

GPS-X modeling of sidestreams elimination for enhanced energy recovery and greenhouse gas mitigation in a full-scale anaerobic-anoxic-oxic plant

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ABSTRACT

The balance between effluent quality, energy consumption efficiency, and greenhouse gas (GHG) emissions should be well maintained in modern wastewater treatment plants (WWTP's). In this study, a novel process was employed to eliminate sidestreams from a full-scale anaerobic-anoxic-oxic (A²/O) WWTP, reducing carbon footprint and energy consumption while improving renewable energy production. The integrated plant processes were then modeled using GPS-X simulation, and the model was assessed using comprehensive data from a full-scale WWTP (A²/O) process. The results highlighted that the novel process increased renewable energy by 100 m³/day of bio-gas, equivalent to 214 kW. It also contributed to a high reduction in energy consumption by about 442.51 kW. Furthermore, the elimination of sidestreams has contributed to a 12 and 13% reduction in net carbon footprint and N₂O released into the atmosphere, respectively. These results conclude that treating the sidestreams separately can improve the sustainable management of the A²/O WWTP.

Keywords: sustainable development, renewable energy, greenhouse gas, modeling, GPS-X simulation, A²/O process, air pollution, wastewater treatment plants.

INTRODUCTION

Nowadays, the transition from fossil energy to renewable sources is at the heart of the international political agenda for climate protection (Timmons and Weil, 2021). Several European projects and plans address this issue and provide a platform for the energy sector's future development. The EU 2020 targets propose that the temperature rise of 2 °C or less should be limited to global warming (Masini, 2021). These objectives formed the foundation for the European Commission's 2030 climate and energy framework, which includes three additional key targets for the year 2030. Emissions of greenhouse

gases (GHG) must be reduced by at least 40% (from 1990 levels), the proportion of at least 27%, and improved energy efficiency by at least 27% (Kubin, 2021).

Additionally, the EU aims to reduce greenhouse gas (GHG) emissions by 80–95% by 2050 compared to 1990 levels. The Energy Roadmap 2050 from the European Commission explores methods to shift the energy system in alignment with greenhouse gas reduction goals while enhancing competitiveness and ensuring supply security (Scharf et al., 2021). Furthermore, the European Commission's Strategic Energy Technology Plan outlines long-term energy research, development, and deployment of low-carbon

technologies, as well as market promotion. On a global scale, the United Nations has announced the Sustainable Development Goals, which include, among other things, universal access to affordable, reliable, sustainable, and modern energy. At the Paris climate summit (COP21) in December 2015, 195 nations approved the first universal, legally binding international climate agreement (Dutta, 2021).

The accord lays out a worldwide action plan to get the world on track to avoid climate change by keeping warming far below 2 °C. As a result, increasing renewable energy supplies is a critical societal priority. Hence, the quest for more renewable energy sources is ongoing. From this perspective, sewage piques the interest of professionals because it can be regarded as a municipal, inexhaustible resource with perpetual availability. Iraq joined the Paris Climate Agreement after the President's ratification on 13/01/2021. According to this agreement, Iraq has become obligated to find appropriate solutions to reduce greenhouse gas emissions (Iraqi Presidency, 2021). However, the primary function of wastewater treatment plants (WWTPs) is to remove undissolved and dissolved chemicals, organic and nutrient compounds from wastewater (Kollmann et al., 2017). WWTPs therefore serve a crucial role in environmental engineering and in controlling water pollution. The potential of WWTPs for energy generation beyond ordinary on-site digester gas combustion or cogeneration, as well as resource recovery, has recently piqued the interest of wastewater specialists. Along with resource recovery, the capability of WWTPs to produce energy beyond typical on-site digester gas use or cogeneration has recently attracted the attention of wastewater experts (Ding et al., 2021).

According to (Laitinen et al., 2017), new nations are needed to consider wastewater as a source of energy. In the past few years, most efforts have been concentrated on achieving good effluent wastewater quality (Khabiri et al., 2022). Energy consumption and GHG emissions are key indicators of the overall performance of WWTPs. However, new challenges are presently being addressed to ensure the long-term sustainability of WWTPs concerning both financial feasibility and ecological effects (Zaborowska et al., 2021). WWTPs have been recognized as potential sources of anthropogenic GHG emissions, contributing to climate change and air pollution, according to recent studies (Pahunang et al., 2021).

Biological methods for treating wastewater release carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), and these gases are also produced during electricity generation required to operate the plant. The volume of CO_2 emitted from energy use can be reduced directly by improving the energy efficiency of WWTPs. By enhancing energy efficiency, it is possible to reduce both environmental impact and treatment costs simultaneously (Badeti et al., 2021). N_2O is generated during nitrification and denitrification processes used to remove nitrogen compounds from wastewater. About 90% is produced in activated sludge units, with the remaining 10% coming from grit and sludge processes (Campos et al., 2016). The production of CO_2 is driven by two principal factors: biological treatment and energy use. The wastewater organic carbon is either incorporated into biomass or converted to CO_2 in the primary flow of the WWTP (Khudhair et al., 2023). Organic matter is predominantly converted to CO_2 and CH_4 in the anaerobic digestion (AD) of the sludge process, and subsequently, CH_4 is oxidized to CO_2 when biogas is combusted (Katariya and Patolia, 2023).

With enhanced equipment and long-term monitoring, mathematical modeling of GHG production in WWTPs is growing rapidly. This would allow for site-specific estimates of GHG production, as such modeling would take into consideration the layout, process configuration, and operational characteristics of each plant. In addition, a comprehensive mathematical GHG model can be used to develop innovative GHG emission-reduction measures at WWTPs. Several different models for calculating GHG generation are currently available (Gurung et al., 2021). Although all models are based on the acknowledged metabolic pathways of GHG generation, their structures still vary with the number of kinetic and stoichiometric routes incorporated.

The single-route models illustrate N_2O production via one of the ammonia-oxidizing bacteria (AOB) processes (i.e., AOB denitrification or NH_2OH oxidation), whereas the two-pathway model incorporates both methods. The single-route models may be more convenient in certain settings, such as those with high dissolved oxygen (DO) concentrations ($>1.5 \text{ gm}^3$), because the two pathway models include more parameters, resulting in lengthy calibrations (Peng et al., 2015). There have been several detailed studies

of current N_2O models as well as generic GHG models that include N_2O production. Whereas simulation has proven to be a possibly beneficial method for estimating N_2O development and emissions at WWTPs, more research is needed because only a few studies using comprehensive online data have been conducted on full-scale WWTPs. A few active sludge models (ASM) and single-track models have been used to model large-scale wastewater treatment plants, but the GPS-X activated sludge model No. 3 (mantis3) has been used in only a few studies. GPS-X enables more precise reaction kinetics and easier calibration. It is also widely used for modeling in the field of wastewater engineering and related disciplines, also by stakeholders as an integral element of WWTP design and operation (Blomberg et al., 2018).

Previously, a novel process in a full anaerobic-anoxic-oxic (A^2/O) system was adopted by separately treating sidestreams in an extended nutrient-moving-bed biofilm reactor (EN-MBBR) and not returning them to the plant head. The EN-MBBR system's aeration was extended to convert ammonia, nitrite, and protein into nitrate, thereby preventing the formation of N_2O gas (Faris et al., 2022; Faris et al., 2022; Zwain et al., 2024). This research aims to study the gaseous performance of the novel process in the Karbala sewage treatment plant's full-scale A^2/O system. GHG emissions, renewable energy production, and reductions in energy consumption are analyzed. The locations of GHG emissions, the extent of their impacts, and the effects of sidestreams on the emission of these gases are simulated using GPS-X software.

METHODOLOGY

Study site and plant configuration

The Karbala WWTP treats domestic sewage in the city of Karbala, Iraq. The average population load to the plant is equivalent to around 50,0000 capita. Figure 1 depicts a simplified schematic of the plant under investigation. The biological stage, comprising three reactors, is the most important part of the therapy. The three reactors that remove substrate, nitrogen, and phosphorus are called A^2/O , and their sizes are 8736, 14112, and 54054 m^3 , respectively. Raw sludge from the primary settling tank (3216 m^2) and waste activated sludge (WAS) from the secondary sedimentation (6432 m^2) are both routed to anaerobic digesters (13600 m^3) that operate under mesophilic conditions (37 °C). After the primary and secondary sludge have been digested, they are sent to drying beds. The sidestreams from the underflow mechanical thickener, supernatant of the gravity thickener, and centrate or digested water are returned to the plant head (Figure 1). Biogas generated through the AD process is kept in a storage tank before being used for heat generation in a boiler or for combined heat and power in on-site energy production facilities. Structures that house technological equipment, a monitoring center, a research lab, and an administrative office are part of the interconnected facilities.

Mainstream and sidestreams analysis

Sidestreams were mixed and processed separately from three different lines, including a

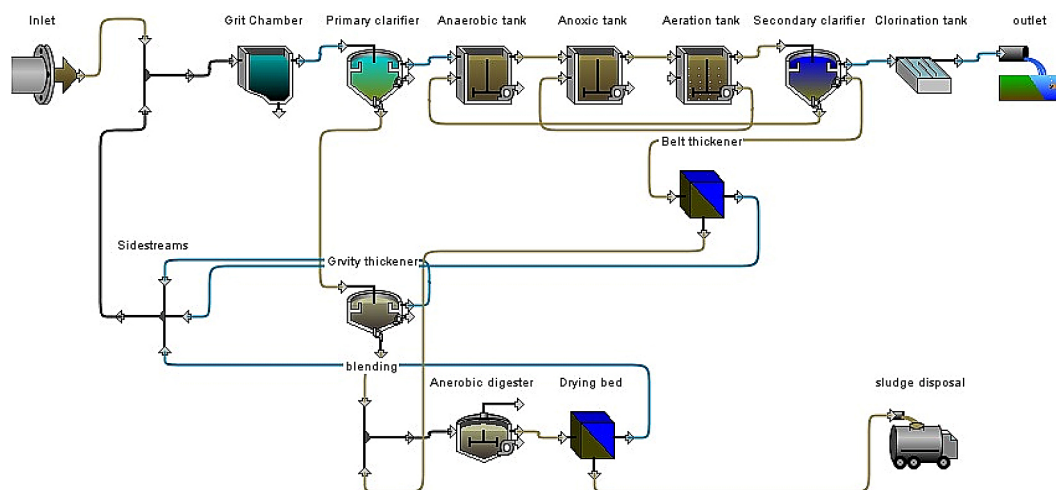


Figure 1. Schematic illustration of the traditional A^2/O system at Karbala WWTP and its sidestreams

mechanical thickener underflow, a flotation gravity thickener, and centrate or digested water. The mainstream and sidestreams of Karbala WWTP have been collected over twelve months. The parameters were tested, and average values are presented in Tables 1 and 2. The examinations were conducted following the established procedure for assessing water and wastewater (APHA, 2017). A Clark-type microsensor (Unisense, Denmark) was used to monitor N_2O concentration in the liquid phase of a closed mobile reactor that was continually fed mixed liquor from the bioreactor. Off-gas N_2O concentrations were measured using a Fourier transform infrared (FTIR) gas analyzer (Gasmeter CX 4000, Finland) and a floating hood.

Karbala WWTP GPS-X modeling

The study employs the GPS-X7 software (Academic license) from Hydromantis Environmental

Simulation Solutions, Inc. It is a commonly used, standalone model that integrates biological wastewater treatment processes for activated sludge and anaerobic digestion, along with several other physical and chemical interactions. As part of the GPS-X software, the Mantis model with modified ASM1 is used to include several additional growth mechanisms for heterotrophic and autotrophic microorganisms and incorporates aerobic denitrification as one of its components. The activated sludge process model used in this study was created in GPS-X simulation using a carbon footprint-carbon, nitrogen, phosphorus, and pH library and the MANTIS3 and simple1d clarifier models. The model consists of over 60 composite and state variables, along with libraries of expressions that define the processes, and it integrates more than 30 stoichiometric and 24 kinetic input and output factors. This part (carbon footprint) of the GPS-X model simulates greenhouse gas emissions and tracks their fate and behavior within wastewater treatment plants (Mu'azu et al., 2020).

Table 1. Karbala WWTP performance characteristics

Parameter	Inlet Concentration	Outlet concentration
PH	6.8–7.5	7–7.4
COD (mg/L)	350–500	20–35
BOD ₅ (mg/L)	150–250	4–10
TSS (mg/L)	160–300	4–10
NO ₃ (mg/L)	0–10	8–45
NH ₄ ⁺ (mg/L)	20–28	0.5
PO ₄ (mg/L)	22–28	0.5–3
H ₂ S (mg/L)	15–35	0.11
Oil & grease (mg/L)	40–60	1–4

Novel processes development and simulation

The sidestreams contain large amounts of nitrogen load. When these nitrogen quantities are returned to the head of the plant, they will contribute significantly to N_2O emissions due to various processes within the plant. In this study, a novel reactor was designed (according to Table 3) that treats all sidestreams lines called the extended nutrient moving bed biofilm reactor EN-MBBR, and the treated water produced from this reactor is mixed

Table 2. Physicochemical characteristics of sidestreams from Karbala WWTP

Parameters	Flotation gravity thickener	Underflow mechanical thickener	Centrate	Total sidestreams
Flowrate (m ³ /d)	83-150	3000	518-1000	3904
TSS (mg/L)	4463	372	1185	508
BOD ₅ (mg/L)	3037	99	144	250
COD (mg/L)	6479	338	951	524
NO ₃ (mg/L)	0	8.6	0	13
NO ₂ (mg/L)	0	0.4	0	0.4
NH ₄ (mg/L)	28	0.5	690	150
PO ₄ -P (mg/L)	5	0.7	1065	50
H ₂ S (mg/L)	40	0	600	100
Alkalinity (mg/L)	325	143	7067	976
TP (mg/L)	22	33	1109	72
DO (mg/L)	0	1	0	0.85

Table 3. Proposed EN-MBBR system design parameters for simulation using GPS-X

Parameter	value
Sidestreams Flowrate	4000 m ³ /d
Surface area loading rate for BOD removal	7.5 g/m ² .d
Surface area loading rate for NH ₄ removal	0.87 g/m ² .d
Dissolved Oxygen	3 mg/l
BOD removal	≥ 95 %
NH ₄ removal	≥ 95 %
Carrier fill	50 %
Hydraulic retention time for BOD removal	1.5 h
Hydraulic retention time for NH ₄ removal	3.5 h
Carrier specific surface area	500 m ² /m ³
Hydraulic loading rate for Lamella	1 m/d
Hydraulic retention time for Lamella	1 h
Angele for lamella plate	60°
Volume of EN-MBBR	1000 m ³

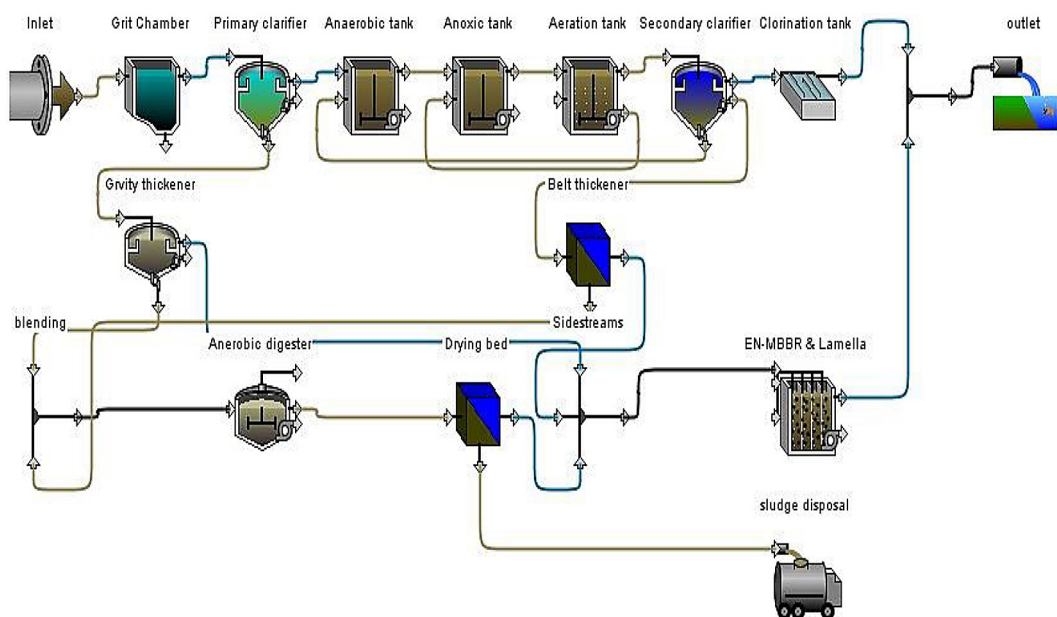
with the treated mainstream. The novelty of this method is shown in Figure 2. The conventional activated sludge system does not return sidestreams to the head of the plant but rather treats and integrates them with the mainstream; therefore, many positives were achieved through this change in the A²/O system, and they will be addressed later.

The novel reactor is a development of the moving bed biofilm reactor system and contains two parts: the first treats organic matter, and the other treats nutrients. In this part, all organic materials

considered as a donor are removed to complete the denitrification process or to contribute to the generation of nitrous oxide gas in the biofilm layers. Aeration is extended in the second part to convert ammonia into nitrate, and both parts have dissolved oxygen levels above 3 mg/L. In this case, this prevents the generation of nitrous oxide and thus reduces Greenhouse gas emissions, plus no anoxic tank. A diffuser system was used in the EN-MBBR process instead of mechanical aerators to reduce nitrous oxide emissions. In this reactor, phosphorus is chemically treated with calcium hydroxide. The system is designed as above to reduce greenhouse gas emissions and to enable the reactor to treat all sidestreams lines efficiently (Sabba et al., 2018).

GPS-X model calibration and validation

Calibration and validation of this study were conducted over three months. The model was calibrated using the results from the first month, and the results from the second and third months were used for model validation. In this study, Figure 3 outlines processes for the systematic model calibration and validation employed. The goodness-of-fit between simulated and measured data was calculated using the measured performance. The root mean square error (RMSE) and correlation coefficient (R) are used to examine the simulation results, as stated in the formulae below (Khudhair et al., 2025):

**Figure 2.** Proposed innovative schematic diagram of A²/O system and development of a novel process (EN-MBBR) for sidestreams treatment

$$R = \frac{(\overline{C_o} - \overline{C_o})(\overline{C_p} - \overline{C_p})}{\sigma_{C_o} \sigma_{C_p}} \quad (1)$$

$$RMSE = \frac{(\overline{C_o} - \overline{C_p})^2}{\overline{C_o} \overline{C_p}} \quad (2)$$

where: C_o represents the actual data, C_p signifies the modeled data, $\overline{C_o}$ indicates the average of the actual data, $\overline{C_p}$ denotes the average of the modeled data, and σ refers to the standard deviation across the dataset. The acceptable values for these statistical criteria are $1 \geq R > 0.8$ and $0 \leq RMSE < 1.5$ (Zwain et al., 2020).

Overall GHG footprint

Within the GPS-X model's characteristics, there is a dedicated library for each pollutant treatment and operational approach. Through this library, the carbon footprint was selected based on the greenhouse gas emissions situation. GHG emissions were categorized in this study using IPCC definitions, and the phrase "GHG footprint" was borrowed from the literature to denote equivalent CO_2 , CH_4 , and N_2O emissions (Zaborowska et al., 2021). In Model GPS-X, the organization of greenhouse gas emissions is according to the following Equation 3:

$$\begin{aligned} Net \ GHG \ emission &= \\ &= GHG \ emission - GHG \ offsets \end{aligned} \quad (3)$$

In wastewater treatment plants, there are three scopes of greenhouse gas emissions, and these three scopes are also found within Model GPS-X. Based on the study carried out, as shown in Figure 4. The GHG offsets also contain three scopes, as shown in Figure 5. The first scope includes direct emissions operations, as shown in Figure 6. As for the second scope, it comprises indirect emissions from the energy consumed by necessary equipment and buildings, as shown in Figure 7. As for the third situation, it depends on the consumption of materials, as shown in equation 4 (Hydromantis, 2017):

$$E_{scope3,i}(t) = \sum Mi(t) \cdot fco2.i(t) \quad (4)$$

where: $E_{scope3,i}(t)$ – scope-2 emission of gas i (gCO_2e/d) at time t , $fco2.i$ – CO_2 factor for the material, gCO_2e/d material, $Mi(t)$ – time dependent daily material consumption, g/d .

RESULTS AND DISCUSSION

Model calibration

To simulate the Karbala WWTP model, the default stoichiometric and kinetic parameter

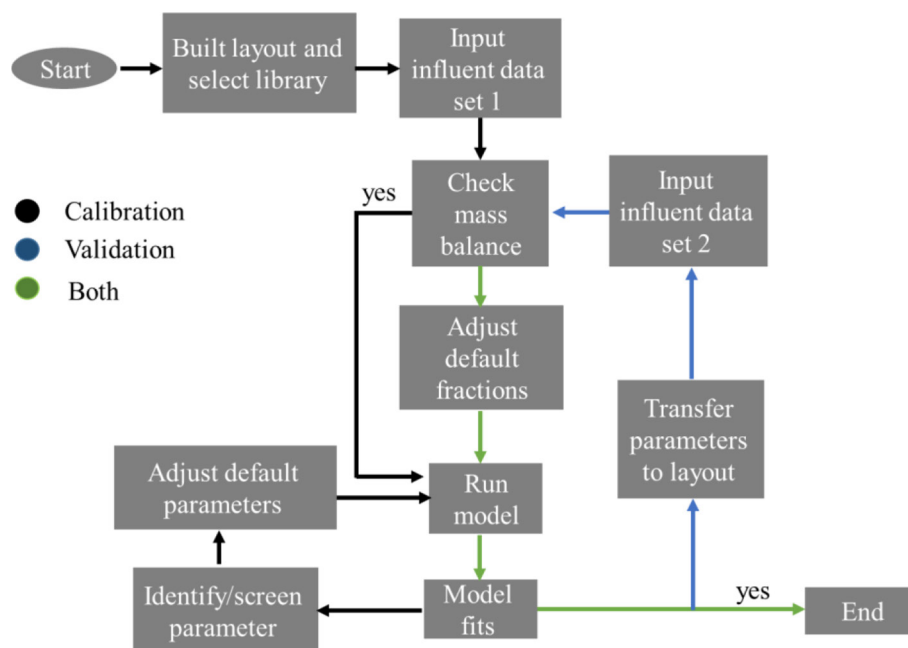


Figure 3. Calibration and verification flowchart in the GPS-X model

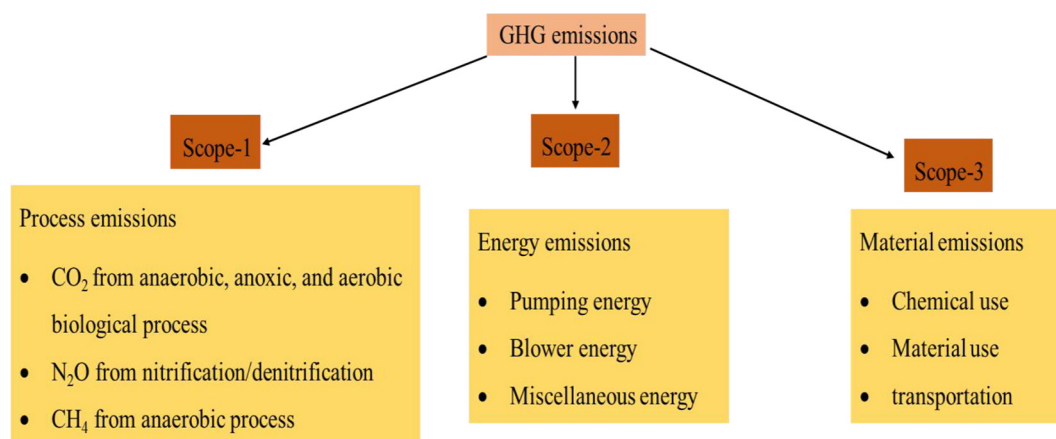


Figure 4. GHG emissions in wastewater treatment plants

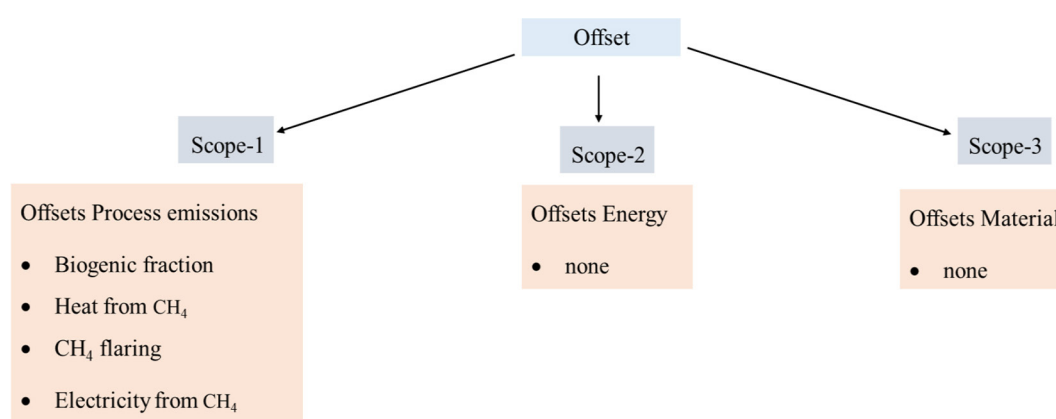


Figure 5. GHG offsets in wastewater treatment plants

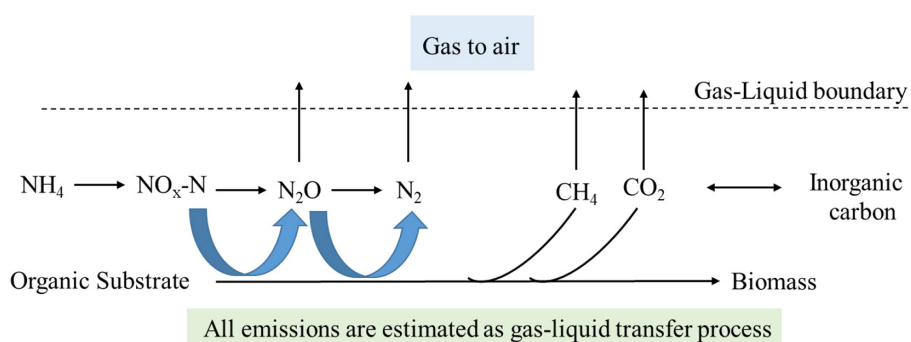


Figure 6. Direct process emissions in scope-1

values were initially applied in GPS-X7. Actual data from the first month of operation of the Karbala WWTP were used for calibration, and the GPS-X7 simulation was run using the default program parameters. The Karbala WWTP estimated effluent initial results were far from actual. Therefore, the model required modifications to adjust the results and bring them as close to the actual as possible. Except for the

two components X_{BA} and X_{BH} , which are the most sensitive parameters for obtaining mass balance at the initial calibration, all parameters were slightly altered. The default values of i_{cv} , X_{BA} , X_{BH} , X_i , S_s , S_i , S_{nh} , pS_i , pX_i , i_{vt} , nS_i , and nX_i were changed from 1.8, 0, 0, 0.13, 0.20, 0.05, 0.9, 0.01, 0.01, 0.75, 0.05, and 0.05 to 1.77, 0.175, 0.144, 0.12, 0.18, 0.04, 0.75, 0.04, 0.75, 0.012, 0.009, 0.77, 0.05, and 0.04, respectively.

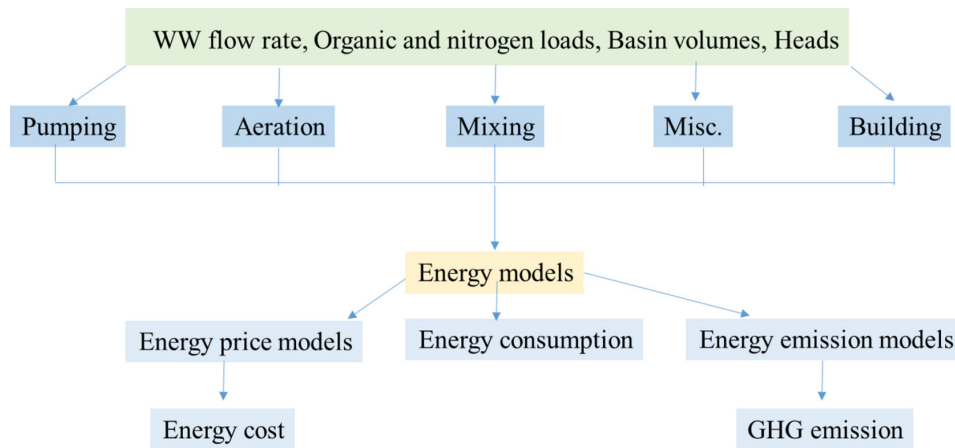


Figure 7. Indirect energy emissions in scope 2

After checking the mass balance and adjusting the sensitive fractions, the sensitive parameters were adjusted to obtain results as close to reality as possible (Cao et al., 2021). In addition, the essential parameters for P uptake and release (q_{PHA} , q_{pp} , and K_{PHA}), denitrification ($\eta_{NO_3, H}$), and nitrification (μ_{AOB}) were also adjusted to fit the predicted model to the measured data. Further adjustments ($K_{O, HET}$, b_{PAO} , K_{pp} , and K_{ipp}) were required to improve the fit of the measured concentrations (NH_4 -N, NO_3 -N, and PO_4^{3-} -P) at full scale. The concentration of nitrous oxide in the aqueous phase was considered during the calibration and validation procedures of the model.

During model operation, the results were far from reality under the default parameters. Some parameters were modified to obtain nitrous oxide results in treated wastewater as close as possible to the actual values. Among the most sensitive parameters were the nitrate reduction factor for heterotrophs $\eta_{NO_3, H}$, the nitrite reduction factor for heterotrophs $\eta_{NO_2, H}$, and the rate reduction factor for AOB μ_{AOB} . The following parameters, $\eta_{NO_3, H}$, $\eta_{NO_2, H}$, and μ_{AOB} , were modified from 0.32, 0.48, and 0.05 to 0.4, 0.6, and 0.04, respectively. The following parameters, $\eta_{NO_3, H}$, $\eta_{NO_2, H}$, and μ_{AOB} , have been adjusted to be 0.55, 0.4, and 0.95, respectively. These findings are consistent with the study of (Zaborowska et al., 2019). As a result of the calibration, Figure 8(a) shows that the predicted and actual effluent values are acceptable compared with the default modeled data. Figure 8(b) shows that the calibration findings for nutrients and N_2O exhibit relatively high variation between the default and anticipated values. However, the calibration findings were quite similar between the actual and predicted after

modifying the most sensitive parameters and attaining mass balance.

Model validation

The next task was to validate the plant after it had been successfully calibrated. Model validation refers to a strong alignment between the model's predictions and an independent dataset not used in the model's development, as outlined by Equations 1 and 2 (Khudhair et al., 2025). The model validation used discrete average monthly effluent quality data from months 2 and 3 of operation, with calibrated model simulations compared against the actual data, as illustrated in Figures 9(a) and 9(b). Additionally, these validation results were within the acceptable range and in line with the most recent plant data. R values, RMSE values, and measured and simulated data are shown in Table 4. With R values greater than 0.8 and RMSE values close to zero across all parameters, the goodness-of-fit results showed that the real and simulated data fit closely (Zwain et al., 2020). According to Iraqi Standard 7, the Karbala WWTP performed exceptionally well, with all effluent concentrations falling below permissible bounds (Al-Waqai Al-Iraqiya, 2012).

It's essential to recognize that all models share identical stoichiometry and kinetic characteristics, which can be leveraged for calibration (month 1 simulated data) and validation (months 2 and 3 simulated data). Nonetheless, in each case, an initial evaluation of the influent stoichiometry fractions is necessary and relies on influent wastewater quality elements that vary each month. After adjusting some sensitive values for the second and third months, good verification

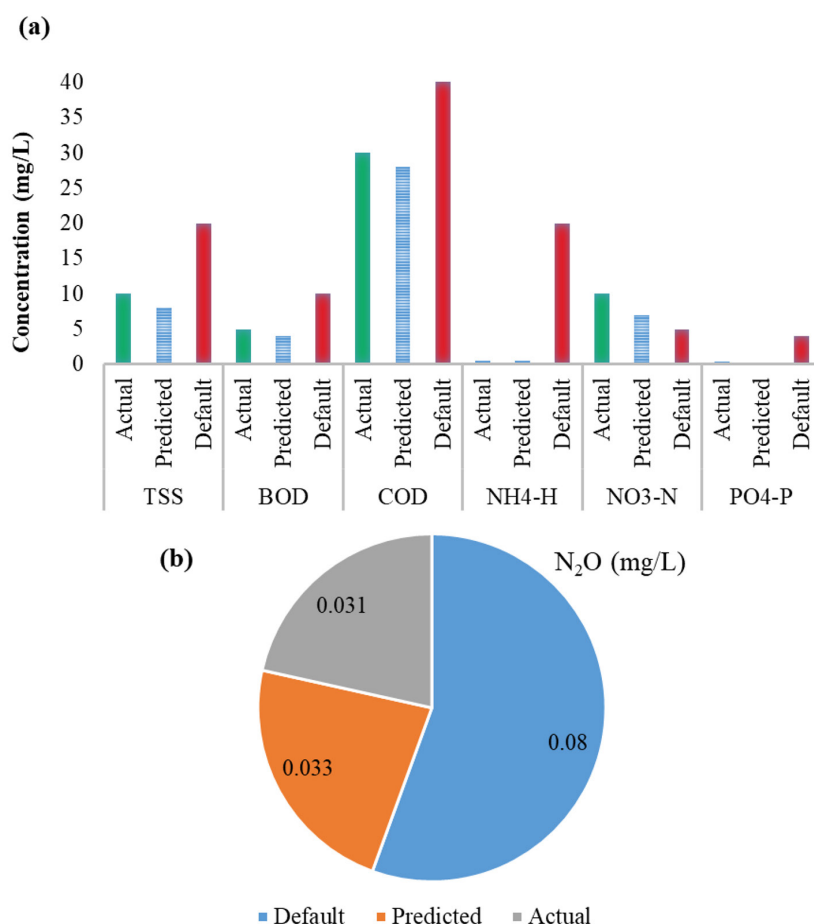


Figure 8. Calibration of the GPS-X model: a) for substrate and nutrients, and b) for nitrous oxide

was obtained. Still, it was not substantially different from the calibration, due to the station's stability throughout the year. The findings from the Karbala WWTP GPS-X model validation indicate that the calibrated models adequately represented the biological processes for treating domestic wastewater, making them acceptable.

Developed model advantages

Sidestreams are among the most significant challenges in the A²/O system because they contain very high concentrations of pollutants, particularly nitrogen and phosphorus. These pollutants, especially nutrients, constitute about 30% of the total load entering the plant. Very large quantities of pollutants are produced from the side stream, and these quantities require additional energy, volumes, and costs, not to mention their environmental impact and greenhouse gas emissions (Campos et al., 2016). In this study, sidestreams were eliminated by treating them independently rather than returning them to the head of the plant. The advantages of eliminating sidestreams are

numerous: eliminating the shocks associated with this line, reducing the nutrient load entering the plant by more than 30%, and reducing the organic load. Improving the nitrification process and improving the removal of phosphorus, etc., among other advantages (Coffey et al., 2021). In this novel study, only three positive aspects were addressed as they pertain to the title of the research, namely, an increase in renewable energy, a reduction in energy consumption, and a reduction in greenhouse gas emissions, as follows:

Renewable energy increase

An important resource for energy recovery is the gas produced in an anaerobic digester. The biogas typically consists of 65–70% CH₄, 25–30% CO₂, and trace concentrations of H₂, N₂, H₂S, H₂O (vapor), and other gases. Biogas has a calorific value of 21,000–24,000 kJ/m³ (550–650 Btu/ft³). In comparison, CH₄ and natural gases have heat values of 35,800 and 37,300 kJ/m³ (960 and 1000 Btu/ft³), respectively. Cogeneration and natural gas supply are two uses for clean biogas.

Table 4. Comparison of R and RMSE after calibration and validation

Parameter	Month 1 (calibration)		Month 2 (validation)		Month 3 (validation)	
	R value	RMSE value	R value	RMSE value	R value	RMSE value
TSS	0.83	0.012	0.88	0.01	0.81	0.01
BOD	0.88	0.08	0.86	0.07	0.83	0.07
COD	0.9	0.02	0.89	0.18	0.87	0.01
NH ₄ ⁺ -N	0.88	0.02	0.87	0.022	0.8	0.02
NO ₂ ⁻ -N	0.83	0.028	0.84	0.027	0.8	0.03
NO ₃ ⁻ -N	0.82	0.14	0.83	0.138	0.84	0.13
PO ₄ -P	0.88	0.01	0.87	0.012	0.82	0.02
N ₂ O	0.89	0.01	0.9	0.001	0.88	0.011

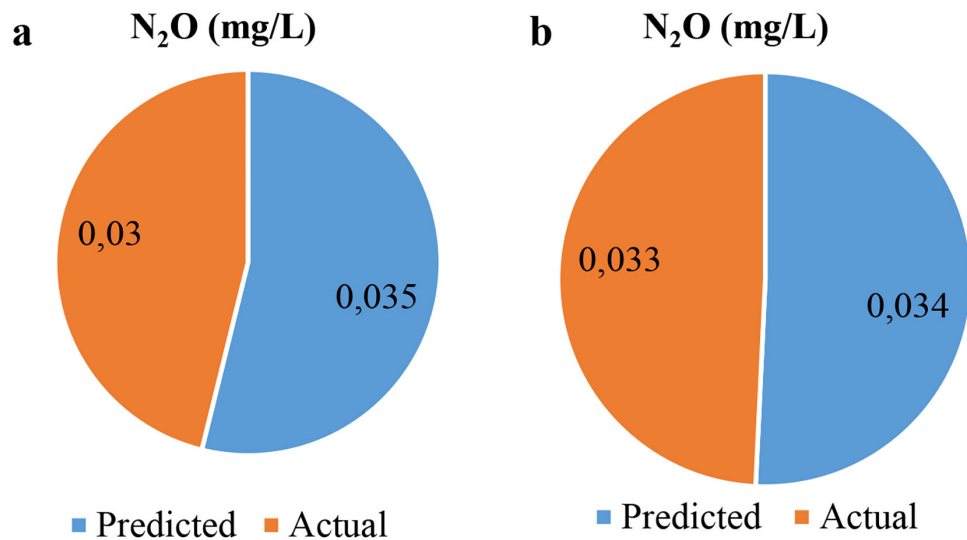


Figure 9. Validation of the GPS-X model for N₂O (a) validation (month 2 data) and (b) validation (month 3 data)

Biogas is used directly to heat digesters, buildings, and maintenance shops at many publicly operated treatment facilities. It is also utilized to power boilers and kilns that produce steam or heat. Internal combustion engines, gas turbines, or micro-turbines are increasingly being used to generate energy for on-site use or for sale to the power grid. A combined heat and power (CHP) system can further increase overall energy efficiency. Biogas-generated electricity is considered renewable energy and a cost-effective and sustainable approach to reducing greenhouse gas emissions (Koonaphapdeelert et al., 2019).

There are two methane gas generators at the Karbala WWTP, with a combined capacity of about 540 kW. The biogas generated from the Karbala WWTP are 8676 and 8577 m³/day, without and with sidestreams returned, respectively. Accordingly, the novel process produced approximately an additional 100 m³/day of biogas,

equivalent to 214 kW. While the EN-MBBR system required 35 kW, this increase can operate the system by its own energy and make it self-sustained. The reason for the increased energy in the EN-MBBR process is the return of pollutants to anaerobic biological process, and when VSS increases, biogas generation increases. The novel process was applied to one of four treatment plants, where it is possible to invest in this method for more than 16 anaerobic digesters, indicating that this method will reduce large quantities of greenhouse gases.

Plant energy consumption reduction

Table 5 shows that the EN-MBBR system effectively treats sidestreams and improves the project's economic viability by reducing energy use. In reactor design, the performance of all equipment mainly depends on the unit's flow characteristics

and size (Andreyev et al., 2018). Removing 4.000 m³/day of sidestreams during initial treatment decreased energy consumption by 4%. The primary sedimentation tank was designed to account for hydraulic and mass loads during initial treatment, resulting in a 4% reduction in energy use. In an A²/O system, mixing intensity depends on mass loading, hydraulic loading, and the presence of organic compounds and nutrients.

However, reactor size is often used to estimate mixing processes (Qasim and Zhu, 2017). When sidestreams were removed, mixing energies in the anaerobic, anoxic, and aeration zones decreased by 10.7%, 6%, and 13.6%, respectively. Meanwhile, because the sludge produced by the EN-MBBR system was returned to mechanical thickening, the thickener's capacity increased by 8%. Additionally, operating the EN-MBBR system used 35 kW of power. Returning the sludge to the anaerobic digester allowed it to be processed into methane gas, generating additional energy. This process generated an additional 214 kW of energy from methane.

Plant carbon footprint reduction

Based on the simulation results and calibration, a substantial decrease was observed in the A²/O system. As shown in Figure 10, the

elimination of sidestreams has contributed to a 12% reduction in net carbon footprint released into space. Most studies on reducing greenhouse gas emissions from wastewater treatment plants have focused on manipulating plant operating conditions, such as DO and IR (Zaborowska et al., 2019). There are three scopes: the largest, first scope, includes biological processes, followed by the second energy scope. The third scope had a very small effect relative to the others. One advantage of this study is the increase in offset emissions, which contributed to reducing net greenhouse gas emissions, as shown in Equation 3. The reduction in greenhouse gas emissions when sidestreams are deleted is due to the ammonia generated from the centrate not being returned to the plant head (Sabba et al., 2018). In addition, sidestreams deletion has contributed to an overall reduction in volume by 4–12%, and energy consumption decreased by 442 kW.

Reactors' gas production rate

Compared with prior full-scale N₂O modeling studies (which were confined to N removal systems without enhanced biological phosphorus removal (EBPR)), the current model demonstrated several significant benefits and novel features.

Table 5. Comparison of energy between novel (S1) and conventional (S2) processes

Facility	S1 energy (KW)	S2 energy (KW)	Difference (KW)
Screw pump	300	288	12
Coarse & fine screen	10.4	10	0.4
Grit & oil removal	98.15	94.22	3.93
Primary clarifier	55.58	53.4	2.18
Intermediate screw	255	245	10
Anaerobic tank	5.6	5	0.6
Anoxic tank	36	33.85	2.15
IR	50.4	30.24	20.16
Aeration tank	1201	1056	145
Secondary clarifier	64	62.5	1.5
RAS	160	154	6
WAS	16.5	16	0.5
Chlorination system	109	109	0
Gravity thickener	5.14	4.9	0.24
Mechanical thickener	37.15	40	2.85
Blending	15.5	15.5	0
Anaerobic digester	118	118	0
EN-MBBR system	0	35	-35
EN-MBBR sludge production	0	-270	270
Total energy saved			442.51

The findings of prior investigations revealed discrepancies between observed data and model projections. In the benchmark simulation model, Arnell et al. (2017) focused solely on nitrogen (N) transformations and N_2O production through the autotrophic denitrification pathway, incorporating GHG (BSM2G). The results indicated that the models predicted average emissions aligned with the measured values. The model, on the other hand, did not accurately predict the whole dynamics of the measured emissions. Blomberg et al. (2018) developed an extended ASM3 model that could represent the kinetics of liquid-phase N_2O transport in the aeration basin.

Moreover, the simulation could only forecast changes in Nitrous oxide emissions, and the projected amounts were significantly higher than the actual emissions. Part of the discrepancy was attributable to flaws in the models used to define the N_2O stripping effect. Ni et al. (2013) investigated an oxidation ditch and a sequencing batch reactor (SBR) plant. Given the prevalence of the NH_2OH oxidation route, there was good agreement between model simulations and observed N_2O and other N species, despite the model not including N_2O synthesis via autotrophic denitrification. In a full-scale nitrogen removal system primarily driven by ammonia-oxidizing bacteria (AOB) processes, research conducted on a step-feed bioreactor illustrates the application and verification of a multi-pathway N_2O model within an operational nitrogen removal framework (Peng et al., 2015). The findings highlight the necessity of

a thorough strategy to determine N_2O generation pathways and accurately predict N_2O behavior.

The model presented in this paper is innovative because it outlines all pathways for generating CH_4 , N_2O , and CO_2 in an A²/O system and evaluates the integrated model against comprehensive experimental data from the full-scale system. The model encompasses all recognized traits of GHG behavior in BNR facilities, including the three identified GHG production pathways in nitrogen transformations, the role of DPAO in denitrification, and GHG transmission between liquid and gas phases. The model was successfully calibrated and validated in the full-scale BNR bioreactor with respect to N_2O dynamics and other key state variables (NO_3^- -N, NH_4^+ -N, and PO_4^{3-} -P). As a result, the verified model may be used to build GHG reduction plans and calculate carbon footprints. In the treatment plant's reactors, and according to the processes that take place within them, several different gases are generated, and these gases may increase in one reactor and decrease in another. Below is a detailed explanation of GHG emissions in the reactors of the Karbala WWTP.

Anaerobic reactor

Before removing the sidestreams, Figure 11(a) shows that the emission rates of CO_2 , CH_4 , and N_2O were 1104, 2.4, and 0.373 kg/day, respectively. By removing the sidestreams and not returning them to the plant head, the greenhouse gas emissions rate drops to 1025, 0, and 0.2 kg/day, respectively. The sidestreams contain high

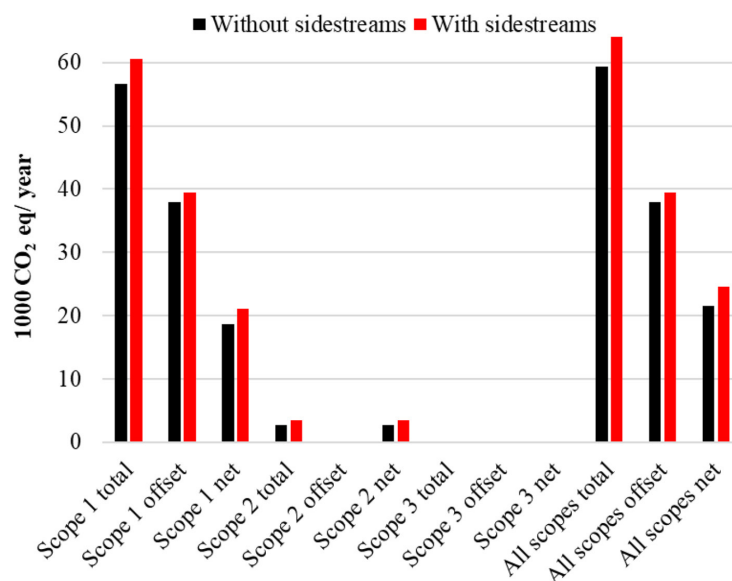


Figure 10. Overall plant carbon footprint

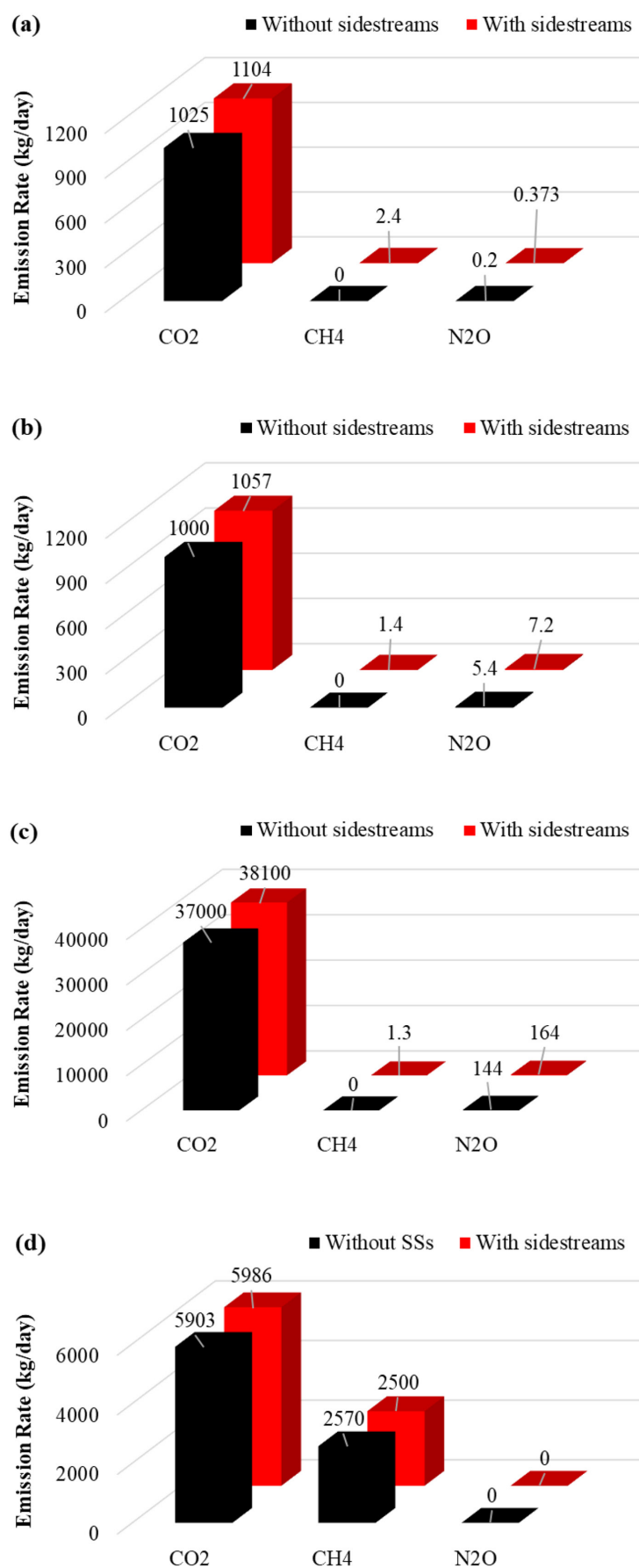


Figure 11. Greenhouse gas emissions in the reactors of the Karbala WWTP: (a) Anaerobic reactor, (b) Anoxic tank, (c) Oxidic reactor, and (d) Anaerobic digester

levels of pollutants that contribute significantly to increases in greenhouse gas emissions, especially ammonia, the main source of nitrous oxide. It was also noted that eliminating sidestreams may contribute to filtering dissolved methane from the sidestreams effluent, which then moves from the liquid phase to the atmosphere through stripping that occurs in all reactors. In this basin, ammonia-oxidizing bacteria (AOB) cannot produce nitrous oxide because this zone lacks dissolved oxygen. Still, heterotrophic and autotrophic denitrifying bacteria convert nitrates and nitrites from RAS and sidestreams into nitrous oxide. Since these concentrations are low, nitrous oxide emissions are lower than those of other greenhouse gases. There is no role for denitrifying phosphorus-accumulating organisms (DPAOs) in nitrous oxide emissions other than converting nitrates into nitrites.

Anoxic reactor

Figure 11(b) displays greenhouse gas emissions in the anoxic basin, where CO_2 , CH_4 , and N_2O emissions were 1057, 1.4, and 7.2 kg/day, respectively. After eliminating the sidestreams, emissions decreased to 1000, 0, and 5.4 kg/day, respectively. Sidestreams elimination has contributed to a 100% reduction in methane emissions in this basin. As for nitrous oxide, it decreased by 25%. Although the nitrous oxide emission rate was 7.2 kg/day, its effect is twice that of carbon dioxide, since nitrous oxide is 300 times more effective than carbon dioxide. The reason for the emission of nitrous oxide gas in this tank is the presence of autotrophic bacteria that convert nitrites into nitrous oxide, as well as heterotrophic bacteria that convert nitrates into nitrous oxide.

Oxic reactor

In this basin, all biological processes are completed, so greenhouse gas emissions are very high in this reactor. Figure 11(c) revealed that after eliminating the sidestreams, the emissions rate decreased to 37,000, 0, and 144 kg/day, respectively. Large amounts of nitrous oxide gas are emitted due to stripping within this basin. This occurs due to the mechanical aerators, which help transfer nitrous oxide from the liquid to the atmosphere. Moreover, the role of nitrifying bacteria in converting ammonia to nitrous oxide was significant. In addition, the processes that took place inside the anoxic basin were not completely

stripped, so they moved to the aeration basin, and this basin contributed to the nature of its work by stripping this gas and its emission into the atmosphere. It was observed that when the sidestreams were eliminated, it reduced the emission of nitrous oxide by 13% in this basin. The elimination of sidestreams reduced the aeration basin's equivalent carbon dioxide footprint to 6000 kg/day.

Anaerobic digester

From Figure 11 (d), it was observed that the greenhouse gas emissions of CO_2 , CH_4 , and N_2O were 0, 5986, 2500, and 0 kg/day, respectively. After eliminating the sidestreams, the methane emission rate increased to 2570 kg/day. It was observed that there is no significant effect on the nitrous oxide rate with a very small change in the carbon dioxide gas. The increase in methane emission rate is due to the return of additional sludge from the new EN-MBBR system. Investments in renewable energy offset this increase in methane emissions and have not been transferred to the atmosphere.

CONCLUSIONS

The developed and validated model could serve as a valuable tool for addressing the complex challenge of reducing GHG emissions in A^2/O systems. In this study, the new process successfully reduced the plant's carbon footprint and boosted renewable energy use. Nitrous oxide has the greatest observed effect among greenhouse gases. The novel method provided good economics for the entire plant and reduced the energy consumption cost. The highest nitrous oxide emission was observed in the aeration basin due to stripping, followed by the anoxic basin due to denitrification. Methane gas has been used to power the plant. The suggested model and strategy may inspire engineers, operators, and managers to implement sustainable operational or technological solutions in WWTPs that meet stringent effluent requirements, achieve acceptable energy performance, and reduce GHG emissions.

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