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Original Article

Process Optimization and Modeling of Tuna Canning Wastewater Treatment Plant Using GPS-X Software: A Full-Scale Case Study

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Abstract

Background: Wastewater treatment from fish processing industries presents major environmental challenges because of high effluent volume, salinity, and complex organic compounds like fats, proteins, nitrogen, and phosphorus. Efficient treatment plant design requires advanced modeling and simulation to enhance pollutant removal and minimize operational costs.

Methods: This study was conducted at the Bandar Abbas tuna canning factory. Wastewater quality data, treatment plant specifications, and previous studies were collected. The treatment process was simulated and optimized using GPS-X software based on the ASM2d biological model. The base model was calibrated and validated, and various operational scenarios, including adjustments to sludge return rate, waste activated sludge discharge, hydraulic retention time, and mixed liquor suspended solids concentration, were evaluated.

Results: Simulation under optimized conditions markedly improved pollutant removal. COD, BOD_5, and TSS decreased by 98.46, 99.25, and 98.52%, respectively, approaching national standards. Total nitrogen, ammonia, and phosphorus were reduced by 93, 97, and 80%. Sensitivity analysis revealed that sludge return rate, waste sludge discharge, hydraulic retention time, and activated sludge concentration most strongly influenced effluent quality.

Conclusion: Dynamic simulation with GPS-X accurately predicted treatment plant behavior, optimized performance, and reduced energy and sludge production. Overall, the study demonstrates that mathematical modeling and scenario optimization are powerful tools for improving fish processing wastewater treatment efficiency and achieving environmental compliance.

Keywords: Wastewater treatment, Dynamic simulation, Process optimization, MLE process, GPS-X software, Fish canning industry

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Introduction

Wastewater management and treatment are essential for reducing environmental pollution and promoting a green economy in industrial processes.[1] Industrial activities generate large quantities of wastewater that may be largely contaminated or contain toxic pollutants, creating challenges for environmental and public health. The main sources of industrial wastewater include industries such as petrochemical, pharmaceutical, pulp and paper, textile, iron and steel production, and food processing.[2] Fish processing industries are among the most important sources of wastewater production, as they generate large amounts of effluent containing high concentrations of organic matter, nutrients, and salts which, if discharged without adequate treatment, can pose serious threats to environmental health.[3] The seafood processing industry, as one of the key sectors in the global food production chain, plays a significant role in meeting nutritional demands. However, this industry faces serious environmental challenges, mainly due to the high volume of wastewater generated at various stages of processing. These effluents contain multiple pollutants and, if not properly treated before discharge, can lead to extensive ecological consequences, including eutrophication. Wastewater from seafood processing is typically divided into two main groups: high-volume, low-pollution wastewater, and low-volume, high-pollution wastewater. The first group includes streams such as aquaculture discharges, wash waters, transport waters, and other low-load streams, while the second group originates mainly from different processing activities and contains higher concentrations of pollutants. The presence of fats, oils, and grease (FOG) in this type of wastewater is a major issue, as these compounds can clog pumps and equipment, disrupt treatment processes, and, upon decomposition, produce unpleasant odors.[4] Additionally, wastewater from fish and seafood processing contains various organic compounds such as flesh, blood, bones, suspended solids, proteins, and fine particles, making it a rich source of organic matter. These substances significantly increase chemical oxygen demand (COD) and biological oxygen demand (BOD), and if discharged untreated into surface waters, can lead to decreased dissolved oxygen and harmful effects on aquatic ecosystems. Furthermore, the presence of nutrients such as nitrogen, phosphorus, and other minerals, along with detergents and disinfectants, makes the composition of the wastewater even more complex. Due to this complex nature, effective treatment of such effluents requires the use of specialized and optimized purification methods before discharge into the environment.[3, 5]

The treatment process for fish processing wastewater typically begins with physicochemical units designed to remove oils, fats, and suspended solids from the wastewater stream. Following this stage, biological reactors are used to degrade and remove dissolved organic matter.[6] However, specific characteristics of tuna canning wastewater such as variable COD, high organic content, high salinity, suspended solids, nitrogen, and oil combined with seasonal fluctuations and diverse sources, pose serious challenges for the design and operation of treatment systems. High salinity reduces the efficiency of biological processes, and compounds such as sulfate in anaerobic digesters can increase hydrogen sulfide production, which must be removed from the biogas stream. Although anaerobic processes are commonly used for this type of wastewater, their effluent often contains significant nitrogen levels, and high salinity can inhibit microbial activity and biogas production. Therefore, in recent years, modern process design methods have been increasingly considered to improve efficiency and effluent quality.[7]

Among these, mathematical modeling has gained growing importance as a novel approach to improving the design and operation of treatment plants. Instead of relying solely on experimental tests, controlled simulations are used to evaluate a wide range of processes under different conditions. Modeling software allows the design and operation processes to be performed with greater accuracy. Moreover, considering the dynamic nature of treatment plant operations, mathematical models help operators better predict system behavior. Furthermore, the integration of biological, chemical, and physical reactions in wastewater treatment plants makes these processes highly complex, requiring intelligent and appropriate tools for designers and operators to analyze the interactions. One of the most important of these tools is GPS-X, which is widely used for modeling municipal and industrial wastewater treatment plants. GPS-X is an advanced dynamic modeling and simulation software specifically developed for the analysis and design of wastewater treatment plants, provided by Hydromantis Environmental.[8, 9] This software enables engineers to test and evaluate different design and operational scenarios under controlled conditions. GPS-X includes a comprehensive library of process models that cover a wide range of physical, chemical, biological, and anaerobic processes.[10] Optimizing the wastewater treatment process can lead to reduced energy consumption, improved effluent quality, lower operational costs, and higher resource efficiency.[8]

To date, numerous studies have been conducted on wastewater treatment process modeling and simulation using GPS-X software. In one applied study, Wondim et al used GPS-X to optimize the performance of a textile factory's wastewater treatment plant. By modeling and adjusting key parameters such as sludge return flow, solids retention time, aeration, and carbon source, operational problems were resolved and system performance significantly improved. The most notable result of this optimization was a 91.5% reduction in aeration energy consumption and the development of an efficient operational guideline for cost-effective plant operation.[1] Similarly, Elachola utilized GPS-X to analyze and simulate the wastewater treatment plant of Karantor Markaz in India to optimize its performance and efficiency. For this purpose, three years of collected data were used for modeling and calibration, and various scenarios were simulated to better control critical parameters such as total suspended solids (TSS) and COD. The results indicated that increasing the simulation duration improved TSS removal and overall system performance, confirming that GPS-X can serve as an effective tool for process optimization.[11]

While wastewater treatment simulation is a well-researched field, most studies concentrate on municipal or conventional industrial plants, largely overlooking the unique complexities of effluent from the fish processing industry. A noticeable research gap exists, as no systematic study has not employed advanced tools like GPS-X software for the dynamic simulation, operational scenario evaluation, and performance optimization of these specific treatment plants. This study focused on that gap by introducing an innovative approach that utilize advanced simulation models to accurately forecast key parameters (COD, BOD, nitrogen, phosphorus), conduct simultaneous mass balance and operational cost analyses, and optimize energy and chemical consumption. Using GPS-X for dynamic scenario analysis, this research aimed to model and optimize the wastewater treatment process at a full-scale tuna canning plant, with the ultimate goals of enhancing efficiency, reducing operational costs, and ensuring in accordance with environmental standards.

Materials and Methods

Study Area and Wastewater Characteristics

This study was performed at the Bandar Abbas tuna canning factory, located in Bandar Abbas city, Hormozgan Province, in southern Iran. As one of the largest fish processing industries in the region, the factory has an annual production capacity of approximately 45 million cans of tuna. The production line involves stages such as initial preparation, washing, cooking, canning, sterilization, and packaging. Each of these stages generates significant amounts of wastewater characterized by a high organic load and salinity. The map of the study area is shown in Figure 1. The factory's wastewater primarily originates from fish residues, washing operations, cooking water, and equipment cleaning. Owing to the seasonal nature of production, both the wastewater flow rate and pollutant concentrations exhibit considerable temporal fluctuations. The influent wastewater typically contains high contents of COD, BOD, TSS, and salinity, which can adversely affect the performance of biological treatment processes. The average properties of the influent wastewater entering the treatment plant has been indicated in Table 1.

Description of the Existing Wastewater Treatment Plant

This wastewater treatment plant has been designed to handle effluent with a high organic load and significant concentrations of fats, nitrogen, and suspended solids, employing physical, chemical, and biological treatment methods. Initially, the influent wastewater passes through a pumping pit and enters a screening unit, where coarse solids such as fish pieces, plastics, and metals are removed to reduce the initial TSS. Next, in the grit chamber, larger particles settle, and the flow is transferred to the equalization tank to balance the flow rate, pollutant load, and temperature. In this unit, pH is measured and adjusted by injecting lime or aluminium sulfate to prevent shock loading to the subsequent treatment stages. Afterward, in the dissolved air flotation (DAF) unit, compressed air is injected to separate fats and oils by floating them to the surface. This step plays a crucial role in reducing the pollution load and improving wastewater quality. The effluent then enters the anoxic reactor for nitrate removal through denitrification, followed by the aeration tank, where aerobic biological treatment takes place to reduce BOD, COD, and nitrate levels. The flow then moves into the sedimentation tank, where solids settle and sludge is separated. A portion of the sludge is recirculated as return activated sludge (RAS), while the excess sludge is transferred to the sludge dewatering and disposal unit. The clarified effluent passes through a pumice filter for final polishing, where fine particles and remaining TSS are

Table 1. Average concentrations of pollutants at the treatment plant inlet

Row	Parameters	Unit of measurement	Amount Input
1	COD	mg/L	2600
2	BOD_5	mg/L	1341
3	TSS	mg/L	1978
4	TKN	mgN/L	140
5	TN	mgN /L	140
6	SnH	mg/L	60
7	TP	mgP /L	20
8	DO	mgO_2/L	2.0
9	TDS	mg/L	980
10	PH	-	6

Figure 1. The map of the study area

removed to enhance water clarity. Finally, chlorination is carried out to disinfect and eliminate microorganisms, and the treated effluent is reused for agricultural irrigation and green space watering. Biological treatment in this facility is based on the LE (Ludzack–Ettinger) and MLE (Modified Ludzack–Ettinger) processes, which are among the most effective technologies for nitrogen removal in industrial wastewater. These two methods combine anoxic and aerobic stages, resulting in significant reductions in total kjeldahl nitrogen (TKN) and dissolved nitrogen. The stages of the Bandar Abbas tuna canning factory wastewater treatment process have been illustrated in Figure 2.

Data Collection

The present research was an applied study conducted during 2024–2025 with the aim of optimizing the wastewater treatment process of the Bandar Abbas tuna canning factory using GPS-X software. In this study, secondary data including wastewater quality data, treatment plant design documents, and results of previous studies were used as tools. These data were collected through a library-based method using reliable scientific sources such as books, related research articles, graduate theses at the master's and doctoral levels, as well as information available in the consulting engineers' project database.

Modelling Approach and Software

The simulation was performed using GPS-X software (Hydromantis, Canada).[12] In the modeling process with GPS-X, biological models from the ASM2d family were used to accurately simulate the treatment processes. After collecting and evaluating the relevant data and influencing variables, different operational scenarios were defined and simulated in the software to examine system behavior under various conditions. The obtained results and analytical graphs were carefully analyzed, and based on these findings, effective operational strategies were proposed to reduce or eliminate adverse outcomes. This approach made it possible to develop preventive policies aimed at improving treatment plant performance and enhancing operational risk management. In this study, efforts were made to evaluate the overall efficiency of the system by considering the impact of influent flow variables on various treatment units. For this purpose, in addition to on-site measured data, a process simulation model was developed to systematically assess the influence of different factors on treatment plant performance. Subsequently, the relative importance of each variable was analyzed, and the key variables with the highest impact were identified. Based on this prioritization, appropriate performance indicators were defined to assess the success of the system in achieving treatment objectives and improving operational efficiency.

In this research, wastewater quality parameters including COD, BOD_5, TSS, TKN, TN, TP, NH_4^+, pH, and DO were measured as the main pollution indicators at the influent of the treatment plant. Then, using GPS-X software, the treatment process was modeled and simulated based on these parameters, and the model was calibrated and validated accordingly.[1, 13]

Model Calibration and Validation

Model calibration in GPS-X software was performed to enhance the accuracy of simulations and align model outputs with actual treatment plant data. In this process, real data on influent and effluent wastewater quality were first collected to ensure that the model could be adjusted based on real operating conditions of the treatment plant.[14] Parameters such as microbial growth rate, half-saturation coefficient, reaction rates, nitrogen and phosphorus adsorption and oxidation constants, sludge retention time (SRT), hydraulic retention time (HRT), and return sludge rates (RAS/WAS) were among the most critical factors adjusted during calibration. These adjustments were carried out using statistical methods such as the least squares approach to minimize discrepancies between simulated results and laboratory data.

In the first stage, a base model was defined in GPS-X. This model was designed according to the MLE process and included anaerobic, anoxic, and aerobic zones,

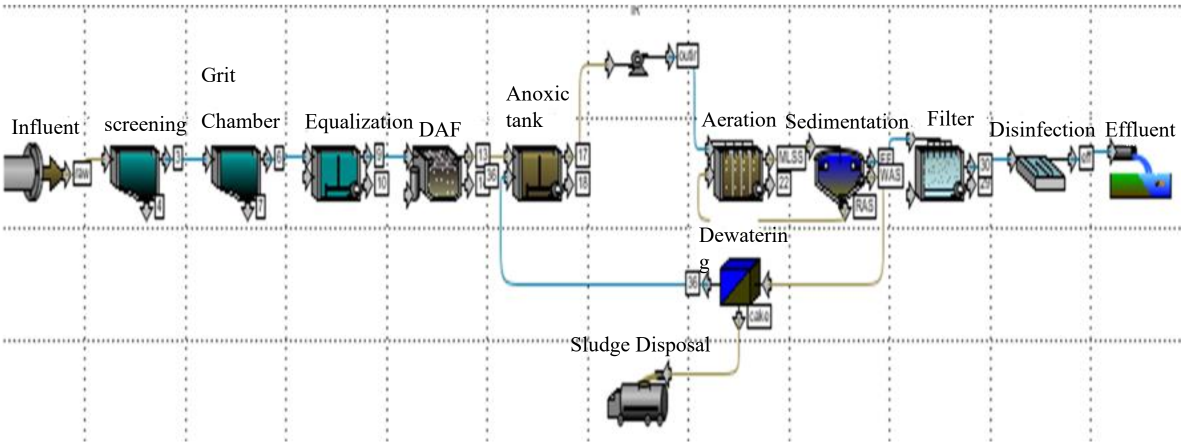

Figure 2. Stages of the wastewater treatment process at the Bandar Abbas tuna canning factory

along with units such as an aeration tank, secondary clarifier, and return sludge flows. Subsequently, influent data such as COD, BOD, TKN, TP, TSS, DO, TN, TDS, VSS, Ammonia-N, pH, temperature, and flow rate were entered into the software using the Influent Builder tool. Then, operational parameters such as SRT, HRT, food-to-microorganism ratio (F/M), Mixed Liquor Suspended Solids (MLSS), Mixed Liquor Volatile Suspended Solids (MLVSS), reactor volume, return flow rates, and hydraulic distribution in different modules were adjusted to replicate actual process conditions within the model. After implementing these adjustments, the model was validated using an independent dataset to verify its accuracy and ability to reproduce system performance reliably. This process played a crucial role in improving simulation precision, analyzing operational scenarios, and providing optimization strategies.

Following model setup, an initial simulation was conducted, and the output values (COD, BOD, TKN, TP, TSS, VSS, Ammonia-N, DO, pH, etc.) were compared with the actual treatment plant data. Since discrepancies were observed between the simulated and real outputs, the calibration phase was initiated. During this stage, microbiological and physical parameters were gradually adjusted. Table 2 presents the suggested values for biological parameters used in the calibration process.[12,13,15]

Also, physical processes such as the settling rate in the clarifier, sludge recirculation rate, and aeration intensity were adjusted to achieve the desired dissolved oxygen (DO) concentration (approximately 2 mg/L). After implementing these adjustments, the model was re-run, and the discrepancies between the simulated and observed data were evaluated. To quantify the deviation between the simulated and measured values, the Average Relative Error (ARE) was calculated using Equation (1):[12]

$$\mathrm{ARE} = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|mi - pi\right|}{mi} * 100 \qquad (1)$$

In this equation, ARE represents the Average Relative Error, m_i denotes the measured values of the output variable, p_i refers to the simulated values of the output variable, and N is the number of samples.

An absolute error of less than 10% for most parameters is considered a valid criterion for calibration accuracy, and the model can therefore be regarded as reliable.[12] Finally, output graphs such as COD, BOD_5, NH_4^+, NO_3^-, TSS, and DO were analyzed, and the final model was saved. In the end, a comprehensive report was prepared, including the adjusted parameters, comparison between observed and simulated data, and sensitivity analysis. This documentation is highly important not only to ensure model accuracy but also for future applications and operational decision-making in the treatment plant.

Sensitivity Analysis

To evaluate the impact of variations in different parameters on the performance of the treatment system, the sensitivity analysis tool in GPS-X software was used. This feature allows assessment of the system's response to changes in each parameter and helps identify the most influential variables.[17] The key parameters examined in this analysis included influent flow rate (Q), aeration tank volume (AST), cross-sectional area (CSA), RAS ratio, waste activated sludge (WAS) ratio, and influent quality parameters such as COD, BOD_5, ammonium, and total nitrogen (TN). Changes in each of these parameters can affect the final effluent quality and the overall treatment efficiency. To conduct the sensitivity analysis, the Analyzer tool of the software was employed. This tool enables the execution of multiple scenarios by changing one or more parameters and evaluating their effects on model outcomes. In this study, several key parameters were varied within defined ranges, and the effects of these changes on system performance indicators were analyzed.

Several key operational parameters were examined for sensitivity analysis. First, SRT was varied within a range of 10 to 20 days to assess its influence on COD and nitrogen removal efficiency. Generally, increasing SRT improves treatment efficiency and pollutant removal, but it also leads to higher sludge production and increased maintenance and disposal costs. Then, the HRT was adjusted between 12 and 24 hours to identify potential variations in effluent quality. In addition, RAS and WAS ratios were investigated as factors affecting MLSS concentration, since changes in these ratios can influence process efficiency and system stability. Finally, the influent flow rate was increased and decreased relative to the baseline to determine how flow variation affects pollutant removal and operating costs. These parameters were selected for sensitivity analysis because of their critical role in treatment plant performance and their controllability under operational conditions. Ultimately, by running a series of simulation scenarios and gradually adjusting each parameter, their effects on key system outputs including COD, BOD_5, nitrogen, and energy consumption were analyzed, and the most sensitive parameters were identified.

Table 2. Calibration of biological model parameters.[12,16]

Parameter	Explanation	Suggested amount
μ_max (Maximum nitrification growth rate)	For the growth of nitrifiers	0.9_1.1/d
Y (Biomass yield)	For heterotrophic bacteria	0.6
B (Cell death rate)	Usually 0.05_0.1/d	-
K_s (Semi-saturated)	For COD and NH_4^+	Model sensitivity check
f_P (Degradable Cellular Materials Section)	To be checked	~0.08_0.1

Simulation Scenarios and Optimization

After ensuring the accuracy of the base model's performance through calibration and validation, the next step involved defining and implementing various simulation scenarios using the GPS-X software. In the optimization stage, the operational and control parameters affecting the system performance were systematically adjusted to achieve an optimal combination that simultaneously led to maximum pollutant removal efficiency and minimum operational costs (including energy consumption and sludge production).[18] At this stage, the system's operating conditions were simulated by changing key parameters to examine the effect of these changes on the wastewater treatment plant performance. To investigate the impact of changing the RAS and WAS rates on the performance of the wastewater treatment system, four simulation scenarios were designed and executed in the GPS-X environment.[15] Initially, the base model of the treatment plant was developed based on actual operational data, including hydraulic, biological, and qualitative parameters. Then, different operational scenarios were systematically defined by altering the flow rates of RAS and WAS. In the first scenario, the RAS rate was increased relative to the baseline value to evaluate the effect of increasing activated sludge recirculation on the effluent quality indicators. In the second scenario, the WAS rate was increased to assess the effect of removing more sludge from the system. In the third scenario, both RAS and WAS flow rates were decreased to simulate conditions of reduced activated sludge in the system. In the fourth scenario, both RAS and WAS parameters were set at their design and balanced values to be considered as the control condition. In all scenarios, the simulations were carried out under steady-state conditions, and the effluent quality parameters including COD, BOD_5, NH_4^+, TN, TP, and TSS were extracted. To ensure the accuracy of the results, the operational conditions of the model and the flow rates were kept constant in all scenarios, and only the RAS and WAS flow rates were systematically changed. Finally, the output of each scenario was compared with the base model to determine the effect of operational changes on system performance.

Results and Discussion

Simulation and optimization of the treatment process using GPS-X software led to significant improvements in the performance of the wastewater treatment plant of the Bandar Abbas tuna factory. The calibrated ASM2d model was able to accurately predict the behavior of the treatment plant and provided a reliable basis for implementing optimization scenarios. After the simulations were performed, the treatment plant performance was evaluated from various aspects, including pollutant removal efficiency, operational parameters, nitrogen and phosphorus compounds, as well as energy and operational costs. Applying the optimized operational parameters resulted in achieving very high removal efficiencies for the main pollutants, and the quality of the treated effluent was significantly improved, fully complying with national environmental standards for discharge and reuse in irrigation. The removal efficiencies of wastewater parameters after optimization have been presented in Table 3.

Based on the data presented in the above table, it is evident that the concentrations of most variables decreased significantly after optimization. Moreover, the pH value of the treated effluent was adjusted to remain within the normal range. These findings are consistent with the results reported by Odeibat et al. In their study, the performance of a wastewater treatment plant was evaluated using modeling in the GPS-X software. The results showed that after system optimization in this software, the removal efficiencies of TSS, COD, and BOD increased to 98.3, 95.1, and 96.1%, respectively. Furthermore, validation of the GPS-X model indicated that this model has a high capability for accurately simulating the actual performance of the treatment plant and provides a reliable representation of the treatment processes.[19]

Analysis of the influent and effluent wastewater parameters of the factory

The trend of changes in the influent and effluent parameters, including COD, BOD_5, TSS, TKN, TN, Snh, TP, DO, and TDS, after performing the simulation process in the GPS-X software environment, is shown in Figure S1. The significant decrease in COD and BOD_5 values indicates the effective removal of organic pollutants with an efficiency of over 98%. Moreover, the reduction in TSS demonstrates the satisfactory performance of the system in sedimentation and filtration processes. In addition, the considerable decrease in TKN, TP, TN, and Snh values indicates the proper removal of nitrogen and phosphorus compounds. The DO value in the effluent was measured at 2 mg/L, which is an acceptable level for the final effluent and indicates the presence of sufficient oxygen for aquatic organisms. However, the treatment plant's performance in reducing TDS was evaluated as weak, since this parameter is not typically removed by physical–biological treatment processes and requires the use of advanced methods such as reverse osmosis (RO), ion exchange, or distillation.

Examination of the MLSS parameter diagram

Figure S2 represents the MLSS which indicates the concentration of activated sludge in the aeration tank. The MLSS (mg/L) value in all five samples is nearly constant, ranging between 3200 and 4000 mg/L. Moreover, the slight fluctuation in this value indicates the stable performance of the aeration tank and proper control of the biological process. This range is consistent with the design guidelines for activated sludge systems intended for simultaneous nitrogen and phosphorus removal, which recommend maintaining MLSS levels around 2000 to 4000 mg/L.[20]

Table 3. Changes in quality parameters of wastewater treatment plant effluent after simulation and optimization with GPS-X software

Parameter	Input value	Output simulator value	Removal efficiency (%)	Permissible limit (irrigation and agriculture)	Permissible limit (discharge to surface water)
COD (mg/L)	2600	40	98.46	200	100
BOD_5 (mg/L)	1341	10	99.25	100	30
TSS (mg/L)	1357	20	98.52	100	40
TKN (mgN/L)	140	6	95.71	-	-
TN (mgN/L)	140	10	92.85	50	10-20
Snh (mg/L)	60	4	93.33	10-20	2-5
TP (mgP/L)	20	2	90.00	6	1-2
DO (mgO_2/L)	0.2	2	Increased	2 <	2 <
TDS (mg/L)	980	850	13.26	Maximum 2000	Depends on the region
PH	6	7.2	Set	6-8.5	6-8.5

Furthermore, recent studies have also emphasized that increasing MLSS concentration to a certain extent can improve nitrogen removal.[21] Considering these points, maintaining MLSS concentration within this range may indicate an optimal balance between microbial feeding, WAS discharge rate, and F/M, all of which are essential for effective nitrogen and phosphorus removal.

Examination of the diagrams of flow rate, activated sludge concentration, and HRT parameters

Figures 3–5 illustrate the effects of variations in flow rate, MLSS, and HRT on key parameters such as BOD_5, COD, reactor volume, and sludge production rate.

Effect of wastewater flow rate

As observed, with the increase in flow rate from 0 to 450 m^3/day, the removal efficiency of BOD and COD shows a decreasing trend. At low flow rates (around 0–50 m^3/day), the removal efficiency of both parameters is at its highest level (close to 90–100%). This phenomenon can be attributed to the higher HRT at these flow rates. A longer HRT provides sufficient contact time for microorganisms to effectively decompose organic matter (BOD and COD). However, with the gradual increase in flow rate, the retention time in the reactor decreases, resulting in insufficient time for effective biological degradation. In contrast, sludge production and the required reactor volume show a direct relationship with flow rate. As the flow rate increases, the biomass (microbial mass) in the system increases, which in turn leads to higher sludge production. Moreover, to maintain an adequate biomass concentration and prevent the washout of microorganisms from the system at higher flow rates, a larger reactor volume is required. The reactor volume increases from about 1000 m^3 at the lowest flow rate to more than 4500 m^3 at a flow rate of 450 m^3/day. An important point is to determine the optimal operating point. As shown in the diagram, within the flow rate range of 150–200 m^3/day, a relative balance is achieved between removal efficiency (around 70–80%) and economic factors (reactor volume and sludge production). Beyond this range, although the treatment capacity increases, the significant decrease in efficiency and the rise in investment and operational costs (due to the construction of a larger reactor and excess sludge management) are not justifiable. These findings are consistent with the results of the study by Kawan et al, which demonstrated that HRT plays a decisive role in the efficiency of organic pollutant removal, and that increasing HRT significantly improves BOD_5 and COD removal efficiency. Conversely, reducing HRT leads to a drop in efficiency due to insufficient contact time.[22] Overall, it can be concluded that excessive flow rate may reduce the effective capacity of the treatment plant and lower the quality of the effluent.

Effect of MLSS

An increase in the concentration of MLSS leads to improved BOD_5 removal efficiency, as a higher MLSS provides a larger amount of active biological mass in the system, which has a greater ability to decompose organic compounds. Under these conditions, the required reactor volume decreases; however, sludge production increases, necessitating proper control, dewatering, and disposal. Moreover, an increase in MLSS enhances COD removal capacity, although high MLSS concentrations require stronger settling and greater aeration, which can result in higher operational costs for the treatment system. Many studies have reported a correlation between increased MLSS concentration and improved removal efficiency of organic pollutants such as BOD_5 and COD. For example, in the study by Luo et al, increasing MLSS concentration up to 8 g/L significantly enhanced the removal efficiencies of BOD_5, COD, and TN.[21]

Effect of HRT

An increase in HRT improves BOD_5 removal efficiency because it provides more time for microorganisms to contact pollutants and decompose organic compounds. Likewise, increasing HRT enhances COD removal efficiency, as biological processes have more opportunity for the oxidation of organic matter.[23] However, increasing HRT leads to a larger reactor volume, which consequently raises construction, maintenance, and capital costs. On the other hand, although sludge production increases

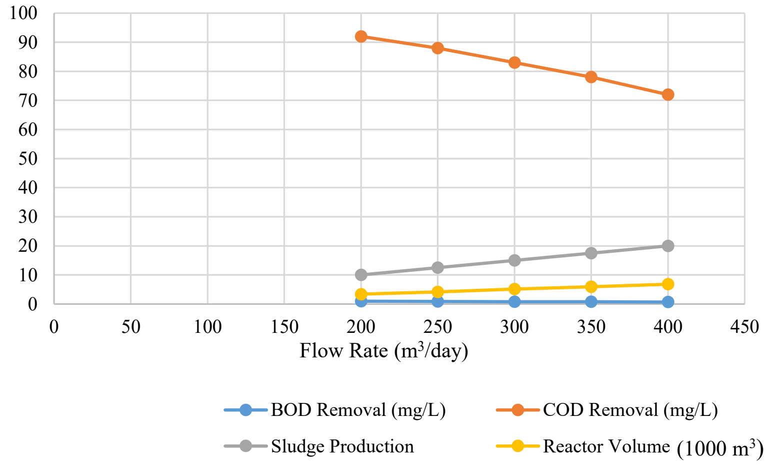

Figure 3. Analysis of the effect of flow rate on BOD$_5$, COD, reactor volume, and sludge production factors

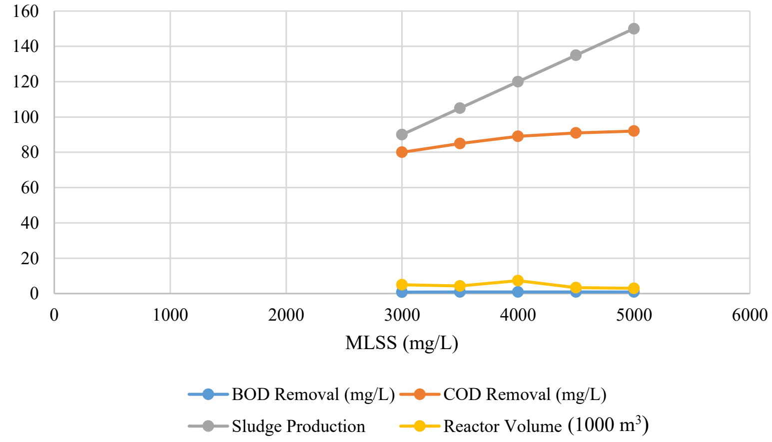

Figure 4. Analysis of the effect of MLSS on BOD$_5$, COD, reactor volume, and sludge production factors

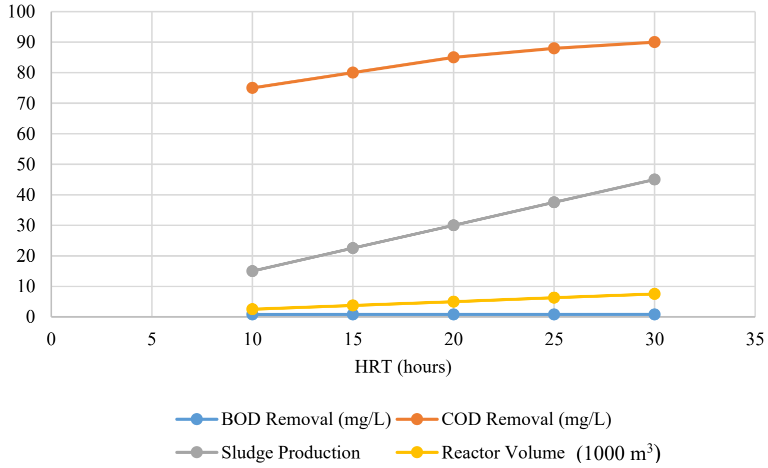

Figure 5. Analysis of the effect of HRT on BOD$_5$, COD, reactor volume, and sludge production factors

linearly with higher HRT, the intensity of this effect is lower compared to changes in MLSS and flow rate. Evidence suggests that variations in sludge production are more influenced by parameters such as SRT and MLSS than by HRT itself. In other words, while an increase in HRT can lead to greater sludge production, the magnitude of this effect is usually smaller than that caused by changes in MLSS or influent flow rate, and it depends on the biomass retention mechanism. Therefore, determining the optimal HRT should be based on a multi-criteria analysis that considers both its impact on effluent quality (BOD/COD removal efficiency) and its economic implications and sludge production (additional costs for maintenance, dewatering, and disposal).[24, 25]

Examination of the variation trends of nitrogen compounds

Based on the results shown in Figure 6, the variations of nitrogen compounds in the wastewater treatment process of the fish canning factory exhibit a distinct trend. Ammonia (NH_4^+) concentration gradually and significantly decreases during the aeration and settling stages, ultimately reaching about 2 mg/L in the effluent. This reduction indicates the effective conversion of ammonia to nitrate through biological nitrification.[26] Regarding nitrite (NO_2^-), its concentration temporarily rises to around 4 mg/L during the aeration stage and then decreases. This behavior is normal and reflects the transient role of nitrite as an intermediate in the nitrification process. Additionally, nitrate (NO_3^-), which initially was nearly zero, significantly increases to approximately 95 mg/L during aeration and then decreases to around 12 mg/L in the effluent. These changes indicate complete nitrification in the aeration stage and partial denitrification in the subsequent stages of the treatment process.

Based on the data presented in Table 4, a significant reduction in nitrogen and phosphorus levels is observed after the treatment process. The satisfactory performance of the system in removing ammonia and total nitrogen indicates an appropriate design and efficient operation of the biological unit. Moreover, the noticeable decrease in phosphorus concentration demonstrates the relative efficiency of the biological process in removing this element; however, to achieve higher phosphorus removal efficiency, the application of complementary chemical methods such as the addition of iron or aluminum salts may be necessary.[27]

Analysis of the effect of RAS on the effluent COD of the factory wastewater

An increase in the RAS rate from 50 to 100% resulted in a significant decrease in COD concentration in the effluent, as returning a larger volume of activated sludge increases the biomass in the aeration basin, thereby enhancing the capacity for organic matter degradation. However, excessive RAS rates particularly above 100% (e.g., 150%) lead to a renewed increase in COD levels. This occurs due to high hydraulic loading, which disrupts the settling process and affects the aeration system performance. Overall, there is an optimal RAS value at which COD removal efficiency reaches its maximum, and any increase or decrease beyond this point leads to reduced treatment system performance. The observed COD concentration aligns closely with the findings of Mirian and Ebrahimi (2023), who reported that the return sludge rate and internal recirculation interact with each other, and that increasing RAS up to an optimal point enhances COD removal. Both studies emphasize the importance of determining the optimal RAS parameter to prevent a decline in system efficiency.[9] Figure S3 shows the effect of RAS variations on the effluent COD concentration in the wastewater from the fish canning factory.

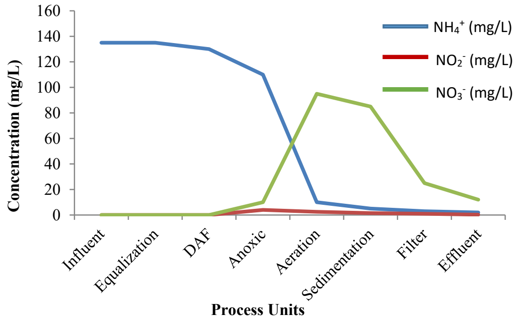

Figure 6. Variation trends of nitrogen compounds in the wastewater treatment process of the fish canning factory

Analysis of the effect of WAS discharge rate on NH_4+-N and NO_3^--N

The analysis of the effect of WAS discharge rate on nitrogen compounds, including NH_4^+-N and NO_3^--N, shows that increasing the WAS rate leads to a rise in ammonia concentration in the effluent. This phenomenon occurs because excessive sludge removal eliminates part of the nitrifying bacteria, thereby weakening the nitrification process. Conversely, as the WAS rate increases, nitrate concentration decreases, since the reduction in the nitrifier population results in lower nitrate production. Furthermore, in the absence of proper anoxic conditions, the denitrification process is also reduced. Therefore, the optimal WAS discharge rate should be determined in such a way that it maintains a balance between ammonia removal and nitrate production and reduction, as an excessive WAS rate can eliminate nitrifying bacteria and ultimately deteriorate effluent quality.[28] Figure S4 shows the variations of nitrogen compounds in the effluent during the wastewater treatment process of the fish canning factory.

Analysis of the effect of WAS and RAS variations on effluent nitrogen, phosphorus, and COD

The effect of WAS and RAS variations on effluent nitrogen, phosphorus, and COD, which is highly important in the optimization of wastewater treatment plant performance, has been presented in Table 5.

In the analysis of different scenarios related to RAS and WAS, the results indicate that any change in these parameters significantly affects the performance of the treatment system. In the first scenario, where the RAS

Table 4. Concentrations of nitrogen and phosphorus compounds before and after the wastewater treatment process of the fish canning factory

Parameter	Before treatment (mg/L)	After treatment (mg/L)	Removal efficiency (%)
TKN	140	6	96
TN	140	10	93
NH_4^+_N	60	4	97
TP	20	2	80

Table 5. Effect of WAS and RAS variations on BOD_5, COD, and effluent nitrogen and phosphorus compounds

Scenario	**Effluent COD**	**Effluent BOD_5**	**NH_4^+_N**	**NO_3^-_N**	**TN**	**TP**	**TSS**
RAS ↑ WAS Constant	COD ↓	BOD_5 ↓ ↓	NH_4 ↓	NO_3 ↑	TN ↓	Slight decrease	TSS ↑
WAS ↑ RAS Constant	COD ↑	BOD_5 ↑ ↑	NH_4 ↑	NO_3 ↓	TN ↑	TP ↑	TSS ↓
RAS ↓ WAS ↓	COD ↑ ↑	BOD_5 ↑ ↑ ↑	NH_4 ↑ ↑	NO3 ↓ ↓	TN ↑ ↑	TP ↑	TSS ↑ ↑
RAS & WAS Balanced	Optimal COD	Optimal BOD_5	Optimal NH_4	Optimal NO_3	TN ↓	TP ↓	TSS Controlled

rate is increased, the concentrations of NH_4^+, COD, BOD_5, and TN decrease, indicating improved nitrification and enhanced pollutant removal efficiency. However, this condition may lead to an increase in TSS due to the return of a larger volume of sludge and higher suspended solids load. This scenario is suitable when the main goal is to strengthen the nitrification process, although careful control of the returned sludge volume is required. In the second scenario, increasing the WAS rate results in higher TN, NH_4^+, COD, BOD_5, and TP concentrations, thereby reducing treatment efficiency, particularly in nitrogen removal. Nevertheless, a decrease in TSS is observed because higher sludge discharge reduces the suspended solids in the system. This condition is suitable when the objective is to reduce sludge and solids volume, although it leads to lower effluent quality. In the third scenario, simultaneous reduction of RAS and WAS causes a significant increase in NH_4^+, TN, COD, BOD_5, TP, and TSS, as reduced sludge in the system drastically lowers microbial activity and treatment efficiency. Therefore, this situation may occur only under critical conditions and is not recommended. In contrast, the fourth scenario, which maintains balanced RAS and WAS values, provides the best operational performance, keeping all effluent quality parameters within the desired range. Therefore, it is recommended to maintain RAS and WAS rates within the designed limits to ensure process stability and maximize treatment efficiency. These findings are consistent with the results of Wondim et al, in which the optimal RAS rate was determined to be within 150 ± 10 m^3/day. Additionally, increasing the WAS rate in that study led to a reduction in nitrifying bacteria population, resulting in higher ammonia concentrations in the effluent. This outcome aligns with the reference study, which emphasized that controlling WAS is essential to maintain biomass balance.[1]

Process diagrams

The process diagrams section in this study includes four main types of charts, each playing an important role in analyzing the performance of the treatment plant. These charts are the Sankey Diagram, Energy Usage Summary, Operation Cost Summary, and Mass Balance Diagram.

In the Sankey Diagram, the flow of energy, materials, or costs between different units of the system is visually represented. The thickness of the lines corresponds to the magnitude of the flow; the greater the flow, the thicker the line. This diagram is useful for examining energy, material, and financial flows in treatment plants and helps managers identify areas with the highest energy or cost consumption, enabling corrective actions to reduce consumption and optimize the system. According to the simulation results of the Bandar Abbas fish canning factory wastewater treatment process (Figure S5a), wastewater with an influent flow of about 250 m^3/day and high concentrations of COD, BOD_5, TSS, and TKN enters the system. After screening and equalization, the outflow from the settling tank decreases to about 14.44 m^3/day, indicating stable performance and effective flow management in the system.

The Energy Usage Summary chart shows energy consumption in different sections of the treatment plant and helps identify high-energy-consuming processes. In this study, the highest energy consumption occurred during the aeration stage, with a total power consumption of 1.81 kW (Figure S5b). Considering the aeration reactor volume of 177 m^3/day, this indicates optimal system performance in terms of energy use. Other units consume negligible energy, suggesting that energy optimization should focus on aeration, RAS control, and HRT management.

The Operation Cost Summary chart examines various operational costs, including energy, chemicals, labor, maintenance, and sludge disposal. The results (Figure S5c) show that the largest share of costs is associated with the aeration unit, with a daily cost estimated at about $87.07. This cost focus is logical, as aeration is typically the most energy- and equipment-intensive stage. To reduce operational costs, strategies such as using more energy-efficient equipment, smart aeration control, precise chemical dosing, automation to reduce labor needs, sludge volume reduction technologies, and water recycling are recommended. Additionally, process modeling and simulation can play a key role in identifying weaknesses and optimizing costs.

The Mass Balance Diagram examines the changes in material mass throughout different stages of the treatment process. This chart illustrates how pollutants such as COD, BOD_5, nitrogen, and phosphorus are reduced or transformed during the process. Analysis of this diagram (Figure S5d) helps managers identify areas of material accumulation or excessive sludge production and take corrective actions to improve process efficiency. It is also crucial for evaluating the effectiveness of biological, chemical, and physical processes and for optimizing energy and chemical consumption.

Ultimately, the integration of these four diagrams allows for a comprehensive analysis of the treatment plant's performance. The Sankey Diagram identifies the paths and magnitudes of energy and cost flows, the Energy Usage Summary highlights high-energy-consuming sections, the Mass Balance Diagram shows how well organic matter removal aligns with energy and cost use, and the Operation Cost Summary evaluates the balance between expenses and system efficiency. This analytical combination provides a comprehensive view of performance, efficiency, and economic viability of the treatment process at the Bandar Abbas fish canning factory.

Cost Analysis Using GPS-X Software

In the results analysis section using GPS-X software, a set of computational tools was employed to examine and evaluate costs in the wastewater treatment process. Sankey diagrams graphically represented the flow of water, sludge, and nutrients in the system, enabling a more detailed analysis of costs associated with each stream. Additionally, energy consumption variables in different sections, including aeration, pumping, mixing, and heating, were calculated, providing a comprehensive understanding of total energy usage and the contribution of each section to the overall process. Moreover, GPS-X can estimate operational costs related to aeration, pumping, chemical usage, and sludge disposal, thereby facilitating the economic evaluation of the system. The analysis of operational costs for the wastewater treatment plant (based on GPS-X modeling) is presented in Table 6.

The mass balance results showed that with an influent COD of 2600 mg/L and an effluent COD of 40 mg/L, the removal efficiency of organic matter exceeded 98%, indicating a highly satisfactory system performance. Sankey diagrams generated in GPS-X accurately illustrated the flow paths of various substances, including COD, nitrogen, phosphorus, and sludge, and it was found that oxygen consumption and sludge production were within the optimal range. These findings generally indicate the high technical and economic efficiency of the MLE system and its capability to achieve stable and cost-effective conditions in the wastewater treatment process. The study by Hosseini et al. supports the present findings. They reported that the MLE process exhibits high efficiency in the removal of TSS, COD, TN, and TP. According to their findings, the system demonstrated resilience to minor and qualitative shocks, with 18% and 17% tolerance, respectively. It was also found that despite producing a relatively high sludge volume (21 m^3/day), the MLE process has lower sludge concentration and volatile solids content. Economically, this process is cost-effective, with an initial investment of approximately 1,328 USD and an operational cost of 34 USD per cubic meter of treated wastewater. Moreover, a daily energy consumption of 1.82 kWh and a land requirement of about 7.22 m^2 per cubic meter of treated wastewater were reported, indicating the favorable technical and economic efficiency of the MLE process.[13]

Sensitivity analysis using GPS-X software

In this study, sensitivity analysis was conducted using GPS-X software to examine the effect of changes in various parameters on the performance of the wastewater treatment system. The results of this analysis showed that variations in key parameters could have a significant impact on the final effluent quality, pollutant removal efficiency, and energy consumption. Using the Analyzer tool, the effect of each parameter on the model output was evaluated individually. The study revealed that increasing or decreasing the influent Q has a direct impact on effluent quality; specifically, higher flow rates can reduce treatment efficiency. Additionally, the AST plays an important role in improving the sludge retention time and enhancing the nitrification process efficiency. CSA indicated that increasing the settling surface improves sludge separation and enhances effluent quality. Furthermore, RAS and WAS directly affect MLSS concentration and the biological performance of the system; proper adjustment of these ratios can maintain a balance between organic matter removal and biomass stability. In another part of the analysis, the effect of varying the SRT between 10 and 20 days was examined. Results showed that increasing SRT improves COD and nitrogen removal, but also increases maintenance and sludge disposal costs. Variation in HRT between 12 and 24 hours showed that higher HRT improves effluent quality, although it may lead to larger tank volumes and higher construction costs. Moreover, changes in Flow rate had a significant impact on pollutant removal and energy

Table 6. Estimation and analysis of operational costs of the wastewater treatment process using the MLE method based on GPS-X software simulation

Section	Description	Quantity	Cost (Daily)
Energy costs			
Aeration	177 $m^3 \times 0.75$ kW × 24 hours	3,186 kWh	7,965,000 IRR
Pumping	Approximately 10% of aeration consumption	~320 kWh	-
Chemical costs			
Chemicals	50 kg per month (assumed)	-	5,000,000 Tomans (monthly)
Labor costs			
Specialized personnel	2 permanent personnel	-	20,000,000 Tomans (monthly)
Annual maintenance costs	Approximately 10% of equipment cost	(Calculated based on asset value)	-

consumption.

Overall, the results from running different scenarios in GPS-X indicated that parameters such as SRT, HRT, RAS, WAS, and Q are among the most sensitive variables affecting system performance. Evaluating their effect on key outputs like COD, BOD_5, nitrogen, and energy consumption demonstrated that optimizing these parameters can increase treatment efficiency and reduce operational costs. These findings highlight the importance of sensitivity analysis in optimizing the design and operation of wastewater treatment systems.[1]

Model calibration in GPS-X software

The model calibration process in GPS-X software was conducted to align the simulation results with actual wastewater treatment plant data. In this study, the MLE process model, including anaerobic, anoxic, and aerobic zones along with a secondary clarifier, RAS, and WAS, was used. In the first step, actual influent wastewater data were input into the model. Next, the system's operational parameters, such as SRT = 15 days, HRT = 17 hours, MLSS = 4000 mg/L, MLVSS = 3000 mg/L, F/M = 0.4, RAS = 150 m^3/d, WAS = 41.3 m^3/d, and aeration tank volume of 177 m^3, were defined in the software. Initial model results were compared with actual effluent data, and the actual output values were obtained. The comparison of initial simulation results with real data showed discrepancies between measured and predicted values; therefore, the model calibration stage was conducted. During calibration, the model's microbiological and physical parameters were reviewed and adjusted. In the physical section, parameters such as settling rates in the clarifier, the RAS/WAS, and aeration rate were adjusted to achieve DO ≈ 2 mg/L. After these adjustments, the model was rerun, and the output results were compared with actual data. The results showed that discrepancies between simulated and real data were significantly reduced, and the absolute error for most variables was below 10%, indicating successful calibration. These findings are consistent with the study by Mirian and Ebrahimi, who emphasized validating the constructed model with actual data as a prerequisite for any reliable analysis. The success of the calibration process in both studies confirms the critical role of GPS-X as a powerful tool for accurately simulating real wastewater treatment processes.[9] Similarly, Elachola noted that model calibration through a detailed study of organic and nutrient fractions in the influent wastewater is essential for obtaining reliable results.[11] In this study, the SRT of 15 days and HRT of 17 hours were determined as optimal values. These values fall within the ranges reported by Wondim et al, where SRT varied between 5 and 6.7 days, and HRT depended on system design. Both studies indicated that an optimal SRT plays a decisive role in increasing nitrogen and phosphorus removal efficiency through nitrification and denitrification processes.[1] Examination of COD, BOD_5, NH_4^+, NO_3^-, TSS, and DO variation charts also showed good agreement between actual and modeled data. Finally, the finalized model was saved, and optimal parameters were extracted. Documentation, including comparisons of actual and simulated data, sensitivity analysis, and parameter adjustments, was prepared, which can serve as a basis for evaluating system performance under different operational conditions.

Conclusion

This study demonstrated the successful application of GPS-X software in the simulation, calibration, and optimization of the wastewater treatment process of the Bandar Abbas fish canning factory. The use of process modeling enabled a deeper understanding of the complex biological and physicochemical interactions occurring within the treatment units and led to the identification of key parameters influencing process efficiency. The calibration of the GPS-X model for the wastewater treatment system with the MLE process configuration showed that by precisely adjusting biological and physical parameters, a remarkable agreement between simulated and actual data could be achieved. Adjusting operational parameters resulted in simulated values of COD, BOD_5, NH_4^+, NO_3^-, TSS, and DO differing by less than 10% from the actual effluent data. This indicates the high accuracy of the calibration and the model's capability to represent the real behavior of the treatment system. Sensitivity analysis revealed that variables such as SRT, HRT, and RAS/WAS have the greatest influence on the effluent quality. Simulation of different operational scenarios also showed that optimizing these parameters can significantly improve the removal efficiency of COD, BOD_5, and total nitrogen while reducing energy consumption and excess sludge production. Among the evaluated configurations, maintaining a balanced RAS/WAS ratio and properly adjusting SRT provided the best balance between effluent quality and operational costs. Furthermore, simulation of the performance of different treatment units demonstrated that precise adjustment of operational parameters and optimization of chemical and energy consumption can enhance system efficiency and minimize the environmental impacts of wastewater. Overall, the observations of this study emphasize the high potential of dynamic modeling using GPS-X as an effective tool for decision-making and improving the performance of wastewater treatment plants in the fish processing industry. Implementing the optimal conditions derived from modeling can lead to greater process stability, better compliance with environmental standards, and reduced operational costs. It is recommended that future studies combine modeling with advanced control systems, real-time monitoring, and energy recovery approaches to further enhance the sustainability and efficiency of wastewater treatment systems in the food industry.

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Competing Interests

The authors declare that they have no financial or personal relationships with any individuals or organizations that could inappropriately influence or bias the content of this paper. This includes, but is not limited to, employment, consultancies, honoraria, grants, stock ownership, or any other forms of financial or personal connections.

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Supplementary Files

Supplementary file 1 contains Figures S1-S5.

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