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Tannery effluent treatment and its environmental impact: a review of current practices and emerging technologies

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ABSTRACT

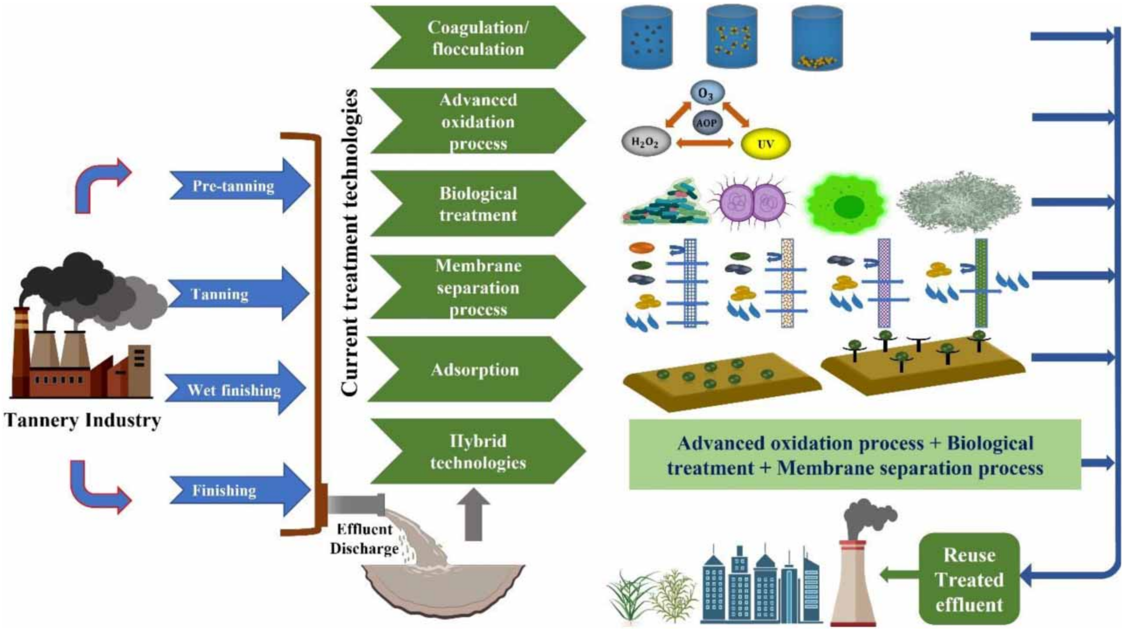
The tannery industry plays a significant role in the economy but poses a severe environmental threat due to its high water and chemical usage, leading to wastewater generation with a high concentration of pollutants. This wastewater contains a range of contaminants created throughout the leather manufacturing process, making effluent disposal a significant challenge for the industry. The tanning process also contributes significantly to the pH, biological oxygen demand (BOD), total suspended solids (TSS), chemical oxygen demand (COD), total dissolved solids (TDS), and concentrations of T Cr, Cr(III), Cr(VI), Cl^-, sulfate, sulfide, and inorganic constituents in the wastewater. This review paper provides a concise overview of the origins and characteristics of post-tanning effluent, different treatment techniques, and applications of treated wastewater. Comparing the prominent tannery effluent technologies, adsorption and advanced oxidation processes (AOPs) effectively improved wastewater biodegradability before biological treatment. AOPs, enzymatic, adsorption, and coagulation treatment effectively upgraded the effluent to desired levels for disposal. Additionally, membrane separation processes have shown high pertinency in cases where the treated effluent is intended for reuse, whereas hybrid technologies can be the answer for better and cost-effective results.

Key words: leather, tannery effluent, tanning process, toxicity, treatment techniques

HIGHLIGHTS

- Tannery wastewater (TW) has grown to be one of the dominant sources of industrial pollution.
- The present article comments on the need for TW treatment in developing countries.
- Different treatment techniques and their advantages and limitations have been discussed.
- Reuse and recycling of TW are crucial for sustainable development.
- The primary operating circumstances, novelties, and difficulties are discussed.

GRAPHICAL ABSTRACT



ABBREVIATIONS

AOP	advanced oxidation process
BOD	biological oxygen demand
Cl^-	chloride
COD	chemical oxygen demand
CPHEEO	Central Public Health and Environment Engineering Organization, India
DWW	domestic wastewater
T Cr	total chromium
Cr(III)	trivalent chromium
Cr(VI)	hexavalent chromium
NH_4-N	ammonium
MBBR	moving-bed biofilm reactor
MF	microfiltration
MOEFGOI	Ministry of Environment & Forests Government of India
MSP	membrane separation process
NF	nanofiltration
PTE	post treated effluent
RO	reverse osmosis
S^{2-}	sulfide
SO_4^{2-}	sulfate
TS	total solids
TDS	total dissolved solids
TOC	total organic carbon
TKN	total Kjeldahl nitrogen
TSS	total suspended solids
TTE	treated tannery effluent
TWE	tannery wastewater effluent
UF	ultrafiltration
UNIDO	United Nations Industrial Development Organization
UNWWD	United Nations World Water Development

1. INTRODUCTION

The age of industrialization has brought significant economic benefits to developing and developed countries. Among the various industries that have emerged, the leather industry has significantly contributed to the growth of nations and the global economy (Klein *et al.* 2022; Silveira *et al.* 2023; Xie *et al.* 2023). Leather tanning is one of the major industries that has flourished worldwide, particularly in India, Bangladesh, China, Pakistan, Turkey, and Brazil (Moktadir *et al.* 2018; Alemu *et al.* 2019a; Kumar & Singh 2021). In India, the tannery, tannery product, tannery garment, and footwear industries form a significant sector of the economy and are among the nation's top 10 foreign exchange earners. India ranks second in the world for the export of leather clothing, third for saddles and harnesses, and fourth for leather items, with a total export value of $3.68 billion in 2020–2022 ('India: Hides and Skins | USDA Foreign Agricultural Service' 2019). Being one of the biggest exporters of finished leather, India has more than 2,000 tanneries and produces around 2 billion square feet of leather yearly ('India: Toxic Tanneries | Pulitzer Center' 2021). The nation is one of the world's largest producers of leather, with a significant proportion of its tanneries located in Tamil Nadu, followed by West Bengal, Uttar Pradesh, Punjab, Maharashtra, Andhra Pradesh, and other states as shown in Figure 1. This concentration of tanneries can lead to significant environmental and health impacts, as the production of leather often generates large volumes of hazardous waste (Pastapure *et al.* 2023; Ranjan *et al.* 2023). Efforts to regulate and mitigate the environmental impact of tanneries are underway, but further action is needed to address this ongoing challenge (Hansen *et al.* 2021a).

In order to produce leather from animal hide to the requisite final quality, a number of batch processes are necessary, including pre-tanning, wet finishing, and finishing processes, to transform the raw hide into leather goods. Sources and types of pollutants created during leather production are depicted using a flow chart in Figure 2. Studies describe the process involved, which requires a considerable number of hazardous chemicals (Korpe *et al.* 2019; Nur-E-Alam *et al.* 2020; Kumar & Deswal 2022). The sort of hides and the mechanical and chemical tanning processes affect the wastewater's quality. Therefore, over the past 20–30 years, tannery wastewater control by treatment methods has received significant research attention. Based on a report by the United Nations Industrial Development Organization (UNIDO 2000), in the various steps of the tannery, over 175 different chemicals are used, e.g., sodium hydroxide (NaOH), sodium chloride (NaCl), pentachlorophenol (C_6HCL_5O), sodium sulfide (Na_2S), enzymes, milk of lime ($Ca(OH)_2$), chlorides (Cl^-), sulfuric acid (H_2SO_4), total chromium (T Cr), formic acid (CH_2O_2), ammonium chloride (NH_4Cl), ammonium sulfate ($(NH_4)_2SO_4$), non-identical metallic salts, and organic chemicals, including significant water consumption (Mannucci *et al.* 2010).

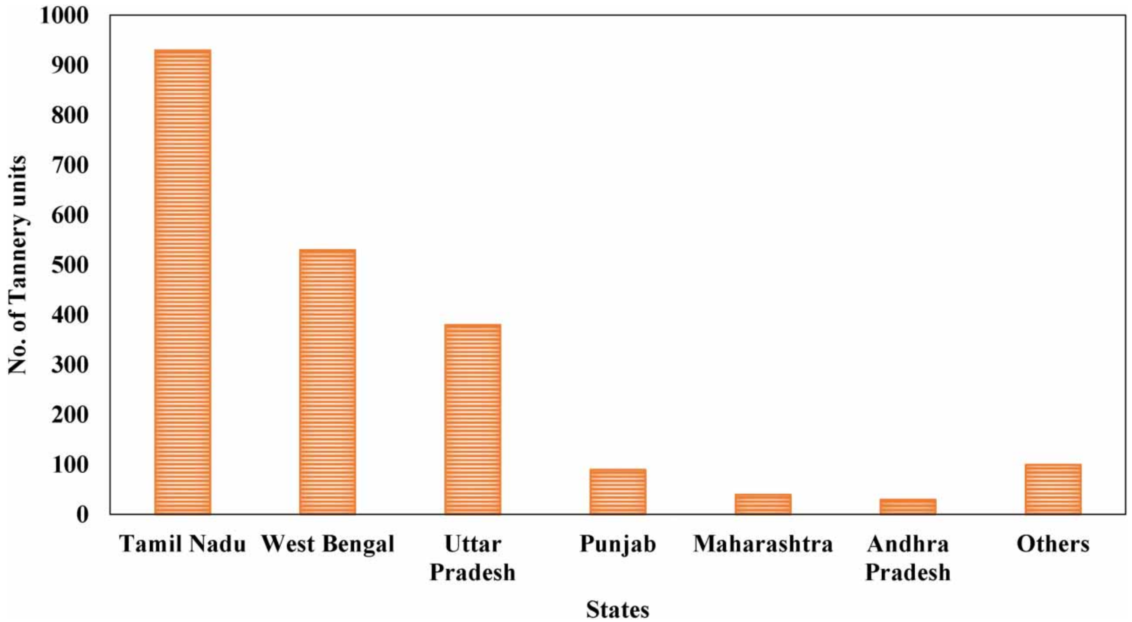


Figure 1 | State-wise distribution of tanneries in India ('India: Hides and Skins | USDA Foreign Agricultural Service' 2021).

Figure 2 | Sources and types of pollutants created during the production of leather.

Sustainable waste disposal in the leather processing industry has become a major problem due to the continual origination of an enormous number of pollutants worldwide (Selvaraj *et al.* 2019; Patel *et al.* 2021; Kumar & Singh 2023). Tannery wastewater has grown to be one of the dominant sources of industrial pollution due to the expansion of the tannery sector. Each year, the global leather industry produces 600 million m^3 of effluent. According to a report on tannery operations in Asia, an estimated 350 million cubic meters of wastewater containing chemicals and other contaminants are produced annually from processing around 10 million tonnes of hides and skins (Rajamani 2018). This represents a significant environmental challenge, as the effluent can negatively impact local ecosystems and human health (Shahbazi & Pedram 2021; Zaheer *et al.* 2022; Selvan *et al.* 2023). Further research is needed to fully understand the scope of this issue and develop effective mitigation strategies.

In beamhouse operations, green fleshing unhairing, liming splitting, deliming batting, degreasing, and pickling processes generate wastewater, as shown in Table 1, which contains a large quantity of biological oxygen demand (BOD), total dissolved solids (TDS), chemical oxygen demand (COD), sulfides, chlorides, and a variety of other chemicals which contribute 60–70% of the total contaminant load generated by tanneries (Wu *et al.* 2018). Tannery wastewater is mainly characterized by a variety of organic waste, hazardous substances, and metallic and non-metallic pollutants that arise in tannery wastewater effluent (TWE), as described in Table 2, that leads to wastewater from tanneries having a dark brown color and a foul smell (Tamersit & Bouhidel 2020). Metallic and non-metallic contaminants like T Cr, Cr(III), Cr(VI), Cl^-, total Kjeldahl nitrogen (TKN), SO_4^{2-}, S^{2-}, $NH_4 - N$, iron, and calcium are present in tannery effluents (Kassim *et al.* 2022). The number of total solids (TS) increases as a result of either or both organic and inorganic matter in tannery effluent. In addition, high BOD and COD, which decrease dissolved oxygen concentration in the aquatic environment and toxic chemicals, make the effluent extremely acidic (Chowdhury *et al.* 2013; Ali *et al.* 2021; Fouda *et al.* 2021; Ahmed *et al.* 2022).

The activities involved in tannery operations generate wastewater that can negatively impact the environment and the health of living organisms, including humans and animals. Specifically, the untreated effluent from tanneries can contain high levels of organic matter that consume dissolved oxygen and deprive aquatic life of the oxygen they need to survive. Also, the wastewater may contain nutrients that can promote the growth of aquatic plants and algae, leading to the eutrophication of lakes and streams. Finally, untreated effluent can also harbor pathogenic microorganisms and toxic substances that can cause disease and pose a risk to human health if ingested (Chiampo *et al.* 2023). Therefore, liquid and solid wastes from the tannery industry and tanneries, which produce major pollution unless they have undergone some treatment before release, are putting a rising strain on the environment (Jiang *et al.* 2020). Permissible pollution limits for releasing tannery wastewater into surface bodies and sewers for some selected countries are mentioned in Table 3.

This paper aims to review the wastewater treatment techniques used for tannery effluent. The literature has been studied in detail, and improvement to an existing process has been suggested. Therefore, this study aims to discuss and update the information on major environmental problems associated with the tanning procedure: contamination parameters, water utilization, chemical consumption, and loads of the generated raw wastewater.

2. ENVIRONMENTAL IMPACT

Goal 6 of the United Nations' environmental sustainability agenda aims to provide everyone access to clean, safe, drinkable water, and basic sanitation facilities by 2030 (Fito & Van Hulle 2021). The UN World Water Development Report has indicated that the global water crisis and severe water shortages are mainly due to the decline in freshwater availability and water quality degradation. By 2030, 40% of the world's population is predicted to lack access to fresh water (Ryder 2017). Safe drinking water is essential for humans to maintain a healthy body, ecosystem, and economy. Even today, around 29% of the worldwide inhabitants rely on contaminated water sources for drinking, putting them in danger of contracting cholera, dysentery, amoebiasis, polio, hepatitis, and typhoid (WHO/UNICEF (JMP)-2000| UN-Water 2021). Urbanization has accelerated in recent decades due to population expansion, and economic growth has led to an increase in wastewater generation, of which 80% is returned to the environment untreated and rises to 95% in the least developed nations (United Nations Educational Scientific and Cultural Organization 2021). Environmental contaminants and their toxicity are a big global problem because of their detrimental effects and considerable health hazards. The contamination of water is the consequence of both man-made and natural actions. Chemicals have contaminated water bodies worldwide in different industries, including textiles, tanning, and dyeing, which are highly toxic (Osman 2014). Due to their negative consequences such as severe health risks, they produce environmental contaminants, and their toxicity is a major global issue. It can mitigate to some extent by giving proper and effective treatment to industrial effluent like tannery before reusing or disposing of it in the environment that avoids contamination of water bodies (Bagla *et al.* 2021). After effective and sufficient treatment, wastewater may be utilized again for various purposes as per recommended norms given by CPHEEO, India, as shown in Table 4.

3. TANNERY EFFLUENT TREATMENT TECHNOLOGIES

Control of water sources has been viewed as effective with wastewater treatment. The techniques used to manage post treated effluents (PTEs), the effectiveness of removal, the kind of effluent, the main parameters, and the specifics of the study are stated in the systematic review in Table 5. Numerous treatment methods include coagulation/flocculation, advanced oxidation processes (AOPs), biological treatment, membrane separation processes (MSPs), adsorption, and hybrid

Table 1 | Wastewater characteristics at different stages of the tanning process (UNIDO 2000)

Parameter	pH	BOD 5 day at 20 °C	Suspended solids	COD	Sulfide	Dissolved solids	Chlorides	Total solids	Total chromium	Volume of the wastewater in litres /ton of hides/skins
Soaking	7.5–8	1,100–2,500	3,000–7,000	3,000–6,000	–	32,000–48,000	15,000–30,000	35,000–55,000	–	6,000–9,000
Liming, Re-liming, Fleshing, Deliming	8–12	2,000–8,000	3,000–15,000	3,000–15,000	50–200	5,000–15,000	3,000–6,000	6,000–20,000	–	6,000–10,000
Pickling and chrome tanning	2.2–4.0	400–800	1,000–2,000	1,000–3,000	–	29,000–58,000	15,000–25,000	30,000–60,000	1,500–3,000	1,500–3,000
Wet finish -Re-chroming, dyeing and fat liquor	3.5–4.5	1,000–2,000	600–1,000	2,500–7,000	–	3,400–9,000	500–1,000	4,000–10,000	30–60	3,000–5,000
Composite (including washings)	7.0–9.0	1,200–3,000	2,000–5,000	2,500–8,000	30–150	13,000–20,000	6,000–9,500	15,000–25,000	80–200	30,000–40,000

Except for pH, all are in mg/l .

Table 2(a) | Characteristics parameters of post-tanning effluent (PTE)

S. No.	Parameters										References
	pH	Temperature (°C)	Conductivity (mS/cm)	Suspended solids (mg/l)	TDS (mg/l)	TS (mg/l)	BOD (mg O_2/l)	COD (mg/l)	TOC (mg/l)	Biodegradability index (BI)	
1	4	6.5	11.71	912	–	–	–	2,200–3,000	–	–	Deghles & Kurt (2016)
2	4.30 ± 0.81	21 ± 0.75	27.30 ± 0.87	–	–	27,300 ± 735.60	300 ± 3.30	1,750 ± 50	–	0.17	Moges *et al.* (2022)
3	7.5–8.14	–	–	–	11,030–11,970	18,280–19,420	2,200–2,800	8,160–8,760	3,672–3,767	0.27–0.32	Saxena *et al.* (2021)
4	7.76	–	–	–	11,820	–	3,024	7,760	–	0.38	Sasidhar *et al.* (2021)
5	8.67 ± 3.5	–	15.5 ± 2	–	–	–	3,120.6 ± 172	7,273 ± 536	–	0.43	Alemu *et al.* (2019b)
6	7.6	–	28	–	14,000	–	–	4,800	–	–	Tran *et al.* (2020)
7	11	–	32	–	41,200	–	–	7,475	2,942	–	Selvaraj *et al.* (2020)
8	4.68	–	6.67	–	–	–	1,860	7,744	2,772	0.24	Mella *et al.* (2018)
9	6	–	–	–	36,642 ± 232	–	732 ± 146	1,920 ± 385	650 ± 174	0.38	Karthikeyan *et al.* (2015)
10	7–8.5	–	–	2,500	16,000	–	2,000	4,500	–	0.45	Anjali & Sabumon (2014)

Table 2(b) | Metallic and non-metallic pollutants in PTE

	Parameters (mg/l)										
S. No.	T Cr	Cr(III)	Cr(VI)	Chloride	TKN	Sulfate	Sulfide	NH_4-N	Iron	Calcium	References
1.	30	–	6.95	–	–	–	66	–	–	–	Moradi & Moussavi (2019)
2.	69	118	7.04	–	–	–	–	–	–	–	Vilardi *et al.* (2018)
3.	72.1	–	–	–	–	–	–	–	1.68 ± 0.27	4	Módenes *et al.* (2012)
4.	28 ± 5	–	–	–	–	488	268 ± 76	261.5 ± 68	–	–	Alemu *et al.* (2019b)
5.	–	–	–	–	–	20	–	52.9	–	–	Tran *et al.* (2020)
6.	–	–	–	17,000	–	149	3,080	–	0.16	–	Selvaraj *et al.* (2020)
7.	–	–	–	9,458 ± 220	756 ± 128	1,026 ± 192	9 ± 6	–	–	–	Karthikeyan *et al.* (2015)
8.	–	65	–	7,500	300	1,500	200	200	–	–	Anjali & Sabumon (2014)
9.	–	–	–	3,120	172	–	–	142	–	–	Naumczyk & Kucharska (2017)
10.	30.11	–	6.95	–	–	–	66	–	–	–	Moradi & Moussavi (2019)

Table 3 | Contamination standards for effluent release into surface and sewers for some selected countries (UNIDO 2000)

Country	India		China		Brazil		Turkey		UK		Italy	
Parameter	Surface	Sewer	Surface	Sewer	Surface	Sewer	Surface	Sewer	Surface	Sewer	Surface	Sewer
Temperature (°C)	40–45	40–45	–	35	<40	40	–	40	25	40	30–35	30–35
pH	5.5–9.0	5.5–9.5	6.0–9.0	6.0–9.0	5.0–9.0	5.0–9.0	6.0–9.0	6.0–9.0	6.0–9.0	6.0–9.0	5.5–9.5	5.5–9.5
SS (mg/l)	100	600	200	500	–	–	150	350	30–50	500–1,000	40–80	200
Settleable solids (ml/l)	–	–	–	10	1.0	–	–	–	–	–	–	–
BOD (mg O_2/l)	30	500	150	500	60	–	100	250	20–30		40	250
COD (mg/l)	250	–	300	500	–	–	200	800	–	2,000–6,000	160	500
TDS (mg/l)	2,100	2,100	–	–	–	–	–	–	–	–	–	–
Sulfide (mg S^2/l)	2	2	1	10	0.2	5	1	2	1	2–5	1	2
Chrome (III) (mg/l)	2	2	1.5	2	–	5	–	–	2–5	10–35	–	4
Chrome (VI) (mg/l)	0.1	0.1	–	0.5	–	–	0.3	–	0.1	0.1	0.2	0.2
Chrome total (mg/l)	2	2	1.5	–	0.5	–	2	5	1–2	1–20	2	4
Chlorides (mg/l)	1,000	1,000	–	–	–	–	–	–	4,000	5,000	1,200	1,200
Sulfate (mg/l)	1,000	1,000	–	–	–	–	–	1,700	–	1,000–1,200	1,000	1,000
Ammonia (mg N/l)	50	50	–	–	5	–	–	–	100	10–100	10–15	30

technologies. Science Direct, Springer Link, Scopus, and Mendeley were used for an extensive literature review related to the tannery wastewater treatment (TWT) methods.

Table 4 | Standards for the quality of treated wastewater that should be used for a specific application as per CPHEEO, India (CPHEEO 2013)

Parameters	Vehicle exterior washing	Fire protection	Non-contact impoundment	Toilet flushing	Crops: Non-edible crops	Crops: Food crops: Cooked	Crops: Food crops: Raw	Horticulture, golf course
pH	6.5–8	6.5–8	6.5–8	6.5–8	6.5–8	6.5–8.3	6.5–8.3	6.5–8.3
Turbidity (NTU)	<2	<2	<2	<2	AA	AA	<2	<2
SS (mg/l)	AA	AA	AA	AA	30	30	AA	AA
Oil & Grease (mg/l)	Nil	Nil	Nil	10	10	Nil	Nil	10
TDS (mg/l)	2,100	2,100	2,100	2,100	2,100	2,100	2,100	2,100
COD (mg/l)	AA	AA	AA	AA	30	30	AA	AA
TKN as N (mg/l)	10	10	10	10	10	10	10	10
BOD (mg/l)	10	10	10	10	20	20	10	10
Residual Chlorine (mg/l)	1	1	0.5	1	–	–	–	1
PO_4 as P (mg/l)	1	1	1	1	5	5	2	2
Fecal Coliform (MPN/100 ml)	–	–	–	–	230	230	–	–
$NO_{3^-}N$(mg/l)	10	10	5	20	10	10	10	10
Odour	Aesthetic							
Colour	Colourless							

For Crops (Cr:0.10, As:0.1, Ni:0.2, Cd: 0.01) (all limits in mg/l). CPHEEO, India.
AA-as, arising when other parameters are satisfied.

3.1. Coagulation/flocculation

The tanning effluent produced during the production process comprises a number of highly hazardous compounds that might restrict the treatment process and result in low-quality effluent (Korpe & Venkateswara Rao 2022). Coagulation and flocculation help in the removal of suspended particles in the effluent with a size range from 0.1 to 100 μm (Davis 2010). If the size is less than this, then the process takes a lot of time and is not proven to be cost-efficient for the TWT plants. The treatment of TWE has already been investigated using different coagulants and flocculants. The effectiveness of removing Cr(III) and total organic carbon (TOC) from post-tanning wastewaters by coagulation with poly-aluminum chloride (PAC), as well as the status of Cr(III) complexes with standard post-tanning chemicals were examined. Adding 0.1 mol/l NaOH or 0.1 mol/l HCl to the solution, the pH values of simulated post-tanning wastewaters were changed to various levels (5–9) (Tang *et al.* 2018). An extract from the flowers of the *Musa* sp. plants effectively removes recalcitrant chemicals that are typically challenging to eliminate using traditional methods. Specifically, the extract was utilized in the coagulation and flocculation processes for industrial wastewater and resulted in a removal efficiency for Cr(III), T Cr, and Cr(VI) in primary treatment (CETP) (Pinto *et al.* 2019). The electrocoagulation technique for industrial wastewater used electrodes (6 cm × 12 cm) to create $Al(OH)_3$ and $Fe(OH)_3$ was successful in clarifying the PTEs having initial COD concentration varying from 533 to 5,550 (mg/l). During a 60-min electrolysis operation, the aluminum electrodes showed a 72% removal efficiency for COD and a 57% removal efficiency for TOC, while the iron electrodes showed a 69% removal efficiency for COD and a 60% removal efficiency for TOC, all at a current density of 28 mA/cm^2 (De La Luz-Pedro *et al.* 2019). According to studies, certain highly efficient compounds such as Chitosan, Tannins, $FeCl_3$, and K_2FeO_4 have been identified as causing minimal environmental damage. These compounds have been tested for their effectiveness in removing color, TOC, COD, and SS from wastewater using a product called Envifer® (which contains 40% K_2FeO_4). Envifer® utilizes oxidation and coagulation processes to remove pollutants from the PTE (Hansen *et al.* 2020; Zhao *et al.* 2022).

Coagulation/flocculation is a common method used to treat wastewater due to its ability to effectively remove both organic and inorganic pollutants. It is not suitable as a primary process for treating wastewater due to the harsh quality of the wastewater. This typically requires a significant amount of flocculants or coagulants to achieve acceptable decontamination

Table 5 | Applications of technologies for tannery effluent treatment

Wastewater	Treatment techniques	Main parameter(s)	Removal efficiency	Operating conditions	Process/chemical involved	References
Simulated post-tanning wastewater	Coagulation/ flocculation	TOC and Cr(III)	TOC (20–60%), Cr(III) (60–99%)	Using poly-aluminum chloride as a coagulant, detention time was 30 min and centrifuged at 5,000 rpm for 5 min.	–	Tang *et al.* (2018)
	Aerobic biodegradation	Discoloration and Cr(VI)	Discoloration (92%) and Cr(VI) reduction (95%)	Biodegradation by *Lactobacillus paracase* CL1107, initial Cr(VI), and dye concentration is 100 mg/l.	Acid black dye and Cr(VI)	Huang *et al.* (2015)
	Fungal treatment	Discoloration, TOC, Detoxification, and COD	TOC and COD (80%), Biodetoxification (50–70%), and Discoloration (90%)	Using Trametes villosa SCS-10 for fungus treatment. The maximum amount of pollution was reduced when nutrient supplies were reduced.	Acid Orange 142 and Acid Red 357	Ortiz-Monsalve *et al.* (2019)
	Photocatalytic treatment	Discoloration, COD, and TOC	Discoloration (90%), COD (70%), and TOC (35%)	ZnO@MOF is produced when zeolitic imidazolate framework (ZIF)-8 is calcined in an atmosphere and added to 50 ml of dye solution. Degradation of methylene blue under visible light and bandgap of 3 eV with wavelength below 380 nm	Methylene blue - 10^{-5} mg/l	Hongjun *et al.* (2019)
	NF	Discoloration, COD, and BOD	Discoloration (76%), COD (53%), and BOD (66%)	Permeate flux: 2,000L/m^2h, pre-treatment using Whatman filter paper and vacuum filter, keratin-polysulfone blend as membrane 95:5 v/v	Syntans, fat liquor, and azo dye	Karunanidhi *et al.* (2020)
	Modified zeolite	Total chromium (T Cr) and Bromocresol purple (BCP)	T Cr(97%) and Discoloration (90%)	Bromocresol purple and TCr had a maximum adsorption capacity of 175.5 mg/g and 37 mg/g, respectively, onto the CL-SW, TCr removal: initial concentration (C_o) = 16mg/l , sorbent dosage (m) = 400 mg, temperature (T) = 303 K, time (t) = 55 min, pH 8	Bromocresol purple and chromium	Aljerf (2018)
	Cattle hair waste	Acid Blue 161 and acid black 210	Acid Blue 161 (70%) and acid black 210 (77%)	Acid Black 210: Liu isotherm general order kinetic, maximum sorption capacity (26 mg/g), at 303 K, pH 2, Acid blue 161: maximum sorption capacity (104 mg/g) at 323 K and pH 3	Acid Black 210 and Acid Blue 161	Mella *et al.* (2017)
	Adsorption and Coagulation/ Flocculation	Discoloration	85%	Adsorption: Activated carbon adsorption, pH 2, at temperature 303 K, maximum sorption	Acid Black – 210	Puchana-Rosero *et al.* (2018)

(*Continued.*)

Table 5 | Continued

Wastewater	Treatment techniques	Main parameter(s)	Removal efficiency	Operating conditions	Process/chemical involved	References
				capacity: 974 mg/g, flocculant dosage (0.090 mg/l) of polyelectrolyte FX AS1, coagulant dosage (71 mg/l) of $Al_2(SO_4)_3$ sedimentation time is 60 min at pH 10.		
	Coagulation/ flocculation, Ozonation, and adsorption	Discoloration, TOC, Na^+ and COD	Coagulation/flocculation - adsorption: Discoloration (61%), TOC (50%), Na^+ (17%) and COD (23%), Discoloration (85%),Na^+ (11%), TOC (46%) and COD (56%)	As a low-cost adsorbent, hair shavings were investigated.	Acid Red 357	Mella *et al.* (2018)
Industrial post-tanning wastewater	Coagulation/ flocculation	Discoloration	Discoloration (75%)	NaCl extracted protein coagulant from Moringa oleifera (MO) seeds, 40 ml coagulant dosage, 30 min sedimentation time, pH 8.	Post-tanning	Magesh Kumar & Sakthi Saravanan (2022)
	Oxidation and Coagulation	TOC, Discoloration, COD, and SS	SS (96%), Discoloration (98%), TOC (75%), and COD (77%)	using 1.2 g/l K_2FeO_4, pH 3 within 9 min.	Post-tanning	Kozik *et al.* (2019)
	Electrocoagulation	TOC and COD	TOC (35%) and COD (75%)	Using EC with Fe and Al electrodes, 28 mA/cm^2 of current density during a 60-min electrolysis operation.	Post-tanning	De La Luz-Pedro *et al.* (2019)
	Microalgae	BOD, NH_3-N, TOC, TKN, COD and PO_4-N	(Raw/treated effluent): TOC (59 and 57%), NH_3-N (99 and 89%), TKN (89 and 54%), BOD (32 and 44%), PO_4-N (96 and 99%), and COD (40 and 43%)	The dilution ratio of 1 TWE:1 TTE and 3 TWE:1 TTE with Microalgae *Tetraselmis* sp. Treatment.	Post-tanning	De Cassia Campos Pena *et al.* (2018)
	Microalgae	BOD, P, COD, TOC, TKN, and NH_3-N	BOD (20%), P (97%), COD (56%), TOC (31%), TKN (71%), and $N\text{–}NH_3$ (100%)	Tetraselmis sp.-dominated microalgae consortium with a 24 hrs light period. Combined with 25% secondary effluent and 75% raw wastewater.	Post-tanning and finishing	Pena *et al.* (2020)
	Enzymatic treatment	Sulfide	99%	Using RSM, the factors used to produce Bacillus clausii biomass for the extraction of SQR were optimized. Initial sulfide concentration is 200 mg/l, pH 6.0–8.0, at HRT of 24 h, temperature 40 °C.	PTE after anaerobic treatment	Mannacharaju *et al.* (2019)
	Photocatalytic treatment	Turbidity, TS, BOD, TOC, and COD	Turbidity (99%), TS (99%), BOD (99%), TOC (99%), and COD (97%)	TWE diluted in a 1:200 fraction, A. salina microcrustacean	Retaining and dyeing	Hasegawa *et al.* (2014)

(*Continued.*)

Table 5 | Continued

Wastewater	Treatment techniques	Main parameter(s)	Removal efficiency	Operating conditions	Process/chemical involved	References
				irradiated for 4 hrs at pH 8.0 at 30 °C, containing 1 g L^{-1} of ZnO		
	Electrochemical oxidation	COD	81%	Anode: Ti/Pt, Temperature: 286.18 K, time 2.11hrs, current density: 18.70 mA/cm^2. Specific energy consumption: 3.85 kWh/kg of COD.	Dyeing	Oukili & Loukili (2019)
	AOP with cavitation	TOC	87%	Hydrodynamic cavitation and dosage of 2 ml/l of H_2O_2 at pH 3.	Post-tanning	Korpe *et al.* (2019)
	Fenton oxidation	COD	77%	Hydroxyl radical generation potential of cobalt oxide doped nanoporous activated carbon (λ_{exi} 320 nm; λ_{emi} 450 nm), temperature 25° C, pH 3.5, H_2O_2 10 mM and Co-NPAC 1.0% (w/w).	Dyeing	Karthikeyan *et al.* (2015)
	UF	Discoloration and COD	Discoloration (95%) and COD (91%),	Permeate flux: 41.9 L/m^2h, pre-treatment: sieve cloth filtration, membrane material: polysulfone, Transmembrane pressure: 0.09 MPa, Temperature 25 °C	Dyeing and fat liquoring	Wang *et al.* (2014)
	NF followed by RO	Conductivity, Discoloration, BOD, TDS, COD, Cl^-, TS, and Cr(III)	Conductivity (95%), Discoloration (100%), %), COD (99%), TDS (95%), Cl^- (96%), Cr(III) (100%)	no pre-treatment provided; transmembrane pressure: 1,518 kPa. polyamide skin over polysulfone support used as NF membrane material	Industrial post-tanning wastewater	Das *et al.* (2010)
	Commercial powdered activated carbon	Discoloration	90%	1.5 g/50ml of 150 mg/l dye was the optimal amount of adsorbent, pH 4.5 at 35 °C	Post-tanning	Carpenter *et al.* (2013)
	Fenton and biological treatment	Discoloration and COD	Discoloration (89%) and COD (93%)	Using Fenton H_2O_2 and Fe^{2+} to pretreat dye effluent before treating it with a bacterial consortium.	Post-tanning (Acid blue 113 dye)	Shanmugam *et al.* (2019)

performance, which leads to increased treatment costs (Deghles & Kurt 2016; Mella *et al.* 2017; Klein *et al.* 2022). The main drawbacks of using coagulation/flocculation for wastewater treatment include the formation of large quantities of sludge and the inability to handle high-volume treatment, which results in ineffective pollutant elimination and increased energy costs (Ayoub *et al.* 2011; Tolkou & Zouboulis 2014). The treatment sludge is often characterized by high concentrations and toxicity, which may pollute the nearby environment if not disposed of scientifically. In addition to sludge production, the energy required for mixing and settling the flocs can be substantial, especially for large-scale treatment systems. Also, the effectiveness of the process is highly dependent on the properties of the wastewater, and it may not be effective for some types of pollutants, such as dissolved pollutants or heavy metals.

3.2. Advanced oxidation process

AOPs, or advanced oxidation processes, utilize in situ generated hydroxyl (OH) radicals as the primary oxidant, as shown in Figure 3. This approach is environmentally benign and has demonstrated remarkable flexibility in the disintegration of bio-refractory contaminants. AOPs have been commonly employed as a last stage of treatment in conjunction with membrane filtration, particularly for treating concentrate channels before their release into the environment (Ganiyu *et al.* 2015; Korpe & Rao 2021; Bravo-Yumi *et al.* 2022). Several AOP techniques have been shown to have the highest removal efficiency for COD, including zinc oxide-assisted photocatalysis, photo-assisted electrochemical oxidation, and electrochemical oxidation processes. Zinc oxide-assisted photocatalysis, photo-assisted electrochemical oxidation and electrochemical oxidation processes have all shown high COD removal rates (Hasegawa *et al.* 2014; Naumczyk & Kucharska 2017; Korpe *et al.* 2019; Selvaraj *et al.* 2020).

Photo-assisted AOPs, such as heterogeneous TiO_2/UV system and photochemical (Photo-Fenton (H_2O_2/Fe^{2+}/UV system) are the most effective methods for discoloring or degrading organic matter. The Photo-Electro-Fenton process is known for producing homogeneous OH radicals that efficiently accelerate the breakdown of organic materials. This process produces a heterogeneous OH radical through a TiO_2-based photo electrocatalytic process, which depends on the applied current density. Compared to electro-oxidation, the photo-assisted electrochemical oxidation procedure is more effective in producing results with higher efficiency (Selvaraj *et al.* 2020).

The oxidation of substances such as Cr(III) is crucial in establishing effective effluent treatment after tanning using AOPs (Lofrano *et al.* 2013). To reduce the toxicity of wastewater, it is recommended to use electro-oxidation, photocatalytic, and photo electrocatalytic treatments instead of other AOPs, as they can be used to simultaneously reduce Cr and oxidation of

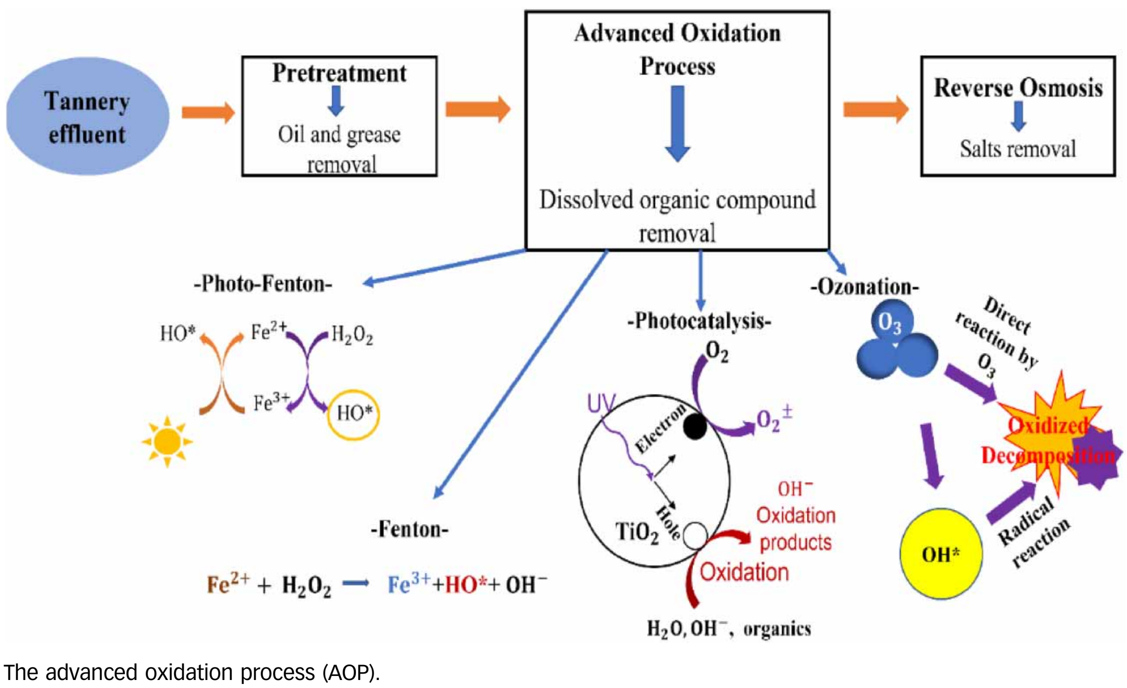


Figure 3 | The advanced oxidation process (AOP).

organic species (Ritterbusch *et al.* 2019). These methods have shown promising results in remediating PTEs due to their strong capacity to break down bio-refractory chemicals without producing sludge, except for Fenton-based procedures. Fenton processes can produce a significant amount of sludge due to the precipitation of metal hydroxides generated during the reaction. In the case of modified Fenton processes and heterogeneous Fenton catalysts, the amount of sludge production is reduced. The intermediates produced during the process may escape into the environment and become more hazardous than the original substances. Some common intermediates for photolysis, UV, and sonolysis are methoxytrinitrophenols, 2,4,6-trinitrophenol, and 4-amino-3-nitrobenzoic acid, respectively (Halasz *et al.* 2018; Rayaroth *et al.* 2018; Yang *et al.* 2018). Therefore, further research is necessary to advance scientific understanding, including cost and by-product toxicity studies. Generally, AOPs represent a promising approach for the environmentally friendly removal of bio-refractory contaminants in wastewater treatment (Caliari *et al.* 2022; Doumbi *et al.* 2022).

AOPs are effective in treating tannery wastewater, but several drawbacks are associated with their use. One of the primary concerns is the high operating cost associated with using AOPs, which are often more expensive than traditional treatment methods such as coagulation/flocculation or biological treatment. Operating AOPs requires significant energy, which may not be feasible for smaller or rural tanneries. Another issue with AOPs is that the process can be time-consuming, and the required treatment time may not be practical for some industrial operations. Also, the effectiveness of AOPs may be limited by certain organic and inorganic pollutants in tannery wastewater. The AOPs can produce harmful byproducts such as formaldehyde, which must be removed before the treated water can be discharged into the environment. Finally, AOPs require careful monitoring and control to prevent excessive treatment, which can lead to over-oxidation and the formation of harmful byproducts.

3.3. Biological treatment

Biological wastewater treatment procedures are vulnerable to toxic substances in the wastewater being treated due to the reliance on living organisms for the treatment process (Silambarasan *et al.* 2022). Before biological treatment, it is necessary to undertake the primary treatment procedure through the physico-chemical process (screening, equalization, pH adjustment, and chemical treatment). Biological treatment methods, especially activated sludge, play a critical role in environmental protection by removing pollutants from wastewater (Xiao *et al.* 2015). Recently, some methods have been used to remediate wastewater that contains colors or heavy metals (Huang *et al.* 2015). Biological procedures using microalgae, fungal, activated sludge, bacterium strains, and enzymes are a few of them, as shown in Figure 4. It can be shown from the outcomes gathered in Table 5 that fungus treatment at 100 mg/l, pH 5.5, 150 rpm, 30 °C within 168 h of treatment (Ortiz-Monsalve *et al.* 2017, 2019) and aerobic decomposition (Kalyanaraman *et al.* 2013; Senthilvelan *et al.* 2014; Huang *et al.* 2015) indicated that the PTEs had significant removal of COD (above 80%) and color (above 90%) at the effective pH range of 5–7, the temperature range of 25–35 °C, and the NaCl content range of 0–6% were examined. Because of the complicated aromatic structure of azo dyes and byproducts of azo dyes, traditional biological treatment approaches are frequently inadequate for degradation (Kertèsz *et al.* 2014). The azo linkage in the dye molecule might be degraded by the biological treatment

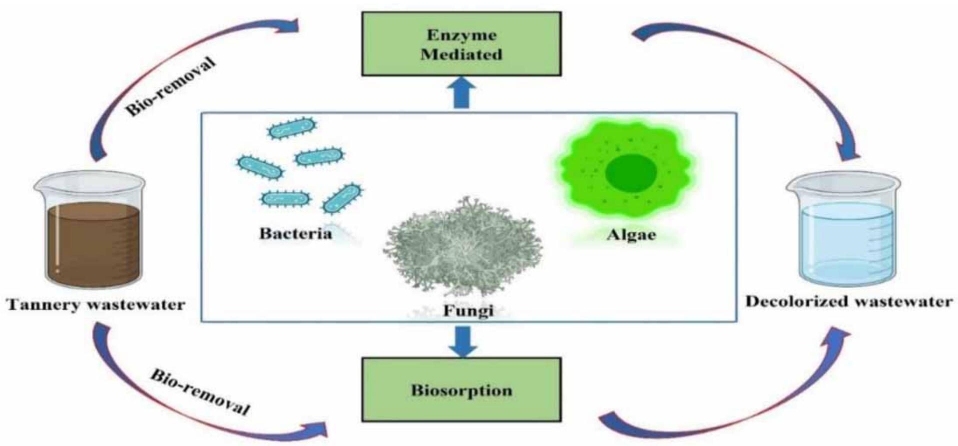


Figure 4 | Biological treatment methods.

processes investigated utilizing the aerobic decomposition or fungi treatment, turning them into dinitrogen (N_2) or ammonia (NH_3) or being integrated into biomass (Senthilvelan *et al.* 2014). Chromium (VI) reduction and azo dye removal were accomplished by *Lactobacillus paracase*, an isolate from deep-sea sediment (Huang *et al.* 2015). Additionally, *Pseudomonas putida* strain KI showed proficiency in removing Cr(VI) and decolorizing azo dyes in packed bed bioreactors (Mahmood *et al.* 2013). The fungal treatment also demonstrated high TOC removal (over 80%), while aerobic decomposition demonstrated BOD removal efficiency above 95%. When set side by side with an alternative biological method, using a microalgae consortium containing mainly *Tetraselmis sp.* revealed removals for COD, TOC, and BOD that were consistently below 60%, respectively evaluation and comparison of cultivations under various light conditions (0-light, 12-light, and 24-light). The 24-light wastewater in the mixture produced the most growth (De Cassia Campos Pena *et al.* 2018; Pena *et al.* 2020). Effluent can be a source of organic or inorganic nutrients, such as phosphates and ammoniacal nitrogen, that can be assimilated by various algae species, including *Chlorella, Scenedesmus, Chlamydomonas, and Nanochloropsis* (Saranya & Shanthakumar 2020). The 24-light culture showed the highest biomass concentrations in the wastewater, the specimen having a concentration of 1.04 and with 1.40 g/l were the highest removals of ammonium (100%), BOD (20%), COD (56%), TOC (31%), total nitrogen (71%), and total phosphorus (97%) as well. As a result, growing microalgae in wastewater has proven to be a viable method for removing nutrients and producing biomass that may be used for various purposes, including biofuels (Pena *et al.* 2020).

High conductivity and salt content, particularly sulfates and chlorides, are characteristics of PTEs (Hansen *et al.* 2021c; Kumar *et al.* 2022; Saran *et al.* 2023). When tannery wastewater is treated aerobically with a modest salt content, the findings with a salt-tolerant bacteria (*L. paracase*) may thus be beneficial (Huang *et al.* 2015). PTEs may benefit from employing salt-permissive halophytic algae, which have also been studied for remediating salty wastewater (Saranya & Shanthakumar 2020). For the biological treatment of TWE, the moving-bed biofilm reactor (MBBR) has been researched as a novel method. A free-moving carrier system, MBBR, uses mostly plastics to immobilize cells and promote microbial growth (Swain *et al.* 2020). Compared to most traditional activated sludge treatments, a comprehensive assessment of MBBR is used for treating TWE, indicating that consistent development of the attached biomass in MBBR yields a better biological load and sludge diminution (Rech *et al.* 2020). The main drawbacks of biological treatment methods are time-consuming, unstable effluent quality, excessive salinity inhibition, and large-scale sludge formation.

Treatment wetlands can effectively treat tannery effluent in underdeveloped countries by using natural processes to remove pollutants from water. These wetlands are designed as shallow basins or channels filled with wetland plants, gravel, or sand (Shahid *et al.* 2019; Zhao *et al.* 2022). Three primary types of treatment wetlands used for TWT: surface flow, horizontal subsurface flow wetlands, and vertical flow wetlands (Vymazal 2014; Sultana *et al.* 2015). While treatment wetlands can be effective, their design and operation depend on the characteristics of the wastewater and the treatment goals. Hydraulic retention time, substrate type, plant species, and other factors can impact their performance.

A pilot-scale wetland in Venezuela planted with phragmites showed high removal rates of COD and NH^{4+}-N, as well as almost complete removal of Cr in the outflow (Ramírez *et al.* 2019). Hybrid-constructed wetlands, which combine different types of flow, have also been studied and shown to exhibit excellent properties for denitrification, dephosphorization, and detoxification. In addition to conventional wetlands with plants growing on gravel, sand, and porous soil, a novel floating treatment wetland inoculated with selected bacteria has been designed and tested for treating tannery effluent (Shahid *et al.* 2019). Several studies have demonstrated the promising potential of constructed wetlands for multiple target contaminants removal (Alemu *et al.* 2019b; Younas *et al.* 2022). Practical experiences, selecting plants, substrate, and operation load have been summarized in a substantial work (Dotro *et al.* 2011; Ashraf *et al.* 2018). Treatment wetlands may be unable to remove all pollutants completely and may need to be combined with other treatment methods. Biological treatments face challenges such as difficulty isolating tolerant species and non-biodegradable pollutants (Calheiros *et al.* 2012; Saeed *et al.* 2012; Zapana *et al.* 2020).

Biological treatment options are generally considered more sustainable, cost-effective, and environmentally friendly, as they rely on microorganisms to break down pollutants. Additionally, they can treat a wide range of pollutants and effectively reduce the wastewater's toxicity. But there are also some drawbacks to biological treatment. One significant disadvantage is the need for a large amount of land, as constructed wetlands require significant space. In addition, these processes can be sensitive to fluctuations in environmental conditions and require strict control to ensure optimal performance.

Furthermore, the efficiency of biological treatment processes can be affected by toxic substances or high levels of organic matter, leading to decreased treatment efficiency and sludge accumulation. At the same time, biological treatment processes have several advantages but require careful management and monitoring to ensure optimal performance. Continued research and development may help to address these challenges and improve the effectiveness of biological treatments.

3.4. Membrane separation process

MSPs may remove dissolved compounds from tannery wastewater. These methods can be characterized by the pressure difference (reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), microfiltration (MF)), potential difference, and osmosis pressure (forward osmosis) (Venzke *et al.* 2018; Li *et al.* 2021). Based on scientific studies (Das *et al.* 2010; Galiana-Aleixandre *et al.* 2013; Nicolini *et al.* 2016; Licona *et al.* 2018), it has been observed that the maximum level of pollution can be effectively reduced through the use of NF membranes, followed by RO membranes. NF membranes can separate multivalent ions, while RO membranes can lead to the accumulation of discrete monovalent ions. UF membranes can eliminate solutes with a molecular weight greater than 1,000 Da. Pollutant elimination is not solely determined by pore size; other factors, such as membrane surface charge, can also play a crucial role. The surface charge of a membrane can be influenced by the pH of the environment, where a negative zeta potential is observed when the pH exceeds the isoelectric point of the membrane, leading to the deprotonation of functional groups. Conversely, a positive zeta potential is observed when the pH is below the membrane isoelectric point, causing a positive surface charge due to the protonation of functional groups. In a reported study, the values for COD (2,850–10,000 mg/l), TDS (5,100–14,011 mg/l), and conductivity (12,290–19,400 μS/cm) are all high in PTEs (Hansen *et al.* 2021b). Some of these difficulties have also been noticed when dealing with the waste products of other leather production steps, such as dehairing (Galiana-Aleixandre *et al.* 2013; Tamersit *et al.* 2018), tanning as well as total tannery effluent, which needs further research on these adverse effects for the handling of post-tanning wastewaters.

Membrane separation processes have gained popularity due to their ability to produce high-quality treated water, but they also have some drawbacks. One of the major disadvantages of membrane separation processes is their high energy consumption, which can lead to high operational costs. Fouling of the membrane is another common issue, resulting in decreased efficiency and increased costs associated with cleaning and replacing the membrane. Additionally, using chemical cleaning agents to remove fouling can lead to the formation of hazardous waste, which requires careful handling and disposal. The membrane separation process is also sensitive to variations in influent wastewater quality, and pre-treatment may be necessary to avoid fouling and ensure optimal performance. Finally, the process may not be suitable for treating wastewater with high salinity, as salt deposits can damage the membranes and require frequent replacement.

3.5. Adsorption

Tannery effluent is challenging to treat due to the presence of phenols in tanning amalgamation, which forms polyphenolic structures that make the effluent refractory (Benvenuti *et al.* 2017). Adsorption effectively treats wastewater contaminated with heavy metals, aromatic chemicals, and dye by reducing their concentration (Gomes *et al.* 2016; Payel *et al.* 2021; Hashem *et al.* 2022; Shaibur 2023). Compared to conventional methods, adsorption is cost-effective, easy to use, and has a high removal efficiency, making it a popular choice for wastewater treatment (Piccin *et al.* 2012; Rigueto *et al.* 2020; Xiong *et al.* 2023). Typically, cattle hair and shavings from chrome-tanned leather are the most common adsorbents used in post-tanning wastewater treatment. However, various other adsorbent materials such as zeolite, green macro-algae, modified kaolin, and commercial activated carbon have also been employed. Results from previous studies indicate that acid dyes (anionic) were successfully removed from chrome-tanned leather shavings by 58–87% using adsorption (Gomes *et al.* 2016; Piccin *et al.* 2016).

Activated carbon from bovine hair and cattle hair waste indicated a 71–77% color removal rate (Mella *et al.* 2017, 2018, 2019). Commercial activated carbon (Carpenter *et al.* 2013) in powder form produced the highest levels of pollution removal, followed by modified zeolite (Aljerf 2018) and kaolin (Zen & El Berrichi 2014) with discoloration greater than 90%. Several factors affect adsorption efficiencies, such as pH, dye concentration, temperature, and adsorbent material (Gomes *et al.* 2016). Most studies have acidic pH ranges for their ideal pH values, favoring applicability in post-tanning wastewater, which likewise has a lower pH (Hansen *et al.* 2020). These studies revealed temperatures below 50 °C as the ideal range, with most studies showing temperatures below 35 °C. Increased energy consumption and process costs are inferred from an increase in operational temperature.

Adsorption processes have shown great potential for treating tannery wastewater due to their ability to remove organic and inorganic pollutants with few limitations. One major drawback is the high cost of using adsorbents, especially for large-scale operations. Additionally, the adsorption capacity of the adsorbents is influenced by several factors which may require optimization to achieve an effective removal of pollutants. Likewise, the spent adsorbents, after usage, may become hazardous waste and require proper disposal. Another disadvantage of adsorption processes is the need for frequent replacement of adsorbents, leading to the generation of waste materials, which may cause environmental pollution if not properly disposed of (Elkarrach *et al.* 2023). Finally, adsorption processes may not be effective for removing some pollutants, especially those with low molecular weights or those highly soluble in water.

3.6. Integrated technologies

Treating tannery wastewater effluent is a complex task that requires careful consideration of various treatment methods. In previous sections, several methods were discussed, each with advantages and disadvantages. Despite ongoing efforts to improve these methods, complete detoxification of recalcitrant organic and inorganic pollutants in TWE using a single method remains challenging and costly (Shahbazi & Pedram 2021; Jallouli *et al.* 2022). Studies suggest that combining different treatment methods can achieve a more effective and cost-efficient approach. By carefully considering the pros and cons of each method, a suitable combination of techniques can be chosen that yields multi-effective performance and reduces costs. This is an increasingly popular trend among researchers working on tannery effluent treatment, who have been experimenting with diverse techniques to achieve better results (Grandclément *et al.* 2017). Combining RO, NF, gravity settling, and coagulation/flocculation among hybrid treatments produced the maximum COD removal. Coagulation and flocculation removed COD of 64%, followed by the consecutive use of NF, which removed 91% of COD, and RO, which removed 99% of COD. Adsorption was employed after coagulation or flocculation as a pre-treatment in other hybrid procedures (Mella *et al.* 2018; Puchana-Rosero *et al.* 2018; Mella *et al.* 2019).

The biodegradability of wastewater for biological treatment was also increased using the Fenton technique. High COD (93%) and color (89%) elimination were obtained when these approaches were combined (Shanmugam *et al.* 2019). Some AOPs can be used during biological treatment to improve the TWE biodegradability or as an end treatment to eliminate residual refractory contaminants following biological methods (Caliari *et al.* 2022). In some cases, integrating AOPs with biological treatment can improve their economic viability, as higher oxidant dosages are typically required when used as a standalone final treatment (Ganiyu *et al.* 2015; Saranya & Shanthakumar 2020).

Integrated technologies or combined techniques for TWT have several advantages, such as high pollutant removal efficiency, cost-effectiveness, and the ability to treat a wide range of pollutants. There are also some disadvantages to these methods. For example, the complexity of the treatment process may lead to operational difficulties and maintenance issues. Furthermore, the initial investment cost can be high, which may not be feasible for small-scale industries. Additionally, the efficiency of these methods can be affected by various factors, such as pH, temperature, and the presence of other contaminants, which require careful monitoring and adjustment. Finally, selecting the appropriate combination of techniques and optimizing the treatment parameters can be challenging and require high expertise. Although integrated technologies have many benefits, their implementation and operation require careful consideration of these potential drawbacks.

4. TREATED EFFLUENT REUSE OPTIONS

The reuse of treated wastewater, or effluent, can play a significant role in improving the overall quality and quantity of the world's water supply. While effluent reuse may not be the sole solution to address water scarcity, it can be a viable approach to recovering and repurposing water. Treated tannery wastewater use standards vary from country to country, but generally, limits are set on the amount of pollutants that can be discharged into the environment and specify the quality of treated wastewater that can be reused for non-potable purposes such as irrigation, industrial processes, and cooling. The Environmental Protection Agency (EPA) controls the effluent limitations for the tannery in the United States. The EPA's guidelines for wastewater reuse recommend that treated wastewater used for irrigation should contain less than 2 mg/l of total suspended solids (TSS) and less than 10 mg/l of BOD.

Similarly, in the European Union, the Urban Wastewater Treatment Directive requires tannery facilities to meet specific discharge standards for pollutants such as TSS, BOD, and COD. The EU guidelines for reusing treated wastewater in agriculture recommend that the wastewater contain less than 10 mg/l of BOD and less than 2 mg/l of TSS. In India, the Central Pollution Control Board (CPCB) has established guidelines that specify the quality of treated wastewater that can be reused for different purposes. The treated wastewater can be used for irrigation if it contains less than 30 mg/l of BOD and less than 50 mg/l of TSS. In China, the Ministry of Environmental Protection (MEP) has issued standards that limit the concentrations of pollutants such as TSS, BOD, and COD in tannery wastewater discharge. The MEP's guidelines for reusing treated wastewater in agriculture recommend that the wastewater contain less than 30 mg/l of BOD and less than 10 mg/l of TSS. Australia's National Water Quality Management Strategy provides guidelines for reusing treated wastewater in agriculture and industrial processes. The guidelines recommend that the wastewater contain less than 10 mg/l of BOD, less than 5 mg/l of TSS for irrigation purposes, and less than 30 mg/l of BOD and less than 10 mg/l of TSS for industrial processes. By implementing ecologically sound treatments in wastewater, it can be safely reused for various purposes, as illustrated in Table 6 for different countries. Reusing treated effluent can also drive the development of new and improved

Table 6 | Reuse of treated tannery wastewater in various nations

Country	Effluent	Treatment	Reuse	Results	References
India	1 TTE:3 DDW	Common effluent treatment (secondary treatment)	Irrigation purpose for Aztec marigold	Root length 12 cm, vigor index 1,872. Compared to other mixing ratios of TTE and DWW, the 1:3 ratio had performed better and was utilized for producing non-food crops.	Balasubramanian & Dhevagi (2016)
Brazil	TTE	Primary and secondary treatment	Leather industry for post-tanning process	The leather made with primary effluent as reuse water performed the best in organoleptic qualities. The post-tanning operations that used primary and secondary effluent as the reuse water produced residual baths that had greater conductivities than the groundwater techniques, which supports the salt build-up in the effluents after their reuse.	Klein *et al.* (2022)
Bangladesh	TTE	Secondary and tertiary treatment	Concrete	Concrete compressive strength up to a 6-month age limit was reduced by 9–18% when treated with secondary treated wastewater and up to 7% when treated with tertiary treated wastewater. When applied at a proportion of 25–100%, the use of recovered wastewater exhibited an improvement in strength of 8–17%.	Varshney *et al.* (2021)
Ethiopia	TTE	Pilot integrated treatment	Irrigation purpose for vegetable growth (onion, Swiss chard, tomato, cabbage, beetroot, and carrot)	There is a possibility of reusing the TTE for irrigation. There was no statistically significant change in shoot length between the control and treatments, except for the onion (at $p < 0.05$).	Alemu *et al.* (2019b)
Pakistan	TWE	No treatment involved	Irrigation purpose	The plant height and dry weight increased by 50:50 tap and wastewater irrigation compared to simply tap water or wastewater irrigation. Major findings include–TCr: 6.67 mg/l, Pb: 1.34 mg/l, Ni: 0.12 mg/l, and Cd: 0.02 mg/l	Maqbool *et al.* (2018)
Italy	TWE	No treatment involved	Building material: geopolymerization	The metakaolin was combined with 10% wastewater and sodium hydroxide and sodium silicate as activators to create a geopolymer. The average compressive strength was between 14 and 43 MPa.	Boldrini *et al.* (2021)

techniques for treating wastewater. Research into applying AOPs for bacterial inactivation and removing pollutants of urgent concern in effluent reuse can further strengthen wastewater treatment practices (Garrido-Cardenas *et al.* 2020).

5. CONCLUSION

After an extensive review of the literature, it is evident that the effluent from the leather industry contains a high concentration of various pollutants that exceed the established regulatory limits. This makes discharging untreated effluent into surface water a significant threat to the environment and human health. Also, it is reassuring to note that various treatment methods, such as coagulation/flocculation, membrane separation processes, AOPs, adsorption, biological treatment, and hybrid treatment technologies, have been studied and found to be effective in treating tannery wastewater.

It is worth mentioning that although these treatment methods have been proven effective, they require further development and improvement to meet more stringent regulatory standards. The use of additional techniques such as enzymatic treatment, fungal processes, isolated bacteria, conventional biological processes, and microalgae can be explored to enhance the quality of the effluent further. The application of the membrane separation process has been identified as an appropriate technique for reusing treated wastewater, making it a viable option for sustainable tanning processes. Some tanneries have implemented closed-loop systems that minimize water usage and treat wastewater onsite for reuse in the tanning process. Although using treated leather tanning effluent as a raw material is not yet a common practice, there are opportunities for innovation and advanced solutions in the leather industry to reduce waste and promote sustainability.

In conclusion, it is recommended that a combination of various treatment technologies should be employed to effectively treat tannery wastewater and meet the regulatory requirements for disposal and reuse. Further research and development in TWT and sustainability can result in more advanced and sustainable solutions for the leather industry.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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