Article

Tannery wastewater treatment technologies: From conventional methods to emerging sustainable solutions

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Abstract
The tannery industry is a significant contributor to global economic development but also generates highly complex and hazardous wastewater that poses serious threats to aquatic ecosystems and human health. Tannery wastewater is characterized by extremely high concentrations of organic matter, chromium compounds, sulfides, chlorides, sulfates, nitrogenous species, and total dissolved solids. This review provides a comprehensive and critical analysis of treatment technologies for tannery wastewater reported in peer-reviewed literature. Conventional treatment schemes comprising physicochemical pretreatment, biological secondary treatment, and tertiary polishing are examined in detail. Individual unit processes including chemical coagulation–flocculation, various biological systems (activated sludge, sequencing batch reactors, anaerobic digestion, constructed wetlands), membrane technologies (microfiltration, ultrafiltration, nanofiltration, reverse osmosis, membrane bioreactors), advanced oxidation processes (Fenton, photo-Fenton, sono-Fenton, ozonation, photocatalysis), and adsorption techniques are critically evaluated in terms of their removal efficiencies, operational conditions, and limitations. The review highlights that no single technology can achieve complete remediation, and integrated treatment trains combining complementary processes are essential for meeting stringent discharge standards. Particular attention is given to emerging trends toward zero liquid discharge, resource recovery (chromium recycling, water reuse, energy generation), and circular economy principles. Persistent challenges including membrane fouling, sludge management, high salinity, and economic feasibility are discussed. Future research directions emphasizing hybrid systems, novel materials, process intensification, and life-cycle assessment are proposed to guide sustainable tannery wastewater management.

Keywords tannery wastewater; chromium removal; advanced oxidation processes; membrane bioreactor; sequencing batch reactor; zero liquid discharge; resource recovery; circular economy.

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1 Introduction

1.1 The Tannery Industry and Its Wastewater Problem

The leather tanning industry plays a significant role in the global economy, yet it poses a severe environmental threat due to its intensive water and chemical consumption (Bhardwaj et al., 2023; Zheng et al., 2026). The transformation of animal hides into leather is a highly water-intensive process, with approximately 90 percent of the water used being discharged as effluent (Meena et al., 2025). Annually, the global tannery industry generates approximately 300 million tonnes of wastewater and 65,000 tonnes of sludge (Meena et al., 2025). Chrome tanning constitutes approximately 90 percent of global leather production, during which only 30 to 40 percent of chromium is absorbed by the hides, with the remainder discharged in solid or liquid waste (Bhattacharjee et al., 2025).

Tannery effluent contains a complex mixture of contaminants created throughout the various stages of leather manufacturing, making disposal a significant challenge (Bhardwaj et al., 2023; Zheng et al., 2026). The tanning process contributes substantially to elevated levels of pH, biological oxygen demand, total suspended solids, chemical oxygen demand, total dissolved solids, total chromium, trivalent chromium, hexavalent chromium, chloride ions, sulfate, sulfide, and various inorganic constituents (Su et al., 2014; Bhardwaj et al., 2023; Zheng et al., 2026).

1.2 Environmental and Health Impacts

The environmental consequences of untreated or inadequately treated tannery effluent are severe. Tannery wastewater contains a variety of hazardous compounds including chromium, calcium, sodium, potassium, chloride, sulfate, and high levels of electrical conductivity, color, and odor (Kamalakkannan et al., 2024). Chromium contamination of aquatic environments near tannery industries remains a significant concern, with tanneries being major contributors of chromium to aquatic systems (Silva et al., 2025). While trivalent chromium used in tanning is relatively less toxic, hexavalent chromium is soluble, highly mobile, and poses severe risks to human health including respiratory issues, liver and kidney damage, and carcinogenic effects (Bhattacharjee et al., 2025).

The impact extends beyond chromium contamination. Tannery effluents have been shown to affect adult *Drosophila melanogaster* physiology (Moysés et al., 2017), induce oxidative stress in rodent brain structures and liver (Moysés et al., 2017), and generally compromise ecosystem health in regions where leather production is concentrated, such as Kanpur, India, where the leather industry significantly contributes to water pollution (Uttam et al., 2025).

1.3 Scope and Framework of This Study

This study provides a comprehensive and critical examination of treatment technologies for tannery wastewater as reported in the peer-reviewed literature (Fig. 1). The study is organized as follows. Section 2 discusses the physicochemical characteristics of tannery wastewater that influence treatment selection. Section 3 examines physicochemical pretreatment methods including coagulation–flocculation, electrocoagulation, and adsorption. Section 4 covers biological treatment systems ranging from conventional activated sludge to sequencing batch reactors and constructed wetlands. Section 5 explores membrane-based processes including membrane bioreactors, nanofiltration, and reverse osmosis. Section 6 discusses advanced oxidation processes for recalcitrant pollutant degradation. Section 7 analyzes integrated and hybrid treatment schemes. Section 8 addresses resource recovery and circular economy approaches. Section 9 identifies challenges and future research directions. Section 10 presents concluding remarks.

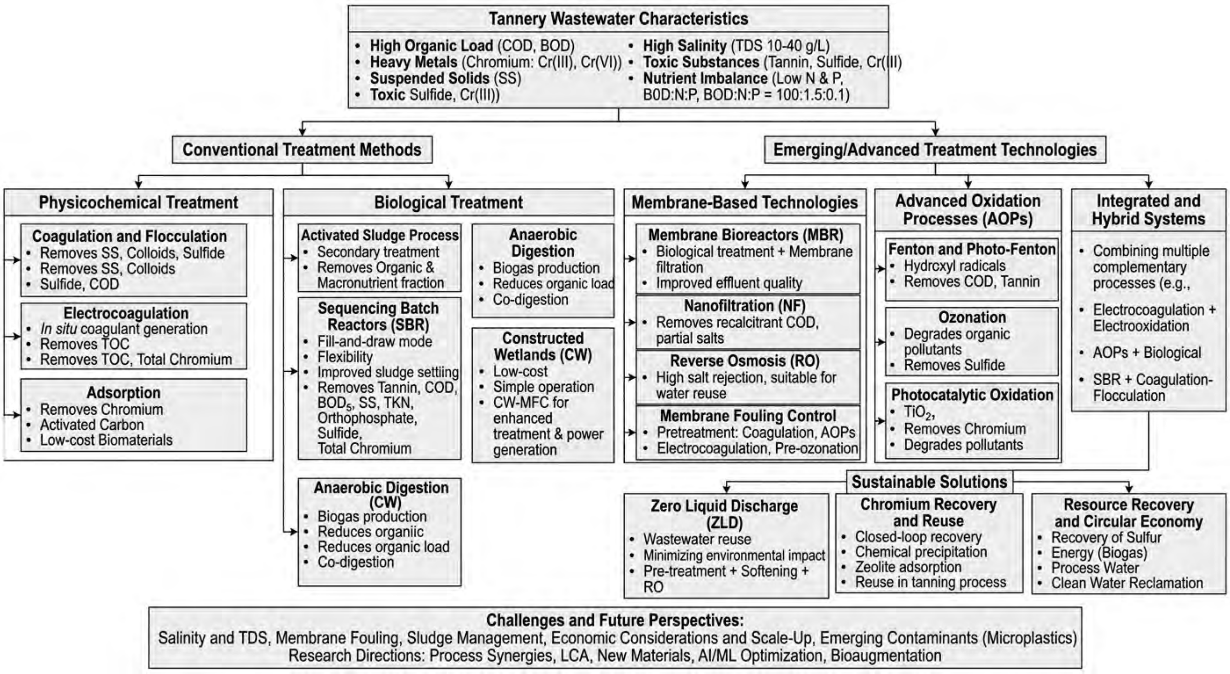

Fig. 1 Systematic diagram of tannery wastewater treatment technologies: From conventional methods to emerging sustainable solutions.

2 Characteristics of Tannery Wastewater

The composition of tannery wastewater varies considerably depending on the type of processes employed, the chemicals used, and the scale of operation. Tanneries generate copious amounts of potentially toxic sludge and effluent from the processing of skins and hides to leather, requiring remediation before discharge to protect receiving environments (Ngobeni et al., 2024).

The massive effluent from tanning processes is characterized by serious physicochemical conditions: a basic dark brown colored waste with high contents of COD, BOD, TDS, chromium, phenolics, high pH, and pungent odor (Zhao et al., 2022; Zheng et al., 2026). Chrome tanning wastewater exhibits COD concentrations of 5357 mg/L or higher, far exceeding permissible limits for discharge to sewage (300–3000 mg/L) or inland drainage (50–450 mg/L) (Gichana, 2018).

Tannery wastewater is widely recognized as one of the most challenging industrial effluents due to its extremely high organic load, heavy metals (particularly chromium), suspended solids, and substantial salinity (Tehrani and Taheri, 2026; Zheng et al., 2026). The presence of high salinity severely limits the performance of many wastewater treatment techniques, with conventional activated sludge systems functioning properly at salinity levels below approximately 10 g/L TDS, while real tannery wastewater often ranges between 10 and 40 g/L TDS (Tehrani and Taheri, 2026).

Toxic substances including tannin, sulfide, and trivalent chromium can inhibit biological treatment performance. Studies on upflow anaerobic contact filters have identified limiting concentrations of toxicity for these substances, with tannin concentrations beyond 914 mg/L inhibiting reactor performance (Vijayaraghavan and Murthy, 2008).

The nutrient composition of tannery wastewater is also critical for biological treatment. The observed BOD to nitrogen to phosphorus ratio of vegetable tannery wastewater is often 100 to 1.5 to 0.1, which is insufficient for proper biomass synthesis, indicating that supplementation of nitrogen and phosphorus may be necessary for effective biological degradation (Balakrishnan et al., 2021).

3 Physicochemical Treatment Methods

3.1 Coagulation and Flocculation

Coagulation–flocculation remains one of the most widely applied pretreatment methods for tannery wastewater. The process aims to destabilize suspended particles and colloids, promoting their aggregation and subsequent removal by sedimentation.

Wastewater from the unhairing–liming unit contains high concentrations of sulfide ions due to the use of sodium sulfide, making it highly toxic and hazardous (Omor et al., 2025). Treatment of such effluents using coagulation–flocculation with aluminum sulfate as coagulant and praestol as flocculant has demonstrated significant removal efficiency. Under optimal conditions of pH 7, coagulant dose of 0.4 g/L, flocculant dose of 1 mg/L, coagulation time of 10 minutes, and flocculation time of 20 minutes, COD removal reached 93.7 percent and sulfide reduction reached 86.9 percent (Omor et al., 2025). Among tested parameters, pH and coagulant dosage had the most significant impact on pollutant removal efficiency (Omor et al., 2025).

Coagulation–flocculation at pH 6 to 7 minimizes hydrogen sulfide gas formation, reducing toxic emissions significantly (Omor et al., 2025). The process has also been successfully applied to treat wastewater from Moroccan leather tanning industries, with results indicating successful removal of a wide range of pollutants (Mouhri et al., 2024).

3.2 Electrocoagulation

Electrocoagulation has emerged as an effective alternative to chemical coagulation, generating coagulant species in situ through the electrolytic dissolution of sacrificial anodes. The process offers advantages including reduced chemical consumption and lower sludge production.

Treatment of tannery liming drum wastewater by electrocoagulation has been extensively studied (Şengil, 2009). A synergistic electrocoagulation process using a self-induced external-loop airlift reactor operated without mechanical mixing, relying on hydrogen and oxygen microbubbles for internal circulation, achieved significant pollutant removal under optimal conditions of pH 6 and current density of 50 mA/cm^2 (Zahnoune et al., 2026).

A comparative study of chemical coagulation (using aluminum sulfate and iron chloride) and electrocoagulation (using aluminum and iron electrodes) for TOC and total chromium removal from tannery wastewater found high TOC removal efficiencies in chemical coagulation of 60.8 percent and 75.6 percent using aluminum sulfate and iron chloride respectively, while electrocoagulation achieved 75.0 percent and 84.6 percent removal (Erkan et al., 2018).

However, chloride removal efficiency by electrocoagulation remained low at less than 12 percent, highlighting the need for complementary treatment processes (Erkan et al., 2018).

3.3 Adsorption

Adsorption is widely employed for the removal of chromium and other pollutants from tannery wastewater. The process utilizes various adsorbent materials including activated carbon, low-cost biomaterials, zeolites, and biochar.

Activated carbon adsorption offers targeted metal removal, while membrane technologies permit fine separation but incur fouling and energy costs (Nature Index, 2023). The adsorption and advanced oxidation processes most effectively improve wastewater biodegradability prior to biological polishing (Bhardwaj et al., 2023).

Recent research has focused on developing low-cost natural adsorbents. A biological material derived from scales of the fish Catla catla has been employed as an adsorbent for biosorption of contaminants from tannery effluent, offering a sustainable use for fish market waste. Rice hull biochar has demonstrated efficacy as a sustainable biosorbent for hexavalent chromium removal from tannery effluent under optimized conditions (Yadav et al., 2026).

A mesoporous magnetic iron oxide–aluminum silicate adsorbent exhibiting an exceptionally large surface area achieved near-complete hexavalent chromium removal from real tannery effluent at neutral pH and maintained performance over multiple regeneration cycles (Nature Index, 2023).

Biosorption using Bacillus cereus F4810/72 isolated from tannery effluents has shown systematic potential for hexavalent chromium removal under varying physicochemical conditions, highlighting its viability as a low-cost, eco-friendly biosorbent (Bhattacharjee et al., 2025).

4 Biological Treatment Systems

4.1 Activated Sludge Process

A range of physicochemical methods are used for pre- and post-treatment of tannery effluent, but biological secondary remediation remains the most popular choice for the reduction of the organic and macronutrient fraction of tannery effluent (Ngobeni et al., 2024). However, the conventional activated sludge process and similar technologies have inherent problems related to poor sludge settling, low removal efficiencies, and high energy requirements (Ngobeni et al., 2024).

4.2 Sequencing Batch Reactors

The sequencing batch reactor is a modified form of the activated sludge process that operates in fill-and-draw mode, offering flexibility and improved sludge settling characteristics.

Treatment of tannin-laden wastewater in the activated sludge process of low residence time (36 hours) does not yield desired results, necessitating the development of methodology for tannin elimination under extended aeration periods (Kanchanabhan et al., 2005). A sequencing batch reactor of 5-liter capacity treating high-strength wastewater achieved cumulative COD and tannin removal efficiencies of 77 percent and 88 percent respectively, with tannin degradation confirmed through enzyme assay tests (Kanchanabhan et al., 2005).

A study on the treatment of tannery wastewater from Fez city in Morocco using SBR with an organic load of 0.3 kg $COD \cdot m^{-3} \cdot d^{-1}$ and a treatment cycle of 12 hours obtained abatement rates of 98.17 percent for COD, 97.5 percent for BOD_5, 97.35 percent for suspended solids, 95.45 percent for total Kjeldahl nitrogen, 98.6 percent for orthophosphate, 99.57 percent for sulfide ions, and 96.1 percent for total chromium (Elkarrach et al., 2020). The treated effluents conformed to Moroccan discharge standards (Elkarrach et al., 2020).

Kinetic studies on the biodegradation of tannery wastewater in a sequential batch bioreactor using mixed culture obtained from activated sludge process treating tannery wastewater have been conducted at different operating conditions by varying the hydraulic retention time (Durai et al., 2011).

4.3 Anaerobic Digestion

Anaerobic treatment offers the advantage of biogas production while reducing organic pollutant load. Anaerobic treatment of tannery wastewater in the context of a circular bioeconomy for developing countries has been reviewed (Welz et al., 2021).

Co-digestion of tannery wastewater primary sludge and fleshings significantly increased methane yield compared to digesting tannery wastewater primary sludge alone, though the addition of chromium-tanned and vegetable-tanned leather wastes decreased yield (Andriamanohiarisoamanana et al., 2024).

Anaerobic co-digestion of tannery fleshing, cow dung, and sewage water has been optimized using central composite design and response surface methodology to maximize biogas production (Basak et al., 2025).

An integrated biological system for remediation and valorization of tannery wastewater focusing on microbial communities responsible for methanogenesis and sulfidogenesis showed that complete oxidizers dominated the sulfidogenic populations during pre-treatment, while aceticlastic genera dominated the methanogenic populations during anaerobic digestion, with the system showing promise for remediation and recovery of biogas and sulfur in support of a bio-circular economy (Welz et al., 2024).

4.4 Constructed Wetlands

Constructed wetlands are considered low-cost, simple operation-based wastewater treatment technologies that make them convenient for use even under uneven climatic conditions (Sayadi et al., 2012; Hayati et al., 2013; Al-Abbas and Ismail et al., 2024).

A constructed wetland integrated with a microbial fuel cell enhanced treatment of real leather tannery effluent, with biodegradation of organic contents by anodic biofilm being the sole mechanism of their removal (Al-Abbas and Ismail et al., 2024). Five CW-MFC systems operated in batch mode for two cycles of 10 days each achieved maximum COD removal efficiencies of 99.8 percent, 99.5 percent, 99.7 percent, 99.6 percent, and 99.5 percent with power outputs of 10,502.8, 10,254.6, 9,956.4, 10,029.6, and 9,888.0 mW/m^3 respectively (Al-Abbas and Ismail et al., 2024).

No adverse effect was observed on the four types of vegetations (Conocarpus, *Arundo donax*, *Canna lily*, and *Cyperus papyrus*) by tannery wastewater in CW-MFCs, and unplanted CW-MFC exhibited comparable efficiency of organic content removal as planted CW-MFCs (Al-Abbas and Ismail et al., 2024).

A continuously operated upflow CW-MFC treating real leather tannery wastewater for 180 days achieved steady-state conditions within 10 days, with maximum removal efficiencies for COD of 98.7 percent, TDS of 66.7 percent, and complete removal (100 percent) of chromium and arsenic (Abbas and Ismail, 2025). Maximum generated power was 1614.5 mW/m^3, and three microbial growth models (Monod, Blackman, and Halden) were evaluated, with the Monod model showing superiority for describing biofilm development and growth (Abbas and Ismail, 2025). The results demonstrated that CW-MFC is a potential option for the treatment of harmful tannery wastewater associated with power generation (Abbas and Ismail, 2025).

5 Membrane-Based Treatment Technologies

5.1 Membrane Bioreactors

Membrane bioreactors combine biological treatment with membrane filtration, offering improved effluent quality and reduced footprint compared to conventional activated sludge systems.

As a highly complex aqueous effluent, tannery wastewater from the leather industry should be treated appropriately before discharge, and membrane technology has been shown to be a promising approach as it may achieve zero liquid discharge (ZLD) (Yang et al., 2023). Manufactured membranes, membrane-based integrated processes, MBR, NF, UF, and RO are the hotspots in this field, and details of different membrane technologies configured for tannery wastewater treatment such as membrane materials, membrane modules, operating conditions, and removal efficiency of pollutants have been summarized (Yang et al., 2023). Membrane fouling remains a major challenge, and process coupling within diverse membrane technologies or between membrane and non-membrane technologies is considered a promising alternative (Yang et al., 2023).

A hybrid treatment system combining coagulation, flocculation, and settling followed by a membrane bioreactor significantly reduced tannery wastewater pollution. Optimizing the parameters achieved 97 percent removal for chromium, 63 percent for COD, and 90 percent for turbidity during the chemical treatment step, and the MBR system further improved removal efficiency to 99 percent for chromium, 96 percent for COD, and 99.8 percent for turbidity (Bhattacharjee et al., 2025). The hybrid approach ensured compliance with Environmental Protection Agency standards and European Regulation (EU) 2020/741.

5.2 Nanofiltration and Reverse Osmosis

Although suspended solids and high percentages of organic matter can be eliminated by physicochemical and biological processes, refractory chemical oxygen demand and salts remain in the wastewater after these processes, and chloride and sulfate ion concentrations may hinder the treated wastewater from being reused or even discharged according to legal standards (Fernández-Medrano et al., 2022).

In a comparative study of two nanofiltration membranes and two reverse osmosis membranes for biologically treated tannery wastewater, the difference between permeate fluxes of nanofiltration and reverse osmosis membranes was very high. At 20 bar and 1.77 $m \cdot s^{-1}$, the permeate fluxes of the two tested NF membranes were 106 and 67 $L \cdot m^{-2} \cdot h^{-1}$, while the obtained permeate fluxes for RO membranes were 25 and 18 $L \cdot m^{-2} \cdot h^{-1}$ (Fernández-Medrano et al., 2022).

Reverse osmosis membranes rejected almost 100 percent of the salts, whereas NF membranes reduced their rejection when faced with increasing concentration factors, with salt rejection between 50 and 60 percent at the highest concentration factor (Fernández-Medrano et al., 2022). Fouling of RO membranes was lower than that of NF membranes, recovering more than 90 percent of initial permeability by only water rinsing, while chemical cleaning was necessary to increase permeability recovery of NF membranes above 90 percent (Fernández-Medrano et al., 2022). The considerably lower rejections and higher membrane fouling of NF membranes suggest that reverse osmosis could be the most feasible technique for water reuse in the tannery industry, though permeate fluxes are lower than those achieved with NF membranes (Fernández-Medrano et al., 2022).

5.3 Membrane Fouling Control

Persistent membrane fouling remains a significant obstacle to long-term operational sustainability in treating tannery wastewater (Yang et al., 2024). Advanced pretreatment techniques such as coagulation, advanced oxidation processes, and electrocoagulation have been extensively studied to control membrane fouling and enhance treatment efficacy (Jha et al., 2025).

Pre-ozonation enhances UF membrane flux and reduces fouling resistance by degrading macromolecular organics into smaller fractions, leading to a substantial reduction in the number of identified polar organic compounds (Yang et al., 2024).

Ceramic UF membranes with 10 nm average pore size have been investigated for tannery wastewater treatment, with permeate flux reduced due to membrane fouling after operation but fouling effectively removed using chemical cleaning procedures (Kaplan-Bekaroglu and Gode, 2016).

6 Advanced Oxidation Processes

Advanced oxidation processes generate highly reactive hydroxyl radicals that can mineralize recalcitrant organic pollutants that are resistant to conventional biological treatment (Zheng et al., 2026). A comprehensive review assessed existing practices and emerging technologies for tannery effluent treatment, highlighting that adsorption and advanced oxidation processes most effectively improve wastewater biodegradability prior to biological polishing (Bhardwaj et al., 2023).

6.1 Fenton and Photo-Fenton Processes

The Fenton reaction, an advanced oxidation process, is extensively employed in wastewater treatment to degrade recalcitrant organic pollutants through hydroxyl radicals generated from the catalytic decomposition of hydrogen peroxide by ferrous ions (Gowtham and Pauline, 2021, Fig. 2; Satyam and Patra, 2025).

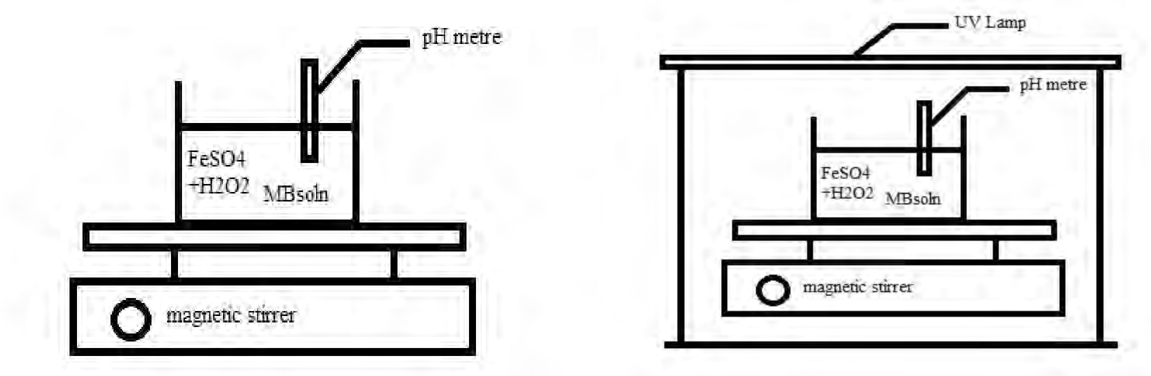

Fig. 2 Reactor setup for Fenton (left) photo-Fenton (right) process (Gowtham and Pauline, 2021).

In an integrated process combining advanced oxidation ($UV/TiO_2/H_2O_2$) and adsorption to decompose chromium complexes formed with organic substances in tannery wastewater, the advanced oxidation process significantly increased the decomposition rate. After 9 hours, COD rapidly decreased to 504 mg/L from 7600 mg/L, while COD only decreased to 6535 mg/L without photocatalyst (Yu et al., 2024). Dissociated Cr (III) can be converted into Cr(VI) and adsorbed with anion exchange resin D296, achieving total chromium removal efficiency of 99.5 percent with Cr(VI) concentration below 0.5 mg/L (Yu et al., 2024).

Fenton and photo-Fenton oxidation of synthetic tannin and nonylphenol ethoxylate based degreasing agent in tannery wastewater demonstrated that photo-Fenton provided appreciably high COD greater than 80 percent and UV_{254} and UV_{280} removals greater than 90 percent for synthetic tannin (Lofrano et al., 2010). Toxicity was drastically reduced in photo-Fenton treated synthetic tannin samples, while Fenton alone resulted in 90 percent toxicity even after 30 minutes of oxidation (Lofrano et al., 2010). Fenton oxidation of degreasing wastewater achieved 72 percent COD removal (Lofrano et al., 2010).

A comparative study of various AOPs for tannery residue treatment assessed UV/H_2O_2, Fenton, photo-Fenton, and sono-Fenton using 70 percent hydrogen peroxide. Under optimal conditions determined by response surface methodology for the Fenton method, 96 percent decrease in absorbent species and 95 percent COD removal occurred in 30 minutes using the sono-Fenton process at pH 3.0 and 298 K, which is approximately 5.4-fold higher than that obtained with UV/H_2O_2 (Souza et al., 2020).

The sequential application of Donnan dialysis and Fenton oxidation has been investigated for effective removal of ammonium ions and COD from deliming tannery effluent, with advanced oxidation processes, especially Fenton treatment, extensively utilized for the degradation of hazardous and persistent organic pollutants (Bahammou et al., 2025).

Sequential treatment of tannery effluent by coagulation–flocculation and sono-photo-Fenton has been optimized using Box–Behnken design, demonstrating that the sono-photo-Fenton process is a viable and efficient method for treating tannery effluent (Bahammou et al., 2025).

6.2 Ozonation

Ozonation is considered one of the emerging alternative and widely studied methods for the degradation of organic pollutants in tannery wastewater (Sivagami et al., 2018). A combined system using UASB (two-stage)-ozonation-BAF demonstrated promising potential for treatment of high-strength tannery wastewater, with the ozonation process enhancing the biodegradability of UASB effluent before post-polish treatment in the biological aerated filter (Chen et al., 2018).

Sequential treatment of tannery wastewater using electrocoagulation followed by ozonation has been assessed for physicochemical and ecotoxicological characterization, with the electrocoagulation–ozonation treated samples showing improved quality compared to electrocoagulation alone (Aguilar-Ascón et al., 2025). The removal of sulfides using ozone is a technique applicable for alkaline pH, allowing reduction of oxidation times and becoming a viable alternative for the leather tanning industry (Rodríguez and Agudelo-Valencia, 2019).

6.3 Photocatalytic Oxidation

Photocatalytic oxidation using titanium dioxide has been extensively engaged for the degradation of organic pollutants in wastewater treatment (Zheng et al., 2026). Dual step synthesis of chromium removal from tannery industry wastewater with photocatalytic effects of TiO_2 demonstrated that photocatalysis effects showed highest removal of chromium at different concentrations and short periods of reaction time, representing a sustainable and green synthesis approach (Masabanda et al., 2025).

Degradation of amoxicillin residue has been performed using TiO_2 photocatalyst doped with chromium prepared from tannery wastewater under visible light exposure, demonstrating a circular approach where waste-derived material serves as a treatment agent (Wahyuni et al., 2024).

7 Integrated and Hybrid Treatment Systems

The complexity of tannery wastewater necessitates integrated treatment trains that combine multiple complementary processes. A comprehensive review of existing practices and emerging technologies argued that hybrid systems tailored to site-specific influent characteristics deliver cost-effective and resilient performance (Bhardwaj et al., 2023).

Integration of electrocoagulation and electrooxidation in a once-through continuous mode for synthetic tannery wastewater treatment achieved removal efficiencies of 75.97 percent for 4-chlorophenol, 82.33 percent for hexavalent chromium, 89.00 percent for COD, and 37.30 percent for TOC under optimized conditions (Meena et al., 2025). The energy consumption was measured at 28.85 kWh/m^3, with operating costs calculated at 2.11 USD/m^3 (Meena et al., 2025).

Amalgamation of advanced oxidation processes with biological techniques for treatment of tannery wastewater has been examined, with the combined process proven as an alternate and cost-effective methodology for treatment of tannery wastewater to comply with applicable regulations worldwide and ensure the quality of treated wastewater for reuse purposes (Gopal et al., 2025). The biodegradability of tannery wastewater was 0.40 during primary treatment, indicating that biological treatment needs to be performed (Gopal et al., 2025).

A novel strategy of tannery sludge disposal by converting into biochar and reusing for hexavalent chromium removal from tannery wastewater has been proposed, demonstrating a circular approach to waste management (Li et al., 2024).

Treatment of real tannery industrial wastewater via sequential biological and ultrasound/UV/activated persulfate–hydrogen peroxide processes has been investigated (Aber et al., 2010).

Integrated wastewater treatment combining biological treatment using a sequencing batch reactor followed by physicochemical treatment based on coagulation–flocculation has been evaluated for nitrogen and COD removal from tannery effluent (Pire-Sierra et al., 2016).

Combining electrocoagulation, ozonation, and ion exchange technologies for removal of ammonia nitrogen from tannery wastewater has been assessed, with an electrocoagulation reactor equipped with aluminum electrodes, an ozonation tank, and a filtration system with zeolite employed (Aguilar-Ascón et al., 2024).

The integration of Donnan dialysis and Fenton oxidation for enhanced ammonium and COD removal from deliming tannery effluent represents another innovative hybrid approach (Bahammou et al., 2025).

Combining SBR and phycoremediation for tanning effluent achieved high removal efficiencies with COD reduced by 85 percent, BOD reduced by 80 percent, and ammonia reduced by more than 75 percent (Manoj et al., 2024).

8 Zero Liquid Discharge and Circular Economy Approaches

8.1. Zero Liquid Discharge Systems

Zero liquid discharge systems present a sustainable solution by efficiently treating and reusing wastewater while minimizing environmental impact, and studies have explored successful implementation of ZLD in the tannery industry considering its economic and environmental benefits (Pundir et al., 2025).

The ZLD system ensures zero water emission as well as treatment facilities by recycling, recovery, and reuse of treated wastewater using advanced cleanup technology, consisting of pre-treatment, softening of treated effluent, and reverse osmosis treatment for desalination (Ricky et al., 2022). The ZLD systems used in leather tanning include thermal-based ZLD systems and reverse osmosis (Rahmawati, 2024).

Membrane technology has been shown to be a promising approach for tannery wastewater treatment as it may achieve zero liquid discharge (Yang et al., 2023). Recovery and reuse of chromium from chrome tanning waste water aiming toward zero discharge of pollution has been investigated (Kanagaraj et al., 2008).

8.2 Chromium Recovery and Reuse

Chromium recovery is pivotal for sustainable resource utilization, yet conventional approaches remain plagued by inefficiency and hazardous chromium sludge generation (Quanet al., 2025). Closed-loop chromium recovery from tannery wastewater has achieved dual breakthroughs of closed-loop chromium recovery concurrent with near-zero sludge generation and secondary pollution (Quan et al., 2025).

Pilot-scale recovery and removal of chromium from tannery wastewater by chemical precipitation using sodium hydroxide and sulfuric acid has been investigated, with life cycle assessment used to estimate energy consumption and environmental burden and evaluate whether the proposed method is environmentally justifiable (Husain et al., 2025).

A chain of treatment processes for better management of mineral and vegetable tannery wastewaters involved chromium precipitation from spent chrome tanning bath by sodium hydroxide and reformulation to form a complex of basic chromium sulfate tested successfully in mineral tanning process (Tahiri et al., 2013). The supernatant recovered after chromium precipitation was used to dilute vegetable tanning wastewaters, which were then treated by liming and tangential microfiltration using a ceramic membrane, achieving quasi-complete removal of polyphenolic compounds and COD reduction of 86 to 87 percent (Tahiri et al., 2013).

Chromium recovery from tannery wastewater by zeolite-based materials as a circular and sustainable approach has been presented (Grifasi et al., 2025).

8.3 Resource Recovery and Circular Economy

Novel systems have been proposed for the removal and recovery of elemental sulfur, energy, and process water in support of a circular economy (Ngobeni et al., 2024). Full-scale studies showing successful long-term operation of such systems are required to convince tanneries to modernize and invest in new infrastructure (Ngobeni et al., 2024).

The current economy of tanneries in developing countries is mainly linear, with certain elements of circularity promoting the recycling of skins and hides and direct or indirect water reuse, though solid waste management remains largely linear and characterized by high disposal costs (Ricky et al., 2022).

Clean water reclamation from tannery industrial wastewater in integrated treatment schemes represents a substantial review toward viable solutions, with research directed toward reduction and separation strategies and the circular economy (Ricky et al., 2022).

9 Challenges and Future Perspectives

9.1 Salinity and Total Dissolved Solids

Despite significant advances in treatment technologies, certain challenges persist. Residual chromium in treatment sludge and high salinity in effluent remain unresolved problems, with potential solutions requiring further investigation (Zhao et al., 2022). High salinity showed minimal impact on the performance of hybrid systems, while conventional biological processes are severely affected (Tehrani and Taheri, 2026). The presence of halophiles has been shown to improve biological treatment of hypersaline wastewater (Tehrani and Taheri, 2026).

9.2 Membrane Fouling

Membrane fouling is still a major challenge in membrane technology during tannery wastewater treatment, necessitating process coupling either within diverse membrane technologies or between membrane and non-membrane technologies as a promising alternative (Yang et al., 2023). Advanced pretreatment strategies to control membrane fouling in tannery wastewater treatment aim to identify the most effective pretreatment method for minimizing membrane fouling in the treatment of complex tannery wastewater (Jha et al., 2025).

9.3 Sludge Management

Conventional activated sludge process and similar technologies widely used by tanneries have inherent problems related to poor sludge settling, low removal efficiencies, and high energy requirements (Ngobeni et al., 2024). Traditional biological nutrient removal systems for nitrogen, phosphorus, and organic matter result in generation of considerable amounts of sludge requiring treatment before final disposal (Zhou et al., 2014).

Dewaterability of chromium-rich sludge typical of tanning wastewater treatment plants has been tested, with results opening the way to develop a simplified MBR treatment plant as an effective and efficient solution to reduce sludge treatment and disposal costs (Ricky et al., 2022).

9.4 Economic Considerations and Scale-Up

Life cycle assessment has been used for quantification and evaluation of the impacts of the chromium tanning process as a basis to propose further improvement actions (Rivela et al., 2004). The scope of LCA studies includes estimating energy consumption and environmental burden of chromium recovery from tannery wastewater and evaluating whether proposed methods are environmentally justifiable (Husain et al., 2025).

Future studies using real tannery wastewater rather than synthetic wastewater are recommended to better validate the efficiency and scalability of hybrid processes under practical conditions (Meena et al., 2025). Process intensification through novel reactor designs, such as the self-induced external-loop airlift reactor for electrocoagulation, has demonstrated improved energy efficiency and sustainability (Zahnoune et al., 2026).

9.5 Emerging Contaminants

The occurrence of emerging contaminants including microplastics in tannery wastewater has become a major concern in recent years, as they can be recognized as transport vectors for pollutants in the environment (Khatun et al., 2024). Tannery wastewater contains highly toxic, recalcitrant organic and inorganic pollutants, and microplastics represent an additional challenge requiring attention (Khatun et al., 2024).

9.6 Research Directions

Future research should focus on optimizing process synergies and conducting life-cycle assessments to ensure economic viability and resource recovery (Bhardwaj et al., 2023). The development of novel materials for adsorption and catalysis, process intensification through advanced reactor design, and integration of machine learning and artificial intelligence for process optimization represent promising directions.

The application of artificial neural network–genetic algorithm models using transfer learning algorithms has demonstrated the ability to predict tannery wastewater treatment outcomes with maximum error between predicted values and actual treated wastewater of only 0.28 percent, offering valuable guidance for process control and optimization (Yu et al., 2024).

Bioaugmentation treatment strategies leveraging progressive microbial consortium development represent another innovative direction for improving treatment efficiency (Tang et al., 2017).

10 Conclusions

Tannery wastewater presents one of the most challenging industrial effluent treatment problems due to its complex composition, high pollutant concentrations, and the presence of toxic and recalcitrant compounds including chromium, sulfides, tannins, and high salinity. This review has critically evaluated the major treatment technologies reported in the peer-reviewed literature, including physicochemical methods (coagulation–flocculation, electrocoagulation, adsorption), biological systems (activated sludge, SBR, anaerobic digestion, constructed wetlands), membrane technologies (MF, UF, NF, RO, MBR), advanced oxidation processes (Fenton, photo-Fenton, sono-Fenton, ozonation, photocatalysis), and integrated hybrid schemes.

Key findings from the literature indicate that no single technology can achieve complete treatment of tannery wastewater to meet discharge standards. Conventional activated sludge processes, while widely used, suffer from poor sludge settling, low removal efficiencies for certain pollutants, and high energy consumption. Membrane technologies offer excellent separation performance but face fouling challenges that require effective pretreatment. Advanced oxidation processes can degrade recalcitrant organics but are energy-intensive and may be cost-prohibitive for large-scale applications.

Integrated treatment trains combining complementary processes have demonstrated superior performance. The most effective approaches typically involve physicochemical pretreatment for solids and chromium removal, followed by biological secondary treatment for organic carbon and nitrogen removal, and finally membrane or advanced oxidation polishing for water reuse applications. Emerging trends toward zero liquid discharge and resource recovery align with circular economy principles, enabling chromium recycling, water reuse, and biogas production from organic waste streams.

Persistent challenges requiring further research include the management of chromium-laden sludge, the treatment of high-salinity effluents that inhibit biological processes, membrane fouling control, the presence of emerging contaminants such as microplastics, and the economic feasibility of advanced treatment technologies for implementation in developing countries where most tanneries are located.

Future research should prioritize the development of robust, cost-effective hybrid systems validated at pilot and full scale, the application of life cycle assessment to guide sustainable technology selection, the exploration of novel materials for adsorption and catalysis, and the integration of artificial intelligence for process optimization and control. Full-scale studies demonstrating successful long-term operation of integrated systems are essential to convince the tannery industry to modernize and invest in sustainable wastewater management infrastructure in support of a circular bioeconomy.

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References

Abbas AA, Ismail ZZ. 2025. Green approach for reclamation of leather tannery wastewater in an upflow continuously operated constructed wetland coupled microbial fuel cell system: Experimental and modeling studies. Environmental Science and Pollution Research, 32(26): 15790-15810. https://link.springer.com/article/10.1007/s11356-025-36632-9

Aber S, Salari D, Parsa MR. 2010. Employing the Taguchi method to obtain the optimum conditions of coagulation–flocculation process in tannery wastewater treatment. Chemical Engineering Journal, 162(1): 127-134. https://www.sciencedirect.com/science/article/pii/S1385894710004377

Aguilar-Ascón E, Marrufo-Saldaña L, Barra-Hinojosa JA. 2024. Combining effluent treatment methods to remove ammonia nitrogen from tannery wastewater. Ecological Engineering & Environmental Technology, 25(12): 371-386. https://www.ecoeet.com/Combining-Effluent-Treatment-Methods-to-Remove-Ammonia-Nitrogen-from-Tannery-Wastewater,194949,0,2.html

Aguilar-Ascón E, Marrufo-Saldaña L, Barra-Hinojosa J, Buleje-del-Carpio R. 2025. Assessment of tannery effluents quality treated by electrocoagulation and ozonation: Physicochemical and ecotoxicological characterization. PLoS One 20(7): e0328654. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0328654

Al-Abbas AA, Ismail ZZ. 2024. Performance and mechanisms of constructed wetland integrated microbial fuel cell for remediation and detoxification of leather tannery wastewater. Journal of Environmental Management, 369: 122353. https://www.sciencedirect.com/science/article/pii/S0301479724023399

Andriamanohiarisoamanana FJ, Farghali M, Mohamed IMA, et al. 2024. Impact of tannery wastes on anaerobic co-digestion: Enhancing biogas production and process efficiency. Collagen and Leather, 6: 19. https://link.springer.com/article/10.1186/s42825-024-00162-w

Bahammou O, Mrabet IE, Nawdali M, et al. 2025. Sequential treatment of tannery effluent by coagulation–flocculation and sono-photo-Fenton: Performance, optimisation and phytotoxicity evaluation. Journal of Environmental Engineering and Science, 20(3): 222-234. https://www.sciencedirect.com/org/science/article/abs/pii/S1496255125000148

Balakrishnan A, Kanchinadham SBK, Kalyanaraman C. 2021. Nutrient requirement of tannery wastewater containing tannins. Environmental Technology & Innovation, 23: 101776. https://www.sciencedirect.com/science/article/pii/S2352186421004247

Basak SR, Nury AH, Swarup SD, et al. 2025. Optimizing biogas production through the co-digestion of tannery fleshing, cowdung, and sewage water using response surface methodology. Cleaner Waste Systems, 12: 100332. . https://www.sciencedirect.com/science/article/pii/S2772912525001307

Bhardwaj A, Kumar S, Singh D. 2023. Tannery effluent treatment and its environmental impact: A review of current practices and emerging technologies. Water Quality Research Journal, 58(2): 128-152. https://iwaponline.com/wqrj/article/58/2/128/94991/Tannery-effluent-treatment-and-its-environmental

Bhattacharjee A, Chatterjee D, Poddar S, et al. 2025. Biosorption-based elimination of hexavalent chromium using Bacillus cereus F4810/72 isolated from tannery effluents. Biodegradation, 37: 17. https://link.springer.com/article/10.1007/s10532-025-10239-w

Chen F, Li XX, Luo ZB, et al. 2018. Treatment of tannery wastewater using a combined UASB (2 stage)-ozonation-BAF system. Desalination and Water Treatment, 116(2018): 277-283. https://www.deswater.com/DWT_articles/vol_116_papers/116_2018_277.pdf

Durai G, Rajasimman M, Rajamohan N. 2011. Kinetic studies on biodegradation of tannery wastewater in a sequential batch bioreactor. Journal of Biotech Research, 3: 19-26. http://www.btsjournals.com/assets/2011v3p19-26.pdf

Elkarrach A, Merzouki M, Laidi O, et al. 2020. Sequencing batch reactor: Inexpensive and efficient treatment for tannery effluents of Fez city in Morocco. Desalination and Water Treatment, 202: 71-77. https://www.sciencedirect.com/science/article/pii/S1944398624076331

Erkan HS, Guvenc SY, Varank G, Engin GO. 2018. The investigation of chemical coagulation and electrocoagulation processes for tannery wastewater treatment using response surface methodology. Desalination and Water Treatment, 113: 57-73. https://www.sciencedirect.com/science/article/pii/S1944398624124289?via%3Dihub

Fernández-Medrano V, Cuartas-Uribe B, Bes-Piá MA, Mendoza-Roca JA. 2022. Application of nanofiltration and reverse osmosis membranes for tannery wastewater reuse. Water, 14(13): 2035. https://www.mdpi.com/2073-4441/14/13/2035

Gopal S, Jayabalan J, Jayaraman D, et al. 2025. Amalgamation of advanced oxidation process with biological techniques for treatment of tannery wastewater. Physics and Chemistry of the Earth, Parts A/B/C, 138: 103883. https://www.sciencedirect.com/science/article/pii/S1474706525000336?via%3Dihub

Gowtham B, Pauline S. 2021. Experimental study on performance assessment of Fenton and photo-Fenton oxidation process for methylene blue. Proceedings of the International Academy of Ecology and Environmental Sciences, 11(2): 43-51. http://www.iaees.org/publications/journals/piaees/articles/2021-11(2)/2-Gowtham-Abstract.asp

Grifasi N, Fornaro M, Piumetti M, et al. 2025. Chromium recovery from tannery wastewater by zeolite-based materials: A circular and sustainable approach. In: Advanced Technologies in Wastewater Treatment, 243-261. https://www.sciencedirect.com/science/chapter/edited-volume/abs/pii/B9780443138447000029

Hayati H, Doosti M, Sayadi MH. 2013. Performance evaluation of waste stabilization pond in Birjand, Iran for the treatment of municipal sewage. Proceedings of the International Academy of Ecology and Environmental Sciences, 3(1): 52-58. http://www.iaees.org/publications/journals/piaees/articles/2013-3(1)/performance-evaluation-of-waste-stabilization-pond.pdf

Husain A, Ayub S, Khan AH, et al. 2025. Pilot scale recovery, and removal of chromium from tannery wastewater by chemical precipitation: Life cycle assessment and cost analysis. Journal of Environmental Management, 391: 126502. . https://www.sciencedirect.com/science/article/pii/S0301479725024788

Jha S, Sonal S, Mishra BK. 2025. Advanced pre-treatment strategies to control membrane fouling in tannery wastewater treatment. Applied Water Science, 15: 285. https://link.springer.com/article/10.1007/s13201-025-02558-3

Kanagaraj J, Babu NKC, Mandal AB. 2008. Recovery and reuse of chromium from chrome tanning waste water aiming towards zero discharge of pollution. Journal of Cleaner Production, 16(16): 1807-1813. https://www.sciencedirect.com/science/article/pii/S0959652607002569?via%3Dihub

Kanchanabhan, Arutchelvan TE, Sekaran V, Mohaideen A. 2005. Removal of natural tannin from tannery wastewater using sequencing batch reactor. Journal of Industrial Pollution Control, 21(2): 424-429. https://www.icontrolpollution.com/articles/removal-of-natural-tannin-fromtannery-wastewater-using-sequencingbatch-reactor-.php?aid=45462

Kaplan-Bekaroglu SS, Gode S. 2016. Investigation of ceramic membranes performance for tannery wastewater treatment. Desalination and Water Treatment, 57(37): 17300-17307. https://www.sciencedirect.com/science/article/pii/S1944398624031072?via%3Dihub

Kamalakkannan P, Younis M, Gezici S, Kailash S, Iqbal J. 2024. Characterization and impact of physicochemical parameters of tannery effluent on the aquatic environment. Biosciences Biotechnology Research Asia, 21(1). https://www.biotech-asia.org/vol21no1/characterization-and-impact-of-physicochemical-parameters-of-tannery-effluent-on-the-aquatic-environment/

Khatun J, Mukherjee A, Dhak D. 2024. Emerging contaminants of tannery sludge and their environmental impact and health hazards. In: Environmental Engineering and Waste Management (Kumar V, Bhat, SA, Kumar S, Verma P, eds). Springer, Cham. https://link.springer.com/chapter/10.1007/978-3-031-58441-1_1

Li ZW, Yu D, Wang XD, et al. 2024. A novel strategy of tannery sludge disposal – converting into biochar and reusing for Cr(VI) removal from tannery wastewater. Journal of Environmental Sciences, 138: 637-649. https://www.sciencedirect.com/science/article/pii/S1001074223001699?via%3Dihub

Lofrano G, Meric S, Inglese M, et al. 2010. Fenton oxidation treatment of tannery wastewater and tanning agents: Synthetic tannin and nonylphenol ethoxylate based degreasing agent. Desalination and Water Treatment, 23(1-3): 173-180. https://www.sciencedirect.com/science/article/pii/S1944398624182495

Masabanda MV, Delgado V, Rajasekhar E, Maddela NR. 2025. Dual step synthesis of chromium removal from tannery industry wastewater with photocatalytic effects of TiO2. International Journal of Environment and Waste Management, 36(4): 404-418. https://www.inderscienceonline.com/doi/abs/10.1504/IJEWM.2025.144989

Manoj KM, Goplakrishna GVT, Ibrahim BM. 2024. Innovative strategies for tannery wastewater remediation with sequential batch reactor and phycoremediation. Global NEST Journal, 27(1): gnest_05825. https://journal.gnest.org/publication/gnest_05825

Meena SK, Meena SO, Sangal VK, et al. 2025. Integration of electrocoagulation and electrooxidation for continuous mode treatment of tannery effluents: Experimental, optimization, and economic analysis. Journal of Water Process Engineering, 77: 108314. https://www.sciencedirect.com/science/article/pii/S2214714425013868

Mouhri GE, Elmansouri I, Amakdouf H, et al. 2024. Evaluating the effectiveness of coagulation–flocculation treatment on a wastewater from the Moroccan leather tanning industry: An ecological approach. Heliyon, 10(5): e27056. https://www.sciencedirect.com/science/article/pii/S2405844024030871

Moysés FS, Bertoldi K, Lovatel G, et al. 2017. Effects of tannery wastewater exposure on adult Drosophila melanogaster. Environmental Science and Pollution Research, 24: 26387-26395. https://link.springer.com/article/10.1007/s11356-017-0197-6

Mpofu AB, Oyekola O, Welz PJ, et al. 2021. Anaerobic treatment of tannery wastewater in the context of a circular bioeconomy for developing countries. Journal of Cleaner Production, 296: 126490. https://www.sciencedirect.com/science/article/pii/S0959652621007101

Nature Index. 2023. Wastewater treatment techniques for tannery effluents. Nature Index. https://www.nature.com/nature-index/topics/l4/wastewater-treatment-techniques-for-tannery-effluents

Ngobeni PV, Mpofu AB, Ranjan A, Welz PJ. 2024. A critical review of systems for bioremediation of tannery effluent with a focus on nitrogenous and sulfurous species removal and resource recovery. Processes, 12(7): 1527. https://www.mdpi.com/2227-9717/12/7/1527

Omor A, Laidi O, Elmachmachi O, et al. 2025. Treatment of effluents loaded with sulfide from unhairing-liming tannery unit by coagulation-flocculation process: Parameters effect and statistical approach. Next Research, 2(2): 100371. https://www.sciencedirect.com/science/article/pii/S3050475925002428

Pire-Sierra MC, Cegarra-Badell DD, Angulo-Cubillan NE, et al. 2016. Nitrogen and COD removal from tannery wastewater using biological and physicochemical treatments. Revista Facultad de Ingeniería Universidad de Antioquia, 80: 63-73. https://www.redalyc.org/journal/430/43047073008/html/

Pundir A, Thakur MS, Goel B, et al. 2025. Innovations in tannery wastewater management: A review of zero liquid discharge technology. International Journal of Environmental Science and Technology, 22: 3873-3894. https://link.springer.com/article/10.1007/s13762-024-05986-x

Quan WJ, Ma HR, Zhu C, et al. 2025. Closed-loop chromium recovery from tannery wastewater: Mechanism of multiphase Cr(III) electrode position under low-concentration sulfate and chloride coordination. Water Research, 285: 124150. https://www.sciencedirect.com/science/article/pii/S0043135425010577

Rahmawati A. 2024. Concept of cleaner production approach dan zero liquid discharge system in the tannery industry. Berkala Penelitian Kulit, Sepatu, dan Produk Kulit, 23(1). https://e-jurnal.politeknikatk.ac.id/index.php/bptkspk/article/view/48

Ricky R, Shanthakumar S, Ganapathy GP, Chiampo F. 2022. Zero liquid discharge system for the tannery industry—an overview of sustainable approaches. Recycling, 7(3): 31. https://www.mdpi.com/2313-4321/7/3/31

Rivela B, Moreira MT, Bornhardt C, et al. 2004. Life cycle assessment as a tool for the environmental improvement of the tannery industry in developing countries. Environmental Science and Technology, 38(6): 1901-1909. https://pubs.acs.org/doi/10.1021/es034316t

Rodríguez JS, Agudelo-Valencia RN. 2019. Sulfide removal using ozone as an oxidizing agent in tannery wastewater. Revista Facultad De Ingeniería, 28(51): 25-38. https://revistas.uptc.edu.co/index.php/ingenieria/article/view/9081

Satyam S, Patra S. 2025. Xanthine oxidase driven bio-Fenton system for advanced pollutant degradation in sustainable wastewater treatment. International Journal of Biological Macromolecules, 313: 144323. https://www.sciencedirect.com/science/article/pii/S0141813025048755

Sayadi MH, Kargar R, Doosti MR, Salehi H. 2012. Hybrid constructed wetlands for wastewater treatment: A worldwide review. Proceedings of the International Academy of Ecology and Environmental Sciences, 2(4): 204-222. http://www.iaees.org/publications/journals/piaees/articles/2012-2(4)/1-Sayadi-Abstract.asp

Şengil İA, Kulaç S, Özacar M. 2009. Treatment of tannery liming drum wastewater by electrocoagulation. Journal of Hazardous Materials, 167(1-3): 940-945. https://www.sciencedirect.com/science/article/pii/S0304389409001174?via%3Dihub

Silva LJG, Casimiro MJG, Pena A, et al. 2025. Assessment of chromium contamination in aquatic environments near tannery industries: A Portuguese case study. Toxics, 13(12): 1068. https://www.mdpi.com/2305-6304/13/12/1068

Sivagami K, Sakthivel KP, Nambi IM. 2018. Advanced oxidation processes for the treatment of tannery wastewater. Environmental Chemical Engineering, 6(3): 3656-3663. https://www.sciencedirect.com/science/article/pii/S2213343717302555

Souza EA, Cerqueira UMFM, Silva LA. 2020. Comparative study of various advanced oxidation processes for the treatment of tannery wastewater. Desalination and Water Treatment, 182: 88-97. https://www.sciencedirect.com/science/article/pii/S1944398624096243

Su C, Jiang LQ, Zhang WJ. 2014. A review on heavy metal contamination in the soil worldwide: Situation, impact and remediation techniques. Environmental Skeptics and Critics, 3(2): 24-38. http://www.iaees.org/publications/journals/environsc/articles/2014-3(2)/a-review-on-heavy-metal-contamination-in-the-soil-worldwide.pdf

Tahiri S, Hassoune J, Younssi SA. 2013. Management of tannery wastewaters: Treatment of spent chrome tanning bath and vegetable tanning effluents. Desalination and Water Treatment, 51(22-24): 4467-4477. https://www.sciencedirect.com/science/article/pii/S1944398624188285

Tang SY, Zhang ZH, Zhang XH. 2017. New insight into the effect of mixed liquor properties changed by pre-ozonation on ceramic UF membrane fouling in wastewater treatment. Chemical Engineering Journal, 314: 670-680. https://www.sciencedirect.com/science/article/pii/S1385894716317843

Tehrani MF, Taheri S. 2026. Efficiency of biological treatment processes in the leather industry under wastewater salinity. Iranian Water Resources Research Journal, 20(1): 60. https://iwrj.sku.ac.ir/article_116639_7ba8705cb519b32057469b0d1fec92dd.pdf

Uttam S, Singh D, Kumar R, Verma S. 2025. Assessing the environmental impact due to the influence of tannery effluent on water quality. Chemistry Africa, 8: 5635–5651. https://link.springer.com/article/10.1007/s42250-025-01377-y

Wahyuni ET, Cahyono RN, Nora M, et al. 2024. Degradation of amoxicillin residue under visible light over TiO2 doped with Cr prepared from tannery wastewater. Results in Chemistry, 7: 101302. https://www.sciencedirect.com/science/article/pii/S2211715623005416

Welz PJ, Jonge ND, Lilly M, et al. 2024. Integrated biological system for remediation and valorization of tannery wastewater: Focus on microbial communities responsible for methanogenesis and sulfidogenesis. Bioresource Technology, 395: 130411. https://www.sciencedirect.com/science/article/pii/S0960852424001147

Yadav S, Kundu N, Bhattacharya A, et al. 2026. A green approach for remediation of hexavalent chromium [Cr(VI)] from tannery effluent using rice hull biochar and assessing its impact on germination of Cicer arietinum (Chickpea). Biotechnology for Sustainable Materials, 3: 8. https://link.springer.com/article/10.1186/s44316-026-00058-1

Yang F, Wang XB, Shan YY. 2023. Research recap of membrane technology for tannery wastewater treatment: A review. Collagen and Leather, 5: 24. https://link.springer.com/article/10.1186/s42825-023-00132-8

Yang F, Wang XB, Shan YY, et al. 2024. Pre-ozonation coupled with forward osmosis with fertilizer as draw solution for simultaneous wastewater treatment and agricultural irrigation. Desalination, 592: 118187. https://www.sciencedirect.com/science/article/pii/S0011916424008981

Yu HM, Tang MM, He J, et al. 2024. Intelligent treatment of tannery wastewater via H2O2 photocatalytic oxidation coupled adsorption process. Journal of Water Process Engineering, 63: 105378. https://www.sciencedirect.com/science/article/pii/S221471442400610X

Zahnoune R, Boudouch O, El Amri R, et al. 2026. Synergistic electrocoagulation in a self-induced airlift reactor: A leap towards energy-efficient and sustainable tannery wastewater remediation. Water Science and Engineering, 19(2): 198-210. https://www.sciencedirect.com/science/article/pii/S1674237026000281

Zhao J, Wu QL, Tang YL, et al. 2022. Tannery wastewater treatment: Conventional and promising processes, an updated 20-year review. Journal of Leather Science and Engineering, 4: 10. https://link.springer.com/article/10.1186/s42825-022-00082-7

Zheng H, Tan XZ, Tan Y, Zhang WJ. 2026. A study on the removal of ammonia nitrogen and sulfides in tannery wastewater using photocatalytic oxidant. Proceedings of the International Academy of Ecology and Environmental Sciences, 16(4): 123-144. http://www.iaees.org/publications/journals/piaees/articles/2026-16(4)/1-Tan-Abstract.asp

Zhou JF, Wang YN, Zhang WH, Shi B. 2014. Nutrient balance in aerobic biological treatment of tannery wastewater. Journal of the American Leather Chemists Association, 109(5):154-160. https://journals.uc.edu/index.php/JALCA/article/view/3540