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Innovative and Sustainable Leather Processing in Ethiopia: Trends, Technologies, and Future Directions

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Abstract

The leather industry in Ethiopia plays a critical role in economic development, offering significant opportunities for export growth, employment generation, and industrial transformation. This paper examines current trends toward sustainability in Ethiopian leather processing, highlighting key initiatives such as the Green Tannery Initiative (piloting enzymatic unhairing to replace toxic chemicals and valorizing solid wastes into biofertilizers for circular economy models), the Leather Initiative for Sustainable Employment Creation (LISEC) project (promoting chrome-free tanning, improved waste management, and LWG certification for global compliance), and collaborations involving UNIDO, EU, SMEP, and local institutions. Innovative technologies driving progress include enzyme-based unhairing, cleaner production strategies (e.g., high-exhaustion chrome tanning, CO_2 deliming, and waste-to-resource conversion), adoption of eco-friendly alternatives like vegetable or metal-free tanning, digital traceability systems, and supporting infrastructure such as satellite laboratories and modern facilities in hubs like Modjo Leather City.

Despite advancements, persistent barriers remain, including limited technical capacity, financial constraints, raw material quality issues, and regulatory alignment with international standards (e.g., EU regulations and Zero Discharge of Hazardous Chemicals). The review concludes that Ethiopia's leather sector is transitioning toward greener, more competitive practices through targeted investments, technology transfer, skills development, and public-private partnerships. Future directions should prioritize scaling successful pilots, enhancing R&D (including biotechnology and digitalization), strengthening policy frameworks for environmental compliance, and fostering inclusive growth to position Ethiopia as a leader in sustainable African leather production.

Keywords: Sustainable Leather Processing, Ethiopia Leather Industry, Cleaner Production, Enzymatic Unhairing, Chrome-Free Tanning, Waste Valorization, Circular Economy, Green Tannery Initiative, LISEC Project, Eco-Friendly Technologies, Modjo Leather Cluster

1. Introduction

The leather industry in Ethiopia holds significant economic importance, leveraging the country's abundant livestock resources to position it as one of Africa's leading producers of hides and skins [1]. However, traditional leather processing methods, predominantly reliant on chrome tanning, generate substantial environmental pollution through high volumes of wastewater containing hazardous chemicals, solid wastes, and emissions that contribute to water contamination, soil degradation, and health risks in surrounding communities [1,2]. These challenges are exacerbated in developing contexts like Ethiopia, where regulatory enforcement and technological adoption lag behind global standards, resulting in severe ecological footprints despite the sector's potential for job creation and export revenue [3].

In recent years, there has been a growing shift toward innovative and sustainable approaches in leather processing globally and within Ethiopia. Emerging green technologies include enzymatic unhairing to replace sodium sulfide, plant-based or bio-based tanning agents as chromium alternatives, waste valorization for biofertilizers from solid wastes (such as fleshings and trimmings), and cleaner production strategies that reduce chemical consumption, water usage, and effluent pollution [4,5]. In Ethiopia specifically, initiatives such as the Green Tannery Initiative (piloting enzymatic processes and waste-to-fertilizer conversion), the Leather Initiative for Sustainable Employment Creation (LISEC) project promoting chrome-free tanning and LWG certification, and efforts toward eco-friendly industrial zones like Modjo Leather Park demonstrate practical advancements in reducing environmental impacts while enhancing competitiveness and inclusivity (e.g., through youth employment and women's empowerment) [1,3].

These trends align with broader global demands for sustainable supply chains and circular economy principles [6], offering Ethiopia opportunities to transition from resource-intensive practices to innovative, low-impact technologies such as enzymatic unhairing and chrome-free tanning that improve leather quality, market access, and long-term viability [7,8].

While the implementation of Green Supply Chain Management (GSCM) in Ethiopia is currently in its early stages, research indicates that institutional pressures and global export requirements are the primary drivers for local tanneries to adopt cleaner production frameworks [7,9]. Furthermore, the development of eco-industrial hubs like Modjo Leather City serves as a strategic platform for integrating waste-to-value solutions, effectively closing resource loops in accordance with circular economy models [8,10].

The objective of this paper is to:

- Examine current trends and innovative technologies in sustainable leather processing within the Ethiopian context;
- Evaluate their implementation challenges and environmental benefits; and
- Propose future directions for policy, research, and industry adoption to foster a more eco-friendly and economically resilient leather sector.

2. Methodology

This study adopts a systematic literature review (SLR) approach to synthesize existing knowledge on innovative approaches to leather processing in Ethiopia, emphasizing cleaner production, technological advancements, environmental sustainability, current trends, and future prospects.

1. Search Strategy

Mixed-methods approach combining qualitative and quantitative techniques, Focus on case studies of Ethiopian tanneries **t**o capture real-world practices, and Comparative analysis with global sustainable leather technologies were the Research Design applied. Relevant literatures were identified through comprehensive searches in major academic databases and search engines, including: Google Scholar, Scopus, Web of Science, Science Direct, Research Gate, PubMed Central (PMC) and Ethiopian institutional repositories (e.g., Bahir Dar University, Addis Ababa University).

Additional searches targeted grey literature (industry reports, UNIDO, EU-funded project documents such as LISEC and Green Tannery Initiative, LIDI publications) using keywords such as "Modjo Leather City", "LISEC Ethiopia", and "sustainable leather Ethiopia". No strict temporal restriction was applied, but priority was given to publications from 2015–2026 to capture recent innovations and Ethiopia-specific developments.

2. Inclusion and Exclusion Criteria

Inclusion criteria:

- Publications addressing leather processing technologies, innovations, sustainability challenges, or prospects in Ethiopia (or with substantial Ethiopian case studies/context).
- Peer-reviewed journal articles, conference papers, book chapters, theses, and credible technical reports.
- English-language publications (or English abstracts with key data).

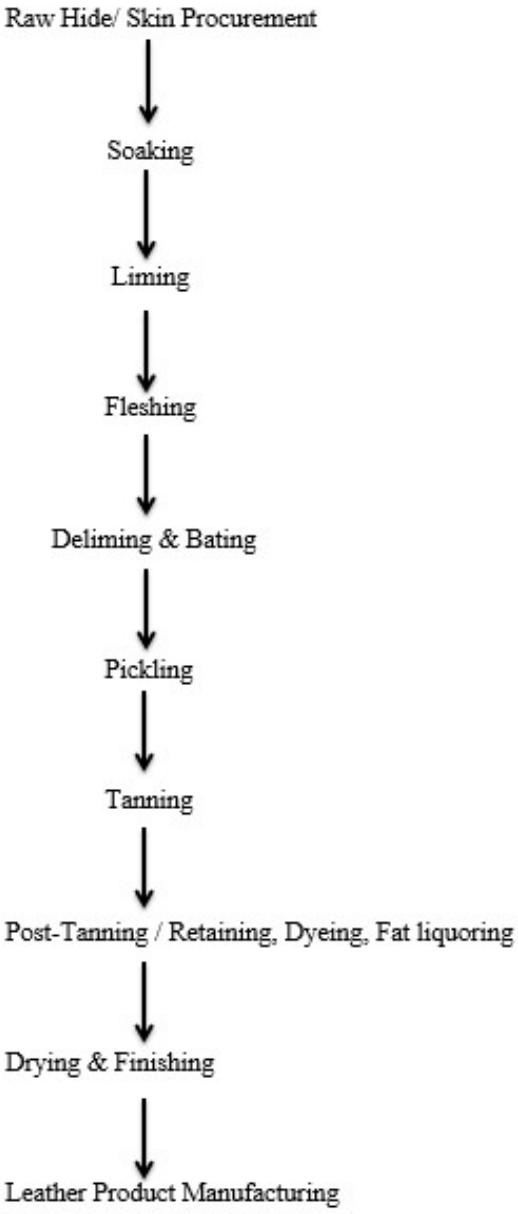
Exclusion criteria:

- Studies focused solely on downstream leather products/manufacturing without processing links.
- Non-Ethiopian contexts unless explicitly comparative or transferable to Ethiopia.
- Duplicate publications or non-substantive editorials.

Study Selection and Screening Process

- The systematic literature review followed a structured screening process aligned with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility.
- An initial search across selected databases yielded approximately **236 records**. After removing duplicates, **178 articles** remained for title and abstract screening. Based on relevance to Ethiopian leather processing and sustainability themes, **92 studies** were shortlisted for full-text review. Finally, **57 studies** were selected for inclusion in this review based on predefined inclusion and exclusion criteria.
- The screening process emphasized relevance to sustainable leather technologies, Ethiopian context applicability, and

methodological rigor. A PRISMA flow diagram is recommended to visually summarize this selection process.



Flow Process Diagram

3. Literature Review

3.1. Current Trends of the Ethiopian Leather Processing

3.1.1. Green Tanning & Waste Management

The Ethiopian leather processing industry, a key economic sector driven by the country's large livestock population, has historically relied on conventional chrome-based tanning methods that generate significant environmental pollution through hazardous chemicals (e.g., chromium, sulfides, and salts) and substantial solid and liquid waste. However, current trends show a shift toward green tanning and improved waste management, motivated by regulatory pressures, international market demands for sustainable products, and initiatives promoting cleaner production.

Tanneries in Ethiopia are increasingly adopting cleaner production methods to reduce environmental impacts. This includes efforts to minimize or eliminate hazardous chemicals such as chromium in tanning processes and sodium sulfide in unhairing. For instance, initiatives like the Green Tanning Initiative (GTI), supported by international partners, have piloted enzymatic unhairing to replace hazardous sodium sulfide, reducing pollution from the beamhouse stage, and advanced solid waste valorization technologies to convert protein- and fat-rich fleshings, trimmings, and other organic wastes into high-value products like biofertilizers. This creates a circular economy model by addressing poor solid waste management, where wastes were previously landfilled, leading to methane emissions, pathogens, odors, and organic overload in landfills and wastewater [11].

A key focus is on reducing chromium usage and pollution, as chrome tanning still dominant results in toxic effluents and solid wastes containing residual chromium, which poses risks to water bodies, soils, crops, and groundwater [12,13]. Cleaner alternatives include high-exhaustion chrome tanning to increase uptake rates (reducing effluent chromium), exploration of chrome-free or low-chrome methods (e.g., vegetable, polymeric, or bio-based tanning agents), and technologies like electro-oxidization for effluent treatment [1,12]. Salt-free curing or preservation methods are also gaining attention as part of broader cleaner strategies to avoid salt-related pollution, though adoption remains emerging compared to unhairing and tanning innovations [1].

These transitions are driven by a complex interplay of sociotechnical factors, including green design, regular supervision, site waste management plans, and enhanced regulatory compliance [2]. Practical implementation of these strategies has been demonstrated through initiatives like the Green Tanning Initiative (GTI), which has shown that Ethiopian tanneries can improve environmental performance while simultaneously creating sustainable employment opportunities [14]. Such advancements are critical for positioning the sector within global markets that increasingly demand eco-friendly leather products [15]. Overall, while significant challenges persist including limited technical capabilities, variable effluent treatment performance, and a continued reliance on chromium-based tanning processes the industry is steadily progressing toward sustainability. This evolution is being achieved through the adoption of targeted cleaner technologies and waste recovery systems, bolstered by international collaborations and the enforcement of national environmental guidelines [12,16].

3.1.2. Modernization & Industrial Parks

The development of Modjo Leather City (MLC) represents a pivotal shift in Ethiopia's industrial strategy, moving from fragmented, traditional tanning operations toward a centralized, eco-industrial hub model. As the host to approximately 80% of the country's tanneries, Modjo has historically faced severe ecological strain [17]. The MLC project, supported by international partners such as UNIDO and the European Union's LISEC initiative, aims to mitigate these impacts by providing a shared, modern infrastructure for Common Effluent Treatment Plants (CETP) and chrome recovery systems [18,19].

This concentration of production is designed to achieve several strategic objectives:

- **Environmental Sustainability:** By implementing "Green Tannery" initiatives, such as enzymatic unhairing and waste-to-value circularity, the MLC aims to replace hazardous sodium-sulphide processes with eco-friendly alternatives [11].
- **Foreign Direct Investment (FDI):** The Park serves as a "plug-and-play" environment for global investors. Currently, over 75% of the tanneries in the Modjo cluster are powered by FDI, which facilitates technology transfer and enhances the industry's competitiveness in the global market [17].
- **Operational Efficiency:** Centralisation reduces logistics costs and allows for specialized services, such as shared chemical storage and dedicated leather training centers, to be accessible to all resident firms [20,21].

Despite its promise, the transition to this modernized hub faces challenges related to the "polluter pays" principle and the high

cost of relocating existing urban tanneries into the industrial district [18,22]. However, recent empirical data suggests that these parks are essential for Ethiopia to meet international sustainability certifications, which are increasingly required for high-value leather exports to Europe and North America [11,23].

3.1.3. Shift towards High-Value Products

The Ethiopian leather processing industry has undergone a notable transformation in recent years, with a clear policy-driven shift towards high-value products. Historically, Ethiopia exported primarily raw hides and skins or semi-processed leather (such as wet-blue or crust), which captured limited economic returns due to low value addition. Government interventions, including export bans and high taxes (up to 150%) on raw and semi-processed hides since around 2008–2012, aimed to discourage raw exports and promote domestic processing into finished leather and manufactured leather garments, leather goods, gloves and footwear products [24,25].

This policy has encouraged a move away from low-value raw material exports toward finished leather products, including shoes, jackets, bags, gloves, and other garments. The emphasis is on increasing economic returns by capturing higher margins through value addition within the country, fostering job creation, and boosting export earnings from manufactured items rather than commodities [26,27]. The shift from low-value raw materials to high-value manufactured goods is a hallmark of Ethiopia's Growth and Transformation Plans (GTP I and II). Scholars note that while the country possesses one of the largest livestock populations in Africa, the quality of "crust" leather often suffers due to poor animal husbandry and pre-slaughter defects [28].

Despite these hurdles, the footwear sub-sector has emerged as a primary driver of export growth. This is largely attributed to the influx of Foreign Direct Investment (FDI), particularly from East Asian firms operating within specialized industrial parks. However, the "raw material paradox" persists: firms often struggle to source high-quality local leather, forcing a reliance on imported chemicals and semi-processed skins, which diminishes the intended competitive advantage of local sourcing [29].

Recent trends reinforce this direction: Ethiopia's leather sector increasingly focuses on sustainable, chrome-free finished products and manufactured goods for international markets, including Europe, with companies producing shoes, bags, jackets, and accessories [30]. Investments, including foreign direct investment (FDI) in integrated facilities (e.g., footwear factories); support this shift, positioning Ethiopia as a potential hub for high-value leather items. Ethiopia's leather and leather products sector has long been prioritized under national industrial policies, with efforts since the early 2000s to move beyond raw material exports toward value-added manufacturing [31]. A key driver of this transition has been targeted FDI attraction strategies, particularly in leather processing (tanneries) and downstream manufacturing such as footwear. By relaxing restrictions on foreign involvement in tanning and encouraging integrated operations, the government facilitated a surge in FDI from countries like China, India, and others starting around 2004 [32]. This influx has supported the establishment of modern, integrated facilities that combine processing and production stages, enabling higher-value outputs like finished leather goods and footwear.

Notable examples include Chinese-led investments, such as the Huajian Group's footwear operations, which have served as "lead goose" pioneers in export-oriented production and demonstrated the potential for scaling up [33]. These investments have contributed to technology transfer, albeit limited, and increased export volumes of leather footwear and related products [34]. Foreign firms often operate in industrial parks or clusters, fostering integrated supply chains that process local hides into high-value items for global markets [35].

While challenges persist such as weak backward linkages to the livestock sector, limited spillovers to domestic firms, and constraints in achieving full upgrading these FDI-driven developments have helped position Ethiopia as an emerging hub for high--value leather manufacturing, particularly footwear and accessories [31,35]. Continued policy focus on integrated facilities and

local capability building could further enhance this trajectory.

Despite setbacks such as declining tannery operations and export earnings in recent years due to input shortages and policy inconsistencies the strategic intent remains to prioritize finished products like footwear and leather goods to maximize value [36,37]. This transition aligns with broader industrial policy goals to enhance competitiveness and integrate into global value chains through product upgrading [38].

3.1.4. Quality & Standards Compliance

In the Ethiopian leather processing sector, there is a pronounced emphasis on enhancing quality and achieving compliance with international standards, particularly through certifications such as the Leather Working Group (LWG) audit. This certification is increasingly viewed as essential for accessing demanding export markets in Europe and the USA, where buyers prioritize environmentally responsible, traceable, and socially accountable production practices.

The LWG audit standard, originally launched in 2005 and updated over time (with Protocol 7 introduced in 2021 and further evolution toward the LWG Leather Production Standard), evaluates tanneries on environmental performance, chemical management, traceability, social responsibility, and governance [39]. Compliance enables tanneries to secure ratings (e.g., Gold, Silver, Bronze) and meet requirements from global brands, facilitating higher-value exports and partnerships.

Historically, Ethiopian tanneries faced challenges in meeting these benchmarks, with limited or no LWG-certified facilities prior to recent years [40]. However, targeted interventions such as the EU-funded Leather Initiative for Sustainable Employment Creation (LISEC) project implemented by UNIDO have supported capacity building, training, and audit preparation for multiple tanneries. This has resulted in notable progress, including LWG certifications for facilities like Ethio Leather Industry plc - Awash Tannery (achieving Gold rating and continuous certification since December 2024) and others [39,41].

By mid-2025, reports indicate that six Ethiopian factories had obtained LWG certification, a significant increase from zero just two years earlier [42]. This trend aligns with broader national ambitions outlined in roadmaps, which aimed for widespread LWG compliance by around 2025 to attract quality foreign direct investment and improve environmental and social standards [43]. Projects like LISEC have demonstrated tangible benefits, such as cleaner production, reduced energy costs, modernized water treatment, and expanded market access for sustainable leather [41].

Stakeholders emphasize that LWG certification is critical for breaking into global markets, particularly amid regulatory hurdles like Ethiopia's ban on exporting semi-processed 'wet blue' hides, which pushes toward value-added, certified finished leather [44]. While challenges persist including supply chain issues, technology gaps, and ensuring long-term sustainability of certifications the focus on LWG reflects a strategic shift toward quality-driven competitiveness in the sector [45].

3.1.5. Digitalization and Innovation

The integration of **digital technologies** in the Ethiopian leather processing sector is an emerging trend, aimed at enhancing efficiency, competitiveness, and value addition in a traditionally labor-intensive industry. Digitalization streamlines production workflows, improves **supply chain management** through better visibility, coordination, and responsiveness, and facilitates access to global markets via e-commerce and digital marketing [46]. For instance, the adoption of technologies aligned with Industry 4.0 paradigms such as automation, data analytics, and related tools positively impacts supply chain integration, reduces lead times, minimizes defects, and boosts overall productivity in leather firms, though barriers like high costs, skill gaps, and infrastructure persist [47].

In product design, the use of **Computer-Aided Design (CAD)** and related systems (e.g., CAD/CAM) is gaining traction to en-

able rapid prototyping, precise pattern making, and innovation in leather goods and footwear. Investments in CAD/CAM systems support faster development cycles and alignment with international standards, as highlighted in national roadmaps and industry analyses [43]. This shift helps Ethiopian producers move toward customer-centric designs and higher-value products.

A key driver of these trends is the establishment of **creative hubs** targeted at supporting **small and medium enterprises (SMEs)**. The **Creative Hub Ethiopia**, launched in 2021 by UNIDO in collaboration with the Ethiopian Ministry of Industry and Trade, the Italian Agency for Development Cooperation (AICS), and the Federal Small and Medium Manufacturing Industry Promotion Authority, promotes creativity, **digitalization**, and knowledge sharing [48]. Located to benefit the leather and leather products sector (among others like fashion and textiles), it provides SMEs particularly women-owned businesses—with access to digital tools such as 3D printers, laser cutters, and digital libraries for product development, prototyping, and experimentation [49]. This hub fosters innovation ecosystems, links innovators with industry and government, and supports MSMEs in navigating global markets amid challenges like the COVID-19 recovery.

These developments align with broader initiatives, such as the United Nations Industrial Development Organization's [UNIDO] Leather Initiative for Sustainable Employment Creation (LISEC) project. This initiative emphasizes the integration of modern technologies, comprehensive skills training, and inclusive growth within specific leather clusters, most notably in Modjo [50,51]. By fostering a collaborative ecosystem, the project aims to bridge the gap between traditional manufacturing and international quality standards. Overall, while the adoption of these advancements remains uneven across the region due to persistent structural constraints, the emergence of digitalization and innovation hubs represents a concerted effort to transform the sector toward long-term environmental sustainability and seamless global market integration [52].

3.2. Innovative Technologies and Approaches

3.2.1. Biotechnology in Processing

The Green Tannery Initiative represents a landmark effort toward eco-friendly industrialization in Ethiopia, specifically addressing the heavy environmental burden of traditional leather tanning [53]. Central to this initiative is the adoption of enzymatic unhairing, a biotechnological alternative to the conventional lime-sulfide process. This cleaner production method significantly reduces the discharge of toxic sulfides and organic pollutants into local water systems [54].

The Green Tannery Initiative represents a significant advancement in sustainable leather processing in Ethiopia, focusing on biotechnology through enzymatic unhairing. This initiative, implemented through a collaboration between the CSIR-Central Leather Research Institute (India), Ethiopia's Leather and Leather Products Industry Research and Development Centre (LLPIRC), and supported by the UNIDO and the UK-funded Sustainable Manufacturing and Environmental Pollution (SMEP) programme, is piloting enzymatic unhairing in five Ethiopian tanneries to foster a circular economy and improve the sector's international competitiveness [55-57].

Enzymatic unhairing replaces the conventional use of hazardous sodium sulphide (often combined with lime) in the liming/unhairing stage, which is a major source of pollution in traditional leather processing. Sodium sulphide contributes to high levels of chemical oxygen demand (COD), total suspended solids (TSS), sulfides, and hydrogen sulfide emissions, posing risks to both the environment and worker health [1]. In contrast, the enzyme-based approach (using commercial proteases) achieves complete unhairing often within 12 hours while enabling intact hair recovery for valorization into by-products, eliminating sodium sulphide entirely (100% reduction), and significantly lowering effluent pollution loads. Pilot trials have shown reductions in COD by approximately 72-73% compared to conventional processes, along with notable decreases in TSS and improved grain quality of the leather [58].

Although the initiative's specific claims emphasize substantial pollution mitigation, including near-complete elimination of sul-

phide-related hazards, broader literature on enzymatic unhairing supports reductions in key parameters (e.g., BOD, COD, TDS, and sulfides) by 60-90% or more in optimized systems, aligning with the reported benefits [1,59]. The Green Tannery Initiative's pilots demonstrate operational feasibility under local Ethiopian conditions, promoting cleaner production, occupational safety, and circular economy principles through waste valorization (e.g., converting hair and fleshings into value-added products like organic fertilizers).

3.2.2. Waste-to-Product Conversion

In the Ethiopian tanning sector, innovative technologies and approaches are increasingly focused on waste-to-product conversion to address environmental challenges and promote sustainability. Leather processing generates substantial solid waste, particularly during beamhouse operations such as liming and fleshing. Specifically, waste generated during these stages includes hair and fleshing, with fleshing often accounting for 50–60% of the total solid waste volume [60,61]. By repurposing these protein-rich by-products into items such as fertilizers, animal feed, or biofuels, the industry aims to mitigate the ecological footprint of traditional disposal methods.

Technologies are being implemented to convert these wastes (hair, fleshing) into valuable by-products such as organic fertilizer or biogas. For instance, through enzymatic unhairing processes that replace hazardous sodium sulfide, cleaner wastes (hair and fleshings) rich in proteins, fats, and keratin are produced, enabling valorization. A patented hydrolysis technology has been piloted in Ethiopia under initiatives like the Green Tannery Initiative, converting these wastes into high-value biofertilizers (organic fertilizers) for the first time in the country. This creates a circular economy model by channeling wastes into shared facilities for fertilizer production or biogas generation, reducing methane emissions from dumping and generating revenue [56,57].

Anaerobic digestion has been explored specifically in Ethiopian contexts, such as at Modjo Tannery, where tannery solid waste (TSW) is co-digested with cow dung to produce biogas. Batch digesters showed optimal results with mixtures like 75% TSW and 25% cow dung, yielding high biogas volumes (e.g., 4,756 ml) and methane content around 60%, alongside significant reductions in total and volatile solids. This demonstrates TSW as a viable feedstock for bioenergy while managing agro-industrial waste [62].

Broader efforts include composting or vermicomposting of non-chrome wastes like fleshings and hair to produce nutrient-enriched organic fertilizers, improving soil quality in agricultural applications [63]. These approaches align with Ethiopia's push for green manufacturing, supported by projects demonstrating centralized valorization to minimize pollution and create economic opportunities from wastes previously disposed of at cost or environmental harm [64]. These innovations reduce pollution, recover resources, and position Ethiopia's leather sector toward global sustainability standards.

3.2.3. Sustainable Material Development

Researchers in the Ethiopian tanning sector are actively exploring sustainable material development, with a particular focus on alternative materials such as plant-based tanning agents and eco-friendly leather production methods to enhance overall sustainability. The Ethiopian leather industry, heavily reliant on chrome-based tanning, faces significant environmental challenges from chemical pollution, prompting shifts toward greener alternatives [2].

Plant-based or vegetable tanning agents derived from local Ethiopian flora have shown promise as eco-friendly substitutes for conventional chrome tanning. Studies have investigated indigenous plants for their tannin content and application in cleaner leather processing. For instance, extracts from plants such as Hagenia abyssinica have been evaluated for their tanning potential, demonstrating characteristics suitable for clean leather production due to their natural, biodegradable properties and ability to produce leather with good physical qualities [65]. Similarly, research on Rumex abyssinicus (known locally as mekmeko) highlights its use as a preservation and potential tanning material for goat skins, offering a greener approach by reducing re-

liance on synthetic chemicals [66].

Other Ethiopian plant sources, including Cassia singueana, Solanum incanum, Eichhornia crassipes, and Osyris lanceolata, have been identified in broader reviews as containing condensed tannins viable for sustainable tanning, contributing to reduced environmental impact and potential local sourcing [67]. These efforts align with global trends toward chrome-free or combination tanning systems that incorporate vegetable tannins for better ecological profiles while maintaining leather quality [68].

Initiatives like the Green Tannery Initiative (GTI) in Ethiopia emphasize enzymatic processes and waste valorization as critical strategies for reducing the environmental burden of traditional leather manufacturing [53]. By integrating biocatalysts, such as keratinases for dehairing, tanneries can significantly lower their biochemical oxygen demand (BOD) and chemical oxygen demand (COD) while facilitating the recovery of hair and protein residues [70].

These programs also support broader eco-friendly practices, indirectly fostering the exploration of sustainable tanning materials by reducing chemical dependency and promoting circular economy models within the sector [53]. For instance, the conversion of solid waste into value-added products like protein binders or biogas exemplifies a shift toward resource efficiency [69,70]. Such developments aim to position Ethiopia's leather industry more competitively in global markets that increasingly demand sustainable and ethically produced goods [53]. However, significant challenges remain in scaling indigenous plant-based agents commercially. While local species like *Azadirachta indica* (Neem) and water hyacinth show promise as renewable tanning or retanning alternatives, issues such as low thermal stability (shrinkage temperature) and inconsistent tanning strength often hinder their ability to meet rigorous international quality standards [69,70].

3.2.4. Advanced Chemical Usage

Advanced chemical usage in leather tanning has shifted toward high-chrome exhaustion methods, which optimize the biochemical affinity between trivalent chromium salts and the collagen matrix of hides. By manipulating parameters such as pH, temperature, and the use of specialized cross-linking agents, these methods enhance the uptake of chromium (Cr^{3+}) by collagen fibers, achieving efficiencies that frequently exceed 90–98%, and in highly optimized systems, reach as high as 99% [71,72]. In contrast to conventional tanning where exhaustion rates typically languish between 60% and 80% these advanced techniques significantly reduce the concentration of residual chromium in tanning effluents. This reduction is critical for environmental sustainability, as it minimizes the discharge of chromium-laden wastewater, a primary pollutant in the leather industry known for its high chemical oxygen demand and potential for soil contamination [73,74].

One effective strategy involves **salt-free pickling combined with high-exhaustion chrome tanning**. By using p-toluenesulfonic acid monohydrate (p-TsOH) during pickling instead of traditional acids and salts, the process alters the basicity of chrome compounds and regulates tanning kinetics. This results in chromium exhaustion exceeding **98%** (e.g., 98.37%), compared to ~68.7% in conventional pickling, allowing reduced basic chromium sulfate dosage while maintaining equivalent chromium content in wet-blue leather and comparable crust leather properties [75].

Another innovative method employs **sulphonic aromatic acids** (e.g., in non-float or low-float tanning processes) to achieve high chrome exhaustion at an industrial scale. This alternative to traditional pickle-chrome tanning reduces chloride discharge by 94%, chrome discharge by 99%, and residual float by 75%, while improving overall process efficiency and leather quality [76].

Advanced auxiliaries and modified systems further push exhaustion limits. For instance, high-exhaustion chrome syntans (e.g., organo-chromium complexes without formaldehyde) enable >90% uptake, eliminate pickling, and drastically cut total dis-

solved solids (TDS) by 50–60% and chlorides by 98–99% in effluents [77]. Specialized high-exhaustion systems, including those with masking agents or syntans, can reach up to **98%** chrome utilization, reducing offered chrome from ~2.0% to 1.3% Cr_2O_3 while maintaining leather hydrothermal stability [78].

In some reported processes, such as optimized "Thrublu" or similar high-exhaustion approaches with auxiliary enhancements, chrome exhaustion exceeds 99% for certain hides. This efficiency is achieved through the use of syntans or specialized polymers that increase the number of carboxyl groups available for cross-linking [79]. These methods not only shorten processing time and improve area yield but also produce boil-resistant leather with a minimal environmental footprint by significantly reducing the chromium load in tannery wastewater [80].

These methods represent key innovations in sustainable leather processing, aligning with cleaner production frameworks by mitigating chromium pollution without compromising essential leather qualities, such as shrinkage temperature (Ts), tensile strength, and handle [81]. By maintaining a shrinkage temperature often exceeding 100°C, these high-exhaustion techniques prove that environmental sustainability can coexist with the rigorous technical standards required for global export.

The practical implementation of green technologies in Ethiopia's leather sector varies significantly despite their clear environmental advantages. Enzymatic unhairing offers substantial pollution reduction by eliminating sulfides; however, its adoption is constrained by high enzyme costs and the specific technical expertise required for process control [82]. Similarly, chrome-free and vegetable tanning methods improve environmental performance but often struggle to meet the specific thermal stability and durability standards required by high-end global export markets [83].

Table 1: Comparison Table Sustainable Leather Technologies in Ethiopia

Technology	Environmental Benefit	Limitation	Applicability in Ethiopia	Sources
Enzyme Unhairing	Reduces sulfide pollution by up to 70% and lowers COD/BOD levels.	High enzymatic cost and requires precise pH/temperature control.	Medium (Ongoing pilot stages in Modjo area).	Dettmer, A., et al. (2013)
Chrome-free Tanning	Eliminates chromium-rich sludge and toxic effluent discharge.	Results in lower hydrothermal stability and higher chemical costs.	Low–Medium (Mainly for niche "organic" export markets).	Zehra, A., et al. (2020)
High Exhaustion Chrome	Reduces chromium discharge by ensuring 90%+ absorption into the hide.	Still relies on basic chromium sulfate, which requires treatment.	High (Technically feasible for current Ethiopian infrastructure).	[72]
Waste Valorization	Promotes a circular economy by turning trimmings into fertilizer or energy.	Requires significant logistics and waste-segregation infrastructure.	Medium (Growing interest in collagen and biofuel extraction).	Kanagaraj, J., et al. (2015)
Digitalization (CAD/CAM)	Minimizes material waste through precise cutting and layout efficiency.	High initial investment and a steep learning curve for staff.	Emerging (Integration beginning in footwear and garment factories).	Sumathi, C., et al. (2016).

While waste valorization presents a promising circular economy opportunity, its scalability within Ethiopia is hindered by significant infrastructure gaps and limited capital investment [84]. In comparison, high-exhaustion chrome tanning remains more feasible in the short term due to existing industrial familiarity and lower transition costs, even though it provides only partial mitigation of heavy metal discharge [85]. Consequently, a hybrid approach combining incremental improvements in conventio-

nal methods with the gradual adoption of advanced green technologies is the most realistic path forward for the Ethiopian context

3.3. Future Directions and Strategies

3.3.1. Strengthening the Value Chain

Future directions in Ethiopia's leather sector emphasize **strengthening the value chain** through targeted improvements in raw material quality and enhanced linkages between rural suppliers and urban tanneries. A primary focus is on elevating raw material quality by adopting better animal husbandry practices, which address pre-slaughter defects such as scratches, parasitic damage, and poor health management that currently result in high rejection rates (often exceeding 60%) in hides and skins [86,87].

Improving husbandry involves transitioning from traditional, extensive systems often characterized by low off-take rates, inadequate feed, and limited veterinary services to more modern approaches. These modern strategies prioritize selective breeding, optimized nutrition, and rigorous disease control. Such advancements are specifically designed to increase both the quantity and the quality of raw hides and skins supplied from rural areas, which remain the primary source of these raw materials [88]. Furthermore, the implementation of targeted extension services for smallholder farmers and pastoralists is essential. These services aim to reduce ante-mortem defects such as brand marks, parasite damage, and scarring while promoting sustainable livestock management practices that align with global value chain standards [89].

Complementing this, future efforts prioritize **enhancing linkages** between rural suppliers (farmers, collectors, and informal slaughterers) and urban tanneries. This involves streamlining supply chains, improving collection systems, and fostering direct or cooperative arrangements to ensure consistent, quality-assured supply while providing price incentives based on quality grading [89]. Poor rural-urban connections currently contribute to quality deterioration during transportation, preservation, and handling, as well as market inefficiencies where prices fail to signal quality [88].

Integrated approaches, such as developing leather clusters (e.g., Modjo Leather City) and supporting institutions like the Leather and Leather Products Industry Research and Development Center (LLPIRDC), aim to facilitate technology transfer, training, and collaboration across the chain [90]. These strategies align with broader goals of value addition, sustainability, and export competitiveness, including environmental standards and reduced waste [31]. By centralizing production and waste management, these clusters allow for shared environmental infrastructure, which is essential for meeting international compliance standards [91].

The transformation of the Ethiopian leather industry necessitates a dual-pronged approach that addresses structural vulnerabilities across the entire value chain. Upstream, the sector is hampered by poor animal husbandry practices, environmental stressors, and inadequate veterinary services, which result in high rates of skin defects and diminished raw material quality [92]. By mitigating these rural supply weaknesses, the industry can secure a more consistent flow of high-grade inputs.

Downstream, the focus shifts toward value addition and the modernization of processing capabilities. Establishing robust ties between rural suppliers and urban tanneries is critical for reducing transactional inefficiencies and meeting the rigorous quality standards of international buyers [93]. Ultimately, aligning these segments is expected to pivot Ethiopia from an exporter of raw commodities to a competitive player in the global finished leather goods market, fostering sustainable economic growth [94].

3.3.2. Capacity Building & Technical Support

Continued investment in training and capacity building is essential for advancing the leather processing, footwear, leather

goods, garments and gloves manufacturing, particularly in specialized areas such as leather products design and chemical management [95]. These efforts enhance workforce skills, promote sustainable practices, and improve competitiveness, especially in developing regions like Africa and Ethiopia, where the industry faces challenges in technical proficiency and environmental compliance [20]. Research indicates that while Ethiopia possesses significant resource potential, the sector has historically struggled to translate this into high-quality, value-added products that meet international standards due to skill gaps and inadequate training in modern production techniques [26]. Furthermore, systematic training is recognized as a critical tool for both personal and organizational success, helping to mitigate high rejection rates caused by technical defects and ensuring that firms can meet the rigorous social and environmental compliance requirements of global markets [96].

In footwear design, targeted training programmes focus on building technical proficiency, creativity, and entrepreneurial skills to meet market demands. For instance, short-term intensive programmes, often lasting between three days and three months, equip participants with hands-on competencies in pattern-making, shoe design, cutting, stitching, assembling, and machinery operation [97-99]. These initiatives foster entrepreneurial thinking for small-scale enterprises by addressing the "low skills trap" typically found in micro-firms that rely solely on traditional apprenticeship [98,99]. Such initiatives frequently supported by institutions like the Ethiopian Institute of Textile and Fashion Technology at Bahir Dar University prioritise inclusivity by targeting youth, women, and migrant returnees to address skill gaps and support employment in growing industries [98,100,101].

Capacity building extends to institutional strengthening, including training in design and pattern development for entrepreneurs, as demonstrated in cluster-based projects that improve product quality and market orientation [102]. Collaborative efforts, such as those by the Africa Leather and Leather Products Institute (ALLPI), provide technical support and advanced training in footwear design and product development to enhance Small and Medium Enterprise (SME) capabilities across the continent [103]. These initiatives are critical for transitioning local artisans from traditional methods to globally competitive manufacturing standards.

In chemical management, ongoing training is critical for adopting cleaner production technologies, reducing hazardous substances, and complying with global standards like the Zero Discharge of Hazardous Chemicals (ZDHC) framework. Specialized programs emphasize eco-leather manufacture, chrome-free tanning, wastewater treatment, and the implementation of green chemicals to mitigate environmental impacts in tanning and footwear production [104]. To ensure the efficacy of these technical shifts, international collaborations promote best practices through capacity building, policy support, and knowledge sharing [105]. These initiatives are essential for ensuring safer workplaces and sustainable supply chains, particularly as the industry moves toward a circular economy model that prioritizes the elimination of persistent organic pollutants and the reduction of heavy metal discharge [106,107].

The strategic integration of specialized skills particularly in design and chemical management—is a primary catalyst for innovation, productivity, and regulatory compliance within the framework of Sustainable Development Goals [108]. Beyond operational efficiency, the adoption of green chemistry principles requires a workforce capable of navigating complex toxicological data and circular design frameworks [109]. By prioritizing demand-driven, practical training and longitudinal learning initiatives, stakeholders can effectively bridge existing competency gaps and transition toward "Industry 4.0" environmental standards [110]. Ultimately, fostering this greener manufacturing ethos through targeted human capital investment is essential for strengthening a sector's resilience and competitive positioning in the global market [111].

3.3.3. Strengthening Regional Partnerships

Strengthening regional partnerships through the African Continental Free Trade Area (AfCFTA) represents a pivotal strategy for expanding market access in the agricultural sector [112]. By reducing tariffs on the majority of goods, eliminating non-tariff barriers, and enhancing trade facilitation, the AfCFTA enables African countries to leverage a unified continental market of

over 1.3 billion people and a combined GDP exceeding $3 trillion [113,114]. This integration is particularly promising for agriculture, a sector that employs a large share of the population and holds significant potential for value addition, intra-regional trade growth, and food security improvements [115,116]. Empirical simulations suggest that the reduction of non-tariff measures alone could lead to much greater gains in intra-African trade than simple tariff elimination, particularly by connecting agricultural surplus regions to deficit areas [115,117].

Forecasts indicate substantial export gains under full AfCFTA implementation. For instance, intra-African exports overall could rise by approximately 109%, with manufacturing leading but agriculture also benefiting notably through expanded regional value chains [118]. In the agricultural domain, intra-African trade in agricultural products is projected to increase by 20–30% by 2040 compared to a no-AfCFTA scenario, with particularly strong gains in categories such as sugar, vegetables, fruits, nuts, beverages, and dairy [119]. Broader deep integration scenarios, including tariff reductions, non-tariff barrier cuts, and trade facilitation measures, could amplify total export volumes by nearly 29% by 2035, with intra-continental exports surging over 81% and agriculture seeing intra-African trade gains of around 49% [118].

The 111% increase in export value referenced for the sector aligns closely with projections for intra-African manufacturing exports approximately 110% under AfCFTA scenarios, though agriculture-specific gains are more modest yet still transformative when combined with complementary reforms like productivity enhancements and value chain development [118]. These dynamics support a strategic shift from raw commodity exports to processed agro-products, fostering job creation, income growth, and resilience against external shocks [120].

To maximize these opportunities, strategies should prioritize harmonizing sanitary and phytosanitary (SPS) standards, investing in critical infrastructure such as transport and cold-storage facilities, and promoting private-sector participation in regional value chains [121]. Such measures can help convert AfCFTA's legislative potential into tangible sectoral expansion and inclusive growth across the continent [122].

3.3.4. Environmental Regulation & Policy

Implementing stricter environmental standards and incentives for tanneries that adopt eco-friendly practices represents a critical future direction for mitigating the leather industry's substantial environmental footprint, particularly in water pollution, chemical discharges, and resource consumption from tanning processes. Stricter regulations, such as limits on chromium and other pollutants in effluents, compel tanneries to transition toward cleaner production methods, while incentives like tax benefits, subsidies, or preferential market access encourage voluntary adoption of sustainable technologies [123].

Governments and international bodies play a pivotal role by enforcing stringent discharge standards and promoting frameworks like ISO 14001 for environmental management systems, which help tanneries reduce water and chemical usage while improving compliance [45]. Increasingly rigorous policies in regions with heavy leather production push for pollution prevention strategies categorized under the 4R principles (reduce, reuse, recycle, recover), which are critical for transforming the industry's significant environmental footprint into a circular model [124]. These strategies aid alignment with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production), by mitigating the release of toxic effluents like chromium and organic waste into local ecosystems [125]. Furthermore, the integration of these cleaner production technologies is increasingly driven by international market pressures and the need for economic resilience within the global supply chain [126].

In developing countries, where enforcement may lag, combining regulative pressures such as mandatory effluent treatment plants with economic incentives has proven effective in driving sustainable manufacturing. These include government promotions, financial rewards for eco-friendly benchmarks, and support for cleaner technologies like chrome recovery or alternative

tanning agents [45,123]. Such mixed approaches address compliance costs by offering benefits like reduced operational expenses through resource efficiency and enhanced export competitiveness via certifications (e.g., Leather Working Group standards), which often exceed basic regulatory requirements.

Evidence from systematic reviews highlights that regulative pressures from environmental laws, alongside normative standards and global initiatives, significantly influence the integration of sustainability in leather supply chains [45]. Incentives, including those tied to circular economy models, further motivate shifts away from conventional chrome tanning toward greener alternatives, reducing ecological damage while maintaining industry viability [127].

The implementation of stricter environmental standards, when strategically paired with targeted fiscal incentives, serves as a primary catalyst for innovation within the leather industry [128]. This dual approach facilitates the adoption of advanced wastewater treatment technologies, such as membrane bioreactors and advanced oxidation processes, which significantly mitigate the sector's high chemical oxygen demand [129]. Furthermore, these policies drive waste valorization the conversion of chromium-laden shavings and fleshings into high-value by-products like biofuels or collagen hydrolysates thereby transforming linear disposal models into circular systems [130]. Ultimately, this regulatory synergy ensures the long-term environmental sustainability and global competitiveness of the tannery sector in an increasingly eco-conscious market.

Conclusion and Recommendation

Conclusions

The leather processing industry in Ethiopia has strong potential to serve as a key driver of economic development, supported by the country's abundant livestock resources. It offers important opportunities for generating foreign exchange, creating employment particularly for youth and women and promoting value addition within the manufacturing sector. However, traditional processing methods have long been associated with significant environmental challenges. These include high water consumption, the discharge of hazardous chemicals such as chromium and sodium sulfide, severe water pollution, accumulation of solid waste, and air emissions. As a result, the sector's global competitiveness has been constrained, limiting access to premium international markets that demand strict sustainability standards, such as those defined by the Leather Working Group and European Union regulations. In addition, these environmental impacts have contributed to social and public health concerns in communities located near tannery operations.

In recent years, encouraging progress has been observed toward more sustainable and innovative practices. Key developments include the adoption of cleaner production techniques, such as enzymatic unhairing to reduce reliance on sodium sulfide, high-exhaustion chrome tanning and chrome-free alternatives (including vegetable-based and nanomaterial tanning), as well as CO_2-based deliming processes. Efforts in solid waste valorization are also gaining attention, with by-products such as fleshings, trimmings, and chrome shavings being converted into biofertilizers, protein hydrolysates, adhesives, and leather boards through hydrolysis and related technologies. In parallel, pilot initiatives are demonstrating circular economy approaches, particularly in waste-to-value conversion and improved effluent management systems. The integration of green practices including sustainable manufacturing environmentally oriented marketing strategies and green investment has further contributed to improved economic and environmental performance through innovation.

Several initiatives have played a significant role in advancing these transformations. Programs such as the Green Tannery Initiative have introduced enzymatic processing and waste-to-fertilizer solutions, while the Leather Initiative for Sustainable Employment Creation (LISEC) has supported the adoption of chrome-free tanning, enhanced waste management practices, skills development, and the establishment of shared facilities in key industrial areas such as Modjo. Collaboration with international partn-

ers, including UNIDO, the European Union, SMEP, and Solidaridad, has further strengthened these efforts. These initiatives have led to tangible outcomes, including certification under the Leather Working Group for selected tanneries, improvements in occupational safety, and increased employment opportunities. In addition, emerging digital tools for supply chain management and growing entrepreneurial activities are contributing to greater efficiency and improved market access.

Despite these positive developments, several challenges remain. The high cost of advanced technologies, limited access to foreign currency, persistent issues with the quality of raw hides and skins, inadequate infrastructure particularly centralized effluent treatment facilities and weak regulatory enforcement continue to hinder progress. Furthermore, supply chain inefficiencies and rising input costs add to the complexity of transformation within the sector.

Overall, Ethiopia's leather industry is at a critical turning point. It is transitioning from a largely pollution-intensive, low-value production system toward a more sustainable and higher-value industry aligned with global demand for environmentally responsible and ethically sourced products. Advances in cleaner technologies and waste valorization not only help reduce environmental impacts but also create new economic opportunities through cost savings, diversification of revenue streams, and enhanced export competitiveness. Government-led initiatives, such as the development of the Modjo Leather City cluster with centralized wastewater treatment and chrome recovery systems, demonstrate strong institutional commitment. If these efforts are sustained and scaled, Ethiopia has the potential to emerge as a leading hub for sustainable leather production in Africa, contributing to broader goals of job creation, inclusive economic growth, and climate resilience.

Recommendations

To accelerate progress toward innovative and sustainable leather processing, stakeholders should prioritize:

- **Scale up proven cleaner technologies:** Expand enzymatic unhairing, chrome-free/vegetable tanning, and waste valorization nationwide through subsidies, technology transfer partnerships, and demonstration pilots in tannery clusters.

- **Invest in infrastructure and shared facilities:** Fast-track development of the Modjo Leather Park, including common effluent treatment plants (CETPs) with chrome recovery, solid waste processing units, and centralized services to reduce individual tannery costs and pollution.

- **Strengthen skills and capacity building**: Enhance training programs (via TVET colleges, LIDI, and projects like LISEC) in modern processing, occupational health/safety, digital tools, and product design to empower youth, women, and MSMEs.

- **Improve policy and regulatory frameworks**: Enforce stricter environmental compliance, incentivize green investments (e.g., tax breaks for sustainable tech adoption), and align with international standards (LWG, ZDHC, REACH) to attract FDI and premium buyers.

- **Promote circular economy and value addition** Encourage R&D linkages for by-product innovation, support MSMEs in transforming waste into marketable goods, and foster branding of Ethiopian leather as "sustainable and high-quality."

- **Enhance collaboration and market access** Deepen partnerships with global entities for technology/finance, conduct B2B matchmaking, and leverage digital platforms for export promotion.

Declarations

Author's Contribution

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

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Conflict of 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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