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Optimizing Wastewater Treatment Efficiency at North Esfahan WWTP Using GPS-X Simulation: Enhancing Aeration Strategies

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Original Paper

Abstract

This study utilizes GPS-X simulation software to enhance the wastewater treatment processes at the North Esfahan Wastewater Treatment Plant, which handles an average inflow of 44,000 m^3/day. The facility utilizes a conventional activated sludge aeration process, and this research focuses on improving effluent quality through optimized aeration strategies and effective management of dissolved oxygen levels. GPS-X software was used to model the aeration process, adjusting kinetic and stoichiometric parameters, such as heterotrophic yield, to match the plant's wastewater characteristics. The aeration tank was divided into four sections to simulate various air distribution scenarios, including dynamic DO control and creating anoxic zones for denitrification. Sensitivity analysis identified key parameters, and the model was calibrated using real operational data. Fourteen aeration scenarios were tested to evaluate their impact on treatment efficiency. Key findings indicate that the treatment system is particularly sensitive to heterotrophic yield, with kinetic and stoichiometric parameters adjusted from an initial value of 0.66 to 0.75 to align the model with the specific wastewater characteristics. The study emphasizes the significance of dynamic aeration control and the establishment of anoxic zones to facilitate denitrification, which ultimately enhances effluent quality. The research revealed that achieving a uniform DO distribution in the aeration tank significantly boosted overall treatment efficiency, with chemical oxygen demand and total suspended solids removal rates reaching 92% and 93%, respectively. In other words, COD decreases from 691 to 59 mg/L and TSS decreases from 336 to 25 mg/L. Furthermore, the introduction of an anoxic zone within the aeration process proved effective for denitrification, reducing total nitrogen in the effluent to 35 mg/L, compared to 42 mg/L in the current condition (with an influent TN of 87 mg/L). Furthermore, the study highlights the significant impact of influent quality fluctuations and temperature variations on wastewater treatment performance. Sensitivity analyses under optimal aeration conditions showed that a ±10% change in influent COD and TSS concentrations directly affects effluent quality, with COD increasing to 110 mg/L and TSS rising to 63 mg/L during a 10% shock. This research highlights the potential of simulation tools like GPS-X in optimizing wastewater treatment operations, providing valuable insights for enhancing environmental sustainability and public health. Future studies are encouraged to explore additional operational variables and their effects on treatment efficiency, thereby promoting sustainable practices in wastewater management throughout Iran.

Keywords:
Wastewater, GPS-X, North Esfahan WWTP, Aeration Optimization, Effluent Quality, Activated Sludge Process.

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1. Introduction

Wastewater treatment plants[1] are essential for processing wastewater collected from residences, public and private entities, and stormwater (Qasim, 2017). Wastewater treatment facilities are essential for protecting our environment. They help keep harmful substances like organic carbon, nitrogen, and phosphorus from flowing into our rivers and lakes. As people become more aware of the importance of environmental conservation, there's a growing need to improve these treatment plants. Upgrading their processes and designs ensures they meet stricter regulations for what can be released into our waters, helping to keep our ecosystems healthy (Liu and Wang, 2015).

Although empirical methods provide accurate information regarding the performance of activated sludge, the cost and time required limit the measurement of a limited number of parameters in treatment plants. On the other hand, modeling is becoming a technique among researchers and engineers for studying the behavior of wastewater treatment processes. Mathematical models have the potential to enhance understanding of activated sludge units and provide insights into their performance in various operational scenarios. Furthermore, these models can be formulated to maximize efficiency, thereby minimizing both operating and capital expenses (Henze et al., 2006).

Over the past few years, numerous commercially available numerical simulation software programs (such as Simba, GPS-X, BioWin and CapdetWork) have been developed specifically for engineering applications. These software programs incorporate activated sludge models (such as ASM1, ASM2, ASM2d and ASM3) to further enhance their capabilities (Wu et al., 2016).

Mathematical modeling has emerged as an effective tool for evaluating and enhancing wastewater treatment processes. In other word, sustainable improvement is a strategy that integrates enhancement, efficiency in performance, and the preservation of environmental resources. Advancing wastewater treatment techniques through contemporary technology safeguards these resources and promotes sustainable improvement practices (Muga and Mihelcic, 2008).

Employing simulation and mathematical techniques alongside data like BOD_5, COD and TSS establishes criteria for assessing and ensuring the safe disposal of wastewater (Asami et al., 2021).

Fadaei Tehrani and Jamshidipoor examine the optimization of phosphate removal from industrial wastewater utilizing SBR[2] and MBBR[3] systems, simulated through BioWIN software. They test various operational conditions, such as returning sludge to anaerobic tanks and nitrogen injection into aerobic tanks, achieving phosphate levels of zero within two weeks. Similarly, the MBBR system also reached zero phosphate concentrations through nitrogen injection, proper aeration, and alum dosing. The research highlights that key factors influencing treatment efficiency vary between systems. Overall, the results underscore the significance of optimizing operational parameters to enhance removal effectively (Fadaei Tehrani and Jamshidipoor, 2024).

A study by Waqas and colleagues takes a closer look at how different operational factors influence the effectiveness of IFAS[4] systems in treating wastewater. The researchers explored several important aspects, including hydraulic retention time[5], solid retention time[6], levels of DO[7], temperature, nutrient loading rates, and aeration levels. Their findings aim to provide insights into optimizing these systems for better wastewater treatment outcomes. The findings revealed that optimizing these parameters significantly improves treatment efficiency (Waqas et al., 2023).

GPS-X program is a dynamic state modeling and simulation software specifically designed for treatment plants, created by Hydromantis Environmental (Jasim, 2020). GPS-X software, developed specifically for wastewater treatment simulation, enables engineers to analyze various design and operational scenarios. The software encompasses the models utilized in wastewater treatment facilities and includes a comprehensive library covering various physical, chemical, biological, and anaerobic processes. GPS-X 8 is an advanced tool for dynamic simulations in wastewater treatment, offering functionalities that support resource recovery, including energy and nutrient recovery (Cao et al., 2021).

Hasan et al. have made some interesting discoveries about how we can better understand and improve wastewater treatment. Their research highlights the GPS-X model, which offers fresh insights into how sedimentation basins work. This model helps us see the inner workings of sewage treatment plants[8], making it a useful resource for future studies and management strategies. One key finding from the study is that expanding the surface area of sedimentation basins could lead to more efficient treatment processes. They identified several important factors-like the type of waste-activated sludge used, the maximum settling velocity, and the temperature of the liquid-that can all play a role in enhancing sedimentation. Overall, this research opens the door to new approaches to managing wastewater treatment effectively (Hasan et al., 2024).

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[1] Wastewater Treatment Plants (WWTP)

[2] Sequential Batch Reactor (SBR)

[3] Moving Bed Biofilm Reactor (MBBR)

[4] Integrated Fixed-Film Activated Sludge (IFAS)

[5] Hydraulic Retention Time (HRT)

[6] Solid Retention Time (SRT)

[7] Dissolved Oxygen (DO)

[8] Sewage Treatment Plant (STP)

Among the operational costs that will exist during the lifetime of a WWTP, the required air plays a significant role in the sewage treatment process. By making the most of the air we produce, we can save on operating costs while also improving the quality of the wastewater without needing to change any of the existing treatment plant structures or systems. One of the key factors in the activated sludge process[1] is the concentration of DO, which plays a crucial role in its effectiveness. However, managing the ASP can be quite challenging due to its complex nature. The process involves unpredictable changes, significant time delays, and multiple interacting elements, making it difficult for traditional control systems commonly used in the industry to maintain effective control (Bishop, 1992).

Waqas et al. illustrated that in IFAS systems, increasing DO levels support aerobic microorganism growth, promoting organic matter degradation, The study emphasizes the need for effective aeration to ensure proper wastewater distribution and contact between microorganisms and pollutants (Waqas et al., 2023). The paper by Kandare and Nevado Reviriego discusses the implementation of ADEX[2] controllers to manage DO levels in the aerobic reactors of a WWTP in Madrid. The ADEX controllers enhance DO control by utilizing adaptive predictive control that adjusts model parameters in real-time based on prediction errors. The ADEX controllers demonstrated better stability and precision in maintaining desired DO levels compared to traditional PID controllers, significantly reducing oscillations in DO signals and improving overall process stability (Kandare and Nevado Reviriego, 2011).

The results indicate that the nitrogen injection rate and the percentage of sludge return in the SBR system, as well as the selection of the appropriate dosage for aluminum injection and aeration rate in the MBBR system, are key variables in wastewater treatment.

In a study conducted by Mirian and Ebrahimi in 2023, an operational WWTP was modeled using the MLE process with the GPS-X software, and the quality results of the treated effluent in the software were validated against laboratory test results from the WWTP. Additionally, the rates of return sludge, recycled effluent, and disposed sludge from the plant were optimized to have the greatest impact on the quality of the effluent. The results showed that the return sludge and internal recycling rates had interactive effects on the removal of COD and nitrate (Mirian and Ebrahimi, 2023).

Srivastava et al. used GPS-X software to create a model of a WWTP with a MBBR system. This approach allowed them to investigate various operational challenges faced by these facilities through simulations and sensitivity analyses, yielding valuable insights into their performance. This research highlights important kinetic and stoichiometric parameters that influence the performance of the treatment plant, aiding in model calibration. To improve treatment efficiency, this study recommends adding a pre-anoxic tank and adjusting the sludge recycling ratio (Srivastava et al., 2024).

Kao and his colleagues modeled the A^2O activated sludge system using GPS-X, examining the HRT and the distribution of air in five sections of the aeration tank and its effects on the COD removal rate. Their research also pointed out that the manner of air distribution plays a significant role in determining the nitrogen levels in the effluent (Cao et al., 2021).

The North Esfahan WWTP constructed several decades ago, employs an ASP, producing effluent suitable for agricultural reuse. As wastewater discharge continues to rise, it's becoming increasingly important to improve our existing treatment plants, many of which were built years ago. Upgrading these facilities is essential to ensure they can meet the tougher regulations we now face regarding water quality (Insel et al., 2012).

Additionally, aeration plays a vital role in wastewater treatment, so finding ways to improve how air is distributed in the system is key to making the treatment process more effective. In 2013, to ensure the required oxygen for biological activities, the aeration system of this WWTP was changed from surface aerators to deep aerators by installing diffusers at the bottom of the aeration tanks. These diffusers are uniformly spaced along the tank's length, while wastewater enters the aeration tank with a high organic load, resulting in greater oxygen demand in the beginning section compared to the rest of the tank. This configuration leads to a reduction in DO concentration as the wastewater moves through the tank, occasionally creating anaerobic conditions in certain areas. Such conditions hinder the growth of aerobic microorganisms, which are vital for effective treatment. To tackle these challenges, we need to make the most of the systems we already have. This research investigates the use of GPS-X software to assess how oxygen distribution alongside the aeration tank can affect effluent.

2. Materials and methods

2.1. Study area

This study has been carried out in the Northern Esfahan WWTP which is located at 2°44'55.21"N, 51°43'56.03"E, and 1557m of sea level elevation. It treats the wastewater from the northern areas of Esfahan in two phases which the first phase has been studied in this research. The average yearly temperature in the region is about 15.8 degrees Celsius. When it comes to rainfall, the area gets around 91.7 millimeters of precipitation each year, while it experiences much higher evaporation rates at 1466.5 millimeters. Overall, the

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[1] Activated Sludge Process (ASP)

[2] Adaptive Predictive Expert (ADEX)

climate here is considered semi-arid, meaning it has some dry characteristics but still sees a bit of moisture throughout the year.

The WWTP currently utilizes biological processes, handling an average flow of 44,000 m^3/day. The treatment sequence includes primary sedimentation, biological treatment, and secondary settling. Figs. 1, 2 and 3 respectively depict the Google Earth image, flow diagram, and a real photograph of the North Esfahan WWTP (phase I).

The wastewater enters the primary settling tank after passing through the screening and grit removal unit. Then, the effluent from the primary settling tanks is conveyed to the aeration tank. Following this, the wastewater is transferred from the aeration tanks to the secondary settling tanks, and the treated effluent is directed to the chlorination unit. The excess sludge from the secondary settling tanks is transferred to the primary settling tanks. Subsequently, the excess sludge from the system, along with the primary sludge from the primary settling tanks, is transported to the gravity thickening units and anaerobic digesters. Finally, the sludge is moved to the sludge drying beds. Moreover, a part of the sludge as return sludge for providing the essential MLSS of biological process is returned to the beginning of the aeration tank. The supernatant of sludge is transferred to the second phase and does not affect the treatment process of the first phase.

This research adopted several approaches, involving data collection, statistical analysis of influent, simulation, sensitivity analysis, calibration, modeling, running aeration scenarios, and finally selecting the best approach for improving the effluent quality, this milestone is demonstrated in Fig. 4.

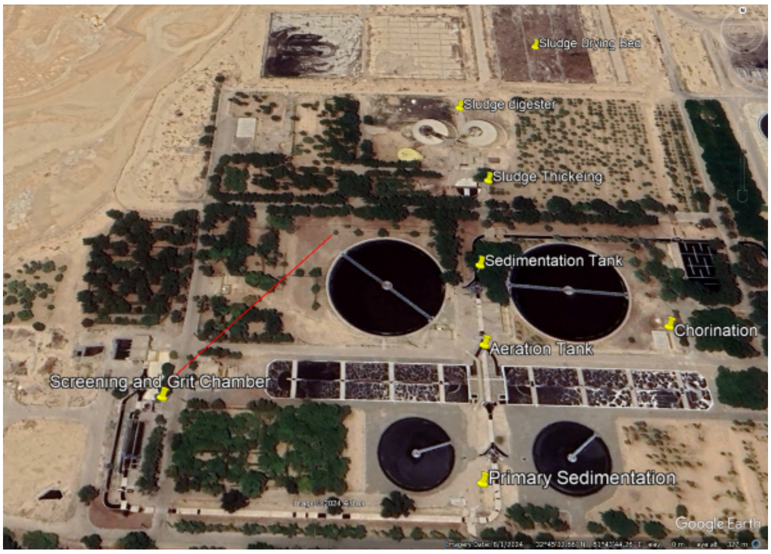


Fig. 1. North Esfahan WWTP Google Earth image

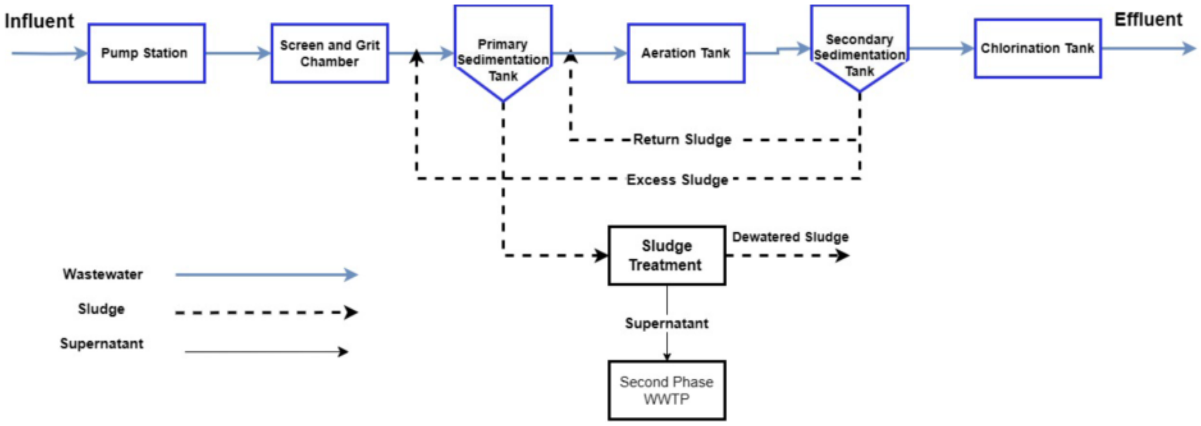
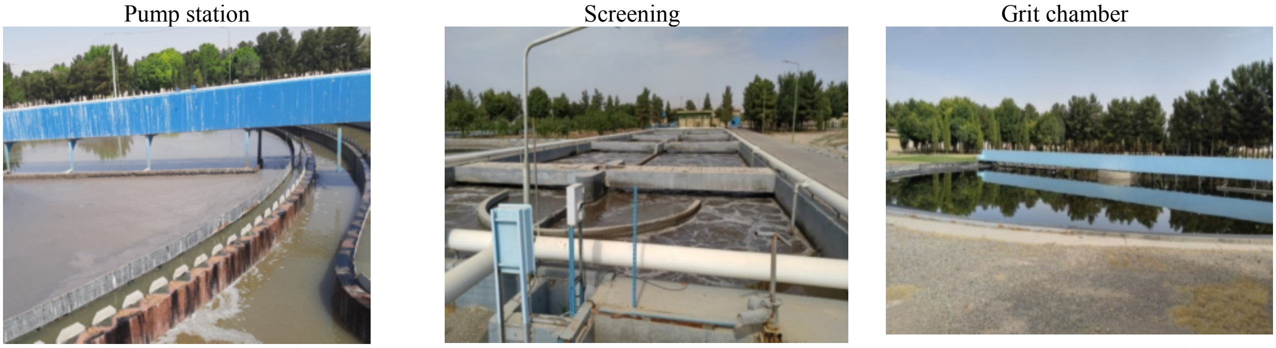


Fig. 2. Flow diagram of North Esfahan WWTP (phase I)

Pump station Screening Grit chamber



Primary sedimentation tank Aeration tank Secondary sedimentation tank

Fig. 3. Images of North Esfahan WWTP (phase I)

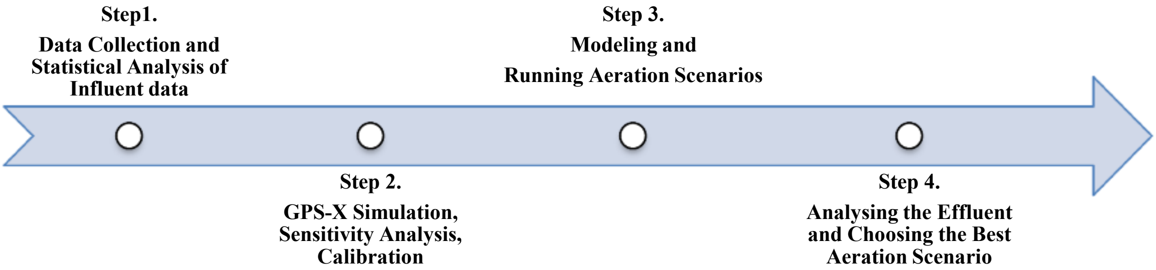


Fig. 4. Steps of modeling of the North Esfahan WWTP (phase I) in GPS-X software

2.1. Data collection and statistical analysis of influent

2.1.1. Data collection

Key datasets were obtained from the North Esfahan WWTP and measured in its laboratory using standard methods, including:

- Meteorological data of the region.
- Daily influent and effluent quality data and DO of aeration tank from 2007 to 2019 including BOD_5[1], COD[2] and TSS[3].
- Daily influent and effluent quality data and aeration tank DO in July 2020.
- Dimensional specifications and operational details of different units of the treatment plant obtained from operational data and as-built drawings and execution plans such MLSS, SVI and aeration capacity of blowers.

2.1.2. Statistical analysis of influent

Using SPSS software, influent characteristics including BOD_5, COD and TSS were analyzed. Non-normal datasets were normalized to ensure compatibility with statistical models. Results of statistical analysis in SPSS Software of North Esfahan WWTP (phase I) influent are presented in table 1.

The North Isfahan treatment plant's phase I operates with an average daily flow of 44,000 cubic meters. When inflows exceed this capacity during operation, the surplus is diverted to phase II, ensuring efficient management of wastewater volumes and maintaining optimal treatment performance for phases I.

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[1] Biochemical Oxygen Demand (BOD_5)

[2] Chemical Oxygen Demand (COD)

[3] Total Suspended Solids (TSS)

Table 1. Result of statistical analysis in SPSS software of North Esfahan WWTP (phase I) influent

Parameter		BOD (mg/l)	COD (mg/l)	TSS (mg/l)
Normal parameters	Mean	354	691	336
	Std. Deviation	52	153.4	86
Most extreme differences	Absolute	0.083	0.096	0.110
	Positive	0.083	0.096	0.110
	Negative	-0.044	-0.056	-0.067

The study by Sara Galb et al. emphasizes the sensitivity of effluent to variations in influent parameters, particularly the COD levels. It concludes that proper modeling and simulation can significantly enhance understanding of the treatment processes, aiding in the optimization of wastewater management and resource recovery efforts (Asami et al., 2021).

In tables 2 and 3, influent characteristics and modeling parameters of North Esfahan WWTP (phase I) in GPS-X Software are presented. In addition, the typical Parameter for complete mix activated sludge according to Metcalf and Eddy is presented in Table 4 (Eddy et al., 2014).

Table 2. Influent characteristics of North Esfahan WWTP (phase I) in GPS-X software

Influent composition		Unit	Value
Q	Average wastewater flow	m^3/d	44,000
COD	Total COD	$gCOD/m^3$	691
TKN	Total TKN	gN/m^3	87
sNH	Free and Ionized Ammonia	gN/m^3	60
Influent fractions			
iCV	XCOD/VSS ratio	gCOD/gVSS	1.85
fBOD	BOD_5/BOD ultimate ratio	-	0.64
iVT	VSS/TSS ratio	gVSS/gTSS	0.8
Organic fractions			
fRSI	Soluble inert fraction of total COD	-	0.04
fRSS	Readily biodegradable fraction of Total COD	-	0.24
fRXI	Particulate inert fraction of total COD	-	0.16
Composite variables			
TSS	Total suspended solids	g/m^3	336
VSS	Volatile suspended solids	g/m^3	268
xISS	Total inorganic suspended solids	g/m^3	67
BOD	Total carbonaceous BOD_5	gO_2/m^3	354
Others			
T	Temperature	Degrees celsius	22

Table 3. Modeling parameter of North Esfahan WWTP (phase I) in GPS-X software

Unit	Primary sedimentation	Aeration tank	Secondary sedimentation
Parameter	Surface area: 1923 m^2 Depth: 2.2 m Pumped flow: 1110 m^3/d Removal efficiency: 58 %	Volume: 11680 m^3 Depth: 3.1 m Total air: 28400 m^3/h Alfa factor: 0.6 Beta factor: 0.95 Oxygen transfer efficiency: 21% MLSS: 1900 mg/L	Surface area: 5655 m^2 Depth: 2.2 m Underflow rate: 29400 m^3/d pumped flow: 880 m^3/d

Table 4. Typical parameter for complete mix activated sludge (Eddy et al., 2014)

Parameter	SRT, day	MLSS, (mg/L)	F/M (kg BOD/ Kg MLVSS.d)	Volumetric loading (kg BOD/ m^3.d)
Typical	3-15	1500-4000	0.2-0.6	0.3-1.6
Esfahan North phase I	7.7*	1900	0.55	0.82

* Before adjustment of kinetic coefficients

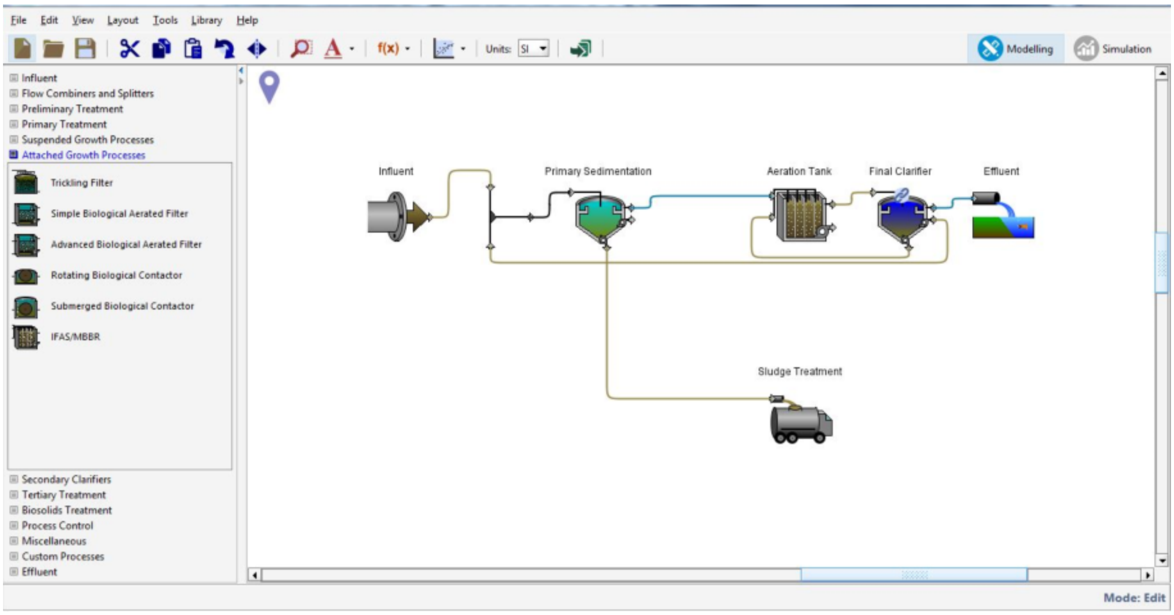

Fig. 5. Modeling of North Esfahan WWTP (phase I) in GPS-X software

Temperature plays a critical role in the biological processes within the aeration tank. Higher temperatures typically enhance microbial activity, accelerating the degradation of organic matter. In this study, a summer wastewater temperature of 22°C was selected as the baseline, as it represents the period of peak oxygen consumption. This ensures that the analysis reflects the most demanding operational conditions for the treatment process, providing a robust evaluation of system performance.

According to table 4, the software output is consistent with the design criteria of the complete mix ASP.

Sadri Moghaddam and Pirali develop a full-scale model of the southern Tehran wastewater treatment plant using GPS-X software. Determining the quality characteristics of the influent was the most critical modeling step, significantly impacting simulation accuracy. The sensitivity of various stoichiometric and kinetic parameters in GPS-X are carried out. The result shows that the calibrated model was validated using real input and output data and the model's accuracy is acceptable (Sadri Moghaddam and Pirali, 2021).

2.2. GPS-X simulation and calibration

To model the first phase of the northern Esfahan WWTP, the input units, primary sedimentation, aeration, secondary sedimentation, and sludge units have been implemented in the software according to Fig. 5. As supernatant of sludge is transferred to the second phase and has no effect on the treatment process of the first phase and for more simplicity the sludge part of the process is regarded as sludge treatment in total.

2.2.1. Sensitivity analysis on kinetic and stoichiometric parameters of wastewater

In a study by Cao et al. a new strategy was proposed to increase TN[1] removal at a treatment plant using GPS-X. The sensitivity of 61 parameters was analyzed, and ultimately, six key parameters (including μmax A, KA/a, μmax H, KH/ss, YH, and μmaxPAO) were selected for calibration (Cao et al., 2021). Based on this study, these parameters (table 5) are examined for sensitivity analysis.

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[1] Total Nitrogen (TN)

Table 5. Kinetic and stoichiometric parameters

Parameter	Default	Reference values	Reference
Autotrophic maximum specific growth rate (μmax,A)	0.9	0.25 - 1.2	(Lopez-Vazquez et al., 2013)
Ammonia half saturation coefficient (KA/a)	0.7	0.35 - 1.0	(Eidroos, 2014)
Heterotrophic maximum specific growth rate (μmax,H)	3.2	3 - 6	(Henze et al., 2006)
Readily biodegradable substrate half saturation coefficient (KH/ss)	5.0	5.0	(Henze et al., 2006)
Heterotrophic yield (YH)	0.67	0.4 - 0.8	(Aguilar et al., 2020)

According to EPA guidelines, the normalized sensitivity coefficient ($S_{i,j}$) is defined as the ratio of the percentage change in the output variable (y_i) to a 10% change in the input variable (x_i). This formula is presented in Equation 1

$$\left| S_{i,j} = \frac{\Delta y_i / y_i}{\Delta x_i / x_{i\ i}} \right| \qquad (1)$$

The influence of certain parameters on the output variable in the simulated model can be understood in the following way:

If: $S_{i,j} < 0.25$: negligible
$0.25 < S_{i,j} < 1$: influential
$1 < S_{i,j} < 2$: very influential
$S_{i,j} \geq 2$: extraordinarily influential

2.2.2. Kinetic and stoichiometric coefficients calibration by real data

By changing to the synthetic parameter YH, the effluent TSS and COD were compared with July 2020 real data from WWTP, and the Theil index (T) was used to measure the degree of difference.

The Theil index is a statistical measure that can be used to assess the goodness of fit of a model, particularly in the context of environmental modeling and simulation. This index serves as an important indicator of model fit by quantifying the alignment between predicted and observed values. A low Theil Index suggests that the model is effectively capturing the dynamics of the system being studied, which is crucial for reliable environmental modeling and decision-making

$$\mathrm{TIC} = \frac{\sum_{i=1}(O_i - P_i)^2}{\sum_{i=1} O_i^{\,2}} \qquad (2)$$

Where
Oi = the observed (measured)
Pi = the predicted (simulated) value

Cao et al. used the Thiel inequality coefficient[1] to validate the simulated model by GPS-X with the measured concentrations of pollutants in the effluents. They consider the beyond the typical effective limit for this parameter ≤0.3 (Cao et al., 2021).

Catenacci et al. also used this coefficient to evaluate the goodness of fit of the model an anaerobic co-digestion in WWTP for alkalinity, total volatile fatty acids, pH, COD, volatile solids, and nitrogen, modelling was less accurate while TIC > 0.3 (Catenacci et al., 2021).

2.3. Running aeration scenario

The aeration tank was segmented into four distinct sections, allowing for the simulation of various aeration scenarios through a trial-and-error approach. In traditional aeration systems, the organic load is typically highest at the inlet and decreases downstream, resulting in an imbalance in oxygen concentration. By strategically distributing air throughout the tank, oxygen utilization can be enhanced and the risk of over-aeration in the latter sections can be reduced. This approach not only supports the aerobic nitrification process but also creates favorable conditions for denitrification in the anoxic zones, which is crucial for effective biological nutrient removal[2].

2.3.1. Design of scenarios

Our modeling approach incorporates a diverse range of scenarios designed to address the complexities of oxygen distribution within the aeration tank. These scenarios span from evenly distributing air across all sections, as demonstrated in Scenario 1, which mirrors the current operational conditions of the WWTP, to more strategic interventions that adjust air distribution to achieve specific treatment objectives.

This study evaluates 14 distinct scenarios to analyze various operational conditions, as detailed in table 6. Importantly, the total volume of air supplied remains consistent across all scenarios, matching the capacity of the blowers currently available at the treatment plant.

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[1] Thiel Inegulity Coefficient (TIC)
[2] Biological Nutrient Removal (BNR)

The primary goal of this research is to optimize the utilization of the existing blower infrastructure to enhance treatment efficiency.

Scenario 1: This scenario serves as the baseline, representing the conventional method of evenly distributing air across all sections of the aeration tank. While this approach is straightforward, it often leads to inefficiencies, particularly in the later sections where the organic load diminishes, resulting in uneven oxygen concentrations and suboptimal utilization.

Scenario 2: By reducing the air supply in section four and reallocating it to earlier sections, the overall oxygen utilization can be enhanced. This approach is designed to optimize the conditions for nitrifying bacteria, which require adequate DO levels for the oxidation of ammonia to nitrite and subsequently to nitrate.

Scenarios 3 to 6: In wastewater treatment, pre-anoxicand post-anoxic configurations are two common strategies used to enhance nitrogen removal through BNR processes. Both approaches rely on creating anoxic zones (oxygen-deficient but nitrate-rich environments) to facilitate denitrification, the process by which nitrate is converted into nitrogen gas.

Scenarios 7 and 8: These scenarios focus on the effect of varying DO concentrations in the initial and subsequent sections.

Scenario 9: This scenario explores the allocation of air from section four to section three, examining the resulting changes in DO concentrations.

Scenario 10: Setting a uniform DO concentration of 2 mg/L across all sections allows to assess the impact of consistent oxygen levels on biological treatment processes.

Scenarios 11 and 12: These scenarios investigate the effects of DO in the initial sections, where the organic load is high.

Scenarios 13 and 14: By systematically decreasing and increasing air supply, these scenarios allow to analyze the responsive behavior of the biological processes involved in nitrogen removal.

Oxygen distribution in different scenarios and different parts of the aeration tank are presented in Fig. 6, while results were obtained over 30-day period under steady-state conditions.

Table 6. Different scenarios in modeling

Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Air distribution ratio (Percent)														
First part	25	30	33	33	33	0	30	20	30	46	30	20	50	10
Second part	25	30	33	33	0	33	40	50	30	25	40	50	20	20
Third part	25	30	33	0	33	33	0	0	40	19	20	20	20	30
Fourth part	25	10	0	33	33	33	30	30	0	10	10	10	10	40

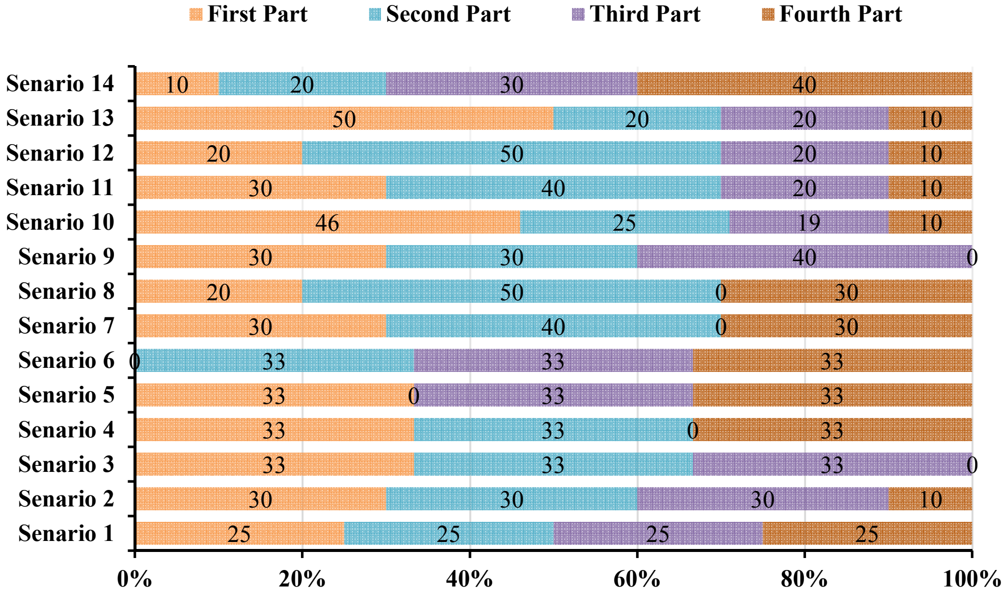


Fig. 6. Oxygen distribution in different scenarios and different parts of the aeration tank

3. Results and discussion

3.1. Sensitivity analysis and calibration on kinetic coefficients

The local calibration of kinetic coefficients for the influent wastewater in phase I of the Northern Esfahan WWTP was conducted in this study. The kinetic and stoichiometric coefficients of the municipal wastewater produced in Esfahan, including (μmax, A), (KA/a), (μmax, H), (KH/ss) and (YH), were examined.

In this study, a steady-state sensitivity analysis of kinetic and stoichiometry parameters on the dependent variables (effluent COD and TSS) was conducted. Normalized sensitivity coefficients ($S_{i,\,j}$) are displayed in Fig. 7.

It was determined that only the kinetic parameter YH has a significant impact on the output parameters. Therefore, this parameter needs to be calibrated with trial and error. Results of the normalized sensitivity coefficient are presented in table 7.

Through an iterative trial-and-error process, the yield coefficient (YH) was adjusted from 0.66 to 0.75, resulting in a correction of the Theil index. As a result, this parameter is now considered calibrated. The calibration of the model using real data is illustrated in Fig. 8.

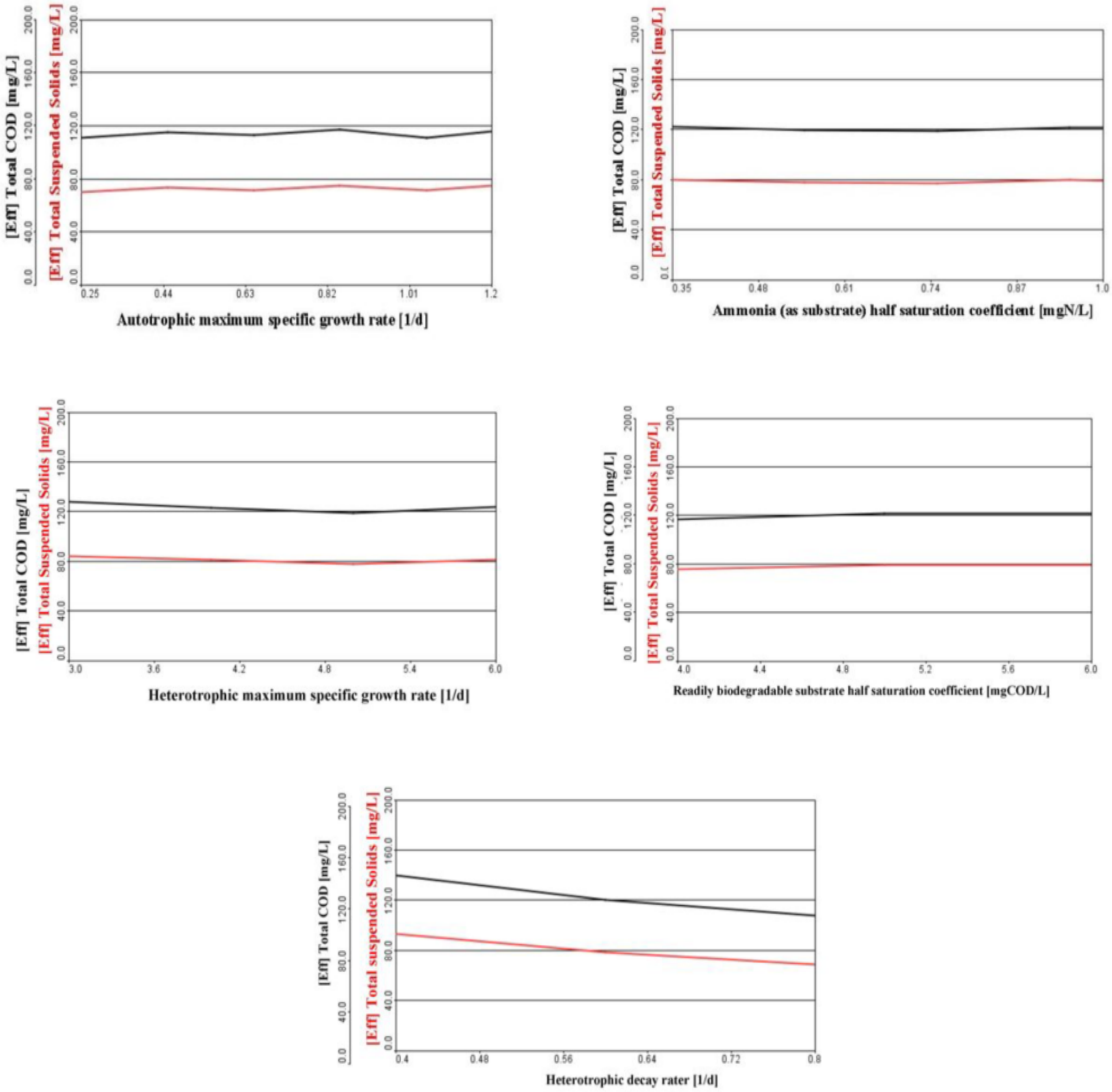
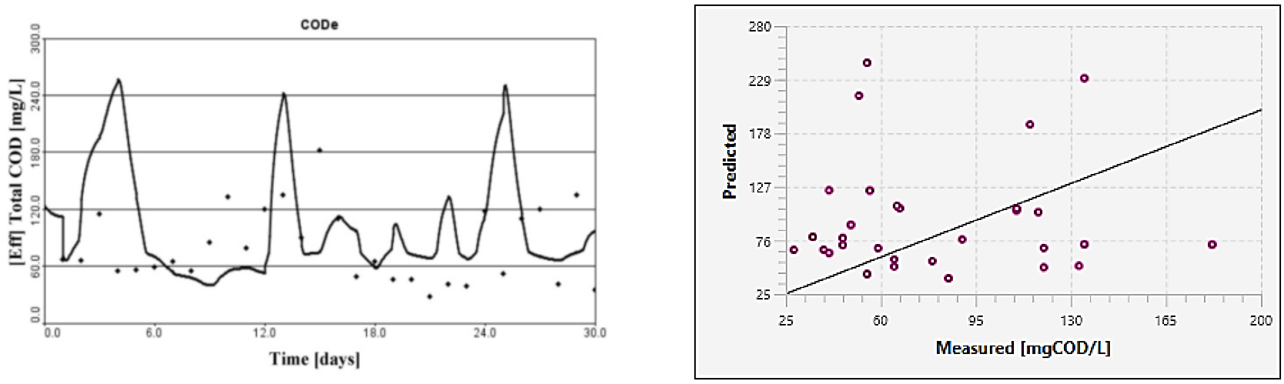


Fig. 7. Normalized sensitivity coefficient ($S_{i,\,j}$) on kinetic and stoichiometric parameters

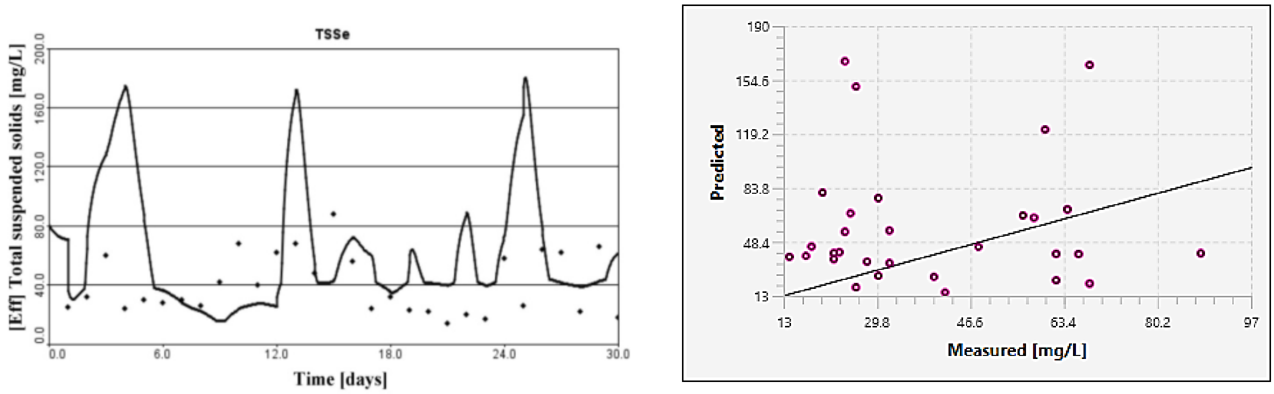
Table 7. Results of the normalized sensitivity coefficient

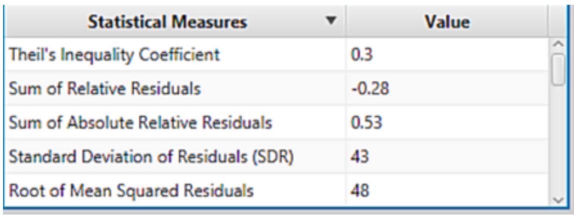
Parameter	$S_{i,j}$	Effect
Autotrophic maximum specific growth rate (μmax,A)	< 0.25	Negligible
Ammonia half Saturation coefficient (KA/a)	< 0.25	Negligible
Heterotrophic maximum specific growth rate (μmax,H)	< 0.25	Negligible
Readily biodegradable substrate half saturation coefficient (KH/ss)	< 0.25	Negligible
Heterotrophic yield (YH)	$0.25 < S_{i,j} < 1$:	Influential



Statistical Measures	Value
Theil's Inequality Coefficient	0.25
Sum of Relative Residuals	-0.17
Sum of Absolute Relative Residuals	0.48
Standard Deviation of Residuals (SDR)	42
Root of Mean Squared Residuals	44

A) COD





Statistical Measures	Value
Theil's Inequality Coefficient	0.3
Sum of Relative Residuals	-0.28
Sum of Absolute Relative Residuals	0.53
Standard Deviation of Residuals (SDR)	43
Root of Mean Squared Residuals	48

B) TSS

Fig. 8. Calibration of the model by real data A) COD, B) TSS

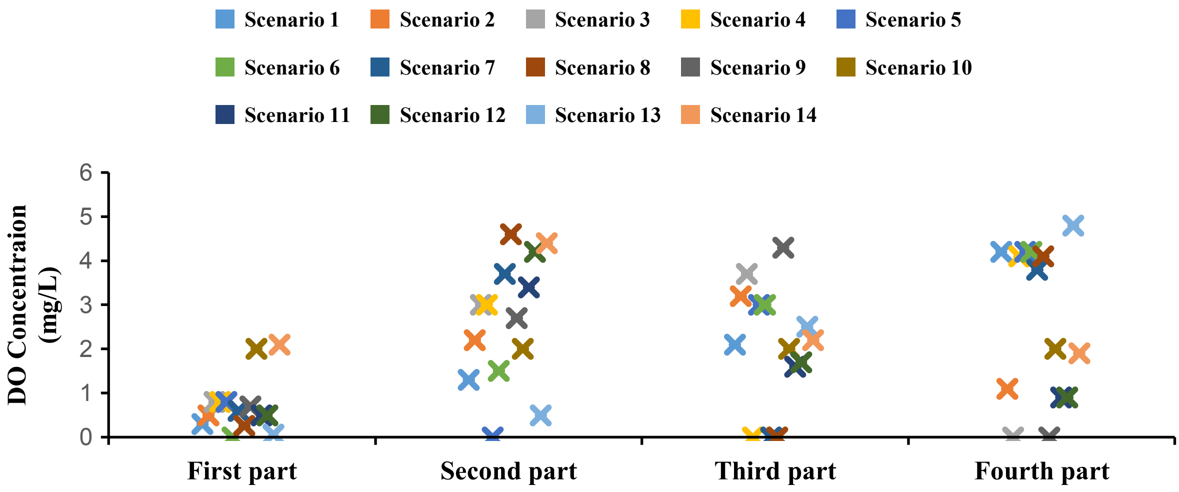


Fig. 9. DO concentration in different scenarios and different parts of the aeration tank

It is important to emphasize that we ensured no operational changes occurred during the specified time period, and all tests were conducted in strict adherence to our standard procedures.

The findings suggested that the GPS-X simulation for wastewater treatment was deemed acceptable, as there was no significant statistical difference between the surveyed variables of the simulated and actual measurements.

The heterotrophic decay rate (kd) indicates the speed at which heterotrophic microorganisms, which rely on consuming organic matter, die and decompose. A higher kd value signifies a more rapid decay of biomass. As biomass decays over time, it transforms from active biomass into inert particulate matter and soluble byproducts. As a result, when the MLSS concentration is held constant, the system must generate additional new biomass to sustain that fixed MLSS level.

In this study, the yield coefficient (YH) was increased from 0.66 to 0.75, resulting in an increase in SRT from 7.7 days to 8.82 days (in the first scenario). Notably, the total amount of sludge production remained largely unchanged.

The heterotrophic decay rate indicates how quickly heterotrophic microorganisms, which feed on organic matter, die and decompose. A higher decay rate (kd) signifies a more rapid breakdown of biomass. As more biomass decays over time, it transforms active biomass into inert particulate matter and soluble byproducts. As a result, to maintain a constant MLSS level, the system must generate additional new biomass. Similarly, in this study, increasing the yield coefficient (YH) from 0.66 to 0.75 led to an increase in SRT from 7.7 days to 8.82 days, while the amount of produced sludge remained relatively unchanged.

3.2. Air distribution

The distribution of DO concentration (mg/L) in different scenarios is presented in Fig. 9. As can be seen, the DO in different parts of the tank in each scenario differs greatly. Moreover, aeration scenarios for North Esfahan phase I are shown in table 8.

The SRT, which is a critical parameter in biological treatment processes, determines the duration for which microorganisms remain in the system. In this study, the software dynamically adjusted the SRT based on operational parameters, including air distribution across the divided sections of the aeration tank. Changes in air distribution influenced microbial activity and solids retention, which were reflected in the SRT values. For the North Esfahan phase I model, the MLSS concentration in the aeration tank is 1900 mg/L, with the SRT varying between 7.7 and 8.82 days across different aeration scenarios. This dynamic adjustment highlights the interplay between aeration strategies and biological process efficiency.

The software also recalibrates the oxygen transfer efficiency parameters to align with the new aeration conditions. This includes updating key metrics such as the OTR[1] , which is critical for accurately modeling how effectively oxygen is transferred to the water and utilized by microorganisms. These adjustments ensure the simulation remains precise and representative of actual treatment processes. Each section may exhibit distinct OTR depending on the airflow, and these rates are monitored through the software's output variables.

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[1] Oxygen Transfer Rate (OTR)

Table 8. Aeration scenarios in Esfahan North phase I

Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SRT	8.82	8.67	8.51	8.37	7.49	7.74	7.7	7.53	7.73	7.83	7.55	8.76	8.5	8.33
Air distribution ratio (Percent)														
First part	25	30	33	33	33	0	30	20	30	46	30	20	50	10
Second part	25	30	33	33	0	33	40	50	30	25	40	50	20	20
Third part	25	30	33	0	33	33	0	0	40	19	20	20	20	30
Fourth part	25	10	0	33	33	33	30	30	0	10	10	10	10	40
DO concertation (mg/L)														
First part	0.3	0.5	0.8	0.8	0.8	0	0.6	0.26	0.7	2	0.5	0.5	0.06	2.1
Second part	1.3	2.2	3	3	0	1.5	3.7	4.6	2.7	2	3.4	4.2	0.5	4.4
Third part	2.1	3.2	3.7	0	3	3	0	0	4.3	2	1.6	1.7	2.5	2.2
Fourth part	4.2	1.1	0	4.1	4.2	4.2	3.8	4.1	0	2	0.9	0.9	4.8	1.9
Oxygen mass transfer coefficient (d^{-1})														
First part	894	877	861	844	760	760	756	655	749	758	734	826	839	832
Second part	937	919	902	886	811	810	746	724	800	809	787	870	880	873
Third part	961	942	925	908	844	799	792	777	789	798	822	895	903	896
Fourth part	977	958	939	923	833	828	824	811	820	829	811	913	919	910

3.3. Effluent quality improvement

3.3.1. COD and TSS removal

The effluent concentrations of TSS and COD showed no significant differences across various aeration scenarios, even as aeration rates were adjusted. The removal efficiencies for COD and TSS remained consistently high, at approximately 92% and 93%, respectively. Specifically, COD levels decreased from 691 to 59 mg/L, while TSS levels dropped from 336 to 25 mg/L.

Cao et al. also observed that adjusting the retention time and air distribution across the five sections of the aeration tank had no significant effect on the COD removal rate in their A^2O activated sludge system, as analyzed using GPS-X software (Cao et al., 2021).

Additionally, in some scenarios, one-fourth of the aerobic tank was converted into an anoxic tank, thereby reducing the retention time. However, the results indicate that this modification had no significant impact on the concentration of effluent COD and TSS. This suggests that the WWTP exhibits resilience to reductions in retention time, maintaining stable treatment performance.

3.3.2. Nitrogen removal

On the other hand, in the present study in phase I of the Northern Esfahan WWTP, changes in DO concentration in different sections of the aeration tank caused changes in the TN removal rate. Effluent characteristics of the North Esfahan WWTP (phase I) are presented in Fig. 10. The concentration of DO is critical for both nitrification and denitrification processes. Nitrification, which converts ammonia to nitrate, requires aerobic conditions, while denitrification, which reduces nitrate to nitrogen gas, occurs under anoxic conditions. In the Esfahan North WWTP, total effluent nitrogen in existing condition was around 42 mg/L while the NOx effluent was 36 mg/L, indicating effective Nitrogen conversion to nitrate. However, the ammonia concentration was about 4 mg/L, suggesting that although nitrification is efficient, the subsequent reduction of nitrate is less so, primarily due to insufficient anoxic conditions. This imbalance can lead to high TN levels in effluents.

Notably, the results demonstrated a significantly high DO level of 4.2 mg/L in the final section, which exceeds the typical threshold of 2 mg/L.

Bian et al. investigated the effect of DO on nitrogen removal in high carbon-to-nitrogen ratio (C/N) wastewater treatment using MBBRs. The study focused on the mechanisms of heterotrophic nitrification and aerobic denitrification, revealing that optimal aeration conditions significantly enhance nitrogen removal performance. The findings suggest that adjusting DO levels can improve the efficiency of nitrogen removal processes in wastewater treatment systems, particularly in environments with high C/N ratios (Bian et al., 2022).

Analysis reveals that the anoxic zone in the first section in scenario 6 exhibited optimal nitrogen removal efficiency, reducing the TN from 87 to 35 mg/L, attributed to a higher concentration of DO. This scenario mirrors the MLE[1] activated sludge process, which strategically positions the anoxic unit prior to the aeration tank to enhance denitrification. The findings support the notion that maintaining an anoxic environment can be beneficial for nitrogen removal.

Srivastava and colleagues used GPS-X software to create a model of a STP. The STP consists of various

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[1] Modified Ludzack-Ettinger (MLE)

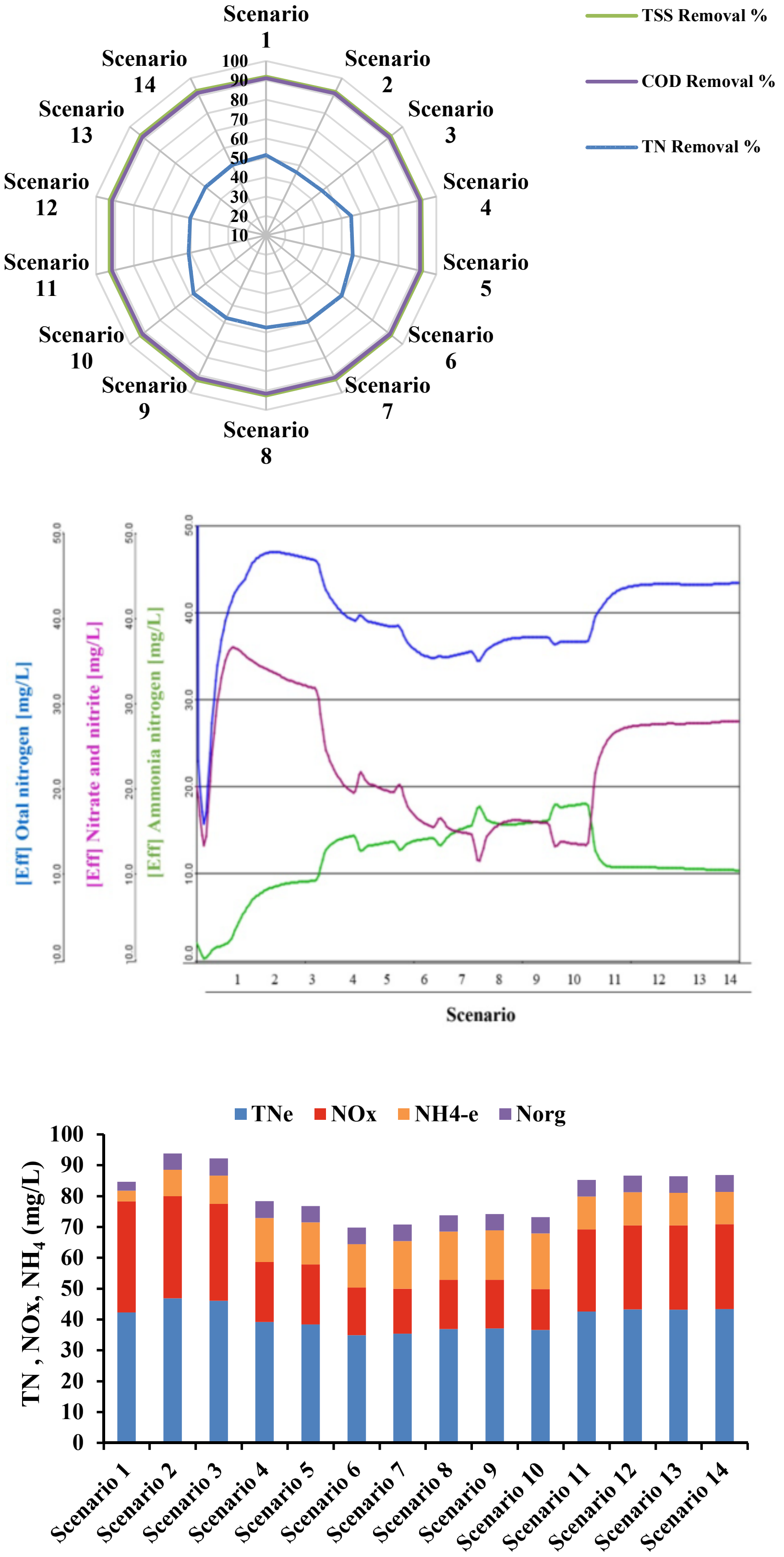

Fig. 10. Effluent characteristics of North Esfahan WWTP (phase I) in GPS-X software

treatment units, including an equalization tank and two series-connected MBBRs, which are essential for diagnosing operational issues. The STP exhibits less than 5% ammonia removal efficiency, with an average influent ammonia concentration of 50 mg/L, and faces difficulties in achieving adequate BOD_5 removal, reflecting significant inefficiencies. To improve treatment efficiency, the study recommends the addition of a 15 m^3 pre-anoxic tank with a recirculation ratio of 3 (Srivastava et al., 2024).

In a study by Rajaei and Nazif, researchers looked into how different control strategies, particularly focusing on DO levels, impacted the performance of a WWTP in southern Tehran. Their findings showed that by effectively managing the aeration system and the sludge flow, they could significantly enhance the quality of the effluent produced (Rajaei and Nazif, 2022).

In comparing Scenarios 7 and 8, it was noted that Scenario 8 achieved a more uniform distribution of DO across the first, third, and fourth sections. The increased air supply in the second section relative to the first likely contributed to enhanced nitrogen removal efficiency in this scenario. This indicates that a balanced oxygen distribution can positively influence denitrification processes.

Akter et al. demonstrated that stable aeration conditions significantly enhance the retention of nitrifying bacteria, thereby improving overall nitrogen removal efficiency. In their study, a lab-scale fixed-film bio-media process was developed to evaluate nitrogen removal in domestic STP. The process consisted of three separate reactors (anaerobic, anoxic and aerobic) operated in series. Each reactor was maintained under consistent loading rates and HRT, ensuring optimal conditions for nitrogen removal. The findings highlighted the importance of stable aeration in promoting the growth and activity of nitrifying bacteria, which are critical for efficient nitrogen removal in wastewater treatment systems (Akter et al., 2022).

Cao et al. enhanced the A^2O activated sludge system using GPS-X software. They found that optimal TN removal in the effluent was achieved by configuring the aeration tank into five compartments. Specifically, they implemented zero air distribution in the first, third, and fifth compartments, while maintaining an equal 50% airflow in the second and fourth compartments (Cao et al., 2021).This reinforces the idea that uniform air distribution is advantageous for maintaining nitrogen removal efficiency.

Results from Scenario 10, which utilizes a DO controller to maintain DO levels at 2 mg/L, demonstrate a reduction in TN to approximately 37 mg/L. This highlights the importance of maintaining consistent DO levels throughout the entire tank for effective nitrogen removal.

The findings from Scenarios 11 and 12 indicate that increasing the air supply by 10% in the first segment does not result in a significant improvement in nitrogen removal.

Moreover, the findings from Scenarios 13 and 14 revealed that both an increase and a decrease in air distribution resulted in reduced nitrogen removal. This suggests that maintaining a balanced oxygen distribution can enhance denitrification processes effectively.

The results indicate that the implementation of an anoxic zone in the aeration process facilitates effective denitrification, leading to a reduction of the total TN in the effluent to 35 mg/L compared to the existing condition of 52 mg/L. Moreover, the limited nitrogen removal efficiency can be attributed to the absence of internal effluent recirculation from the final stage of the aeration tank. Effective nitrogen removal processes, such as the MLE method, rely on the presence of nitrates and nitrites generated under aerobic conditions. These compounds are then returned to the anoxic zone through the internal recirculation of effluent.

It is important to note that the phase I process at the Northern Esfahan WWTP is specifically designed for agricultural reuse of effluent. Its primary objective is to reduce BOD_5 and TSS, with less emphasis on optimizing nitrogen removal. Furthermore, the system operates with a total retention time of approximately 6 hours, which is insufficient to facilitate complete denitrification and nitrification processes due to an inadequately designed retention time. Consequently, even if anoxic conditions are established in one section, the limited retention time prevents the full conversion of organic nitrogen into nitrite and nitrate.

However, the primary objective of this research is to optimize the use of existing infrastructure and equipment and to avoid making modifications to the current treatment system. Additionally, this study aims to investigate how changes in the air distribution generated by the existing blowers affect the quality of the final effluent. This is particularly relevant under the assumption that the organic load at the inlet of the aeration tank is higher than in other sections, leading to a significant drop in oxygen concentration at the tank's entrance.

3.4. Impact of influent fluctuation

GPS-X is capable of processing daily input data sets, which allows for a more detailed representation of the dynamic fluctuations in wastewater characteristics. By incorporating such data, the model can significantly enhance its reliability and accuracy in simulating real-world conditions.

To evaluate the impact of influent quality on effluent performance, a sensitivity analysis was conducted under the optimal aeration scenario (Scenario 6). This analysis

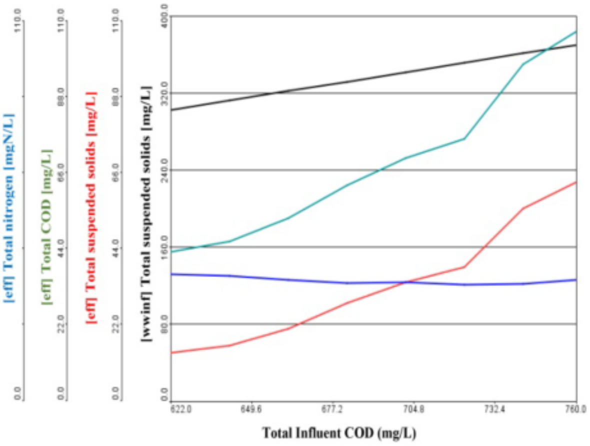

Fig. 11. Impact of influent COD and TSS fluctuation on effluent (±10% change)

involved applying a ±10% variation (shock) to the concentrations of COD and TSS in the influent.

The impact of influent COD and TSS fluctuation on effluent is presented Fig. 11. The results were then used to assess how these changes influenced the quality of the effluent, providing valuable insights into the system's responsiveness to variations in influent parameters.

As illustrated in Fig. 11, an increase in the influent COD and TSS concentrations results in a corresponding rise in the effluent quality parameters. Specifically. When both COD and TSS concentrations in the influent are increased by 10%, the effluent COD concentration rises to 110 mg/L, and the effluent TSS concentration increases to 63 mg/L. Conversely, a 10% reduction in influent COD and TSS concentrations would likely lead to a proportional decrease in the respective effluent quality parameters.

This analysis highlights the direct relationship between influent characteristics and effluent quality, emphasizing the importance of monitoring and managing influent variations to maintain optimal treatment performance.

3.5. Impact of temperature

To account for the significant seasonal variations in wastewater temperatures, dynamic temperature modeling should be incorporated into the analysis. This approach would provide a more accurate representation of microbial activity and oxygen demand throughout the year, thereby enhancing the robustness and comprehensiveness of the system's performance evaluation under real-world conditions.

In order to investigate the effect of temperature on effluent quality, a sensitivity analysis was conducted under the optimal aeration scenario (Scenario Six: oxygen distribution ratio of 0%, 33%, 33% and 33%). The average monthly wastewater temperature is presented in table 9. The wastewater temperature in phase I of the North Esfahan WWTP varies between 15°C and 22°C during the year.

Table 9. Average North Esfahan wastewater temperature in various months

Season	Month	Day	Wastewater temperature (°C)
Spring	1	30	16
	2	60	17
	3	90	20
Summer	4	120	22
	5	150	22
	6	180	21
Autumn	7	210	17
	8	240	16
	9	270	15
Winter	10	300	15
	11	330	15
	12	360	16

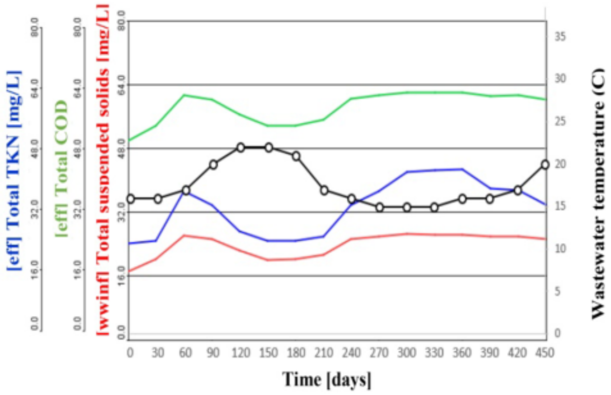

Fig. 12. Impact of seasonal temperature change on effluent

The impact of temperature on effluent is shown in Fig. 12.

Seasonal variations in wastewater temperature significantly impact the performance of the wastewater treatment process. During the summer months, increased microbial activity accelerates the degradation of organic matter, leading to a reduction in COD concentration in the effluent. Conversely, lower temperatures during winter reduce microbial metabolism, resulting in decreased COD removal and higher COD concentrations in the effluent. Additionally, at colder temperatures, reduced biological activity and altered flocculation dynamics lead to an increase in TSS concentration in the effluent. Similarly, since nitrification and denitrification processes are temperature-dependent, TN removal is affected by temperature changes. In warmer seasons, enhanced microbial activity improves nitrification, converting ammonia to nitrate more effectively. However, during colder months, both nitrification and denitrification processes slow down, causing an increase in TN concentration in the effluent.

Based on the analysis conducted, wastewater temperature plays a crucial role in determining the efficiency of pollutant removal processes. Understanding these relationships is essential for developing effective strategies to mitigate the effects of temperature fluctuations and ensure consistent effluent quality throughout the year.

4. Conclusion

This study demonstrates the significant impact of GPS-X simulation in enhancing the wastewater treatment processes at the North Esfahan WWTP, revealing a pathway for improved operational efficiency and effluent quality. By meticulously analyzing and optimizing aeration strategies, the research highlights how dynamic control of DO and the integration of denitrification zones can lead to substantial advances in nitrogen removal, achieving TN concentrations as low as 35 mg/L in the effluent.

The findings advocate for the widespread adoption of simulation-based optimization techniques in wastewater treatment facilities across various operational contexts. The application of these methodologies not only fosters a deeper understanding of best practices tailored to the unique challenges faced by different plants but also empowers engineers and decision-makers to simulate diverse scenarios and anticipate outcomes without incurring significant costs.

Future research should focus on exploring additional operational variables, such as return sludge flow rates and MLSS concentrations, as these could further enhance treatment outcomes. Moreover, the study highlights the importance of sharing these insights among stakeholders to bolster improvements in wastewater treatment infrastructure nationwide.

In summary, using advanced simulation tools like GPS-X is transformative for wastewater treatment facilities. These tools help refine processes and create more resilient and efficient management systems. The insights gained from this research have broader applications across the sector, ultimately promoting better environmental engineering practices that benefit public health and sustainability. By implementing optimal aeration methods, facilities can significantly improve the quality of their effluent and enhance their operational performance. This research underscores the crucial role of simulation in addressing the urgent challenges of wastewater treatment in Iran, paving the way for innovative and effective solutions that align with national environmental goals.

4.1. Suggestions for further research

- Utilize the findings from this research as a foundation for further investigations at the North Esfahan WWTP and similar facilities.
- Explore the influence of additional operational parameters, such as return sludge flow rates and MLSS concentrations, on the efficiency of wastewater treatment processes.
- Investigate the correlation between air flow rates in different sections of the aeration tank and the quality of sludge produced under varying operational conditions.
- Analyze the effects of fluctuating flow rates and wastewater characteristics on pollutant removal efficacy during operational shocks.
- Develop a comprehensive model using GPS-X for the first phase of the North Esfahan treatment plant that can be employed in future assessments, allowing for cost-effective scenario testing with minimal error.
- Expand the application of these optimization strategies to other WWTP across the country, facilitating enhancements in effluent quality.

Disseminate the findings of this research and similar studies to key stakeholders, including decision-makers and plant operators, to promote the adoption of best practices and improve wastewater treatment systems nationwide.

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