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A HOLISTIC APPROACH TO SUSTAINABILITY: ASSESSING THE ENVIRONMENTAL IMPACTS OF TEXTILE AND LEATHER INDUSTRIES IN ETHIOPIA

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ABSTRACT

Textile and leather industries drive economic growth worldwide, yet their heavy use of resources takes a serious toll on the environment. In Ethiopia, the rapid expansion of these sectors has accelerated growth without effective environmental safeguards, and no comprehensive environmentally predictive impact assessment planning model is in place. Furthermore, existing strategies are uncoordinated and are not and will not be effective in solving the multifaceted issues of the related consequences from unmonitored, unregulated production supply chains. This study, using multi-source data, including peer-reviewed research, documents from regulating authorities, and operational documents, assesses the environmental impact caused by Ethiopia's textile and leather industries and the related public health impact. Previous findings show that factory effluents in Ethiopia regularly exceed legal discharge limits, with Chemical Oxygen Demand (COD) climbing to 850.75 mg/L and chromium levels hitting 3.54 mg/L. These pollutants damage aquatic life, contaminate soils and crops, and cause serious health issues, including a 67% dermatitis rate among tannery workers. Recent records show that pollution levels across Ethiopia's textile and leather supply chains remain alarmingly high. This indicates that the conventional end-of-pipe treatment approach is no longer effective. Based on the evidence gathered, this review proposes a holistic sustainability framework built on circular economy principles, cleaner production technologies (such as chromium recovery and enzymatic processing), and stricter policy enforcement. Ethiopia's industrial, social, and ecological economic growth integrated approach will provide a relevant model of sustainable development to achieve low-resource rehabilitation and integrated environmentally/socially hand improvement within the economy's industrialized society.

KEYWORDS: Textile and leather industries, environmental impact, wastewater pollution, holistic sustainability

1. INTRODUCTION

The textile and leather industries are vital to the global economy, particularly for developing nations, serving as major sources of employment and export revenue. The global textile and apparel market, valued at approximately USD 1.11 trillion in 2024, is projected to grow to USD 1.61 trillion by 2033, driven by fast fashion and rising disposable incomes. [1, 2]. Similarly, the leather goods market, estimated at USD 253.82 billion in 2023, is forecast to expand to USD 405.28 billion by 2030, underpinning a global trade valued at US $100 billion annually. [3, 4]. **However, this economic significance is intrinsically linked to a formidable environmental burden. These industries are among the world's most polluting, characterized by staggering resource consumption: the textile sector alone uses an estimated 93 billion cubic meters of water annually, while leather processing is chemically intensive, generating over 4 million tonnes of solid waste each year** [2–4]**.**

It is within this global context that Ethiopia's situation becomes a pressing subject for study. Ethiopia is actively positioning itself as a premier manufacturing hub in Africa, with the textile and leather sectors serving as critical pillars for export revenue, foreign direct investment, and employment generation [5]. This rapid industrialization offers immense economic opportunities but risks replicating the severe environmental degradation witnessed in other industrializing regions, such as the Hazaribagh tannery zone in Bangladesh [6].

The environmental footprint of these sectors is extensive; they are notoriously water-intensive and generate enormous volumes of highly contaminated effluent, often discharged untreated into the environment. Textile wastewater is laden with toxic synthetic dyes, heavy metals, and chemicals, characterized by dangerously high levels of chemical oxygen demand (COD) and biological oxygen demand (BOD), which devastate aquatic ecosystems [7–10]. Similarly, the tannery industry generates effluent containing high concentrations of chromium from the predominant chrome-tanning process, which is recognized as a significant source of surface water pollution [11–15].

Consequently, this rapid industrial expansion in Ethiopia presents a profound paradox: the pursuit of economic growth is intrinsically linked to severe and multifaceted environmental degradation. Conventional, fragmented assessments focusing on isolated issues like wastewater or solid waste have proven inadequate to address these interconnected challenges. **A**

critical knowledge gap persists: the lack of an integrated, holistic approach that examines the entire value chain and provides a coherent strategy for sustainable development. This study aims to bridge this gap by addressing two primary objectives: (1) to systematically synthesize the quantitative and qualitative evidence on the environmental impacts of Ethiopia's textile and leather industries, and (2) **based on this synthesis, to develop an evidence-based holistic sustainability framework to mitigate these impacts and guide future policy and practice.**

This paper is structured into six main sections. Following this introduction, Section 2 details the systematic literature review methodology. Section 3 presents the results of the review, covering the current status of the industries and a synthesis of their environmental impacts. Section 4 discusses these findings, situating them within a comparative global context and presenting the evidence-based holistic sustainability framework. Section 5 examines the persistent challenges and future pathways for sustainable development. Finally, Section 6 provides the conclusion, specific recommendations, and a discussion of the study's limitations.

2. METHODOLOGY

This study employed a systematic literature review (SLR) to provide a comprehensive and transparent analysis of the environmental impacts of Ethiopia's textile and leather industries. The review followed a structured process comprising three stages: planning, execution, and synthesis, as outlined below.

2.1 RESEARCH DESIGN AND QUESTIONS

The review was designed to answer the following main review questions (RQs):

RQ1: What is the current operational and economic status of the textile and leather industries in Ethiopia?

RQ2: What are the primary environmental impacts and pollution characteristics of these sectors within the Ethiopian context?

Based on the synthesis of RQ1 and RQ2, what evidence-based holistic framework can be developed to mitigate these impacts and guide sustainable development?

2.2 SYSTEMATIC LITERATURE REVIEW PROCESS

The SLR was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

2.2.1 SEARCH STRATEGY

A comprehensive literature search was performed using Scopus and Google Scholar. Search terms included combinations of "textile industry," "tannery industry," "environmental impacts," "wastewater management," "chemical use," "solid waste generation," and "holistic approach," all contextualized within "Ethiopia." The search was limited to English-language publications from 2000 to 2024 to ensure contemporary relevance.

2.2.2 INCLUSION AND EXCLUSION CRITERIA

Studies were selected based on predefined criteria to ensure relevance and quality. Peer-reviewed articles, conference proceedings, theses, and reports from organizations such as UNIDO and the World Bank were included if they contained empirical data or theoretical analysis on pollution, environmental impacts, or mitigation strategies relevant to Ethiopia or comparable developing contexts. Excluded were editorials, opinion pieces, news articles, and studies lacking an environmental focus.

2.2.3 SCREENING AND SELECTION PROCESS

The selection process is summarized in a PRISMA flow diagram as shown in **Figure 1**. Initial database searches yielded 355 records. After removing 15 duplicates, 340 records were screened by title and abstract, resulting in the exclusion of 190 records. The remaining 150 full-text articles were assessed for eligibility, and 20 were excluded for not meeting the inclusion criteria. This left a final corpus of 130 studies for qualitative synthesis.

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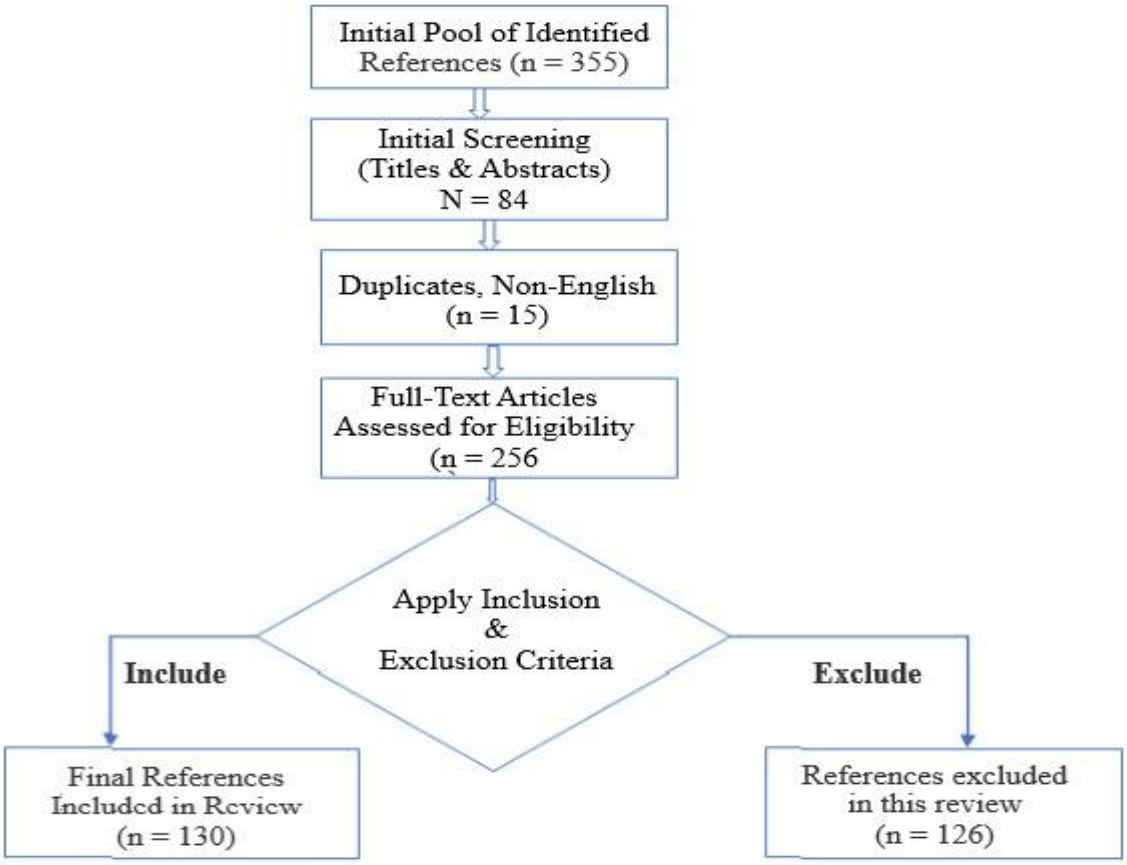

Figure 1: PRISMA flow diagram illustrating the process of study selection for the systematic review.

2.2.4. DATA ANALYSIS AND SYNTHESIS

The quality of included empirical studies was assessed using the Joanna Briggs Institute (JBI) critical appraisal checklist [16]. Each study was rated as high, moderate, or low quality based on criteria such as clarity of aims, appropriateness of study design, and robustness of analysis. These ratings informed the weighting of evidence during synthesis.

Data from the 130 studies were extracted into a standardized template capturing study location, methodology, key pollutants, environmental impacts, and proposed mitigation strategies. Thematic analysis, supported by NVivo 12 software, was used to identify recurring themes such as water pollution parameters, soil contamination, health impacts, and policy gaps. These themes were synthesized to construct a coherent narrative addressing RQ1 and RQ2. Conflicting evidence was resolved by prioritizing recent, peer-reviewed studies with high JBI scores.

2.3. FRAMEWORK DEVELOPMENT

The holistic sustainability framework (addressing RQ3) was developed through an iterative process grounded in the review's empirical findings. First, key environmental "hotspots"—such as untreated effluent discharge, chromium pollution, solid waste accumulation, and weak regulatory enforcement were identified from the synthesized evidence. These hotspots were then analyzed against established sustainability principles (e.g., UN Sustainable Development Goals, circular economy concepts) and compared with successful interventions documented in similar contexts (e.g., chromium recovery in India, effluent treatment plant enforcement in Bangladesh). Mitigation strategies extracted from the literature were grouped into four interdependent pillars: technological innovation, circular economy integration, strengthened governance and enforcement, and social and capacity development. The framework was refined iteratively by the author team to ensure consistency with Ethiopian industrial realities and was cross-referenced with local case studies to validate its applicability.

3. RESULTS OF THE SYSTEMATIC REVIEW

3.1 CURRENT STATUS OF THE TEXTILE AND LEATHER INDUSTRIES IN ETHIOPIA

The leather lifecycle begins at slaughterhouses; however, in developing regions, hides and skins are often collected by traders from rural butchers and households before being sold to tanneries for processing into finished leather [17]. The tanning industry is a significant global economic sector. From 2015 to 2020, data indicates that developing nations, including China, India, and Brazil, ranked among the world's top leather producers [18]. Collectively, the leading manufacturing countries China, Brazil, Russia, India, and Italy account for approximately 54.2% of global production. **Figure 2** illustrates

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the dominance of developing economies like China and India in global leather production. This places Ethiopia, as an emerging producer, in direct competition within a value-driven market. **To compete effectively, the sector may need to adopt cleaner technologies and sustainability practices to establish a competitive advantage based on quality and environmental stewardship, a strategy that aligns with national industrial policy goals** [19, 20]**.**

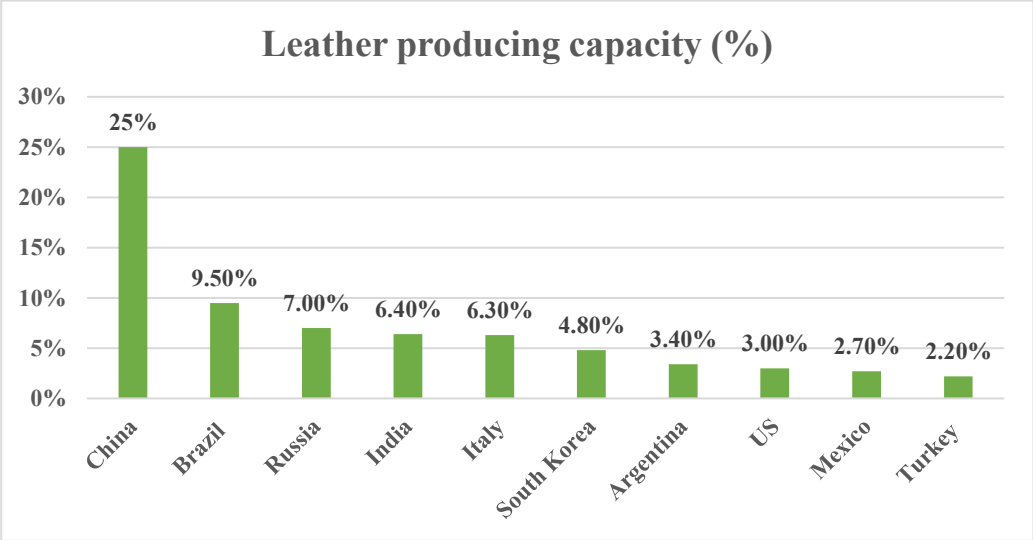

Figure 2: Top Ten Leather Producing Countries in 2020

(Source: ComTrade)

Ethiopia possesses substantial livestock resources, with a national herd of cattle, sheep, and goats that reached approximately 56.5 million head in 2022, forming the foundation of a formal leather and leather products (LLP) sector with a nearly century-long history [19]. However, despite this significant resource base, Ethiopia does not appear among the top ten leather-producing countries listed in **Figure 2**, indicating a gap between raw material availability and finished leather production. This sector is structured as a vertically integrated value chain, beginning with small-scale farmers who dominate livestock production. Their output is channeled through collectors and local traders to tanneries, which process raw hides into wet blue, crust, and finished leather. This finished leather is either exported directly or supplied to domestic manufacturers of goods such as footwear, gloves, bags, and jackets. A significant constraint for these local manufacturers is their heavy reliance on imported inputs, including soles and various accessories. Nonetheless, the sector is identified as a strategic priority for national development, with the potential to significantly boost foreign exchange earnings, generate employment, and attract foreign direct investment (FDI). This potential is underpinned by Ethiopia's status as Africa's leading and the world's tenth-largest livestock producer [19], approximately 24.5% to 48.3% between 2013 and 2022 illustrated in Figure 3.

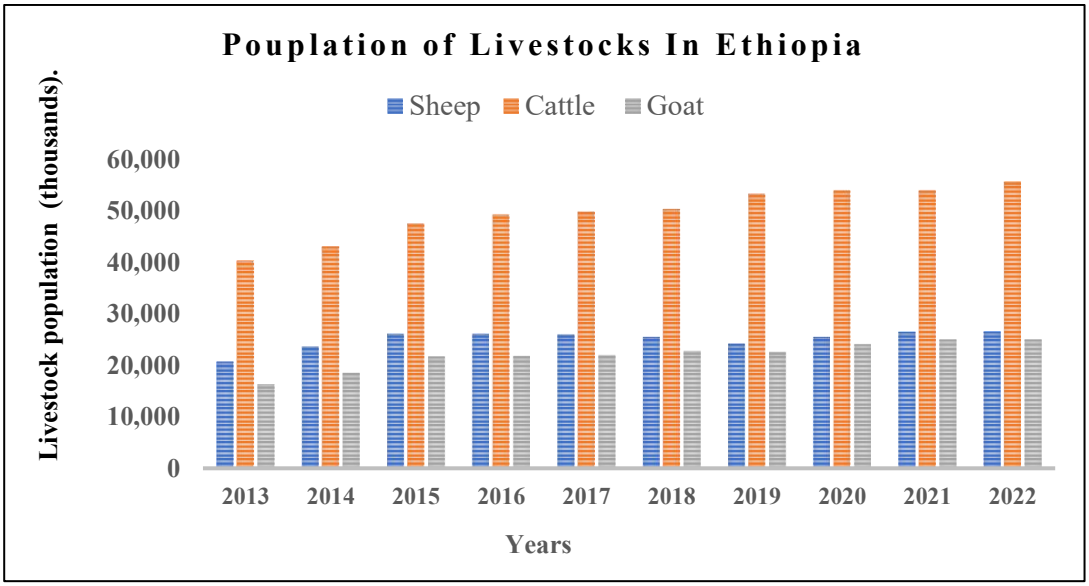

Figure 3: Livestock population of Ethiopia, from 2012–2022 (thousands).

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The data presented ends in 2022, as this was the latest comprehensive national dataset available at the time of the primary studies included in this review [19] . More recent disaggregated data were not consistently available in the peer-reviewed literature at the time of this synthesis.

According to UNIDO (2023), Ethiopia's livestock sector is a cornerstone of its economy, contributing a quarter of the national GDP and 40% of the agricultural GDP. Maximizing the economic benefits from these abundant resources is therefore crucial for national development. The leather industry is a prime candidate for this, being a leading export item (**Figure 4**) with significant potential for growth. Moreover, **Figure 4** highlights the leather industry's prominence within Ethiopia's manufacturing export profile, demonstrating its strategic economic role. This prominence underscores its potential as a driver of national industrial growth and foreign exchange earnings. However, this strong export focus must be balanced with investments in domestic waste treatment and sustainable practices to ensure long-term environmental and economic resilience, rather than prioritizing volume over value and sustainability.

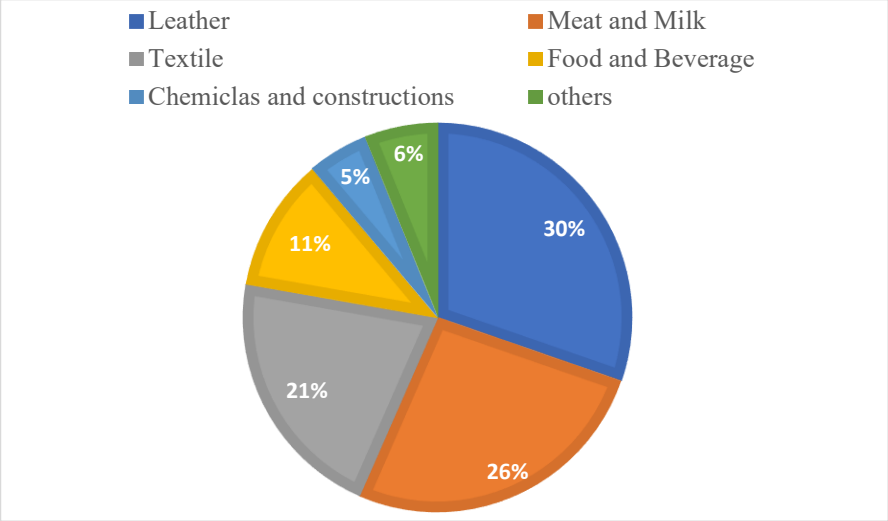

Figure 4: Manufacturing export product of Ethiopia

The sector exports finished leather products to various countries, with China constituting the largest export market. **Figure 5** clearly demonstrates Ethiopia's strategic economic position in the global leather market, with China as its dominant export destination. **This trade dependency presents both an opportunity and a vulnerability, as it exposes the sector to geopolitical and market risks while providing a stable revenue stream** [20].

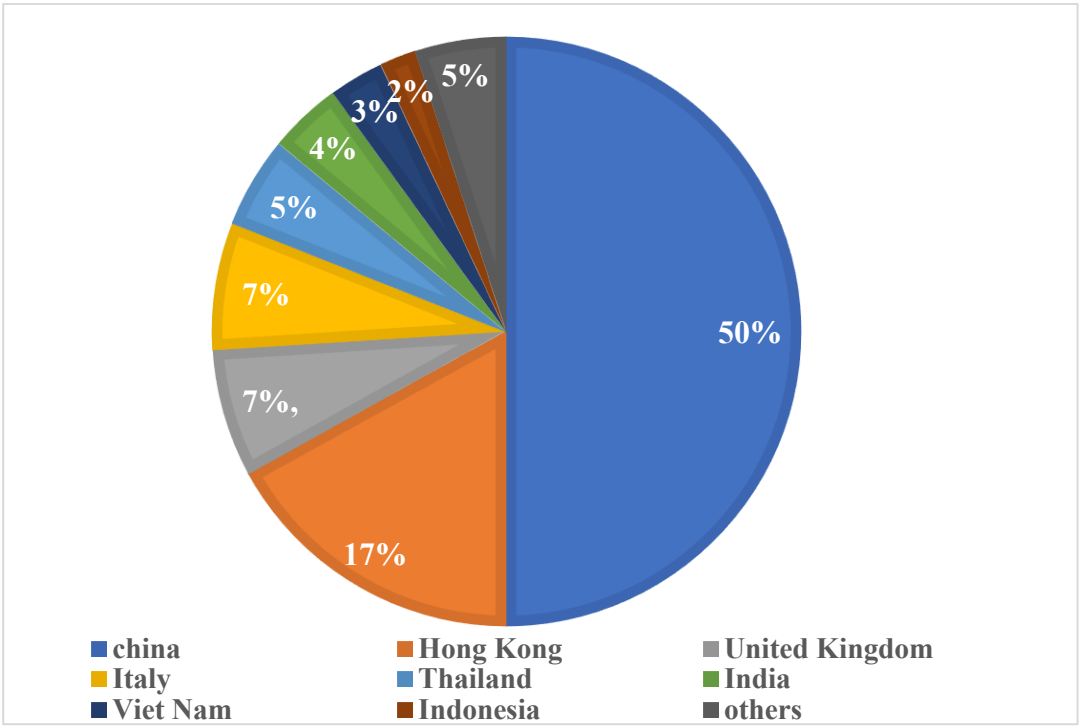

Figure 5: Finished Leather Export Destination

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The global textile industry represents a significant economic powerhouse, characterized by a well-documented shift in production from developed to developing nations. This transition is largely driven by the competitive advantages these countries offer, particularly in manufacturing capabilities and lower labor costs. As this production grows, the industry has solidified its role as one of the most vital sources of economic activity worldwide, especially within developing economies where it is often the second-largest industrial employer and contributor to GDP [21]. The sector's impact is immense, supporting an estimated 120 million jobs directly and generating an annual market value of approximately $2,000 billion globally. Current market analysis underscores this robust and continuous expansion. As illustrated in **Figure 6**, the global textile market size was valued at an estimated USD 1,976.84 billion in 2024. Projections indicate a strong upward trajectory, with the market expected to reach USD 2,123.72 billion in 2025 and grow to approximately USD 4,016.50 billion by 2034. This represents a compound annual growth rate (CAGR) of 7.35% over the forecast period from 2025 to 2034. A primary catalyst for this sustained growth is the rising international demand for natural fibers, which continues to drive innovation and investment throughout the textile value chain. Consequently, the industry remains a critical engine for economic development, despite the parallel and significant environmental challenges associated with its scale and processes.

Figure 6: Textile Market Size and Growth 2024 to 2034

(Source: https://www.precedenceresearch.com/)

The global textile industry is a major economic driver, with leading nations generating $592.8 billion in textile exports in 2024 . **Figure 7Error! Reference source not found.** confirms China's dominance as the world's leading textile exporter, establishing a high-volume, competitive benchmark for emerging producers like Ethiopia. **Literature suggests that to compete in this landscape, emerging economies like Ethiopia can focus on differentiation strategies, including sustainability and supply chain transparency, to carve out a distinct market position** [21].

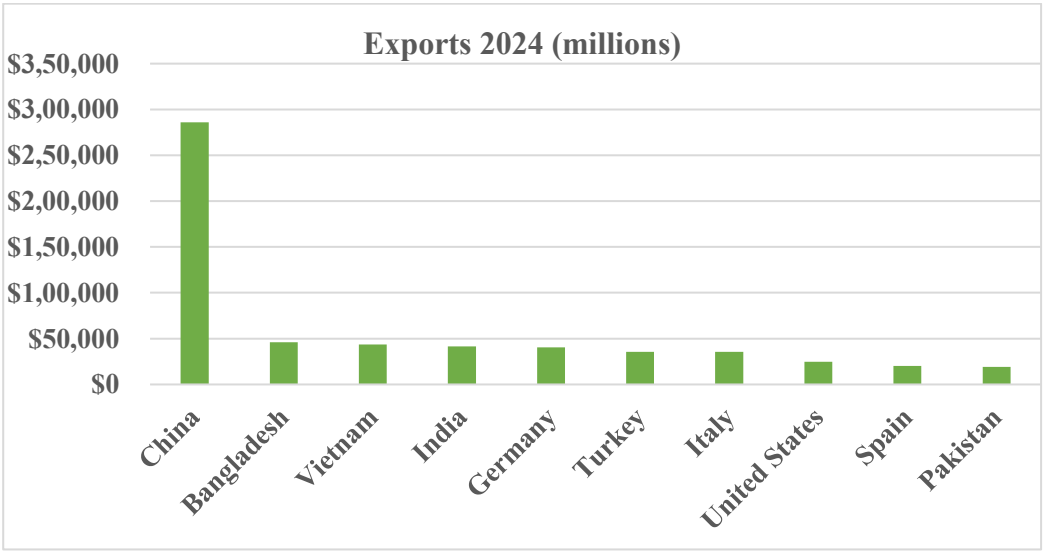

Figure 7: Most textile manufacturing countries in the world in 2024

(Source: https://www.royaleuropetextile.com)

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3.2 ENVIRONMENTAL IMPACTS OF TEXTILE AND LEATHER INDUSTRIES

3.2.1 SOURCE AND CHARACTERIZATION OF TEXTILE EFFLUENTS IN ETHIOPIA

The textile dyeing industry is a major source of global water pollution, accounting for an estimated 17–20% of industrial wastewater contamination [22]. The effluent from conventional dyeing processes contains a high concentration of pollutants, including salts, unfixed dyes, surfactants, acids, and various auxiliary chemicals. Salts alone can constitute up to 50% of the effluent, leading to elevated levels of total dissolved solids (TDS), chemical oxygen demand (COD), and biological oxygen demand (BOD) [22, 23]. The presence of organic and inorganic compounds from dyes and auxiliaries directly increases COD and BOD, severely degrading water quality. Consequently, textile wastewater is characterized by extreme fluctuations in critical parameters, including COD, BOD, TDS, colour, pH, and salinity [24–26].

Total Dissolve Solid (TDS): Total Dissolved Solids (TDS) represent the soluble inorganic salts, such as sodium and calcium, in textile wastewater [27–30]. Analytically, TDS is calculated by subtracting the measured Total Suspended Solids (TSS) from the Total Solids (TS). These elevated TDS levels significantly contribute to water pollution. Modern practices efficiently monitor this parameter using portable meters [31, 32].

Colors: The visible colour in textile effluent, while attracting significant public and regulatory attention, is often not a mandated parameter [27, 29, 33, 34]. However, from a technical and environmental health perspective, it is secondary to parameters like Biological Oxygen Demand (BOD), which directly threaten aquatic ecosystems by depleting oxygen. Decolorization thus addresses aesthetic and social concerns more than core pollution.

Biological oxygen demand (BOD): is a key water quality metric, measuring the dissolved oxygen (mg/L) required by aerobic microbes to decompose organic matter over a set period, typically five days (BOD_5) [35, 36]. The organic load in discharged textile effluent stimulates microbial activity, depleting oxygen and directly threatening aquatic life. These microorganisms decompose the organic pollutants through aerobic respiration, ultimately converting them into stable inorganic end products such as carbon dioxide (CO_2), sulfates (SO_4^{2-}), phosphates (PO_4^{3-}), and nitrates (NO_3^-) [23, 37, 38]. This process can be represented as:

$$\text{Organic matter} + \text{Bacteria} \rightarrow CO2 + H2O + \text{new cells} + \text{stable products} \quad (1)$$

When oxygen is insufficient, anaerobic decomposition occurs, producing undesirable byproducts such as H_2S, NH_3, and CH_4 [23, 37, 39]. Moreover, when oxygen becomes depleted, anaerobic decomposition occurs, producing undesirable byproducts and shown in equation (2).

$$\text{Organic matter} + \text{Bacteria} \rightarrow CO2 + CH4 + \text{new cells} + \text{unstable products} + H2S + NH3 \quad (2)$$

The BOD value (in mg/L) is fundamentally determined by the microbial population and their metabolic activity [40]. A high BOD value indicates severe oxygen depletion, posing a critical threat to aquatic ecosystems.

$$BOD = N \times R \quad (3)$$

where N represents the number of aerobic microorganisms and R denotes their metabolic rate.

For instance, in the Bahir Dar textile factory, influent BOD levels were high, averaging 150.25 mg/L, with some measurements reaching up to 163.2 mg/L. Although treatment reduced the concentration, the effluent BOD averaged 48.45 mg/L, consistently exceeding the national discharge limit of 40 mg/L. This persistent organic pollution depletes dissolved oxygen in receiving waters, threatening fish and other aerobic aquatic organisms [41]. ***Figure 8*** illustrates the methodology for measuring Biological Oxygen Demand (BOD). It typically shows two water samples: one measured for initial dissolved oxygen (DO) and another incubated for five days at 20°C before measuring final DO. The difference in oxygen levels (BOD) indicates the organic pollution load, as oxygen is consumed by microorganisms decomposing organic matter.

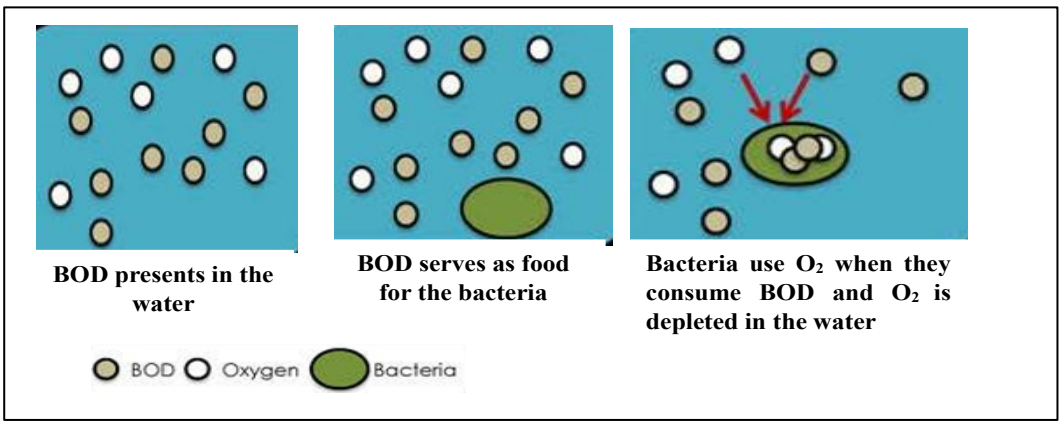

Figure 8*:* Measuring of Biological Oxygen Demand (BOD)

Chemical Oxygen Demand (COD): is a vital water quality parameter, offering a rapid alternative to the 5-day Biological Oxygen Demand (BOD) test. It measures the oxygen equivalent of organic matter chemically oxidized, typically using potassium dichromate (Equation 4) [23, 42–44]. COD quantifies total oxidizable material, including both biodegradable and non-biodegradable components, whereas BOD assesses only the fraction broken down by microbes. Consequently, COD values are always higher than BOD for the same effluent [33, 39, 45].

Dissolved Oxygen (DO) concentration, critical for sustaining aerobic aquatic life, is optimally maintained between 6.5 and 8 mg/L [39, 46–49]. DO enters water via atmospheric diffusion and photosynthesis. However, the oxidation of organic pollutants, indicated by high COD and BOD, consumes this oxygen. Discharging effluent with a high organic load leads to microbial decomposition that can deplete DO to critically low levels. This process is worsened by algal blooms; subsequent bacterial decomposition of dead algae further consumes oxygen through respiration. This cascade can cause severe hypoxia, resulting in fish kills and mortality of oxygen-dependent organisms. Therefore, controlling COD is essential for protecting aquatic ecosystem health. [50, 51]. The oxidation reaction is represented as:

$$\text{Organic Matter} + Cr_2O_7^{-2} \rightarrow Cr^{-3} + CO_2 + H_2O \quad (4)$$

pH: measures the acidity or alkalinity of textile dyeing effluent, which is the negative logarithm of hydrogen ion concentration. Most aquatic life requires a narrow pH range of 6–9. Textile wastewater is often highly alkaline (pH 9–11) due to compounds like hydroxides, which harm ecosystems and soil. This necessitates neutralization to approximately pH 7 before safe discharge [31, 42, 52–54]

Sulphur and Sulphides: wastewater contains various sulfur compounds, including sulfate, which can rapidly convert to sulfide under low-oxygen conditions caused by high biological oxygen demand (BOD). This process generates hydrogen sulfide, a highly toxic gas with a foul odor, which also poses operational challenges for biological treatment systems [25, 27, 29, 55, 56]. Furthermore, the effluent also contains oil and grease, which form surface films. These films block light, impair photosynthesis, and inhibit oxygen transfer, depleting dissolved oxygen and disrupting aquatic ecosystems and treatment processes [27, 29, 57, 58].

Key pollutant parameters in Ethiopian context: In Ethiopia, studies consistently report effluent parameters exceeding national standards. As a result, the pollution characteristics of Ethiopian textile wastewater are particularly alarming. Studies conducted near major industrial clusters consistently report parameter values far exceeding the Ethiopian Environmental Protection Authority (EPA) standards. For instance, Dadi et al. (2017) **reported that, in the Gelan and Dukem industrial zones of Oromia, textile effluents exhibit COD levels ranging from 130.28 to 733.5 mg/L and BOD levels of 84 to 252 mg/L, which are up to 4.9 times and up to 5 times higher than permissible limits, respectively** [10]. **Similarly, Mehari et al. (2015) reported that the mean BOD_5 levels in the effluent from the Bahir Dar textile factory reached 40.3 mg/L at the discharge point, exceeding the International Finance Corporation (IFC) guideline of 30 mg/L for surface water discharge** [8]. High BOD depletes dissolved oxygen, endangering aquatic life. Azo dyes add complexity by causing intense coloration (absorbance >0.5) and releasing carcinogenic aromatic amines [59]. This reduces light penetration, inhibiting photosynthesis in plants and phytoplankton that form the base of aquatic food webs. **Key pollutant parameters from Ethiopian textile industries are summarized in Table 1.**

Table 1*:* Summary of key effluent parameters in Ethiopian textile industries

Parameter	Reported Range (Ethiopian Studies)	National Discharge Limit	Litratures
Chemical Oxygen Demand (COD)	130.28 – 733.5 mg/L	150 mg/L	[10]
Biological Oxygen Demand (BOD)	40.3 – 252 mg/L	40 mg/L	[8, 10]
Total Dissolved Solids (TDS)	> 2,500 mg/L	2,500 mg/L	[10]
pH	Up to 11.5	6–9	[10]

The chemical complexity of textile effluent stems from the diverse processes involved in textile manufacturing, as illustrated in **Figure 9**. Each stage from desizing and scouring to bleaching, dyeing, and finishing introduces specific pollutants into the wastewater stream. Desizing contributes starch, enzymes, and waxes; scouring adds alkalis, surfactants, and fats; bleaching introduces chlorine compounds and peroxides; while dyeing and finishing contribute the most problematic pollutants: synthetic dyes, heavy metals (from metal-complex dyes), and various toxic auxiliary chemicals [36].

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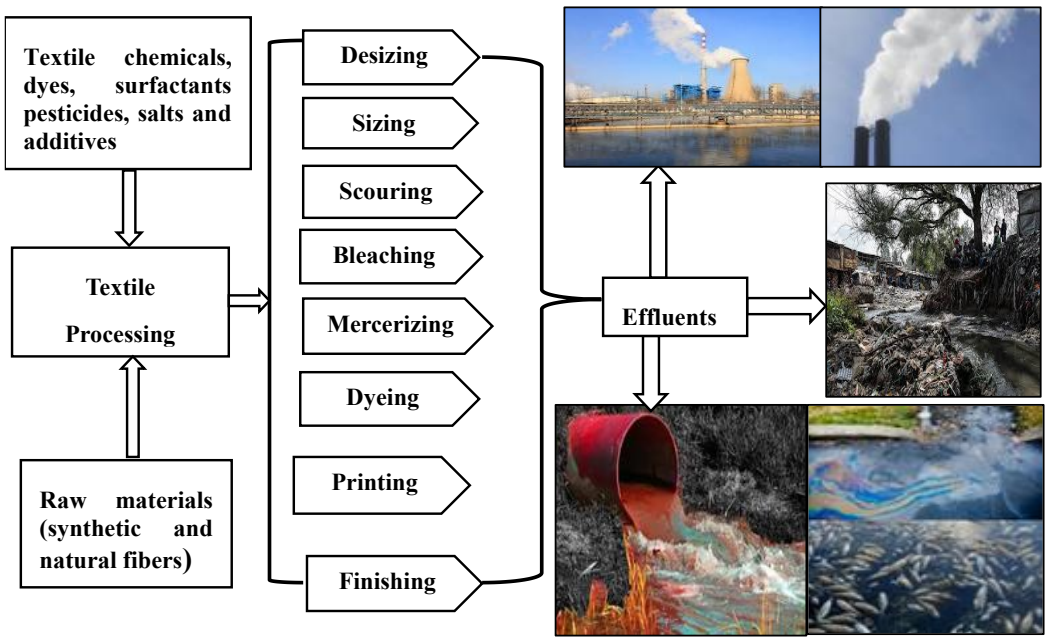

Figure 9*:* Source of textile effluents through entire operational process

3.2.2 SOURCE AND CHARACTERIZATION OF LEATHER INDUSTRY EFFLUENTS IN ETHIOPIA

The tannery industry is globally recognized as one of the most polluting manufacturing sectors, and in Ethiopia, this reputation is borne out by empirical evidence from major tanning clusters. The chrome tanning method, employed by approximately 85–90% of Ethiopian tanneries due to its efficiency and quality outcomes, is particularly problematic from an environmental perspective [60]. This process is almost entirely water-based, consuming 30–40 m^3 of water per ton of raw hides processed and releasing nearly 90% of this volume as highly contaminated wastewater [61, 62]

The pollution profile of Ethiopian tannery effluent presents a severe environmental challenge. Comprehensive analysis of wastewater from tanneries in Addis Ababa (particularly those discharging into the Akaki River system) [7], and Bahir Dar (impacting the Blue Nile headwaters) reveals consistent violations of national discharge standards [41]. The tanning stage alone contributes disproportionately to pollution, responsible for approximately 52% of sulfate pollution and 70% of chromium pollution in the complete manufacturing process [63, 64]. Overall, tannery wastewater is characterized by extremely high levels of biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, alkalinity, and specific pollutants like organic nitrogen, sulfide, and chromium [63–66]. A detailed study of the Bahir Dar tannery documented pH values of 7.1–8.3, BOD of 290–420 mg/L, COD of 780–1,050 mg/L, total suspended solids (TSS) of 1,200–1,800 mg/L, and total chromium concentrations of 2.8–4.1 mg/L [67]. Similarly , Faye & Sibali, (2025) reported tannery effluents in Ethiopia contain elevated levels of pollutants including chemical oxygen demand (COD) ranging from 1,070 to 6,755 mg/L and biological oxygen demand (BOD) ranging from 148 to 1,472 mg/L, along with total dissolved solids (TDS), chromium (Cr), sulfide (S^{2-}), and total nitrogen, all of which exceed national discharge limits and compromise water quality in rivers, notably the Little Akaki River [7]. Consequently, the Akaki River Basin exemplifies cumulative pollution, receiving untreated discharges from multiple tanneries. Locally termed "Leather River," it exhibits a characteristic contamination profile: persistently high chromium (up to 3.8 mg/L), elevated sulfides (25–65 mg/L), and severe organic loading, with chemical oxygen demand (COD) ranging from 850 to 1,350 mg/L. In addition, Gemeda et al. (2020) reported tannery wastewater exhibits high pollution loads, with chemical oxygen demand (COD) ranging from 2,517–5,450 mg/L and biological oxygen demand (BOD) from 460–1,024 mg/L. Alcohol industry effluents are even more extreme, with COD reaching up to 14,928 mg/L and BOD as high as 4,880 mg/L These values drastically exceed permissible discharge limits, indicating intense organic contamination that critically depletes river oxygen levels, threatens aquatic ecosystems, and compromises water quality, underscoring an urgent need for regulatory enforcement and treatment infrastructure [68].

The pollution pathway extends beyond liquid effluents to encompass solid wastes and air emissions. Tanneries generate approximately 200–250 kg of solid waste (including hair, fleshings, and trimmings) per ton of raw hides processed, much of which is disposed of in uncontrolled landfills or open dumps [69]. The degradation of protein-rich solid wastes produces offensive odors and attracts disease vectors, while chromium-laden sludge poses long-term contamination risks through leaching. The chemical processes involved in leather manufacturing, as depicted in **Figure 10**, contribute specific pollutants at each stage. Beamhouse operations (soaking, liming, unhairing) generate wastewater high in organic matter, sulfides, and lime; tanning contributes chromium, acids, and salts; while post-tanning operations (neutralization, retanning, dyeing,

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fatliquoring) add further complexity with synthetic tannins, dyes, and fatliquoring agents. This multi-stage pollution generation creates a wastewater stream that is not only highly toxic but also chemically complex, challenging conventional treatment approaches.

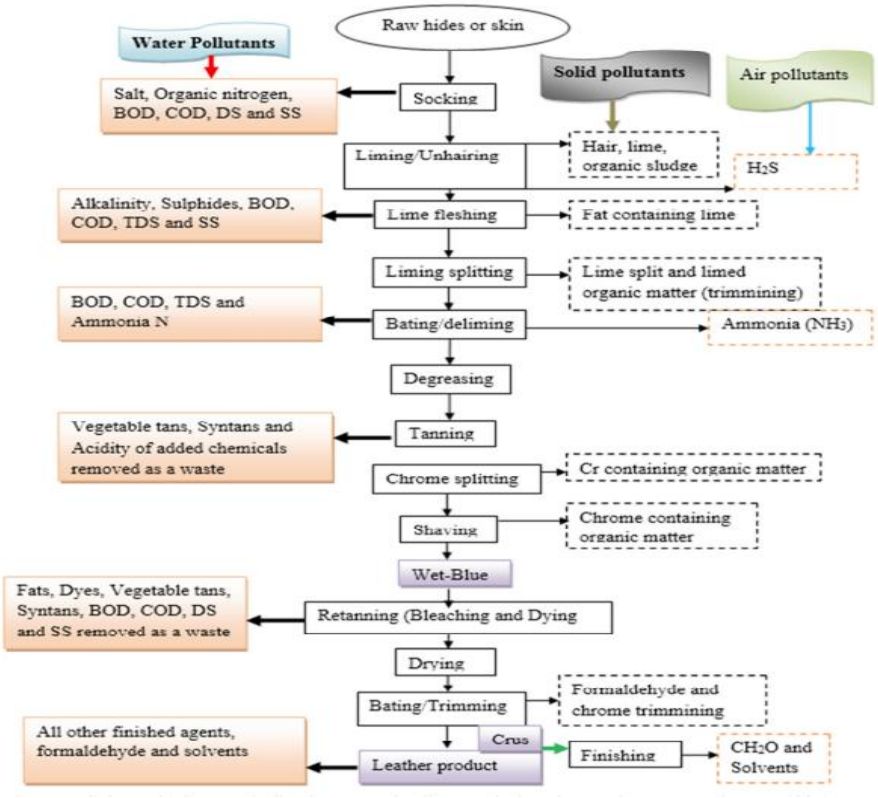

Figure 10*:* Source of ternary effluent in entire process of leather industry [66].

3.3 ENVIRONMENT IMPACTS OF TEXTILE AND LEATHER WASTE

In Ethiopia, the textile and leather sectors have experienced substantial growth, making a significant positive impact on national economic development, employment, and export earnings [70]. However, this rapid industrial expansion, particularly around areas like Addis Ababa, has intensified environmental pressures. Ethiopian textile and tanneries consume vast quantities of water and generate large volumes of liquid waste laden with organic, inorganic, and toxic elements. A critical environmental concern is that this effluent is frequently discharged without treatment into nearby rivers, lakes, agricultural fields, and landfills. Consequently, pollution from toxic waste has become a major socio-environmental issue, underscoring the urgent need for sustainable wastewater management practices to mitigate its detrimental effects [11, 71]. The specific impacts of this pollution in Ethiopia are discussed in the following section.

Soil: In Ethiopia, textile and tannery industries are significant sources of heavy metal contamination in agricultural soils, especially where wastewater is used for irrigation. This practice leads to the accumulation of metals such as cadmium, zinc, chromium, nickel, lead, and manganese in surface soils. Over time, the soil's capacity to retain these metals diminishes, allowing them to leach into groundwater or become available for plant uptake. Such contamination not only adversely affects plant health and reduces soil fertility but also poses serious risks to human health through the food chain [72–74].Irrigation with tannery wastewater, which is rich in chromium sulfate, results in notably high chromium concentrations in soil. Additionally, elevated phosphorus levels from these wastes can further contribute to water pollution [75, 76]. The release of harmful metals and chemicals degrades the physicochemical properties of soil, reducing its productivity and ecological value [77]. For instance, a study near Addis Ababa tanneries found soil chromium levels exceeding 500 mg/kg, far above background concentrations, directly linked to irrigation with contaminated water [78, 79].

Water: Water resources are equally impacted, as many textile and tannery facilities operate without effluent treatment plants, releasing wastewater directly into the environment [80, 81]. The presence of colored compounds reduces light penetration, affecting photosynthesis, while biodegradable organic matter depletes dissolved oxygen as it decomposes, harming aquatic organisms and promoting anaerobic conditions that release harmful gases. This contamination also poses direct risks to human health, causing skin irritations, allergies, and more severe conditions like cancer due to exposure to toxic substances [82, 83].

In Ethiopia, over 65% of industries are concentrated in Addis Ababa [84], with nearly 90% discharging untreated waste into nearby rivers [85]. Studies confirm that tannery effluents near the capital exceed national and international standards for

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chromium, sulfur, nitrogen, and chemical oxygen demand (COD), severely polluting local water resources [11, 86]. The Akaki
River, often called Leather River by downstream communities due to its association with tannery waste, is among the most polluted waterways in the country [87, 88]. Similarly, in Bahir Dar, industries including textiles and tanneries discharge waste directly into the headwaters of the Blue Nile River, degrading water quality and endangering communities who rely on it for drinking, irrigation, and fishing [8, 67]. A study by Mehari et al. (2015) provides concrete evidence that this pollution causes dissolved oxygen (DO) levels to plummet to near-zero [8]. This finding, combined with the contextual analysis of the area's water quality by Goshu & Aynalem (2017), demonstrates that industrial discharges are creating hypoxic conditions fatal to the aquatic ecosystem of the Blue Nile headwaters [89].This underscores the critical need for effective effluent treatment and regulatory enforcement to mitigate environmental and public health risks.

Plant: The use of untreated textile and tannery wastewater for irrigation has severe detrimental effects on plant health and agricultural productivity. This practice introduces toxic heavy metals such as cadmium, copper, lead, chromium, and mercury into the soil, which are then absorbed by crops. This leads to phytotoxic effects, including salinity stress that disrupts metabolic processes, reduces vegetative growth, and impairs respiration and photosynthesis. An increase in reactive oxygen species further damages plant cells. Consequently, germination is inhibited, growth is restricted, and yields of vital crops like maize, soybean, and wheat are significantly reduced [90, 91]. The accumulation of these metals in edible plants also enables their transfer through the food chain, resulting in biomagnification and posing serious risks to consumer health. According to a 2014 study by Girmaye, vegetables irrigated with the Awash River were found to have cadmium and lead concentrations exceeding FAO/WHO safety limits by 200-400% [92]..This is particularly concerning in Ethiopia, where urban agriculture relies on such polluted water for irrigation, jeopardizing both a critical food source and the livelihoods of low-income communities [93].

Health Problems: the health hazards extend beyond agriculture. Direct discharge of industrial effluents into water bodies introduces synthetic dyes and heavy metals that are toxic to all forms of life. Many dyes break down into carcinogenic compounds under anaerobic conditions and are harmful to aquatic ecosystems, inhibiting microbial growth and harming fish and mammals [94, 95]. Human exposure to these pollutants, whether through contaminated water or occupational contact, causes significant health issues. These include skin irritations, contact dermatitis, respiratory ailments, and allergic reactions. The heavy metals present, such as chromium, arsenic, and lead, are associated with liver damage, hematological disorders, and cancer [96, 97]. In Ethiopia, where chrome tanning is prevalent, tannery workers face particularly severe risks, including dermatological problems and systemic organ damage due to chromium's ability to oxidize and destroy cell membranes [98, 99]. A health assessment of tannery workers in Ethiopia revealed a significantly higher prevalence of dermatitis (67% vs. 15% in controls) and respiratory symptoms linked to chromium and sulfide exposure [100]. Thus, the unchecked release of this wastewater creates a pervasive threat to both environmental and public health.

3.4 ANALYSIS OF THE LITERATURE CORPUS

The analysis of the 130 references provides insights into the research landscape, revealing a field dominated by recent publications.

3.4.1 CLASSIFICATION BY PUBLICATION YEAR

The distribution of references by publication year reveals that over 78% were published within the last decade (2015–2024), highlighting the dynamic and evolving nature of research in this area (***Figure 11***). This underscores the timeliness of the review and the increasing recognition of sustainability challenges in Ethiopia's industrial sectors. Literature published prior to 2010 constitutes a negligible 2.4% of the total.

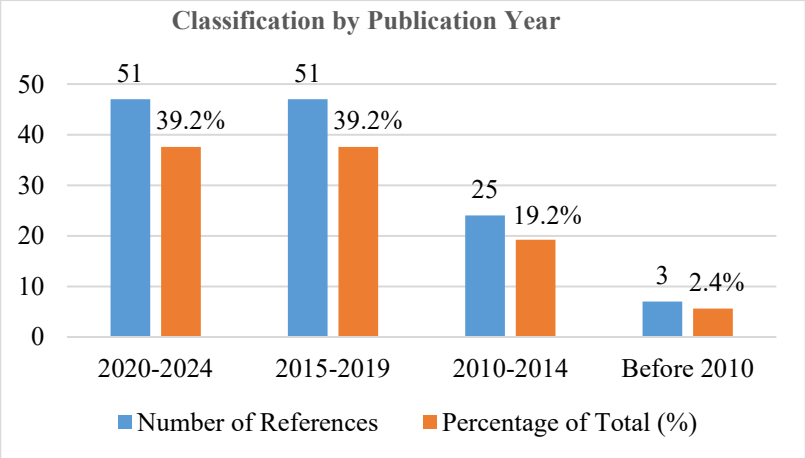

Figure 11: Classification of literature references by publication year.

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3.4.2 REFERENCE CLASSIFICATION BY TYPE

The review draws on a diverse range of source types, with a heavy reliance on peer-reviewed journal articles (74.6%) as shown in *Error! Not a valid bookmark self-reference.* , establishing a strong academic foundation for the review.

Table 2: Reference classification by type

Type of Material	Count	Percentage (%)
Journal Articles	97	74.6%
Books / Book Chapters	9	6.9%
Reports (Govt., UN, etc.)	8	6.2%
Conference Proceedings	5	3.8%
Theses / Dissertations	4	3.1%
Websites / Market Research	4	3.1%
Standards / Regulations	3	2.3%
Total	130	100%

3.4.3 CLASSIFICATION BY JOURNAL/PUBLISHER

The literature corpus is drawn from a mix of international high-impact journals and regionally focused publications, ensuring both global relevance and local specificity..

Table 3*:* Classification of literature references by journal/publisher.

Journal / Publisher	Focus Area	Number of References
Elsevier (e.g., J. of Cleaner Production, J. of Hazardous Materials, Chemosphere)	Environmental Science, Chemical Engineering, Sustainability	~30
Springer Nature (e.g., Environmental Science and Pollution Research, Applied Water Science)	Broad Environmental Science, Pollution Studies	~24
Taylor & Francis (e.g., International Journal of Environmental Science and Technology)	Environmental Technology, Engineering, Chemistry	~16
Wiley (e.g., Water Environment Research, Journal of Industrial Ecology)	Environmental Engineering, Water Research, Sustainability	~13
MDPI (e.g., Sustainability, Toxics, Water)	Broad Multidisciplinary, Fast-Paced Research	~12
Academic Journals (e.g., African J. of Environmental Sci. and Tech., Ethiopian J. of Health Dev.)	Regionally focused Environmental and Health Research	~18
Others (Reports from UNIDO, World Bank, Gov't Proclamations, other publishers)	Policy, Economics, Industry Reports, Diverse Fields	~17
Total	130	

This analysis, shown in ***Table 3***, reveals that the review is built upon a strong foundation of international, high-impact environmental science literature. Publishers like Elsevier and Springer Nature are the most cited, providing peer-reviewed studies on pollution characterization, treatment technologies, and sustainability frameworks. The significant number of references from Ethiopian academic journals and international organizational reports (~35 combined) highlights the review's successful integration of global scientific principles with critical local context, data, and policy analysis, which is central to its argument.

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3.4.4 CLASSIFICATION BY ENVIRONMENTAL MEDIA IMPACTED

The reviewed literature primarily focuses on water pollution, consistent with the dominant environmental challenge posed by textile and leather effluents.

Table 4: Classification of literature references based on impacted environmental media.

Impacted media	Specific focus areas	Number of references
Water	Wastewater characterization (BOD, COD, heavy metals), river pollution, aquatic ecosystem degradation, water quality monitoring.	~98
Soil	Heavy metal accumulation (e.g., Chromium), soil fertility degradation, contamination from solid waste and sludge.	~58
Human Health	Worker safety (dermatitis, respiratory issues), public health risks from contaminated food/water, carcinogenic effects.	~44
Plants/Agriculture	Phytotoxicity, reduced crop yield, heavy metal uptake in food crops, irrigation with polluted water.	~34
Air	Emissions from production processes, odour from wastewater.	~9

The classification of literature by environmental media shows water pollution dominates (75%), as shown in **Table *4***, reflecting the industries' water-intensive nature. Studies on soil and human health trace the pollution pathway, while fewer address air pollution. This focus validates the review's central argument on the primary vectors of environmental degradation.,

3.4.5 CLASSIFICATION BY POLLUTANT TYPE

The literature corpus systematically addresses the key pollutants associated with textile and leather manufacturing.

Table 5*:* Classification of literature references based on primary pollutant type.

Pollutant type	Key substances	Number of references
Heavy Metals	Chromium (Cr) from tanneries, Cadmium (Cd), Lead (Pb), Zinc (Zn) from effluents and sludge.	~70
Organic Load	High Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) from dyes, fats, and other organics.	~65
Synthetic Dyes & Colorants	Azo dyes, pigments, and color in textile wastewater.	~47
Salts & Solids	Total Dissolved Solids (TDS), chlorides, sulfates, suspended solids.	~40
Other Chemicals	Sulfides, acids, alkalis, pesticides, surfactants.	~32

The classification by pollutant in **Table *5*** identifies the specific chemical drivers of the documented environmental damage. Heavy metals, particularly chromium from the tanning industry, are the most frequently studied pollutant, directly linked to soil contamination and severe health risks. The high number of references focusing on the organic load (BOD/COD) underscores the role of these industries in depleting aquatic oxygen and disrupting ecosystems. The significant body of work on synthetic dyes highlights their dual role as visual pollutants and sources of toxic, sometimes carcinogenic, compounds. This taxonomy effectively maps the pollution characteristics that the review set out to synthesize.

3.5 THEMATIC SYNTHESIS AND VISUAL MAPPING

The classification and thematic analysis culminate in an integrated understanding of Ethiopia's textile and leather pollution profile, visually summarized in **Figure 12**. This thematic map synthesizes the five interconnected themes that emerged from the systematic review, illustrating both the direct impact pathways (solid arrows) and the systemic enabling factors (dotted arrows).

Three key insights emerge from this synthesis: First, water pollution acts as the primary vector, with parameters consistently exceeding standards by up to 5 times (e.g., COD 733.5 mg/L vs. EPA limits) [10]. Second, this pollution propagates through environmental media, affecting soil (chromium >500 mg/kg) [78], agriculture (crop yield reduction) [90], and public health (67% dermatitis among tannery workers) [100]. Third, structural challenges particularly weak enforcement of regulations like Proclamation No. 1090/2018 and technical skill shortages [95] create a permissive environment for continued pollution.

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The thematic map demonstrates that isolated interventions targeting single themes (e.g., wastewater treatment without addressing policy enforcement or worker training) are likely to fail. This visual synthesis directly informed the structure of the **evidence-based** holistic sustainability framework presented in Section 4.2, where each pillar corresponds to and addresses multiple interconnected themes identified in this review.

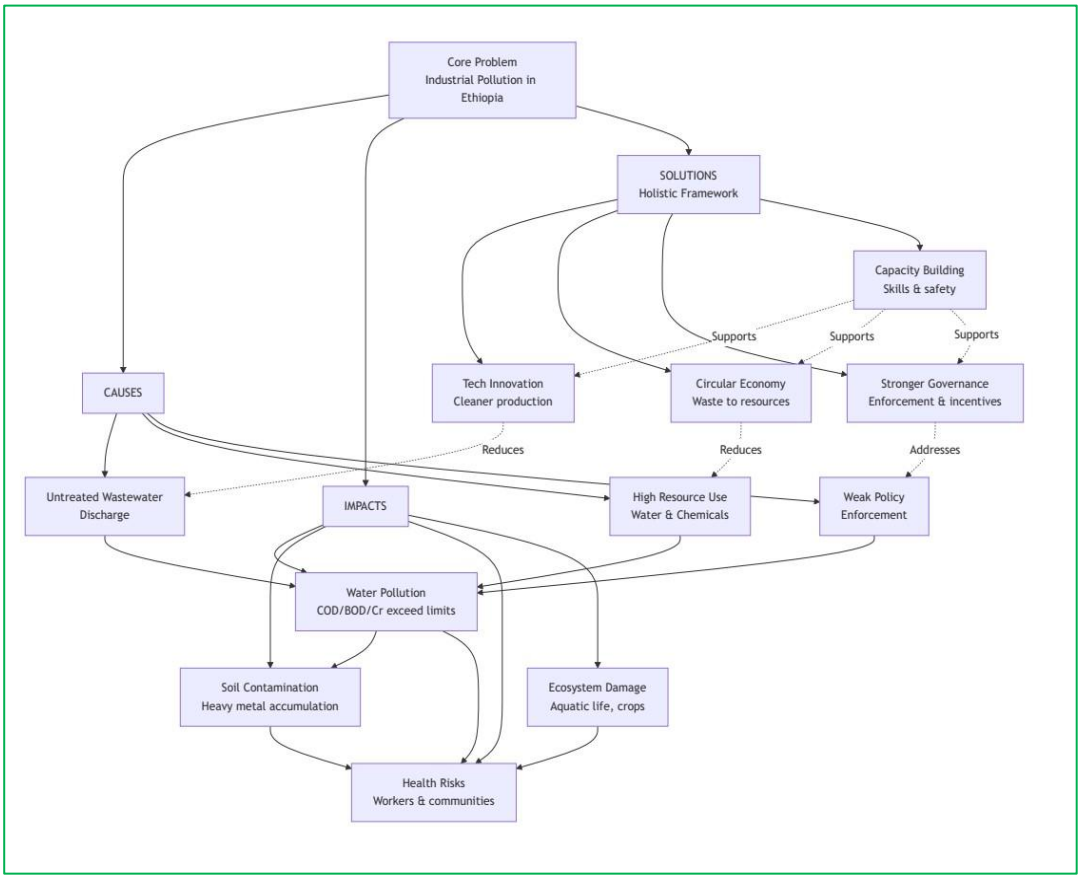

Figure 12: Thematic map synthesizing the key themes, interconnections, and systemic factors influencing the environmental impacts of Ethiopia's textile and tannery industries.

4. DISCUSSION

4.1 SYNTHESIS OF ENVIRONMENTAL CHALLENGES

The systematic review reveals a consistent and severe environmental crisis associated with Ethiopia's textile and leather industries. Pollution data demonstrate a systematic failure in control measures, with effluent parameters such as chemical oxygen demand (COD) reaching 850.75 mg/L and chromium concentrations of 3.54 mg/L regularly exceeding national discharge limits [67]. This contamination triggers a cascade of interconnected impacts: polluted water used for irrigation introduces heavy metals like chromium into soils, where levels have been recorded above 500 mg/kg. This soil degradation reduces agricultural productivity and introduces toxins into the food chain, culminating in significant public health issues. For instance, tannery workers exhibit a markedly higher prevalence of dermatitis (67%) compared to control groups (15%) [100]**.** The literature analysis confirms that research efforts have logically concentrated on these primary pathways of environmental damage.

This pattern mirrors the experience of other industrializing nations. The severe contamination of Ethiopia's Akaki River, for example, is reminiscent of the well-documented pollution of the Buriganga River in Bangladesh, another center for tannery activity [9, 87]. These parallels, however, offer instructive lessons. Bangladesh's subsequent policy of mandating operational effluent treatment plants (ETPs) as a condition for business licensing provides a compelling model for strengthening regulatory enforcement in Ethiopia [101–103]. Similarly, advancements in chromium recovery and recycling technologies in countries like India, which can reduce chromium consumption and related pollution by over 90%, present a viable technical pathway for Ethiopian tanneries to adopt [104, 105].

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4.2 DEVELOPMENT AND JUSTIFICATION OF A HOLISTIC SUSTAINABILITY FRAMEWORK FOR ETHIOPIA

The environmental and operational challenges identified are multifaceted and interlinked, rendering isolated, end-of-pipe solutions ineffective. **Drawing directly on the synthesized evidence from the systematic literature review, this section presents an evidence-based holistic sustainability framework specifically designed for the Ethiopian context.** The development process was iterative and grounded in the SLR findings. First, key environmental "hotspots" such as untreated effluent discharge, chromium pollution, solid waste accumulation, and soil contamination were mapped from the synthesized data (Sections 3.1–3.4). These challenges were then analyzed against established global sustainability principles, including the UN Sustainable Development Goals (SDGs) and Ethiopia's Climate-Resilient Green Economy (CRGE) strategy, as well as proven mitigation strategies documented in the literature [71, 87].

Ethiopia's leather and textile sectors have undergone dramatic expansion in recent years, becoming cornerstones of the nation's economic development strategy. These industries are significant contributors to employment, export revenues, and foreign currency generation, playing a vital role in poverty reduction and industrial growth [106, 107]. However, this rapid economic advancement has incurred substantial environmental costs. Globally recognized as highly polluting and resource-intensive, these sectors consume vast amounts of water and energy and generate large volumes of toxic wastewater, making them major sources of environmental degradation in Ethiopia [8, 10, 108–110].

Recognizing this challenge, there is a growing, albeit nascent, movement within Ethiopia to adopt greener business practices. Recent research has begun to explore this transition, investigating the structural links between green practices such as green manufacturing, green marketing, and green human resource management and the economic performance of firms, often mediated through green innovation [107]. Despite being a priority sector, the leather tanning industry faces significant hurdles in adopting sustainable manufacturing practices, primarily due to limitations in technical capabilities and social development [87]. Studies indicate that key practices like organizational commitment, green purchasing, eco-design, and investment recovery are not yet fully integrated into the supply chains of Ethiopian tanneries [111]. This gap highlights a persistent misconception in some developing economies that environmental responsibility is incompatible with financial performance.

To address this perceived opposition and ensure long-term, sustainable growth, a holistic approach is essential. For this review, a holistic approach is defined as an integrated management strategy that concurrently addresses technological, policy, economic, and social dimensions across the entire value chain .This strategy moves beyond isolated fixes to integrate environmental, economic, and social considerations across the entire value chain, from raw material sourcing and production to waste management and stakeholder engagement. Such an approach, aligned with national and international standards, is critical for minimizing negative impacts and enhancing global competitiveness. As suggested by Quintana-García et al. (2022), holism promotes cleaner production, improves worker conditions, and ensures responsible resource management [112]. It fosters innovation and collaboration between industries, research institutions, and governments, while also emphasizing transparency.

The proposed framework, illustrated in

Figure 13, integrates these elements into four synergistic pillars. Its novelty lies in the explicit and systematic translation of context-specific Ethiopian challenges, as revealed by the SLR, into an integrated model that combines technological, economic, governance, and social dimensions. While existing models often focus on singular aspects like cleaner production or policy, this framework explicitly connects these areas, reflecting the interconnected reality of the problems in Ethiopia. For instance, the link between weak enforcement (Pillar 3) and the lack of advanced treatment technologies (Pillar 1) is directly addressed, as is the connection between skill gaps (Pillar 4) and the underutilization of circular economy opportunities (Pillar 2).

PILLAR 1: TECHNOLOGICAL AND PROCESS INNOVATION

This pillar is directly informed by the review's findings on predominant pollutants. For tanneries, the high chromium levels reported [67], necessitate adopting chromium recovery and recycling systems, shown to reduce pollution by over 90%[104, 105]. Similarly, the prevalence of sulfide pollution from beamhouse operations [63] supports a shift to enzymatic unhairing, which can reduce sulfide loads by up to 40–50% compared to conventional methods [113–115]. For textiles, the characterization of effluent with high COD, BOD, and TDS [10, 23] underscores the need for water-efficient technologies like low-liquor-ratio dyeing (which can reduce water consumption by 30–50%) and advanced membrane filtration for water reuse [116, 117].

PILLAR 2: CIRCULAR ECONOMY AND WASTE VALORIZATION

The review highlights solid waste and sludge as major disposal challenges, with tanneries generating 200–250 kg of solid waste per ton of raw hides and textile factories producing significant sludge volumes [61, 118]. This pillar responds by promoting a circular approach, transforming waste into resources [119, 120]. Evidence from Ethiopian studies on valorizing

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tannery sludge and textile waste into construction materials such as bricks and concrete blocks provides a locally relevant foundation for this strategy, offering both environmental and potential economic benefits [118, 121, 122].

PILLAR 3: POLICY, GOVERNANCE, AND ENFORCEMENT

The consistent reporting of non-compliance with standards [8, 10] points to a critical governance gap. This pillar advocates for the stringent enforcement of existing regulations, such as the Hazardous Waste Management Proclamation No. 1090/2018. It also proposes economic instruments like tax incentives for compliance and pollution charges for non-compliance, drawing on successful international examples such as Bangladesh's ETP licensing model, which mandated functional treatment plants as a condition for operating licenses [101–103]

PILLAR 4: SOCIAL AND CAPACITY DEVELOPMENT

The review identifies significant social challenges, including health risks for workers (67% dermatitis prevalence among tannery workers) [100] and a shortage of skilled labor in sustainable manufacturing practices [87]. This pillar addresses these directly by linking environmental sustainability with social equity. It emphasizes improving occupational safety through provision of personal protective equipment and regular health monitoring, providing fair wages, and developing technical curricula in partnership with universities and technical and vocational education and training (TVET) institutions to build local capacity, ensuring the workforce can implement and sustain the new technologies and practices promoted in other pillars [71, 87].

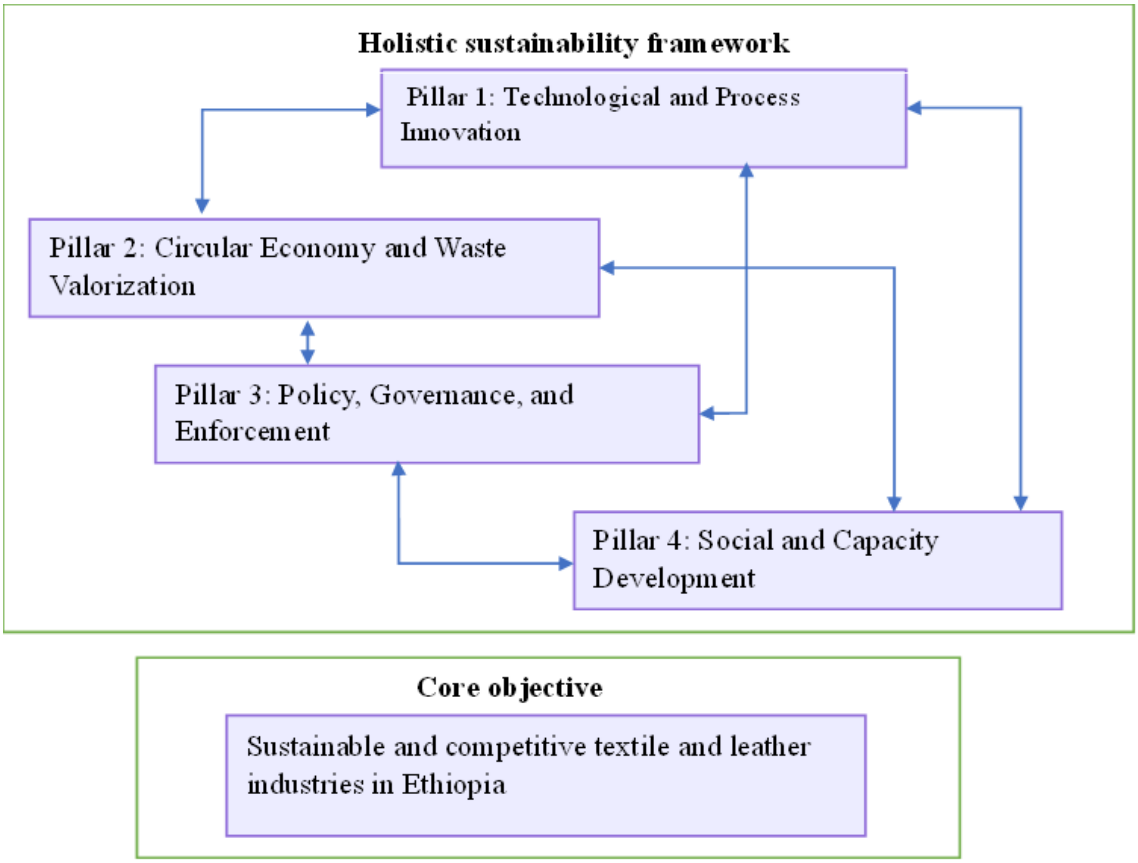

Figure 13: A Holistic sustainability framework for Ethiopia's textile and leather industries

4.3 CRITICAL ANALYSIS OF POLICY AND GOVERNANCE CHALLENGES IN ETHIOPIA

Despite a progressive regulatory framework including the Environmental Pollution Control Proclamation No. 300/2002 and the Hazardous Waste Management Proclamation No. 1090/2018 effective governance remains a critical barrier [8, 106]. The SLR reveals a consistent pattern of non-compliance, where effluent parameters regularly exceed national standards by factors of up to five [10, 67]. **This implementation gap is documented in the literature as stemming from a combination of institutional, capacity, and economic factors [95, 114].**

4.3.1 FRAGMENTED INSTITUTIONAL MANDATES AND COORDINATION FAILURES

Environmental governance is dispersed across multiple entities: the federal EPA, regional environmental bureaus, the Ministry of Industry, and municipal authorities [87]. **This fragmentation leads to overlapping jurisdictions and ambiguous accountability, where industrial licensing (Ministry of Industry) can operate independently from**

environmental compliance monitoring (EPA), allowing factories to operate without functional effluent treatment [87, 106]**.**

4.3.2 WEAK ENFORCEMENT CAPACITY AND MONITORING DEFICITS

Regulatory agencies are critically under-resourced, lacking technical staff, analytical laboratories, and real-time monitoring equipment [87]. Inspections are infrequent and often announced in advance, reducing deterrence. **This reliance on self-reporting by industries without independent verification creates a permissive environment for non-compliance** [106]**. Penalties for violations are documented as minimal and rarely enforced, failing to outweigh the economic incentives for pollution [8, 87].**

4.3.3 ECONOMIC PRIORITIZATION OVER ENVIRONMENTAL PROTECTION

Ethiopia's aggressive industrialization drive, which prioritizes export growth and job creation, often sidelines environmental concerns. Political and economic pressures discourage strict enforcement, particularly in strategic sectors like textiles and leather. **This results in a *de facto* tolerance of pollution, which undermines regulatory credibility** [71]**.**

4.3.4 LACK OF TRANSPARENCY AND STAKEHOLDER INCLUSION

The literature indicates that pollution data are not systematically collected or made publicly accessible, limiting accountability. Affected communities, workers, and civil society organizations have minimal involvement in environmental decision-making or monitoring, which reduces social pressure for compliance and hinders participatory governance [7, 100].

4.3.5 INADEQUATE INCENTIVE STRUCTURES FOR GREEN TRANSITION

Current policies lack robust economic instruments to encourage cleaner production. There are no meaningful pollution taxes, tradable emission permits, or green procurement mandates . **Conversely, subsidies for water and energy inadvertently encourage resource-intensive practices. Financial incentives for adopting clean technologies (e.g., tax breaks, soft loans) are underdeveloped and poorly promoted [71, 87].**

4.4 IMPLICATIONS FOR THE HOLISTIC FRAMEWORK

These governance failures directly inform Pillar 3 of the proposed framework. Effective implementation will require not only stricter enforcement but also institutional reforms: consolidating regulatory authority, building monitoring capacity, integrating environmental conditionalities into industrial licensing, and fostering multi-stakeholder oversight mechanisms **[87, 101]. However, translating the proposed framework into practice requires confronting significant economic and operational constraints. While technologies such as chromium recovery systems and advanced effluent treatment are proven, their adoption in Ethiopia faces formidable barriers [104, 105].**

5. CHALLENGES AND FUTURE PATHWAYS

Ethiopia's pursuit of industrial growth, particularly within its strategic textile and leather sectors, is increasingly juxtaposed with severe environmental and operational sustainability challenges. This is especially acute in Addis Ababa, where industrial concentration exacerbates waste management crises, as most establishments discharge partially treated or untreated effluent, leading to detrimental contamination of water, soil, and public health [109]. the core of the issue lies in the production processes: both industries are notoriously resource-intensive, consuming vast quantities of fresh water and utilizing a wide spectrum of toxic chemicals. A critical gap persists, as there is no comprehensive, integrated solid and liquid waste management plan to effectively address these complex industrial byproducts. While advanced bioremediation and treatment technologies offer potential solutions for such highly coloured and toxic wastewater, their application in Ethiopia remains limited due to infrastructural deficits, weak policy enforcement, and a scarcity of technical expertise [87]. This implementation gap is a primary barrier to mitigating the sectors' environmental impacts.

Beyond environmental concerns, the tannery industry faces profound systemic challenges that undermine its economic viability. A fundamental issue is the chronic lack of quality raw hides and skins, stemming from parasitic diseases, poor animal husbandry practices (e.g., flawed flaying and curing), and substandard post-mortem management due to backyard slaughtering and inadequate collection infrastructure [19, 87]. The low commercial value offered to farmers disincentivizes improvements, while supply seasonality linked to major festival seasons creates erratic price fluctuations and operational instability for tanneries. This results in low-capacity utilization and has eroded confidence among global buyers, who have reduced imports of finished Ethiopian leather, especially as market demand for diverse, high-quality finishes has grown [19, 106]. Furthermore, the sector's heavy dependence on imported inputs from chemicals to zippers increases costs, complicates supply chains, and strains foreign exchange reserves, a problem industrial policy has struggled to overcome. Compounding these issues is a critical shortage of skilled labor, particularly designers and marketing managers capable of penetrating competitive export markets.

The sustainability challenges extend critically into the social sphere. Tanning is characterized by relatively low wages, disproportionately affecting women who constitute a large portion of the manufacturing workforce. This contributes to high labor turnover and increased training costs for firms. The low wage structure is perpetuated by high unemployment rates

and intense international competition, limiting workers' bargaining power. Similarly, the textile industry faces significant social challenges, including reports of long working hours and low wages [107]. Environmentally, despite the existence of regulatory standards and proclamations like the Hazardous waste management and disposal proclamation No. 1090/2018, enforcement remains weak [8, 106]. While government pressure has spurred some investment in wastewater treatment plants, pollution problems are far from resolved. Textile factories generate large volumes of wastewater with high chemical oxygen demand (COD), strong coloration, and low biodegradability [8, 123]. which is often discharged untreated. Solid waste management is equally critical; both industries accumulate hazardous sludge and fabric waste, often disposed of in unsecured open landfils due to a lack of operational standards, technical capacity, and financial resources[118]. Although this waste holds promise for valorization such as in composite materials or construction products [118, 121] its potential is stifled by hazardous pollutants, limited research, and the absence of standardized processes and strong research-industry partnerships

Therefore, addressing these multifaceted challenges requires a holistic strategy that strengthens policy implementation, fosters technical capacity, promotes sustainable circular economy principles, and ensures that industrial growth does not come at the expense of environmental integrity and social equity. A holistic approach is essential to mitigate these impacts, integrating participatory management, strict policy enforcement, capacity building, and green supply chain initiatives [87, 124, 125]. Despite the proposed framework, significant challenges persist. These include infrastructural deficits, weak policy enforcement, a critical shortage of skilled labor, and poor raw material quality in the tannery sector [104]. The low wage structure and high labor turnover further undermine social sustainability. Future success hinges on a concerted effort to bridge these gaps. Future research should prioritize developing cost-effective integrated treatment systems, conducting techno-economic analysis of waste valorization pathways, and investigating the socio-economic barriers that hinder the adoption of green practices by local industries. By systematically tackling these challenges, Ethiopia can steer its vital textile and leather industries onto a path that is both economically prosperous and environmentally sustainable.

6. CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

This study set out to synthesize the evidence on the environmental impacts of Ethiopia's growing textile and leather industries and to propose an integrated strategy for sustainable development. The systematic review of over 130 studies confirms a severe and consistent pattern of pollution that threatens both ecological integrity and public health. Effluents from these sectors routinely exceed national discharge limits, with chemical oxygen demand (COD) and chromium concentrations reaching alarming levels 850.75 mg/L and 3.54 mg/L, respectively [67]. This contamination is not confined to wastewater; it infiltrates soils, disrupts aquatic ecosystems, reduces agricultural yields, and exposes communities especially tannery workers to significant health risks, including a dramatically higher incidence of dermatitis (67% vs. 15% in controls) [100].

The evidence reveals that the environmental challenges are interconnected and systemic, spanning water, soil, health, and socio-economic dimensions. Conventional, fragmented approaches that address isolated issues such as wastewater treatment in isolation from solid waste management or worker safety have proven inadequate. In response, **this study introduces an evidence-based holistic sustainability framework, directly derived from the synthesized literature, structured around four interdependent pillars: technological innovation, circular economy integration, strengthened governance and enforcement, and social and capacity development.** This framework is designed to provide a coherent, actionable pathway for aligning Ethiopia's industrial ambitions with long-term environmental and social sustainability.

However, this study is not without limitations. Its findings are constrained by the scope, quality, and geographic focus of the existing published literature, which may not fully capture unmonitored or underreported pollution. The proposed framework, while grounded in synthesized evidence and aligned with global best practices, remains conceptual until validated through empirical pilot studies in Ethiopian industrial zones. Furthermore, the review highlights a research landscape dominated by studies on water pollution, with comparatively less attention to air quality, social equity, and lifecycle impacts indicating important gaps for future inquiry.

6.2 RECOMMENDATION

To move from diagnosis to action, the following targeted recommendations are offered, directly derived from the synthesis of evidence and the framework proposed:

- For Policymakers and Regulators: Strengthen enforcement of existing regulations, such as the Hazardous Waste Management Proclamation No. 1090/2018, by linking operating licenses to verified effluent treatment performance a model successfully adopted in Bangladesh. Introduce tiered fiscal incentives for industries investing in cleaner technologies, particularly chromium recovery systems, which our review shows can reduce pollution by over 90% [104, 105]. Priority monitoring should be directed toward industrial clusters in Gelan, Dukem, and Bahir Dar, where effluent parameters most consistently exceed standards [8, 10, 67].
- For Industry Leaders: Prioritize integrated waste management, starting with low-cost, high-impact measures such as water recycling and chromium recovery systems, which directly address the high COD and chromium loads

documented in this review [67, 104]. Explore circular business models for example, valorizing tannery sludge into construction materials, as evidenced by emerging local research to transform waste liabilities into economic opportunities while reducing environmental footprints [118, 121].

- For Researchers and Academia: Conduct applied, context-specific studies to address the gaps identified in this review. Priority areas include pilot testing the proposed holistic framework in selected Ethiopian industrial zones; techno-economic analysis of waste valorization pathways for tannery and textile sludge [119, 120, 126, 127]; development of affordable, adaptable treatment technologies suitable for small and medium enterprises; and interdisciplinary research into the socio-economic barriers hindering the adoption of green practices among local firms [71, 87].
- For International and Development Partners: Support capacity-building initiatives that enhance technical skills in sustainable manufacturing and environmental monitoring, addressing the critical skill shortages identified in our review [87]. Facilitate knowledge exchange with regions that have undergone similar industrial transitions, such as Bangladesh and India [101, 104], and help mobilize green financing for small and medium-sized enterprises to adopt cleaner production technologies [128–130].

The path to sustainable industrialization in Ethiopia is complex but achievable. It requires a concerted, collaborative effort that views environmental stewardship not as a barrier to growth, but as its essential foundation. By adopting the integrated, holistic approach proposed here one that connects technology, policy, economy, and society Ethiopia can transform its textile and leather sectors into models of inclusive and resilient development.

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COMPETING INTERESTS

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Not applicable, as this study is a review article and does not involve direct human or animal subject research.

DATA AVAILABILITY

This review article is based on existing published literature, and all referenced studies are appropriately cited. No new primary data were generated for this work.

AUTHOR CONTRIBUTIONS

All authors contributed equally to the conceptualization, literature review, analysis, and writing of this manuscript. The authors collaboratively discussed the structure, content, and conclusions of the review. The final manuscript has been reviewed and approved by all authors.

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