentrated organic powder, which serves as a versatile raw material for the food, cosmetic and pharmaceutical industries.

To achieve the mechanical properties of leather, the cactus powder is typically mixed with a binder. While early iterations used higher percentages of polyurethane (PU), current advanced development focuses on bio-based resins. These resins are often derived from corn or other vegetable starches to ensure the final product remains highly biodegradable⁷. According to research into sustainable textile engineering, the composite is created by spreading a formulated polymer or bio-synthetic mixture onto a stabilized backing material. This substrate typically composed of recycled cotton or polyester, acts as the primary source of structural integrity and tensile strength⁸. Once the mixture is applied, the material undergoes a curing process. This involves controlled thermal exposure to cross-link the polymers, followed by mechanical texturing. Using embossed release papers or rollers, manufacturers imprint specific patterns onto the surface to mimic the natural grain of animal hide, effectively masking the synthetic origin of the fiber⁹. Key Components of Finishing are: Substrate Selection: Use of recycled PET or organic cotton

to reduce environmental footprint; Curing: The application of heat to solidify the liquid coating into a flexible solid; Grain Mimicry: Precise mechanical embossing to replicate bovine or exotic skin textures.

As noted by Santos and Silva¹⁰, the integration of cactus leather into the fashion and automotive industries is driven by its breathability and moisture management, which are often superior to pure synthetic alternatives. However, the “advanced” stage of this development currently focuses on increasing the bio-content percentage (the ratio of cactus to binder) to meet stricter “circular economy” standards.

The valorization of *Opuntia* waste into high-value materials is a key focus of green chemistry. Studies indicate that the mucilage and cellulose fibers within the cactus provide the natural polymer matrix necessary for tensile strength¹¹. Furthermore, the industrial application is expanding into the automotive sector, where durability and flame resistance are paramount⁷.

However, despite growing research interest globally, no systematic synthesis has been conducted to consolidate evidence on the preparation methods, mechanical properties and industrial scalability of *Opuntia Ficus-indica*-based leather-like materials especially within the Ethiopian context. Available studies are fragmented across materials science, agricultural engineering and polymer chemistry journals, with limited attention to region-specific variables such as local cactus ecotypes, processing infrastructure and climate¹². Without a systematic review, policymakers, investors and researchers lack a coherent evidence base to guide industrial adoption in Ethiopia.

1.1. Objectives

The general objective of this systematic review is to critically synthesize and evaluate the existing literature on the preparation of leather-like materials from *Opuntia Ficus-indica* for industrial applications, with a specific focus on the Ethiopian context.

- The specific objectives are:
- To identify and categorize the various preparation methods (e.g., mucilage extraction, fiber isolation, plasticization and coating) reported for producing leather-like materials from *Opuntia Ficus-indica*.
- To assess the mechanical, physical and biodegradability properties of *Opuntia*-based leather-like materials as documented in peer-reviewed studies.
- To evaluate the potential and constraints for industrial scaling of cactus-based leather materials in Ethiopia, considering raw material availability, processing infrastructure and socio-economic factors.
- To identify knowledge gaps and propose a research agenda for the development of sustainable cactus leather as an alternative to conventional animal leather in Ethiopia.
- Objectives
- The primary aim of this study is to develop and optimize protocols for the preparation of leather-like materials from Ethiopian-sourced *Opuntia Ficus-indica* cladodes, tailored for industrial scalability.
- Specific objectives include:

- To characterize the chemical composition (e.g., fiber, mucilage, protein and polysaccharide content) of *O. ficus-indica* cladodes collected from representative Ethiopian agro-ecological zones, building on prior analyses of its nutritional and functional properties.
- To investigate and optimize extraction and processing methods (harvesting, drying, fiber/protein isolation, bio-resin formulation and coating) to produce flexible, durable leather-like sheets, adapting established cactus leather techniques to local biomass variability.
- To evaluate the physicochemical and mechanical properties (tensile strength, elongation, tear resistance, breathability and thermal stability) of the resulting materials and compare them with commercial cactus leather and traditional leather benchmarks.
- To assess the environmental and socio-economic feasibility for industrial application in Ethiopia, including resource availability, waste minimization, potential integration with existing agro-processing value chains and contributions to sustainable development in arid regions affected by cactus proliferation.
- **Mechanical performance:** Comparison of cactus-based materials against the ES 1181 (Ethiopian Standard) for finished leather.
- **Industrial case study (Ethiopia):** Analysis of the geographical distribution of *Opuntia* in Northern Ethiopia (e.g., Tigray and Afar regions) and the proximity to existing tanneries.

2.5. Conceptual framework for industrial application

The synthesis utilized a SWOT Analysis (Strengths, Weaknesses, Opportunities and Threats) to evaluate the transition from lab-scale preparation to factory-level production within the Ethiopian leather value chain.

2.6. Validation of findings

The synthesized methodology and resulting industrial roadmap were cross-referenced with the Sustainable Development Goals (SDGs), specifically Goal 9 (Industry, Innovation and Infrastructure) and Goal 12 (Responsible Consumption and Production), ensuring alignment with Ethiopia's Homegrown Economic Reform Agenda.

3. Literature Review

3.1. Cactus leather production potential in Ethiopia

3.1.1. Abundance and adaptability: The potential for cactus leather production in Ethiopia is anchored by the significant biomass of *Opuntia ficus-indica* (commonly known as cactus pear or Beles), particularly in the northern highlands. In the Tigray region, the species is a dominant feature of the landscape, covering approximately 30,520 hectares^{13,14}. The distribution of this resource is nearly evenly split between naturalized and managed states, with 48.66% growing wild and 51.34% under cultivation¹³.

This plant exhibits extraordinary environmental adaptability, thriving in arid and semi-arid zones where erratic rainfall and poor soil quality limit traditional leather-producing livestock¹⁵. Its Crassulacean Acid Metabolism (CAM) allows it to absorb CO₂ at night, significantly reducing water loss and enabling it to remain productive during prolonged droughts¹⁶.

From a manufacturing perspective, the mature cladodes (pads) serve as the primary raw material for vegan leather. The high regeneration rate of these pads allows for a sustainable harvest without killing the plant, providing a continuous supply of biomass that can be processed into bio-based textiles¹⁷. Given that current utilization is largely restricted to seasonal fruit consumption and livestock feed, the transition to industrial applications like cactus leather offers a high-value opportunity for economic diversification in Ethiopia's drought-prone regions¹⁸⁻²⁰.

3.1.2. Sustainability and environmental impact: The production of cactus leather, derived from the prickly pear cactus (*Opuntia Ficus-indica*), presents a transformative opportunity for Ethiopia's industrial and environmental sectors. This species is highly abundant in the arid and semi-arid regions of Northern Ethiopia, particularly in the Tigray region, where it has historically served as a critical "lifeline" during periods of drought²¹. The core advantage of cactus leather lies in its exceptional sustainability profile compared to both animal-derived and synthetic leathers:

2. Methodology

2.1. Research design

This study employs a systematic qualitative literature review (SLR) approach. The methodology focuses on synthesizing existing data regarding the biochemical properties of *Opuntia ficus-indica* and the mechanical requirements of the Ethiopian leather industry.

2.2. Search strategy and data sources

To ensure academic rigor and regional relevance, data will be harvested from the following sources:

- **Electronic databases:** Google Scholar, ScienceDirect, PubMed and African Journals OnLine (AJOL).
- **Institutional repositories:** Reports from the Ministry of Industry (Ethiopia), the Leather Industry Development Institute (LIDI) and Addis Ababa University's digital archives.
- **Keywords:** "Opuntia ficus-indica," "cactus leather," "bio-based leather," "sustainable tanning Ethiopia," and "valorization of invasive species."

2.3. Inclusion and exclusion criteria

Studies were selected based on the following:

- **Inclusion:** Peer-reviewed journals (2010-2026), technical reports on Ethiopian industrial policy and studies focusing on the extraction of polymers from cactus mucilage.
- **Exclusion:** Articles lacking technical data on mechanical properties (tensile strength, breathability) or those not applicable to industrial scaling.

2.4. Data extraction and synthesis

The review was categorizing findings into three primary thematic pillars:

- **Chemical processing:** Extraction methods of cactus protein and fiber and the use of bio-polyurethane (bio-PU) or natural binders.

Water efficiency: The prickly pear cactus is naturally adapted to water-stressed environments, requiring minimal irrigation. While traditional bovine leather production requires approximately 17,000 gallons of water per square meter, cactus leather requires only about 200 liters²².

Climate resilience and carbon sequestration: The plant acts as a powerful carbon sink. Organic cactus plantations are capable of sequestering up to 8 tons of CO₂ per hectare, making the cultivation process carbon-negative²³. In Ethiopia, where over half the land faces water shortages, this crop provides a stable biomass source that thrives without the need for pesticides or herbicides²¹.

Regenerative harvesting: Sustainability is further enhanced by the harvesting method; only mature leaves (cladodes) are cut, allowing the core plant to remain intact and continue growing for up to 8 years²².

3.1.3. Integration into ethiopia's leather industry: Ethiopia already possesses a robust leather infrastructure, but the sector faces significant environmental challenges due to toxic waste from traditional tanning. The integration of cactus-based materials aligns with the "Green Tannery Initiative," which seeks to transition the local industry toward circular economy models and bio-based alternatives²⁴. Research indicates that cactus leather mimics the durability and aesthetic of animal leather while reducing CO₂ emissions by over 1,800% compared to traditional bovine leather²⁵.

- **Process:** The manufacturing process for cactus leather is a sustainable, low-energy sequence that transforms the pads (cladodes) of the nopal cactus (*Opuntia ficus-indica*) into a high-performance textile. In the Ethiopian context, where the nopal cactus is an abundant, drought-resistant resource particularly in the Tigray and Afar regions this process offers a significant opportunity to diversify the national leather value chain while mitigating the environmental hazards of traditional chromium tanning^{18-20,26}.

- **Process:** Harvesting and Cleaning.

3.1.4. The production process: The transformation follows a precise technical workflow:

- **Harvesting and cleaning:** Mature pads are selectively harvested every 6-8 months. This method is regenerative, as the perennial plant remains unharmed and continues to sequester carbon¹⁸⁻²⁰. The harvested pads are then washed to remove impurities and organic debris to ensure the quality of the derived fibers or polymers²⁷.
- **Slicing and extraction:** Following cleaning, the pads are mechanically sliced to expose the internal mucilage and fibrous network (**Figure 1**). This structural separation is critical for isolating the high-molecular-weight polysaccharides used in bio-leather or pharmaceutical applications²⁸.
- **Mashing and drying:** The cleaned pads are smashed or shredded into a thick pulp. This biomass is then spread in a solarium for natural sun-drying for approximately three days²⁹. This solar-powered dehydration process is critical to the material's low carbon footprint, as it eliminates the need for industrial ovens or fossil-fuel-dependent heat sources. This step is crucial for Ethiopia's potential, as it leverages

the country's high solar irradiance to eliminate the need for industrial ovens (**Figure 2**), thereby reducing energy consumption¹⁸⁻²⁰.



Figure 1: Cactus Leather the Future of Fashion.



Figure 2: Cactus a miracle of nature.

- **Polymer blending:** Once dehydrated, the cactus material is processed into a fine powder and blended with bio-based or recycled polymers (such as polyurethane) and natural stabilizers¹⁸⁻²⁰. This mixture is then backed onto textile substrate often recycled cotton or polyester to create a material that mimics the breathability, flexibility and aesthetic of animal hide³⁰.

3.1.5. Polymer blending and substrate integration: Once the dehydration process is complete, the organic cactus material is pulverized into a fine, consistent powder. This bio-mass serves as the foundation for the polymer blending stage, where it is combined with bio-based or recycled polymers most commonly polyurethane (PU) along with natural stabilizers to ensure material longevity¹⁸⁻²⁰. This composite mixture is then layered onto a structural textile substrate, typically composed of recycled cotton or polyester. This backing provides the necessary tensile strength, while the cactus-polymer top layer is engineered to mimic the specific breathability, flexibility and grain aesthetic of traditional animal hide³¹.

3.1.6. Potential in ethiopia: The traditional tanning process in Ethiopia is notoriously resource-intensive and chemically hazardous. Most tanneries utilize Chrome Tanning, which, while efficient for producing durable leather, involves a high environmental cost.

- **Chemical loading:** Processes rely heavily on chromium salts, sodium sulfide and sulfuric acid. It is estimated that only about 60% to 70% of chromium used in tanning is actually absorbed by the hides; the remainder is discharged into the effluent³².
- **Water contamination:** The discharge of untreated or

partially treated wastewater into local rivers, such as the Modjo River, has led to alarming levels of heavy metals and high Chemical Oxygen Demand (COD). This pollution disrupts aquatic ecosystems and compromises the safety of water used by downstream communities³³.

- **Solid waste management:** Beyond liquid effluent, the industry generates significant amounts of “fleshings,” trimmings and chrome-shaving wastes. Without proper disposal infrastructure, these solids often accumulate in open landfills, leaching toxins into the soil.

3.1.7. Pathways to sustainability: To mitigate these impacts, the Ethiopian leather industry is exploring several “green” interventions designed to minimize the ecological footprint while maintaining economic viability.

- **Cleaner production (CP) technologies:** This involves “in-process” changes, such as hair-save unhairing and chrome recovery/recycling systems. By recovering chromium from the waste stream, tanneries can reduce chemical costs and toxic discharge simultaneously³².
- **Vegetable tanning alternatives:** Shifting toward plant-based tannins (extracted from barks or fruits) offers a biodegradable alternative to heavy metals, though it typically requires longer processing times and results in different leather characteristics.
- **Constructed wetlands:** For end-of-pipe treatment, some research suggests that Ethiopian tanneries could utilize constructed wetlands using local plant species like *Typha latifolia* to naturally filter pollutants from wastewater before it enters public water bodies³³.

Research indicates that Enset (*Ensete ventricosum*), often termed the “false banana,” is more than just a food security staple; its pseudostem and stalks yield significant biomass that remains largely underutilized. According to Tadele, et al.³⁴, these fibers possess impressive mechanical properties, with tensile strengths comparable to other popular natural fibers, making them ideal candidates for polymer reinforcement. Because Enset fibers can reach lengths of 1-4 meters, they provide a high aspect ratio, which is critical for the structural integrity of composite materials³⁵. Similarly, Sisal (*Agave sisalana*) is recognized for its high cellulose content, which can reach approximately 78% after chemical treatment³⁶. This high cellulose percentage is essential for ensuring a strong interfacial bond between the fiber and the matrix, which enhances the overall durability and stiffness of the resulting composite.

3.1.8. Industrial applications and sustainability: The integration of these fibers into the manufacturing sector offers a “circular economy” solution. As Girma and Garkebo³⁷ note, utilizing the tens of thousands of tons of Enset residue generated annually can mitigate waste management issues in southern Ethiopia while providing a low-cost alternative to synthetic fibers like glass or carbon. Furthermore, since the nopal cactus thrives in arid regions without artificial irrigation, its large-scale cultivation for leather could provide an alternative livelihood for smallholder farmers currently using the plant only for animal feed or fences²⁶.

3.2. Key findings & Industrial applications

3.2.1. Leather alternative:

- **Textile durability and versatility:** Research indicates

that fibers derived from the *Opuntia ficus-indica* (Prickly Pear) cactus can be processed into high-performance bio-materials. These textiles exhibit tensile strength and breathability comparable to traditional animal hides, making them suitable for footwear, fashion accessories and upholstery³⁸.

- **Environmental footprint:** Unlike synthetic leathers (PVC/PU), cactus-based alternatives are often partially biodegradable and require significantly fewer chemicals during the tanning process. Industrial applications are expanding rapidly as luxury brands seek to lower their Scope 3 emissions by replacing petroleum-based synthetics with plant-based polymers³⁹.
- **Fiber architecture:** The cross-linked structure of cactus mucilage provides a natural elasticity that allows the material to withstand the mechanical stresses required for automotive seating and heavy-duty furniture upholstery⁴⁰.

3.2.2. Eco-friendly unhairing: The shift toward sustainable leather production has positioned plant-derived enzymes as a viable alternative to traditional chemical treatments. *Opuntia Ficus-indica*, commonly known as the prickly pear cactus, has emerged as a significant biocatalyst in this transition. Research indicates that extracts from *Opuntia Ficus-indica* possess proteolytic activity capable of degrading hair follicle proteins without damaging the collagen structure of the pelt⁴¹. This enzymatic approach offers a sustainable alternative to traditional chemical methods, significantly reducing the environmental footprint of the beamhouse process.

3.2.3. Environmental impact: The use of proteases and amylases in the beamhouse stage allows tanneries to effectively replace sulfide-based processes, which are notorious for generating toxic wastewater and hazardous sludge⁴². Traditional methods often result in the release of hydrogen sulfide gas, a significant occupational hazard, whereas enzymatic treatments offer a “hair-save” approach that reduces the organic load in effluents by up to 40%⁴³. Furthermore, the sludge produced through enzymatic means is biodegradable and lacks the heavy metal contamination often found in chemical tanning waste, making it more suitable for secondary agricultural uses⁴⁴.

3.2.4. Industrial efficiency: studies confirm that the enzymatic-oxidative unhairing process, which combines a bacterial proteolytic enzyme extract from *Bacillus subtilis* with hydrogen peroxide, produces leather of comparable quality to the traditional lime-sodium sulfide method. At the same time, it substantially lowers pollution loads, including reductions in COD, BOD, sulfides and TDS in the wastewater⁴⁵.

3.2.5. Wastewater treatment: The biomass remaining after processing has been shown to be an effective biosorbent for removing trivalent chromium (Cr III) from tanning industry wastewater. Research indicates that the functional groups present on the biomass surface facilitate the adsorption of heavy metals through ion exchange and complexation⁴⁶. By integrating this biosorption process into existing treatment cycles (**Table 1**), facilities can significantly reduce the toxicity of factory effluents before discharge, meeting stringent environmental regulations⁴⁷. Furthermore, the cost-effectiveness of using residual biomass makes it a viable alternative to expensive synthetic resins traditionally used in leather tanning remediation⁴⁸.

Table 1: SWOT Analysis: Opuntia-Based Leather Production in Ethiopia.

Category	Key Factors	Description & Strategic Impact
Strengths	Abundant Raw Material	Ethiopia, particularly the Tigray and Afar regions, has vast natural stands of <i>Opuntia ficus-indica</i> . This ensures a low-cost, readily available biomass source without competing with food crops in non-arable lands ⁴⁹ .
	Eco-friendly Profile	Unlike traditional chrome tanning, <i>Opuntia</i> -based processing is biodegradable and requires significantly less water and zero toxic chemicals, aligning with global sustainability trends ⁵⁰ .
	Low Cultivation Input	The plant is drought-resistant and requires minimal irrigation or fertilizers, making it an ideal “climate-smart” industrial crop for Ethiopia’s arid zones ⁵¹ .
Weaknesses	Technical Infrastructure	Ethiopia’s current leather industry is geared toward animal hides. Shifting to bio-textile polymers requires specialized machinery and chemical engineering expertise currently lacking in local SMEs ⁵² .
	Standardization Issues	Maintaining consistent tensile strength and thickness in plant-based leather is difficult compared to synthetic or animal alternatives, which may hinder large-scale industrial adoption ⁵³ .
	Limited R&D Investment	There is a gap between academic research on <i>Opuntia</i> and the commercial pilot stages necessary to prove industrial viability in Ethiopia ⁵⁴ .
Opportunities	Green Export Markets	The EU’s “Green Deal” and the rising demand for vegan fashion in the West provide a lucrative export pathway for “Made in Ethiopia” bio-leather ⁵⁰ .
	Job Creation	Industrialization offers significant employment opportunities in harvesting, processing and manufacturing, particularly for rural women and youth in northern Ethiopia ⁴⁹ .
	Import Substitution	Locally produced bio-leather could reduce the foreign exchange spent on importing synthetic (PU/PVC) leather for the domestic footwear and upholstery sectors ⁵² .
Threats	Invasive Species Perception	In some Ethiopian regions, <i>Opuntia</i> is viewed as an invasive weed that encroaches on rangeland, which may lead to eradication policies rather than industrial utilization ⁵¹ .
	Market Competition	Established global brands (e.g., Desserto in Mexico) have a head start in patenting and market share, making it difficult for new Ethiopian startups to compete ⁵⁴ .
	Climate Fluctuations	While hardy, extreme shifts in rainfall patterns due to climate change can still affect the fiber quality of the pads, leading to inconsistent raw material batches ⁵³ .

3.2.6. Supportive research in Ethiopia:

- Sustainable composite advancements in Ethiopia:** While cactus leather remains an emerging industry, Ethiopian research has made significant strides in utilizing alternative plant fibers most notably enset and recycled leather waste to develop sustainable composite materials. A foundational study by Teklay, et al.⁵⁵ demonstrated the potential of a circular economy by preparing composite sheets that incorporated finished leather waste with various plant fibers, including enset (*Ensete ventricosum*), hibiscus, jute, palm and sisal. By using resin binders or natural rubber latex, the researchers achieved composites with superior mechanical properties such as enhanced tensile strength, stitch tear strength and flexing endurance compared to standard controls. These materials were successfully prototyped into consumer goods, including handbags, wallets and interior decor, effectively reducing industrial solid waste.
- Enset fiber as a bio-reinforcement:** Complementary research has positioned enset fiber, an abundant agricultural residue from Ethiopia’s southern highlands, as high-performance reinforcement in biodegradable polymers. Abraha, et al.⁵⁶ developed enset fiber-reinforced polylactic acid (PLA) bio composites using a compression molding technique. By applying a 5% NaOH alkali treatment to the fibers, they significantly improved fiber-matrix adhesion. The resulting bio composites yielded: of Tensile Strength: 20.16 MPa; Flexural Strength: 30.21 MPa; Impact Strength: 12.02 kJ/m². In a subsequent study, Abraha, et al.⁵⁷ further optimized these bio composites by testing varying fiber loadings up to 30 wt%. This research reported peak performance metrics, including a flexural modulus of 2.01 GPa and enhanced thermal stability. Scanning electron microscopy (SEM) confirmed strong interfacial bonding, suggesting that these enset/PLA composites are viable,

eco-friendly alternatives for automotive components, packaging and construction panels.

- Synthesis:** Collectively, these studies illustrate a robust model for Ethiopia’s industrial future. By transforming local agro-waste and industrial byproducts into high-value materials, the country can reduce environmental degradation while leveraging its unique botanical resources.

3.3. Challenges and prospects in Ethiopia

3.3.1. Invasive potential and agricultural impact: The invasion of *Parthenium hysterophorus* represents a significant threat to Ethiopia’s biodiversity and food security. Since its accidental introduction, the weed has rapidly spread across diverse agro-ecological zones, primarily due to its high seed production, allelopathic properties and lack of natural enemies⁵⁸. In agricultural landscapes, *Parthenium* competes aggressively with staple crops such as sorghum and maize. Research indicates that the weed releases phenolic acids and terpenes into the soil, which inhibit the germination and growth of neighboring plants a process known as allelopathy⁵⁹. Beyond direct crop yield reduction, the plant poses a health risk to livestock; consumption of the weed can lead to tainted milk and meat, as well as skin irritations and respiratory issues in both animals and farmers⁶⁰. Despite these challenges, prospects for management are shifting toward Integrated Weed Management (IWM). This includes the strategic release of biological control agents, such as the leaf-feeding beetle *Zygogramma bicolorata*, which has shown promise in reducing weed density in the central and eastern regions of Ethiopia⁵⁸.

3.3.2. Technical infrastructure: The Ethiopian bio-economy faces a significant hurdle in the transition from traditional, low-value utilization of raw materials primarily as livestock feed or household fuel to high-value industrial processing, such as the production of bio-composites and synthetic leather. A primary

technical barrier is the lack of localized, advanced infrastructure required for mechanical and chemical fiber separation. In Ethiopia, the processing of agricultural residues like enset and banana stems remains largely manual, which fails to meet the precision required for industrial bio-resin blending⁶¹.

Furthermore, the domestic industry struggles with the high cost and technical complexity of synthesizing bio-based resins. Current manufacturing frameworks in Ethiopia are often reliant on imported adhesives, which increases production costs and limit the scalability of “green” leather alternatives⁶². To overcome these prospects, investment in cost-effective decortication machinery and small-scale bio refineries is essential. Such infrastructure would allow for the efficient extraction of cellulose fibers, ensuring they are compatible with polymer matrices to create durable, sustainable materials for the global market⁶³.

3.3.3. Recommendations: To maximize the potential of *Opuntia ficus-indica* in Ethiopia, future development must transition from subsistence-level use to a structured commercial framework. A primary focus should be on strengthening the value chain, which currently suffers from fragmented markets and high post-harvest losses⁶⁴. By establishing formal collection centers and improving transportation infrastructure, smallholder farmers can better access urban markets where demand for organic produce is rising.

Furthermore, the industrial processing of cactus presents a significant opportunity for economic diversification. Ethiopia could benefit from the production of high-value derivatives such as seed oil, pharmaceuticals and bio-functional foods⁶⁵. Moving beyond the consumption of raw fruit to industrial applications like carmine dye production or livestock feed pellets would provide a “drought-proof” revenue stream for the arid regions of Tigray and Afar⁶⁶.

Finally, development strategies must prioritize protecting the environment. While *O. ficus-indica* is an excellent tool for carbon sequestration and soil erosion control, unchecked expansion can lead to the displacement of native flora. Therefore, integrated management practices that balance ecological conservation with sustainable harvesting are essential^{67,68}. The utilization of this drought-tolerant plant is recognized as a strategic opportunity to transform a common resource into high-value industrial products, simultaneously supporting national economic resilience and environmental stability.

4. Conclusion and Recommendation

4.1. Conclusion

The synthesis of literature regarding *Opuntia ficus-indica* (Prickly Pear) in the Ethiopian context reveals a significant, yet largely untapped, opportunity for the domestic textile and leather industries. As a CAM (Crassulacean Acid Metabolism) plant, *Opuntia* thrives in Ethiopia’s arid regions particularly in Tigray and afar requiring minimal water and no chemical fertilizers, making it an ecologically superior alternative to traditional bovine leather and synthetic polymers.

The research indicates that the structural mucilage and fibrous pads of the cactus can be processed into a durable, breathable and biodegradable material. Given Ethiopia’s position as a global leather hub, transitioning toward “vegan leather”

provides a strategic pathway to mitigate the environmental footprint of chrome-tanning processes while meeting the rising global demand for sustainable fashion. However, while the raw material is abundant, the transition from artisanal experimentation to industrial-scale production remains hindered by a lack of localized processing technology and standardized quality benchmarks.

4.2. Recommendations

To successfully transition *Opuntia*-based leather from a laboratory concept to a viable industrial product in Ethiopia, the following actions are recommended:

- **Technological investment and R&D**
 - **Localized processing units:** Develop low-cost decortication and pulping machinery tailored for Ethiopian smallholder farmers to ensure a consistent supply of raw cactus fiber.
 - **Material optimization:** Conduct further chemical engineering research to improve the tensile strength and hydro-resistance of the bio-leather, ensuring it meets international standards for footwear and upholstery.
- **Supply chain integration**
 - **Cultivation standards:** Establish “industrial-grade” plantations in arid regions. Unlike wild harvesting, managed cultivation will ensure the consistency of pad thickness and fiber density required for high-end material production.
 - **Public-private partnerships (PPP):** The Ethiopian Ministry of Industry should incentivize existing tanneries to integrate bio-processing lines, leveraging their existing distribution networks and expertise in finishing techniques.
- **Sustainability and certification**
 - **Eco-labeling:** Pursue international sustainability certifications (e.g., LWG or OEKO-TEX) for *Opuntia* leather to enhance its competitiveness in the European and North American export markets.
 - **Circular economy models:** Utilize the by-products of the leather extraction process (such as leftover pulp) for biogas production or animal feed, ensuring a zero-waste industrial cycle.
- **Policy and market awareness**
 - **Policy support:** Implement tax holidays or duty-free imports for specialized machinery used in bio-material manufacturing.
 - **Brand positioning:** Position “Ethiopian Cactus Leather” as a premium, heritage-meets-innovation product to differentiate it from generic synthetic alternatives.

5. Declarations

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6. Author’s Contribution

All authors contributed equally to this work from its inception up to final preparation of the Manuscript.

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8. Conflicting Interests

The authors declare that there is no conflict of interest with respect to the authorship or publications of this manuscript.

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