International Journal of Engineering Trends and Technology
ISSN: 2231–5381 / https://doi.org/10.14445/22315381/IJETT-V72I3P126

Volume 72 Issue 3, 288-311, March 2024

Review Article

Tannery Wastewater Treatment: Trace Organic Pollutants, Toxicity and Innovative Removal Methods

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Received: 11 November 2023 Revised: 20 February 2024 Accepted: 26 February 2024 Published: 17 March 2024

Abstract *- The tanning industry is a major source of wastewater containing complex organic contaminants, which is crucial to the international leather trade. This article takes a deep dive into the topic of treating tannery effluent by focusing on trace organic contaminants, the dangers they pose, and the cutting-edge techniques used to get rid of them. Dye, heavy metals, sulphides, and other harmful organic compounds are only some of the organic chemicals commonly found in tannery effluents. Due to their propensity for bioaccumulation in aquatic environments, these pollutants offer a substantial environmental problem and raise concerns for human health. In this article, we will examine the origins, toxicity, and persistence of trace organic contaminants often detected in tannery effluent and their identification and characterization. Stressing the importance of strict wastewater treatment techniques, it investigates the ecological and health dangers posed by these toxins. In light of these difficulties, cutting-edge strategies for eliminating trace organic contaminants from tannery effluent are carefully evaluated. Physical, chemical, and biological processes, such as advanced oxidation processes, adsorption, membrane filtering, and biological degradation procedures, are all included in this category of treatment methods. The review analyses the efficacy, practicability, and scalability of various techniques in the context of treating effluent from tanneries. Future possibilities and new trends in tannery wastewater treatment are also examined, such as deploying decentralized treatment systems, incorporating sustainable and environmentally friendly technologies, and the possibility of resource recovery from tannery effluents.*

Keywords *- Environmental contaminants, Tannery wastewater, Toxicity assessment, Wastewater treatment, Water pollution.*

1. Introduction

Industrial expansion is the single most important factor in a country's overall economic development. Depending on the goods produced, many sorts of industries might exist. The rapid industrialization of certain areas, especially those in or near major cities, has exceeded the carrying capacity of the local ecosystem [1]. The discharge of toxins into these areas often has a devastating effect on nearby water sources such as rivers, lakes, and coastal waterways. Human activities involved with raw-material processing and manufacture produce effluents known as industrial wastewaters. Washing, cooking, chilling, heating, extracting, reaction by-products, separating, and quality control, leading to product rejection, all contribute to these wastewater streams. The centralized approach used to create older treatment methods is becoming less effective, leading to a growing stockpile of effluents. The difficulties produced by previous techniques are now less severe due to the introducing of new ones. To ensure the treated wastewater is safe to discharge, wastewater treatment facilities are constructed [1]. In addition to lowering the quantity of pollutants in the water, many treatment procedures also remove the content of suspended particles, the molecules of which can pollute the rivers and hinder the flow of water in the channels and pipes after they have been deposited. The amount of biodegradable organic matter, as indicated by the Biological Oxygen Demand (BOD), is likewise reduced. To purify wastewater to a safe level, wastewater treatment is essential. Because of this, the treatment plant must be constructed to account for certain influent characteristics that need to be managed to maximize the plant's efficacy [2]. Environmental protection calls for applying appropriate purification/treatment systems with high removal efficiency for pollutants because of the unchecked release of wastewater effluent into the environment and the transit of toxins into the anthropoid system**.** Figure 1 depicts an overview of tannery wastewater's components and environmental effects. Economically, conserving water and avoiding artificial water shortages are two of the most important effects of efficient wastewater treatment. Considering the characteristics of wastewater and the geographical location of the relevant businesses, this study aims to summarize the treatment techniques for effluent created by various industries and their efficacy in eliminating the contaminants. [3] and [4] both agree that water is crucial to life on Earth. Water is increasingly being seen as an asset for economic and social development in many world regions [5] [3]. There is only around 2.5% pure water out of the entire water content of the planet, which makes up roughly 71%. Clean water is essential for human and environmental survival. Some examples of freshwater resources are rivers, lakes, ponds, groundwater, and streams.

Only around one percent is useful by humans and industry; the remainder is locked up in glaciers and underground aquifers. However, population growth and increased industrial production are rapidly draining these supplies. Besides human activities, climate change, inter-annual climatic variability, and water use for energy generation all contribute to freshwater shortage and depletion. Freshwater scarcity has emerged as a prominent environmental concern [6] [7]. According to the United Nations Food and Agriculture Organization (FAO) research from 2007, over 1.8 billion individuals residing in various nations are currently experiencing absolute water shortage, while two-thirds of the global population may be under water stress. To address the challenges associated with water shortage, it is essential to implement strategies such as water reclamation from current wastewater sources or exploring alternate water reservoirs for human use. The implementation of wastewater remediation has been proposed as a viable approach to water recovery from industrial wastewater, as suggested by [36]. In several industrial sectors, manufacturing and other operational operations often result in the production of an aqueous solution that contains dissolved compounds.

Because of the large quantities of effluent, the variety of effluent compositions, and the presence of numerous different industrial sectors, the management of wastewater treatment has been identified as an important environmental priority. The composition of industrial wastewater often includes a variety of contaminants such as heavy metals, dyes, pesticides, herbicides, medicines, and other aromatic [8] [9]. Introducing these compounds into the surrounding environment poses a significant risk to the ecological system.

Fig. 1 Overview of components and environmental effects of tannery wastewater

At low concentrations, these pollutants may not pose any immediate danger. However, prolonged buildup of these pollutants can lead to potentially severe consequences. The discharge from mining, petrochemical, and textile or dye industries contains hazardous chemicals that potentially risk human health [10].

The soil and water exhibit a pronounced presence of heavy metals, characterized by their elevated concentrations. The escalating pollution levels and associated risks of consuming contaminated water are becoming increasingly severe in various emerging nations. The shown maximum allowable thresholds for BOD and Chemical Oxygen Demand (COD) in the treated wastewater were found to be 40 mg/L and 120 mg/L, respectively.

Recently, emerging nations have detected worrying quantities of harmful substances in their drinking water. According to estimations, around 1.1 billion individuals worldwide are exposed to the use of water that does not meet safety standards. Chemical spills often refer to introducing a non-aqueous phase liquid containing a substantial amount of organic matrix and other components, such as polyaromatic hydrocarbons, in conjunction with other contaminants. The cessation of oil spills in aquatic environments necessitates the development of a water treatment technology that is both cost-effective and efficient.

According to[11], in cases when water pollution has been identified and the presence of pollutants at unacceptable levels continues, it becomes imperative to choose and apply appropriate remedial technologies carefully. The development of wastewater treatment methods primarily sprang from concerns over the adverse impacts of wastewater on the surrounding environment. The rapid growth of the population has resulted in a scarcity of land for human habitation, as well as challenges in managing and treating wastewater. In addition, there has been a significant rise in the volume of wastewater produced, accompanied by a decline in the natural ability of the environment to restore water quality, as noted by [12] and [13].

Water remediation refers to systematically treating contaminated water to transform it into environmentally safe substances. The huge growth in the quantity of hazardous wastes can be attributed to inappropriate disposal practices that neglect adherence to environmental standards. The impact of still water can be influenced by excessive use of pesticides and fertilizers, leakage from landfills, spills from industrial activities, and penetration of urban run-off [14].

Tannery wastewater is the term used to describe the liquid waste produced as a byproduct of the leather tanning process within tanneries. Leather processing necessitates using several chemicals and compounds, all of which contribute to the unique characteristics of leather processing effluent. These characteristics set this sort of wastewater apart from others. This study delves further into tannery wastewater, including its precise definition, distinguishing characteristics, and the need for effective treatment.

1.1. Characteristics of Tannery Wastewater

1.1.1. Composition

Chemical substances, both organic and inorganic, are both present in and contribute to the effluent from tanneries. Among the many ingredients that go into this concoction are tannins (from sources like chromium or vegetable extracts), dyes, acids, bases, and oils. In addition, it is sometimes defined by a high concentration of suspended debris and organic components derived from a wide variety of animal hides and skins.

1.1.2. Color

Tannins and pigments are components of the tanning process and are responsible for giving the tannery effluent its distinctive dark brown or black color.

1.1.3. High pH

The alkalinity of wastewater produced by tanneries is often observed to be markedly higher, as shown by the pH levels. This phenomenon is mostly attributed to using lime and other alkaline compounds in the tanning procedure. The potential exists for adverse effects on aquatic ecosystems in the absence of effective management practices due to elevated pH levels.

1.1.4. Heavy Metals

The presence of increased levels of heavy metals, such as chromium, in the wastewater emitted by tanning factories can be attributed to the necessity of chromium in the chrome tanning process. Chromium is an element renowned for its inherent hazardous properties. If these qualities are not effectively controlled and managed, they possess the potential to pose significant risks to both human health and environmental well-being.

1.1.5. Organic Load

The wastewater has a substantial organic load, characterized by a notable presence of organic substances such as lipids, proteins, and carbohydrates. The presence of organic matter has the potential to cause a reduction in oxygen levels inside water bodies where it is deposited, resulting in negative consequences for the ecosystem and the organisms that inhabit it.

1.2. Importance of Tannery Wastewater Treatment

Treating wastewater from tanneries holds significant significance due to many factors associated with preserving the environment, safeguarding human health, and promoting sustainable industrial practises [15]. Tanneries are establishments engaged in the transformation of animal hides and skins into leather goods.

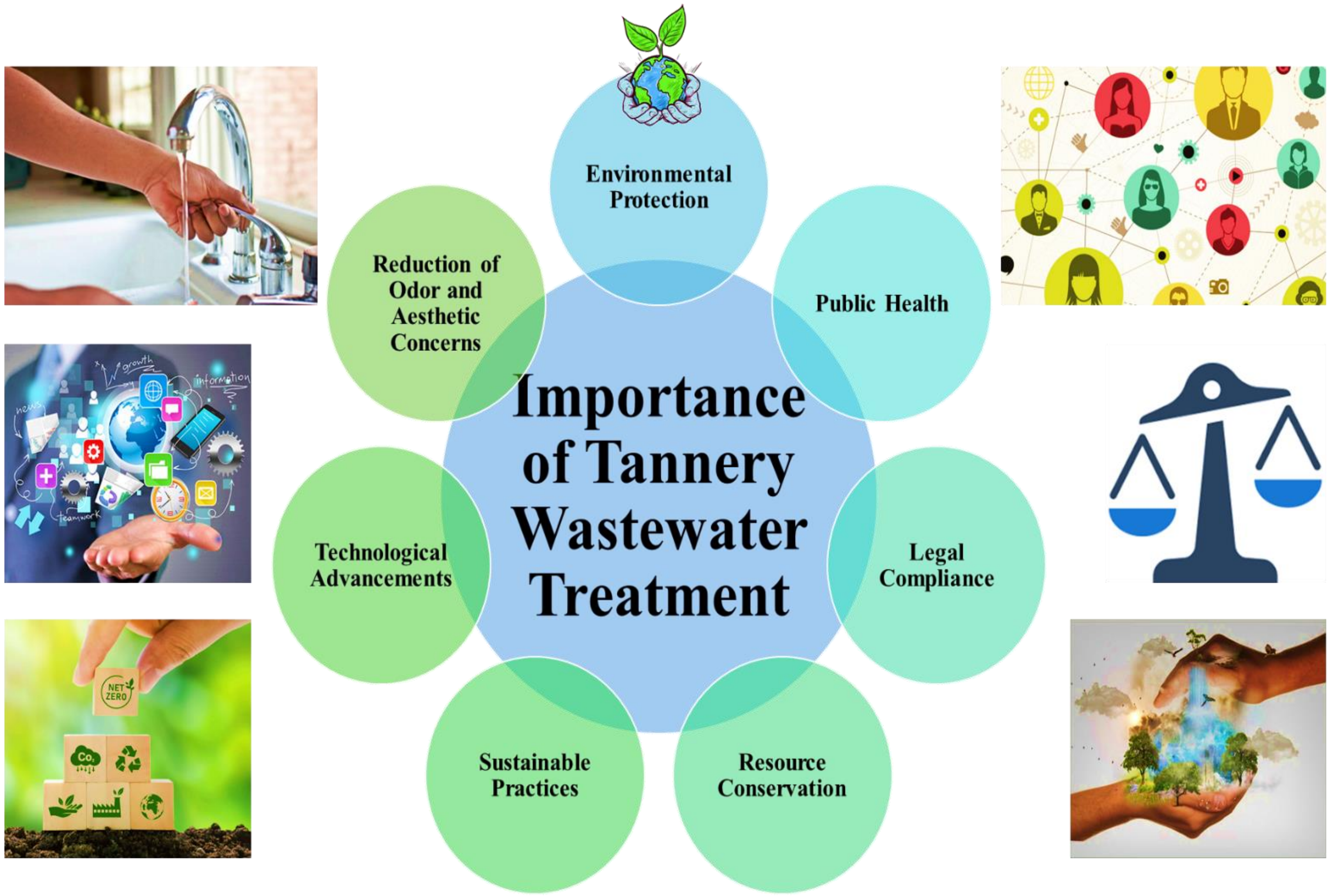

Fig. 2 Importance of tannery wastewater

The aforementioned procedure produces substantial volumes of wastewater that can potentially be heavily contaminated and detrimental if not adequately handled. Several significant factors underscore the significance of tannery wastewater treatment [16].

The treatment of wastewater generated by tanneries is of utmost importance for the preservation of human health and the protection of the environment [17]. The leather business produces significant quantities of wastewater, including various hazardous chemicals, heavy metals, and organic contaminants. In the absence of appropriate treatment, the presence of this polluted wastewater presents a significant threat to both public health and the ecosystems it infiltrates [18].

From a health standpoint, the absence of treatment for tannery effluent can result in the pollution of neighboring water sources, exposing adjacent communities to ingesting contaminated water [19]. This phenomenon can lead to significant health complications, such as dermatological irritations, respiratory ailments, and chronic health disorders. The presence of some compounds, such as chromium, in tannery effluent, has been found to possess carcinogenic properties. It can lead to significant health concerns when individuals are exposed to them [20]. Figure 2 depicts the importance of tannery wastewater. In addition, the unprocessed release of effluent from tanneries into rivers and streams can result in severe repercussions for both the aquatic ecosystem and the surrounding environment [21]. The disruption of ecosystems caused by this phenomenon has detrimental effects on fish populations and aquatic creatures, as well as the contamination of soil and groundwater [22]. The presence of hazardous substances inside tannery effluent has the potential to last in the surrounding environment for an extended period, resulting in sustained detrimental effects.

Implementing efficient tannery wastewater treatment methods is not just a matter of adhering to regulations but a moral and environmental need [23]. Various treatment methods, including biological and chemical procedures, can effectively eliminate or substantially diminish the presence of detrimental contaminants, ensuring the suitability of water for either environmental release or reuse [24]. This practice not only serves to ensure the preservation of human health but also aids in conserving valuable ecosystems, making a significant contribution towards attaining a cleaner and healthier world for future generations. Table 1 shows the list of pollutants and their sources. Impact of human health effects and their environmental toxic effects.

Table 1. List of pollutants and their sources. impact of human health effects, and their environmental toxic effects

Pollutant	Sources	Human Health Effects	Environmental Toxic Effects
Particulate Matter	Combustion of fossil fuels, industrial emissions, construction dust	Respiratory problems (asthma, bronchitis), cardiovascular diseases, premature death	Reduced visibility harms wildlife, soil, and water pollution
Nitrogen Oxides (NOx)	Combustion engines, industrial processes	Respiratory issues, cardiovascular diseases, decreased lung function	Acid rain, smog formation, harm to aquatic ecosystems
Sulfur Dioxide (SO2)	Combustion of coal and oil, industrial processes	Respiratory problems (wheezing, coughing), aggravation of asthma	Acid rain damages vegetation, harms aquatic life
Carbon Monoxide (CO)	Incomplete combustion, vehicle emissions	Headaches, dizziness, reduced oxygen transport in blood	Impairs oxygen supply to aquatic organisms
Ozone (O3)	Photochemical reactions (smog), industrial emissions	Respiratory irritation, reduced lung function, exacerbation of asthma	Damage to vegetation, reduced crop yields, harm to aquatic ecosystems
Lead (Pb)	Lead-based paint, old plumbing, industrial emissions	Neurological damage, developmental issues in children	Contaminates soil and water, harm to wildlife
Mercury (Hg)	Coal combustion, industrial processes, fish consumption	Neurological and developmental damage, cardiovascular problems	Accumulates in aquatic food chains, harms aquatic ecosystems
Persistent Organic Pollutants (POPs)	Pesticides, industrial chemicals, waste incineration	Carcinogenic, disrupts endocrine system, birth defects	Bioaccumulation in wildlife, long-term environmental persistence
Volatile Organic Compounds (VOCs)	Solvent use, vehicle emissions, industrial processes	Respiratory problems, neurological symptoms, ozone formation	Contribute to smog and ground-level ozone formation
Greenhouse Gases (e.g., CO2, CH4)	Fossil fuel combustion, deforestation, agriculture	Climate change (global warming), sea-level rise, extreme weather events	Alters global climate disrupts ecosystems

2. Trace Organic Pollutants in Tannery Wastewater

The presence of diverse trace organic contaminants in tannery effluent is widely acknowledged, and their inadequate treatment and management can result in adverse consequences for the environment and human well-being [25]. The emission of these pollutants commonly occurs as a consequence of the leather production process, wherein animal hides and skins are treated with a variety of chemicals [26]. Figure 3 depicts the different sources of environmental pollution by heavy metals.

The following is a list of frequently encountered trace organic contaminants that have been detected in tannery wastewater:

2.1. Heavy Metals

Metals possessing a density over 4 g/cm3 are commonly categorized as heavy metals. A significant quantity of heavy metals is predominantly released by electroplating, mining, fertilizer, paper, and mining sectors [27]. In the lower regions, notable heavy metals with high toxicity levels encompass arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), manganese (Mn), mercury (Hg), and zinc (Zn). According to Saravanan et al. (2020a), The persistent nature of heavy metals results in their accumulation throughout the food chain, hence exerting detrimental impacts on both aquatic and terrestrial ecosystems [28]. Heavy metals are commonly introduced into the environment via anthropogenic or natural pathways, ultimately accumulating in water supplies.

The strong attraction between heavy metals and humus, an organic component found in soil, leads to the leaching of these metals from the soil when contaminated water flows through it [29]. Chromium, particularly in the form of hexavalent chromium (Cr(VI)), is a prominent contaminant found in tannery effluent.

Chromium is employed in the tanning procedure to stabilize the leather structure, yet its usage entails significant environmental and health hazards owing to its poisonous properties.The process of heavy metal absorption occurs when plant roots uptake water, leading to the transfer of these metals to animals that consume the plants [30]. Particles of heavy metals absorbed in water tend to settle to the bottom, leading to the buildup of sediments.

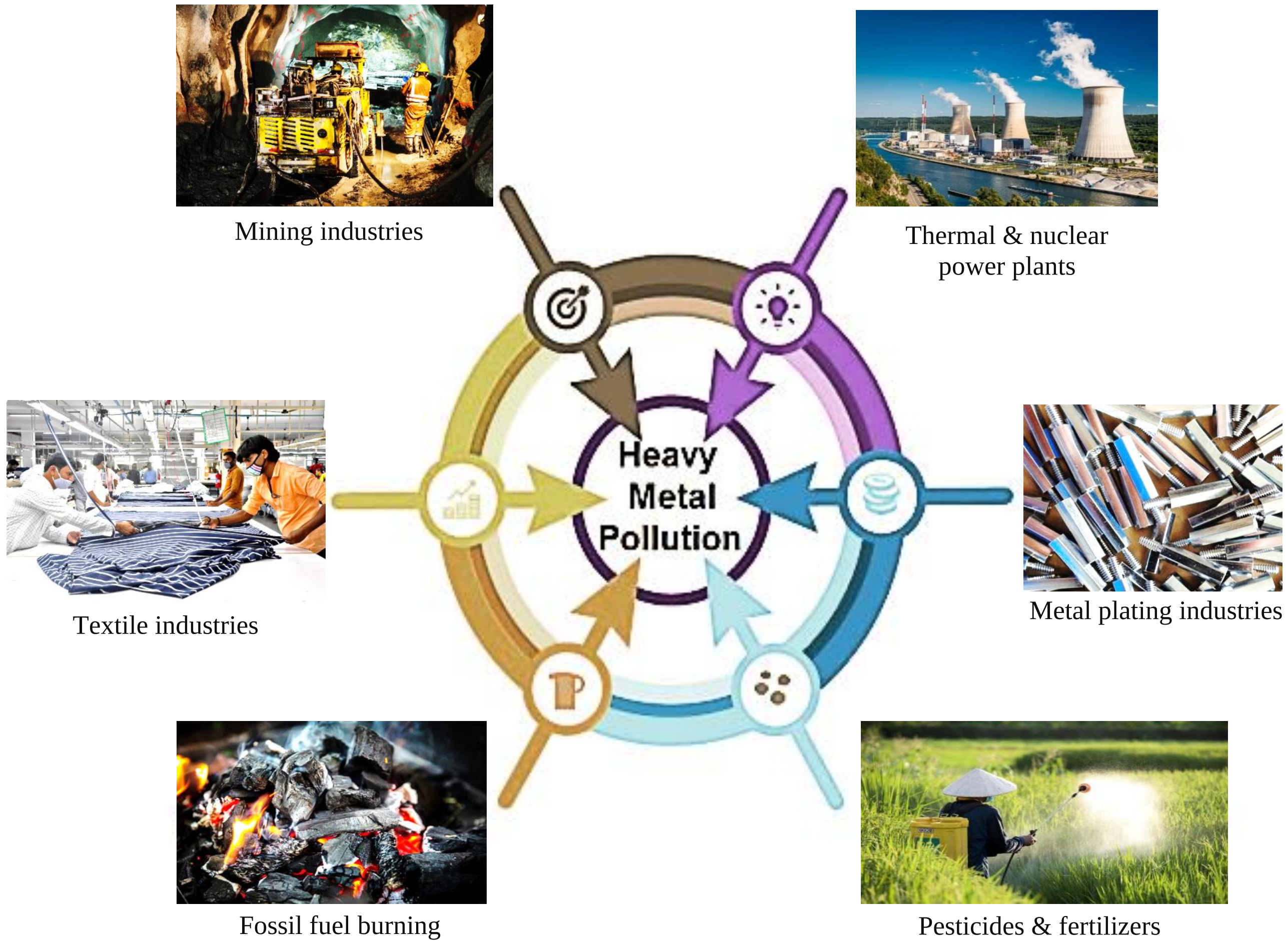

Fig. 3 Different sources of environmental pollution by heavy metals

This accumulation exacerbates the health dangers associated with consuming such water. In the context of human physiology, the consumption of heavy metal ions can generate oxidative stress and subsequently impact cellular organelles and components. One potential illustration is the potential role of arsenic consumption in promoting abnormal gene expression and DNA hypomethylation. According to [31], it has been shown that copper has the potential to contribute to the development of Wilson's disease. In contrast, chromium has been found to promote oxidative stress and DNA damage in human cells.

2.2. Organic Solvents

Organic solvents have a notable impact on the tanning industry, as they are frequently employed in diverse procedures to dissolve and modify the characteristics of leather [32]. Nevertheless, the existence of these substances in the wastewater produced by tanneries has given rise to environmental apprehensions owing to their potential toxicity and adverse effects on aquatic ecosystems. A multitude of research has been undertaken to examine the prevalence, characteristics, and mitigation strategies of organic solvents present in wastewater from tanneries [33].

Volatile Organic Compounds (VOCs) are a prominent category of organic solvents commonly detected in tannery effluents. Volatile Organic Compounds (VOCs), including toluene, xylene, and acetone, have the potential to be discharged into water systems as a result of degreasing, dyeing, and finishing operations [34]. The existence of these solvents not only presents environmental hazards but also provides potential threats to human well-being since exposure to these substances can result in respiratory and neurological complications.

The primary focus of addressing the environmental consequences associated with organic solvents in tannery water has been directed at the use of modern treatment technology [35]. Numerous investigations have been conducted to examine the efficacy of employing biological treatment, activated carbon adsorption, and membrane filtering techniques to efficiently eliminate or diminish the levels of solvents present in wastewater streams. Furthermore, current investigations are being conducted to explore the advancement of environmentally sustainable tanning techniques that depend on alternative solvents or methodologies with less potential for damage.

2.3. Phenolic Compounds

The presence of phenolic chemicals in tannery water presents notable environmental issues as a result of their poisonous and enduring characteristics [26]. Tanneries play a crucial role in facilitating the operations of the leather industry; nevertheless, they also produce significant volumes of wastewater that include phenolic compounds as a byproduct of the tanning process. Compounds such as phenol, cresols, and other polyphenols have a high degree of solubility in water, hence posing a risk of contaminating adjacent water bodies if appropriate management measures are not implemented [27].

Phenolic compounds are well recognized for their deleterious impacts on aquatic ecosystems, as they have the potential to disturb the equilibrium of aquatic species, inflict injury upon fish and other living beings, and even compromise the potability of water supplies for human use. Hence, the implementation of efficient treatment and disposal techniques is vital to minimize the environmental consequences associated with phenolic compounds present in tannery wastewater. This is essential for promoting the long-term viability of the leather industry and safeguarding our finite natural resources [34].

2.4. Sulfides

Sulphides present in tannery water pose a notable environmental problem due to their prevalence as a result of the leather tanning process [35]. Tanneries utilize a range of chemical agents and procedures to convert unprocessed animal hides into functional leather, with one common procedure being the application of sodium sulphide or other sulphur-based compounds. These chemical agents facilitate the removal of hair and other undesired substances from animal skins, albeit concurrently leading to the discharge of sulphides into wastewater [16].

The presence of sulphides in tannery water might adversely impact the surrounding ecosystem. When introduced into rivers or other aqueous environments, they have the potential to contribute to water pollution and adversely impact the biodiversity of aquatic organisms [36]. Sulphides exhibit toxicity towards several aquatic creatures, hence posing a potential disruption to the ecological equilibrium within ecosystems. Moreover, the interaction between sulphides and other chemical compounds present in water can result in the formation of hydrogen sulphide gas, characterized by its unpleasant smell and potential health hazards for both people and animals [37]. Efforts aimed at mitigating the adverse effects of sulphides in tannery water encompass the use of wastewater treatment technologies capable of eliminating or neutralizing these compounds before their release. Regulations have been implemented in several regions to restrict the content of sulphides in industrial effluent, hence promoting the adoption of cleaner and more sustainable tanning practices by tanneries [38].

By acknowledging the presence of sulphides in tannery wastewater, efforts may be made to foster a more conscientious and environmentally sustainable leather manufacturing sector [39].

2.5. Ammonia

Ammonia, a chemical molecule, is frequently present in tannery water, where it assumes a notable function in both the tanning procedure and the following wastewater treatment [40]. Ammonia is frequently employed in tanneries to regulate the pH levels of water, which is an essential procedure within the leather manufacturing process [38]. The process aids in the facilitation of hair and other undesirable substances extracted from animal skins, rendering them appropriate for the tanning process. Nevertheless, after the tanning process, there is a generation of effluent containing high ammonia levels, which gives rise to significant environmental issues [39].

The possible ecological impact of ammonia in tannery effluent is a matter of concern. Ammonia possesses toxicity towards aquatic organisms, and its introduction into water bodies without adequate treatment can result in the contamination of water and disturbance of ecosystems [40]. Hence, tanneries must use efficient wastewater treatment methodologies to eliminate ammonia and other contaminants before discharging the treated effluent into the surrounding ecosystem [41].

Various approaches, including biological treatment, chemical precipitation, and ion exchange, are employed to manage ammonia in tannery water. These technologies allow the reduction of ammonia levels to permissible thresholds, guaranteeing that the effluent from tanneries complies with environmental standards and minimizes its ecological repercussions in the surrounding areas [42]. In summary, the proper handling and treatment of ammonia are imperative in tannery operations to effectively address its possible environmental consequences.

2.6. Volatile Organic Compounds (VOCs)

Organic substances belonging to the class known as "volatile organic compounds" (VOCs) are sometimes found in tannery water. Many distinct chemical procedures are utilized to create leather, and these processes are responsible for the bulk of VOCs [43]. The production of gaseous pollutants, also known as VOCs, can have toxic effects on humans and ecosystems. The emissions might have negative effects on both parties. During the production and finishing stages of leather skin treatment, VOCs may be emitted into the environment as a result of the use of solvents, dyes, and chemicals. These substances could be harmful to the human body. If this situation continues, the air quality might deteriorate [44]. Effluent from the tannery contains VOCs, which can damage nearby air and water supplies and should raise serious concerns. The potential exists for these chemicals to react with other atmospheric pollutants, resulting in an increase in ground-level ozone and smog generation in the event of their release into the environment [45]. It is possible that these phenomena may lead to an increase in smog and ground-level ozone, both of which can have harmful effects on people's respiratory systems and the environment. Tannery effluent is known to contain VOCs and, if not properly managed, can contribute to the pollution of surface and groundwater, endangering aquatic ecosystems and perhaps affecting human regions farther downstream [46].

Water used in tanning operations often contains VOCs; hence, tanneries must establish effective wastewater treatment practices. The only way to guarantee that water is free of VOCs before being released into the environment is to use cutting-edge treatment technologies, such as activated carbon adsorption or biological treatment [47]. Stringent rules and environmental standards have been implemented to restrict the quantity of VOCs in industrial effluent. These measures aim to promote responsible operations inside tanneries and mitigate their adverse effects on air and water quality [48]. In summary, the effective management and mitigation of VOCs present in tannery water are imperative for the leather industry to achieve sustainable operations and minimize its environmental impact.

2.7. Dyes and Pigments

Dyes are a category of water contaminants that possess both environmental toxicity and the ability to modify the color of the water. It is estimated that around 10,000 dyes have been utilized in industrial applications, with an annual global synthesis of 0.7 million tonnes. Discharging a significant volume of dyes through wastewater from sectors such as tanning, textile, paper, and printing has been identified as a substantial environmental concern [49].

The presence of dye molecules obstructs or diminishes the ingress of sunlight into the water flow, diminishing photosynthetic activity and impacting the aquatic ecology. The use of dyes in humans is associated with carcinogenic and mutagenesis effects, as well as anomalies and malfunction in the brain, kidney, liver, and cerebrospinal neurological system [50]. The wastewater generated by tanneries has the potential to include leftover dyes and pigments that are utilized throughout the process of coloring leather. These factors can potentially result in water discoloration and may contain compounds that pose a risk to human health and the environment [51].

2.8. Pesticides and Herbicides

Pesticides and herbicides, while not inherently linked to the process of leather manufacture, may occasionally infiltrate tannery water as pollutants that originate from agricultural runoff or surrounding farming practices. The presence of these compounds in tannery effluent gives rise to a notable apprehension [52]. Pesticides are specifically formulated to regulate or eradicate undesired pests, whilst herbicides are employed to manage undesirable vegetation. The introduction of these chemicals into tannery water can result in detrimental consequences for both the environment and human health [53].

The potential for pesticides and herbicides to infiltrate water sources, which afterwards serve as the water supply for tanneries, can result from the runoff originating from agricultural areas. This process may increase pollution in the surrounding area [54]. Effluent from tanneries may include persistent and accumulating chemicals and herbicides, endangering aquatic habitats and the creatures who depend on them [55]. Furthermore, the presence of these compounds has the potential to disrupt the correct functioning of wastewater treatment operations, posing difficulties in efficiently removing these compounds before their release into the local environment [56].

Water used in the tanning process may include pesticides and herbicides, making it imperative that tanneries regularly monitor and manage the quality of their water sources in their operational operations. Wastewater may be effectively treated with cutting-edge techniques, including activated carbon filtration and sophisticated oxidation procedures to reduce the concentrations of these pollutants [37].

The reduction of pesticide and herbicide contamination in tannery water might be hastened by the establishment of cooperative efforts between tanneries and agricultural stakeholders, which could reduce the usage of these chemicals in neighboring fields. One of the best strategies to prevent pesticide and herbicide contamination in tannery water is to reduce the usage of these chemicals in neighboring farms. If the tanning business acknowledges this problem and actively works to fix it, it can help protect the environment and boost the quality of its leather products [16].

2.9. Oils and Plastics

Oil is a notable water contaminant that is discharged into water bodies as a result of wastewater generated by petroleum companies [7]. Oil spills are widely recognized as the primary contributors to the occurrence of oil contamination in aquatic environments. Transportation oil spills account for around 13% of oil pollution.

The dispersion of oil on the surface of water leads to a decrease in the penetration of sunlight, disrupting the process of photosynthesis in marine plants [38]. Furthermore, it modifies the oxygen concentration in aquatic environments by decreasing the dissolved oxygen level. The adhesion of oil to the plumage of aquatic avian species obstructs the respiratory system of marine organisms, ultimately resulting in their demise.

Consequently, the food chain undergoes an impact that subsequently gives rise to potential health risks in human populations as well. Plastic is widely present in marine environments, introduced by poor land-based disposal practices or inadequate waste management systems. Marine creatures are drawn to plastics based on their color and odor [39].

The ingestion of plastics by marine creatures results in the accumulation of hazardous compounds in their stomachs, hence diminishing their ability to swallow food. The existence of these minute organic contaminants within the wastewater generated by tanneries presents considerable obstacles for both wastewater treatment plants and regulatory bodies responsible for environmental oversight [40].

Implementing appropriate methods for treating and disposing of tannery wastewater is crucial to effectively address the adverse environmental consequences associated with its release. This frequently entails using sophisticated treatment techniques such as coagulation, flocculation, biological treatment, and occasionally, membrane filtration to eliminate or diminish these contaminants to permissible thresholds before their release into aquatic systems or the surrounding ecosystem [58].

3. Treatment Technologies for Tannery Wastewater

The use of treatment methods for tannery wastewater is crucial to address the environmental and health risks that arise from the release of untreated or inadequately treated wastewater originating from leather tanneries [59]. Tannery wastewater is commonly distinguished by elevated concentrations of organic matter, suspended particles, heavy metals, and chemicals employed in the tanning procedure [60].

Implementing efficient treatment measures to eliminate or diminish the presence of these pollutants is imperative before the release of water into the environment or its reuse. Figure 4 shows the schematic illustration of various techniques of tannery wastewater treatment.

3.1. Conventional Treatment Methods

Treating wastewater from tanneries encompasses a series of stages to reduce the environmental consequences associated with the discharge of heavily contaminated effluents produced in leather manufacturing plants. The therapies may be classified into three main modalities, namely primary, secondary, and tertiary [61]. The first stage in treating tannery effluent is known as primary treatment. The phenomenon encompasses physical processes, namely sedimentation and coagulation. During the sedimentation process, the solid particles within a tank undergo a settling mechanism, resulting in the formation of sludge [62]. Additionally, coagulants are introduced into the system to facilitate the agglomeration of smaller suspended particles.

The primary objective of this stage is to eliminate bigger solid pollutants and some organic substances. Secondary treatment is a subsequent step that succeeds the first treatment and is primarily concerned with the biological breakdown of organic contaminants [63].

During this phase, the wastewater undergoes either aerobic or anaerobic processes, wherein microorganisms facilitate the decomposition of the residual organic substances. Aerobic therapy is predicated upon the presence of oxygen to facilitate microbial action, whereas anaerobic treatment takes place in an oxygen-deprived environment. Both approaches effectively decrease the organic content present in the wastewater and enhance its overall quality [64].

Secondary treatment may not effectively remove all hazardous trace organic contaminants present in tannery effluent. The composition and impact of pollutants can exhibit variability contingent upon several aspects, including the method of tanning employed, the individual chemical agents utilised, and the efficiency of wastewater treatment measures [65]. Table 2 shows the prevalent harmful trace organic contaminants that have the potential to be present in tannery effluent subsequent to undergoing secondary treatment, accompanied by their respective potential impacts.

Tertiary treatment constitutes the ultimate phase in the treatment of tannery wastewater, specifically intended to enhance the quality of the effluent further in order to comply with rigorous environmental regulations [66]. This phase utilises sophisticated methodologies such as chemical coagulation, filtering, and adsorption.

Chemical coagulation is employed to eliminate any leftover suspended materials effectively, and filtering and adsorption methods are utilised to address residual organic and inorganic pollutants [67] specifically. The use of tertiary treatment processes guarantees that the wastewater that has undergone treatment is suitable for release into bodies of water or for utilisation in non-potable applications.

In brief, the management of tannery wastewater entails a methodical process that advances from primary to secondary and, ultimately, to tertiary treatment techniques [68]. Every stage in the process plays a crucial role in mitigating the environmental effects of tannery operations, ensuring the preservation of water quality, and adhering to legal obligations [69]. Conventional treatment methods are extensively employed across many sectors and municipal wastewater treatment facilities to eliminate pollutants and toxins from water and wastewater streams. The methods often employed encompass physical, biological, and chemical treatment procedures, each serving distinct purposes and finding specialized applications [66]. Figure 5 depicts the different tannery treatments.

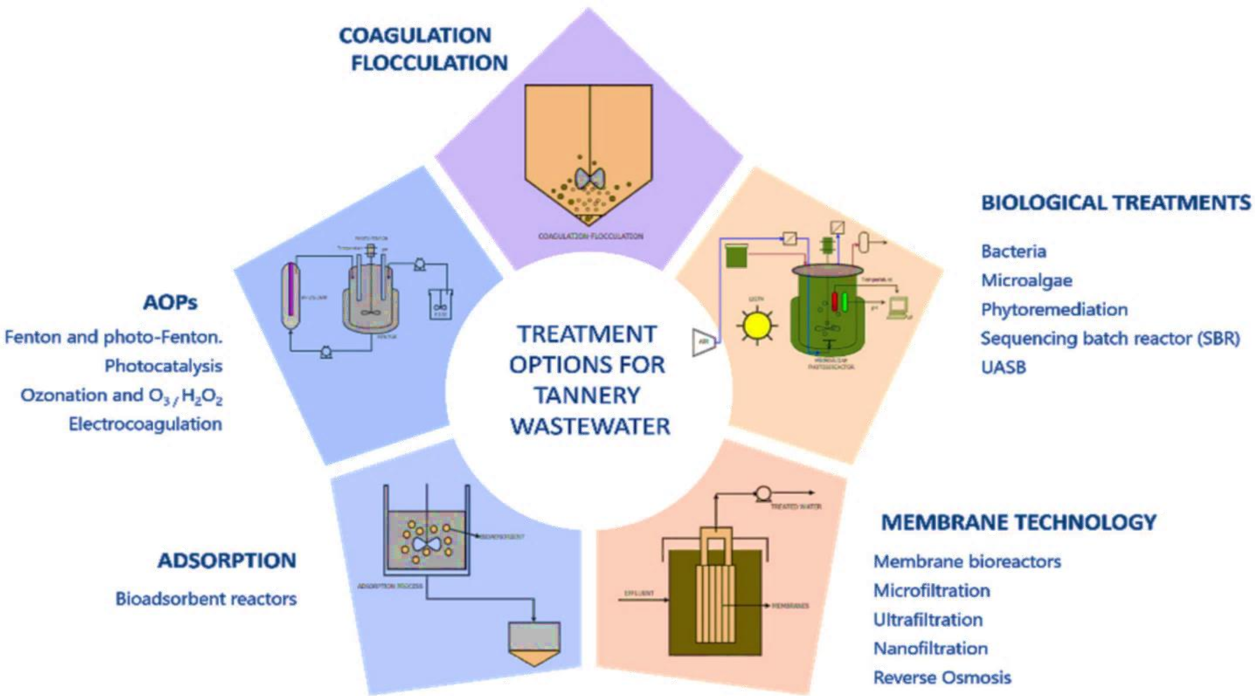

Fig. 4 Techniques of tannery wastewater treatment

Table 2. Toxic trace organic pollutants present in tannery wastewater after secondary treatment and their effects

Pollutant	Potential Effects
Chromium (Cr)	- Carcinogenic when hexavalent (Cr(VI)).
	- Can damage DNA and cause respiratory problems.
	- Bioaccumulates in aquatic organisms.
Arsenic (As)	- Carcinogenic.
	- Can cause skin, lung, and bladder cancer.
	- Harmful to aquatic life.
Lead (Pb)	- Neurotoxic; can damage the nervous system.
	- Impairs cognitive development in children.
	- Harmful to aquatic organisms.
Cadmium (Cd)	- Carcinogenic.
	- Kidney damage and bone disorders.
	- Bioaccumulates in aquatic organisms.
Benzene	- Carcinogenic; associated with leukemia.
	- Affects the central nervous system.
	- Can contaminate groundwater.
Toluene	- Neurological effects, such as dizziness and impaired coordination.
	- Irritates the respiratory system.
Formaldehyde	- Carcinogenic.
	- Irritates the eyes, nose, and throat.
	- Can cause respiratory problems.
Naphthalene	- Can damage red blood cells (hemolysis).
	- Associated with cataracts and skin disorders.
Phenols	- Can be toxic to aquatic life.
	- Skin and eye irritation in humans.
	- Disrupt endocrine systems in aquatic organisms.
Polycyclic Aromatic Hydrocarbons (PAHs)	- Carcinogenic; some PAHs are potent carcinogens.
	- Respiratory and skin irritation.
	- Can bioaccumulate in aquatic ecosystems.

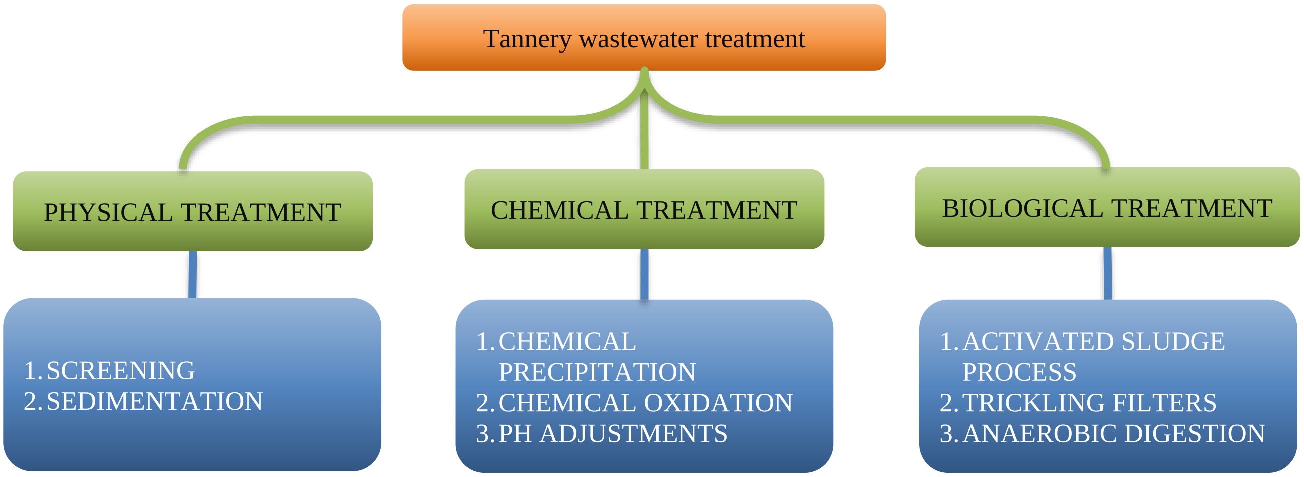

Fig. 5 Different tannery treatment

The following is a comprehensive summary of the traditional treatment modalities:

3.1.1. Physical Treatment

Screening

Screens or grates are used to filter out trash and other big particles from wastewater during the screening process. This method is useful because it helps keep downstream machinery free of obstructions [70].

Sedimentation

Wastewater can be treated by allowing solid particles to sink to the bottom of a sedimentation tank. This method is ideal for removing solids that can be settled [71].

3.1.2. Biological Treatment

Activated Sludge Process

Microbial bioremediation is a prevalent biological treatment approach that employs microorganisms, predominantly bacteria, to degrade organic substances present in wastewater. The process entails the utilization of aeration and settling tanks to facilitate the proliferation of microorganisms and the segregation of biomass from the treated water [72].

Trickling Filters

Trickling filters employ a medium, such as pebbles or plastic, as a substrate for the cultivation of biofilms consisting of microorganisms. The wastewater is distributed in a trickling manner over the medium, facilitating the metabolic activity of microorganisms responsible for biodegradation and subsequent removal of organic contaminants [70].

Anaerobic Digestion

The process of anaerobic digestion is employed to treat the sludge produced as a byproduct of wastewater treatment. In an environment devoid of oxygen, anaerobic bacteria engage in the decomposition of organic materials, resulting in the generation of biogas and the stabilization of the sludge [73].

3.2. Chemical Treatment

3.2.1. Chemical Precipitation

Chemical agents are introduced into wastewater to facilitate the formation of insoluble precipitates with targeted contaminants. Subsequently, the aforementioned precipitates can be effectively isolated from the aqueous solution using sedimentation or filtration techniques. Frequently employed substances encompass coagulants, such as alum or ferric chloride, and flocculants, including polymers [52].

3.2.2. Chemical Oxidation

Chemical oxidants such as chlorine or ozone are employed to decompose or oxidize contaminants present in wastewater chemically. The aforementioned procedure demonstrates efficacy in eradicating both organic and inorganic pollutants [53].

3.2.3. pH Adjustment

The process of pH adjustment is employed to regulate the levels of acidity or alkalinity in wastewater. The use of acids or bases serves to optimize the conditions for various treatment procedures and mitigate the occurrence of equipment corrosion [54]. The use of traditional treatment methods can be employed either independently or in conjunction, contingent upon the distinctive attributes of the wastewater and the intended objectives of the treatment process [55].

The selection of treatment methodologies frequently relies on several aspects, including the characteristics of the pollutants, the quantity of wastewater requiring treatment, financial concerns, and compliance with regulatory standards. To comply with rigorous water quality regulations, supplementary treatment technologies of a more advanced kind may be utilized alongside conventional procedures.

3.3. Limitations of Conventional Methods in Removing Trace Organic Pollutants

The existing approaches to eliminating trace organic contaminants from water and wastewater are subject to various constraints [56]. Consequently, researchers have undertaken investigations into alternative and enhanced treatment methods. Several significant drawbacks are associated with traditional approaches.

3.3.1. Incomplete Removal

Traditional treatment techniques, including coagulation, sedimentation, and filtration, frequently exhibit limited efficacy in eliminating trace organic contaminants [57]. Numerous organic molecules exhibit resistance against physical and chemical treatment methodologies, resulting in inadequate elimination and the possibility of adverse consequences on the environment and human health [58].

3.3.2. Limited Specificity

Traditional approaches are not specifically tailored to address certain organic contaminants. Physical or chemical procedures are utilized, which have the potential to eliminate both pollutants and non-hazardous substances [59]. However, this might lead to the production of waste streams and an escalation in treatment expenses.

3.3.3. Environmental Impact

Certain traditional techniques, including chlorination, have the potential to generate detrimental disinfection byproducts upon interaction with organic contaminants [60]. The presence of these byproducts may give rise to supplementary hazards to both human health and the environment.

3.3.4. Energy Intensive

Methods such as activated carbon adsorption as well as air stripping have the potential to use significant amounts of energy, hence leading to elevated operational expenses for treatment facilities [61].

3.3.5. Resilience to Biodegradation

Certain types of trace organic contaminants, such as medicines and personal care items, have low biodegradability in microorganisms present in wastewater treatment facilities, hence diminishing the efficacy of biological treatment methods [62].

3.3.6. Generation of Sludge and Waste

Numerous conventional techniques produce sludge or waste byproducts, necessitating their disposal or subsequent treatment, contributing to the total operating expenses and environmental consequences [63].

3.3.7. High Capital and Operating Costs

The cost associated with the installation and maintenance of traditional treatment systems can pose a significant financial burden, particularly for smaller towns or developing countries that have limited resources at their disposal [64].

3.3.8. Limited Capacity for Emerging Contaminants

Traditional treatment approaches may not be adequately equipped to mitigate emerging contaminants effectively since they cannot effectively manage the diverse array of novel and developing trace organic pollutants.

3.3.9. Variability in Efficiency

The efficacy of traditional approaches may fluctuate based on factors such as the characteristics and concentration of organic contaminants, the quality of water, and the conditions in which the procedures are implemented [65]. Attaining consistent rates of elimination might be a significant challenge. To overcome these constraints, scholars and practitioners have undertaken investigations into sophisticated water treatment methodologies, including Advanced Oxidation Processes (AOPs), membrane filtration, nanotechnology-based approaches, and advanced sorbent materials [66]. These technologies exhibit enhanced capabilities in eliminating trace organic pollutants and demonstrate heightened selectivity in targeting contaminants of particular concern [67]. Modern techniques frequently offer enhanced and economically viable approaches for the remediation of water polluted with minute amounts of organic contaminants.

4. Advanced Treatment Methods

Advanced techniques for treatment are employed to enhance the purification of water and wastewater to more stringent standards, therefore eliminating pollutants that may not be adequately addressed by traditional treatment approaches [68]. The following information pertains to the advanced treatment procedures that have been referenced:

4.1. Membrane Filtration Techniques

4.1.1. Ultrafiltration (UF)

Ultrafiltration (UF) is a form of membrane filtration that employs semi-permeable membranes characterized by pore diameters generally falling within the spectrum of 0.01 to 0.1 micrometers. The process effectively removes particulates, germs, and some pathogens from water [69].

4.1.2. Nanofiltration (NF)

Nanofiltration (NF) employs membranes characterized by lower pore sizes compared to Ultrafiltration (UF), often falling within the range of 0.001 to 0.01 micrometers. The filtration process can eliminate minute particles, organic substances, and certain ions, rendering it advantageous for water-softening purposes and eliminating certain impurities [70].

4.1.3. Biofiltration (BF)

The utilization of biofiltration has proven to be a very efficient and environmentally sustainable approach in the remediation of tannery effluent.

Tanneries are widely recognised for producing effluent that contains a range of contaminants, such as organic compounds, heavy metals, and hazardous chemicals.

Table 3. Potential improvements or modifications to enhance biofiltration in tannery wastewater treatment

Improvement/Modification	Description
Selection of Microorganisms	Choose specific strains of bacteria and fungi with a high tolerance for tannery wastewater pollutants to improve treatment efficiency.
Media Type	Experiment with different filter media (e.g., peat, activated carbon, zeolite) to optimize the removal of specific contaminants.
pH Control	Implement pH adjustment to create optimal conditions for microbial activity, as tannery wastewater can be highly acidic or alkaline.
Temperature Control	Maintain a consistent temperature within the biofilter to promote microbial activity, potentially through heating or cooling systems.
Nutrient Addition	Supplement nutrients like nitrogen and phosphorus to support microbial growth and enhance pollutant degradation.
Microbial Diversity	Encourage the growth of diverse microbial communities to effectively tackle a wider range of pollutants.
Pre-Treatment	Install a pre-treatment step to remove large solids and grease before biofiltration, preventing clogging and extending the media's lifespan.
Monitoring and Control	Implement advanced monitoring and control systems, such as online sensors, to optimize operational parameters in real-time.
Recirculation	Consider recirculating treated effluent to improve contact time between microorganisms and pollutants.
Bioaugmentation	Introduce specialized microorganisms into the biofilter to enhance the degradation of specific recalcitrant contaminants.
Scale-up	Evaluate the scalability of the biofiltration system to accommodate varying tannery wastewater volumes.
Hybrid Systems	Combine biofiltration with other treatment methods like activated sludge or membrane filtration to achieve higher efficiency.
Green Energy	Explore using renewable energy sources to power biofiltration systems, reducing operational costs and environmental impact.
Post-Treatment	Implement additional treatment steps, such as adsorption or chemical precipitation, after biofiltration to polish the effluent further.
Research and Development	Invest in ongoing research and development to identify novel approaches and technologies for improving tannery wastewater biofiltration.

Biofiltration utilises the metabolic capabilities of microorganisms to degrade and eliminate these pollutants, hence presenting a viable and effective approach from an environmental sustainability standpoint [71]. Certainly, Table 3 is a simplified table outlining some potential improvements or modifications that can be made to enhance biofiltration in tannery wastewater treatment.

Within the context of a biofiltration system, the wastewater is purposefully channelled through a layer of either organic or inorganic media. This medium serves as a habitat for a wide array of microorganisms, including bacteria, fungus, and other microbial entities, which flourish and thrive within this environment [72]. The bacteria in question derive sustenance from the organic stuff found within the wastewater, subsequently transforming it into less complex and less deleterious chemicals via biological mechanisms such as oxidation and reduction. Consequently, the pollutants undergo a process of transformation into less harmful states or undergo total mineralization, so ensuring that the effluent is suitable for release into the environment or for subsequent treatment [73].

One of the primary benefits associated with the utilization of biofiltration in the treatment of tannery effluent is its capacity to manage a diverse array of pollutants effectively, hence reducing reliance on chemical treatments and energy-intensive procedures [74]. Moreover, this alternative process generates a reduced quantity of detrimental byproducts compared to traditional treatment approaches, rendering it an environmentally viable option for enterprises aiming to mitigate their ecological footprint.

Nevertheless, the effective execution of biofiltration necessitates meticulous surveillance and upkeep to guarantee the optimal functioning of the microbial populations and the durability of the filtration materials [75].

In brief, biofiltration presents a potential and ecologically conscientious strategy for addressing the environmental complexities associated with tannery effluent. Implementing these enhancements and adjustments can effectively customize biofiltration systems to address the unique complexities associated with tannery effluent, resulting in enhanced efficacy and sustainability of treatment procedures.

4.2. Advanced Oxidation Processes (AOPs)

4.2.1. Ozone Treatment

Ozone (O3) functions as a very effective oxidizing agent utilized to decompose and remove organic and inorganic contaminants found in water. The treatment exhibits effectiveness in resolving issues related to taste and odor, reducing discoloration, and offering disinfection [76].

4.2.2. Photocatalysis

Photocatalytic techniques include using a catalyst, commonly titanium dioxide, combined with ultraviolet (UV) radiation to accelerate the degradation of organic pollutants found in water. The aforementioned technique has significant effectiveness in the degradation of organic compounds, making it well-suited for use in the fields of water purification as well as wastewater treatment [77].

4.3. Adsorption Techniques

4.3.1. Activated Carbon

Activated carbon is a material that possesses notable porosity and a large surface area, allowing it to adsorb various organic and inorganic contaminants found in water efficiently. The procedure is commonly utilized to remove taste and odor constituents, organic compounds, and specific heavy metals [11].

4.3.2. Molecular Sieves

Molecular sieves are distinguished by their well-defined crystalline structure and feature uniform pores, allowing them to demonstrate discerning adsorption characteristics towards molecules, which depend on their sizes and polarities. These devices are utilized to remove certain pollutants, such as decreasing calcium and magnesium ions to achieve water softening [12].

The application of these advanced treatment techniques is commonly employed in combination with each other or with conventional treatment methods to achieve the desired water quality standards [13]. The choice of approach depends on the specific contaminants present in the water, the desired standards for water quality, and the goals of the treatment procedure. In addition, the evaluation of each approach's cost, energy requirements, and feasibility play significant roles in identifying the most suitable treatment alternative [14]. Table 4 lists the advantages and disadvantages of tannery wastewater treatments.

5. Biological Treatment and Microbial Remediation

5.1. Microbial Degradation of Organic Pollutants

The microbial degradation process plays a crucial role in the cleanup of tannery wastewater, characterized by high levels of organic contaminants, heavy metals, and several other toxic substances. Microorganisms, specifically bacteria and fungi, can decompose and transform organic pollutants into less harmful substances through various biological processes [15]. This research presents a thorough examination of the application of microbial degradation throughout the remediation of tannery wastewater. Figure 6 depicts different bioremediation techniques.

5.1.1. Aerobic Biological Treatment

Activated Sludge Process

The present study outlines an aerobic treatment methodology that utilizes microorganisms, including bacteria and protozoa, to enhance the breakdown of organic matter in the presence of oxygen [16]. The effluent originating from tanneries is mixed with a sludge matrix that harbors microorganisms, enabling the process of oxidizing organic pollutants. This process leads to the transformation of these contaminants into carbon dioxide, water, and microbial biomass [16].

Sequencing Batch Reactors (SBR)

The Sequential Batch Reactor (SBR) systems utilize a sequence of discrete operations, including loading, reacting, settling, and decanting, to treat wastewater efficiently. During the process of microbial degradation, organic pollutants are broken down by microorganisms in the presence of oxygen, which is referred to as the reaction phase [17].

5.1.2. Anaerobic Biological Treatment

Anaerobic Digestion

During this particular process, microorganisms carry out anaerobic digestion, wherein they metabolize complex organic molecules to produce biogas consisting of methane and carbon dioxide, as well as stabilized sludge [18]. Although this approach is predominantly employed for treating organic sludge, it may also be effectively utilized for the remediation of tannery wastewater characterized by a significant organic load [19].

5.1.3. Fungal Treatment

White-rot fungi, exemplified by Phanerochaete chrysosporium and Trametes versicolor, have been recognized for their capacity to decompose intricate organic contaminants, encompassing lignin-like substances present in wastewater generated by tanneries. These fungal organisms are capable of synthesizing enzymes such as lignin peroxidase and manganese peroxidase, which facilitate the degradation of resistant organic compounds [20].

5.1.4. Composting

Microbial composting techniques can be employed to treat tannery sludge characterized by the presence of organic materials. The present methodology involves the enzymatic degradation of organic matter by microorganisms present in the sludge, leading to the formation of a compost product that exhibits stability and may be effectively utilized for land application purposes [23].

Table 4. Advantages and disadvantages of tannery wastewater treatments

Methodology	Advantages	Disadvantages
Physical Treatment	Effective for removing solids and sediments	Limited effectiveness for organic pollutants
	Simple operation and maintenance	It may require pre-treatment for organic removal
	Low operational cost	Not suitable for complete wastewater treatment
Chemical Treatment	Effective for removing heavy metals	High chemical costs
	Can improve odor control	Generation of sludge and chemical waste
	Suitable for pH adjustment	Potential for chemical residue in treated water
Biological Treatment	Effective for organic pollutant removal	Requires skilled operation and monitoring
	Reduces BOD and COD levels	Longer retention times may be needed
	Produces less chemical waste	Vulnerable to shock loads and temperature changes
Membrane Filtration	High removal efficiency for pollutants	High operational and maintenance costs
	Can treat a wide range of contaminants	Membrane fouling and replacement costs
	Compact system design	Energy-intensive process
Adsorption	Effective for removing organic compounds	Requires regular regeneration or replacement
	Can remove color and odor compounds	Limited adsorption capacity
	Versatile adsorbents available	May generate hazardous waste during regeneration
Advanced Oxidation Processes (AOPs)	Effective for recalcitrant pollutants	High energy consumption
	Can degrade a wide range of contaminants	It may require chemical additives
	It can be applied as a tertiary treatment	Treatment efficiency depends on the conditions
Constructed Wetlands	Natural and sustainable treatment approach	Limited removal of heavy metals and salts
	Aesthetic value and wildlife habitat	Requires sufficient land area
	Low operational and maintenance costs	Slower treatment compared to other methods

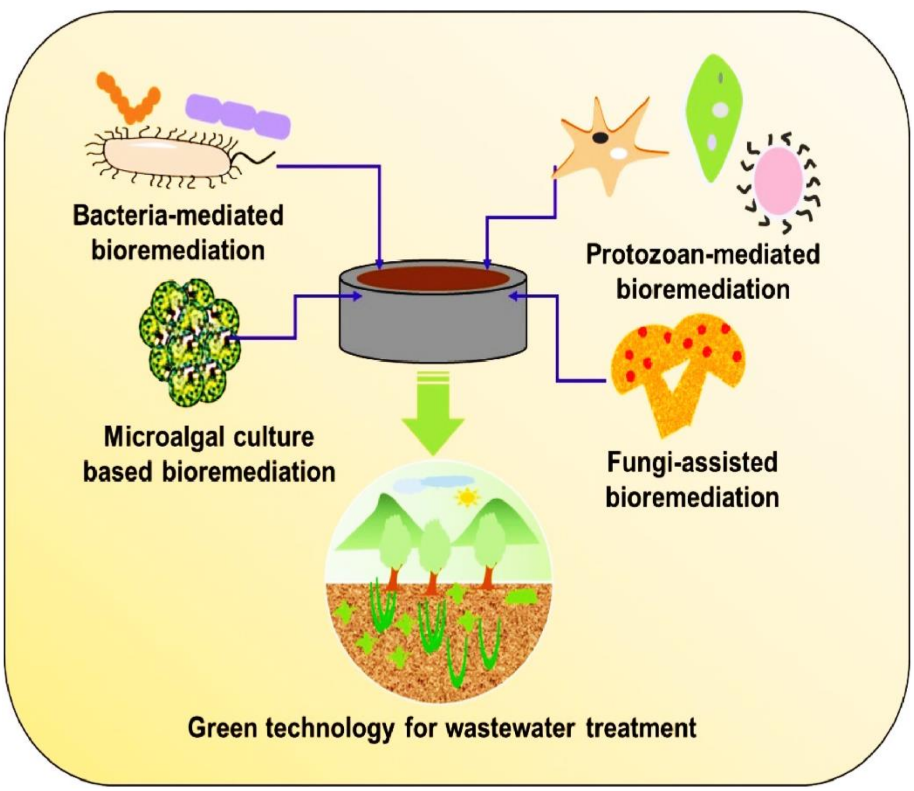

Fig. 6 Different bioremediation techniques

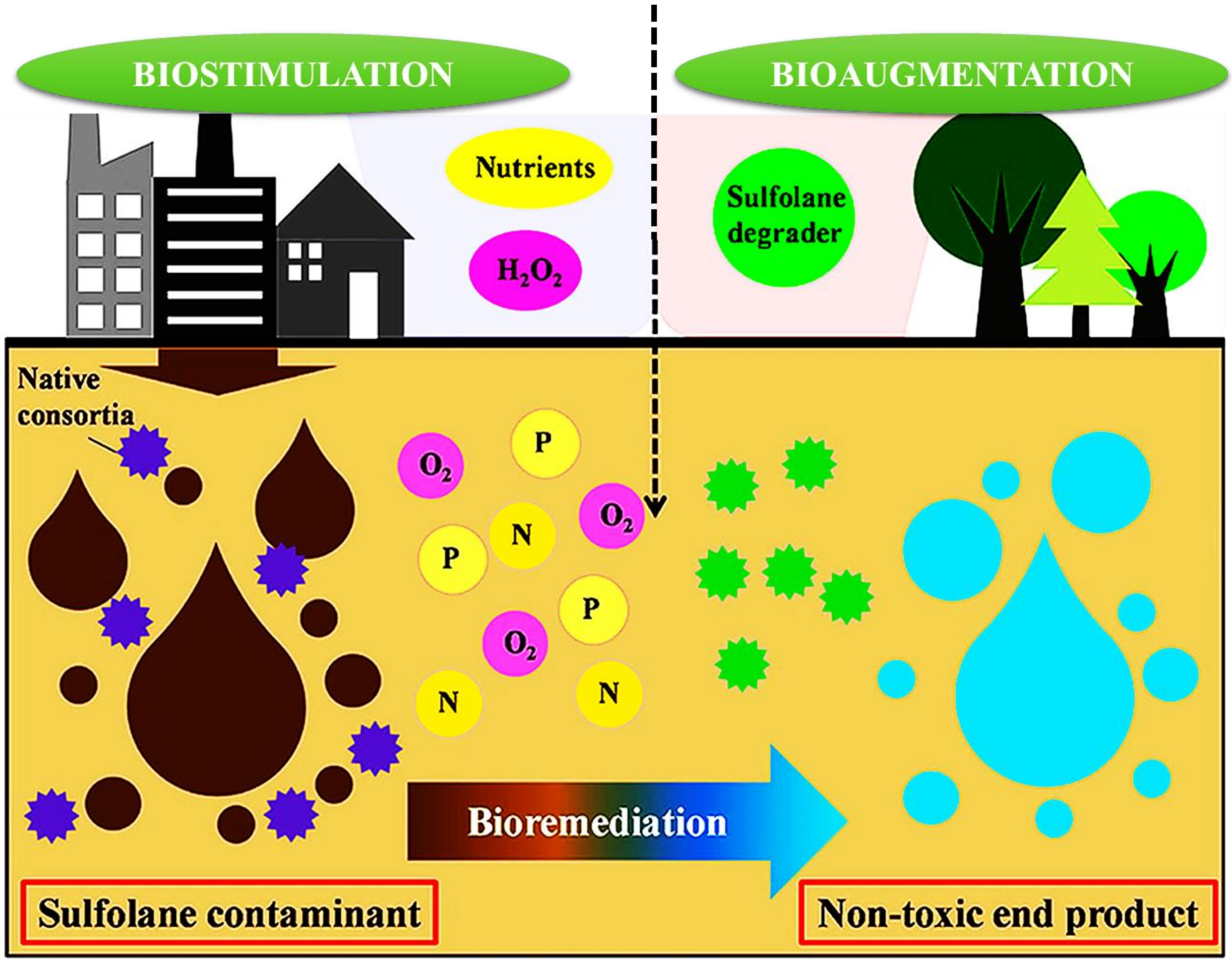

Fig. 7 Mechanism of biostimulation and bioaugmentation

5.1.5. Phytoremediation

Although phytoremediation is not inherently a microbial process, it can be effectively integrated with microbial degradation techniques. Several plant species can uptake and accumulate heavy metals present in tannery wastewater, resulting in a decrease in their concentrations within the effluent. This process facilitates the subsequent microbial breakdown of organic contaminants, enhancing overall treatment efficiency [24]. It is imperative to acknowledge that the efficacy of microbial degradation in treating tannery effluent is contingent upon many aspects, including the kind and quantity of contaminants, pH levels, temperature, and the individual microorganisms employed. Implementing effective monitoring and control measures for these parameters is crucial to guarantee the efficient and ecologically sustainable treatment of tannery effluent [25].

5.2. Bioaugmentation and Biostimulation Strategies

Bioaugmentation and biostimulation are widely employed techniques in the remediation of tannery wastewater, aimed at improving its biodegradability and mitigating its adverse ecological consequences [26]. The wastewater generated by tanneries is distinguished by its elevated levels of organic matter and toxicity, which can be attributed to the diverse range of chemicals employed throughout the leather manufacturing process. Figure 7 shows the mechanism of biostimulation and bioaugmentation. This section discusses the potential use of bioaugmentation and biostimulation techniques in treating tannery effluent.

5.2.1. Bioaugmentation

Bioaugmentation is a process that entails the deliberate introduction of certain microbial cultures or enzymes into a wastewater treatment system to improve the breakdown of pollutants. In the context of tannery wastewater treatment, many bioaugmentation procedures might be implemented [27].

Enzyme Addition

To facilitate the degradation of intricate organic compounds found in tannins and other chemicals utilized during leather processing, it is possible to introduce certain enzymes, such as proteases, lipases, and amylases, into the wastewater [28].

Biodegradable Bacteria

The introduction of strains of bacteria, fungi, or algae that have undergone targeted adaptations to breakdown chemicals associated with tanneries can be implemented inside the treatment system. These bacteria possess a high degree of efficiency in the process of decomposing complex organic compounds [29].

Genetically Engineered Microorganisms (GEMs)

Scientists can engineer genetically engineered microbes that exhibit exceptional efficacy in the degradation of contaminants found in tannery effluent. Nevertheless, it is imperative to exercise meticulous regulation and monitoring of GEM implementation owing to plausible ecological implications [30].

5.2.2. Biostimulation

Biostimulation refers to the process of creating an environment that promotes the development and metabolic activity of native microorganisms that are already present in the wastewater treatment system by supplying them with the required conditions and nutrients [33]. In the context of tannery wastewater treatment, biostimulation can be effectively accomplished by employing the subsequent methodologies:

Nutrient Addition

The introduction of crucial nutrients such as nitrogen, phosphorus, and trace elements has the potential to stimulate the proliferation of microorganisms and augment their metabolic functionality [34].

Adjusting pH

The acidity of tannery effluent is frequently elevated. Modifying the pH level to a state closer to neutrality or slightly alkaline can foster a more conducive setting for the proliferation of microorganisms [35].

Oxygenation

The adequate introduction of air or oxygen into wastewater can potentially improve the aerobic breakdown of organic contaminants by naturally occurring microbes [36].

Temperature Control

The stimulation of microbial activity can be achieved by maintaining an appropriate temperature range. The selection of thermophilic or mesophilic bacteria is contingent upon the prevailing temperature conditions [37].

Co-substrate Addition

The introduction of co-substrates, which are organic molecules that readily degrade, has been shown to facilitate the adaptation of indigenous microbes to the intricate array of contaminants present in tannery effluent [38]. The optimal outcomes in tannery wastewater treatment can be achieved by integrating bioaugmentation and biostimulation approaches [39]. Nevertheless, it is important to closely observe and enhance these procedures to guarantee effective and eco-friendly treatment while simultaneously reducing the production of sludge or other residual materials that may necessitate further handling.

6. Economic and Environmental Considerations

Treating wastewater from tanneries is an essential component of the leather industry since it has significant economic and environmental implications. The tanning process produces substantial volumes of wastewater, including a diverse range of contaminants, including organic substances, heavy metals, and salts [34]. This discussion will examine the economic and environmental dimensions associated with treating tannery effluent.

6.1. Economic Considerations

6.1.1. Compliance with Regulations

The treatment of tannery effluent is frequently mandated by regulatory regulations. Tanneries may incur financial burdens due to the imposition of penalties and legal consequences resulting from non-adherence to environmental standards [40].

6.1.2. Resource Efficiency

Using efficient wastewater treatment methods can facilitate the retrieval of precious resources, including water and chemicals, by tanneries [41]. The implementation of water recycling and chemical reuse practices has the potential to decrease operating expenditures significantly.

6.1.3. Product Quality

The use of effective wastewater treatment methods has the potential to improve the overall quality of leather goods, therefore assuring their compliance with industry regulations and meeting the demands of customers [42]. In the market, items of superior quality can demand higher prices.

6.1.4. Reduced Disposal Costs

The implementation of wastewater treatment processes to achieve compliance with discharge regulations results in a reduction in the expenses associated with the disposal of hazardous waste [43]. Additionally, it serves to mitigate the potential hazards associated with soil and groundwater contamination.

6.1.5. Positive Reputation

Tanneries that place a high emphasis on environmental responsibility and adopting sustainable practices tend to cultivate a favorable image, attracting environmentally concerned clients and partners [44]. Consequently, these tanneries stand to gain financial advantages, eventually enhancing their overall financial performance.

6.2. Environmental Considerations

6.2.1. Pollution Prevention

The wastewater generated by tanneries includes several contaminants, including chromium, sulphides, and organic matter. In the absence of appropriate treatment measures, these pollutants have the potential to cause detrimental effects on both aquatic ecosystems and groundwater resources [45]. The implementation of efficacious interventions mitigates the ecological consequences.

6.2.2. Ecosystem Protection

The discharge of untreated wastewater has the potential to cause significant harm to aquatic organisms and ecosystems. The implementation of appropriate treatment measures plays a crucial role in safeguarding the ecological integrity and overall health of rivers and streams [46].

6.2.3. Reduced Greenhouse Gas Emissions

The anaerobic treatment of wastewater generated by tanneries has the potential to yield biogas, specifically methane, as a secondary product [47]. Using biogas for energy purposes effectively mitigates the release of greenhouse gas emissions.

6.2.4. Resource Conservation

Implementing water and chemical recycling techniques in the tanning process mitigates the need for freshwater and raw materials, making a valuable contribution to the conservation of resources [48].

6.2.5. Compliance with Environmental Laws

Adhering to environmental norms and laws guarantees that tanneries engage in ecologically conscientious practices, hence mitigating adverse impacts on the environment [49].

6.2.6. Public Health

The presence of hazardous compounds in tannery effluent has the potential to pose risks to public health if appropriate treatment measures are not implemented. Implementing wastewater treatment measures plays a crucial role in safeguarding the well-being of populations close to tanneries [50]. To simultaneously address economic and environmental factors in the treatment of tannery wastewater, tanneries have the option to allocate resources towards efficient treatment technologies, implement water and chemical recycling practices, and consistently monitor and optimize their operational procedures [51]. This practice not only contributes to reducing the environmental impact but also has the potential to provide long-term financial savings and enhance market competitiveness.

7. Challenges

The treatment of tannery wastewater is a multifaceted and formidable undertaking owing to the existence of diverse pollutants and toxins [52]. The wastewater generated by tanneries has a combination of organic and inorganic constituents, including heavy metals, organic colors, salts, and elevated concentrations of organic debris [52]. The following are many significant issues that are commonly encountered in the treatment of tannery wastewater:

7.1. High Organic Load

Tannery wastewater is known to have a substantial presence of organic components, such as proteins, lipids, and oils, in elevated concentrations [53]. The presence of a substantial organic load poses challenges when employing traditional technologies for wastewater treatment.

7.2. Toxic Chemicals

Tannery effluent frequently includes hazardous substances, including chromium, employed in the tanning procedure [54]. The presence of these noxious compounds poses potential risks to both human well-being and the natural environment.

7.3. Heavy Metals

The wastewater generated by tanneries has heightened concentrations of heavy metals such as chromium, lead, and cadmium [55]. These metallic elements possess inherent dangers and might potentially cause significant and enduring ecological consequences if not adequately eliminated.

7.4. High Salt Content

The presence of elevated salts in tannery effluents has the potential to impact the effectiveness of biological treatment methods adversely and contribute to the problem of soil salinity upon land disposal [56].

7.5. Variable Composition

The composition of wastewater generated by tanneries exhibits significant variability, mostly attributed to the specific tanning process employed, the types of raw materials utilized, and the procedures employed throughout production [57]. The inherent diversity poses a significant challenge in developing a universally applicable treatment approach.

7.6. Color and Odor

The wastewater generated by tanneries is frequently distinguished by its intense pigmentation and disagreeable scent, rendering it visually unappealing and socially undesirable if discharged without undergoing treatment [58].

7.7. Energy and Resource Intensive

The energy consumption associated with treating tannery effluent can be substantial, particularly in cases where sophisticated treatment methods like membrane filtration or chemical precipitation are necessary [59]. Furthermore, it is important to consider that the sludge generated as a byproduct of the treatment process may require specific protocols for handling and proper disposal.

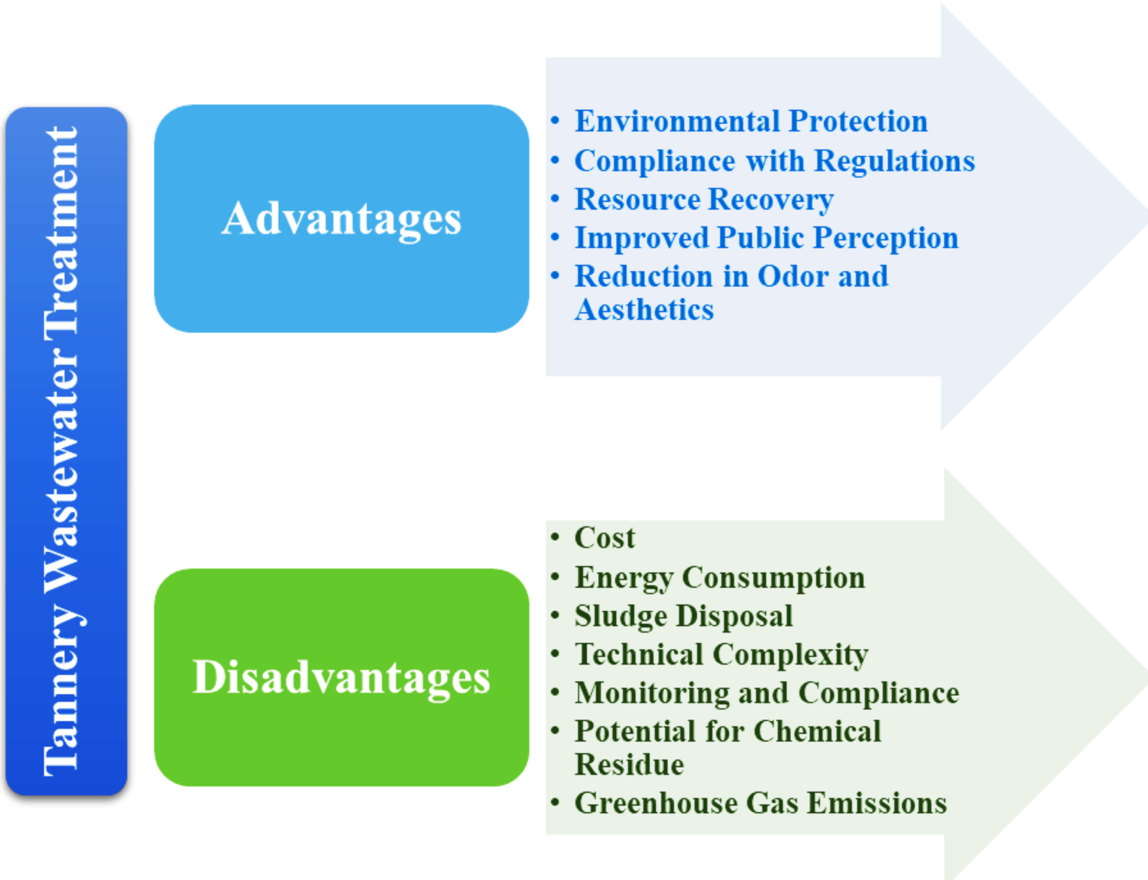

Fig. 8 Advantages and disadvantages of tannery wastewater treatment

7.8. Regulatory Compliance

Tanneries often have difficulty adhering to stringent environmental rules and discharge requirements since failure to comply can lead to financial penalties and legal ramifications [60].

7.9. Cost

Implementing efficient wastewater treatment technologies might pose a financial burden for tanneries, especially for small-scale and artisanal businesses that may face challenges in allocating funds toward acquiring sophisticated treatment infrastructure [61]. To tackle these issues, tanneries frequently adopt a combination of physical, chemical, and biological treatment methods [62]. Potential examples of treatment methods often employed in wastewater treatment include primary and secondary treatment systems, chemical precipitation, activated sludge processes, and modern technologies such as membrane filtration and reverse osmosis [63].

Furthermore, implementing pollution control measures and adopting more sustainable tanning methods can contribute to reducing the overall wastewater load created by tanneries, hence enhancing the manageability of treatment. Figure 8 depicts the overall advantages and disadvantages of tannery wastewater treatment.

8. Future Directions

The forthcoming trajectory of tannery wastewater treatment is anticipated to prioritize sustainability, efficiency, and the incorporation of pioneering technology to tackle the complexities linked to tannery effluents [64]. The following are prospective avenues for future research and development in the field of tannery wastewater treatment:

8.1. Advanced Treatment Technologies

Further investigation and enhancement of cutting-edge treatment technologies, including electrocoagulation, Advanced Oxidation Processes (AOPs), and nanotechnology-based approaches, can potentially enhance the efficacy of eliminating targeted pollutants, such as heavy metals and organic compounds [65].

8.2. Biological Treatment Enhancements

The investigation of genetically modified microbes or designed ecosystems can potentially optimize efficiency and decrease operating expenses in biological treatment methods, such as anaerobic digestion and artificial wetlands [66].

8.3. Resource Recovery

The primary emphasis of advancements in wastewater treatment will be directed toward extracting and recreating valuable materials from tannery effluent. An illustration of this concept is the retrieval of metals such as chromium and the generation of biogas from organic substances, which may effectively transform wastewater treatment into a process that optimizes resource utilization [67].

8.4. Zero Liquid Discharge (ZLD)

The use of Zero Liquid Discharge (ZLD) systems, which aim to minimize the discharge of wastewater from tanneries while simultaneously recovering important salts and chemicals, has the potential to effectively mitigate the environmental consequences associated with these industries and enhance their overall sustainability [68].

8.5. Smart Monitoring and Control

The use of sensor technology and real-time monitoring systems has the potential to enhance treatment procedures, minimize energy usage, and guarantee adherence to environmental requirements.

8.6. Green Chemistry in Tanning

There is a growing trend among tanneries to embrace green chemistry concepts and employ eco-friendly tanning procedures, which result in reduced pollutant emissions and decreased reliance on expensive treatment methods [69].

8.7. Public-Private Partnerships

Promoting cost-effective and environmentally friendly wastewater treatment systems can be facilitated by collaborative endeavors, including tanneries, government organizations, and research institutes [70].

8.8. Small-Scale and Artisanal Tanneries

The focal point will be solutions specifically designed to address the distinct issues encountered by small-scale and artisanal tanneries situated in underdeveloped nations [71]. This study will investigate treatment techniques that are both cost-effective and appropriate for the given situations.

8.9. Circular Economy Approaches

The use of circular economy principles in the leather sector has the potential to facilitate the recycling and utilization of resources, therefore mitigating the industry's environmental footprint, including the creation of wastewater [72].

8.10. Education and Awareness

The need for effecting change lies in the need to enhance the understanding of tannery operators regarding the adverse environmental ramifications stemming from inadequate wastewater management and the advantages associated with adopting sustainable practices [73].

8.11. Regulatory Standards

There is a possibility that governments and environmental agencies will persist in enhancing and implementing legislation about the discharge of wastewater from tanneries, therefore compelling tanneries to embrace more environmentally friendly technology and practices [74].

8.12. International Collaboration

The facilitation of information exchange and technology transfer through collaboration across nations and areas with tannery industries can contribute to developing global solutions for difficulties related to tannery wastewater treatment [75].

The forthcoming trajectory of tannery wastewater treatment will be centered on the adoption of sustainable methodologies, advancements in technology, and a steadfast dedication to mitigating the ecological repercussions associated with the leather sector [76, 77].

With the rising recognition of environmental concerns and the implementation of more stringent laws, tanneries will be more motivated to allocate resources towards adopting more environmentally friendly and efficient wastewater treatment techniques.

9. Conclusion

The treatment of wastewater from tanneries is an essential procedure that seeks to address the environmental and public health consequences associated with the leather manufacturing sector. Tanneries generate a substantial quantity of effluent containing diverse contaminants, such as organic substances, heavy metals, and chemicals employed in the process of leather production. Specialized treatment techniques are utilized to tackle these issues.

The initial stage of treatment commonly entails the separation of substantial particulate matter using sedimentation and screening processes. Following this, further treatment methods, including biological treatment, activated sludge, and aerobic and anaerobic digestion, are employed to decompose organic pollutants.

These sophisticated technologies have proven to be successful in removing organic matter, heavy metals, and hazardous chemicals from tannery effluents. The potential to substantially reduce their environmental impact, safeguard local ecosystems, and foster the development of a more sustainable and socially accountable leather sector.

Acknowledgement

The authors are grateful to the corresponding departments of the author’s university for their cooperation with this undertaking.

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