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An Updated Review on Tannery Waste Treatment with Emphasis on Fungal Mediated Applications

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Abstract— *Current estimates state that the global leather industry produces 600 million m³ of effluent annually. Since tannery effluents are toxic with high salinity, and contain several recalcitrant organics, they cannot be broken down by conventional biological treatment methods. Biological treatment options are more sustainable, cost-effective, and environmentally friendly, as they rely on microorganisms. Recently, fungi have garnered attention from the research community for their potential use in the remediation of wastes and wastewaters. A number of filamentous fungi are found naturally in wastewater treatment systems as spores or vegetative cells which metabolize organic substances, e.g., Phanerochaete chrysosporium, Trametes versicolor, etc., which produce key enzymes like lignin peroxidase (LiP), manganese peroxidase (MnP), and laccase. These enzymes break down persistent organic pollutants, including polyaromatic hydrocarbons (PAHs), dyes, and pesticides. Other fungi like Aspergillus spp., Irpex lacteus, and Fusarium spp. bioaccumulate heavy metals and degrade complex organic compounds. Tannins represent one of the least biodegradable substances in tannery wastewaters, with high recalcitrant compounds. Further, several biophysical, enzymatic, cellular, and metabolic advantages of fungi have advantages in tannery effluent treatment. The current review with an introduction on tannery treatment delves into the fungal bioremediation in detail. The recent developments in this area are also covered to update the readers on the developments in genomics and proteomics. Additional methods, viz., enzymatic treatment, strain improvement, scale-up biological processes, and microalgae applications, can enhance the quality and efficacy of the treatment*.

Keywords— Chemical oxygen demand (COD), tannery wastewater effluent (TWE), white-rot fungi (WRF), Reverse osmosis, Tannase.

I. INTRODUCTION

Tannery effluent contains heavy loads of tannins, chromium, and sulfides, alongside over 175 other chemicals used in leather processing. This highly toxic, dark-brown wastewater requires complex physical, chemical, and biological treatments to prevent severe soil and aquatic pollution. Because tannery effluents are high in salinity, toxicity, and recalcitrant organics, conventional biological treatment methods (like activated sludge) struggle to break them down. Advanced methods like electrocoagulation, membrane filtration, and advanced oxidation processes (AOPs) are required to target recalcitrant compounds like tannins and toxic metals. Biological treatment options are generally considered more sustainable, cost-effective, and environmentally friendly, as they rely on microorganisms to break down pollutants. Recently, fungi have garnered attention from the research community for their potential use in the remediation of wastes and wastewaters. A number of filamentous fungi are found naturally in wastewater treatment systems as spores or vegetative cells which metabolize organic substances. Using fungi in tannery effluent treatment provides an eco-friendly, highly efficient biological alternative to conventional chemical methods. Fungi excel at breaking down complex organic pollutants and capturing toxic heavy metals, making them a sustainable solution for leather industry wastewater. The present review is an effort to collate literature with this back with emphasis on fungi. Advancements and current trends are also included to give a comprehensive view on the topic.

The objectives of this review are: (i) to summarize the characteristics and environmental impact of tannery wastewater; (ii) to review conventional and advanced treatment methods; (iii) to provide a comprehensive overview of fungal-mediated bioremediation of tannery wastewater; (iv) to highlight recent developments in genomics, metagenomics, enzyme immobilization, and microbial consortia; and (v) to identify research gaps and future directions for sustainable tannery wastewater management.

II. REVIEW METHODOLOGY

This narrative review was prepared by synthesizing peer-reviewed literature on tannery wastewater treatment with a focus on fungal-mediated applications. Literature was identified through targeted searches of major scientific databases including Web of Science, Scopus, PubMed Central, Google Scholar, and ScienceDirect using search terms such as "tannery wastewater," "tannin degradation," "fungal bioremediation," "white-rot fungi," "tannase," "laccase," "COD removal," and "heavy metal biosorption." The search covered the period from 2000 to 2026, with emphasis on recent developments from 2020 onwards. Foundational papers necessary to define the field were also included. Studies were included if they addressed tannery wastewater treatment, fungal bioremediation, or related enzymatic processes. The retrieved literature was critically evaluated for scientific quality, relevance, and contribution to the understanding of fungal applications in tannery wastewater treatment.

III. TANNINS: CHEMISTRY, TYPES, AND AS SOURCE OF WATER POLLUTION

Tannins are complex, naturally occurring polyphenolic compounds widely distributed in nature. They are produced by plants (pteridophytes, gymnosperms, and angiosperms) and are accumulated in leaves, fruit, bark, roots, seeds, and wood. Tannins differ from other natural phenols in their ability to precipitate proteins (Lorenz et al., 2014), and they are used in the tanning process to bind to the collagen matrix of animal skin and make the leather more durable and resistant to decay. Tanning is an essential phase in one of civilization's oldest processes, the transformation of skins into leather, and vegetable tannins were probably the earliest used reagents. Tannins are applied in the leather tanning industry to transform the animal skin, making leather more durable and resistant to decay.

Tannins used in the tanning processes are polyphenolic compounds with elevated molecular weight (from 500 to 4000 Da). They are considered "recalcitrant" because their complex structures resist standard biological degradation, causing severe aquatic toxicity, high chemical oxygen demand (COD), and dark discoloration in effluents. Because standard biological treatments (such as activated sludge) are largely ineffective against them, specialized tertiary treatment methods are required to break down or remove tannins from industrial wastewater. Technologies like Fenton's oxidation, ozonation, and heterogeneous photocatalysis break down the complex tannin structures into smaller, biodegradable byproducts. Highly effective filter media, such as activated carbon or specialized polymer resins, trap and remove tannin molecules from aqueous solutions. Processes like reverse osmosis and nanofiltration physically filter out the recalcitrant compounds, producing highly purified, reusable water. Figure 1 describes the various steps of tannery treatment.

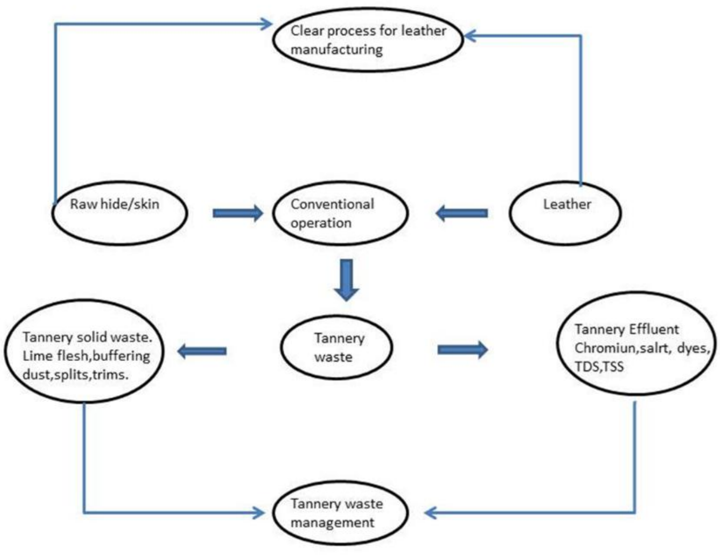

FIGURE 1: Schematic representation of tannery wastewater treatment steps

IV. TANNERY EFFLUENT AS A POTENTIAL POLLUTANT AND ITS TREATMENT

Each year, the global leather industry produces 600 million m³ of effluent. According to a report on tannery operations in Asia, an estimated 350 million cubic meters of wastewater containing chemicals and other contaminants are produced annually from processing around 10 million tonnes of hides and skins (Rajamani, 2018). This represents a significant environmental challenge, as the effluent can negatively impact local ecosystems and human health (Zaheer et al., 2022; Selvan et al., 2023). Tannery operations require excess water which contains a large quantity of biological oxygen demand (BOD), total dissolved solids (TDS), chemical oxygen demand (COD), sulfides, chlorides, and a variety of other chemicals which contribute 60–70% of the total contaminant load generated by tanneries (Wu et al., 2018). Tannery wastewater is mainly characterized by a variety of organic waste, hazardous substances, and metallic and non-metallic pollutants that arise in tannery wastewater effluent (TWE). These components lead to dark brown coloring and a foul smell (Tamersit & Bouhidel, 2020). Metallic and non-metallic contaminants like T Cr, Cr(III), Cr(VI), Cl, total Kjeldahl nitrogen (TKN), SO_4^{2-}, S^{2-}, NH_4-N, iron, and calcium are present in tannery effluents (Kassim et al., 2022). The number of total solids (TS) increases as a result of either or both organic and inorganic matter in tannery effluent. In addition, high BOD and COD, which decrease dissolved oxygen concentration in the aquatic environment and toxic chemicals, make the effluent extremely acidic (Fouda et al., 2021; Ahmed et al., 2022). Further, the activities involved in tannery operations generate wastewater that can negatively impact the environment and the health of living organisms, including humans and animals. Specifically, the untreated effluent from tanneries can contain high levels of organic matter that consume dissolved oxygen and deprive aquatic life of the oxygen they need to survive. Also, the wastewater may contain nutrients that can promote the growth of aquatic plants and algae, leading to the eutrophication of lakes and streams. Finally, untreated effluent can also harbor pathogenic microorganisms and toxic substances that can cause disease and pose a risk to human health if ingested (Chiampo et al., 2023).

TABLE 1
PHYSICO-CHEMICAL PROPERTIES OF EFFLUENTS: A COMPARATIVE SUMMARY

Parameters	Apaydin et al. 2009	Yadav et al., 2016	Abba et al., 2019	Joël Akea et al., 2022	Bharadwaj et al., 2023
pH	7.4	8.7	8.4	2.69	4
TDS (mg L^{-1})	-	2,219	-	22,566	11,030
Total solids (mg L^{-1})	-	2500	-	28,966	27,300
Suspended solids (mg L^{-1})	2690	281	1600	6,400	912
Volatile Suspended solids (mg L^{-1})	1260	-	-	-	-
COD (mg L^{-1})	3700	449	10670	939.33	8,160
BOD (mg L^{-1})	1470	250	4168	2400	2,200
TKN (mg L^{-1})	-	-	-	-	-
Nitrogen (mg L^{-1})	180	234	85	-	-
Chromium (mg L^{-1})	-	19	-	200	-
Sulfide (mg L^{-1})	440	2,490	560	1,021	-

4.1 Treatment Methods for Tannery Wastewater

The techniques used to manage post-treated effluents in the tannery industry (PTEs) are contingent on the effectiveness of removal, the kind of effluent, operation parameters, and the specifics of the study. Numerous treatment methods currently in use are coagulation/flocculation, advanced oxidation processes (AOPs), biological treatment, membrane separation processes (MSPs), adsorption, and hybrid methods. The treatment of tannery wastewater is categorized into specific, sequential steps to ensure all pollutants are managed effectively.

4.1.1 Pre-treatment (Beamhouse Operations)

This step prevents damage to downstream equipment by removing coarse materials, large solids, and oils. It consists of screening and grit removal: bar screens and settling tanks physically remove hides, fleshings, and heavy debris. Because tanneries discharge waste intermittently, equalization basins mix streams to create a uniform flow with consistent pollutant loads.

4.1.2 Physical-Chemical Treatment

This stage focuses on removing specific chemical pollutants and suspended solids. Sulfides from the unhairing process are oxidized using aeration or chemical catalysts (like manganese sulfate) to prevent toxic hydrogen sulfide gas from forming. Chrome-tanning waste is segregated and precipitated using alkaline chemicals (such as magnesium oxide or lime), forming chromium hydroxide, which can be separated and recycled back into the tanning process.

- **Coagulation/Flocculation:** This is a common method used to treat wastewater due to its ability to effectively remove both organic and inorganic pollutants. Coagulation and flocculation help in the removal of suspended particles in the effluent with a size range from 0.1 to 100 µm (Davis, 2010). The treatment of TWE has already been investigated using different coagulants and flocculants, viz., poly-aluminum chloride (PAC), $Al(OH)_3$, $Fe(OH)_3$, and $FeCl_3$. Biological treatment with chitosan, tannins, and extract from the flowers of *Musa* sp. plants are also reported. Drawbacks of the method include not being suitable as a primary process for treating wastewater due to the harsh quality of the wastewater. The method requires a significant amount of flocculants or coagulants to achieve acceptable decontamination. Another drawback is the formation of large quantities of sludge.
- **Advanced Oxidation Processes (AOPs):** AOPs utilize in situ generated hydroxyl (OH) radicals as the primary oxidant. This approach is environmentally benign and has demonstrated remarkable flexibility in the disintegration of biorefractory contaminants. Several AOP techniques have been shown to have the highest removal efficiency for COD, including zinc oxide-assisted photocatalysis and photo-assisted electrochemical oxidation. The oxidation of substances such as Cr(III) is crucial in establishing effective effluent treatment after tanning using AOPs (Lofrano et al., 2013). High operating cost, time-consumption, and higher energy demands are the drawbacks of this method. Fenton processes can produce a significant amount of sludge.

4.1.3 Biological Treatment Methods

Biological procedures of effluent treatment include the application of microalgae, fungi, activated sludge, bacterial strains, and enzymes. Biological treatment options are generally considered more sustainable, cost-effective, and environmentally friendly, as they rely on microorganisms to break down pollutants. Biological treatment methods, especially activated sludge, play a critical role in environmental protection by removing pollutants from wastewater (Xiao et al., 2015). Recently, some methods have enabled the remediation of wastewater that contains colors or heavy metals (Huang et al., 2015). Due to the complicated aromatic structure of azo dyes and their byproducts, traditional biological treatment approaches are frequently inadequate for degradation (Kertèsz et al., 2014). The azo linkage in the dye molecule might be degraded by the biological treatment processes investigated utilizing aerobic decomposition or fungal treatment, turning them into dinitrogen (N_2) or ammonia (NH_3) or being integrated into biomass (Senthilvelan et al., 2014). A study using fungal treatment at 100 mg/l, pH 5.5, 168 h of treatment and aerobic decomposition indicated that the PTEs had significant removal of COD (above 80%) and color (above 90%) at the effective pH range of 5–7, and the temperature range of 25–35 °C. Chromium (VI) reduction and azo dye removal were accomplished by *Lactobacillus paracase*, an isolate from deep-sea sediment (Huang et al., 2015). Effluent can be a source of organic or inorganic nutrients, such as phosphates and ammoniacal nitrogen, that can be assimilated by various algae species, including *Chlorella*, *Scenedesmus*, *Chlamydomonas*, and *Nanochloropsis* (Saranya & Shanthakumar, 2020). A microalgae consortium containing mainly *Tetraselmis* sp. revealed removals for COD, TOC, and BOD that were consistently below 60%. The main drawbacks of biological treatment methods are time consumption, unstable effluent quality, excessive salinity inhibition, and large-scale sludge formation. Additionally, they can treat a wide range of pollutants and effectively reduce the wastewater's toxicity. However, it is necessary to undertake the primary treatment procedure through the physico-chemical process (screening, equalization, pH adjustment, and chemical treatment). Furthermore, the efficiency of biological treatment processes can be affected by toxic substances or high levels of organic matter.

4.1.4 Membrane Separation Processes

These processes have gained popularity due to their ability to produce high-quality treated water. Membrane separation processes (MSPs) may remove dissolved compounds from tannery wastewater. These methods can be characterized by the pressure difference (reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), microfiltration (MF)), potential difference, and osmosis pressure (forward osmosis) (Venzke et al., 2018; Li et al., 2021). Based on studies, it has been observed that the maximum level of pollution can be effectively reduced through the use of NF membranes, followed by RO membranes (Nicolini et al., 2016; Licona et al., 2018). UF membranes can eliminate solutes with a molecular weight greater than 1,000 Da. One of the major disadvantages of membrane separation processes is their high energy consumption, which can lead to high operational costs. Fouling of the membrane is another common issue, resulting in decreased efficiency and increased costs, and they may not be suitable for treating wastewater with high salinity, as salt deposits can damage the membranes and require frequent replacement.

4.1.5 Adsorption

Tannery effluent is challenging to treat due to the presence of phenols in tanning amalgamation, which forms polyphenolic structures that make the effluent refractory (Benvenuti et al., 2017). Adsorption effectively treats wastewater contaminated with heavy metals, aromatic chemicals, and dye by reducing their concentration (Hashem et al., 2022; Shaibur, 2023). However, various other adsorbent materials such as zeolite, green macro-algae, modified kaolin, and commercial activated carbon have also been employed. Results from previous studies indicate that acid dyes (anionic) were successfully removed from chrome-tanned leather shavings by 58–87% using adsorption (Piccin et al., 2016). Commercial activated carbon in powder form produced the highest levels of pollution removal, followed by modified zeolite (Aljerf, 2018) and kaolin with discoloration greater than 90%. Several factors affect adsorption efficiencies, such as pH, dye concentration, temperature, and adsorbent material (Gomes et al., 2016). The high cost of using adsorbents, especially for large-scale operations, is a drawback. Additionally, the adsorption capacity of the adsorbents is influenced by several factors which may require optimization to achieve effective removal of pollutants. Another disadvantage of adsorption processes is the need for frequent replacement of adsorbents and their disposal.

4.1.6 Hybrid Treatment Methods

Studies suggest that combining different treatment methods can achieve a more effective and cost-efficient approach. By carefully considering the pros and cons of each method, a suitable combination of techniques can be chosen that yields multi-effective performance and reduces costs. This is an increasingly popular trend among researchers working on tannery effluent treatment, who have been experimenting with diverse techniques to achieve better results (Grandclément et al., 2017). Combining RO, NF, gravity settling, and coagulation/flocculation among hybrid treatments produced the maximum COD removal. Adsorption was employed after coagulation or flocculation as a pre-treatment in other hybrid procedures (Puchana-Rosero et al., 2018; Mella et al., 2019). In some cases, integrating AOPs with biological treatment can improve their economic viability, as higher oxidant dosages are typically required when used as a standalone final treatment (Ganiyu et al., 2015).

V. FUNGI AND THEIR ROLES IN TANNERY WASTE TREATMENTS

Fungi are abundant worldwide, because they can exist and survive in a wide range of habitats (Madigan et al., 2018). Within their ecosystems, fungi might be symbionts, parasites, or saprophytes of plants, animals, and other fungi (Prescott et al., 2016). Various biochemical activities in the fungi can be exploited for the production of compounds useful in many fields, such as antibiotics, steroids, and cyclosporins. Recently, fungi have garnered attention from the research community for their potential use in the remediation of wastes and wastewaters (Madigan et al., 2018). A number of filamentous fungi are found naturally in wastewater treatment systems as spores or vegetative cells which metabolize organic substances (Subasri et al., 2020). Using fungi in tannery effluent treatment provides an eco-friendly, highly efficient biological alternative to conventional chemical methods (Ameen, 2023). Fungi excel at breaking down complex organic pollutants and capturing toxic heavy metals, making them a sustainable solution for leather industry wastewater. Among the most effective are white-rot fungi (WRF) e.g., *Phanerochaete chrysosporium*, *Trametes versicolor*, and *Pleurotus ostreatus*, which produce key enzymes like lignin peroxidase (LiP), manganese peroxidase (MnP), and laccase (Deepa et al., 2011). These enzymes break down persistent organic pollutants, including polyaromatic hydrocarbons (PAHs), dyes, and pesticides. Other fungi like *Aspergillus* spp., *Irpex lacteus*, *Penicillium* spp., and *Fusarium* spp. contribute through their bioaccumulation of heavy metals and ability to degrade complex organic compounds (Ghosh et al., 2023).

5.1 Advantages of Fungi in Tannery Effluent Treatment

Fungi have been shown to be capable candidates to remove azo dye compounds during the wastewater treatment process (Rajhans et al., 2021). Fungal biomass can absorb dyes from wastewater regardless of whether the fungus is dry or wet. Further, fungi are a rich source of degrading enzymes (Ugbede et al., 2023) and possess the ability to withstand extremely harsh conditions such as low pH, fluctuating pollution load, and low nutrient concentrations (Yadav et al., 2024). Fungi also have a greater resistance to inhibitory compounds in comparison to bacterial species (Spennati et al., 2021). The hyphal growth of fungi provides greater protection for their sensitive organelles. The cell walls of fungi, a layer of extra-polysaccharide matrix, protect them from inhibitory compounds through adsorption (Gow et al., 2017). The higher number of genes in fungi imparts greater reproductive selectivity, which might result in better adaptations to the environment (Priest et al., 2020). Fungal enzymes are highly non-specific with regard to their substrate, which gives them the capability to degrade a wide range of highly recalcitrant organopollutants (Ningombam et al., 2025). A number of fungi species, such as *Aspergillus*, *Penicillium*, and a host of others, have been implicated in the removal of carbon and nutrient sources in wastewater (Dalecka et al., 2020). Additionally, some fungi use their fungal hyphae for trapping and adsorbing suspended solids to accomplish their energy and nutrient requirements (Vaksmaa et al., 2023). Unlike chemical precipitation, which produces massive volumes of hazardous chemical sludge, fungal biomass significantly reduces the overall volume of secondary sludge and can often be composted safely after treatment (Civzele et al., 2025). Fungal cell walls contain functional groups that act as an excellent natural sponge for toxic metals like chromium, lead, and cadmium through a process called biosorption (Staszak & Regel-Rosocka, 2024). Species like *Aspergillus niger* have been shown to drastically reduce metal concentration. Although fungi represent a promising biological resource in environmental biotechnology, their application is limited due to a lack of knowledge regarding the optimal process conditions and due to their lack of stability in non-sterile conditions (Palli, 2016; Svobodová & Novotný, 2017).

5.2 Tannin-Degrading Fungal Strains

Despite the antimicrobial properties of tannins, many fungi, bacteria, and yeast are quite resistant to tannins and can use tannins as carbon and energy sources (Cherian & Madhan, 2021). The biodegradation of natural tannins in the environment is mainly associated with fungi rather than bacteria. Fungi express a large number of degradative enzymes including peroxidases, laccases, and tannases (Viswanath et al., 2014). Tannase catalyses the hydrolysis of ester bonds, releasing glucose, gallic acid, and galloyl esters (Tang et al., 2024). Some authors suggest a correlation between tannase activity from fungi in phenol-rich wastewater and the reduction of COD, Total Organic Carbon (TOC), and phenol content (Salgado et al., 2016). In particular, *Aspergillus* spp. and *Penicillium* spp. have been isolated from tannery wastewaters and were reportedly able to biodegrade tannins (Ben et al., 2021).

The following paragraphs summarize various studies spanning source of substrate, carbon source, process parameters, and fungal strains in tannin degradation. Spennati et al. (2020) report four novel rotating submerged packed bed reactors with *Aspergillus tubingensis* MUT 990a immobilized in polyurethane foam cubes carriers and inserted inside a submerged rotating cage reactor for biodegradation of tannins in non-sterile conditions. The results implicate that after two months, 80% of COD and 90% dissolved organic carbon removal was achieved. Further, important tannase activity was also detected. Quebracho tannin and Tara tannin are intensively used by the tanning industry and are two of the most recalcitrant compounds that can be found in tannery wastewaters. Spennati et al. (2019) used two reactors inoculated with *Aspergillus tubingensis* MUT 990. Soluble chemical oxygen demand removals up to 53% and 90% and maximum elimination capacities of 9.1 g sCOD m^{-3} h^{-1} and 37.9 g sCOD m^{-3} h^{-1} of Quebracho and Tara tannins were achieved.

Studies have reported the roles of culture and process parameters as variables influencing fungal degradation. The study by Buenrostro-Figueroa et al. (2021) was aimed at obtaining ellagitannase enzymatic extracts from *Aspergillus niger* GH1 in solid-state fermentation, using dextrose and ellagitannins as inducers. The influence of culture conditions on ellagitannase expression and fungal ellagitannin degradation was studied. Three groups of proteins were identified, viz., β-glucosidase, phospholipase C, and triacylglycerol lipase. However, only phospholipase C was overexpressed with ellagitannins as inducers, showing the most spontaneous reaction with punicalagin (ΔG -8.56). These results suggest that phospholipase could be involved in ellagitannin biosynthesis. Prendecka et al. (2016) studied the dynamic changes in tannase activity depending on the carbon source in the culture medium using fungi *Phellinus pini*, *Fomes fomentarius*, and *Tyromyces pubescens*, respectively. The inducible potential of TA and rapeseed meal on the activity of tannin acyl hydrolase was confirmed during 14 days of culturing. The highest concentrations of GA were observed after stimulation by the TA in the cultures of *F. fomentarius* and *T. pubescens*.

Bhoite et al. (2013) report gallic acid production optimization using response surface methodology (RSM). Process parameters such as pH, moisture, and fermentation period were considered for optimization. Among the various fungi isolated from coffee by-products, *Penicillium verrucosum* produced 35.23 µg/g of gallic acid using a carbon source in solid-state fermentation. The optimum values of the parameters obtained were pH 3.32, moisture 58.40%, and fermentation period of 96 hr. Further, gallic acid production with an increase of 4.6-fold was achieved. Several researchers report the application of fungi in degradation of vegetable and fruit-based tannin substrates. Hydrolysis of pomegranate ellagitannins by *Aspergillus niger* GH1 by solid-state culture using polyurethane foam as support and pomegranate ellagitannins as substrate is reported by Ascacio-Valdés et al. (2016). The results show that ellagitannin reached the maximal biodegradation value at 18 h. The activity of ellagitannase was 390.15 U/L. Finally, HPLC/MS analysis identified gallagic acid as an intermediate molecule and immediate precursor of ellagic acid. De León-Medina et al. (2023) report rambutan peel as a source of ellagitannins through SSF. Ellagitannase was the main enzyme responsible for biodegradation of ellagitannins using ultrasound/microwave hybrid technology. Fungi have demonstrated degradation of synthetic sources of tannin. Bardi et al. (2019) studied the efficiency of the white-rot fungus, *Bjerkandera adusta* MUT 2295 in the treatment of a synthetic solution prepared with tannic acid. At the end of the process, an increase of fungal dry weight and the presence of ergosterol were detected. COD and TOC removal of 81% and 73% was achieved which correlated with the detection of tannase and Lignin Peroxidase (LiP) activities. Based on these studies, it can be summarized that fungi are the best fit microorganism for treatment of the recalcitrant fraction of wastewater containing a high concentration of tannins, such as tannery wastewater.

VI. RECENT DEVELOPMENTS

Several genetic and genomic studies have been carried out in this realm of bioremediation to study gene expression, identify key genes in pathways, and conduct metagenomics surveys. *Coriolopsis gallica* is a ligninolytic basidiomycete that produces high levels of this extracellular enzyme. The role of tannic acid was shown to be an inductor of laccase activity in this fungus, due to the enhancement of expression of the laccase gene at the transcriptional level (Carbajo et al., 2002). *Aureobasidium melanogenum* T9 isolated from red wine starter showing ability for tannin degradation (Zhang et al., 2019). Highest biomass was achieved when the initial tannic acid concentration was 20 g/L. Genes *tan A*, *tan B*, and *tan C* encoding three different tannases, respectively, were identified. Among these genes, *tan A* and *tan B* can be induced by tannin acid simultaneously at both gene transcription and protein expression levels. Deletion assays showed that the deletion of *tanA* and *tanB* resulted in tannase activity decline (51.3 ± 4.1 and 64.1 ± 1.9 U/mL), respectively.

A study analyzed the tannin biodegradation efficiency and the transcriptomic responses of *A. tubingensis* in liquid and solid cultures with tannin added. A total of 54.6% of the 11,248 differentially expressed genes were upregulated in liquid cultures, including AtWU_03490 (encoding ABC multidrug transporter), AtWU_03807 (ribonuclease III), AtWU_10270 (peptidyl-tRNA hydrolase), and AtWU_00075 (arabinogalactan endo-1,4-beta-galactosidase). Functional and gene ontology enrichment analyses indicated upregulation in processes including oxidation reduction, drug metabolism, and monocarboxylic acid metabolism. Overall, this study provides insight into the transcriptomic response to tannin biodegradation by *A. tubingensis* in different cultures and reveals that liquid cultures induce greater transcriptomic variability compared to solid cultures.

The metagenomics technique is a potent tool for examining the biodiversity of soil microbial communities. Sinduja et al. (2025) report ten most abundant dominant bacteria in metal-contaminated soil samples, viz., Proteobacteria, Firmicutes, Bacteroidetes, Actinobacteria, Cyanobacteria, Acidobacteria, and Archaea. Meanwhile, Nitrososphaerales exhibited the highest abundance in the control samples accounting for 48% of microbial diversity. This study provides an in-depth analysis of microbial composition and metagenomics for bioremediation of metal-contaminated soil. In another study, Quintana et al. (2026) metagenomics revealed microbiome profiles dominated by Pseudomonadota (77.2%), primarily *Thiocapsa* (27.8%) and *Francisella* (23.0%). The phototrophic and sulfur-oxidizing metabolism characteristic of *Thiocapsa* may explain the distinctive coloration of the effluent, while the predominance of *Francisella* is consistent with tolerance to hostile environmental conditions. DNA sequences revealed species including *Pseudomonas aeruginosa*, *Salmonella enterica*, and *Klebsiella pneumoniae*. These findings demonstrate that treated tannery effluent can retain clinically relevant genetic material and ARGs, underscoring the need to integrate metagenomic surveillance into environmental monitoring frameworks to better understand and mitigate emerging resistance determinants in aquatic systems.

An alternative source of tannase from human oral mucosa is reported. Tomás-Cortázar identified and expressed in *E. coli* a tannase from the oral microbiota member *Fusobacterium nucleatum* subs. *polymorphum* (TanBFnp). Sequence analyses revealed close relation to bacterial tannases. The enzyme exhibits biochemical properties that make it an interesting target for industrial use. The enzyme properties were 100% activity at different temperatures (incubations up to 45 °C) and activity against esters of gallic and protocatechuic acid, including tannic acid, gallocatechin gallate, and epigallocatechin gallate.

Condensed tannins (proanthocyanidins) are naturally occurring polyphenols formed by the polymerization of flavonoid units, such as catechin and epicatechin. They also possess antioxidant and astringent properties. Lin et al. (2016) studied polyphenol extraction recovery and 2,2-diphenyl-1-picrylhydrazyl (DPPH) scavenging activity of the extracted polyphenol after litchi pericarp was treated with *Aspergillus awamori*, *Aspergillus sojae*, or *Aspergillus oryzae*. The treatment of *A. awamori* produced the highest antioxidant activity of polyphenol from litchi pericarp. Further studies suggested that the treatment of *A. awamori* releases the non-extractable condensed tannin from cell walls of litchi pericarp. The total extractable tannin in the litchi pericarp residue after a six-time extraction with 60% ethanol increased from 199.92 ± 14.47 to 318.38 ± 7.59 μg/g dry weight (DW). The ESI-TOF-MS and HPLC-MS^2 analyses further revealed degradation of B-type condensed tannin (condensed flavan-3-ol via C4-C8 linkage).

An engineered ecosystem, based on fungal tannin biodegradation, has been successfully tested in a laboratory-scale bioreactor under non-sterile conditions. Several steps are critical in scaling-up a novel fungal-based technology for tannins biodegradation. A mathematical model was developed by Spennati et al. (2020) and applied to describe both the respirometric profiles and the experimental data collected from the laboratory-scale tests performed in the bioreactor. The microbial growth was described through a Monod-type kinetic equation as a first approach. Substrate inhibition, decay rate, and tannin hydrolysis process were included to better describe the behaviour of immobilised biomass selected in the tannin-degrading bioreactor. The model was implemented in AQUASIM using the specific tool Biofilm Compartment to simulate the attached fungal biofilm.

Maintaining optimal conditions for fungal growth in fluctuating industrial effluents is challenging. AI can bridge this gap through several core applications. Machine Learning (ML) algorithms (like Artificial Neural Networks and Random Forest models) accurately predict pollutant degradation rates and forecast effluent quality in real-time. To this end, Manoj et al. (2025) report a machine learning-assisted prediction of heavy metal adsorption from tannery effluent wastewater using *Delonix regia* with random forest, isotherms, and kinetics modelling.

The outburst of green biotechnology has facilitated a substantial upsurge in the usage of enzymes in a plethora of industrial bioconversion processes. The tremendous biocatalytic potential of industrial enzymes provides an upper edge over chemical technologies in terms of safety, reusability, and better process control. Tannase is one such enzyme loaded with huge potential for bioconversion of hydrolysable tannins to gallic acid (Dhiman et al., 2018). Furthermore, toxic tannery effluents from various tanneries are loaded with significant levels of tannins in the form of tannic acid. Tannase can be principally employed for debasing the tannins that predominately occur in the toxic tannery effluents, thus providing a relatively much cheaper measure for their biodegradation. Over the years, microbial tannase-catalyzed tannin degradation has gained momentum. The plentious availability of tannin-containing agro- and industrial waste paves a way for efficient utilization of microbial tannase for tannin degradation eventually resulting in gallic acid production.

Saad et al. (2024) report bioremoval of tannins and heavy metals using immobilized tannase and biomass of *Aspergillus glaucus*. The results demonstrate that tannase showed high stability with 50% of its activity at 60 °C and pH range 5.0-6.0. Immobilization of tannase on Na-alginate (3%) and covalent binding to chitosan and effects of concentrations on the bead formation and enzyme immobilization revealed that maximum immobilization efficiency (75%). A potential reusability of the immobilized enzyme was shown through keeping 70% of its relative activity up to the fourth cycle. Bioconversion efficiency of tannic acid to gallic acid by immobilized tannase was at 40 °C with tannic acid concentration up to 50 g/L. Bioremediation of heavy metal (Cr^{3+}, Pb^{2+}, Cu^{2+}, Fe^{3+}, and Mn^{2+}) was achieved with uptake percentages of (37.20, 60.30, 55.27, 79.03, and 21.13), respectively. The biomass was successfully used repeatedly for removing Cr^{3+} after using a desorbing agent (0.1 N HCl) for three cycles.

In another study by Prigione et al. (2018), using four different tannins (the hydrolysable chestnut ellagitannin and tara gallotannin and the condensed quebracho and wattle tannins) with an aim of selecting fungal strains capable of growing in the presence of high tannin concentration and thus their potential usefulness in biotransformations of tannery effluent was studied. A total of 125 isolates of filamentous fungi belonging to 10 species and four genera (*Aspergillus*, *Paecilomyces*, *Penicillium*, and *Talaromyces*) were isolated from the tannin industrial preparations. Miniaturized biotransformation tests with 10 fungal strains and the HPLC analysis pointed out a strong activity of all the tested fungi on both chestnut and tara tannins. Two strains (*Aspergillus tubingensis* MUT 990 and *Paecilomyces variotii* MUT 1125), tested against real tannery wastewater, were particularly efficient in COD and tannin removal (>60%), with a detoxification above 74%.

Using bacterial and fungal consortia is a highly effective, eco-friendly approach to bioremediating toxic tannery effluents. These mixed-microbe systems degrade complex organic matter, reduce high heavy metal concentrations (like toxic Chromium), and decolorize the wastewater, performing far better than single-strain treatments (Nagabalaji et al., 2023). Microbial communities are more robust, maintaining their metabolic efficiency under varying pH levels, high salinity, and fluctuating temperatures common in tanning wastewaters (Sharma & Malaviya, 2016). Ameen et al. (2023) report a consortium of microorganisms (five single bacterial and five fungal species from different genera) is more efficient than the single microorganisms in the consortium. The results indicate *Corynebacterium glutamicum* and the fungus *Acremonium* sp. were the most efficient in the single-microbe treatment. In the consortium treatment, the consortium of these two was the most efficient at treating the effluent. The TDS was reduced to 80 mg/L and BOD to 20 mg/L and the total heavy-metal concentration (Cd, Cr, Cu, Mn, and Pb) was reduced to 0.2 µg/L by the consortium.

VII. DISCUSSION

Tannins are polyphenolic compounds produced by plants that have been used for centuries in the vegetable tanning of leather (Morrison Boyd & Bhattacharjee, 2010). Tannins represent one of the least biodegradable substances in tannery wastewaters, with high recalcitrant soluble COD. A high concentration of tannins can additionally inhibit biological treatment (Maisuria et al., 2022). Moreover, tannins represent a complex class of compounds, and several studies are currently underway to improve our understanding of their physical and chemical properties, their effect on biological activity, their role in microbial ecosystems, and finally, their potential applications in other fields (production of glues, pharmaceuticals, surfactants, etc.).

Tannins in tannery wastewater are treated inefficiently by the activated sludge process and at high cost by physico-chemical treatment. It is worth mentioning that although these treatment methods have been proven effective, they require further development and improvement to meet more stringent regulatory standards (Ramisha et al., 2026). The use of additional techniques such as enzymatic treatment, fungal processes, isolated bacteria, conventional biological processes, and microalgae should be explored to enhance the quality of the effluent further (Venugopal & Khambhaty, 2024). The application of the membrane separation process has been identified as an appropriate technique for reusing treated wastewater, making it a viable option for sustainable tanning processes (Monnot et al., 2020). Some tanneries have implemented closed-loop systems that minimize water usage and treat wastewater onsite for reuse in the tanning process. Although using treated leather tanning effluent as a raw material is not yet a common practice, there are opportunities for innovation and advanced solutions in the leather industry to reduce waste and promote sustainability.

The advantages of fungal treatment over conventional methods are significant. Fungi offer a sustainable, cost-effective alternative to chemical treatments, with the ability to degrade a wide range of recalcitrant compounds and bioaccumulate heavy metals. The non-specific nature of fungal enzymes allows them to break down diverse pollutants, and the fungal biomass itself can be composted safely after treatment, reducing secondary waste. However, challenges remain, including the need for optimized process conditions, stability in non-sterile conditions, and scalability for industrial applications.

TABLE 2
COMPARATIVE ANALYSIS OF TREATMENT METHODS:

Method	Advantages	Disadvantages	Efficiency
Coagulation/Flocculation	Simple, effective for suspended solids	High sludge production, chemical costs	Moderate
AOPs	High degradation of recalcitrant compounds	High energy costs, chemical consumption	High
Biological (Activated Sludge)	Cost-effective, sustainable	Ineffective for recalcitrant compounds, slow	Moderate
Membrane Filtration	High-quality effluent, reusable water	High energy costs, membrane fouling	High
Adsorption	Effective for heavy metals and dyes	High adsorbent cost, disposal issues	Moderate-High
Fungal Treatment	Degrades recalcitrant compounds, biosorbs metals	Slow, requires optimization, non-sterile instability	High

Several avenues for future applications include full-scale use of a segregated flux of vegetable tannin bath with an optimized process based on fungal bioreactors (Bardi et al., 2019). Treatment in a side-stream reactor could reduce the overall cost of treatment, since the tertiary treatment applied for removing soluble recalcitrant COD from the tannery wastewater could be minimised. Also, in-depth investigation is needed into the different degradation pathways of tannins and the chemical compositions and structures of tannins. This research could be carried out, for example, using specially-developed methods and procedures such as LC-MS and MALDI-TOF (Mott et al., 2010). The population monitoring involved in each degradation step, coupled with the enzymatic activity and mechanisms of action, could also improve the production of those enzymes at industrial scale, given that tannase is one of the most expensive enzymes to produce. Additional investigation related to the different inhibitory mechanisms of QT and TT (and tannins in general) is required. This would require an investigation of the different mechanisms of action of bacteria versus fungi, with an additional consideration of the possible interference of quorum sensing (Zeng et al., 2023). A third potential avenue of investigation would be the study of biofilm dynamics for modelling (Ananta et al., 2025). The diffusion of tannins and oxygen inside the fungal biofilm and the associated biological reactions could be described with microsensors.

VIII. CONCLUSION AND FUTURE PERSPECTIVES

This review has comprehensively examined the current state of tannery wastewater treatment, with a particular focus on fungal-mediated bioremediation. Tannery effluents represent a significant environmental challenge due to their high toxicity, salinity, and recalcitrant organic content. While conventional physical-chemical and biological treatment methods have been employed, they often fall short of achieving complete remediation. Fungi, particularly white-rot fungi and tannin-degrading species, offer a promising, sustainable, and cost-effective alternative for the treatment of tannery wastewater. Their ability to produce non-specific extracellular enzymes (LiP, MnP, laccase, tannase) enables the degradation of a wide range of recalcitrant compounds, while their cell walls facilitate the biosorption of heavy metals.

Recent developments in genomics, metagenomics, enzyme immobilization, and microbial consortia have further enhanced the potential of fungal bioremediation. The integration of AI and machine learning for process optimization, coupled with the development of hybrid treatment systems combining fungal treatment with other methods, represents a promising direction for future research. However, challenges remain, including the need for optimized process conditions, stability in non-sterile environments, and scalability for industrial applications.

Key Recommendations:

1) **Process Optimization**: Further research is needed to optimize culture conditions (pH, temperature, nutrient availability) for fungal growth and enzyme production in non-sterile tannery wastewater.
2) **Strain Improvement**: Genetic engineering and strain improvement techniques should be employed to enhance the efficiency and stability of fungal strains under industrial conditions.
3) **Enzyme Immobilization**: Development of cost-effective immobilization techniques for fungal enzymes to improve reusability and stability.
4) **Consortia Development**: Optimization of fungal-bacterial consortia for enhanced degradation of complex tannery effluents.
5) **Scale-up Studies**: Pilot-scale and full-scale studies are needed to demonstrate the feasibility and cost-effectiveness of fungal treatment at industrial scale.
6) **Integration with Other Methods**: Hybrid treatment systems combining fungal treatment with membrane filtration, AOPs, or adsorption should be explored for complete remediation.
7) **Genomic and Metagenomic Studies**: Further genomic and metagenomic studies are needed to understand the mechanisms of tannin degradation and heavy metal resistance in fungi.
8) **Regulatory Frameworks**: Development of regulatory frameworks and guidelines for the safe and effective use of fungal bioremediation in tannery wastewater treatment.

Limitations of the Review: This review is based on a narrative synthesis of published literature rather than a formal systematic review. The examples are selected to illustrate the diversity of approaches and should not be considered exhaustive. The focus is primarily on fungal bioremediation, with less attention to other biological treatment methods. The review prioritizes recent developments from 2020 onwards, but may not capture all relevant studies.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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