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A comprehensive review of life cycle assessment in the leather industry: progress toward circularity, key challenges, and future directions

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Abstract
This comprehensive review examines the application of life cycle assessment (LCA) in the leather industry, emphasizing its pivotal role in advancing circular economy integration. Through literature analysis and case studies, this review demonstrates how LCA facilitates animal by-product valorization, waste minimization, and material circularity, transforming traditional leather production into a paradigm of resource efficiency. Key environmental hotspots are identified across system boundaries: animal husbandry dominates Cradle-to-Grave impacts, while chemical usage (e.g., chrome agents) and energy-intensive processes prevail in leather processing, modulated by regional energy mixes. Emerging sustainable technologies and waste valorization innovations show promise in curbing ecological footprints. However, challenges persist, including methodological inconsistencies, data shortages, and regional disparities. To overcome these challenges, the review advocates for unified sector-specific databases, multidimensional assessment frameworks, and AI-driven modeling. Ultimately, LCA emerges as an essential tool for impact quantification, circular transitions, and sustainable industry evolution.

Keywords Life cycle assessment (LCA), Leather industry, Environmental hotspots, Green transformation, Methodological challenges, Future research priorities

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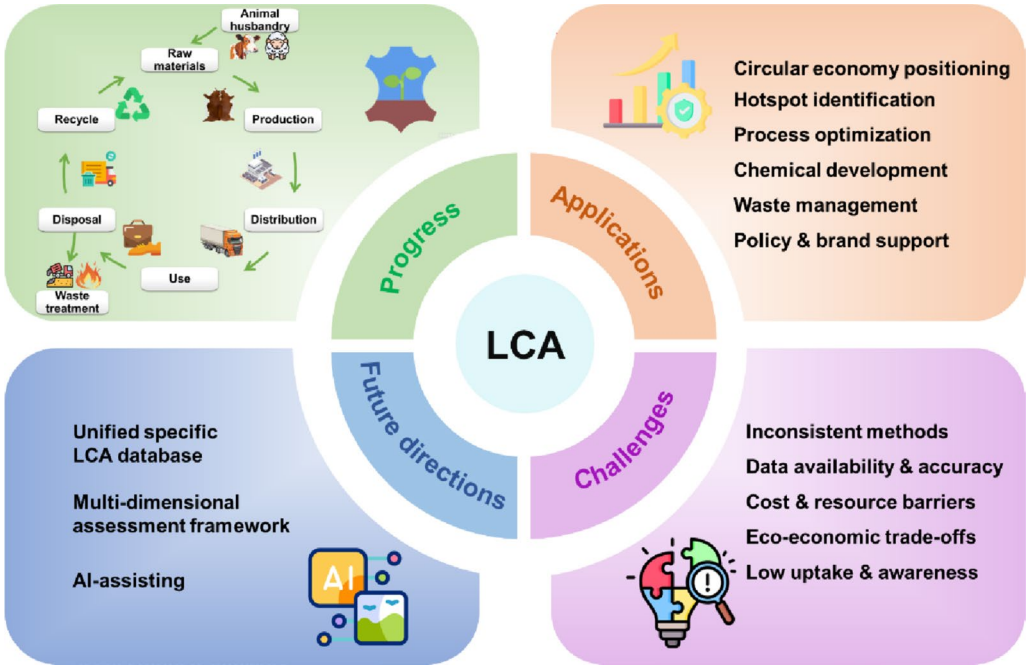
Graphical Abstract



1 Introduction

The leather industry occupies a unique position in the global sustainability landscape [1]. Leather manufacturing has long been considered an industry with significant environmental implications, due to its traditional reliance on substantial water consumption, the use of various chemicals (Fig. 1), and energy-intensive production [2, 3]. However, amid growing global efforts to reduce carbon emissions, minimize waste, and transition towards circular economies, the leather industry has the potential to become an unexpected enabler of resource circularity and by-product valorization [4].

One of the key mechanisms for driving this transformation is life cycle assessment (LCA), a scientific methodology designed to quantify environmental impacts across the full life cycle of products and processes [5, 6]. In the leather industry, LCA has evolved from a diagnostic tool into a decision-support system, guiding industry stakeholders toward cleaner leather production technologies, reduced emissions, improved resource efficiency, and sustainable material substitution [7–9]. Moreover, LCA provides the analytical foundation for green certifications (e.g., European Union's Product Environmental Footprint Category Rules, EU PEFCR), carbon labeling, and eco-design practices that are essential in global trade and regulatory compliance [10–13].

Despite increasing application of LCA in leather-related research and policy, most existing studies remain fragmented and primarily descriptive, often lacking a coherent framework to connect LCA metrics with broader sustainability goals such as circular economy (CE) integration, climate mitigation, or policy alignment. Key methodological inconsistencies, including variations in system boundaries (e.g., Cradle-to-Gate vs. Gate-to-Gate), allocation methods for by-products, and regional technological disparities, further limit the comparability and practical utility of existing LCA results. Such discrepancies can result in incomparable results and perpetuate what Marrucci et al. [14] term "circular washing", the superficial invocation of circular economy principles without meaningful environmental gains. Moreover, the strategic role of LCA in positioning leather as a low-waste, carbon-sequestering, and biodegradable alternative to petrochemical-based synthetics remains underexplored.

This review aims to reevaluate the environmental potential of the leather sector through a circular economy lens, highlighting the role of LCA in enabling by-product valorization, waste reduction, and material circularity. It systematically compares and evaluates current LCA practices in the leather industry, including methodological choices, system boundaries, allocation approaches, and identified environmental hotspots, to provide conceptual clarity for researchers. Building on this analysis, the review proposes pathways to advance LCA applications in the leather industry, such as developing unified sector-specific databases, adopting multidimensional assessment frameworks, and integrating AI-assisted modeling

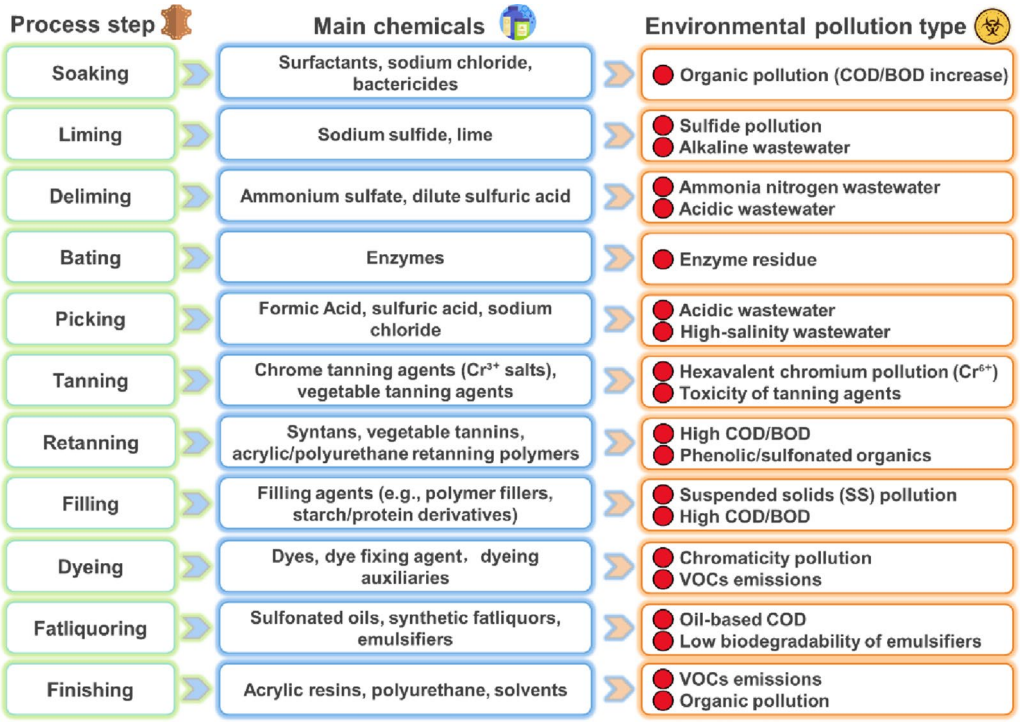


Fig. 1 Chemical consumption and associated environmental impacts across key stages of leather production

to address data gaps and methodological inconsistencies. Overall, the study argues that the leather industry, traditionally viewed as pollution-intensive, has significant untapped potential as a model of circular material use when supported by robust and harmonized LCA frameworks, offering both academic insights and practical guidance for science-based sustainability transitions.

2 Evolution and standardization of LCA

As a systematic environmental management tool, the concept of LCA can be traced back to the late 1960s [15]. Evolving from initial energy analyses focused on packaging materials to the gradual formation of a comprehensive "Cradle-to-Grave" assessment framework, LCA progressed from fragmented case studies into a systematic methodology [16]. In the 1990s, the Society of Environmental Toxicology and Chemistry (SETAC) promoted the establishment of a standardized four-phase framework (Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment, and Interpretation) [17, 18]. This framework was later adopted by the International Organization for Standardization (ISO), forming the core ISO 14,040 and 14,044 series standards, which laid a solid foundation for the standardized application of LCA.

With the maturation of the methodology, the application scope of LCA has continuously expanded, demonstrating clear trends toward specialization and digitalization. International standardization efforts since the mid-1990s have established a robust framework for LCA implementation [19–21]. The consolidation of ISO standards in 2006 further enhanced methodological consistency [22], facilitating cross-national environmental comparisons and policy development. This international standardization framework has been complemented by various regional adaptations, including but not limited to the Product Environmental Footprint (PEF), the U.S. Environmental Protection Agency (EPA) guidelines emphasizing tools like Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) [23], Japanese Industrial Standards Q (JIS Q), China Nation Standards (GB), and other national initiatives such as Publicly Available Specification (PAS) 2050. Concurrently, specialized standards addressing specific environmental concerns such as carbon footprint and water footprint have been progressively introduced, exemplified by ISO 14,067 [24] and ISO 14,046 [25]. The evolutionary pathway and core elements of the international LCA standard system are systematically detailed in Table 1.

Meanwhile, technical advancements in software and databases have democratized LCA implementation. Prominent software tools include OpenLCA (an open-source platform for modeling and analysis), SimaPro (widely used for comprehensive impact assessments and scenario modeling), Sphera (formerly GaBi, offering robust supply chain integration and compliance features), and Umberto (focused on material flow analysis

Table 1 Summary table of key international LCA-related standards

Year	Standard name	Key content	Status
1997	**ISO 14040:1997**	Established the basic framework for LCA, laying the foundation for the LCA field	Deprecated (Revised and integrated into the 2006 version)
1998	**ISO 14041:1998**	Standardized specific methods for lifecycle inventory analysis (LCI) and data quality requirements	Deprecated (Replaced by ISO 14044 in 2006)
2000	**ISO 14042:2000**	Defined the steps and model selection principles for lifecycle impact assessment (LCIA)	Deprecated (Replaced by ISO 14044 in 2006)
2000	**ISO 14043:2000**	Defined the methodology for the lifecycle interpretation phase and reporting requirements	Deprecated (Replaced by ISO 14044 in 2006)
2006	**ISO 14040:2006**	Revised the LCA framework, emphasizing the synergistic relationship with ISO 14,044	Currently valid (Core standard along with ISO 14044)
2006	**ISO 14044:2006**	Integrated ISO 14041/42/43, standardized LCI, LCIA, and interpretation processes, and added key review requirements	Currently valid (Authoritative LCA methodology standard)
2006	**ISO 14025:2006**	Established the Environmental Product Declaration (EPD) system, standardized rules and verification process for Type III environmental labels	Replaced (Updated in 2021)
2008	**PAS 2050:2008**	The world's first product carbon footprint standard (published by the British Standards Institution), focusing on greenhouse gas accounting	Replaced (Revised in 2011)
2008	**GB/T 24040 – 2008**	Chinese national standard, equivalent to ISO 14040:2006. Provides principles and framework for LCA	Currently in force (Chinese national standard)
2008	**GB/T 24044 – 2008**	Chinese national standard, equivalent to ISO 14044:2006. Provides detailed requirements and guidelines for LCA	Currently in force (Chinese national standard)
2010	**JIS Q 14040:2010**	The Japanese formal adoption and confirmation of ISO 14040:2006. Provides principles and framework for LCA	Currently valid (Japanese national standard)
2010	**JIS Q 14044:2010**	The Japanese formal adoption and confirmation of ISO 14044:2006. Provides detailed requirements and guidelines for LCA	Currently valid (Japanese national standard)
2011	**PAS 2050:2011**	Revised carbon footprint calculation rules, adding guidelines for special scenarios like land use change and carbon storage	Still widely used (Non-ISO standard)
2014	**ISO 14046:2014**	Established water footprint assessment standards, requiring quantification of water resource consumption and impact based on LCA methodology	Currently valid
2017	**ISO/TR 14073 – 2017**	Provided technical guidelines for case applications of ISO 14046 water footprint	Currently valid
2018	**ISO 14067:2018**	Standardized product carbon footprint (CFP) quantification and communication requirements, aligned with ISO 14044 methodology	Currently valid (Replaced PAS 2050 and became an international mainstream standard)
2021	**ISO 14025:2021**	Updated EPD standard, strengthened data quality requirements and digital declaration format compatibility	Currently valid

and efficiency optimization). Key databases encompass Ecoinvent (a global repository with over 18,000 datasets covering diverse sectors, regularly updated for transparency and consistency), Sphera' s Managed LCA Content (featuring more than 20,000 annually refreshed datasets from industry sources), and specialized ones like the U.S. Life Cycle Inventory (US LCI) for North American contexts. These tools have lowered barriers by enabling user-friendly interfaces, automation, and interoperability, facilitating LCA integration into green material substitution, environmental product declarations, and policy-driven sustainability reporting.

In China, LCA research has seen significant progress since 2010, driven by national sustainability goals like carbon neutrality by 2060 [26]. Breakthroughs have been achieved in the development of localized databases; specifically, the Chinese Life Cycle Database (CLCD) [27] and the High-Quality Life Cycle Database (HiQLCD) provide core data support for conducting environmental assessments tailored to China's national context. Within the leather industry, the research team led by Professor Shi Bi at Sichuan University has made particularly outstanding contributions [28]. This team developed their own life cycle inventory databases for leather chemicals and domestic bovine hides. Building on this foundation, they systematically conducted environmental footprint analyses for products such as bovine upholstery leather and fatliquors, providing a scientific basis for the industry's adoption of low-carbon transition measures like chrome-free tanning and process optimization [29, 30].

3 Development history and research trends of LCA in the leather industry

The systematic application of LCA in the leather industry began in 1998, marked by Rita Puig's study [31] on leather production. Subsequently, the methodology expanded to cover comprehensive processes, including animal husbandry and rawhide processing [32]. A significant

milestone in the integration of LCA practices within the leather industry was the launch of the EU's PEF project in 2013. This initiative led to the development of the world's first PEF Category Rules (PEFCR) for leather products in 2020, reinforcing LCA as an essential tool for evaluating the environmental performance of green products in Europe [33].

To analyze trends in LCA application, a search of the Web of Science Core Collection (up to September 2025) using the query "life cycle assessment" AND "leather" identified 82 peer-reviewed studies in English, excluding books, conference papers, and reports. The temporal distribution of publications reveals three distinct phases:

> Budding stage (pre-2013): this initial phase featured limited research output, with fewer than two articles published annually on average.
> Slight upturn stage (2014–2016): triggered by the EU PEF policy pilot, this period marked an increase in research activities.
> Hot spot stage (2017-present): characterized by a surge in studies, driven by the formal adoption of the EU PEFCR legislation, with the number of publications peaking at 11 in 2023.

This chronological trend, illustrated in Fig. 2, highlights LCA's vital role as a decision-making tool in the green transformation of the global leather industry. As the global push for sustainable supply chains and low-carbon leather production intensifies, LCA's significance is expected to expand from purely environmental assessments to include process optimization, policy integration, and industrial collaboration. Therefore, it is essential to systematically analyze the current state and challenges associated with LCA application in the leather sector to support the industry's sustainable development.

4 Practical applications of LCA in the leather industry

This chapter systematically reviews the application of LCA in the leather industry from four perspectives. First, it analyzes the positioning of the leather industry within the circular economy from an LCA perspective, with a focus on its contributions to carbon emission reduction and animal waste valorization. Second, it identifies environmental hotspots across production processes using LCA, while proposing targeted optimization strategies to mitigate these impacts. Third, it explores LCA-driven innovations in clean leather production technologies, while projecting future development trajectories for eco-friendly alternatives. Finally, it evaluates the role of LCA in obtaining eco-labels for leather products, thereby enhancing export competitiveness and promoting carbon transparency in global supply chains.

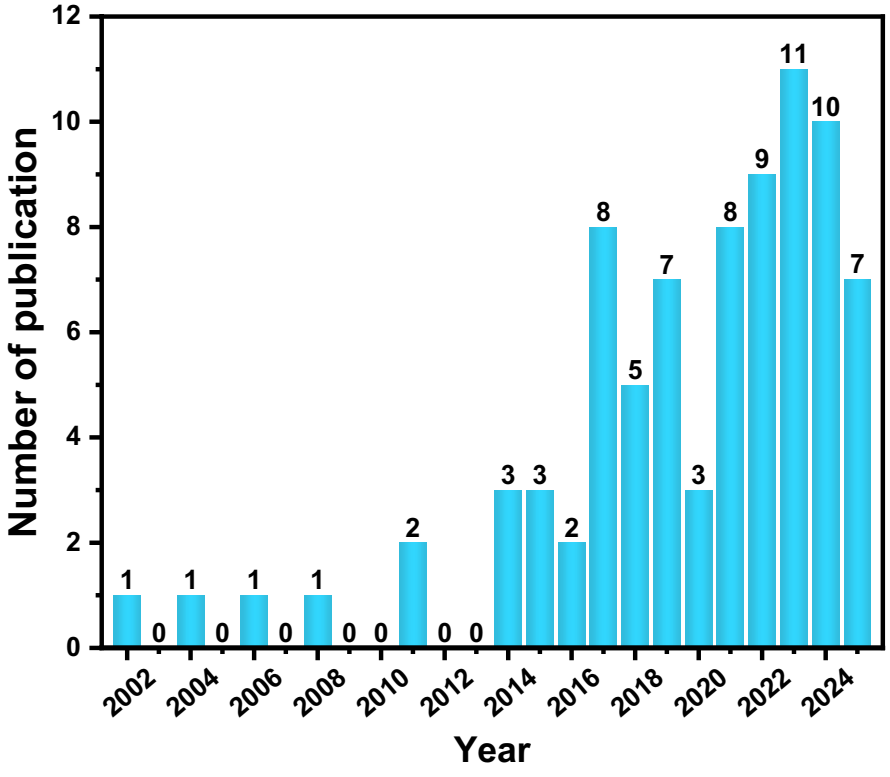


Fig. 2 Annual number of LCA publications for the leather industry (2002-September 2025)

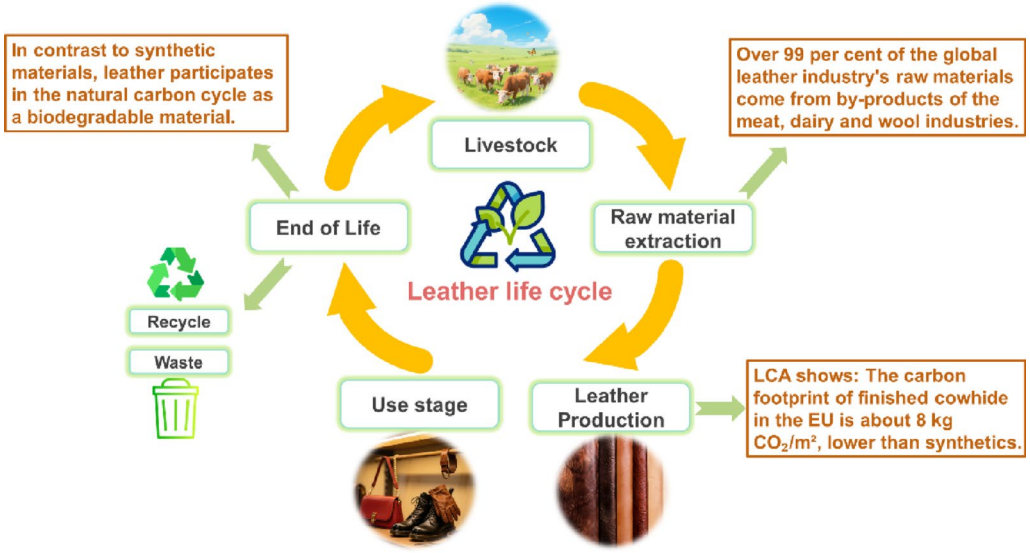


Fig. 3 Closed-loop modeling of the circular economy in the leather industry from a LCA perspective

Table 2 Comparative environmental indicators of leather vs. synthetic fibers

Indicator	Bovine leather	Synthetic leather	References
Sources of raw materials	Animal skins (livestock by-products), renewable resources	Petrochemicals (e.g. PVC, PU), nonrenewable resource	[11, 41]
Carbon footprint (kg CO_2 eq/m^2)	~ 8–17	~ 15.8–20.6	[39, 40]
Water consumption (L/m^2)	200 –600	100–200	[4, 42]
Microplastic pollution	None (biodegradable at end-of-life)	Contributes ~ 35% of global primary microplastics	[37, 43]
End-of-life	Biodegradable, compostable (under controlled conditions)	Persistent, non-biodegradable, and landfill accumulation	[43, 44]

4.1 Positioning the leather industry in the circular economy from an LCA perspective

Animal husbandry provides essential raw materials for food and other products but also generates low-value by-products such as hides, which pose management challenges. Increasing demand for animal protein, together with cost pressures, consumer trends, and environmental regulations, is accelerating the shift toward a CE [34]. The leather industry addresses these by transforming hides, over 99% of global leather raw materials, into durable, high-value products, thereby enhancing resource efficiency, minimizing waste, and closing material loops in line with CE principles [35]. LCA provides a quantitative tool to evaluate and demonstrate these environmental contributions (Fig. 3). By valorizing hides that would otherwise be landfilled, leather production prevents methane and other greenhouse gas emissions from decomposition and reduces upstream disposal costs by approximately 20% [35]. LCA studies estimate that unprocessed hides in major producing countries could release over 40 million tons of CO_2-eq annually if discarded [36].

In contrast, fast fashion's reliance on petrochemical textiles, particularly polyester, consumes around 350 million barrels of oil yearly and contributes substantially to GHG emissions and microplastic pollution, accounting for about 35% of primary oceanic microplastics [37, 38]. Leather, sourced from biogenic carbon, participates in the natural carbon cycle, exhibits biodegradability under controlled conditions, and avoids fossil resource dependency (Table 2). These comparative advantages are supported by whole-process LCAs. The European Green Deal Leather Project reported that [39] finished bovine leather in the EU has an average carbon footprint of ~ 8 kg CO_2-eq/m^2, significantly lower than synthetic polyurethane (PU) or polyvinyl chloride (PVC)-based leather alternatives, which typically range from 15 to 20 kg CO_2-eq/m^2 [40]. Ongoing innovations, including chrome-free tanning, enzyme-assisted processing, and advanced wastewater treatment, further reduce chemical and effluent impacts.

In conclusion, the leather industry exemplifies circular economy principles by converting animal by-products into sustainable, long-lasting materials while avoiding waste-related emissions and reducing reliance on fossil-based textiles. Continued progress in cleaner technologies, refined LCA methodologies, and supportive policies will further strengthen its role in the global green transition.

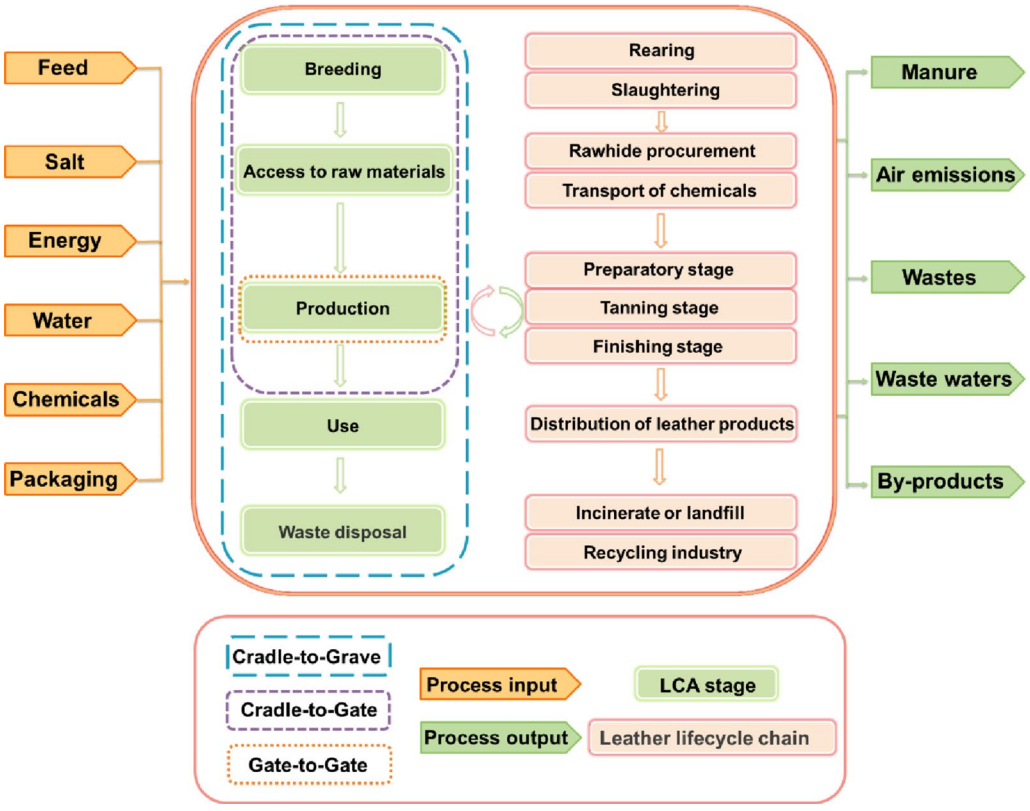


Fig. 4 System boundaries of LCA in the leather industry, illustrating the production chain alongside three commonly used LCA boundaries: Cradle-to-Grave, Cradle-to-Gate, and Gate-to-Gate, together with key process inputs and corresponding environmental output

4.2 Environmental hotspot identification in the leather industry

LCA serves as a pivotal methodology for quantifying and mitigating the environmental impacts of the leather industry. However, LCA outcomes are highly sensitive to the selected system boundaries, which delineate the scope of analysis and can lead to divergent interpretations of hotspots. This section examines environmental hotspots under varying LCA boundaries, while also addressing regional variations and allocation methodologies that introduce further variability.

4.2.1 LCA system boundaries and their implications

The environmental footprint of leather production processes is highly dependent on the selected LCA system boundary, which determines the scope of life cycle stages incorporated into the analysis. As illustrated in Fig. 4, the most commonly used boundaries are Cradle-to-Grave, Cradle-to-Gate, and Gate-to-Gate. Ultimately, choosing the right boundary ensures a more comprehensive and reliable evaluation, enabling the leather industry to better identify hotspots.

4.2.1.1 Cradle-to-Grave LCA: a holistic supply chain view Cradle-to-Grave LCA provides a comprehensive evaluation of leather products from raw material acquisition (e.g., animal husbandry) through to disposal, capturing cumulative impacts across the entire value chain. This boundary is instrumental for policymakers and stakeholders seeking to address systemic environmental burdens.

A pioneering study in Spain [31] analyzed the full life cycle environmental impact of leather footwear in Spain through LCA. The findings revealed that the livestock phase contributes 25–45% of the Global Warming Potential (GWP) and Acidification Potential (AP), primarily due to methane (CH_4) emissions and manure management. The tannery phase was identified as the dominant contributor to Eutrophication Potential (EP) (over 50%) and non-renewable resource consumption, primarily due to wastewater discharge and chemical usage. In addition, Spain is a major source of environmental impacts in the energy category due to its high fossil fuel electricity mix. These results provide a scientific basis for promoting a low-carbon transition in the Spanish footwear industry and highlight the importance of reducing emissions upstream in the supply chain. A critical reference from United Nations Industrial Development Organization (UNIDO) [40] provides quantitative insight into carbon emissions across the lifecycle. As shown in Fig. 5, when evaluating the entire chain starting from cattle farming, the carbon footprint of leather is approximately 110 kg CO_2 eq/m² of finished leather. However, if the analysis

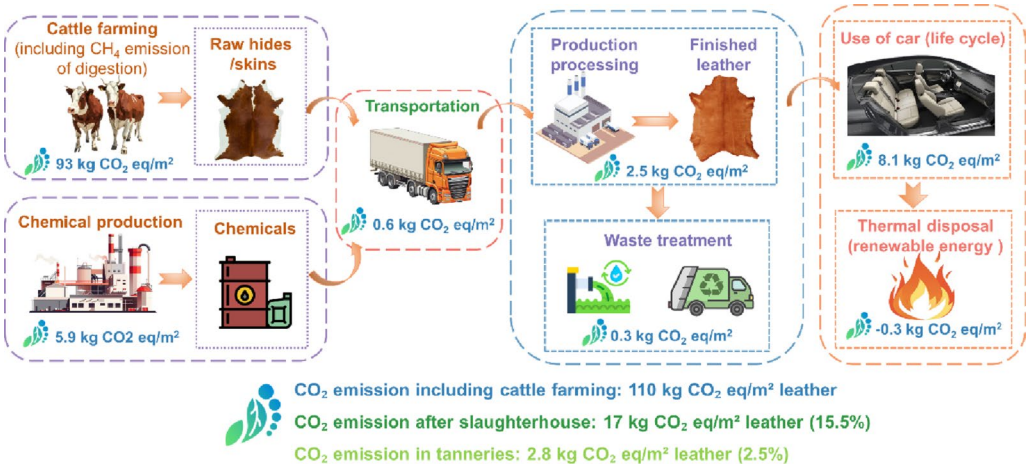


Fig. 5 CO_2 eq emissions of 1 m^2 leather throughout lifecycle (including cattle farming and end-of-life) [40]

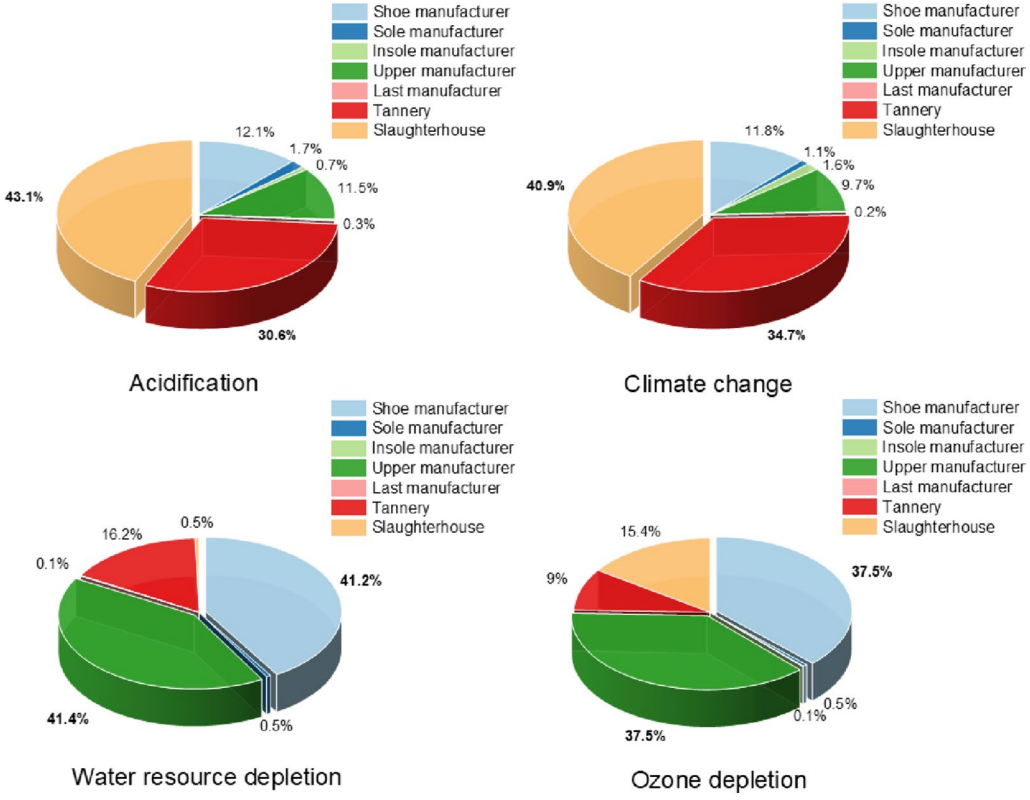


Fig. 6 Distribution of environmental impacts across life cycle stages in leather footwear production, based on LCA results [47]

begins at the slaughterhouse (excluding upstream animal agriculture), this drops sharply to just 17 kg CO_2 eq/m^2. This disparity reflects ongoing debates in LCA methodology over the inclusion of emissions from animal husbandry.

Indeed, the leather industry's LCA practices vary due to challenges in data collection and differing interpretations of system boundaries. One argument, supported by Djekic et al. [45] and Huerta et al. [46], posits that since animal husbandry is primarily raised for meat and milk, hides should be treated as by-products with minimal allocated emissions. A footwear supply chain LCA adopting this approach identified slaughterhouses and tanneries as primary hotspots, contributing ~75% of climate change impacts (Fig. 6) [47]. Proposed mitigation strategies include transportation optimization (15% emission reduction), cotton-based material substitution (71% water savings), and green procurement (up to 30% combined reductions).

Table 3 Comparative LCA of leather production under Cradle-to-Gate system boundaries: five regional case studies

Serial number	Leather type	Research location	Key environmental hotspots	References
1	Aniline leather	Taiwan Province of China	Upstream raw materials > 75% GHG; tanning electricity & chemicals ~20%; drive climate and toxicity impacts.	[53]
2	Chrome-tanned leather	Turkey	Solid waste landfilling (95% methane) dominates biogenic GHGs; electricity/fuel adds GHGs; Cr sulfate & resins drive toxicity and depletion; Cr causes 99% cancer risk.	[54]
3	Full-chrome leather (FCL) and chrome retanned crust leather (CRL)	Bangladesh	The environmental impacts of FCL significantly exceed those of CRL, primarily due to chromium toxicity and ammonia-induced eutrophication.	[42]
4	Chrome-tanned leather	Chile	Cr (69.4%) and NH_3 (3.9%) dominate toxic impacts; full-chrome tanning causes 44–50% higher ecosystem damage; fossil energy and transport add secondary burdens.	[51]
5	Chrome-tanned and Vegetable-tanned leather	Italy	Cr retanning causes 99% cancer risk; Vegetable tanning: liming with lime and Na_2S contributes 45% to eutrophication.	[52]

Thus, Cradle-to-Grave LCA illuminates interconnected hotspots, methane-driven GWP in animal husbandry, chromium-related toxicity in tanning, and waste-induced EP, guiding integrated sustainability strategies.

4.2.1.2 Cradle-to-gate LCA: focus on production phases Cradle-to-Gate LCA evaluates environmental impacts from raw material extraction to the factory gate, focusing on manufacturing processes while excluding downstream stages such as product use and disposal. This approach is particularly effective for identifying environmental hotspots in leather production, as it isolates impacts directly associated with tannery operations, including energy consumption, chemical emissions, and wastewater generation [48].

As summarized in Table 3, recent LCA studies consistently identify the tanning stage, especially chrome tanning, as the dominant contributor to the overall environmental footprint of leather processing [49, 50]. Chrome tanning employs trivalent chromium salts, offering superior efficiency and versatility, and currently accounts for 80–90% of global leather production. However, its environmental implications are significant, contributing substantially to GWP, human toxicity, and eutrophication.

For instance, an LCA of a Chilean tannery found that the tanning subsystem, comprising deliming, pickling, and chrome tanning, was the principal environmental hotspot, with chromium discharges representing 69.4% of the total impact score [51]. Similarly, in an Italian tannery, annual chromium emissions in wastewater and sludge were reported to reach 75.8 kg, posing serious risks of human toxicity and freshwater ecotoxicity [50]. Comparative studies between chrome tanning and vegetable tanning further underscore these findings. A Cradle-to-Gate LCA on goat hide leather production revealed that chrome tanning had a markedly higher environmental footprint due to the persistence and carcinogenic potential of chromium compounds, whereas vegetable tanning, which relied on natural tannins, exhibited substantially lower impacts across all toxicity categories and negligible carcinogenic risk [52]. Consistent with these results, a study conducted in Bangladesh also applied a Cradle-to-Gate LCA to assess the environmental footprint of its leather processing industry [42]. The study identified the tanning stage, particularly full-chrome tanning, as the critical contributor to overall impacts. Key pollutants included trivalent chromium from the tanning process and ammonia from deliming and bating, both of which significantly affect aquatic ecotoxicity, acidification potential, and ecosystem quality.

4.2.1.3 Gate-to-gate LCA: focused tanning process analysis Gate-to-Gate LCA narrows further to factory-level processes, excluding external stages to scrutinize operational specifics like material flows and energy use [55]. This boundary facilitates precise comparisons of leather production techniques. Studies from Italy, New Zealand, and Indonesia consistently highlight energy use and chemical consumption as the primary drivers of environmental impacts, though their relative importance varies significantly based on regional context.

In countries with fossil fuel-dependent electricity mixes, such as Italy, energy consumption, particularly for processes like drum rotation, dominates impacts including climate change, acidification, and human toxicity

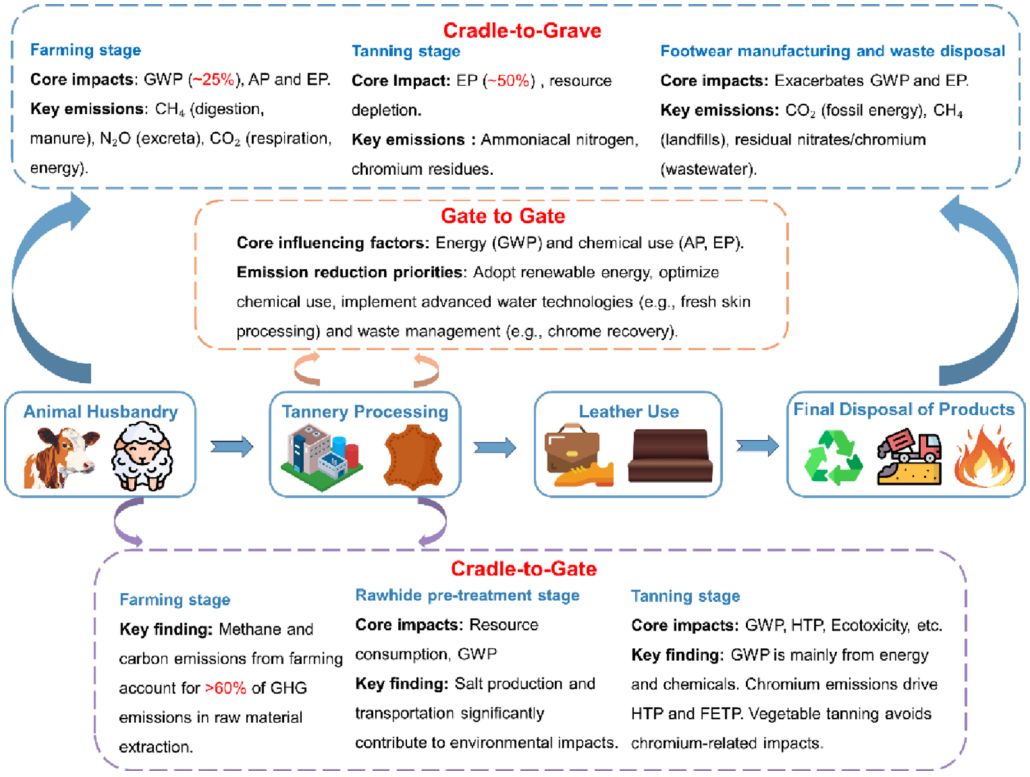


Fig. 7 System boundaries, processes and environmental hotspots in the leather industry from the LCA perspective

[56]. In contrast, regions with cleaner energy profiles, like New Zealand (78% renewable electricity) [57], shift the burden to chemical production, where substances like chromium oxide, aniline, and synthetic polymers become the major contributors to toxicity, resource depletion, and climate change. Water management plays another critical role. Efficient practices, such as using fresh hides to avoid soaking, can reduce water consumption. Wastewater treatment offers water recovery benefits but contributes to eutrophication through nitrate emissions, with treatment intensity varying based on pollutant load [58]. Evaluations of alternative materials reveal important trade-offs: while bio-based substitutes (e.g., vegetable oils) reduce fossil resource use, they may increase toxicity or eutrophication due to agricultural inputs. Process innovations, such as green fleshing and chromium recovery (up to 90%), demonstrate significant potential for reducing chemical use and toxicity impacts [57].

In conclusion, Gate-to-Gate analysis highlights that tanneries can most effectively reduce their footprint by focusing on three core areas: transitioning to renewable energy, optimizing chemical use, and advancing water and waste management. Finally, Fig. 7 outlines the typical system boundaries used in leather LCA studies and highlights the main environmental hotspots across the value chain.

4.2.2 Factors influencing LCA variability

The identification of environmental hotspots in leather production through LCA is strongly influenced by multiple interacting factors. These include regional disparities, methodological decisions, life cycle inventory (LCI) database and data availability [59]. Among them, regional disparities and allocation methods are especially critical and often debated [48, 60], as they strongly shape the perceived environmental performance of the industry.

4.2.2.1 Regional differences As highlighted in the Gate-to-Gate LCA analyses, regional characteristics significantly influence environmental outcomes. Beyond energy mix, other factors, including technological levels, regulatory frameworks, and waste management practices, further diversify LCA results [48]. For instance, European tanneries, particularly those in Italy and Spain [50], often implement advanced wastewater treatment technologies to mitigate water pollution from chromium and other pollutants. While these technologies reduce specific pollutants, they can increase energy consumption and associated carbon emissions. Conversely, tanneries in countries like Bangladesh and India [42], where production costs are lower, may contribute more significantly to eutrophication due to less effective wastewater treatment. These technological disparities directly impact the environmental footprint of leather production.

4.2.2.2 Allocation methods A key challenge in LCA of leather is the allocation of environmental burdens associated with raw hides, as they are by-products of the meat industry [32]. Different allocation methods, such as economic allocation (based on market value) and mass allocation (based on physical weight), can yield significantly different results [61]. Economic allocation can overestimate the environmental burden of leather, as demonstrated by studies [61] on Danish pork production where it increased climate change-related impacts by up to 80%. Conversely, mass allocation may underestimate the environmental impacts attributed to leather [62].

Several studies recommend a hybrid approach that combines economic and mass factors to provide a more balanced and representative assessment [57, 62]. For example, a hybrid approach that accounts for both the economic value and the quality of the hide may offer a more nuanced perspective [32]. Sensitivity analyses are important to address these inconsistencies by identifying how varying allocation parameters can alter LCA outcomes [32]. Recent studies [52] highlight the importance of allocation choices. Research on goat leather production revealed that different allocation methods can lead to varying results, particularly regarding water use and chemical pollution during tanning. Similarly, a study [50] comparing traditional chrome tanning with innovative metal-free tanning in Italy found that the allocation of methane emissions from livestock significantly affected the climate change impact results.

In summary, regional disparities, especially in energy composition and technological capacity, along with the selection of allocation methods, are key factors contributing to variability in leather LCA studies. To improve the reliability and comparability of assessments, standardized allocation procedures and region-specific data reporting are essential. This not only strengthens methodological consistency but also enables more context-aware and effective sustainability interventions across the global leather industry [62].

4.3 Process optimization and innovation driven by LCA

As established earlier, LCA has identified key environmental hotspots in leather production. This section reviews resulting technological advancements, such as cleaner tanning agents and enzymatic processes, that reduce chemical use, water demand, and emissions, thereby supporting the industry's sustainable transition.

4.3.1 LCA-driven innovations in green leather processing technologies

4.3.1.1 Green tanning technology As previously stated, the tanning process remains the most critical environmental hotspot in leather production, largely due to its intensive chemical use and chromium-related emissions. To mitigate these impacts, LCA-driven innovations have increasingly focused on developing chrome-free tanning systems that minimize chemical pollution, energy demand, and GHG emissions while maintaining leather quality.

Among these, chrome-free tanning systems (CFTS), such as the tannic acid-zirconium (TA-ZE) complex, have demonstrated the lowest environmental burdens across 16 midpoint categories, including human toxicity and eutrophication, when evaluated using the EF 3.0 impact assessment method [63]. Comparative studies further indicate that metal-free tanning systems (MFTS) can substantially reduce resource depletion and climate change impacts compared with both chromium tanning systems (CTS) and chrome-free metal tanning systems (CFMTS), although their performance regarding human toxicity and water pollution remains similar [8].

Vegetable tanning, based on natural plant polyphenols, provides a more sustainable benchmark, achieving reductions of up to 50% in GWP and 82% in freshwater ecotoxicity relative to chrome tanning [64, 65]. Building on these findings, the development of bio-based tanning agents has gained momentum as a strategy to mitigate hotspots associated with chemical production. For example, Zhou et al. [9] introduced a biomass-derived aldehyde acid (AA) for a salt-free, high-exhaustion chrome tanning system (AA-Cr), achieving reductions of 19.8% in GWP, 14.7% in PED, and 21.5% in ADP compared to conventional chrome tanning. Similarly, Conde et al. [66] utilized pine bark waste as a substitute for mimosa tannin, reducing the carbon intensity of tanning agent production by 94%; however, increased water and energy consumption during tanning offset some of these gains. Ballús et al. [67] evaluated bio-based acrylic graft copolymers (BB) synthesized from polysaccharides, observing a 9% reduction in carbon footprint, though only 4 of 19 impact categories improved. Substituting these with protein-based polymers (BPP) yielded broader improvements across 16 categories, underscoring the importance of feedstock optimization in sustainable material design.

It is important to emphasize that LCA outcomes are highly process-dependent, and environmental advantages at one stage can be offset by trade-offs in others. For instance, while vegetable tanning appears environmentally favorable, post-tanning processes such as waterproofing with zirconium salts and acrylic copolymers can increase the GWP by 13–14% and EP by 44%, highlighting the inherent trade-offs associated with subsequent processing steps [68].

4.3.1.2 Advanced dehairing techniques Dehairing and liming, traditionally dependent on sulfide and lime, are major contributors to the environmental pollution in

the leather industry. These processes are responsible for a significant portion of the biochemical oxygen demand (BOD), chemical oxygen demand (COD), and suspended solids (SS) in wastewater [69]. LCA studies have identified these processes as critical hotspots, prompting cleaner alternatives.

The DEPEXO oxidative dehairing process, utilizing hydrogen peroxide, effectively eliminates sulfide compounds, resulting in a complete 100% reduction in sulfide emissions and more than a 99% reduction in water ecotoxicity [70]. Enzyme-based dehairing with *Bacillus subtilis* complexes offers a single-bath process that outperforms conventional methods across 16 environmental impact categories, reducing overall impact by 24% [71]. Glycine deliming slashes ammonia emissions by 99% but elevates GWP due to energy-intensive production [72]. Keratinase enzymatic dehairing minimizes chemical inputs and waste, producing higher-quality leather with reduced pollution [73].

Thus, LCA-based analysis of advanced dehairing technologies demonstrates clear potential for environmental improvement. However, their industrial scale adoption still depends on real production data and unified evaluation frameworks.

4.3.1.3 Green fatliquors techniques Fatliquors, essential for imparting softness and flexibility to leather, also contribute to environmental impacts, particularly through resource use and toxicity [74]. LCA studies have compared synthetic and bio-based fatliquors to identify sustainable alternatives. Tasca et al. [56] found that epoxidized vegetable oil, while bio-based, increased human and ecosystem toxicity due to pesticide use in feedstock production, compared to sulpho-chlorinated paraffin. Yu et al. [30] conducted a comprehensive LCA of five fatliquors, revealing that chlorinated paraffins (CP) exhibited the highest environmental burden, while bio-based oxidized-sulfited rape oil (OSR) and phosphated rape oil (PR) reduced GWP by 48.5% and 38.5%, respectively. Recent research [7] also explored fatliquors derived from waste biomass, such as fish oil, which reduced ecotoxicity by 30% compared to synthetic alternatives. These findings emphasize the need for LCA to guide the development of fatliquors that balance functional performance with environmental efficiency.

4.3.1.4 Other chemicals Apart from the chemicals discussed above, other auxiliary agents used in leather processing also raise environmental concerns. Their impacts can be systematically evaluated through LCA to identify improvement opportunities.

Degreasing agents, often containing volatile organic compounds (VOCs), contribute to water pollution and long-term environmental accumulation due to poor biodegradability [75]. Rosa et al. [76] developed a lactose-based degreasing formulation (EDF20), which reduced ethoxylated alcohol content to 25 wt%, significantly lowering toxic emissions. However, the energy-intensive synthesis process, particularly protective group operations and solvent purification, accounted for 72% of total energy consumption, highlighting a key bottleneck. Similarly, Ingrao et al. [77] introduced nano-hydroxyapatite (nano-HA) as a replacement for brominated flame retardants, reducing toxicity risks but with high energy consumption (62.8% of total impact) and reliance on phosphoric acid production (25%) as environmental hotspots. These examples illustrate the trade-offs in developing green chemicals, where reductions in toxicity must be balanced against energy and resource demands.

LCA applications have accelerated the development of bio-based tanning agents, fatliquors, and other green chemicals, achieving measurable reductions in GWP, toxicity, and resource depletion. Yet, challenges remain due to energy-intensive synthesis and upstream supply chain burdens. Many bio-based materials still rely on high-temperature reactions and multi-stage purification, and wastewater treatment adds further impacts [77]. Future progress will depend on integrating LCA early in material design, optimizing process efficiency, and minimizing environmental trade-offs. Adopting circular economy strategies, such as utilizing waste biomass and enhancing chemical recycling, can further strengthen sustainability outcomes [1]. Overall, leveraging LCA-guided innovation allows the leather industry to reduce its environmental footprint while maintaining product quality, marking a crucial step toward long-term sustainable leather manufacturing.

4.3.2 LCA study on tannery waste management and utilization

The leather industry generates substantial amounts of waste, including solid residues, sludge, and wastewater, which pose significant environmental challenges [78, 79]. LCA has also emerged as a robust method to evaluate waste treatment strategies, guiding the development of more sustainable waste management practices.

4.3.2.1 Environmental impacts of traditional waste management Traditional methods of tannery waste disposal, such as incineration and landfilling, often result in negative environmental impacts [80, 81]. For example, incineration of leather and fur waste, which accounts for about 42% of tannery waste, recovers energy but also leads to significant toxicity impacts due to emissions [82]. LCA studies have shown that although incineration can have a net positive effect on climate change metrics through energy recovery, it significantly increases ecosystem toxicity and metal resource depletion. Similarly, landfilling

contributes to water ecotoxicity and long-term environmental accumulation of hazardous substances, such as chromium, with studies estimating that tanning and finishing stages generate approximately 95 kg of hazardous waste per 100 m^2 of leather produced [83]. These findings underscore the need for alternative waste management strategies to mitigate the environmental burdens of traditional methods.

4.3.2.2 LCA-driven innovations in waste recycling and valorization LCA studies have highlighted the potential of recycling and valorization technologies to reduce the environmental impacts of tannery waste. Enzymatic processes, such as solid-state fermentation (SSF) for extracting protease enzymes from hair waste, offer significant environmental benefits. Catalán et al. [84] demonstrated that SSF reduced impacts across 18 environmental categories compared to traditional chemical-based depilatory products, primarily by substituting chemical production with enzyme synthesis, thereby lowering indirect emissions. A subsequent LCA study [73] comparing enzymatic and conventional chemical dehairing confirmed that enzymatic methods outperform chemical processes across all environmental indicators, with composting of hair waste showing the lowest water ecotoxicity compared to landfilling or incineration.

Chromium recovery from tanning effluents is another promising approach. Giannetti et al. [85] found that water recycling and chromium recovery reduced water consumption by 50% and chemical demand by 4%, though electricity use increased by 10%. Similarly, Ahmadi et al. [86] reported that chromium recycling via alkaline thermal hydrolysis reduced carbon emissions and metal consumption by over 93%, but the use of caustic soda contributed to 98% of fossil resource consumption and over 90% of human toxicity and photochemical oxidation impacts. These trade-offs highlight the importance of optimizing chemical inputs in recycling processes to maximize environmental benefits.

Innovative valorization techniques, such as converting tannery waste into useful products, have also been assessed using LCA. For instance, pyrolysis of chromium-tanned shavings and buffing dust can produce gas, oil, and carbonaceous residues for fuel or chemical applications, reducing waste disposal impacts by up to 60% compared to incineration [87–89]. Colantoni et al. [90] compared chemical and enzymatic hydrolysis for producing protein hydrolysates from leather waste, finding that enzymatic hydrolysis reduced CO_2 emissions by 57%, fossil energy consumption by 26%, and water use by 78%, compared to chemical methods, offering a cross-industry model for sustainable waste utilization. Additionally, tannery sludge has been explored as a raw material for waterproofing membranes [91], with LCA studies showing reduced environmental impacts compared to conventional fillers, though energy-intensive processing remains a challenge.

4.4 Energy efficiency optimization and circular economy

4.4.1 Energy efficiency improvements

Despite energy costs representing only ~3% of operational expenses, energy use in beamhouse, tanning, and finishing remains a significant source of a tannery's carbon emissions, offering clear potential for mitigation [92]. LCA studies highlight the potential for optimization through renewable energy integration and process modifications.

The integration of renewable energy, such as solar and biogas, has demonstrated significant potential in lowering the carbon intensity of leather production. For instance, Daddi et al. [50] found that solar energy scenarios in metal-free tanning systems can reduce particulate matter impacts by 25% and human toxicity by up to 56%. Similarly, a study of New Zealand's leather industry [57] revealed that a grid comprising 78% clean energy resulted in lower environmental impacts compared to tanneries reliant on fossil fuels. However, inefficiencies persist in many facilities. Morera et al. [93] evaluated a Spanish tannery and identified outdated steam boilers and uninsulated piping as key sources of energy loss. They proposed replacing aging boilers, improving pipe insulation, and installing solar thermal collectors to reduce natural gas consumption by over 90%, depending on system scale. Additionally, coupling photovoltaic panels with energy-efficient machinery not only yields operational cost savings but also enhances performance in Leather Working Group (LWG) audits, further aligning tanneries with sustainability benchmarks.

Advanced technological interventions further enhance energy efficiency. In a recent study, Zhang et al. [94] employed AI-driven optimization to minimize energy use and carbon emissions in chrome tanning. By integrating machine learning models with a genetic algorithm, they identified optimal parameters (pH and time) for penetration and binding phases. The optimized process reduced tanning time from 5 to 3 h while maintaining product quality, and cut energy consumption by 34.95% and CO_2 emissions by 33.87%. At scale, this translates to savings of 8353.33 kgce energy and 87295.6 kg CO_2 annually for a tannery processing 300,000 cowhides. Complementary approaches, such as microwave drying for leather, have demonstrated an 89% reduction in CO_2 emissions [95]. Recycling process heat and adopting energy-efficient machinery further decrease energy demands [96]. A study [97] on tannery wastewater treatment quantified energy intensity at 3.9 kWh/kg COD removed, compared to 1.4 kWh/kg for municipal wastewater, underscoring the need for energy-efficient technologies.

4.4.2 Circular economy

LCA plays a pivotal role in evaluating circular economy strategies by quantifying environmental trade-offs associated with resource recovery. A study by Moktadir et al. [98] assessed tannery sludge energization technologies, finding that power generation with carbon capture (TS-PCC) achieved the best balance of carbon emissions, energy efficiency, and economic benefits, though chemical consumption accounted for 65% of the environmental impact. Another LCA study [14] comparing a baseline scenario (no recycling) with a recycling scenario involving salt recovery and tanning bath effluent reuse found improvements in 14 environmental indicators but a 4% average deterioration in 15 categories due to increased energy demands. These results illustrated the nuanced reality of CE initiatives, where environmental gains may be offset by increased energy burdens, a phenomenon referred to as "circular washing".

The integration of tannery waste into cross-industry applications further supports circular economy goals. For instance, in the preparation of waterproofing membranes, Monica Puccini et al. [91] studied the viability of using tannery wastewaters sludge as an ash replacement for mineral filler. Through LCA analysis, they confirmed that TS-derived membranes outperformed $CaCO_3$-based waterproof membranes when used as a replacement for traditional fillers. However, to fully realize the benefits of such circular applications, ongoing LCA monitoring is essential to identify and mitigate any latent environmental burdens.

4.5 Implications for branding and trade policy

In the contemporary global marketplace, where environmental consciousness is on the rise, LCA has emerged as a linchpin for both branding strategies and trade policy considerations. Within the leather industry, this pivotal role of LCA translates to leveraging LCA data to secure eco-certifications (e.g., EU PEFCR, EU Ecolabel), differentiate low-carbon products, and comply with carbon-border mechanisms like the European Union's Carbon Border Adjustment Mechanism (CBAM), effectively transforming sustainability metrics into competitive and regulatory advantages.

4.5.1 LCA promotes export competitiveness of leather products

LCA provides exporters with a strategic advantage in the global marketplace. By thoroughly evaluating the environmental impacts of products across their entire lifecycle, companies can pinpoint areas for improvement [99]. For instance, in leather product manufacturing, this includes optimizing supply chains [47], refining processes [70], and enhancing energy efficiency [50]. Leather industry, through the environmental protection process of products production, not only can effectively enhance the brand image of the market, but also to create long-term socio-economic benefits [11]. In addition, LCA data can be used to differentiate products in the export market. Many international buyers, especially in developed economies, are increasingly demanding environmentally-friendly products [12]. By being able to provide detailed LCA reports, exporters can demonstrate their commitment to sustainability, making their products more attractive to these discerning customers.

4.5.2 The role of LCA in obtaining green labels

Green labels differentiate products by indicating compliance with strict environmental standards. A key requirement is LCA, which scientifically evaluates a product's impact from raw materials to disposal [100]. Take the globally recognized EU Ecolabel for instance: its certification system relies heavily on LCA principles [13], and leather products must undergo a full-lifecycle LCA assessment to prove compliance at every stage.

LCA acts as both a certification "passport" and a driver for environmental improvement [101]. Compliance with certification standards requires companies to review and optimize their operations, leading to measurable reductions in environmental footprints. The resulting label boosts brand reputation and competitiveness by proving sustainability [102]. Crucial certifications like Leather Working Group (LWG), Sustainable Leather Foundation, PEF certification, and OEKO-TEX promote sustainable leather production [10].

4.5.3 Promoting carbon transparency in trade through LCA

Carbon transparency has become a critical element in international trade, particularly within the context of climate change mitigation efforts. LCA offers a standardized method for quantifying the carbon footprint of products, fostering greater transparency in trade. By using LCA to disclose the carbon emissions associated with their products, countries and companies enable more informed decision-making throughout the supply chain. For instance, importers can compare the carbon footprints of leather products from various sources using LCA data. This transparency encourages market dynamics to favor products with lower carbon emissions, pushing producers to adopt more sustainable practices [94, 103]. Moreover, trade policies can be designed to incentivize carbon-transparent trade [104]. Governments might offer preferential treatment, such as reduced tariffs or expedited customs clearance, for products with verified low-carbon footprints, as determined by LCA [105, 106]. This approach would not only foster sustainable trade but also promote global collaboration in reducing carbon emissions across industries, including leather.

Table 4 Comparative analysis of carbon footprints for leather production across various studies

Product type	Functional unit	System boundary	LCA tool & method	Database	Carbon emission value (kg CO_2 eq)	References
Crust leather to finished	1 m^2 crust leather	Cradle-to-Gate	SimaPro + IMPACT 2002	Ecoinvent	0.75	[42]
Finished bovine shoe leather	1 m^2 finished shoe leather	Gate-to-Gate	Gabi + PEFCR Leather	GaBi + Ecoinvent	8.54	[57]
Finished goat leather	1 kg vegetable-tanned goat leather	Cradle-to-Gate	SimaPro v9.1.1.1 + ReCiPe H	Ecoinvent 3.6	12.9	[52]
Finished bovine leather	1 kg chromium-tanned cow leather	Cradle-to-Gate	SimaPro v9.1.1.1 + ReCiPe H	Ecoinvent 3.6	25.8	[52]
Finished Mycelium based leather	1 m^2 natural Mycelium® leather	Cradle-to-Gate	OpenLCA 2.02 + CML-IA baseline	Ecoinvent 3.8	57.15	[111]
Finished bovine leather (aniline)	1 m^2 finished leather	Cradle-to-Gate	SimaPro 7.3 + PAS 2050	SimaPro database	73.0 (64.8–79.6)*	[53]
Finished bovine leather	1 m^2 finished leather by glucose	Cradle-to-Gate	SimaPro 7.3 + ReCiPe H	Ecoinvent 2.2	175	[112]
Finished goat leather	1 m^2 finished leather by chrome	Cradle-to-Gate	SimaPro 7.3 + ReCiPe H	Ecoinvent 2.2	193	[112]
Finished cow leather	1 batch production (285.4 kg cow leather)	Gate-to-Gate	OpenLCA 1.6.3 + CML (baseline 4.4)	OpenLCA built-in database	202.29	[58]

*The carbon footprint of finished bovine leather (aniline) ranges from 64.8 to 79.6 kg CO_2 eq/m^2 (average. 73.0), depending on leather thickness

** The variability in reported values stems primarily from differences in system boundaries, functional units, LCIA methods, and background databases

In conclusion, LCA has far-reaching implications for branding and trade policy. By integrating LCA into their strategies, companies can boost their export competitiveness, earn valuable green certifications, and contribute to carbon transparency in trade, factors that are increasingly vital for success in the evolving global marketplace.

5 Challenges in LCA implementation for tannery circular economy goals

In the face of intensifying resource scarcity, environmental pollution, and trade barriers like CBAM, LCA has become indispensable for advancing sustainable practices in the leather industry [107–109]. Despite the growing adoption of LCA aligned with global standards like ISO 14040/14044, several challenges hinder its effectiveness and widespread application in the leather industry.

5.1 Lack of standardization

In the leather industry, the inconsistency of LCA methodologies undermines the comparability of findings across studies. For instance, the COTANCE report [39] estimates the carbon footprint of cowhide to be between 4 and 12 kg CO_2 eq/m^2. These methodological variations include differences in functional units (e.g., 1 m^2 versus 1 kg of leather), system boundaries (e.g., cradle-to-gate versus cradle-to-grave), and the tools employed (e.g., SimaPro, GaBi, OpenLCA). Moreover, discrepancies in LCIA methods also contribute to divergent carbon footprint results. For example, methods like TRACI and ReCiPe often yield significantly different outcomes [23, 110]. Table 4 summarizes the reported carbon footprint of leather in the literature, showing estimates ranging from 0.75 to 202.29 kg CO_2 eq. These variations highlight the impact of methodological choices on the final results.

These methodological inconsistencies not only hinder the effectiveness of LCA evaluations in the leather industry but also limit the comparability of sustainability performance across regions and production methods.

5.2 Data availability and accuracy

The reliability of LCA results in the leather industry is substantially constrained by persistent data collection challenges, which directly affect the accuracy, credibility, and comparability of assessment outcomes. These challenges largely arise from the complex and extended value chain of the leather industry, encompassing animal husbandry, chemical production, tanning, finishing, and downstream processing stages.

At the production level, tanneries manufacture a wide range of products with diverse colors and functional properties, resulting in complex cross-process interactions and highly variable material and energy flows [113]. In addition, the degree of digitalization and management sophistication varies considerably among tanneries. While some facilities employ advanced monitoring and control systems, others lack adequate metering equipment and instruments. Regional disparities in equipment modernization, automation levels, and energy supply structures further exacerbate data inconsistency [114]. As emphasized by Notarnicola et al., the combined effects of process diversity, managerial heterogeneity, and

technological gaps make data collection in the leather industry a complex and resource-intensive task [115].

Significant data limitations also originate from upstream processes. Information related to animal husbandry and leather chemical production is often incomplete, aggregated, or inaccessible. In particular, formulations of tanning, retanning, fatliquoring, and finishing chemicals are typically regarded as trade secrets and are therefore seldom disclosed. As a result, LCA practitioners are frequently forced to rely on generic datasets from background databases such as Ecoinvent [116]. Chen et al. [117] have shown that dependence on such generic or proxy data can lead to substantial deviations from real production conditions, thereby undermining the accurate of LCA results. This problem is further compounded when laboratory-scale measurements or literature-based estimates are used as substitutes for industrial-scale inventory data.

Despite the increasing application of LCA in the leather industry, data availability and consistency remain major constraints due to limitations in existing LCI databases. Widely used databases such as Ecoinvent and GaBi provide relatively comprehensive background data for energy systems, generic chemicals, and standard industrial processes. However, their representation of leather-specific operations remains limited. Consequently, chemical-intensive stages such as retanning, fatliquoring, and finishing are modeled with insufficient technological resolution, introducing uncertainty in impact quantification and limiting cross-study comparability. For China-based studies, the CLCD offers improved regional representativeness, particularly with respect to electricity generation, upstream chemical production, and region-specific emission factors. In recent years, research groups at Sichuan University have been actively engaged in developing and refining CLCD datasets relevant to the leather and related industries, representing an important step toward improved data localization and sector relevance [28]. Nevertheless, current CLCD coverage of leather manufacturing processes remains incomplete, and substantial efforts are still required to establish detailed process-level inventories, enhance data transparency, and ensure consistency with international LCA standards.

5.3 Cost and resource barriers

Implementing LCA requires significant financial and technical resources, posing challenges for small and medium-sized enterprises (SMEs). Professional software (e.g., SimaPro, Sphera) and certification services are costly, and SMEs often lack the expertise for in-house LCA, relying on expensive consultants [118]. Thess cost and resource barriers create disparities, as larger firms leverage green premiums and tariff reductions, while SMEs face market exclusion [98, 119].

5.4 Economic and environmental trade-offs

As a traditional industry with low profit margins (only 3.7% in 2023) [120], the leather industry is subject to structural constraints that limit its ability to adopt costly sustainability measures. This micro-profit status exacerbates the challenges of adopting environmentally friendly technologies, such as bio-based tanning agents or water recycling systems, which often inflate production costs through higher material expenses and capital investments, thereby straining economic viability, particularly for SMEs [63]. For example, chrome-free tanning reduces toxicity but raises material costs, impacting competitiveness [1]. Although consumer demand for sustainable leather offers market opportunities, SMEs struggle to adopt green technologies without support [121].

5.5 Limited awareness and adoption

LCA is a well-established methodology in environmental science, yet its application in the leather industry remains limited, primarily confined to academic research and professional circles. Despite its potential to enhance sustainability, LCA has not been widely integrated into the industry's production and management practices. The lack of awareness among corporate decision-makers, industry stakeholders, and the public hinders its broader adoption [122]. This awareness gap results in insufficient motivation and investment in implementing LCA, reducing its practical application and limiting its impact on promoting sustainable practices within the leather industry.

6 Recommendations for LCA application in the leather industry

The transition of the leather industry toward sustainability and circular economy objectives requires not only technological innovation but also systemic reforms in evaluation methods and governance. Building upon the findings of this review, three key recommendations are proposed to enhance the application of LCA in the leather industry.

6.1 Establishing a unified specific LCA database for the leather industry

As discussed above, one of the most pressing challenges in applying LCA to the leather industry is the lack of standardized methodologies and reliable, comparable data. In our review of literature related to LCA applications in the leather sector, we found that current studies often rely on fragmented datasets, region-specific assumptions, or inconsistent allocation rules, which limit the comparability and transferability of results across

regions and technologies. Recent global assessments [60] have shown that aggregated or averaged data fail to accurately represent the environmental performance of leather production, highlighting the urgent need for sector-specific LCI databases that provide harmonized and transparent inventory data.

Establishing a leather-specific LCI database would deliver multiple benefits. First, by applying a shared methodological framework to all datasets, it would substantially increase the robustness and credibility of LCA studies in this sector. Second, it would provide dynamic, up-to-date datasets that reflect both regional energy mixes and evolving leather production technologies, enabling continuous benchmarking and process optimization. Finally, such a database would serve as a critical decision-support tool for policymakers, industry associations, and certification bodies, thereby strengthening the role of LCA in guiding the leather industry's transition towards circular economy principles and carbon neutrality.

In conclusion, the creation of a unified, leather-specific LCI database, together with a clearly defined methodological framework, is not only a technical necessity but also a strategic imperative for the leather industry. By consolidating reliable and transparent data on material flows, energy use, and emissions, it would resolve current inconsistencies, enhance methodological comparability, and provide a robust foundation for sustainable innovation in the leather sector.

6.2 Multi-dimensional assessment framework for holistic evaluation

Multi-dimensional sustainability frameworks often rely on multi-criteria decision analysis, which allows for the simultaneous evaluation of trade-offs across diverse impact categories. As noted by Fidan et al. [122], integrating social indicators into LCA expands its scope beyond ecological impacts to address labor welfare, community well-being, and occupational safety, offering a more comprehensive sustainability perspective.

This approach is particularly relevant to the leather industry, which occupies a unique position in global value chains. As a by-product valorization pathway of animal husbandry, leather production mitigates upstream waste disposal while generating durable materials. However, traditional LCAs focusing solely on environmental indicators risk overlooking this broader contribution. Integrating environmental, economic, and social assessments allows a more balanced understanding of the industry's role in waste management, resource efficiency, and emission absorption. The leather industry also links upstream sectors (animal husbandry, chemical production) with downstream markets (footwear, automotive, fashion). While LCAs consistently identify chemical use, wastewater discharge, and energy demand as major hotspots, these analyses often neglect economic resilience and social responsibility. A multi-dimensional framework combining LCA, Life Cycle Costing (LCC), and Social LCA (S-LCA) can capture trade-offs between environmental improvement, cost efficiency, and social welfare, ensuring a more comprehensive evaluation of sustainability performance. Moreover, this industry's current low-profit margins underscore the need to incorporate economic factors into sustainability assessments. This financial constraint heightens the challenges of implementing green technologies without jeopardizing operational viability. By integrating LCC into a multi-dimensional LCA framework, assessments can evaluate cost-benefit trade-offs, ensuring that environmental enhancements are aligned with economic sustainability and do not place excessive strain on resource-limited businesses.

In summary, a multi-dimensional assessment framework provides a holistic and realistic pathway for evaluating sustainability in the leather sector. By extending LCA beyond environmental boundaries to encompass economic competitiveness and social equity, the leather industry can better align with global sustainability goals and promote balanced, long-term progress.

6.3 AI-assisted LCA for the leather industry

As previously discussed, the complexity of the leather value chain, product diversity, and limited data transparency make LCA implementation particularly challenging. In this context, integrating artificial intelligence (AI) and machine learning (ML) into LCA offers a promising solution by automating data processing, identifying patterns in fragmented datasets, and generating predictive models where primary data are limited, thereby enhancing both efficiency and reliability of sustainability assessments.

Recent reviews demonstrate that ML can be used to predict environmental impacts directly from process descriptors, reducing the reliance on extensive primary data collection and speeding up LCA modeling [123]. For instance, AI-enabled frameworks have been successfully applied to estimate greenhouse gas reduction potentials in automotive lightweighting, indicating their capacity to generalize across industrial sectors [124]. A comprehensive review by Ghoroghi et al. [125] further highlights how supervised and unsupervised ML algorithms can complement conventional LCA by identifying hidden patterns in large datasets, improving hotspot detection, and enhancing uncertainty analysis. More recently, Salla et al. [126] proposed integrative frameworks that embed AI into LCA workflows, enabling predictive modeling of environmental impacts under different process scenarios. Such approaches are particularly relevant for the leather industry, where the long supply chain, diverse

product types, and intersecting material flows make conventional LCAs difficult to standardize. By learning from historical datasets, AI can generate scenario-specific impact predictions, supporting proactive environmental management.

Against this backdrop, the integration of AI and ML into LCA methodologies provides a promising pathway to addressing assessment complexity. AI-assisted approaches can automate data processing, identify patterns across fragmented datasets, and generate predictive models where primary data are lacking, thereby improving both efficiency and reliability of sustainability assessments.

7 Conclusion

This review substantiates LCA's transformative role in advancing the leather industry toward circular economy principles. By systematically quantifying environmental impacts and enabling by-product valorization, LCA helps reconceptualize leather production as a sustainable process that effectively mitigates waste while reducing reliance on fossil-based materials. However, barriers such as methodological inconsistencies, regional disparities in technological capabilities, and limited awareness and adoption among industry stakeholders continue to hinder optimal implementation. Future progress necessitates developing unified sector-specific databases, integrating multidimensional sustainability indicators, and leveraging emerging AI technologies for enhanced modeling accuracy and decision-support capabilities. Through strengthened methodological rigor, policy support, and broader stakeholder collaboration, LCA can further solidify the leather industry's contribution to achieving global sustainability goals and circular economy objectives.

Abbreviations

AA	Aldehyde acid
AA-CR	Aldehyde acid-chrome tanning system
ADP	Abiotic depletion potential
AI	Artificial intelligence
AP	Acidification potential
BB	Bio-based acrylic graft copolymers
BOD	Biochemical oxygen demand
BPP	Protein derivatives
CBAM	Carbon border adjustment mechanism
CE	Circular economy
CFTS	chrome-free tanning systems
CFMTS	Chromium free metal tanning systems
CFP	Carbon footprint of products
CLCD	Chinese life cycle database
COD	Chemical oxygen demand
CP	Chlorinated paraffins
CTS	Chromium tanning systems
DEPOXO	Depilation and oxidation process
EC	European Commission
EDF20	Experimental degreasing formulation 20
EP	Eutrophication potential
EPA	Environmental Protection Agency
EPD	Environmental product declaration
ESG	Environmental, Social, and Governance
EU PEFCR	European Union's Product Environmental Footprint Category Rules
GHG	Greenhouse gas
GWP	Global warming potential
HIQLCD	High quality life cycle database
ISO	International Organization for Standardization
JIS Q	Japanese Industrial Standards Q
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LWG	Leather Working Group
MFTS	Metal free tanning systems
ML	Machine learning
Nano	HA-Nano hydroxyapatite
OSR	Oxidized sulfited rape oil
PAS	Publicly available specification
PED	Primary energy demand
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PR	Phosphated rape oil
PU	Polyurethane
PVC	Polyvinyl chloride
SETAC	Society of Environmental Toxicology and Chemistry
S-LCA	Social Life Cycle Assessment
SMES	Small and medium sized enterprises
SS	Suspended solids
SSF	Solid state fermentation
TA-ZE	Tannic acid-zirconium system
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TS-PCC	Tannery sludge power generation with carbon capture
UNIDO	United Nations Industrial Development Organization
US LCI	U.S. Life Cycle Inventory
VOCS	Volatile organic compounds

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BL: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Writing- review and editing, Visualization. XW: Software, Validation, Investigation, Data curation. SW: Investigation, Formal analysis. XC: Validation, Data curation. WL: Resources, Investigation, Visualization. SC: Investigation, Formal analysis. DZ: Conceptualization, Supervision, Project administration, Funding acquisition, Writing-review and editing.

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