



Leather waste into functional materials: composite nanoarchitectonics, energy systems, and environmental applications

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Abstract

The global leather industry generates large volumes of chromium (Cr)-containing solid waste, creating significant environmental risks to water systems and public health. This mini review highlights recent advances in converting leather residues into high-value materials for water purification and sustainable energy applications. Activated carbon (AC) derived from leather waste has demonstrated superior adsorption performance for heavy metals, dyes, and emerging contaminants, with removal efficiencies exceeding 95% for Cr and pharmaceutical compounds. Integration of leather-based carbons with photocatalysts such as BiOX and TiO₂ has enabled efficient photodegradation of industrial pollutants, supporting low-cost treatment of tannery effluents. In parallel, leather-derived collagen fibers have been engineered into triboelectric nanogenerators and battery electrodes, achieving open-circuit voltages of up to 231 V and specific capacitances of 550 F/g. These technologies demonstrate the potential of leather waste as a renewable feedstock for clean energy generation and storage. Key challenges remain in Cr stabilization, standardization of processing protocols, and scaling up pilot studies to industrial levels. Future work should integrate life-cycle assessment (LCA) and techno-economic analyses (TEA) to ensure safe, cost-effective deployment. By focusing on water remediation and energy harvesting, this review establishes a circular economy framework where leather waste transitions from an environmental liability to a resource for sustainable water and energy systems.

Keywords Leather waste · Sustainable materials · Composites · Circular economy

Abbreviations

AC	Activated Carbon	SCR	Selective Catalytic Reduction
BiOI	Bismuth Oxyiodide	TEA	Techno-economic analyses
BiOX	Bismuth Oxyhalide (X = Cl, Br, I)	TENG	Triboelectric Nanogenerator
CSW	Chrome Shaving Waste	UV	Ultraviolet
GCFS	Graphene-Collagen Fiber Scaffold	XPS	X-ray Photoelectron Spectroscopy
LCA	Lifecycle assessments		

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Introduction

Leather is one of the most globally traded biomaterials, valued for its durability, mechanical strength, and aesthetic appeal. Its usage spans in the production of footwear, garments, furniture, automotive interiors, and fashion accessories. Despite the economic importance of leather, its manufacturing process is highly resource-intensive and generates substantial amounts of solid waste (Rebelato et al., 2024; Tegadye et al., 2023). It was reported that footwear and leather sectors generate significant waste, with leather being a major component, constituting around 60–65% of footwear consumption (Jadhav & Jadhav, 2020). Often, rawhide inputs are discarded as waste during various stages of processing, including trimming, shaving, buffing, and finishing. The tanning process, particularly when chromium (Cr) salts are used, poses additional challenges for waste disposal due to the presence of potentially toxic residues (Li et al., 2024). Inadequate management of these wastes can lead to soil contamination, groundwater pollution, and significant public health risks, especially in developing countries where environmental regulations may be less stringent. The accumulation of Cr in soil can diminish agricultural productivity and degrade soil quality, while elevated concentrations in the human body have been associated with carcinogenic effects and a reduction in life expectancy (Dotaniya et al., 2023; Essam et al., 2024; Younas et al., 2023). Conventional approaches to leather waste management, such as landfilling and incineration, are increasingly deemed unsustainable due to regulatory restrictions, environmental concerns, and the rising cost of disposal.

In this regard, the concept of nanoarchitectonics has emerged as a powerful paradigm in materials science. Nanoarchitectonics involves the rational arrangement and integration of nanoscale building blocks such as nanoparticles, nanofibers, and molecular assemblies into hierarchical structures with tailored properties (Ariga, 2024; Song et al., 2025). Applied to leather waste valorization, nanoarchitectonics provides a unifying lens to describe how heterogeneous residues can be engineered into composites, catalytic systems, and energy devices that exhibit enhanced functionality beyond conventional material recycling. A growing body of research has explored various strategies to valorize leather solid waste into value-added products. For instance, one previous review systematically reviewed on the utilization routes for different types of leather waste such as hair, chrome shavings, and sludge (Li et al., 2019). Their review emphasized treatment techniques and direct reuse in materials like gelatin, biofertilizers, and building products. Similarly, Appala and co-workers presented a biorefinery perspective, highlighting

the potential of leather waste to yield renewable fuels, adsorbents, and biodegradable polymers within a circular economy framework (Appala et al., 2025). Gunasekaran and colleagues explore how leather industry wastes such as chrome shaving waste (CSW), buffing dust, and vegetable-tanned leather can be repurposed for thermal and electrical energy storage, contributing to cleaner production and sustainability (Gunasekaran et al., 2025). Meanwhile, another pertinent review discussed the transformation of leather waste into nitrogen-doped carbon through pyrolysis and its application in energy storage, dye adsorption, and catalysis (Stejskal et al., 2023a). Although electrical conductivity was addressed for the first time in detail, their scope was largely confined to thermochemical treatments of leather-derived carbon. Muralidharan and co-workers adopted an intra-industrial lens, evaluating how solid waste could be looped back into the leather manufacturing process to reduce environmental impact and promote circular practices (Muralidharan et al., 2022).

Although prior reviews have discussed waste management in the leather industry, they often focus on isolated applications such as composites or wastewater treatment, without presenting an integrated analysis across multiple valorization pathways. Moreover, much of the available literature emphasizes laboratory-scale demonstrations, while issues related to scalability, environmental safety, and techno-economic feasibility remain underexplored. The present review addresses this gap by synthesizing recent progress in energy systems, and environmental remediation, framed within the emerging concept of nanoarchitectonics. By adopting this perspective, the review not only consolidates knowledge across different sectors but also provides a cross-cutting framework that links material properties, environmental safety, and economic considerations. In doing so, it advances beyond earlier literature to offer a roadmap for transforming leather waste from an environmental liability into a functional resource within sustainable energy and water systems. Figure 1 presents the conceptual framework and story flow of this review. It outlines the sources and characteristics of leather waste, the main valorization pathways (polymeric composites, construction materials, energy harvesting, and environmental remediation), and cross-cutting themes such as environmental and economic considerations. This schematic serves as a roadmap to guide the discussion in the subsequent sections.

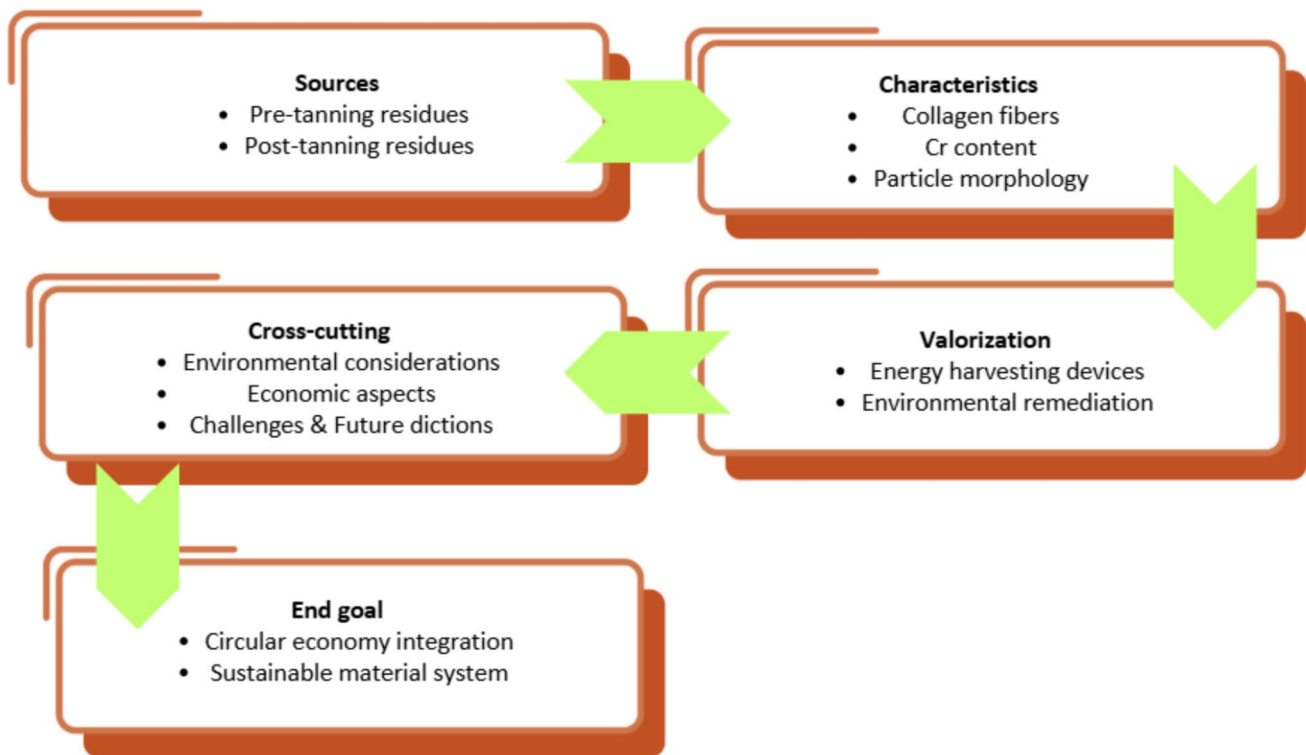


Fig. 1 Conceptual framework and story flow of this review

Environmental challenges and water-energy nexus

Leather wastewater pollution and chromium risks

The leather tanning industry generates large volumes of wastewater and solid residues containing Cr and other hazardous chemicals. Cr salts, particularly trivalent chromium (Cr^{3+}), are widely used during tanning to enhance leather durability and thermal stability (Salernitano et al., 2017). During processing, 30–40% of the Cr salts fail to bind with collagen fibers and are discharged into wastewater streams or accumulate in solid residues such as chrome shavings, buffing dust, and sludge (Esmaeili & Vazirinejad, 2005; Sadig & Tabidi, 2022). Improper disposal of these residues introduces significant environmental risks, especially the oxidation of Cr^{3+} to hexavalent chromium (Cr^{6+}), a highly toxic and carcinogenic form.

Cr^{6+} contamination in water systems poses severe threats to public health and agriculture. Chronic exposure has been linked to respiratory diseases, kidney damage, and various cancers (Pathak et al., 2023; Suter et al., 2024). Elevated Cr concentrations can also disrupt aquatic ecosystems, impair soil fertility, and contaminate food crops (Dotaniya et al., 2014). In regions where tanning industries are clustered, such as South Asia, Southeast Asia, and parts of Africa,

weak regulatory oversight exacerbates these impacts. Conventional treatment methods, including coagulation, precipitation, and reverse osmosis, often struggle to remove Cr completely and generate secondary waste streams that are challenging to manage (Hussain & Memon, 2020; Liu & Yu, 2021).

Global water-energy nexus

Water and energy systems are tightly interconnected. Large volumes of clean water are essential for energy production, while energy is required for water treatment, pumping, and distribution. Pollution from industrial sources like tanneries intensifies this interdependency. Contaminated wastewater increases the energy demand for treatment and limits water availability for power generation and industrial cooling (Kweiner Tetteh et al., 2019). At the same time, unsustainable energy use during water treatment contributes to greenhouse gas emissions, compounding environmental challenges.

Leather waste-derived materials offer an innovative solution to this cycle. By transforming Cr-rich residues into functional adsorbents and photocatalysts, these wastes can directly support low-energy water purification processes. Simultaneously, leather-derived collagen fibers and carbon materials can be engineered into energy harvesting devices,

such as triboelectric nanogenerators (TENGs), battery electrodes, and supercapacitors. These dual roles demonstrate how waste streams can be repurposed to address both clean water and renewable energy needs, reducing environmental footprints on two critical fronts.

Rationale for valorization into water and energy applications

Traditional valorization routes for leather waste have focused on construction materials and polymer composites (Hang et al., 2020; Kiliç et al., 2021; Ławińska, 2021; Parisi et al., 2021; Patchai Murugan et al., 2018; Sharma et al., 2023). While these pathways divert waste from landfills, they provide limited benefits for addressing pressing global issues such as water scarcity and sustainable energy demand. The growing emphasis on circular economy principles highlights the need for integrated solutions that link waste management with environmental protection and resource recovery.

This review prioritizes two high-impact application areas: water purification and energy systems. In water purification, leather-derived activated carbon (AC) and hybrid photocatalysts have demonstrated exceptional performance in removing dyes, heavy metals, pharmaceuticals, and other pollutants from industrial wastewater. These materials not only mitigate the direct impact of tannery effluents but also support treatment of diverse waterborne contaminants. In energy systems, leather collagen and carbonized residues have been incorporated into advanced devices for renewable power generation and energy storage, offering low-cost alternatives to conventional electrode materials (Konikkara et al., 2017).

This review followed a structured narrative approach to synthesize existing knowledge on the valorization of leather waste for water treatment and energy applications. A comprehensive literature search was conducted using Scopus database covering publications from January 2020 to April 2025. The search terms included combinations of keywords such as leather waste, tannery waste, chrome shaving waste, buffing dust, water treatment, wastewater, adsorption, photocatalysis, activated carbon, energy harvesting, triboelectric nanogenerator, supercapacitor, and battery electrode, with only articles published in English considered. Titles and abstracts were screened to exclude irrelevant studies, and full-text articles were then assessed for eligibility. Studies were included if they reported experimental work on converting leather waste into functional materials for water purification, such as adsorption, photocatalysis, and Cr removal, or energy-related applications, including energy harvesting devices and energy storage systems, with measurable performance data such as adsorption capacity, degradation efficiency, or electrochemical performance. Excluded works consisted of those focused on unrelated applications

such as footwear, packaging, or construction, as well as non-peer-reviewed reports and review papers, which were only used for background information. For each selected study, information was extracted on the type and source of leather waste, processing methods such as pyrolysis or chemical activation, target application, and key performance indicators, including adsorption efficiency, Cr removal levels, pollutant degradation, and energy outputs. The extracted data were then synthesized into thematic sections to highlight progress, challenges, and future directions in water and energy systems. This narrative review approach was chosen to allow broad integration of multidisciplinary studies and to critically analyze emerging trends while identifying research gaps that must be addressed to advance the sustainable use of leather waste.

By focusing on these applications, leather waste transitions from an environmental liability to a strategic resource within the water-energy nexus. This approach addresses global sustainability goals by creating a closed-loop system where industrial byproducts are reintegrated into solutions for clean water access and clean energy generation.

Energy harvesting and electronic devices

The emergence of triboelectric nanogenerators (TENGs) and bioelectronic platforms has opened new frontiers for the valorization of collagen-rich leather waste, particularly in applications where mechanical flexibility and charge transfer efficiency are critical. Leather-derived carbons used in batteries, supercapacitors, or catalytic systems have the potential to lower production costs compared with traditional electrode materials. While upfront processing costs remain a challenge, scaling and co-production with other biomass-derived carbons may provide competitive economic pathways. Rather than limiting leather waste to passive structural use, recent studies have exploited its electroactive properties to fabricate self-powered systems for energy harvesting and motion sensing. This represents a paradigm shift in leather waste reuse from bulk fillers to active functional interfaces. For instance, a collagen fiber-based TENG was developed using leather scrap processed into aerogel films, which were subsequently densified to create a roughened surface conducive to charge generation (Zhang et al., 2025). The energy harvesting capability of g-GCFS-TENG device is as shown in Fig. 2, fabricated using a plastic shell with triboelectric layers adhered to copper tape; pressing enabled contact and elastic recovery allowed repeated cycles. The device powered 200 LEDs and a logo panel (Fig. 2b–d), while a rectifier converted AC output to DC for storage in a capacitor (Fig. 2e). An optimized setup charged a 4.7 μF capacitor to 3.5 V in 220 s, successfully powering a commercial timer (Fig. 2f), with repeated cycles confirming

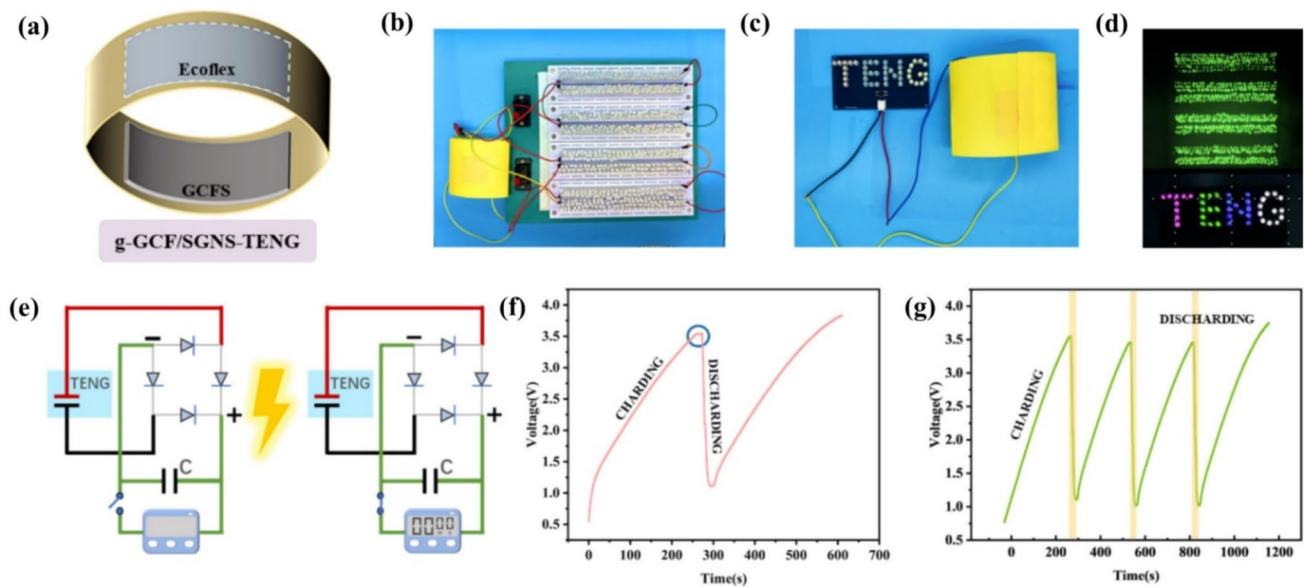


Fig. 2 (a) g-GCFS-TENG for mechanical energy harvesting, including its structural schematic (a), (b) operation under tapping to illuminate 200 LEDs, (c) the resulting light panel, (d) a photograph of the illuminated panel, (e) the circuit diagram used for capacitor charging

and device powering, (f) the voltage output during timer activation alongside a photo of the powered timer, and (g) the cyclic voltage curve indicating repeated timer operation (Zhang et al., 2025)

stable performance (Fig. 2g), highlighting its potential for low-power energy applications. The incorporation of sulfonated graphene nanosheets into the collagen matrix further enhanced electrical output by increasing surface conductivity and trapping charges at the interface. The optimized g-GCFS-TENG device achieved an open-circuit voltage of 231 V under a 20 N load and exhibited robust durability over 5,000 cycles. Its ability to power 200 LEDs and charge a timer through biomechanical motion highlights its practical relevance for wearable energy devices. The architectural design of the TENG played a significant role in performance optimization.

Recent developments of leather waste have demonstrated its applicability in both supercapacitors and battery electrodes, highlighting its multifunctional electrochemical potential (El-Hout et al., 2022; Martínez-Casillas et al., 2018). One recent study demonstrated an effective approach for converting Cr-tanned leather waste into bio-char suitable for supercapacitor electrodes (Stejskal et al., 2025). The work involved three carbonization strategies: direct pyrolysis at 800 °C, a two-step process involving pre-carbonization followed by KOH activation, and direct activation with excess KOH. Among these, the two-step activation method produced a material with superior electrochemical properties, including a high specific surface area of 1180 m²/g and enhanced electrical conductivity of 1.41 S/cm. The electrochemical evaluation revealed that the optimized leather-derived carbon achieved a specific capacitance of 187.7 F/g in a three-electrode configuration using a

6 M KOH electrolyte. When assembled into a symmetrical supercapacitor, the device delivered a capacitance of 150.9 F/g, maintaining 95% retention over 5000 charge–discharge cycles, highlighting its durability and potential for practical applications. Notably, the device exhibited a power density of 10.5 kW/kg in the aqueous electrolyte and an energy density of 21.3 Wh/kg in an organic electrolyte system, demonstrating versatility across different operating conditions. When compared with other biomass-derived ACs, such as those from agricultural residues or food waste, leather-based carbons exhibit comparable or superior performance due to their unique chemical composition and inherent nitrogen content (El-Hout et al., 2022). This positions them as a promising alternative for low-cost, high-performance supercapacitor electrodes, particularly in applications where both waste reduction and renewable energy development are priorities.

MoS₂ nanocrystals confined within N,P co-doped carbon fibers derived from leather waste were also synthesized (Zheng et al., 2023). These composites served as high-capacity, stable anodes for sodium (368 mAh/g) and potassium-ion (241 mAh/g after 2500 cycles) batteries. Their electrochemical performance showcases a novel frontier for leather waste in energy storage and should be appended to the energy harvesting section. Another study evaluated aAC derived from leather waste for supercapacitor applications (El-Hout et al., 2022). The AC was synthesized via carbonization between 700 °C and 900 °C followed by chemical activation, yielding a maximum surface area of 381 m²/g.

The sample carbonized at 700 °C exhibited a high specific capacitance of 550 F/g at 1 A/g in a 6 M KOH electrolyte.

Catalysis and environmental remediation

Photocatalysts and adsorbents play critical roles in environmental remediation, with photocatalysts driving the degradation of organic pollutants under light irradiation and adsorbents capturing contaminants through surface interactions (Maran et al., 2025; Shanmugam et al., 2024; Zheng et al., 2022). A key area of interest is the conversion of leather waste into functional adsorbents and catalysts for the removal of organic dyes, heavy metals, and gaseous pollutants (Carvalho Pinheiro et al., 2022; Tang et al., 2021). Leather solid waste can be effectively converted into AC, which serves as a potent adsorbent due to its high nitrogen content and large surface area (Venkatesan et al., 2023). Pyrolysis has always been the common option to convert them to carbonaceous materials (Ahmad Farid et al., 2024). One interesting presents a novel circular economy strategy for addressing Cr contamination in the leather industry by converting leather industry waste as shown in Fig. 3, specifically fleshing waste, into AC adsorbents (Jimenez-Paz et al., 2023). Using both physical (CO_2) and chemical (KOH) activation processes, including a direct physical activation

method that had not been previously reported, the researchers produced ACs capable of effectively removing Cr (III) with over 95% efficiency and moderately adsorbing Cr (VI) at approximately 17%. The adsorption process followed pseudo-second-order kinetics, with Cr (III) best described by Freundlich and Temkin isotherms, and Cr (VI) by the Dubinin-Kaganer-Radushkevich model. Their study demonstrated the dual benefit of pollutant removal and waste valorization, offering a scalable and low-cost solution suitable for small and medium-sized tanneries, particularly in developing regions such as Colombia. Al_2O_3 was further incorporated into leather-derived AC for the removal of Cr (VI) from aqueous solutions (Bithi et al., 2024). The adsorbent exhibited a capacity of 19.3 mg/g and followed pseudo-second-order kinetics and a Freundlich isotherm, highlighting the role of heterogeneous surface interactions. The utility of leather waste was further broadened by synthesizing polyaniline-coated carbon composites from pyrolyzed shavings (Stejskal et al., 2023b). The bicontinuous network achieved dual functionality in dye adsorption and electrical conductivity, making it suitable for multifunctional filters. The stability of these composites in alkaline conditions suggests their potential in industrial effluent treatment where pH fluctuation is common. Leather waste-based adsorbents and catalysts reduce dependence on high-cost ACs or engineered nanomaterials. The economic appeal is further enhanced in

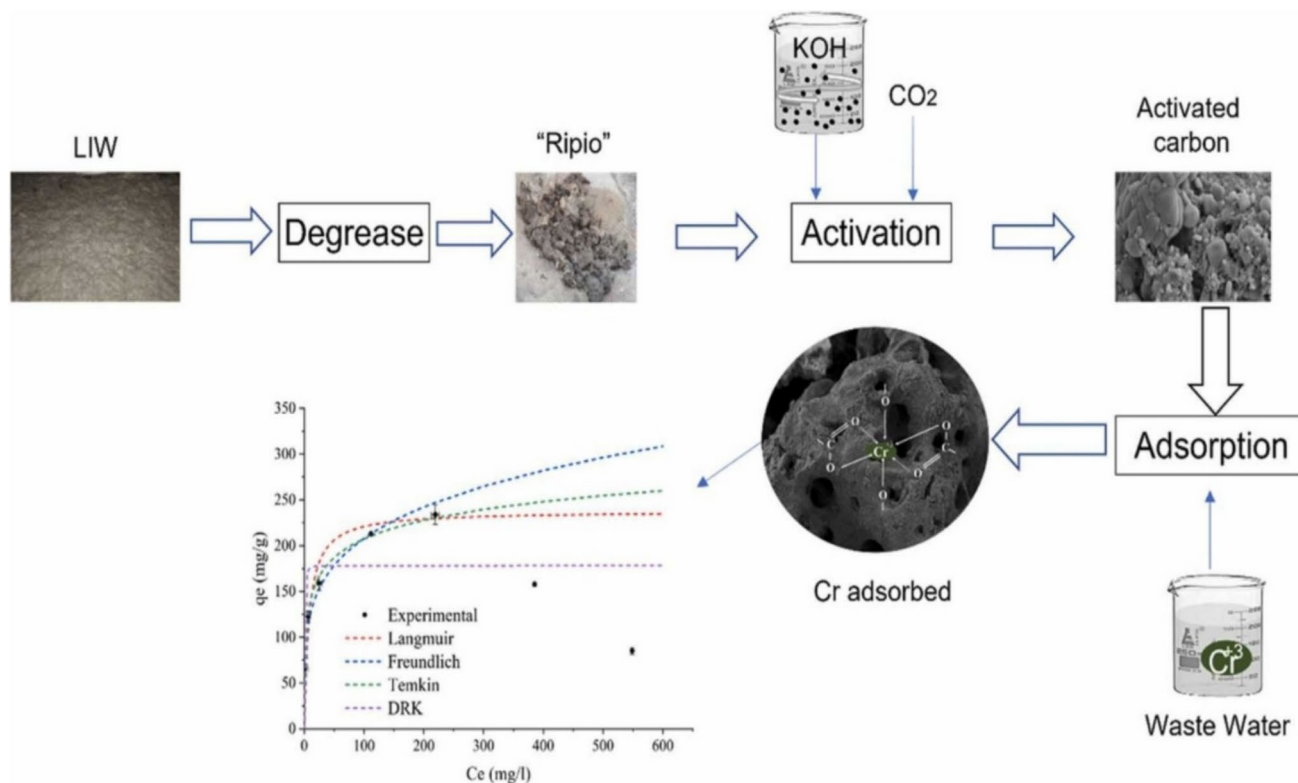


Fig. 3 (a) Schematic representation of the preparation and application of AC derived from leather industry waste (Jimenez-Paz et al., 2023)

regions with abundant tannery clusters, where localized valorization can minimize transportation and disposal expenses.

Photocatalysts derived from leather waste present a promising avenue for both waste management and environmental remediation. These residues can be transformed into effective photocatalytic materials, offering a dual benefit of waste valorization and pollution mitigation.

For instance, AC derived from chrome-tanned leather shavings, when integrated with BiOX ($X = \text{Cl}, \text{Br}, \text{I}$), formed high-surface-area photocatalysts effective under visible light (Roshini et al., 2025). The optimized AC/BiOCl and AC/BiOI composites exhibited dye degradation efficiencies exceeding 97% for Rhodamine B, driven by improved charge separation and the presence of Cr_2O_3 acting as an electron

mediator. These results suggest that leather waste-derived carbon is not merely a structural support but contributes actively to photocatalytic performance. This concept was further extended by synthesizing $\text{Cr}_2\text{O}_3/\text{C}/\text{TiO}_2$ nanocomposites from buffing dust for the degradation of chlorophenols under UV light (Patchai Murugan et al., 2023). Their system achieved near-complete removal within 30 min and demonstrated high stability over extended operation. These findings point to the versatility of chrome-tanned waste as a precursor for multifunctional catalytic systems, provided Cr leaching remains controlled. In the composite system shown in Fig. 4, electrons transfer from Cr_2O_3 (a p-type semiconductor) to TiO_2 (an n-type semiconductor) via the carbon matrix, which acts as an electron

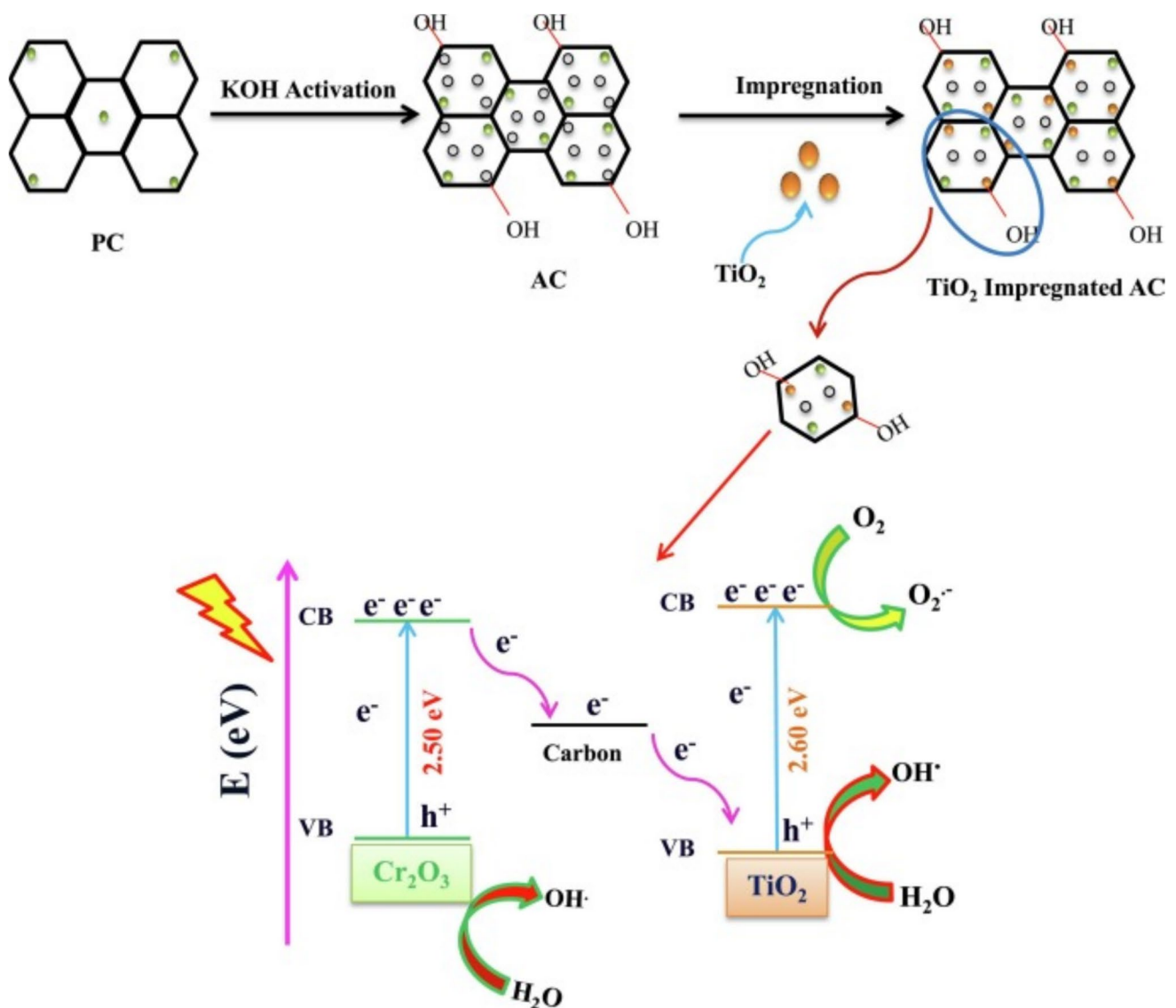


Fig. 4 Schematic diagram illustrating the proposed photocatalytic mechanism of TiO_2 -impregnated porous carbon derived from chemically treated leather buffing waste (Patchai Murugan et al., 2023)

and barrier. Carbon facilitates strong adsorption of pollutants and enhances charge transfer, while holes may migrate from TiO_2 to Cr_2O_3 . Redox reactions predominantly occur on the TiO_2 surface, with oxidation being the dominant process on Cr_2O_3 . The presence of Cr-induced bandgap narrowing improves charge separation and reduces electron–hole recombination. The synergistic interaction among TiO_2 , Cr_2O_3 , and carbon boosts hydroxyl ($\bullet\text{OH}$) and superoxide ($\bullet\text{O}_2^-$) radical formation, enhancing photocatalytic degradation efficiency.

The studies summarized in Table 1 demonstrate the breadth and versatility of leather waste-derived materials in environmental remediation, spanning dye degradation, pharmaceutical removal, heavy metal adsorption, halide and radionuclide capture, and treatment of real industrial effluents. Nechchadi, and co-workers showed that gelatin-based aerogels from tannery hides coupled with ZnO achieve near-complete methylene blue removal through photocatalysis (Nechchadi et al., 2025), while another reported that KOH-activated biochar from tannery hair waste effectively adsorbs pharmaceuticals, with capacities exceeding those of many conventional biomass carbons (Herrera et al., 2024). Heavy metal remediation has also been advanced through different valorization routes. For instance, a tannery shaving dust–PVA composite capable of removing arsenic, chromium, zinc, and lead at efficiencies above 98% was reported (Hosen et al., 2025), whereas even untreated buffing dust can adsorb Cr^{6+} effectively, though with lower capacities (Kumar et al., 2023). More advanced catalytic systems include nitrogen-doped porous carbon from leather waste, applied in Fenton and Fenton-like oxidation for diverse organic pollutants, achieving up to complete removal with sustained performance over multiple cycles (Lv et al., 2023). Functionalization strategies, including heteroatom doping, surface modification, and inorganic coupling, have further expanded the reactivity and selectivity of leather-derived materials, enabling them to target pollutants beyond conventional dyes and metals (Farrag et al., 2024; Shanmugam et al., 2024; Tangjaideborisut et al., 2025; Zheng et al., 2021, 2024a, 2025a, 2025b, 2025c).

Expanding the scope beyond conventional pollutants, one study demonstrated selective iodide ion capture using bismuth-functionalized collagen fibers (Zhu et al., 2023), while Qiang and co-researchers developed amidoxime-functionalized collagen/alginate aerogels for uranium removal in seawater, achieving high adsorption capacities with promising cost metrics (Qiang et al., 2025). Importantly, bridged laboratory studies and practical application by using AC from tannery shavings in polymer composites to treat both synthetic dyes and real textile effluents, demonstrating not only high adsorption capacity but also significant reductions in BOD, COD, turbidity, and color (Melara et al., 2021). Collectively, the findings establish leather waste-derived

materials as competitive and multifunctional candidates for water remediation, with evidence spanning from fundamental adsorption mechanisms to field-relevant effluent treatment.

The feasibility of converting leather waste into carbon-based catalysts for low-temperature NH_3 -SCR applications, a technology used to reduce nitrogen oxides (NO_x) emissions from exhaust gases was also demonstrated (Xia et al., 2023). Their $\text{Mn}_{0.7}\text{Ce}_{0.3}\text{Zr}_{0.5}/\text{AC}$ formulation achieved 97% NO conversion at 200 °C and retained activity under high space velocity and in the presence of SO_2 and water vapor. Through in situ DRIFTS and XPS analyses, the study attributed the high performance to enhanced redox activity and synergistic Mn–Ce interactions. These insights open new avenues for using leather waste in air purification systems, complementing its aqueous-phase applications. Together, these studies illustrate that leather waste can serve as a high-value feedstock for adsorbents and catalysts across environmental remediation platforms.

Environmental and economic considerations

While recent advances have demonstrated the viability of leather waste-based composites, adsorbents, and energy devices, broader implementation hinges on minimizing toxicity concerns and establishing cost-effective processing pathways. The European Union's policy framework for packaging waste management emphasizes the integration of recycled materials and the promotion of circularity. This regulatory support encourages the adoption of sustainable practices in packaging solutions, aligning with broader environmental goals (Rodrigues & Silva, 2024). The obvious environmental concern in the reuse of leather waste, particularly chrome-tanned variants, is the potential release of Cr^{3+} , which can oxidize to carcinogenic Cr^{6+} under certain thermal or oxidative conditions (Nazir et al., 2025). For instance, one previous study proposed using organic acids, specifically oxalic acid, for Cr recovery while minimizing the risk of oxidation to Cr^{6+} . The method achieved a 63.1% extraction efficiency at 43.6 °C, addressing the critical need for safe and sustainable management of Cr-tanned leather waste (Świerczek et al., 2024). Leaching studies have provided reassurance in many cases. For instance, bricks and AC composites produced from leather waste passed standardized leaching protocols, showing that heavy metal migration remained within regulatory limits. However, long-term field studies under varying pH and weathering conditions are still lacking (Jeffrey et al., 2024). Rigorous LCAs are needed to evaluate the true sustainability of these products in real-world scenarios, encompassing upstream processing, energy inputs, emissions, and end-of-life disposal or recycling. Although previous studies confirmed that Cr

Table 1 Comparative performance of leather waste-derived materials in water remediation

Material Type	Target Pollutant(s)	Treatment Method	Performance (Adsorption/Removal Capacity)	References
ZnO/Carbonaceous Gelatin Aerogel (from tannery hide waste)	Methylene Blue	Photocatalytic degradation (UV)	99.25% degradation at 20 mg L ⁻¹ in 3 h; reusable over 4 cycles	Nechchadi et al., (2025)
Tannery hair waste biochar (KOH-activated, 450 °C)	Amoxicillin (AMOX), Diclofenac (DFC), Azithromycin (AZM), Erythromycin (ERY)	Adsorption (aqueous phase)	> 80% removal for all; max 94% AZM, 91% AMOX, 88% ERY, 83% DFC; Langmuir q _m up to 650 mg g ⁻¹	Herrera et al., (2024)
Tannery shaving dust-based composite (PVA-AsD-MC, "PAsMc")	As, Cr, Zn, Pb	Adsorption (aqueous phase)	Removal: 98.9% As, 99.5% Cr, 99.7% Zn, 98.3% Pb; Langmuir q _m : 32.26 mg g ⁻¹ (Zn), 14.18 mg g ⁻¹ (Cr), 13.07 mg g ⁻¹ (Pb), 11.68 mg g ⁻¹ (As); reusable up to 3 cycles (~80% retained)	Hosen et al., (2025)
Al ₂ O ₃ -impregnated AC (from vegetable-tanned leather waste)	Cr (VI)	Adsorption (aqueous phase)	97.9% removal at 60 mg L ⁻¹ ; Langmuir q _m = 19.3 mg g ⁻¹ ; Freundlich isotherm, pseudo-second-order kinetics; reusable up to 5 cycles (declined to ~46%)	Bithi et al., (2024)
Leather waste-derived porous carbon (LPC)	Diethyl phthalate (DEP), dimethyl phthalate (DMP), sulfamethoxazole (SMX), phenol (PE), bisphenol A (BPA), benzoic acid (BA), and the azo dye Acid Orange 7 (AO7)	Fenton and Fenton-like oxidation	98–100% pollutant removal; TOC removal 69.5%; stable over 5 cycles in continuous flow; strong hydroxyl radical generation	Lv et al., (2023)
Buffing dust (untreated, tannery by-product)	Cr (VI)	Adsorption (aqueous phase)	90% removal at 100 mg L ⁻¹ (4 g/100 mL, 240 min); Langmuir q _m = 11.33 mg g ⁻¹ ; pseudo-second-order kinetics	Kumar et al., (2023)
BT@ACF-Bi (Bismuth-functionalized collagen fiber from leather waste)	Iodide ion (I ⁻)	Adsorption (aqueous phase)	Adsorption capacity 55 mg g ⁻¹ at 150 mg L ⁻¹ ; 90.04% removal at 160 mg adsorbent; pseudo-second-order kinetics; Freundlich isotherm	Zhu et al., (2023)
CF-AO/SA aerogel (collagen/sodium alginate, amidoxime-functionalized, Zn ²⁺ -cross-linked)	Uranium (U(VI)) in seawater	Adsorption (aqueous phase)	320.7 mg g ⁻¹ at 14 ppm U; 89% removal in simulated seawater; 5.16 mg g ⁻¹ after 30 days in real seawater; 78.6% efficiency after 5 cycles; cost \$150.87 per kg U extracted	Qiang et al., (2025)
Polyaniline-coated carbonized leather composite	Methylene Blue (MB), Methyl Orange (MO)	Adsorption (aqueous phase)	Carbonized leather: 26% MB, 42% MO; with PANI: MB decreased slightly, MO increased to nearly 100% removal	Stejskal et al., (2023b)
Chitosan/Alginate-AC (from tannery shaving waste)	Remazol Brilliant Blue R (synthetic dye) and real textile effluent	Adsorption (aqueous phase)	Max q _m = 300.96 mg g ⁻¹ (Liu model); 10 regeneration cycles (>50% retained); real effluent: 30% BOD, 39% COD, 78% turbidity, 67% color reduction	Melara et al., (2021)

leaching remains within regulatory limits in fired bricks and cement composites, long-term stability under environmental stressors (e.g., pH shifts, UV exposure, microbial degradation) remains insufficiently understood. Therefore, ensuring the safe immobilization of Cr is essential for compliance with green building standards and environmental health guidelines.

The circularity potential of leather waste is further enhanced when incorporated into energy systems and packaging solutions where direct human contact is minimized. For example, triboelectric nanogenerators and AC electrodes derived from leather avoid end-user exposure while delivering functional benefits. These use cases provide a safer context for Cr-containing residues, mitigating leaching concerns without compromising material performance.

Economic feasibility is also central to the adoption of leather-based technologies. On the one hand, the utilization of waste as a feedstock significantly reduces raw material costs and alleviates landfill burdens (Peter et al., 2025). Integrating leather waste into polymer matrices has been shown to reduce dependency on virgin resources while also lowering manufacturing costs through pigment substitution and reduced energy requirements (Giehl et al., 2024; Kılıç et al., 2024). On the other hand, inconsistencies in leather waste composition and processing standards remain barriers to scalability, requiring the development of streamlined supply chains and pre-treatment protocols. Despite promising developments, there remains a need for comprehensive environmental impact assessments encompassing toxicity profiling, biodegradation behavior, and end-of-life pathways. Similarly, techno-economic analyses (TEA) that quantify cost–benefit ratios across various application domains are essential for guiding investment and policy decisions.

Challenges, future directions and conclusion

The valorization of leather waste has advanced significantly across diverse domains, from polymer composites and construction materials to energy storage devices and environmental remediation. Yet, despite encouraging developments, several overarching challenges remain that limit

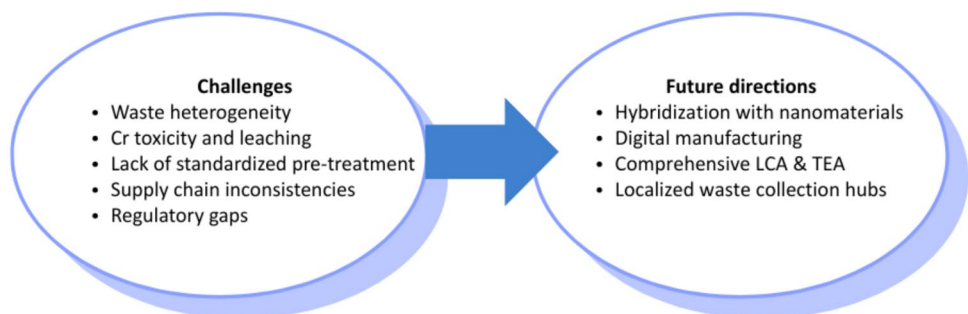
broader industrial uptake, regulatory integration, and long-term material sustainability. To visually summarize the discussion, Fig. 5 presents the key challenges, future research directions, and concluding perspectives on leather waste valorization.

One of the most persistent technical barriers is the inherent heterogeneity of leather waste. The composition, morphology, and residual chemistry of the waste vary widely depending on the tanning method (e.g., Cr, vegetable, aldehyde), leather source (e.g., bovine, ovine), and processing stage (e.g., shaving, buffing, trimming). These inconsistencies directly impact the mechanical, thermal, and functional performance of composite systems. While various studies have successfully incorporated leather waste into matrices such as polymers, cement, and gypsum, a lack of standardization in pre-treatment, particle sizing, and Cr stabilization continues to hinder reproducibility and scalability. Developing universal classification schemes and standardized processing protocols will be pivotal for ensuring cross-sectoral material compatibility and quality assurance (Maixent Loubouth et al., 2024).

Environmental safety, particularly concerning Cr-bearing residues, remains a central consideration. Although several reports have confirmed that leather waste composites fall within regulatory leaching thresholds under controlled conditions, long-term behavior under dynamic environmental exposures is still poorly understood. Potential transformations of Cr (III) to toxic Cr (VI) during material aging, weathering, or high-temperature processing introduce uncertainty in lifecycle safety. Advanced research should prioritize accelerated degradation studies, ecotoxicological profiling, and post-use fate modeling to ensure materials meet emerging green building and sustainable product standards (Chipade et al., 2025; Ram, 2024).

Economic and infrastructure limitations also challenge the feasibility of widespread adoption. However, realizing these economic gains at scale demands the establishment of localized waste collection and processing hubs, particularly in regions with concentrated tannery industries. From a regulatory and policy standpoint, there is a lack of harmonized global frameworks to govern the reuse of leather waste in commercial applications. Current regulations

Fig. 5 Schematic overview of key challenges and future directions in leather waste valorization



often fail to distinguish between chrome-tanned and non-chrome variants or to provide clear guidelines on permissible residual metal content in construction and consumer products (Iwańska et al., 2023). International bodies, such as International Organization for Standardization (ISO) and United Nations Environment Programme (UNEP), must play a stronger role in establishing traceability, certification standards, and cross-border regulations that balance innovation with consumer and environmental safety.

Looking forward, several innovative research directions offer promising pathways to enhance both performance and sustainability. Hybridization strategies combining leather waste with nano-reinforcements, other agricultural fibers, or biochar can address property deficiencies while maximizing waste synergy (Baldassin et al., 2025; Ramu et al., 2024). Similarly, the incorporation of leather-derived AC in catalytic systems demonstrates viable routes for integrating waste valorization into clean energy and water treatment frameworks (Zheng et al., 2024b, 2025d, 2025e). Importantly, researchers should also consider scaling strategies early, including pilot-scale demonstrations that bridge laboratory findings with industry collaboration.

Digital manufacturing technologies such as 3D printing and electrospinning have further expanded the design space, enabling the creation of customized, multifunctional materials using leather waste-based inks or nanofibers (Dhiwar et al., 2024; Zheng et al., 2025f). These platforms could significantly reduce waste-to-product turnaround time and support localized, demand-responsive production systems. Finally, comprehensive LCA and TEA must become standard practice in future studies. These tools will help quantify environmental benefits, identify hotspots for process improvement, and benchmark leather waste-derived products against conventional alternatives (Gatto & Parziale, 2024; Thomasset & Benayoun, 2024).

To address these limitations, future research should prioritize the development of standardized testing protocols that enable cross-comparison of results, conduct long-term degradation and ecotoxicological studies. Broader geographical representation of case studies is needed to enhance global applicability. Furthermore, integrating LCA and TEA analyses into experimental work will be essential for quantifying environmental benefits and economic feasibility. Collectively, these steps will help bridge the gap between laboratory-scale innovations and industrial adoption of leather waste-derived materials.

In conclusion, this mini review establishes a comprehensive, cross-sectoral framework for the valorization of leather waste, highlighting its potential to function not only as a substitute material but also as an active component in functional systems. The synthesis of quantitative performance data, environmental considerations, and regulatory challenges offers a roadmap for translating

laboratory-scale innovations into commercially relevant, sustainable applications.

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Data availability Data is provided within the manuscript or supplementary information files.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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