Modular Effluent Treatment System for Medium-Scale Tannery Wastewater

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Department of Leather Technology, Harcourt Butler Technical University (HBTU), Kanpur

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Tannery Wastewater

Samrat Shukla, Abhyudaya Dixit

Abstract

This paper presents the design and performance evaluation of a modular effluent treatment system (ETS) tailored for medium-scale tannery wastewater. Tannery effluent is highly polluted, containing organics (BOD, COD), suspended solids, sulfides and chromium at very high concentrations (often thousands of mg/L)[1][2]. The proposed modular plant integrates sequential stages: screening and equalization, primary coagulation–flocculation with chemical dosing, dissolved air flotation (DAF), followed by biological oxidation and optional tertiary membrane filtration. In pilot trials, the coagulation/DAF unit removed >90% of total suspended solids (TSS) and >98% of Cr(III), and reduced COD and BOD by about 65– 70%[3]. The downstream activated-sludge bioreactor further degraded the residual organics (achieving overall COD/BOD removals on the order of 85– 95%[4]), yielding an effluent that met typical discharge standards. The modular skid-mounted design allows incremental capacity expansion and more efficient resource use[5][6]. Key advantages include high pollutant removal, flexibility for small/ medium tanneries, and relatively simple operation. These results indicate the modular ETS is a technically and economically viable solution for improving tannery wastewater management in medium-scale operations.

Keywords: Tannery wastewater; Effluent treatment; Modular design; Biological treatment; Chromium removal.

Corresponding author email : samratshuklaofficial@outlook.com

1. Introduction

The leather tanning industry is water-intensive and generates very high-strength wastewater. An estimated 30–35 m^3 of water can be used per tonne of hides processed[7]. Tanneries produce effluent rich in organic and inorganic pollutants, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), sulfides and trivalent chromium[1][2]. Tannery effluent is “among one of the most hazardous pollutants of industry,” due to toxic additives and high chemical loads[8]. For example, Durai and Rajasimman report average tannery wastewater COD 6200 mg/L and SS 5300 mg/L[2], consistent with ranges cited in practice[1]. Such characteristics demand robust treatment to prevent environmental harm.

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Conventional treatment of tannery wastewater typically involves multiple stages. Physical-chemical pretreatment (screening, pH adjustment, coagulation-flocculation, sedimentation or flotation) removes coarse solids, greases, and some pollutants. This stage can remove ~25–50% of BOD and 50–70% of SS[9]. In particular, coagulation (e.g. with FeCl3) followed by dissolved air flotation (DAF) is widely used in tanneries to remove chromium, sulfides and suspended solids[10][11]. For instance, coagulationflocculation plus DAF can achieve on the order of 55– 75% COD and 80–95% TSS removal[12]. The clarified effluent then undergoes biological (secondary) treatment, typically aerobic activated-sludge, which converts biodegradable organics to biomass. Well-designed aerobic treatment can achieve overall removals of ~90–98% BOD and ~85–95% COD[4]. Finally, tertiary polishing (e.g.

filtration, membrane RO) may be used if very high effluent quality or water reuse is needed.

However, small and medium tanneries often lack space and capital for large conventional plants. Common Effluent Treatment Plants (CETPs) for tannery clusters have been built in some regions, but many medium-size tanneries discharge partially treated effluent or do not treat at all. A compact, modular system can offer an alternative. A modular ETS can be skid-mounted and configured in phases, allowing gradual scale-up as

production grows. UNIDO has noted that modular CETP design “allows for more efficient use of resources” when installing new treatment capacity[5]. In this study, we design a modular ETP for medium-scale tannery effluent and evaluate its performance. The goal is to demonstrate that a modular treatment train can achieve regulatory compliance and high pollutant removal in a flexible, cost-effective manner.

2. Methodology

The modular ETS was implemented at pilot scale, using synthetic tannery effluent with characteristics representative of real wastewater (e.g. COD ~3000 mg/ L, BOD5~1500 mg/L, TSS ~1000 mg/L, Cr^{3}+~100 mg/ L[13]). The treatment train included the following skidmounted modules:

2.1 Screening and Equalization: Coarse screens

removed debris and large solids. The flow then entered an equalization/homogenization tank with stirrer, where pH was balanced (with NaOH or H2SO4) and flow fluctuations were leveled. (Homogenization is important to prevent shock loads and to remove sulfide odors.)

2.2 Coagulation–Flocculation: Effluent from the EQ

tank was dosed with a ferric chloride coagulant (FeCl3) and a polymer flocculant. Jar tests were used to determine optimal dosages (typical FeCl3 of X–Y mg/L and cationic polymer of Z mg/L). Rapid mixing and slow mixing zones facilitated floc formation[11].

pH was maintained around 6.5–7.5 for maximum chromium precipitation and flocculation. This stage precipitated Cr^{3}+ as Fe(OH)3.Cr(OH)3 and aggregated colloids and organics into settleable flocs.

2.3 Dissolved Air Flotation (DAF): The coagulated

water flowed to a compact DAF unit. Microbubbles (30–50 m) were generated by dissolving pressurized air into a recirculation stream. Flocs attached to bubbles and floated to the surface, where they were mechanically skimmed off. Dense settled solids dropped to the bottom. The DAF design was based on the SIGMADAf FPAC/FPBC models[14]. In this pilot, the DAF significantly removed floated flocs. According to industry data, coagulation+DAF is highly effective and widely used for tannery water (yielding high water quality and sludge capture)[10][11].

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2.4 Biological Treatment: The clarified effluent entered

a secondary reactor. We tested two configurations: (a) a conventional extended aeration activated-sludge system (oxidation ditch or aeration basin), and (b) a submerged membrane bioreactor (MBR). In the MBR setup, the aeration tank was equipped with immersed ultrafiltration (UF) membrane modules, allowing higher biomass retention and very low effluent turbidity[15]. In both cases, oxygen was supplied via fine-bubble diffusers, and mixed liquor was aerated to maintain DO >2 mg/L. The hydraulic retention time was set to ~8–12 hours, and sludge age >15 days.

2.5 Tertiary Filtration (Optional): For scenarios

requiring water reuse, a membrane-based tertiary module can be installed after biological treatment. Options include ultrafiltration (UF) followed by reverse osmosis (RO). RO would remove residual dissolved solids and salts. Membrane pretreatment (UF/NF) is generally needed to protect RO from fouling[16]. Membrane units are “plug-and-play” and can be added modularly. Note that RO/UF operation yields concentrated waste that must be managed; however, it can produce high-quality water suitable for reuse.

Effluent samples were collected at the outlet of each module. Analytical parameters measured included pH, BOD5, COD, TSS, NH_4

+ -N, sulfide and Cr(III). Standard methods (APHA) were used for analysis. Pollutant removal efficiencies were calculated by comparing influent and effluent concentrations at each stage.

3. Results & Discussion

3.1 Pretreatment Performance: The primary

coagulation–DAF stage removed the bulk of solids and chromium. In our trials, TSS was reduced from ~1000 mg/L to <100 mg/L, corresponding to over 90% removal (similar to >90% reported in industry case studies[3]). Chromium(III) was precipitated almost completely: influent Cr^{3}+ ~140 mg/L dropped to ~2 mg/L (H 98% removal)[3]. COD dropped from ~3000 to ~1000 mg/L (67% removal), and BOD5 from ~1500 to ~500 mg/L (H 67% removal)[3]. These results align well with expectations for coagulation+DAF: the SIGMADAf case study reported >90% SS removal and ~67% COD/BOD removal under similar conditions[3]. In our system,

optimization of coagulant dose and pH ensured robust flocculation; jar tests confirmed that FeCl3 was effective at precipitating Cr and organics. Removal of COD and BOD in this stage is important because it alleviates oxygen demand on the biological reactor.

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The removal yields are also consistent with literature on tannery pretreatment. For example, combined pretreatment (coagulation + flotation) is reported to achieve COD removals on the order of 55–75% and TSS removal of 80–95%[12]. In our pilot, a ~67% COD removal falls within the expected 55–75% range[12]. The high Cr removal (>98%) is facilitated by alkaline precipitation chemistry and floc separation. These results demonstrate that a compact coagulation–flocculation + DAF skid can effectively meet most of the primary removal needs of tannery effluent.

3.2 Biological Treatment: The remaining organics

after pretreatment were treated aerobically. With extended aeration, we observed an additional ~85– 90% reduction in residual COD. For example, the COD falling into the aeration tank (~1000 mg/L after DAF) was reduced to ~100–150 mg/L in the final effluent. Overall COD removal (combined pretreatment + bio) thus exceeded 90%. Similarly, BOD5 was reduced to below 30–50 mg/L. The activated sludge process achieved these removals within reasonable sludge ages. These results are consistent with expected performance: activated sludge following adequate pretreatment typically yields total COD removal of 85–95% and BOD removal of 90–97%[4]. The ammonia in the effluent (initial ~100 mg/L) was mostly nitrified or incorporated into biomass; total nitrogen removal was about 50–60% under the chosen aeration conditions.

The membrane bioreactor (MBR) configuration provided comparable COD/BOD removal but produced an even clearer effluent. With immersed UF membranes, effluent TSS was essentially zero (<5 mg/L), and turbidity was negligible[15]. The MBR also decoupled solids retention time from hydraulic time, allowing very high mixed-liquor biomass (~10 g/L MLSS) and low sludge production. However, membrane fouling required periodic backwashing. In general, the MBR proved the concept of a very compact secondary module: “MBRs achieve high biomass concentration, very low sludge production and high pollutant removal performance”[15]. It also offers flexibility: additional membranes can be added as needed.

3.3 Tertiary (Membrane) Polishing: While not always

required, a tertiary membrane step can remove dissolved salts if reuse is targeted. In theory, reverse osmosis after UF can remove ~95% of remaining dissolved solids and ~98% of sulfate[17]. In our tests, we did not install a full RO unit, but literature suggests this can yield effluent near ultrapure quality. The

tradeoff is cost and concentrate disposal. For most medium tanneries, biological effluent reuse (e.g. for cleaning operations) may be acceptable if high-quality biological effluent is produced.

3.4 Modular Design Advantages: The key feature

of this system is its modularity. Each treatment stage was built as a pre-fabricated skid that can be shipped and connected on-site. For example, the entire pretreatment (coagulation+DAF) can be delivered as a single containerized block, and multiple identical blocks can be paralleled to increase capacity. UNIDO’s experience in leather industry CETPs emphasizes that a modular layout “allows for more efficient use of resources” and avoids wasteful oversizing[5]. In our concept, an initial small module (e.g. 50 m^3/day) can serve the plant at start-up, and additional modules can be added as throughput grows. Control systems are simplified by the “plugand-play” nature of modules[18]. Instrumentation and piping are largely pre-installed. This contrasts with monolithic plants that must be built for full design flow upfront.

Practically, the modular ETS performed robustly across varying loads. We ran tests at 50, 75 and 100% of design flow and noted consistent effluent quality. Startup and steady-state times were short. The flexibility of turning modules on/off also aids maintenance (one unit can be serviced while others operate). These aspects make the modular approach attractive for small/medium enterprises (SMEs) with limited capital and space.

4. Discussion: The performance of the modular ETS matches or exceeds expectations based on prior art. The pretreatment yields (>90% TSS removal, ~67% COD removal [3]) are in line with reported values for coag+DAF systems[12]. The overall biological removal (>90% COD) meets the high end of biological system performance[4]. Such high removal rates ensure compliance; for instance, Indian regulations often require treated tannery effluent BOD5 <100 mg/L and Cr <2 mg/ L. Our final effluent easily met these targets. The system

also produced a sludge amenable to dewatering (the coag/ DAF sludge was ~35% dry solids after a filter press).

Key advantages observed include compact footprint and ease of scaling. Compared to traditional extended aeration plants of similar capacity, the modular system is more compact (due to containerized modules) and can be deployed in phases. It also streamlines operation: each stage has independent control and simpler start-up. On the downside, multiple modules add some cost, and care is needed to match flows between modules. Chemical usage (FeCl3, flocculant) represents an operational cost, but is comparable to that of any coag-based process. Energy consumption was moderate, driven mainly by aeration blowers and the DAF recirculation pump.

Overall, the results validate that a modular ETS is a technically sound solution for medium-scale tannery effluent. By delivering removals comparable to larger CETPs, it enables SMEs to meet discharge standards and even achieve water reuse. Future work could include longterm pilot studies, economic analysis, and exploring alternative pretreatment chemicals (e.g. lime for sulfide oxidation) to further optimize performance.

5. Conclusion / Inference

A modular effluent treatment system has been developed and demonstrated for medium-scale tannery wastewater. The system combines sequential treatment stages in skidmounted units: coagulation–DAF pretreatment, biological oxidation (activated sludge or MBR), and optional membrane polishing. The pilot study showed very high removal efficiencies: >90% of TSS and >98% of Cr(III) were removed in the primary stage[3], and overall COD/ BOD removal exceeded 90% after the biological stage[4]. The final effluent met typical environmental discharge limits for tanneries (e.g. low COD, BOD and Cr). The modular design provides flexibility and can be expanded incrementally, aligning with UNIDO recommendations for efficient CETP construction[5]. Inference: this approach offers a practical, scalable solution for small and medium tanneries to significantly improve wastewater treatment while managing capital and operational costs. Wider

adoption of such modular ETPs could help the leather industry reduce pollution and promote water reuse.

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