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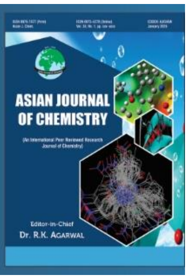

REVIEW

Physico-Chemical Assessment of Tannery Effluents: Heavy Metal Toxicity, Health Implications and its Remediation Strategies

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Environmental sustainability has developed a major world-wide apprehension due to the continuous announcement of industrial contaminants into the ecosystem. Tannery effluents are recognised as some of the most hazardous industrial wastewaters due to their complex composition and high pollutant load. These effluents contain substantial concentrations of heavy metals, particularly chromium, along with elevated levels of dissolved solids, chlorides, sulphides and various organic contaminants. Chromium concentrations in untreated tannery wastewater have been reported in the range of 150-3000 mg/L. Furthermore, the wastewater exhibits an exceptionally high organic burden, with biochemical oxygen demand (BOD) values of 2500-8000 mg/L and chemical oxygen demand (COD) levels of 5500-15000 mg/L. The combined presence of toxic metals and recalcitrant organic pollutants significantly exceeds permissible discharge limits, posing serious environmental and public health concerns if released without adequate treatment. Such concentrations greatly exceed the acceptable discharge standards and pose serious risks to aquatic ecosystems and human health. These pollutants suggestively affect aquatic ecosystems, soil productiveness, seed germination and crop efficiency. Heavy metals such as chromium (Cr), lead (Pb), cadmium (Cd) and nickel (Ni) undertake bioaccumulation and biomagnification, foremost to unembellished human health risks together with kidney dysfunction, liver toxicity, respiratory disorders and carcinogenic belongings. This review appraises the physico-chemical characteristics of tannery sewages, their ecological and toxicological influences and presently accessible remediation strategies. Conventional treatment procedures such as coagulation, chemical precipitation, adsorption and membrane filtration have revealed elimination effectiveness of 60-95%, but boundaries together with higher operational cost and sludge cohort restrict their large-scale application. Developing technologies together with bioremediation, phytoremediation, nanotechnology-based adsorbents and hybrid treatment arrangements demonstrate better-quality heavy metal elimination efficiency exceeding 90% under optimised conditions. The study additional classifies major research gaps associated with long-term field-scale authentication, sludge management and maintainable resource recovery. Future investigations should focus on emerging cost-effective, eco-friendly and energy-efficient remediation knowledges for effective tannery wastewater treatment and environmental protection.

Keywords: Heavy metal, Toxicity, Tannery wastewater, Human health, Bioremediation.

INTRODUCTION

Nowadays, several industrial processes are responsible for the degradation of water quality; most of these activities involve the use of compounds that are extremely harmful to both terrestrial and aquatic ecosystems. As a result, it is essential to treat water before releasing it into various bodies of water. By removing contaminants and superfluous ingredients, the tanning industry makes it possible to convert biodegradable animal leather into non-biodegradable leather [1]. In addition to heavy metals and inorganic contaminants, the tanning process produces highly concentrated wastewater rich in organic residues derived from animal hides and skins. These organic constituents significantly increase total organic carbon (TOC) and biochemical oxygen demand (BOD), contributing to severe environmental pollution and oxygen depletion in aquatic environments. In addition to surfactants, organic dyes and chromium, tanning effluents frequently contain nitrate (NO_3^-), sulphate

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(SO_4^{2-}), chlorides (Cl^-), ammoniacal nitrogen (NH_4^+N) and microorganisms such as *Fusarium chlamydosporium* and *Bacillus subtilis* and [2]. With its well-known environmental impact, the tannery sector contributes significantly to the economies of developing nations by producing a wide range of leather goods, including garments, purses and shoes. Asia, Latin America, and Europe are the major leather-producing regions, while Africa and Latin America exhibit the highest annual growth rates in leather production [3].

Tannery wastewater contains a complex mixture of pollutants that can adversely affect both environmental quality and human health. Consequently, the implementation of effective treatment technologies including chemical precipitation, biological treatment and advanced oxidation processes, is essential for reducing the environmental burden associated with tannery effluents. In addition, stringent regulatory control and continuous monitoring are necessary to ensure safe effluent discharge and environmental protection [4]. Among the various contaminants present, heavy metals are of particular concern due to their toxicity, persistence and bioaccumulative nature. Although heavy metals are widely utilised in many industrial applications, their continuous release through natural and anthropogenic activities has resulted in widespread environmental contamination. In leather industry, heavy metals, especially chromium salts, are extensively employed during the tanning process, leading to significant metal accumulation in the wastewater streams [5,6]. Owing to the intensive use of chemical agents required for converting animal hides into leather, the tanning industry is recognised as one of the major sources of industrial pollution. Therefore, the development of innovative, sustainable and efficient remediation strategies for the removal of toxic metals from tannery effluents is crucial for preserving ecosystem integrity and protecting public health [6].

Heavy metal contamination in ecosystems: The anthropogenic activities represent the primary source of heavy metal contamination in the environment. Major contributors include mining, smelting, foundries and other metal-processing industries, as well as the leaching of metals from landfills, waste disposal sites, livestock and poultry manure, urban runoff, vehicular emissions and road maintenance activities [7]. In the agricultural sector, the extensive use of fertilisers, pesticides and insecticides further contributes to heavy metal accumulation in soil and water systems. In addition, several industrial processes, including leather tanning, electroplating, battery production, glass manufacturing, pharmaceutical production and domestic waste disposal, are recognised as significant sources of hazardous metal ions released into the environment [8,9]. These developmental and industrial activities facilitate the transport and redistribution of heavy metals across environmental compartments, thereby disrupting natural biogeochemical cycles. The accumulation of heavy metals in aquatic ecosystems is of particular concern, as it can degrade water quality, threaten ecological balance and pose serious risks to human health through bioaccumulation and biomagnification processes [10].

Heavy metal accumulation in aquatic and terrestrial ecosystems: Considerable efforts have focused on developing mitigation strategies to limit the release and accumulation of heavy metals in aquatic environments. Assessing heavy metal concentrations in aquatic plants and food crops, particularly rice cultivated in contaminated areas, is essential for evaluating ecological and human health risks, while the adoption of sustainable management practices remains crucial for long-term environmental protection [11]. Heavy metals are regarded as some of the most hazardous aquatic pollutants due of their toxicity, persistence and ability to enter and magnify through food chains. Furthermore, many aquatic plants possess a remarkable capacity to survive under adverse conditions and accumulate nutrients and contaminants within their tissues, making them important indicators of environmental contamination [12]. Agricultural activities also contribute significantly to heavy metal pollution. The extensive application of fertilisers to enhance crop productivity often increases the accumulation of metals such as Cd, Pb, Fe and Hg in agricultural soils and surrounding waterbodies, raising concerns regarding their long-term environmental impacts [13]. In addition, the excessive use of agrochemicals, contaminated irrigation water, animal feed additives and veterinary pharmaceuticals has intensified pollution loads in rivers, lakes, aquifers and coastal ecosystems. Such inputs frequently promote eutrophication, adversely affecting fisheries, aquatic biodiversity and overall ecosystem stability [14].

Improper treatment and disposal of industrial and pharmaceutical effluents further exacerbate environmental contamination and pose serious risks to public health. In this context, bioremediation has emerged as a promising and sustainable approach for the removal of heavy metals and other contaminants from polluted environments. Owing to its cost-effectiveness and eco-friendly nature, microorganism-assisted bioremediation has attracted considerable attention for future environmental management applications [15]. Since conventional physico-chemical methods often show limited effectiveness against persistent xenobiotic pollutants, various bioremediation strategies have been explored for the treatment of pharmaceutical wastewater. Numerous plants, bacterial, fungal and algal species have demonstrated significant potential for the removal and detoxification of pharmaceutical residues and heavy metals from contaminated environments [16].

Fig. 1 illustrates the pathways of heavy metal contamination originating from industrial effluents and their subsequent transfer through aquatic ecosystems, ultimately affecting human health through bioaccumulation and biomagnification. Heavy metals, including Cr (150-3000 mg/L), Pb (0.5-60 mg/L), Cd (0.1-15 mg/L), Hg (0.01-1 mg/L), as well as Ni, As, Co and Cu, can accumulate in aquatic organisms such as fish and shellfish. Their concentrations may increase by 15-100 folds at higher trophic levels, thereby elevating the risk of human exposure through the consumption of contaminated aquatic food products. Chronic exposure to these metals has been associated with cardiovascular disorders, neurotoxicity, pulmonary dysfunction, hematological abnormalities, reproductive impairment and developmental defects [17]. In particular, chromium concentrations exceeding the WHO permissible limit of 0.05 mg/L in drinking water represent a significant threat to both ecological integrity and public health [18].

In this present study, the novelty lies in the wide-ranging evaluation of tannery effluents concluded combined physico-

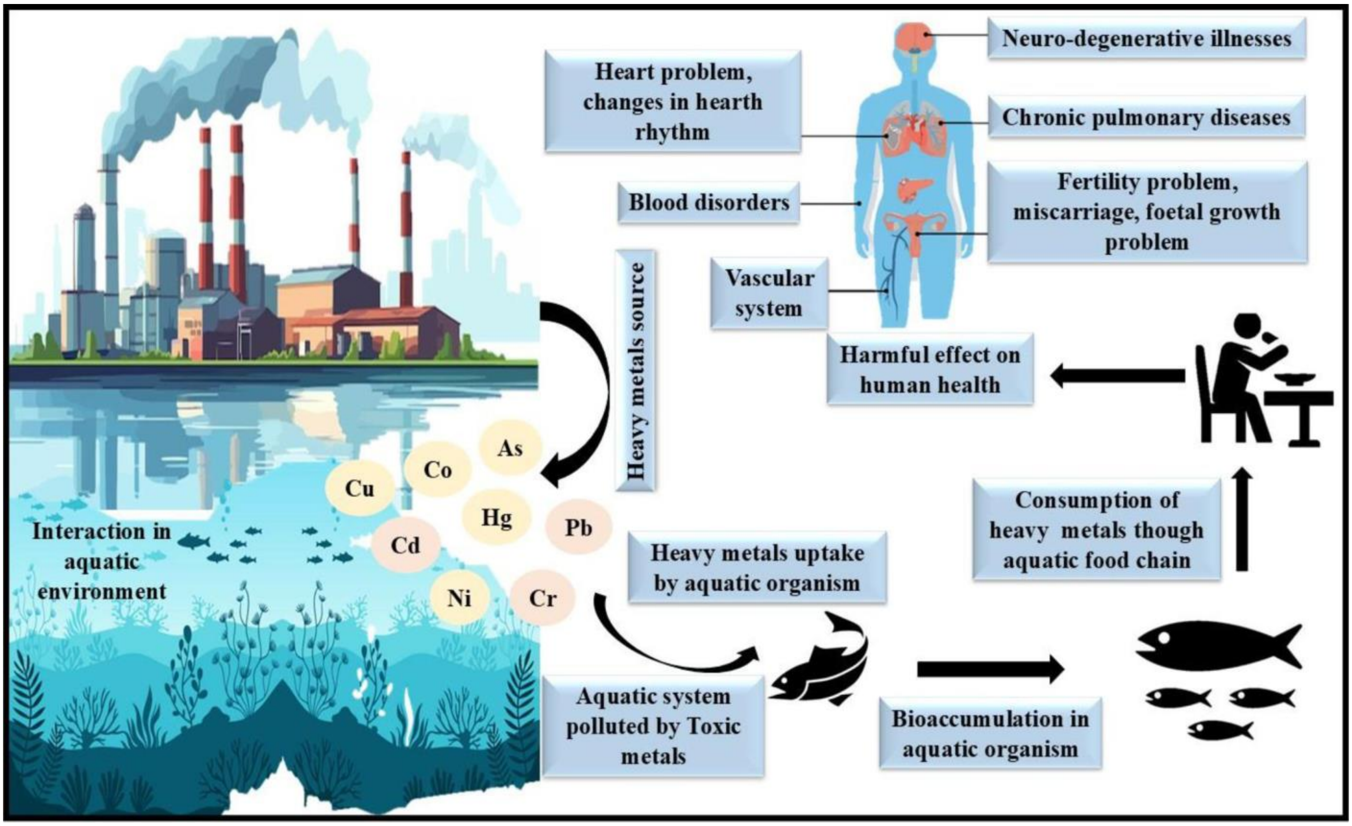

Fig. 1. Schematic representation of tannery effluent interaction in aquatic and terrestrial ecosystems

chemical examination, heavy metal toxicity valuation, health risk consequences and remediation strategies. The study analytically associates the pollution profile of tannery effluent with its probable conservational and human health hazards. In accumulation, it disapprovingly summarises predictable and advanced remediation approaches for effective treatment and sustainable management of tannery effluents. The inclusion of current findings on heavy metal toxicity and developing eco-friendly behaviour technologies improves the scientific consequence of the work. This combined method makes available valuable understanding for pollution monitoring, risk assessment and wastewater remediation in tannery industries.

Composition of tannery wastewater: To better understand the environmental challenges associated with the leather industry, it is important to examine the composition of tannery wastewater and its sources. During beamhouse operations, including soaking, liming and deliming, substantial quantities of sulphides, lime, ammonium salts, chlorides, sulphates and proteinaceous materials are released into the effluent. As a result, tannery wastewater is characterised by elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels. Soaking liquors typically contain dirt, fecal matter, blood residues, suspended solids and high concentrations of chlorides, while liming liquors are highly alkaline in nature [19]. In addition, tannery effluents contain considerable amounts of both organic and inorganic pollutants, including dissolved and suspended solids, chromium compounds and sulphides, making them among the most contaminated industrial waste streams. A significant proportion of the chemicals employed during leather processing is discharged into wastewater rather than being retained within the finished leather product, thereby contributing to severe environmental pollution if not adequately treated before disposal [20].

Heavy metals in tannery wastewater: Heavy metal contamination is one of the most serious environmental concerns associated with the leather tanning industry, primarily due to the extensive use of metal-based chemicals during tanning, dyeing and finishing operations. Among the various contaminants, chromium (Cr), cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), iron (Fe) and nickel (Ni) are the most frequently detected heavy metals in the tannery effluents [6,21]. Chromium is of particular concern due to its widespread use in leather processing and its persistence in the environment. The occupational exposure studies have demonstrated the adverse health effects associated with prolonged contact with tannery pollutants. For example, a study involving tannery workers in Bangladesh reported chromium accumulation levels in hair and toenail samples that were approximately 20-fold and 360-fold higher, respectively, than those observed in non-tannery workers. In addition, exposed workers exhibited hearing impairment, reflected by decreased hearing levels at frequencies of 1 and 4 kHz, highlighting the potential health risks associated with chronic chromium exposure [22].

The environmental impact of tannery-derived heavy metals extends beyond industrial sites and can affect surrounding ecosystems and human populations. Investigations conducted in Kanpur, India, along the southern bank of the Ganga River, revealed elevated concentrations of Cr, Pb, As and Cd in drinking water sources, indicating the widespread dissemination of tannery-related contaminants into the aquatic environment

[23]. Improper disposal of tannery wastewater further aggravates this problem, as the effluents often contain substantial amounts of Cr(VI), a highly toxic and recognised human carcinogen. Exposure to Cr(VI) can adversely affect humans, animals and plants, making it a significant threat to environmental and public health [24].

In addition to heavy metal contamination, tannery wastewater is characterised by poor physico-chemical quality. Studies have reported significantly reduced dissolved oxygen (DO) levels, elevated biochemical oxygen demand (BOD), total dissolved solids (TDS) and increased microbial loads in tannery wastewater compared with non-tannery wastewater samples, reflecting the high pollution burden associated with leather-processing activities [25]. Furthermore, Cr and Pb are commonly discharged into water bodies through untreated or inadequately treated tannery effluents, together with large quantities of organic and inorganic pollutants generated during different stages of leather processing [26]. The combined presence of toxic heavy metals and high organic loads underscores the need for effective treatment technologies to minimise environmental contamination and safeguard ecosystem and human health [26].

Physico-chemical properties of tannery wastewater: The physico-chemical characteristics of tannery effluents have been reported to exert significant adverse effects on aquatic organisms. Variations in parameters such as salinity, pH and odour have been associated with noticeable morphological and behavioural abnormalities in fish exposed to tannery wastewater. The observed effects include excessive mucus secretion, abnormal excretory discharge, irregular opercular movement, persistent opening of the mouth and erratic swimming behaviour, indicating physiological stress and impaired aquatic health [27]. The characterisation studies of tannery effluents have further revealed that these wastewaters are typically dark brown, turbid and malodorous, reflecting their high contaminant content. In addition, elevated levels of total suspended solids (TSS), total dissolved solids (TDS) and total hardness have frequently been reported, while the pH may vary depending on the stage of leather processing and treatment conditions [28]. Comparative analyses of untreated and treated tannery wastewater have shown that most pollution indicators, including organic and inorganic contaminant levels, are substantially higher in untreated effluents. Although treatment processes improve effluent quality, residual concentrations of heavy metals such as Zn, Cu and Cr may still persist, emphasizing the need for effective remediation strategies [29]. Table-1 summarises the physico-chemical characteristics of tannery wastewater before and after treatment.

Impact of heavy metals toxicity: Among the various heavy metals, Cr is considered one of the most hazardous inorganic pollutants due to its toxicity, persistence and widespread occurrence in the environment. Chromium enters environmental systems through both natural processes and anthropogenic activities, with leather tanning operations representing one of the major industrial sources of contamination [35]. Consequently, tannery effluents have emerged as a significant contributor to heavy metal pollution worldwide. The discharge of untreated or inadequately treated tannery wastewater into natural ecosystems has raised serious concerns regarding environmental sustainability, public health and ecological safety. The presence of elevated concentrations of toxic metals and other pollutants in tannery effluents can adversely affect water quality, disrupt ecosystem functions and pose substantial risks to human and animal health through long-term exposure and bioaccumulation [36].

Impact on aquatic ecosystems: Heavy metal toxicity has become a major environmental and public health concern due to its widespread occurrence and potential to cause adverse biological effects. Although some metals are required in trace amounts for normal physiological functions, many heavy metals have little or no beneficial role in the human body and can disrupt essential metabolic processes when present at elevated concentrations. Consequently, the production of safe and high-quality food relies heavily on maintaining pollution free environmental conditions. Certain heavy metals, particularly Cd and Pb, are highly toxic even at very low concentrations, with permissible limits in drinking water set at 0.003 mg/L and 0.01 mg/L, respectively [37]. Excessive accumulation of these metals in aquatic environments can contaminate the food chain, posing significant risks to aquatic organisms and human populations through bioaccumulation and biomagnification processes. Furthermore, inappropriate aquaculture practices have been identified as important contributors to heavy metal contamination and eutrophication in aquaculture ponds, often resulting in pollutant levels that exceed established environmental safety standards [38].

TABLE-1
PHYSICO-CHEMICAL CHARACTERISTIC DATA OF TANNERY EFFLUENT BEFORE AND AFTER TREATMENT

Type of effluent	Colour	pH	BOD (mg/L)	COD (mg/L)	TDS (mg/L)	Hardness (mg/L)	TSS (mg/L)	Heavy metals (mg/L)						Ref.
								Cr	Cd	Zn	As	Co	Pb	
Untreated	Dark brown	7.24	420	1754	23492	19150	2482	81	–	0.121	–	0.364	0.216	[23]
Treated	Light brown	8.29	280	409	13317	14130	1385	7.2	–	0.094	–	0.118	0.071	
Untreated	Grey	5.70	1120	4420	7168	2400	710	1.19	–	–	–	–	–	[27]
Untreated	Dark brown	8.40	925	2781	4370	2195	2856	162	0.07	2.15	1.86	–	–	[30]
Treated	Light brown	6.90	195	562	1537	815	820	79	–	–	0.41	–	–	
Untreated	Dark black	9.80	393	5394	2204	764	35	246	140	187	–	125	190	[31]
Treated	Grayish	8.19	19	243	218	136	5	56	8.48	11.56	–	7.37	12.54	
Untreated	Brown	8.50	2000	1100	37.95	–	1.28	–	–	–	–	–	–	[32]
Treated	Light yellow	7.00	250	150	36.9	–	1.15	–						
Untreated	–	9.40	2434	7917	2702	–	8907	763	0.612	–	–	2.55	1.702	[33]
Treated	–	6.60	312	68.3	358	–	424	65	0.218	–	–	0.684	0.327	
Untreated	–	8.40	1530	3030	67700	–	650	10.4	0.0012	0.49	0.42	0.014	0.032	[34]

Exposure to heavy metals can induce a wide range of adverse biological effects, including genotoxicity, reproductive impairment and increased mortality in both aquatic organisms and humans. Although substantial progress has been made in understanding the toxicological impacts of conventional heavy metals, significant knowledge gaps remain, particularly regarding the environmental and health risks associated with emerging contaminants such as rare earth metals, which may pose future ecological challenges [39]. To better assess ecological risks, advanced approaches such as species sensitivity distribution (SSD) models have been employed to evaluate the spatial and temporal impacts of heavy metals, including Cd, As, Cu, Pb, Cr, Ni and Zn, on aquatic species across different taxonomic groups, as demonstrated in studies conducted in Taihu Lake [40]. In addition to heavy metal pollution, aquatic ecosystems are frequently threatened by other contaminants such as ammonia, which is recognised as a major toxicant affecting aquatic organisms. While the effects of ammonia toxicity on fish are relatively well documented, its impacts on aquatic invertebrates remain insufficiently understood [41]. Furthermore, contamination of aquatic environments can lead to a decline in species diversity and abundance. Fish are particularly sensitive to environmental pollutants, including pesticides, and are therefore considered valuable bioindicators of water quality and ecosystem health. Pesticide exposure can adversely affect the nervous system and vital organs such as the liver, kidneys and gills, ultimately compromising fish survival and aquatic biodiversity [42].

Impact on terrestrial ecosystems: Aquatic organisms are highly vulnerable to contamination by heavy metals and organic pollutants, which can accumulate in their tissues through prolonged exposure to polluted water. Such accumulation may impair growth, reproduction and survival, ultimately threatening aquatic biodiversity. Similarly, animals residing near tannery sites may experience systemic toxicity, organ dysfunction and reduced physiological fitness through direct contact with contaminated soil and wastewater or through the consumption of polluted food and water sources [43]. Tannery wastewater also poses significant risks to plant health. When discharged into agricultural land or used for irrigation, toxic constituents present in the effluent can adversely affect seed germination, plant growth and overall crop productivity [44]. Although considerable efforts have been made to reduce pollutant discharge from industrial activities, the direct environmental impacts of tannins and related contaminants remain insufficiently explored [45].

The accumulation of heavy metals in agricultural soils has emerged as a growing concern due to its potential effects on cereal crops, which constitute a major component of the global food supply. Heavy metals introduced into the environment through anthropogenic activities can be readily absorbed by crops, thereby compromising plant health, crop yield and food quality [46]. Understanding the mechanisms governing heavy metal uptake, transport and tolerance in cereal crops is therefore essential for ensuring sustainable agricultural production and long-term food security. Continued research, together with integrated management strategies, is necessary to mitigate the impacts of heavy metal pollution and enhance the resilience of agricultural systems under changing environmental conditions [47].

Human health implications: Exposure to heavy metals can adversely affect endocrine function throughout life; however, the degree of susceptibility varies depending on the specific metal and the stage of exposure (Fig. 2). Early-life

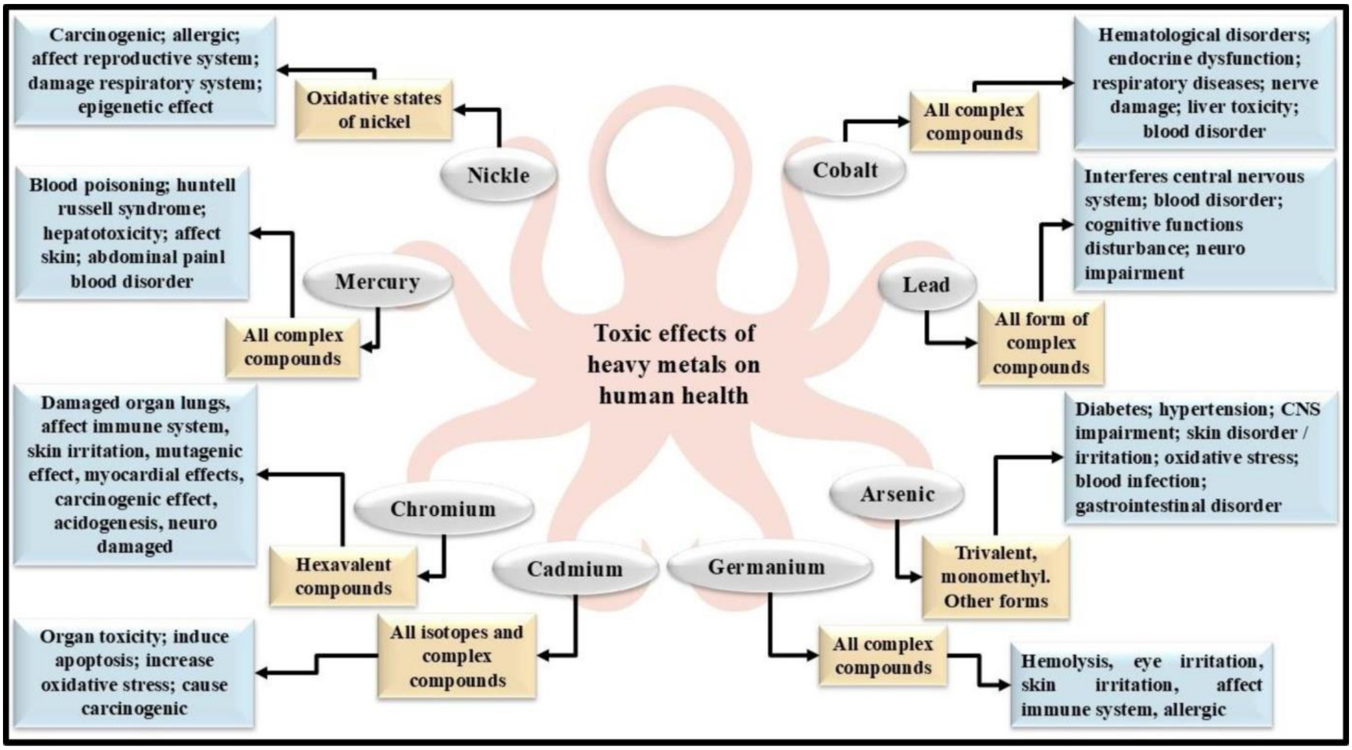

Fig. 2. Potential toxic effects of prominent heavy metals on human health

exposure is particularly concerning because heavy metals can accumulate in biological tissues and produce long-lasting or irreversible health effects. Therefore, both exposure duration and dose are critical factors in evaluating heavy metal associated health risks [48]. Lead, for instance, has been linked to persistent endocrine disruption and continues to warrant extensive investigation. Previous studies have demonstrated that Pb exposure can affect neurological functions through alterations in neurotransmitters and neuropeptides, disrupt endocrine regulation by interfering with thyroid and sex hormones and impair immune responses through changes in inflammatory cytokine production [49]. Similarly, prolonged exposure to Cd has been associated with thyroid dysfunction and other adverse health outcomes. To minimise health risks, the WHO has established reference urinary Cd levels not exceeding 1 μg/g, 2 μg/g creatinine or 5.24 μg/g [50].

In contrast, plants have evolved natural defense mechanisms to mitigate heavy metal toxicity. One important strategy involves the synthesis of low molecular weight thiol compounds, particularly glutathione (GSH) and cysteine, which possess a high affinity for toxic metal ions and contribute to their sequestration and detoxification within plant tissues [51]. Assessment of the environmental and public health impacts of heavy metal contamination commonly involves the application of risk indices such as the hazard quotient (HQ) and carcinogenic risk (CR), which provide quantitative estimates of potential adverse effects [52]. Accordingly, health risk assessment typically comprises four key steps, *e.g.* hazard identification, exposure assessment, contaminant concentration determination and quantitative risk characterisation using dose-response and exposure models [53,54]. Table-2 summarises the major heavy metals present in tannery effluents and their associated impacts on the aquatic microflora and human health.

Bioremediation techniques for heavy metals: The potential application of phosphogypsum in bioremediation has attracted considerable attention, prompting comparative investigations of its elemental composition across different geographical regions. To assess its suitability for environmental remediation, phosphogypsum samples from various sources worldwide were analysed and compared with data reported from Ukraine and other international studies [67]. In parallel, agricultural practices contribute significantly to heavy metal accumulation in soils through the extensive use of mineral fertilisers, which can introduce toxic elements such as Cd and Pb. Additional contaminants, including Cu, Cr, As, Hg, Mn, Pb and Zn, as well as pesticide residues, may also accumulate in soil environments, posing risks to ecosystem and human health [68]. Monitoring the environmental fate of these contaminants requires an understanding of their bioaccumulation behaviour, which serves as a key indicator of heavy metal cycling within aquatic ecosystems. The toxicity and mobility of heavy metals are strongly influenced by their chemical speciation and oxidation states. Chromium, in particular, exists in several oxidation forms, among which Cr(VI) is considered the most toxic and environmentally hazardous,

TABLE-2
SUMMARY OF TANNERY EFFLUENT CONSTITUENT HEAVY METALS AND THEIR EFFECTS ON AQUATIC MICROFLORA AND HUMAN HEALTH

Heavy metals in tannery effluent	Permissible limit as per WHO	Effects on microbes	Effect on human health	Ref.
Cr	0.05 mg/L	Growth inhibition; elongation of lag phase; inhibition enzyme activities; inhibition of oxygen uptake	Nose irritation; breathing problem; skin rashes; stomach ulcers; affect immune system; carcinogenic; mutagenic; neuro disorder	[55,56]
Sulphides	0.05 mg/L	Death; decrease in biomass; denature protein	Cytochrome oxidase inhibition; respiratory tract irritation; olfactory fatigue; unconsciousness in human; temporary paralysis	[57]
Sb	0.02 mg/L	Inhibit growth rate; mutation; cell lysis	Nausea; vomiting; human carcinogen; diarrhea; immune system	[58,59]
Cd	0.003 mg/L	Denature protein; destroy nucleic acid; hinder cell division; disrupt cellular function	Renal disfunction; bone defects; increase blood pressure; obstructive lung diseases	[60,61]
Cu	2.0 mg/L	Disrupt cellular function; inhibit enzyme activities	Casuse anemia; liver damage; kidney damage; stomach irritation; skin irritation	[62]
Pb	0.01 mg/L	Destroyed nucleic acid and protein; inhibit enzyme action; transcription affects	Effects on kidney; GI tract damaged; effect reproductive system; damaged CNS system	[63]
Hg	0.006 mg/L	Denature protein; inhibit enzyme function; disrupt cell membrane	Tumor; carcinogens; blood disorder; gingivitis; congenital malformation; mutagenic	[64]
Ni	0.07 mg/L	Upset cell membrane; hinder enzyme function; hinder oxidative stress	Long term causes body weight reduced; heart damaged; liver damaged; skin irritation	[57]
Se	0.01 mg/L	Inhibit growth rate	Damaged nervous system; fatigue and irritability; damaged liver; circulatory tissues	[63]
Zn	NA	Death; decrease in biomass; inhibit growth	Radioactive cobalt cause CNS damage; effects lungs; including asthma; pneumonia	[65]
V	0.1-0.4 mg	Disrupt protein; inhibit enzyme function	Carcinogenic; skin irritation; chemosis; lacrimation; permanent blindness; oedema	[66]
As	0.01 mg/L	Death; hinder cell division; inhibit growth rate	Genetic disorder; muscarinic syndrome; GI tract; bronchospasm; mitosis; nicotine syndrome	[58]

with a high potential for accumulation in aquatic organisms, including fish [69].

Microbial bioremediation: Microorganisms also play a pivotal role in the remediation of heavy metal-contaminated environments due to their inherent ability to tolerate, transform and immobilise toxic metal ions. Numerous bacterial species have evolved diverse physiological and biochemical mechanisms that enable them to survive under metal-stressed conditions while simultaneously reducing contaminant levels in the environment [70-72]. These mechanisms include the utilisation of pollutants as nutrient or energy sources, as well as the activation of cellular defense systems that mitigate metal-induced toxicity [73]. Owing to these capabilities, microorganisms contribute significantly to maintaining ecological balance and restoring contaminated ecosystems.

The application of microorganisms for the removal, detoxification or transformation of environmental pollutants is collectively known as bioremediation. This environmentally sustainable approach gained prominence following the successful application of *Pseudomonas putida* for petroleum hydrocarbon degradation, which was patented in 1981 and marked a significant advancement in environmental biotechnology [74]. Since then, microbial bioremediation has emerged as a cost-effective and eco-friendly alternative to conventional physico-chemical treatment methods.

Recent developments have further enhanced the efficiency of microbial remediation technologies. Among these, biofilm assisted bioremediation has attracted considerable attention because biofilms provide microorganisms with improved resistance to toxic substances through the production of extracellular polymeric substances (EPS) [75,76]. These negatively charged polymers facilitate the adsorption and sequestration of metal ions, thereby enhancing contaminant removal efficiency [77]. Similarly, bioleaching has emerged as an effective strategy for heavy metal recovery and remediation. Compared with conventional chemical leaching techniques, bioleaching requires lower energy input, minimises secondary pollution and reduces chemical consumption. Microbial bioleaching operates through mechanisms such as redox reactions, mineral dissolution and biotransformation, whereas metal removal may also occur through extracellular complexation, intracellular accumulation and biomineralisation processes [67,68]. Consequently, this technology has found extensive application in the treatment of mine tailings, waste rocks, low-grade ores and other metal-bearing wastes.

Among the various microbial remediation mechanisms, biosorption represents one of the most important pathways for heavy metal removal. This process serves as the primary protective barrier against metal toxicity and involves the binding of metal ions to functional groups present on the microbial cell surface. Negatively charged groups, including carboxyl, amino, phosphoryl and sulfhydryl moieties, act as active metal-binding sites, facilitating ion exchange, adsorption and immobilisation of heavy metals from contaminated environments [78]. These microbial processes highlight the considerable potential of bioremediation as a sustainable and efficient strategy for mitigating heavy metal pollution and protecting environmental health.

Phytoremediation: Phytoremediation has emerged as an environmentally sustainable and cost-effective approach for the remediation of heavy metal-contaminated soils and water bodies. This green technology utilises plants to remove, stabilise, transform or immobilise contaminants through several mechanisms, including phytoextraction, phytostabilisation, phytovolatilisation and phytofiltration [79,80]. The efficiency of phytoremediation largely depends on factors such as plant biomass production, growth rate, tolerance to pollutants and the bioavailability of heavy metals in the contaminated medium [81].

Phytoremediation strategies can be implemented either *in situ*, where contaminants are treated directly at the polluted site or *ex situ*, where contaminated soil or water is excavated, transported and treated elsewhere. *Ex situ* remediation generally involves the extraction of contaminated soil or pumping of polluted groundwater, followed by treatment using physical and chemical processes such as solvent extraction, dehalogenation, oxidation-reduction reactions, soil washing, vapor extraction and stabilisation techniques to facilitate contaminant removal [82]. However, phytoremediation offers a more environmentally benign alternative by harnessing the natural metal-accumulating capacity of plants.

Several studies have demonstrated the effectiveness of various plant species in removing heavy metals from tannery wastewater. For instance, vetiver grass (*Vetiveria zizanioides*) and *Arundo donax* irrigated with treated tannery effluent exhibited significant chromium uptake and translocation from wastewater into root and shoot tissues. Although all tested species accumulated chromium, swamp smartweed showed comparatively lower removal efficiency than para grass and papyrus, indicating species-dependent variations in phytoremediation performance [83]. Similarly, native aquatic macrophytes such as *Wolffia columbiana*, *Lemna gibba* and *Lemna minuta* have demonstrated considerable potential for contaminant removal from domestic and tannery wastewater systems. The integration of these free-floating plants with beneficial microorganisms has further enhanced pollutant removal efficiency, highlighting the advantages of microbe-assisted phytoremediation as a low-cost, non-invasive and environmentally acceptable remediation strategy [84]. The effectiveness of phytoremediation can also be enhanced through the use of remediation-supporting agents. Studies involving *Phragmites australis* have shown that plants grown in tannery effluent disposal systems supplemented with phytoremediation enhancers produced higher biomass than uninoculated controls. Moreover, translocation factors greater than or equal to one for Cr, Cu, Cd and Pb indicated efficient transport of metals from roots to aerial tissues, an important characteristic for successful phytoextraction [85]. Recent investigations have also explored the application of deep eutectic solvents (DESs) for improving heavy metal removal from phytoremediation biomass. Acidic DES formulations exhibited superior Cd removal efficiency compared to neutral and alkaline systems, demonstrating their potential for enhancing post-harvest metal recovery processes [86].

Wetland macrophytes have likewise shown remarkable differences in their capacity to accumulate and tolerate heavy metals. Comparative studies revealed that *Phragmites australis* and *Typha latifolia* possess distinct metal enrichment characteristics, as reflected by their bioconcentration factors. The observed accumulation patterns indicate species-specific preferences and efficiencies for different metals, emphasizing the importance of selecting suitable plant species based on the target contaminant and environmental conditions [87]. Thus, these findings demonstrate that phytoremediation, particularly when integrated with microbial assistance and advanced enhancement strategies, represents a promising and sustainable approach for mitigating heavy metal contamination in wastewater and aquatic ecosystems.

Bioaugmentation and biosorption: Bioaugmentation has emerged as a promising strategy for the treatment of tannery wastewater by enhancing the degradation capacity of conventional biological treatment systems. This approach involves the introduction of specialised functional microorganisms capable of degrading recalcitrant pollutants, thereby increasing microbial abundance, accelerating contaminant removal and improving the stability and efficiency of the treatment process [88]. Compared with phytoremediation, microbial remediation offers several advantages, including shorter treatment periods, easier biomass management and the ability to produce a diverse range of enzymes that facilitate pollutant degradation. Consequently, microorganisms are often preferred for wastewater treatment applications due to their rapid growth and high metabolic versatility [89].

Microbial bioremediation can be carried out under both aerobic and anaerobic conditions, depending on the characteristics of the wastewater and the target contaminants. To maximise treatment efficiency, microbial processes are frequently conducted in engineered bioreactors that provide controlled environmental conditions conducive to microbial growth and metabolic activity. These systems enhance substrate utilisation and promote the degradation of organic pollutants and toxic compounds present in industrial effluents [89]. Among the various microorganisms employed in wastewater remediation, algae have demonstrated considerable potential for the treatment of tannery effluents. Algal cells possess a high surface area-to-volume ratio and a unique cellular architecture that facilitate the adsorption and uptake of heavy metals and other pollutants. As a result, algae are capable of removing a broad spectrum of contaminants released during leather-processing operations [21]. Numerous studies have identified microalgae as one of the most economical biosorbents for the remediation of metal-contaminated industrial wastewater. Optimal treatment performance is generally achieved using highly concentrated algal cultures with biomass levels exceeding 1.5 g/L. However, the recovery of algal biomass following treatment remains a major operational challenge [90]. This limitation can be addressed through immobilisation techniques, in which algal cells are attached to inert support materials, allowing their reuse in multiple treatment cycles while simplifying biomass separation and recovery [91].

Fungi also play an important role in tannery wastewater remediation due to their high tolerance to acidic conditions and their ability to accumulate and transform heavy metals. Species belonging to the genera *Aspergillus*, *Penicillium* and *Fusarium* have frequently been isolated from tannery wastewater and associated contaminated environments [92]. Certain fungal species, particularly *Candida* spp., have demonstrated enhanced Cr(VI) removal capabilities, while metal-resistant strains of *Aspergillus*, *Rhizopus* and *Fusarium chlamydosporium* have shown significant potential for heavy metal remediation in tannery-contaminated sites [93]. Nevertheless, the use of non-living fungal biomass may reduce remediation efficiency since metabolic activity and active transformation mechanisms are absent.

Protozoa constitute another important microbial group involved in wastewater purification. Besides directly accumulating heavy metals such as Cr, Hg, Zn, and Cd, they improve water quality by grazing on bacterial populations and maintaining microbial community balance [94,95]. As protozoan communities comprise species with varying tolerance to pollutants, their composition is strongly influenced by physicochemical and operational conditions, making them reliable bioindicators of wastewater treatment plant efficiency [96].

Among all microbial groups, bacteria remain the most extensively studied and widely applied organisms for industrial effluent remediation due to their remarkable metabolic diversity and ability to produce a broad range of degradative enzymes and metabolites. Several bacterial species have demonstrated significant efficiency in reducing inorganic and organic pollutant loads in tannery wastewater. For example, investigations involving multiple bacterial isolates from Pakistan identified *Rhodopseudomonas blastica* as a particularly effective strain for reducing BOD and COD levels in tannery effluents [97].

The microbial remediation of heavy metals is governed by several interconnected biochemical mechanisms, as shown in Fig. 3. Functional groups present on microbial cell surfaces, including hydroxyl, carboxyl and phosphate moieties, facilitate metal adsorption through surface complexation and ion-exchange processes. Microorganisms can further transform toxic metals into less harmful forms *via* oxidation-reduction reactions, biotransformation, biomineralisation and bioprecipitation. Intracellular sequestration mediated by metallothioneins and polyphosphate granules has been reported to remove up to 75-95% of metals such as Cr, Cd, Pb and Ni under optimised conditions. Furthermore, the bioleaching processes generate organic and inorganic acids that solubilise metal containing minerals, facilitating metal recovery. Biomineralisation reactions can also convert dissolved metals into stable phosphate minerals such as $MHPO_4$, thereby reducing metal mobility, bioavailability and environmental toxicity. Table-3 summarises the major tannery wastewater treatment technologies, together with their advantages, limitations and practical applications.

Challenges in bioremediation of tannery wastewater: Rapid industrialization has led to the continuous release of large quantities of pollutants into the environment, creating significant challenges for environmental monitoring and pollution management. Consequently, there is an increasing need for advanced approaches that can effectively detect, assess and control contaminant levels in various environmental compartments. Once released, these pollutants can persist in soil, water and air, ultimately entering biological systems and posing serious risks to both ecosystem integrity and human health [106].

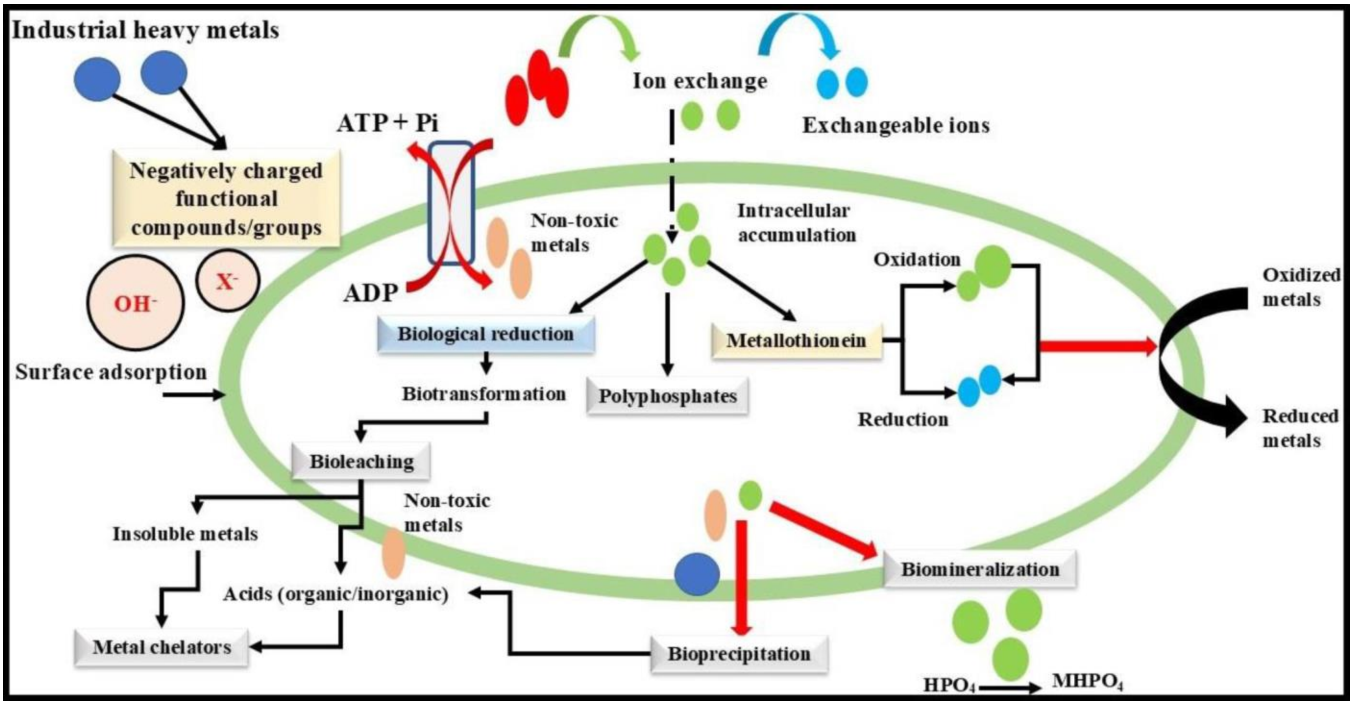

Fig. 3. Schematic representation of bacterial bioremediation mechanism of heavy metal reduction

TABLE-3
LIST OF TANNERY EFFLUENT TREATMENT METHODS AND THEIR ADVANTAGES, LIMITATION WITH APPLICATIONS

Treatment methods	Advantages	Limitation	Application	Ref.
Biological treatment	Facile; adaptable; multi-functional; large treatment capacity	Time-consuming; inhibition by high salinity; massive sludge; unstable effluent quality	Main method for large amounts of COD, BOD, TSS, *etc.* in TWW removal	[98,99]
Membrane filtration	Adaptable; facile; multi-functional; space intensive	More capital investment in power supply when treatment throughput is large	Valuable resources recycling; utilised as post-treatment of TWW for desalination	[100]
Electrochemical treatment	Efficient; clean; adaptable; multi-functional	High requirements for electrode's materials and shapes	Post-treatment of TWW for persistent pollutants removal	[101]
Advanced oxidation	Efficient; clean; deep degradation of pollutants	Require addition of chemical agents; optimal reaction conditions need to be regulated	Served as post-treatment of TWW for persistent pollutants removal	[102]
Coagulation	Multi-functional; adaptable easily	Toxicity of reaction by-products needs further	Not suitable for raw TWW treatment and large throughput	[103]
Flocculation	Low-cost; multi-functional; adaptable easily	Huge sludge; high energy input; not suitable for large process	Pre-post treatment of TWW combined with biological treatment	[104]
Adsorption	Low-cost; multi-functional; adaptable easily	Huge sludge; transferring pollutants; not suitable for large process	Pre-post treatment of TWW combined with biological treatment	[105]

Among environmental contaminants, heavy metals and metalloids are of particular concern since they originate from a wide range of natural and anthropogenic sources and exhibit high persistence, toxicity and bioaccumulative potential. Metals such as chromium (Cr), cadmium (Cd), lead (Pb), nickel (Ni) and mercury (Hg), along with metalloids such as arsenic (As), can enter the human body through multiple exposure pathways, including ingestion, inhalation, dermal absorption and diffusion. Occupational exposure and environmental contamination are major routes through which these toxic elements affect human populations. Prolonged exposure has been associated with numerous adverse health effects, including cytotoxicity, neurotoxicity, hepatotoxicity, nephrotoxicity and carcinogenicity [107,108].

In addition to heavy metals, contamination of water resources by nutrients and microbial pathogens remains a major public health concern. Studies conducted in Malawi have identified microorganisms and nitrate contamination as significant threats to drinking water quality. To determine the sources of nitrate pollution, isotope hydrology techniques were employed and revealed that the widespread use of pit latrines within catchment areas was a major contributor to groundwater nitrate contamination. Furthermore, statistical analyses provided additional evidence supporting the relationship between sanitation practices and elevated nitrate concentrations in groundwater systems [109]. These findings highlight the importance of integrated pollution monitoring and management strategies to safeguard environmental quality and public health.

Future research directions: Future research on tannery effluent management should focus on the development of advanced, sustainable and intelligent treatment technologies capable of handling high pollutant loads with improved efficiency and reduced operational costs. The integration of artificial intelligence (AI) and Internet of Things (IoT)-based monitoring systems offers significant potential for real-time tracking of critical wastewater parameters, including pH, BOD, COD, TDS and heavy metal concentrations [110-112]. Recent studies have demonstrated that machine learning algorithms can achieve prediction accuracies exceeding 80-90% for wastewater quality assessment and process optimization [113-115]. Furthermore, hybrid treatment systems combining membrane filtration, advanced oxidation processes, microbial bioremediation, nanotechnology and phytoremediation may provide synergistic benefits, enabling the removal of more than 90-99% of heavy metals such as Cr, Pb and Cd, as well as various organic pollutants [116,117]. Future investigations should also explore genetically engineered microbial consortia and algal-bacterial systems with enhanced metal sequestration and biodegradation capabilities under dynamic environmental conditions. In addition, resource recovery approaches, including chromium recycling and biogas generation from tannery sludge, should be further developed to support circular economy principles and sustainable waste management [118]. Despite promising laboratory-scale outcomes, long-term pilot-scale and field-scale studies remain limited. Therefore, future efforts should prioritize the evaluation of process stability, energy requirements, sludge generation, economic feasibility and environmental sustainability to facilitate the large-scale implementation of effective tannery wastewater treatment technologies.

Conclusion

Tannery effluent is recognized as one of the most hazardous industrial waste streams due to its complex composition, high pollutant load and significant environmental and public health implications. Untreated tannery wastewater typically contains elevated concentrations of chromium (150-3000 mg/L), total dissolved solids exceeding 10,000 mg/L and chemical oxygen demand (COD) values reaching 15,000 mg/L, substantially exceeding permissible discharge limits. The continuous release of such contaminants into the environment promotes their accumulation and transfer through food chains, leading to bioaccumulation and biomagnification in plants, animals and humans. Consequently, exposure to tannery-derived pollutants has been associated with phytotoxic effects, reduced agricultural productivity, organ damage, neurological disorders and increased carcinogenic risks. This review highlights that conventional treatment technologies including coagulation-flocculation, adsorption and membrane-based processes, can achieve contaminant removal efficiencies ranging from 70% to 95%. However, their large-scale implementation is often constrained by high operational costs, energy requirements and the generation of secondary waste such as sludge. In contrast, biological remediation approaches have emerged as sustainable and environmentally compatible alternatives. As recent studies have demonstrated that algal-based treatment systems can remove approximately 75-98% of heavy metals and nutrients under optimized conditions, while specialized bacterial consortia have achieved maximum chromium removal efficiencies. Furthermore, processes such as biosorption, bioaugmentation, biotransformation and phytoremediation offer effective and eco-friendly solutions for the detoxification of tannery wastewater. Despite these advances, significant challenges remain regarding field-scale implementation, long-term process stability, sludge management and the performance of biological systems under fluctuating environmental conditions. Future research should therefore focus on the development of integrated hybrid treatment technologies that combine physico-chemical and biological processes, as well as the application of genetically engineered microbial consortia, AI-assisted monitoring systems and energy efficient treatment platforms. Such innovations are expected to improve pollutant removal efficiency, facilitate resource recovery and support the sustainable management of tannery effluents while minimizing environmental and health risks.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

DECLARATION OF AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used an AI-assisted tool(s) to improve the language as well the editing of figures. The authors reviewed and edited the content and take full responsibility for the published work.

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