



ORIGINAL RESEARCH ARTICLE

SYNTHESIS AND SIMULATION OF TANNERY WASTEWATER TREATMENT PROCESS WITH BIOGAS GENERATION USING WRC STOAT SOFTWARE

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ABSTRACT

Tannery wastewater is characterized by its high organic load and toxicity, primarily due to the presence of putrescible matter and heavy metals. This study aimed to simulate a comprehensive treatment process for tannery wastewater using Sewage Treatment Operation Analysis over Time (STOAT) software. The quality of treated wastewater from the simulation was evaluated against the National Environmental Standards and Regulations Enforcement Agency (NESREA) discharge standards to meet environmental safety requirements. The treatment system incorporated a multi-stage approach, including physical preliminary treatment units, chemical primary treatment, and biological secondary treatment. Additionally, the system featured a biogas production section and sludge dewatering units to maximize resource recovery. The simulation effectively modeled the treatment processes, capturing operational dynamics and interactions across the treatment units. Key pollutants, such as biochemical oxygen demand (BOD), total suspended solids (TSS), ammonia, and nitrate were monitored. Additionally, the study explored the impact of hydraulic retention time (HRT) on treatment efficiency. The results indicated that all parameters met NESREA's permissible discharge limits at various residence times. Similarly, the observed trends aligned with findings reported in the literature. Furthermore, the biogas yield from the simulation was 0.27 kg/m³ of tannery influent, with a maximum methane purity of 41%. Digested sludge was generated at a rate of 0.072 m³/m³ of tannery influent. However, extending digester residence time did not significantly enhance biogas yield or methane concentration, suggesting the need for process optimization or pre-treatment strategies. This research demonstrates the effectiveness of STOAT as a simulation tool for designing tannery wastewater treatment processes, ensuring compliance with stringent regulatory standards while optimizing resource recovery through biogas generation and sludge management. The findings emphasize the necessity of integrating physical, chemical, and biological treatment processes to enhance contaminant removal and improve the sustainability of tannery wastewater management.

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1.0 Introduction

Tannery wastewater is a major environmental concern due to its complex composition, which includes high concentrations of organic and inorganic pollutants. These contaminants—such as biological oxygen demand (BOD), chemical oxygen demand (COD), heavy metals (e.g., chromium), sulfides, and ammonia—pose significant risks to aquatic ecosystems and human health if not properly treated (Birhanu, 2017; Ghorab et al., 2022; Bhardwaj et al., 2023; Monira & Mostafa, 2023). Given the toxic and persistent nature of these pollutants, effective treatment strategies are essential to minimize environmental degradation, ensure compliance with regulatory standards, and promote sustainable industrial practices (Okereke et al., 2016; Obaideen et al., 2022; Singh et al., 2023; Kato & Kansha, 2024).

Conventional biological treatment methods, such as the Activated Sludge Process (ASP), are widely used for industrial wastewater treatment. However, ASP alone is often ineffective for tannery wastewater due to the

inhibitory effects of toxic compounds, which disrupt microbial communities and reduce treatment efficiency (Zhao *et al.*, 2022; Nigam *et al.*, 2023). To overcome these challenges, integrating ASP with physicochemical processes—such as coagulation-flocculation, adsorption, and advanced oxidation—can enhance pollutant removal by targeting heavy metals and recalcitrant organics (Ayach *et al.*, 2024; Sravan *et al.*, 2024). Additionally, anaerobic digestion offers a viable solution by breaking down complex organic matter in oxygen-limited conditions while simultaneously generating biogas, thereby improving both treatment efficiency and sustainability (Faragò *et al.*, 2021; Capodaglio & Callegari, 2023). This combined approach not only ensures compliance with discharge standards but also contributes to resource recovery and energy generation, making wastewater treatment more economically viable (Breach & Simonovic, 2018; Rafiee *et al.*, 2021; Bohra *et al.*, 2022).

Despite the urgent need for improved tannery wastewater management, research gaps persist in developing and optimizing comprehensive treatment systems that integrate biological, chemical, and resource recovery processes. Existing studies (Sivagami *et al.*, 2018; Korpe *et al.*, 2019; Urbina-Suarez *et al.*, 2021; Lei *et al.*, 2023) often focus on isolated treatment technologies, failing to evaluate the synergistic effects of a fully integrated system. This fragmented approach limits the ability to optimize operational parameters, predict long-term performance, and ensure compliance with environmental standards such as NESREA regulations.

Simulation tools like STOAT have proven effective for modeling wastewater treatment processes; however, their application to tannery effluents is limited. This lack of simulation-based studies hinders the development of optimized, energy-efficient treatment systems tailored to the unique challenges of tannery wastewater. Addressing this gap is essential for designing treatment systems that not only comply with environmental regulations but also enhance sustainability through resource recovery. This study aims to address these challenges by developing and simulating a comprehensive tannery wastewater treatment system using STOAT. The proposed treatment approach integrates the activated sludge process for biological degradation of organic pollutants with anaerobic digestion for biogas recovery. Through detailed simulation, this study analyzes system interactions, evaluates pollutant removal efficiency, assesses biogas and sludge generation potential, and optimizes key operational parameters. The findings will provide valuable insights for designing sustainable tannery wastewater treatment systems that not only meet environmental standards but also support energy recovery and resource utilization.

2. Materials and Methods

2.1 Materials

The simulation of the treatment process was conducted using WRc STOAT 5.0.551 (2013 version), installed in a laptop computer. Also, a Microsoft Excel was utilized for supplementary calculations and the plotting of graphs. Table I presents the physicochemical properties of tannery wastewater from Chowdhary *et al.* (2017), used as secondary data in this study to provide a robust foundation for a realistic simulation. These characteristics are representative of typical pollutant concentrations in high-strength industrial tannery effluents which provided the foundation for simulating and evaluating the performance of the treatment process.

Table I: Physicochemical properties of tannery wastewater used (Chowdhary *et al.*, 2017).

S/N	Parameters	Values
1	Ph	7.86
2	Temperature	32
3	Total BOD	27,266
4	Total COD	56,000
5	Total Suspended Solids (TSS)	16,205
7	Ammonia	40
7	Nitrate	26
7	Heavy Metals (Cu, Cd, Zn, Ni, Fe, Mn, Pb)	70

All the values are in mg/L except pH and temperature (°C)

2.2 Process synthesis and description

For this study, the synthesis was carried out to address the specific challenges posed by tannery effluent, which is characterized by high concentrations of organic pollutants, heavy metals, and ammonia. The process synthesis was guided by:

Characteristics of Tannery Wastewater: Data on the physicochemical properties of tannery wastewater, such as BOD, COD, TSS, ammonia, and chromium levels, informed the selection of treatment components.

Regulatory Standards: The system was designed to meet NESREA discharge permit standards, ensuring the treated effluent is safe for disposal or reuse.

Activated Sludge Process (ASP): The ASP was selected as the treatment method due to its proven effectiveness in handling high organic loads and nitrogen removal.

Biogas Recovery: Anaerobic digestion was incorporated to treat excess sludge from the ASP, enabling biogas recovery for energy sustainability.

Figure 1 represents the schematic diagram of the process. In the proposed treatment process, the tannery wastewater is received, beginning with preliminary screening where coarse solids and debris are removed to prevent damage to downstream equipment. The wastewater then flows into a primary clarifier, where heavier particles settle, reducing total suspended solids (TSS). The clarified water enters the activated sludge process, a biological treatment stage where aerobic microorganisms in the aeration tank degrade organic pollutants, lower BOD and COD, and convert ammonia to nitrates through nitrification (Cervantes *et al.*, 2005). Mixed liquor from the aeration tank enters a secondary clarifier, separating biomass. Some sludge is recycled to sustain microbial activity, while excess sludge and primary clarifier solids are sent to a thickener for consolidation and water separation. This step increases the sludge's solid content, reducing its volume and making it more efficient for subsequent treatment in the anaerobic digester. Concentrated sludge from the thickener is sent to the digester for biogas production, while the separated water is returned to the treatment process for further purification. In the anaerobic digester, the sludge undergoes microbial decomposition under oxygen-free conditions, resulting in the production of biogas. The anaerobic digester is specially designed to accommodate not only excess sludge from the ASP but also solid organic waste generated during the tanning process, such as skin trimmings, fats, and other organic residues. By integrating these high-organic-content materials into the digestion process, the system significantly increases the overall organic load, enhancing microbial activity and maximizing biogas production. The treated effluent, if it meets NESREA discharge standards, is either discharged into the environment or reused, while the stabilized sludge is safely disposed of or utilized as fertilizer.

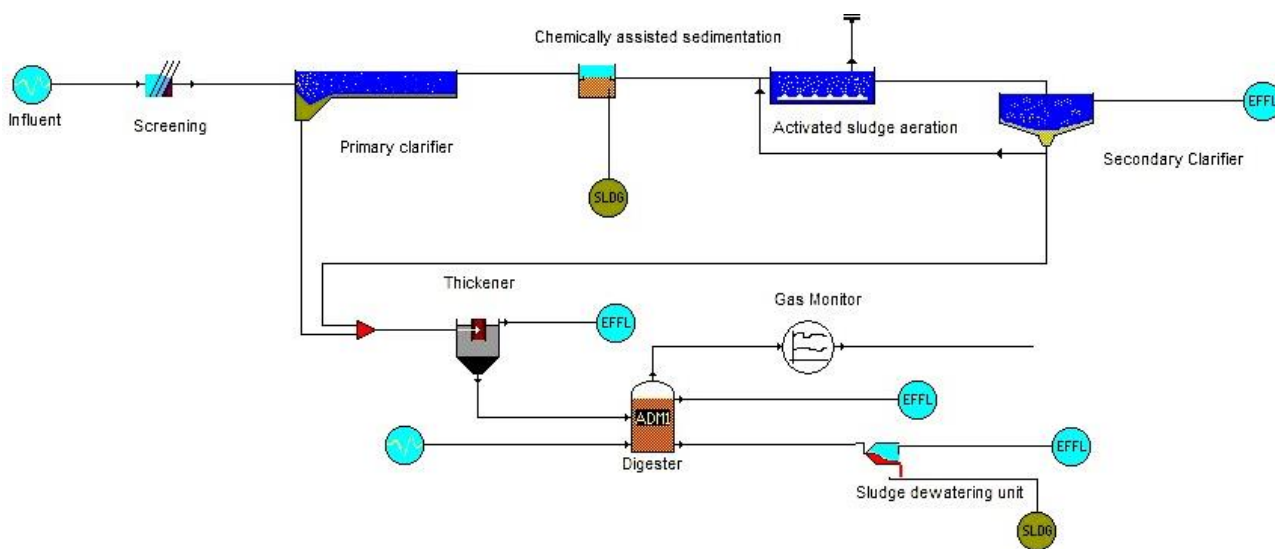


Figure 1: Process schematics of the treatment

2.3 Methods

The inflow data used in the STOAT modelling are the values from Table 1. The BOD, ASAL I and SSED I models were used for the primary clarifier, aeration basin and secondary clarifier respectively. Both models are available on the STOAT™ simulation program and the guidelines of WRC PLC (1994) and Rieger *et al.* (2013) were considered for modelling conduction. Initially, information on tank sizes and operational data were set as shown in Table 2. The influent profile assumed on STOAT was the constant pattern with 20 m³/h chosen as the inflow. In the secondary sedimentation tank, the wastage method selected was fixed-rate over variable time to maintain a specific Mixed-Liquor Suspended Solids (MLSS). Hydraulic Retention Time (HRT) and Solids Retention Time (SRT) were estimated using Equations (1) and (2) respectively (Henze *et al.*, 2008; Tchobanoglous *et al.*, 2014).

$$HRT = \frac{V}{Q}$$

1

$$SRT = \frac{V \cdot X}{Q_w \cdot X + Q_{eff} \cdot X_{eff}}$$

2

V is the volume of the aeration tank, Q is the flow rate, X is the MLSS concentration, Q_w is the sludge wastage flow, Q_{eff} is the effluent flowrate and X_{eff} is the effluent TSS. The wastage method in the aeration basin selected was “None” such that the sludge will only be wasted from the secondary clarifier.

The analysis conducted using STOAT in this study was limited to evaluating key parameters such as total BOD, TSS, ammonia, and nitrate. This focus was necessitated by the constraints posed by the software's modeling capabilities and the availability of input data specific to tannery wastewater. While these parameters provide critical insights into the system's performance regarding organic pollutant removal, solid separation, and nitrogen management, other important aspects, such as heavy metal removal, sulfide concentrations, and specific microbial population dynamics, were not directly analyzed due to these limitations.

Table 2: Initial process dimensions used in the simulation

Primary Clarifier
Process Model: BOD
Number of Stage: 3
Volume: 1,200 m³
Surface Area: 400 m²
Aeration Basin:
Process Model: ASAL I
Volume: 800 m³
Number of Stage: 1
Number of MLSS Recycles: 0
Wastage Method: None
Secondary Clarifier:
Process Model: SSED I
Number of Stages: 8
Surface Area: 400 m²
Depth of Tank: 3 m
Depth of Feed: 2 m
*RAS feed: Ratio (40 %)

RAS (Return Activated Sludge)

2.4 Data analysis

The STOAT simulation analysis in this study primarily focused on the primary clarifier, aeration tank, secondary clarifier, and digester as the main treatment units. This selection was guided by the scope of the study, which aimed to evaluate the core processes involved in tannery wastewater treatment and biogas recovery. Therefore, simulation data analysis was done at four different points in the process: after the primary clarifier, after the aeration basin, after the secondary clarifier where the treated water leaves the plant, and the top of the anaerobic digester where the biogas generated is collected. This focused approach allowed for a detailed examination of critical treatment processes while acknowledging the exclusion of other ancillary units due to the defined limitations of the study's scope.

2.5 Assumptions

The following assumptions allowed for a structured and focused simulation, balancing simplicity and practicality while evaluating the performance of the tannery wastewater treatment process integrated with biogas recovery:

- The tannery wastewater was assumed to have uniform physicochemical characteristics based on the data reported by Chowdhary *et al.* (2017).
- Variations in influent composition and flow rate were considered negligible or within manageable limits.
- The treatment system was assumed to operate under steady-state conditions, with no abrupt changes in influent load or operational parameters.
- All heavy metals present in the tannery wastewater are in a soluble form within the liquid phase and are effectively removed in the chemically assisted sedimentation chamber before the effluent enters the aeration tank
- The microbial populations involved in the activated sludge process and anaerobic digestion were assumed to remain stable and unaffected by inhibitory substances such as heavy metal concentrations.
- The treatment process was assumed to operate at a constant temperature suitable for both aerobic and anaerobic biological activities, typically around 25 – 35° C.
- Biogas production was assumed to be primarily from the anaerobic digestion of organic sludge.

3. Results and Discussion

3.1 Primary Clarifier Results

Figure 2 shows the performance of the primary clarifier based on the initial process dimensions and flow rate. The estimated HRT was 3.5 days which is higher than most values reported in the literature. It was observed that a reduction of approximately 74 % in total BOD and 92 % in TSS was achieved in the primary clarifier. This can be attributed to the very long HRT which allows for settling of suspended solids and removal of some particulate organic matter.

According to Metcalf & Eddy (2003), typical HRT for primary clarifiers is between 1.5 to 2.5 hours for municipal wastewaters. Therefore, a HRT of 3.5 days (84 hours) is very long even for industrial effluents such as tannery. However, as the HRT was decreased to 1.75 days (42 hours) in the simulation, 49 % of the BOD was reduced and 83 % of TSS reduction was achieved. Further reduction in the HRT to 0.35 days (8.4 hours) gave only 17 % and 76 % reductions in the BOD and TSS respectfully. The trend observed is in agreement with Tchobanoglous *et al.* (2014) and Karia *et al.* (2023) who reported that efficiently designed and operated primary sedimentation tanks should remove from 50 to 70 % of the suspended solids and from 25 to 40 % of the BOD. This level of performance demonstrates the importance of primary sedimentation as a pretreatment step, particularly in reducing the organic load before biological treatment.

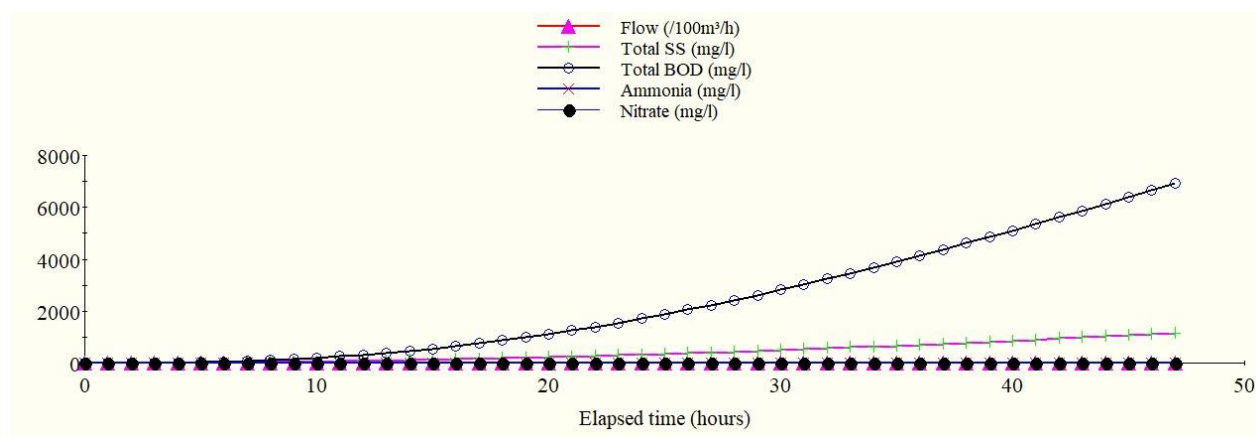


Figure 2: Performance of primary clarifier from the simulation model

3.2 Aeration Tank Results

The aeration tank was simulated with a RAS ratio of 40 % and the estimated SRT from the model was 5.8 days, and the HRT was 2.32 days, based on the initial process dimensions in Table 2. The performance is shown in Figure 3. It can be observed that a reduction of BOD by 97 % was achieved during aeration, reflecting the efficiency of the activated sludge process. It can also be seen that the solids concentration in the aeration basin increased significantly from 398 mg/L (leaving the primary clarifier) to 2181 mg/L. This is due to the removal of BOD, which promotes the growth of biomass (Henze *et al.*, 2008). During the aeration process, microorganisms consume organic pollutants present in the wastewater as their energy and carbon source. The microorganisms proliferate as the BOD levels decreases, leading to an increase in the concentration of suspended solids. The average solids concentration from the results was 2475 mg/L. A longer HRT allows for more thorough treatment, as it provides more time for physical, chemical and biological processes to occur. In tannery wastewater treatment plants, different treatment units have specific HRT requirements; for example, primary clarifiers or sedimentation tanks may have a shorter HRT to allow for the settling of suspended solids and separation of oils and grease (Ho *et al.*, 2017; Mandal *et al.*, 2020). Other biological treatment units, such as aeration tanks, typically require a longer HRT to provide sufficient time for microorganisms to metabolize organics pollutants (Bhattacharyya *et al.*, 2022; Zulfikar *et al.*, 2022; Waqas *et al.*, 2023).

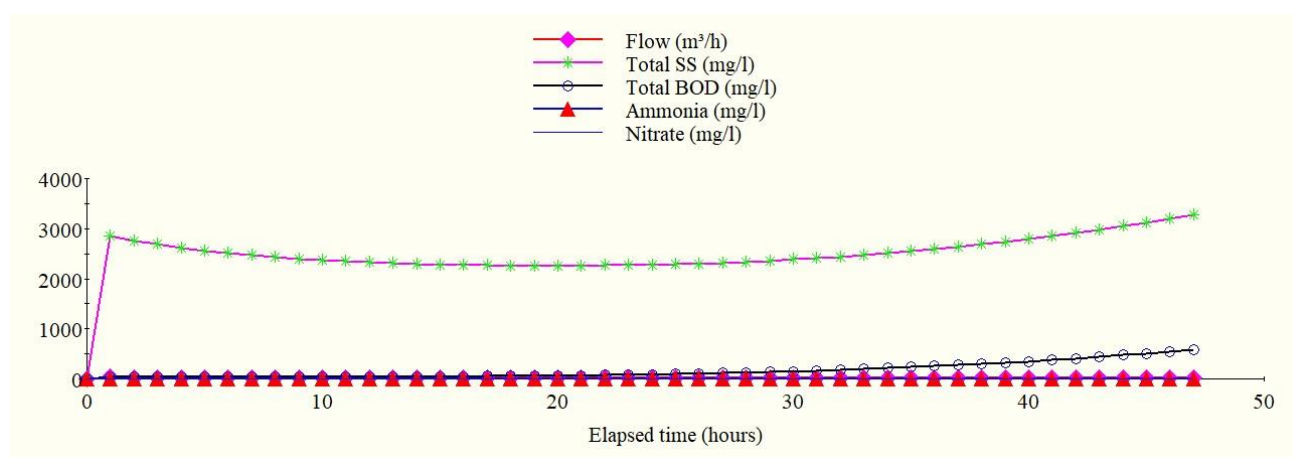


Figure 3: Performance of the aeration tank from the simulation model

The effect of HRT on TSS and BOD inside the aeration basin can be observed in Figure 4. It was observed that decreasing the HRT increases the TSS while reducing the BOD removal efficiency. From Figure 4, decreasing the HRT from 2.32 days to 0.23 days increases the TSS from 2181 mg/L to 4032 mg/L due to increase in the organic load rate. On the other hand, the BOD removal deteriorated from 97 % to 87 %. It has been reported that 1 day HRT has been successfully employed in tannery wastewater treatment. Others indicates a BOD removal of 80 % to 90.8 % for tannery effluent (El-Sheikh *et al.*, 2011; Mekonnen *et al.*, 2017; Prabhakaran *et al.*, 2022; Zulfikar *et al.*, 2022). Typical SRT range for conventional continuous flow activated sludge system is 3 – 15 days (Metcalf & Eddy, 2003). In this study, 97 % BOD removal was achieved in the aeration tank with 5.8 days SRT and 2.32 HRT. The observed trend in Figure 4 is in agreement with the general

theory of activated sludge systems and other reported studies (Bhattacharyya et al., 2022; Prabhakaran et al., 2022; Zulfikar et al., 2022).

A substantial reduction in ammonia concentration ($> 99\%$) occurred due to nitrification, where aerobic bacteria converted ammonia to nitrate. The final ammonia concentration met discharge limits, demonstrating effective nitrogen removal. Nitrate concentrations in the effluent were also within permissible limits, indicating that denitrification and dilution effectively managed nitrate levels.

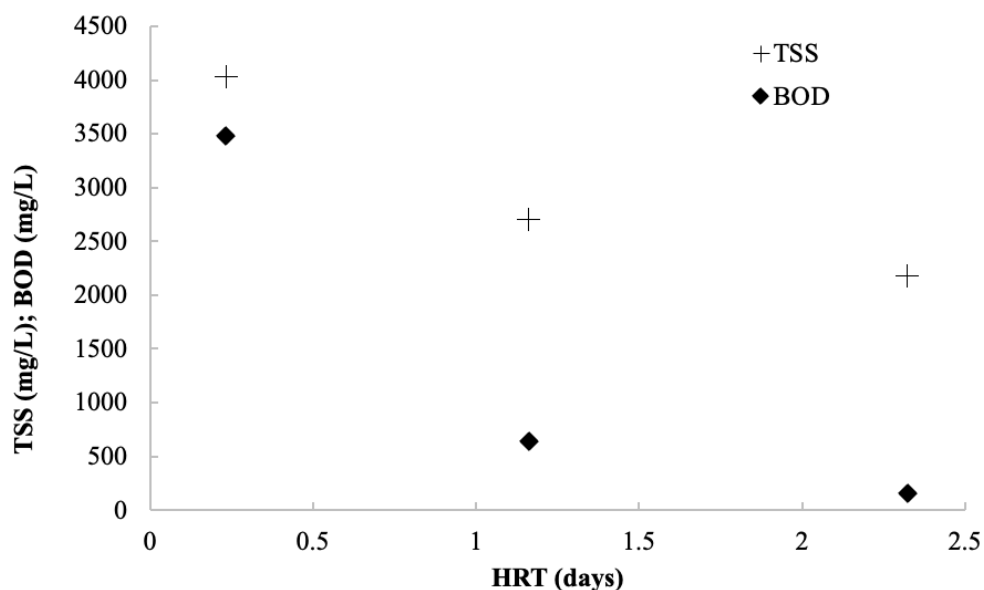


Figure 4: Effect of HRT on TSS and BOD in the aeration tank

3.3 Secondary Clarifier Results

Figure 5 shows the performance of the secondary clarifier based on the initial process dimensions. BOD removal reached 99%, indicating a nearly complete elimination of biodegradable organic pollutants. TSS were also reduced significantly, with over 99 % removal in the primary tank and an additional reduction in the secondary clarifier, achieving effluent quality that complies with regulatory standards

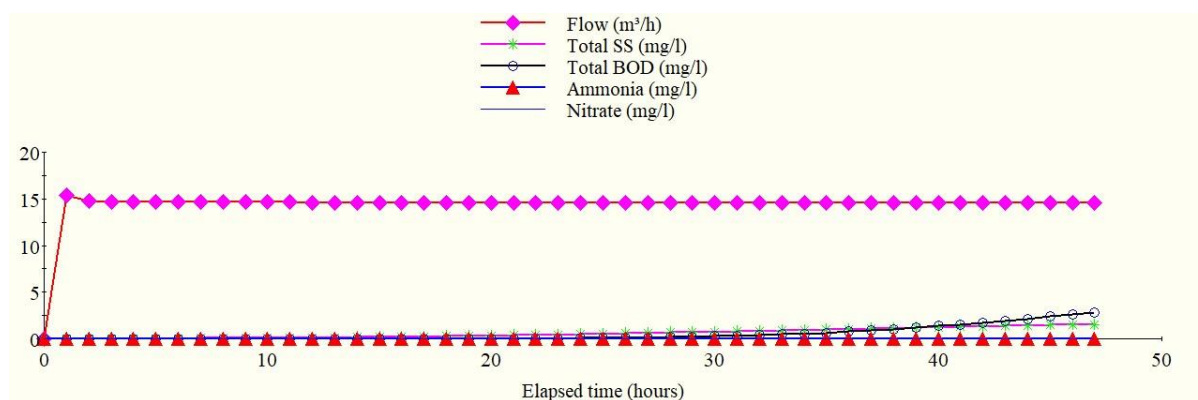


Figure 5: Secondary clarifier performance

Table 3 presents the treated water quality after the secondary clarifier against the effluent limitation standards for tannery wastewaters set by NESREA. This underscores the combined effectiveness of physical sedimentation and biological treatment.

Table 3: Treated water quality from the simulation against effluent limitation standards for tanning and leather set by NESREA (Ladan, 2012)

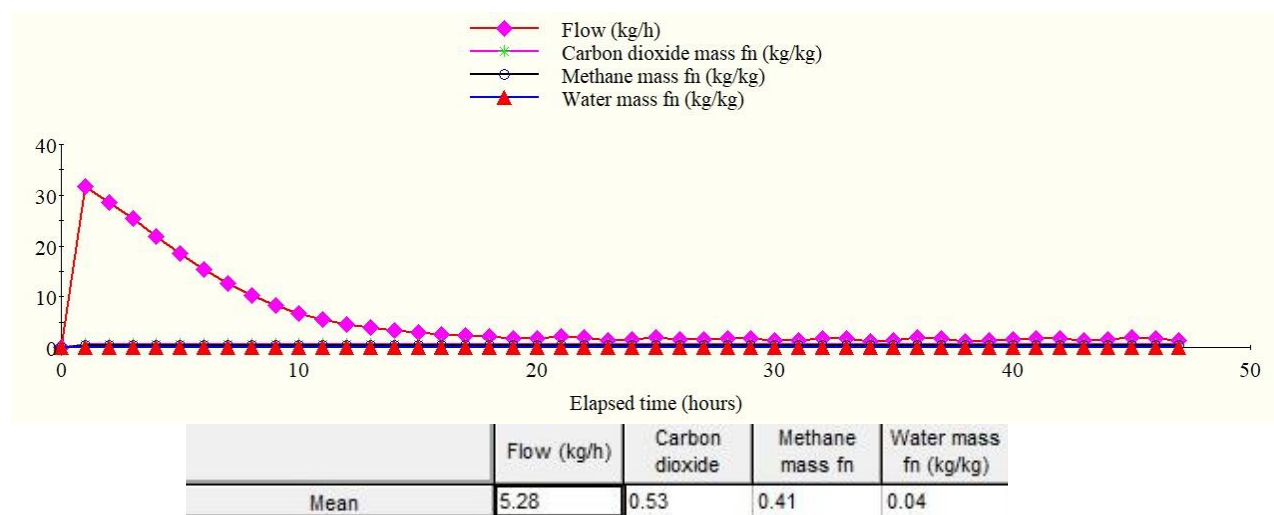
S/N	Selected Parameters	This study	NESREA
1	pH	7.01	6 – 9
2	Temperature	30	40
3	Total BOD	2.37	50
5	Total Suspended Solids (TSS)	1.48	25
8	Ammonia	0.01	10
9	Nitrate	0.01	20

3.4 Biogas Generation

Figure 6 shows the biogas generation profile from the model. The predicted biogas production and methane content from the model revealed a slight deviation from typical standards. While typical methane content in biogas is between 45 % to 70 % (Amon *et al.*, 2007; Li *et al.*, 2019; Jameel *et al.*, 2024), the simulation predicted an average methane purity of 41 %, carbon dioxide content of 53 % and 4 % water, at a rate of 5.28 kg per 20 m³ of tannery influent. This translates to 2.165 kg/h of biomethane. However, digested sludge was produced at a rate of 1.42 m³/h, indicating effective organic matter degradation but suboptimal methane generation.

Biogas yield from the model was 0.26 kg per m³ of influent. Given methane's density of 0.75 kg/m³ at standard conditions, the produced biomethane equates to 2.896 m³/h. At the target methane purity of 60 %, the production would be 3.258 kg/h or 4.344 m³/h of biomethane. This difference highlights the need for optimization in the digestion process to enhance methane yield and purity.

On an annual scale, this production level equates to approximately 38,000 m³ of biomethane per year, translating to a power generation potential of around 57,000 kWh. For reference, 10 m³ of dry biogas with a methane composition of up to 60 % has a lower heating value of about 21.5 MJ/m³ at 20 °C and atmospheric pressure, which supports a power generation capacity of 15 kW per hour (INOPLEX, 2022; Onyekaozuoro *et al.*, 2023).

**Figure 6:** Biogas generation results and profile from the simulation

The suboptimal methane purity from the model suggests potential issues with the digestion process, such as the presence of inhibitory substances like sulfides or insufficient operational parameters (e.g., retention time, pH, or temperature). Additionally, optimizing process variables and ensuring proper pre-treatment of tannery wastewater to reduce inhibitory compounds, like heavy metals, can significantly improve biogas quality and yield. These adjustments are necessary to achieve the target 60 % methane purity, which would enhance the energy recovery potential of the system.

It was further observed in the simulation that the residence time of the digester does not have any significant effect on the biogas yield and purity. The reason is STOAT has limitations when it comes to combining different

modes of treatment mechanisms, such as integrating aerobic and anaerobic models. The transition between the two mechanisms is not inherently coupled or dynamically linked. This can lead to inconsistencies in the simulation, particularly when modeling processes like aerobic pre-treatment followed by anaerobic digestion. Therefore, in the future, a separate STOAT simulation for aerobic and anaerobic units could be carried out, then manually link the outputs (e.g., effluent composition) to approximate system performance.

4. Conclusion

This study successfully demonstrated the use of the STOAT simulation software to design and evaluate a comprehensive treatment process for tannery wastewater. The system effectively combined physical, chemical, and biological treatment units, achieving significant pollutant removal and ensuring compliance with NESREA discharge standards. Key parameters, including BOD, TSS, ammonia, and nitrate, were reduced to within acceptable regulatory limits, validating the efficiency of the modeled treatment system. Additionally, the study explored the impact of HRT on treatment efficiency, showing similar trends as reported elsewhere. The integration of anaerobic digestion for biogas production and sludge dewatering showcased the potential for resource recovery in tannery wastewater treatment. However, the biogas yield of 0.27 kg/m³ of influent and methane purity of 41% were lower than expected, with no significant improvement observed despite increased digester residence time. This highlights the need for further optimization of process parameters and potential pre-treatment to address inhibitory compounds, such as heavy metals, that may hinder microbial activity and gas production. Overall, the study demonstrates the utility of STOAT as a reliable tool for simulating and optimizing wastewater treatment processes. It provides a foundation for future research to enhance resource recovery and improve the sustainability of wastewater treatment systems, particularly for industrial effluents like those from tanneries.

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