

Literature Review

Application Status of Cleaner Technologies and Sustainable Waste Utilization in the Case of Ethiopian Leather Industries: A Systematic Review of Literature

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Abstract

The leather industry in Ethiopia plays a vital role in economic development and employment, but remains one of the most pollution-intensive sectors due to high generation of liquid and solid wastes containing hazardous substances such as chromium, sulfides, and organic matter. This literature review examines the *application status of cleaner technologies* (e.g., high-exhaustion chrome tanning, low-sulfide/enzymatic unhairing, CO₂ delimiting, compact retanning, and wet-white processing) and *sustainable waste utilization* practices in Ethiopian tanneries. Existing studies highlight limited adoption of cleaner production (CP) options, with most tanneries relying on conventional processes and end-of-pipe treatments, leading to environmental challenges including water pollution, soil contamination, and methane emissions from landfilled wastes. Recent initiatives, such as the Green Tannery Initiative, have piloted enzymatic unhairing to replace sodium sulfide and hydrolysis-based valorization of fleshings, trimmings, and other solid wastes into biofertilisers, demonstrating feasible circular economy models. Other Ethiopian-focused efforts include converting finished leather straps and solid wastes into value-added composites (e.g., boards and consumer products) blended with plant fibers, as well as explorations of protein hydrolysates, glue from limed trimmings, and organic compost. Barriers to wider implementation include high costs of advanced technologies, inadequate infrastructure, regulatory enforcement gaps, and limited technical capacity. However, successful cases indicate potential for reduced pollution loads, resource recovery (e.g., chromium recycling, biogas, collagen derivatives) and economic benefits through waste-to-wealth approaches. The review underscores the need for integrated strategies combining technical upgrades, policy support, and industry collaboration to advance sustainability in Ethiopia's leather sector.

Introduction

The Ethiopian leather industry represents a vital component of the nation's manufacturing sector, contributing significantly to employment, export earnings, and rural economic linkages through the processing of abundant livestock hides and skins [1]. However, conventional tanning processes generate substantial environmental burdens, including high volumes of solid waste (such as fleshings, trimmings, and chrome-containing sludge) wastewater

with elevated chemical oxygen demand (COD), biochemical oxygen demand (BOD), sulfides, and chromium, as well as air emissions. These impacts threaten local ecosystems, particularly in industrial clusters like Modjo and Wukro, and undermine the sector's long-term sustainability [2,3].

Cleaner production (CP) technologies encompassing process modifications such as enzymatic unhairing, high-exhaustion chrome tanning, hair-save liming, and resource-efficient practices offer preventive strategies to minimize

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Keywords: Cleaner production; Sustainable waste utilisation; Ethiopian leather industry; Tannery solid waste; Waste valorisation; Circular economy; Enzymatic unhairing; Chrome-free technologies; Biofertiliser; Leather composites



pollution at the source while enhancing resource efficiency and economic viability [4,5]. Sustainable waste utilization approaches, including valorization of solid wastes into biofertilizers, composite boards, biogas, or collagen hydrolysates through composting, enzymatic hydrolysis, or thermal processes, align with circular economy principles and can transform waste liabilities into value-added [3,6]. In Ethiopia, recent initiatives such as enzymatic unhairing pilots and waste-to-fertilizer demonstrations have shown promise, yet adoption remains fragmented due to technological, financial, regulatory, and skill-related barriers [2,4].

Despite growing policy emphasis on green industrialization and documented waste generation rates estimated at significant portions of raw material input becoming non-product outputs [1], a comprehensive synthesis of the current application status of these cleaner technologies and sustainable waste practices specific to Ethiopian leather industries is lacking. Existing studies often focus on individual tanneries or general reviews without systematically mapping implementation levels, challenges, and outcomes across the sector. This literature review addresses these gaps by critically examining peer-reviewed and empirical evidence on the topic.

Objectives

The primary objective of this literature review is to assess the application status of cleaner technologies and sustainable waste utilization practices in the Ethiopian leather industries.

Specific objectives are to:

- Synthesize existing literature on the types, extent, and performance of cleaner production technologies (e.g., enzymatic processes, low-waste tanning) adopted or piloted in Ethiopian tanneries.
- Evaluate current practices, outcomes, and barriers related to sustainable utilization of leather solid wastes (e.g., composting, valorization into fertilizers or composites) in the Ethiopian context.
- Identify key research gaps, policy implications, and recommendations for scaling up cleaner and circular approaches to support environmentally sustainable leather industry development in Ethiopia.

Methodology

This study adopts a Systematic Literature Review (SLR) approach to evaluate the application status of cleaner technologies and sustainable waste utilization in the Ethiopian leather sector. The methodology is structured into four distinct phases:

Search strategy and data sources

To ensure comprehensive coverage, a multi-database search was conducted using Scopus, Web of Science, Google

Scholar, and the Addis Ababa University Institutional Repository (AAU-ETD). The search focused on keywords such as “cleaner production Ethiopia,” “tannery waste valorization,” “sustainable tanning,” and “Ethiopian leather industry environmental impact. Local institutional data is critical because many Ethiopian tanneries have unique operational profiles that are not always captured in international journals.

Inclusion and exclusion criteria

Articles were selected based on their relevance to:

- Cleaner Production (CP) technologies are currently being piloted or implemented in Ethiopia (e.g., enzymatic unhairing and chrome recovery).
- Solid waste utilization, specifically the conversion of fleshings and trimmings into value-added products like organic fertilizers or biogas.
- Geographic Focus: Only studies specifically addressing the Ethiopian context or providing comparative frameworks for developing economies were included.

Data synthesis and framework

The literature was categorized according to the leather processing value chain: Pre-tanning (Beam house), Tanning (Tanyard), and Post-tanning. This allows for a granular assessment of where cleaner technologies are most prevalent. For instance, recent reviews indicate that while beam house innovations (like sulfide-free unhairing) are gaining traction through initiatives like the Green Tannery Initiative, post-tanning waste management remains a significant gap.

Quality assessment and gap analysis

Each source was evaluated for its methodological rigor and the currency of its data. Special attention was paid to the “attitude-behavior gap” in the Ethiopian sector, where technological feasibility does not always translate to industrial adoption due to high costs and technical barriers.

Literature review

Status of cleaner technologies

Low adoption rate: Despite the existence of proven cleaner technologies, the low adoption rate of effective waste management systems remains a critical challenge for the Ethiopian leather industry. A significant number of tanneries, particularly small and medium-sized enterprises (SMEs) clustered in areas like the Modjo Leather City, continue to operate without adequate effluent treatment plants (ETPs) [7]. This directly results in the discharge of untreated or partially treated wastewater containing high levels of chromium, sulfides, and organic load into waterways, leading to high environmental pollution [8].

The primary barriers to adoption are multifaceted.



Research indicates that the high initial capital investment required for integrated ETPs is a major deterrent, especially for tanneries with limited financial capacity [9]. Furthermore, there is often a lack of technical expertise to operate and maintain advanced treatment systems, even when they are installed [10]. Weak enforcement of existing environmental regulations and a policy environment that prioritizes economic output over ecological compliance further exacerbate the problem, allowing non-compliance to persist [11].

Consequently, the environmental impact is severe. Studies document the contamination of rivers and agricultural soils adjacent to tannery clusters, with deleterious effects on ecosystem health and potential risks to human health through bioaccumulation of toxic substances [12]. This persistent gap between available cleaner technologies and their widespread implementation underscores the need for a coordinated approach involving financial incentives, capacity building, and stricter regulatory oversight to foster sustainable practices in the sector.

Conventional vs. Green: The status of cleaner technologies in the global leather tanning industry, particularly concerning chromium pollution, reveals a persistent dichotomy between conventional and green methods. While advanced, less-polluting technologies exist, their adoption remains limited due to entrenched perceptions and economic barriers, creating a significant gap between innovation and widespread implementation.

Dominance of conventional chrome-tanning: Conventional chromium (III) sulfate tanning remains the dominant global method, accounting for approximately 80-90% of all leather production [19]. This process is favored for its speed, reliability, and ability to produce leather with superior hydrothermal stability, softness, and versatility. However, its environmental burden is severe. A significant portion of the chromium used (often 30-40%) is not fixed in the leather and ends up in wastewater as toxic effluent, and the potential oxidation of leftover chromium(III) to carcinogenic chromium(VI) in tanned leather or solid waste poses serious health risks [14]. Despite knowledge of these hazards, the method persists due to deeply integrated supply chains and technical mastery within tanneries.

The landscape of “Green” alternatives and barriers to adoption: Alternative “green” technologies can be categorized as chrome-reducing, chrome-free, or process innovations. Chrome-reducing methods, such as high-exhaustion chrome tanning systems, aim to improve chromium uptake to over 95%, thereby minimizing effluent load [15]. Chrome-free methods employ organic tannins (vegetable tanning) aldehydes (e.g., glutaraldehyde) or other metal complexes (e.g., aluminum, zirconium). Furthermore, novel biological and enzymatic pre-tanning processes can reduce the need for harsh chemicals overall [16].

Despite their environmental promise, these cleaner technologies are often avoided by manufacturers. The primary barrier is the pervasive perception, particularly among leading brands and consumers, that chrome-free leathers are of lower quality, often being criticized for their thicker, stiffer nature, poorer dye uniformity, and lower hydrothermal stability compared to premium chrome-tanned leather [17]. This perception affects marketability. Additionally, green alternatives often involve higher material costs, longer processing times, and require significant process re-engineering, posing economic and technical challenges for tanneries, especially in cost-sensitive developing nations where most tanning occurs [18].

The status: A transition in progress: The current status is one of constrained transition. While research into cleaner technologies is prolific in academic journals, commercial adoption is selective. High-exhaustion chrome tanning is gaining ground as a “best available technology” that reduces pollution without radically altering leather properties [15]. Meanwhile, chrome-free tanning finds niche markets in automotive interiors, luxury goods, and eco-conscious product lines where specific properties are valued or regulatory pressure is high. The gap between “perceived” and “actual” quality of green leather is narrowing with ongoing research, but overcoming the ingrained economic and technical advantages of conventional chrome tanning remains the central challenge for the industry’s sustainable transformation [13].

Potential initiatives: Research on the Addis Ababa Tannery indicates that the environmental footprint of the leather sector can be substantially mitigated through the adoption of cleaner production (CP) strategies. A foundational study by Yilma M & Kaushal A.[18] demonstrated that systematic implementation of CP options, particularly in the resource-intensive beamhouse and soaking stages, is both technically and economically viable for the company. Their analysis, published in the *Journal of Cleaner Production*, highlighted that reducing chemical usage and optimizing water consumption through process modification and chemical substitution could lead to significant decreases in pollutant load [18].

Further supporting this, a detailed assessment by Mekonnen TH, & Mekonnen BA. [20], quantified these potential gains. Their work, in the *Environmental Science and Pollution Research*, specifically modeled interventions at the Addis Ababa Tannery. They concluded that water recycling and the use of more efficient enzymes in beamhouse operations could reduce fresh water intake by up to 30% and lower sulfide emissions by approximately 25%, thereby significantly reducing environmental impacts [20].

The cumulative evidence suggests that for tanneries like Addis Ababa Tannery Sh.Co., moving from conventional to cleaner technologies is not merely an environmental

imperative but also an operational efficiency opportunity. As emphasized by Gebregziabher S. et al. [21], the adoption of such CP initiatives is critical for aligning industrial practices in developing economies with sustainable development goals, offering a pathway to reduced effluent treatment costs and improved compliance [7].

Key cleaner technologies & advantages: enzymatic unhairing: Replaces traditional, highly polluting sulfide-based beamhouse methods with specialized protease enzymes [22]. Advantages: This biotechnology drastically reduces toxic sulfide discharges in tannery effluents, cuts overall processing time, preserves hair structure to lower the organic load, and improves the final tactile and physical quality of the leather [23].

High-exhaustion chrome tanning: Optimizes chemical delivery to maximize the chemical uptake of chromium salts directly into the raw hide matrix. Advantages: Traditionally, up to half of the applied chromium is lost to effluent; high-exhaustion systems drastically reduce chromium concentrations in wastewater, minimize hazardous chemical waste, and lower economic losses without sacrificing the leather's hydrothermal stability [24].

Plant-based & metal-free tanning: Utilizes local botanical extracts (such as Acacia species, Xylocarpus granatum, or specialized vegetable tannins) as completely organic alternatives to heavy metals like chromium [25]. Advantages: Yields highly biodegradable, eco-friendly leather that satisfies strict corporate sustainability requirements, effectively opening up premium international market segments and luxury consumer demographics.

Waste-to-resource conversion: Transforms dangerous, bulky solid tannery residues such as trimmings, shavings, and fleshings into valuable commercial by-products. Advantages: Converts organic solid waste into renewable energy sources through enzyme-assisted anaerobic co-digestion (generating biogas/biofuels) and recovers chromium (III) oxide from residual ash via controlled thermal processing for industrial reuse [26].

Limitations of cleaner technologies

Structural barriers: The sector faces severe upstream challenges regarding the structural quality of raw hides and skins. These raw materials are frequently compromised by severe pre-slaughter handling defects (such as parasitic scars, branding, and mechanical scratches) and post-slaughter issues stemming from highly disorganized collection systems and prolonged transportation delays [15].

Technical constraints: Implementing cleaner processing methods, such as substituting commercial synthetic materials with eco-benign alternatives like keratin or plant-based compounds, is severely bottlenecked. The industry suffers from a critical shortage of localized chemical manufacturing

plants, insufficient specialized engineering training, and limited technical R&D infrastructure capable of upgrading traditional, chrome-heavy tanning frameworks [28].

Stringent compliance: Aligning with rigorous international market expectations presents a steep learning curve for local manufacturers. Ethiopian tanneries struggle to meet complex global environmental guidelines, including the European Union's strict Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulations and Zero Discharge of Hazardous Chemicals (ZDHC) parameters, which require extensive transparency and advanced wastewater treatment operations [29].

Implementation status of cleaner technologies

Process level: The adoption of "green" process innovations within individual firms remains limited but active at the pilot stage. Several tanneries have successfully experimented with eco-friendly alternatives, such as enzymatic unhairing and sulfide-free tanning, utilizing microbial proteases (such as *Bacillus subtilis*) to systematically substitute hazardous sodium sulfide and reduce the severe chemical oxygen demand (COD) and biological oxygen demand (BOD) in processing effluents [30]. Despite these successful trials, full-scale industrial adoption is highly uneven due to structural inhibitors, including the high costs of imported clean technologies, inadequate local financing, and a lack of specialized technical support [30].

Systemic level: To combat the intense pollution generated by traditional leather processing, where a historical majority of regional tanneries discharged untreated, high-sulfide, and heavy-metal-laden wastewater directly into open water systems like the Modjo River, the Ethiopian government has shifted toward systemic infrastructure upgrades [31]. The state actively champions specialized, centralized eco-industrial parks, most notably Modjo Leather City [30,31]. This dedicated cluster is strategically designed to house centralized, environmentally sound infrastructure, including advanced shared effluent treatment plants capable of achieving regulatory compliance at scale.

Value chain: Structurally, the industry is navigating a gradual transition toward higher echelons of the global value chain. Vertical integration is slowly accelerating as the sector implements a strategic pivot away from exporting low-value raw or semi-processed hides (such as wet-blue) in favor of manufacturing high-value finished leather goods and footwear [30]. However, overall progress is gradual, impeded by supply-chain fragmentation, variations in the quality of raw hides, and baseline technological limits within local production units.

Economic feasibility of cleaner technologies

Capital costs vs. Long-term value: Initial investments in wastewater treatment plants, chromium recovery systems, and eco-friendly infrastructure require significant upfront capital. Implementing modern "command-and-control" or



circular environmental infrastructure presents a major hurdle for developing countries like Ethiopia due to these heavy initial financial outlays [32]. However, the public health and macroeconomic costs associated with delayed remediation and heavy metal contamination eventually dwarf these initial expenditures [33].

Export competitiveness: While implementing these technologies is costly, it is no longer optional for long-term economic viability. Global leather supply chains are increasingly dictated by strict international sustainability legislation, such as European Union environmental directives [34]. Meeting these strict environmental compliance criteria is mandatory for Ethiopian tanneries to maintain market access, attract foreign lead firms, and secure premium pricing in European and North American export markets [35].

Resource savings: The integration of closed-loop systems (e.g., recovering and reusing chromium, generating biogas) dramatically reduces long-term operational costs. Because chrome tanning remains the dominant technique in roughly 90% of global tanneries, secondary recovery and recycling loop options offer vital avenues to lower chemical costs while mitigating severe downstream wastewater treatment expenses [36]. Furthermore, utilizing tannery biomass and organic solid waste to generate biogas through anaerobic co-digestion acts as a major enabler for commercialization, significantly cutting factory utility overhead and improving overall energy efficiency [37,38].

Sustainable waste utilization status

Waste generation: In the Ethiopian leather industry, approximately 80–85% of the raw hide/skin mass is discarded as waste during the conversion process into finished leather [1]. This high rate of waste generation remains a critical environmental and economic challenge, as only a small fraction of the raw material is transformed into the final commercial product.

Waste generation profile: The tanning process is characterized by heavy resource consumption and significant byproduct discharge. For every 1,000 kg (1 ton) of wet salted hide processed, only about 150–200 kg is converted into finished leather, while the remainder enters the environment as solid waste or liquid effluent [39].

Distribution of waste: The waste is generally categorized into two streams based on the processing stage:

Solid waste: This includes “green” waste (raw trimmings, fleshings) hair, and tanned waste (chrome shavings, buffing dust) Teklay et al. [1]. quantify that processing one ton of wet salted hide can generate over 83 kg of solid waste in certain Ethiopian tanneries, with hazardous chrome-containing shavings making up a significant portion.

Liquid effluent: Approximately 30–50 m³ of wastewater is generated per ton of raw material. In Ethiopia, much of this effluent is discharged into nearby water bodies with only

partial or no treatment, leading to high levels of Chemical Oxygen Demand (COD) and chromium contamination [40].

Current utilization status: While the industry historically viewed these byproducts as “trash,” recent initiatives have moved toward a Circular Economy model:

Enzymatic unhairing: Recent projects, such as the Green Tannery Initiative (2025) [41], have demonstrated that replacing sodium sulfide with enzymes allows for the recovery of intact hair estimated at 6,000 tons annually in Ethiopia, which can be converted into organic fertilizers [42].

Construction integration: Research at the Ethio-Leather Industry PLC (ELICO) has shown that chrome-shaved waste can be utilized as a reinforcing agent in the production of solid concrete blocks, achieving a compressive strength of up to \$37.33 N/mm² at a 15% replacement rate [43].

Energy recovery: Some studies explore the high calorific value of leather waste (approx. 12-14 MJ/kg) for potential incineration and energy recovery, though this requires specialized technology to prevent toxic emissions [39].

Current disposal: In the Ethiopian leather industry, sustainable waste utilization remains in its nascent stages despite the sector’s high economic importance. The vast majority of solid by-products, specifically hair, fleshings, and chromium-tanned shavings, are still disposed of via open dumping or incineration, leading to significant environmental degradation [44].

Current status of waste disposal

Despite recent pilot initiatives, the standard practice in many Ethiopian tanneries involves discharging solid waste into unauthorized areas or poorly managed landfills.

Hair and fleshings: Traditionally, these are treated as “nuisance” waste. Fleshings, rich in proteins and fats, are often dumped where they degrade rapidly, releasing methane and foul odors [42].

Chromium-tanned shavings (CTS): These are particularly problematic due to the presence of heavy metals. In tanneries like Sheba Leather Industry, CTS are often disposed of in open fields, posing a risk of trivalent chromium leaching or oxidizing into the carcinogenic hexavalent form (Cr VI) [45,46].

Emerging utilization trends (2024–2026): While dumping remains the status quo, several research-driven and international projects are currently demonstrating the “waste-to-wealth” potential in Ethiopia:

Waste Type	Traditional Status	Sustainable Alternative (Current Research/Pilots)
Hair	Dumped/ Burnt	Recovered via enzymatic unhairing for bio-fertilizers [42].
Fleshings	Open dumping	Valorized into bio-energy, protein hydrolysate, or compost [67].
Chrome Shavings	Landfilled	Processed into composite sheets for insoles or building materials [46,68].

Current status of waste utilization: In Ethiopia, the “waste-to-value” concept is largely in the research or pilot phase. Most industrial solid waste is currently managed through open dumping, incineration, or landfilling, which leads to severe environmental degradation [47]. For every 1,000 kg of raw hide processed, only about 200 kg is converted into finished leather, leaving 800 kg to be discarded as solid or liquid waste [47].

Recent initiatives, such as the Green Tannery Initiative (2025) [41], are attempting to bridge this gap by piloting technologies like enzymatic unhairing and the conversion of fleshings into organic bio-fertilizers [42]. However, the widespread industrial adoption of these circular economy models is still hampered by a lack of infrastructure and standardized processing protocols.

Opportunities for utilization: Research identifies several high-potential pathways for transforming tannery waste into marketable products:

1. Energy recovery (biogas and biofuels)

Leather waste, particularly protein-rich fleshings and shavings, serves as an excellent substrate for anaerobic digestion.

- **Biogas:** Studies on the Modjo Tannery demonstrated that co-digestion of tannery solid waste with cow dung can produce biogas with a methane content of approximately 60.37% [47].
- **Biofuels:** Thermal treatments like pyrolysis and gasification can recover nearly 70% of the intrinsic energy found in tannery wastes, converting it into syngas or bio-oil [48].

2. Protein and collagen extraction

Since leather is primarily composed of collagen, extracting protein for industrial use is a major opportunity.

Hydrolysis: Processes involving alkaline or enzymatic hydrolysis can extract collagen hydrolysates from chrome-tanned shavings. These proteins can be repurposed into leather retanning agents, adhesives, or even nitrogen-rich fertilizers [49].

Agricultural use: Research into the valorization of leather industry byproducts indicates that recovered amino acids from untanned collagenous wastes are being actively explored for use in nutritive foliar fluids for crops, offering a sustainable alternative to synthetic fertilizers [50]. This application aligns with circular economy principles by transforming waste into a resource for enhancing plant nutrition and stress tolerance. Further supporting this, a recent study by Chen, et al. [51] demonstrated the efficacy of a hydrolysate derived from untanned hide trimming in promoting the

growth and chlorophyll content of lettuce (*Lactuca sativa*) under greenhouse conditions, suggesting its potential as a biostimulant. The synthesis of these amino acid-rich fluids represents a significant innovation in agricultural inputs, as noted in a broader review on protein waste upcycling [52].

3. Chromium recovery

A significant barrier to utilizing “wet-blue” (chrome-tanned) waste is the presence of trivalent chromium. Research indicates that using oxalic acid at optimized temperatures (around 49°C) can extract chromium ions while minimizing collagen damage, allowing the remaining protein to be safely valorized (MDPI, 2025).

Key challenges of sustainable waste utilization

Inadequate waste treatment infrastructure: The primary obstacle to sustainable waste utilization is the absence of modern, centralized facilities designed for waste recovery. Most Ethiopian tanneries still rely on traditional “end-of-pipe” treatment systems, which focus on disposal rather than resource recovery. According to Teklay, et al. [1], the lack of dedicated infrastructure for segregating and processing solid waste such as hair, fleshings, and chrome shavings leads to these materials being dumped in open landfills, resulting in groundwater pollution and noxious odors. Furthermore, the absence of an integrated ecosystem, including specialized logistics and input supply markets, limits the ability of tanneries to scale up waste-to-value initiatives [53].

Lack of awareness and technical expertise: There is a profound gap in awareness regarding the economic and environmental benefits of cleaner production (CP) technologies. Many industrial managers and workers in the Ethiopian leather sector do not fully understand the quality assurance and compliance requirements of the global market, which increasingly demands sustainable practices [53]. Melese, (2021) [54] notes that even when regulations exist, a lack of technical knowledge on how to implement “4R” (Reduce, Reuse, Recycle, Recover) strategies prevents firms from adopting more efficient waste-handling systems.

Barriers to adopting cleaner technologies: The adoption of cleaner technologies, such as enzymatic unhairing or chrome recovery systems, is hindered by perceived high costs and technical complexity. Retta (1999) [55] and more recent assessments by the SMEP Programme (2025) [42] highlight that while initiatives like the “Green Tannery Initiative” demonstrate that waste can be converted into high-value products like organic fertilizers, widespread adoption is stalled by a shortage of foreign currency for importing technology and a lack of pilot facilities for local testing.

Key economic challenges

1. High initial investment and technology costs

The most significant barrier to sustainable waste



utilization is the capital-intensive nature of modern waste-to-value technologies. Transitioning from traditional methods to enzymatic unhairing or advanced solid waste valorization requires substantial investment in new machinery and specialized chemicals. Research indicates that many firms find the cost of green technology prohibitive, often viewing environmental compliance as a low priority compared to immediate competitiveness [56].

2. Financial constraints and lack of credit

The sector faces a persistent shortage of accessible finance and foreign currency, which are essential for importing eco-friendly technologies. Many Ethiopian tanneries, particularly Small and Medium Enterprises (SMEs), lack the managerial capacity to develop “bankable” loan applications or are already burdened by existing debt, limiting their borrowing capacity for sustainability projects [57].

3. Operational costs vs. market viability

While circular models can eventually lower operational costs by producing value-added by-products (like organic fertilizers from fleshings) the current economic ecosystem often lacks the infrastructure to make this profitable at a small scale. For instance, composting plants for leather waste often require external financial aid to ensure continuity, as the revenue from the end-products may not immediately cover the high maintenance and labor costs [58].

Regulatory framework

The transition toward sustainable waste utilization within the Ethiopian leather industry is hindered by a complex interplay of systemic and structural barriers. Although the sector is a recognized priority for national economic development, as outlined in national industrial policies [59] the practical implementation of a “waste-to-resource” model remains largely aspirational. This gap is primarily attributable to a fragmented and under-enforced regulatory framework that fails to provide clear standards or economic incentives for waste valorization [60]. Furthermore, the absence of specific, actionable policies directly promoting circular economy principles within the industry exacerbates these challenges [61]. Consequently, regulatory gaps are compounded by significant technical limitations, including a lack of accessible cleaner production technologies and limited local capacity for research and development into viable waste conversion processes [62]. This regulatory and technical deficiency creates a significant disconnect between the sector’s strategic importance and its current, predominantly linear, operational practices.

Regulatory framework and enforcement challenges

The primary challenge in Ethiopia’s leather sector is not a lack of policy, but the significant gap between legislative intent and field-level compliance, a common issue in

developing economies where regulatory frameworks often outpace enforcement capacity. This disconnect between formal institutions and practical implementation has been documented in studies of industrial policy. For instance, Godefa (2020) [63] notes that while Ethiopia has a “comprehensive set of industrial policies and environmental regulations” governing the leather industry, enforcement is hampered by “institutional fragmentation, limited technical capacity of inspectors, and the high cost of compliance for small-scale enterprises” (p. 112) Similarly, the problem extends to environmental governance, where Beyene and Geberekidan [64] found that despite existing proclamations, “the monitoring and enforcement of effluent standards from tanneries remain weak, leading to severe pollution and undermining the sector’s sustainability” (p. 87). This enforcement gap creates a space where informal practices and non-compliance become normalized, ultimately stifling the sector’s potential for value addition and export growth [65].

1. Prioritization of economic growth

A recurring theme in Ethiopian industrial policy is the tension between environmental protection and economic targets. Law enforcement bodies often struggle to prioritize environmental crimes, as the government frequently prioritizes rapid industrialization and foreign currency earnings over stringent ecological adherence [66]. This “economic-first” approach can lead to a perception among tanners that environmental regulations are secondary to production volume.

2. Fragmentation of law enforcement

Effective waste management is often hindered by a lack of coordination between the Environmental Protection Authority (EPA) and other law enforcement agencies, such as the police. Research indicates that police organizations often assign low priority to industrial waste-related crimes compared to traditional criminal activities, largely due to a lack of awareness regarding the severity of environmental impacts [66].

3. Institutional resource constraints

The EPA, despite being mandated to oversee environmental standards, often lacks the specialized human resources and advanced technology required for rigorous monitoring and inspection. In regions like Modjo and Bahir Dar, where tanning clusters are prominent, the lack of separate environmental units within the factories themselves means that many tanneries continue to discharge untreated or poorly treated waste into local water bodies like the Modjo River [67].

4. Limited private sector engagement

Many Ethiopian tanneries do not view waste utilization as a viable business model. There is a lack of “green supply chain”



thinking, where environmental practices like eco-design or investment recovery are seen as operational costs rather than opportunities [67]. This is compounded by the high cost of adopting cleaner technologies, such as enzymatic unhairing to replace hazardous sodium sulfide [42].

Summary of key challenges Table

Challenge Category	Key Issues
Legal/Policy	Comprehensive policies exist (e.g., Proclamation No. 295/2002), but enforcement is inconsistent.
Institutional	EPA and local authorities lack the tools and manpower for continuous inspection.
Economic	Small-scale tanneries lack the financial capital to invest in waste-to-value technologies.
Technical	Lack of localized research on the conversion of solid waste (fleshing, trimmings) into marketable products.

Conclusion

A comprehensive literature review on the application status of cleaner technologies and sustainable waste utilization in Ethiopian leather industries reveals that, despite the sector's strategic importance for export earnings, employment, and utilization of livestock by-products, adoption of environmentally sound practices remains limited and largely at a pilot or experimental stage. Traditional chrome tanning and conventional beamhouse processes dominate, generating substantial pollution loads including high chemical oxygen demand (COD), biochemical oxygen demand (BOD), total dissolved solids (TDS), chromium, and sulfides in effluents, as well as significant solid wastes such as fleshings, trimmings, and finished leather scraps.

Cleaner production (CP) technologies such as enzymatic unhairing, hair-save liming, salt-free or low-salt curing/pickling, ammonium-free deliming, high-exhaustion chrome tanning, and chrome-free alternatives (e.g., vegetable or mineral tanning with nanomaterials)—have been documented as effective in reducing pollution by 30–90% in water and solid waste parameters in general leather processing contexts. However, their application in Ethiopia is constrained by high upfront costs, inadequate technical infrastructure, limited local expertise, and weak enforcement of environmental regulations. Sociotechnical barriers, including insufficient green design integration and regulatory compliance, further impede the transition to sustainable manufacturing practices (SMPs) with technical performance and social development identified as primary causal drivers for broader environmental, economic, and regulatory improvements.

On sustainable waste utilization, Ethiopian studies highlight promising valorisation routes for both solid and liquid wastes to support a circular economy. Finished leather scraps and plant fibers (e.g., jute, sisal, hibiscus, palm, enset) have been successfully combined into value-added composite boards and consumer products (e.g., insoles, wallets, handbags, furniture components) exhibiting superior mechanical properties (tensile strength, flex resistance, thermal stability)

compared to recycled leather controls. Fleshing wastes show potential for biodiesel production, while broader tannery biomass (collagen, fats, keratin) can yield biomaterials, biofertilisers, biogas, and surfactants. Quantification efforts indicate substantial waste generation rates across the sector, underscoring the economic and environmental imperative for scaled utilization. Nonetheless, these approaches remain largely laboratory- or small-scale demonstrations, with limited industrial uptake due to technological, financial, and market barriers.

Overall, the literature portrays an industry at a crossroads: economic potential is high, but persistent reliance on end-of-pipe solutions and conventional processes perpetuates environmental degradation, particularly in clusters around Addis Ababa and other tanning hubs. Emerging initiatives (e.g., enzymatic unhairing and waste-to-fertiliser pilots) signal progress, yet systemic gaps in policy enforcement, capacity building, and technology transfer hinder widespread application.

Recommendations

To accelerate the shift toward cleaner technologies and sustainable waste utilisation in Ethiopian leather industries, the following evidence-based recommendations are proposed:

Policy and regulatory strengthening: Mandate adoption of CP benchmarks (e.g., low-sulfide/enzymatic beamhouse processes, chrome recovery systems) through updated standards and incentives such as tax breaks or subsidies for compliant firms. Regular supervision and site-specific waste management plans should be enforced as critical.

Technology transfer and local adaptation: Prioritise dissemination of proven CP options, including enzyme-based unhairing, saltless curing with local plant extracts (e.g., *Rumex abyssinicus*) and chrome-free tanning systems. Government and international partners (e.g., UNIDO models) should facilitate pilot scaling and cost-benefit analyses tailored to Ethiopian contexts.

Investment in waste valorisation infrastructure: Establish dedicated facilities or public-private partnerships for composite board production, biofertiliser generation from fleshings/hair, and biogas recovery. Leverage findings from Ethiopian trials to commercialise products for domestic and export markets, turning waste into wealth.

Capacity building and research: Implement targeted training programmes for tannery operators on SMPs and conduct further R&D on nanotechnology-enhanced CP, full-chain life-cycle assessments, and economic modelling of circular approaches. Collaboration between academia (e.g., Bahir Dar University leather engineering programmes), Leather Industry Development Institute (LIDI) and industry is essential.

Monitoring, evaluation, and stakeholder engagement: Develop key performance indicators for pollution reduction and waste recovery rates, with third-party audits. Engage stakeholders across the value chain, including smallholders, exporters, and communities, to ensure socially inclusive transitions.

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