Optimization of Wastewater Aeration Time in Decentralized Sequencing Batch Reactors in Duhok City, Iraq

Diler N. Hasan† and Nashwan Sh. Mizzouri

Department of Civil Engineering, College of Engineering, Duhok University, Duhok, Kurdistan Region – F.R. Iraq

Abstract—**Aeration costs represent a significant portion of operational expenses (OPEX) in wastewater treatment facilities. Optimizing aeration time can enhance plant sustainability and also contribute to global CO_2 reduction goals. However, research on aeration time optimization in full-scale decentralized Sequencing Batch Reactors (SBRs) remains limited. This study presents the first systematic application of BioWin to evaluate the impact of aeration time optimization on energy consumption, operational costs, and CO_2 emissions in full-scale decentralized SBR plants treating domestic wastewater. Operational, laboratory, and field data were used to develop influent profiles and simulation models. BioWin's simulation-based results indicated that aeration in the equalization (EQ) basin is not required to meet Iraqi effluent standards and that bioreactor aeration times can be optimized without compromising treatment performance, indicating that existing SBR systems are over-aerated. Optimized aeration time resulted in 58.70% reductions in energy use, operating costs, and CO_2 emissions, resulting in annual OPEX cost savings of 234,049,308 IQD and demonstrating that aeration time optimization is a practical and cost-effective approach for improving the sustainability of decentralized SBR plants.**

Index Terms— **Aeration optimization, BioWin, Decentralized wastewater treatment, Domestic wastewater, Sequencing batch reactor.**

I. Introduction

Sequencing batch reactor (SBR) is among the commonly used decentralized wastewater treatment systems (DEWATS), integrating equalization (EQ), aeration, biological treatment, and clarification in a single tank and operating in five steps: fill, react, settle, draw or decant, and idle. Since all mechanisms take place in a single tank, the performance of SBR depends on hydraulic retention time (Tyagi et al., 2024). In Iraq and similar regions, decentralized SBR plants are particularly important for serving urban fringes, new developments, and isolated communities where centralized treatment plants are absent or connection to them is impractical.

In activated sludge systems, aeration consumes the highest energy (67.3%) compared with the physical and chemical treatment processes, particularly in secondary treatment processes where microorganisms depend on a substantial oxygen supply to maintain their life activities and break down pollutants (Muloiwa, Dinka, and Nyende-Byakika 2022).

Aeration time is one of the key operational parameters for optimizing biological processes in SBR systems, and optimized aeration strategies have demonstrated significant potential to improve treatment efficiency in wastewater treatment plants (WWTPs) (Bournazou et al., 2013). Since aeration is the largest energy consumer, optimizing this process can offer significant cost savings for the WWTPs (Shi, Satoh and Mino 2013, Ozturk, Martin Serrat, and Teymour 2016). The saved costs can be used as extra resources to enhance the financial and operational sustainability of the plant.

Simulation models are widely used to optimize the operational performance of existing WWTPs. BioWin is one of the most commonly used simulation programs in academia and the water industry for modeling biological treatment processes at laboratory and full-scale levels (Cheng, Huang and Whang 2024).

Numerous studies have been conducted using BioWin with different technologies such as activated sludge and biofilm reactors. Relevant studies include (Okan, Erguder and Aksoy, 2022) who used BioWin to reduce energy use and carbon footprint in a metropolitan WWTP, and (Bianco et al., 2024) who compared continuous versus intermittent aeration in a full-scale activated sludge plant. In terms of BioWin utilization on SBR systems, several studies have been conducted on nutrient removal (Soliman and Eldyasti, 2017, Šikić et al., 2019), whereas (Barnard, 2001) used BioWin to validate design calculations for a large-scale SBR plant. Moreover, (Robescu et al., 2018) compared SBR and GSBR performance using BioWin.

Most previous studies have applied BioWin for design evaluation, process comparison, and nutrient removal optimization in centralized WWTPs, while full-scale

ARO-The Scientific Journal of Koya University
Vol. XIV, No.1 (2026), Article ID: ARO.12487. 11 pages
DOI: 10.14500/aro.12487
Received: 30 July 2025; Accepted: 20 February 2026
Regular research paper; Published: 04 April 2026
†Corresponding author's e-mail: diler.hasan92@gmail.com

http://dx.doi.org/10.14500/aro.12487

decentralized SBR plants – particularly with respect to aeration time optimization – have received limited attention. To the best of the authors' knowledge, no prior study has used BioWin to optimize the aeration time in full-scale decentralized SBRs treating domestic wastewater. Accordingly, this study addresses a critical knowledge gap by presenting a novel full-scale application of BioWin for aeration optimization.

The study evaluates the current aeration status and operational costs of Duhok city SBRs and explores BioWin's ability to optimize their aeration time to achieve cost-effective compliance with Iraqi effluent standards for biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). Moreover, the optimized aeration time will reduce overall operational costs and lead to a decrease in annual CO_2 emissions, thus mitigating the negative effect on the environment and public health. The results will support practical and efficient plant operation and inform evidence-based policy decisions for sustainable management of decentralized SBR plants. Moreover, the study provides a replicable, decision-support approach that can be used in Iraq and other regions with similar SBR operating conditions.

II. Methodology

A. Study Area

Duhok city is in the northern part of Kurdistan, Iraq. Its coordinates are between 36°50′00″ and 36°54′40″ North latitude and 42°52′00″ and 43°04′44″ East longitude. The city covers about 107 km^2 (Kochary, Byl and Noori 2017).

Duhok lacks a centralized WWTP, relying instead on DEWATS. At present, there are 25 SBR plants in the city, but only 15 are operational; the other 10 are not operating because of financial or mechanical problems and are thus excluded from this analysis (Duhok Sewerage, 2024). Fig. 1 illustrates the study area with the location of functional SBRs. In terms of OPEX expenses, among Duhok city WWTPs, electricity constitutes the largest share of operational expenses (66.86%), as shown in Fig. 2.

B. Site Visits

To collect quantitative data and assess aeration conditions, more than 20 site visits were made to all 15 operational SBR plants, along with over 10 visits to relevant governmental directorates. During institutional visits, official records were collected detailing plant locations, population served, and wastewater generation rates. In addition, structured questionnaires were distributed to plant personnel during site inspections to collect the data required for modeling (Table I).

The primary objective of these visits was to obtain detailed structural and operational data to ensure accurate modeling. In addition, wastewater samples were collected to assess aeration performance and create an influent profile for modeling.

C. Methods of Analysis

A total of 45 grab samples were obtained from the functional plants in three sets: The first set comprised 15 samples from the influent, the second set from the biological reactor, and the final set from the effluent. The samples were collected in the morning to represent typical maximum domestic wastewater flow and organic loading conditions and to ensure consistency by minimizing diurnal variability across sampling events. Sampling was done from mid-March to April 2025, during which the average ambient temperature was 20°C during this period. The collected samples were subsequently stored in a 4°C container and examined at the Duhok Environment Directorate.

Sampling was conducted between mid-March and April to represent stable and moderate operating conditions, avoiding seasonal extremes. This allowed for a consistent and comparable influent profile, which was convenient for the study's objectives since the present study focuses on comparative aeration optimization under representative conditions. However, seasonal variations represent a limitation of the present study. Accordingly, future research should investigate the impact of seasonal variability on aeration optimization.

The samples were subjected to physical and chemical analytical tests; the types of tests performed for each type of sample are listed below:

Influent and effluent samples: TSS, total nitrogen (TN), total phosphorus (TP), pH, COD, and BOD.

Biological reactor samples: Dissolved oxygen (DO), volatile suspended solids (VSS), and TSS.

Wastewater samples were analyzed for BOD_5 (5210 B), TSS (2540 D), and VSS (2540 E) following Standard Methods for the Examination of Water and Wastewater (Rice, 2012). COD (2420711), (TN, 535550), and (TP, 2420700) were measured using Lovibond reagent kits according to procedures described in the Lovibond Manual of Methods (Lovibond® Water Testing and Tintometer® Group 2019). The details of measuring instruments and analytical methods are in Supplementary Table (ST I), while pictures of some of the used devices and collected samples are presented in Fig. 3.

D. BioWin Modeling

For this work, BioWin 6.0 (EnviroSim Associates Ltd., Canada) was used to simulate the performance of all the operative SBR plants in the city. Since BioWin was developed to simulate domestic wastewater (Weiss, 2016), default kinetic and stoichiometric parameters were used in this study, similar to (Johannessen, Samstag and Stensel, 2005, Brown, Vaccari and Vaccari David 2023). Full kinetic calibration was not performed because the objective of this study was to evaluate the relative impact of aeration time optimization on energy consumption and effluent compliance within a city scale, rather than to obtain plant-specific kinetic parameters, and because such calibration is

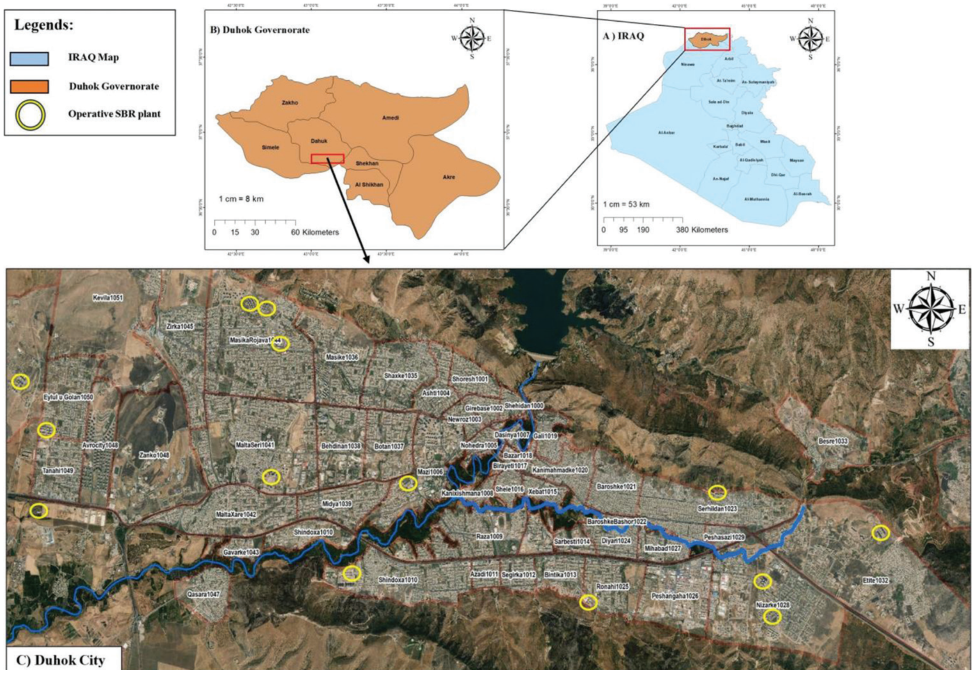

Fig. 1. Study area with locations of functional sequencing batch reactor plants.

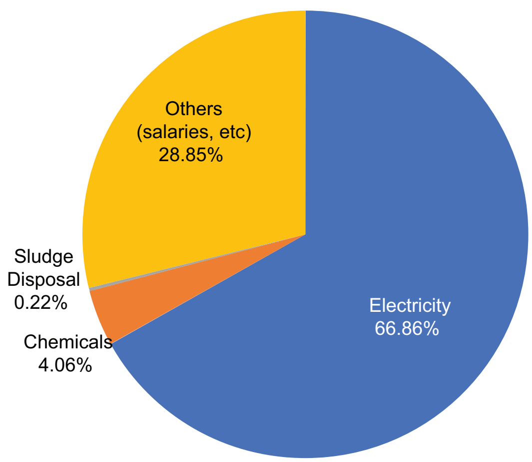

Fig. 2. Percentages of operational cost of Duhok City functional wastewater treatment plants.

TABLE I
Summary of Questionnaire Structure

Category	Information collected
Plant characteristics	Design capacity, total operation time
EQ basin	Dimensions, aeration time
SBR operation	Dimensions, number, and duration of cycles; fill, aeration, settling, and decant times. Plus, aeration schedule and feed layer elevation
Sludge management	SBR underflow rate (Sludge wasting), minimum decant level
Hydraulic operation	SBR fill volume per cycle
Energy and power	Rated power (kW) of all electrical equipment – including EQ and SBR blowers, lift and discharge pumps, chlorine dosing pumps, sludge pumps, and automatic screens. Plus, equipment operating hours per cycle and per day
Economic data	OPEX

SBR: Sequencing batch reactors, OPEX: Operational expenses, EQ: Equalization

typically conducted for individual plants using long-term datasets; however, these records were not available at the plant sites, from local relevant directorates, or in published studies. Consequently, default BioWin kinetic parameters were used, which represents a limitation of the study. For statistical analysis of BioWin results, the RStudio program version 2025.05.1 + 513 was used.

15 SBR models were developed, most representing a configuration of screens, a pre-settlement tank, an EQ basin, and a bioreactor. Fig. 4 shows a sample of the models created. For each model, influent characteristics (ST III) and parameters of each plant unit (volume, depth, underflow, and operational parameters) were defined. Bioreactor settings included SBR phase durations, DO concentration, decant and feed layers, with temperature fixed at 20°C and blower efficiency at 75%.

Numerous dynamic simulations were conducted, with two key runs highlighted to avoid redundancy. Each ran for half a month under identical initial conditions to evaluate the reduced aeration effects. The first run removed EQ basin aeration; in-between runs reduced bioreactor aeration by 0.5-h and subsequently 0.1h, leading to the optimized time in the final run. Effluent COD, BOD, TSS, TP, and TN were monitored. Given that Duhok WWTPs prioritize organic matter removal (Duhok Sewerage, 2024) and no TP or TN standards exist in Iraq; COD, BOD, and TSS results were used to evaluate the effectiveness of simulated aeration times.

Iraqi effluent limits for COD = 100 mg/L, BOD = 40 mg/L, and TSS = 60 mg/L as specified in the Iraqi Environmental Standards, Contract No.: W3QR-50-M074, Rev. No.: 03 Oct 2011 (Ismael and Aziz, 2024). However, EPA in general recommends a minimum operational safety margin of approximately 10% below regulatory limits as a risk-management measure to account for process variability and

http://dx.doi.org/10.14500/aro.12487

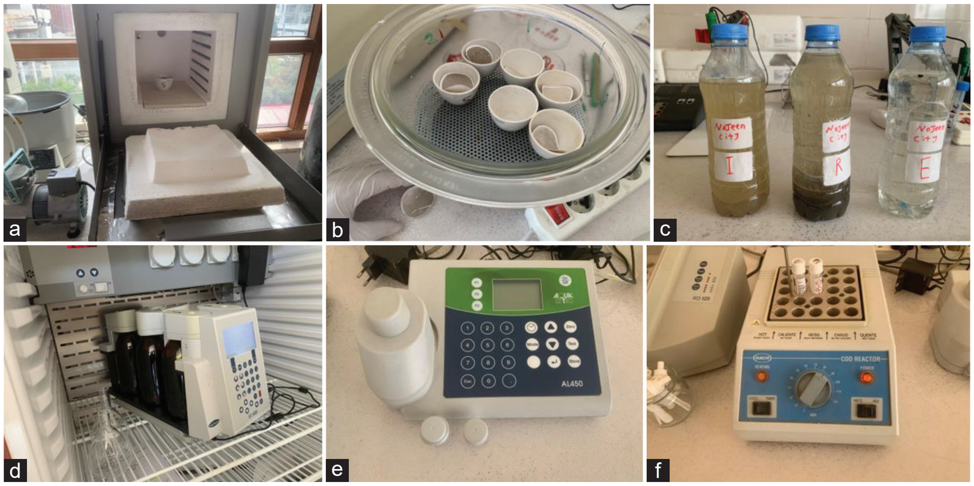

Fig. 3. Wastewater samples and laboratory instruments used in this study. (a) Collected samples, (b) Desiccator, (c) volatile suspended solids furnace, (d) chemical oxygen demand digester, (e) Multi-test Photometer, (f) biochemical oxygen demand respirometric system.

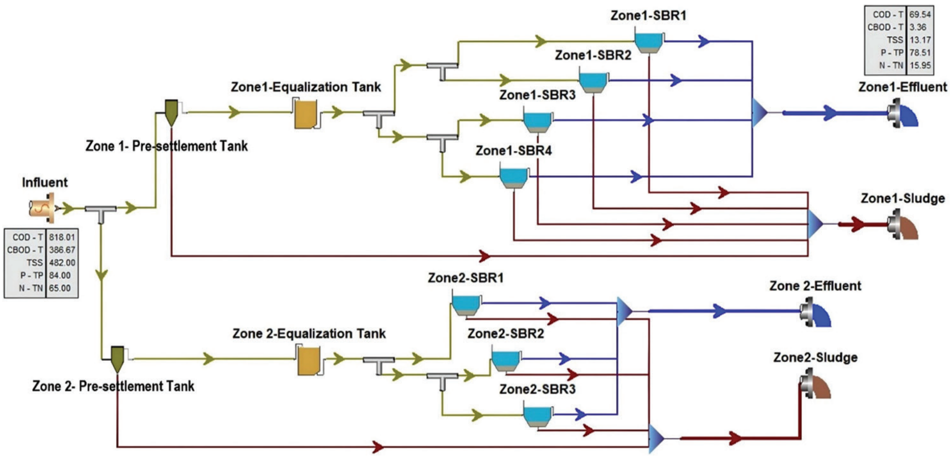

Fig. 4. Schematic Layout of wastewater treatment plants in Roj City/Duhok.

operational uncertainty (EPA, 2004). This study would have targeted 85–90% of the limits, but an additional operational safety margin was applied to account for influent variability and standard deviations, particularly because nine of Duhok's functional SBR plants receive both backwater and greywater, increasing influent heterogeneity. Thus, this study targeted the following limits: the required COD range = 80–90 mg/L, BOD range = 20–30 mg/L, and TSS range = 40–50 mg/L.

E. Aeration Cost and CO_2 Gas Emission Calculations

The annual aeration cost is calculated by multiplying the total daily aeration energy demand (kWh/day) by the commercial electricity tariff rate of 156 (IQD/kWh) and then by 365 days to obtain the annual cost.

Carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter are emitted from operating fossil fuel generators; however, among greenhouse gases (GHG), the primary source of human-induced emissions is the release of CO_2 resulting from the combustion of fossil fuels (Briggs et al., 2023). Moreover, CO_2 is the most abundantly emitted GHG from municipal WWTPs (Chen et al., 2013) and can be more directly estimated using energy-based calculations; thus, this study focused primarily on CO_2 emissions. Given that the air blower itself does not produce any gas emissions, rather, the generator used by the residential complex produces gas emissions; thus, indirect CO_2 emissions can be calculated using energy consumption and the associated emission factor. (Abed, Wahab and Salman, 2024) indicated that the CO_2 emission factor in Iraq ranges from 0.6 to 0.7 kg/kWh and is considered 0.7 kg/kWh; furthermore, the study presented the following equation, which is adopted for this work:

$$CO_2\ (\text{kg/year}) = \text{Energy (kWh/year)} \times 0.7\ (CO_2\ \text{Factor in kg/kWh}) \qquad (1)$$

III. Results and discussion

Fig. 5 shows the comparison results of aeration energy usage and costs for all functional SBR plants in Duhok, with additional details in ST II.

Nine of the fifteen plants use the EQ basin for supplementary aeration to reduce the organic load on the

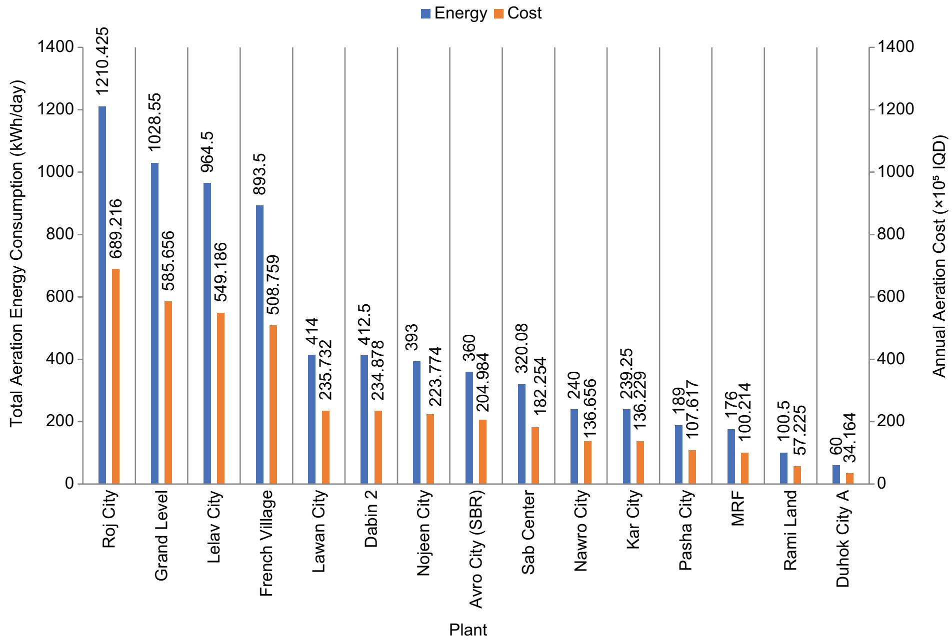

Fig. 5. Aeration energy consumption and annual aeration costs in Duhok city sequencing batch reactor plants.

bioreactor, while the remainder rely solely on bioreactor aeration despite having EQ basins.

EQ blower energy use is highest in Lelav City due to using three 7.5-kW blowers in alternation for 24-h a day, while its lowest is in Sab Center, where a single 4-kW blower is used for 23.77 h daily. Aeration accounts for a substantial share of total OPEX (more than 50% in 11 plants), with the highest proportion observed in Roj City due to high influent (7,460 m^3/day), which necessitates the use of the highest-capacity blower in the city (9.2-kW).

Annually, a total of 398,654,307 IQD are spent to aerate functional SBRs in Duhok city, which is about 52.08% of total OPEX. Moreover, this process results in the emission of 1,788,833 kg of CO_2 annually according to the Iraqi CO_2 emission factor; however, according to the Turkish emission factor of 0.44 (Altin and Yildiz, 2025), 1,124,410 kg of CO_2 will be generated, and according to the Iranian factor of 0.658 (Nabi Bid Hendi, Daryabeigi Zand and Rabiee Abyaneh 2021), 1,681,503 kg of CO_2 will be generated annually. Thus, optimizing aeration time will have a huge positive effect on energy usage, OPEX, and CO_2 emissions to the environment.

In terms of wastewater influent results, all 15 decentralized SBR plants that were operational at the time of the study were included, while the remaining plants were non-functional and could not be sampled. The collected samples are considered representative of Duhok City, as the vast majority of the city's SBR systems were constructed by the same engineering entities and fall into two main design types – onsite-built systems and standardized package plants. This design consistency allows the sampled plants to reflect typical city-wide operational conditions. Moreover, the sampled plants are spatially distributed across the city, further enhancing representativeness. The influent profile of the wastewater entering Duhok city SBRs, which is used for all the runs, is presented in Fig. 6, while more details on the influent profile are presented in ST III.

Overall, the influent profile shows stratification based on wastewater type, as most plants receiving black wastewater (Roj City, Lelav City, Duhok City A, and Nojeen City), with the exception of Grand Level and Lawan City, generally exhibit higher COD, BOD, and TSS concentrations due to stronger organic loading, while nutrient levels remain relatively similar across plants.

In regards to model calibration, only a few adjustments were made in the following COD fractions:

F_{bs}: Fraction of total influent COD which is readily biodegradable

F_{xsp}: Fraction of slowly biodegradable influent COD which is particulate

F_{us}: Fraction of total influent COD which is soluble unbiodegradable

In the influent profile, measured influent BOD values from laboratory analyses were directly input into BioWin, while influent COD was calculated internally by the model. An iterative adjustment of the selected COD fractions was performed to achieve agreement between the model-calculated influent COD and the laboratory-measured COD (i.e., maintaining the COD/BOD ratio the same as the laboratory results). All remaining influent fractions, as well as kinetic and stoichiometric parameters, were kept at default values.

While a formal sensitivity analysis of all model parameters was not done, the impact of aeration time (the key operational control variable) on performance indicators (COD, BOD, TSS, TP, and TN) was examined by varying the aeration time in discrete increments. This parametric exploration showed consistent and stable model behavior within the tested range, supporting the robustness of the optimization results.

http://dx.doi.org/10.14500/aro.12487

A. Dynamic Simulation of Duhok SBRs with no EQ Basin Aeration (First Run)

Table II presents dynamic simulation results of Duhok city SBRs with 0 EQ aeration and original bioreactor aeration time.

Simulation results from the first run indicate that, under proper operational conditions, none of the plants require additional aeration in the EQ basin to meet Iraqi effluent standards, which is somewhat expected since typical aeration time for domestic wastewater is 2-h (Tchobanoglous et al., 2014). Moreover, Avro City – the city's most consistent and one of the best-performing plants – operates successfully without aeration in the EQ basin. The results also show that only Nojeen City and Lelav City reached the target range and cannot bear further optimization due to their high COD influent. All other plants can be further optimized.

In reality, Lelav City achieved excellent effluent results (COD = 2.90 mg/L, BOD = 1.24 mg/L), and Nojeen

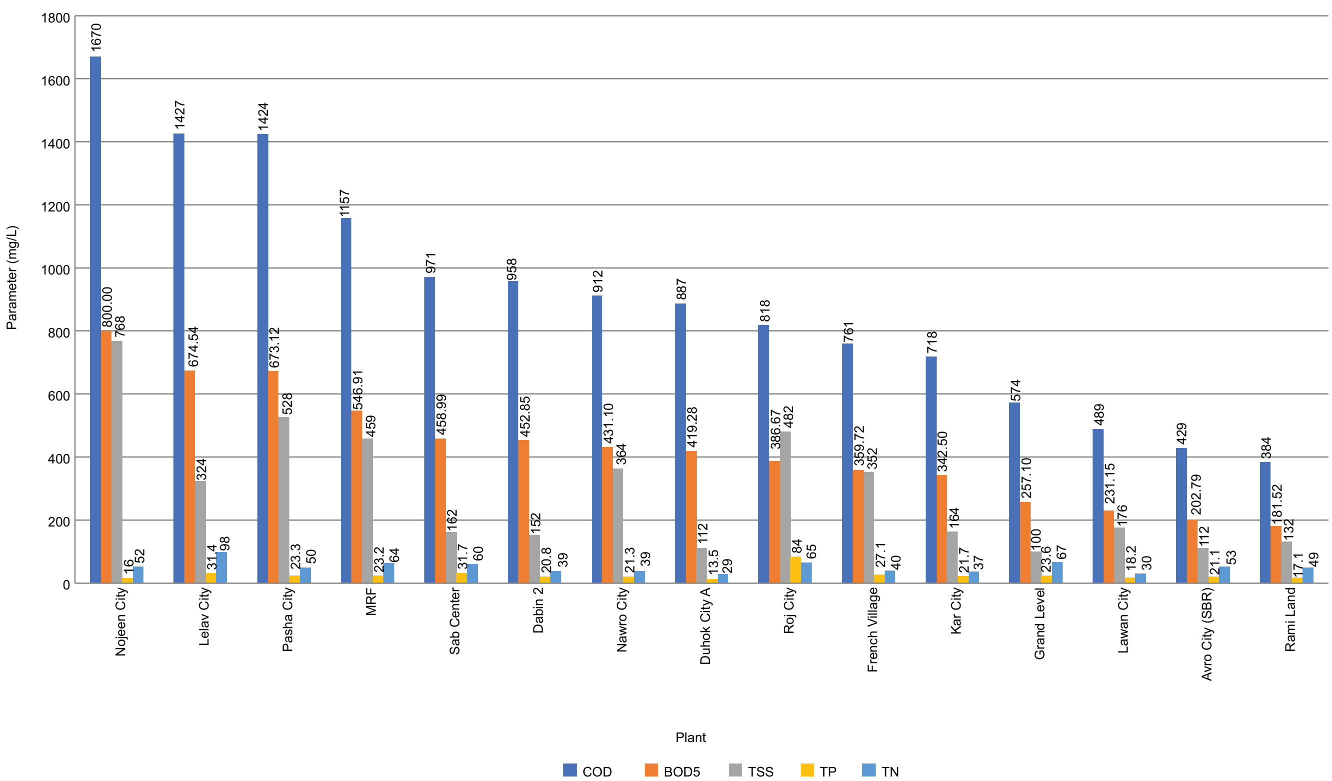

Fig. 6. Influent characteristics of sequencing batch reactor plants in Duhok City.

TABLE II
Dynamic Simulation Effluent Results of Duhok Sbrs Without EQ Basin Aeration (first run)

Plant	Reactor aeration time (h)	COD mean±standard deviation (mg/L)	BOD mean±standard deviation (mg/L)	TSS mean±standard deviation (mg/L)	TP mean±standard deviation (mg/L)	TN mean±standard deviation (mg/L)
Nojeen City	4	88.79±0.70	1.02±0.06	3.22±0.35	3.05±1.09	2.03±0.09
Lawan City	5	48.49±0.93	2.86±0.29	11.00±1.82	13.17±0.96	7.55±1.14
Roj City	5	69.80±1.27	3.80±0.47	13.95±2.10	77.64±5.31	16.92±2.58
Lelav City	2.45	87.17±1.13	0.79±0.14	1.91±0.61	18.92±6.73	9.91±3.25
Duhok City A	4	74.73±0.49	1.30±0.09	3.99±0.40	7.92±0.14	2.35±0.05
Rami Land	4	34.35±0.67	0.99±0.09	2.79±0.42	16.12±1.04	28.65±1.39
Nawro City	4	64.10±5.41	6.12±1.88	21.33±6.93	12.58±0.30	2.82±0.21
Sab Center	5	75.36±0.60	0.80±0.06	2.45±0.18	28.78±0.67	8.38±0.28
MRF	4	76.96±0.96	1.40±0.12	4.24±0.78	14.21±1.89	11.63±3.15
Kar City	4	71.72±3.94	4.74±1.35	13.71±4.34	15.20±2.17	4.78±1.23
Grand Level	5	51.00±0.56	0.81±0.05	5.09±0.55	21.17±0.02	26.21±0.34
Dabin 2	4	74.28±0.69	1.34±0.12	4.61±0.89	17.75±0.21	5.58±0.61
Pasha City	3	79.58±0.18	0.71±0.007	1.80±0.10	2.33±0.59	2.26±0.04
French Village	5	67.61±3.32	2.89±1.05	12.63±5.80	18.11±1.98	7.82±1.12
Avro City (SBR)	4	36.80±0.40	0.66±0.04	1.77±0.01	20.41±0.44	28.86±0.03

SBR: Sequencing batch reactors, COD: Chemical oxygen demand, BOD: Biochemical oxygen demand, TSS: Total suspended solids, TP: Total phosphorus, EQ: Equalization, MRF: Magnetorheological fluid

City also showed good results (COD = 54.80 mg/L, BOD = 23.39 mg/L), likely due to extra aeration in their EQ basins, with Lelav City consuming the highest energy in the EQ basin for this purpose. However, simulation results indicate that such additional aeration is not necessary to meet Iraqi limits. Dabin 2 achieved a COD of 82 mg/L, which is relatively close to the model prediction, while Avro City also remained within Iraqi limits. All remaining plant results, in reality, were way beyond Iraqi limits and far from model predictions, which suggests O&M failure in these plants.

In this study, only partial validation was feasible, as the model represents proper operational conditions, which were met by four plants only, which achieved effluent COD below 100 mg/L and showed reasonable agreement with the simulated results, as explained above. Given the strong engineering and process similarity among all plants, this level of partial validation was considered sufficient for the objectives of this study; however, a complete field validation is recommended for future research.

The BioWin model in this study simulates ideal, steady-state operation under proper process control; therefore, it does not capture transient operational failures, equipment malfunctions, or human errors. As a result, differences between simulated and actual effluent performance may arise from both inherent model assumptions and operational deficiencies at certain plants, which explain differences observed between simulation results and the plants that failed to meet Iraqi effluent limits.

Comparing the influent profile with the first run, the removal percentage of each pollutant was calculated. On average, considering all the plants, COD removal = 92.10%, BOD = 99.44%, TSS = 96.92%, TP = 31.32%, and TN = 78.93%. These results confirm that Duhok City SBR plants are designed and configured to prioritize biodegradable material removal over nutrients, particularly TP.

B. Dynamic Simulation of Duhok SBRs with Optimized Aeration Time (Final Run)

Keeping the same plant configuration, initial conditions, operational parameters, and only reducing the aeration time by 0.5-h steps and subsequently by 0.1-h reductions, numerous runs were generated. To avoid redundancy, only the final (optimized) run is presented in Table III.

Considering the means and comparing the final run to the first run (excluding the plants optimized in the first run), all plants showed the expected increases in COD (0.81–35.03 mg/L), BOD (0.06–8.63 mg/L), and TSS (0.09–45.2 mg/L), except Pasha City, where TSS remained unchanged.

In contrast, nutrient results showed improvements, as all the plants had a decrease in TP results (0.64–7.3 mg/L) and TN (0.05–21.88 mg/L), except Pasha City, Nawro City, and Lawan City showed a slight off-trend behavior, suggesting that aeration time reduction for these plants exceeded the optimal point for nutrient removal, as in-between runs confirmed the expected on-trend response for these plants.

Overall, these results confirm that not only can the aeration time be minimized, thus reducing a significant amount of energy consumption but also the optimized aeration time has a positive effect on TP and TN removal.

Reducing the aeration time can prolong the anoxic and anaerobic phases within the SBR cycle; this shift promotes simultaneous nitrification–denitrification by allowing nitrification during aerobic periods while enabling denitrification during subsequent low-DO intervals, where nitrate and nitrite are reduced to N_2 gas using internally stored carbon. At the same time, the extended anaerobic/anoxic exposure favors the activity of phosphorus-accumulating organisms (PAOs) and denitrifying PAOs (DPAOs), enhancing intracellular carbon (PHA) storage and enabling phosphorus uptake by DPAOs under both aerobic and anoxic conditions, while PAOs uptake phosphorus during aerobic periods (Izadi, Izadi and Eldyasti 2021). This improvement

TABLE III
Dynamic Simulation Effluent Results of Duhok SBRs with Optimized Aeration Time (Final Run)

Plant	Reactor aeration time (h)	COD mean±standard deviation (mg/L)	BOD mean±standard deviation (mg/L)	TSS mean±standard deviation (mg/L)	TP mean±standard deviation (mg/L)	TN mean±standard deviation (mg/L)
Nojeen City	4	88.79±0.70	1.02±0.06	3.22±0.35	3.05±1.09	2.03±0.09
Lawan City	1.9	80.27±0.02	11.49±0.01	44.75±0.04	9.33±0.03	14.01±0.06
Roj City	2.4	81.75±7.37	7.09±2.29	22.93±6.82	72.51±4.50	6.91±2.33
Lelav City	2.45	87.17±1.13	0.79±0.14	1.91±0.61	18.92±6.73	9.91±3.25
Duhok City A	2	80.17±2.40	2.03±0.51	4.97±1.75	5.22±0.38	2.30±0.15
Rami Land	1.9	64.23±0.28	6.76±0.05	46.86±0.43	14.85±0.005	12.82±0.01
Nawro City	2.25	80.63±9.98	11.76±3.89	33.42±11.03	9.78±0.92	4.07±1.45
Sab Center	2.2	81.52±0.32	0.88±0.07	2.54±0.20	23.11±0.26	3.03±0.01
MRF	2	81.17±0.88	1.89±0.36	4.86±0.89	6.91±2.40	4.30±1.37
Kar City	2.5	80.60±9.88	7.15±3.51	18.91±9.60	12.61±1.58	3.39±1.21
Grand Level	1.95	82.00±1.96	4.49±0.20	33.41±1.83	20.71±0.04	7.17±0.05
Dabin 2	2.3	80.91±4.17	2.12±0.93	6.39±3.88	13.57±0.70	2.40±0.26
Pasha City	2.5	80.39±0.33	0.77±0.01	1.80±0.10	3.68±0.41	2.26±0.06
French Village	2.1	80.02±9.11	5.88±2.92	22.14±11.87	12.46±3.06	3.20±1.13
Avro City (SBR)	1.9	71.83±3.89	4.51±0.45	46.97±1.76	19.77±0.04	6.98±0.16

SBR: Sequencing batch reactors, COD: Chemical oxygen demand, BOD: Biochemical oxygen demand, TSS: Total suspended solids, TP: Total phosphorus, EQ: Equalization, MRF: Magnetorheological fluid

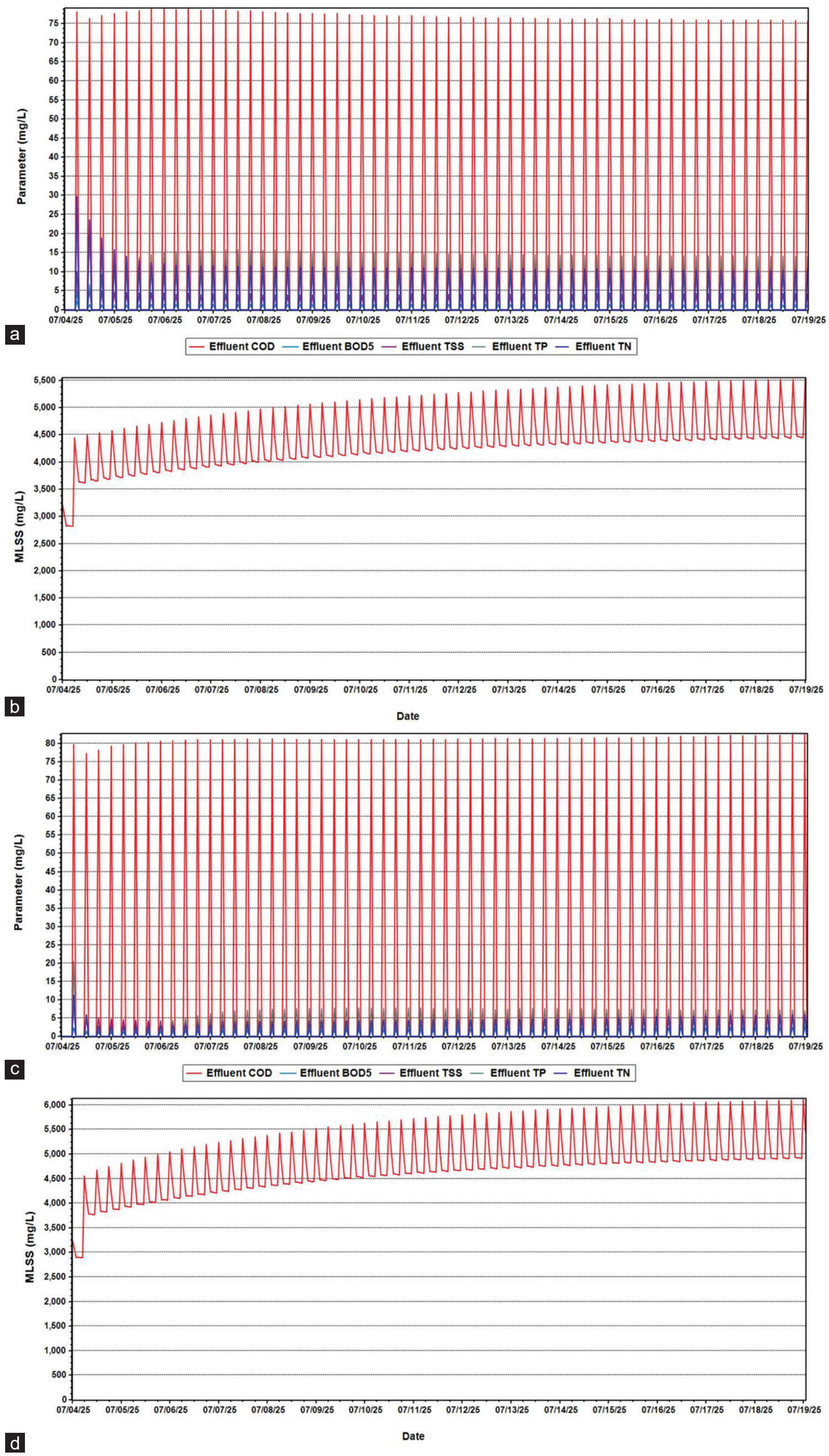

Fig. 7. Dynamic simulation results of the magnetorheological fluid sequencing batch reactors plant obtained using BioWin. (a) Effluent results with 4-h aeration (first run), (b) mixed liquor suspended solids (MLSS) with 4-h aeration, (c) Effluent results with 2-h aeration (final run), (d) MLSS with 2-h aeration.

in nutrient removal under increased anaerobic conditions resembles the findings of (Insel *et al*., 2006, Li *et al*., 2013).

The feasibility of reducing aeration while maintaining high organic removal has been demonstrated experimentally; for example, (Shi *et al*., 2013) reported that laboratory-scale SBRs maintained >92% dissolved organic carbon (DOC) removal even under reduced aeration, with no significant adverse effects.

The change in COD, BOD, and TSS removal with aeration time reduction is due to the accumulation of biodegradable material; this can be observed directly in BioWin. Following, Fig. 7 is a sample of the runs conducted in this study.

Fig. 7 (B&D) shows that although both first and final runs start with the same mixed liquor suspended solids (MLSS) of 3250 mg/L and the same sludge wasting rate, in the first run, the value of MLSS stabilizes to 5500 mg/L, while in the final run, due to the 2-h aeration reduction, it stabilizes to 6100 mg/L. The MLSS increase in the final run is due to organic matter accumulation over time, as in each cycle, biomass will have less time to degrade the organic matter, resulting in increased COD, BOD, and TSS in the effluent.

Considering new optimized aeration time values, we can recalculate energy use, CO_2 emissions, and costs then compare the new values with Fig. 5 to see the significance of the optimized aeration. The optimization results are presented in Fig. 8, while more optimization details are presented in ST IV.

The optimized aeration time resulted in reductions in energy consumption, CO_2 emissions, and annual aeration costs ranging from 38.93% (Nojeen City) to 69.07% (Sab center), with an average 56.78% among all the plants. In total, considering all the plants, the optimized aeration time reduces energy usage by 4110 kWh/day, CO_2 emissions by 1,050,221 kg/year, which is 58.70% lower than original emissions according to the Iraqi emission factor, while CO_2 reductions = 660,139 kg/year using the Turkish factor and = 987,208 kg/year using the Iranian factor. Moreover, the optimized aeration time can save costs by 234,049,308 IQD/year across Duhok City Operational SBRs.

Looking at similar works in the literature, (Kim *et al*., 2001) reported an optimized SBR system with an average aeration cycle of 2.8 h. Achieved excellent removal of phosphorus (93%), COD (90%), and ammonia (98%), though effluent nitrate remained relatively high. (Arbabi *et al*., 2012) proposed an optimized SBR cycle time intervals for enhanced biological phosphorus and nitrogen removal, with two aerobic phases, totaling 3.6 h. (Shi *et al*., 2013) demonstrated in a 1-month lab-scale SBR experiment that DOC removal remained higher than 95% with 50% and 70% reductions of the original 4-h aeration cycle. (Ozturk *et al.*, 2016) demonstrated that aeration could be reduced by 60% through a model optimization of a full-scale activated sludge plant. (Muloiwa *et al.,* 2022) reported a 38.4% reduction in energy consumption after optimizing aeration time in an activated sludge system. These results are somewhat similar to our findings and prove that significant reductions in aeration time can be achieved in SBRs and activated sludge systems while maintaining effective treatment performance.

The present study is subject to the limitation of lacking a direct comparison with modern wastewater treatment technologies; however, the gained results might differ from technologies such as Membrane Bioreactor (MBR), membrane aerated bioreactor (MABR), and Movable Bed Bioreactor (MBBR) due to operational characteristics in these systems. For example, the optimized aeration time for

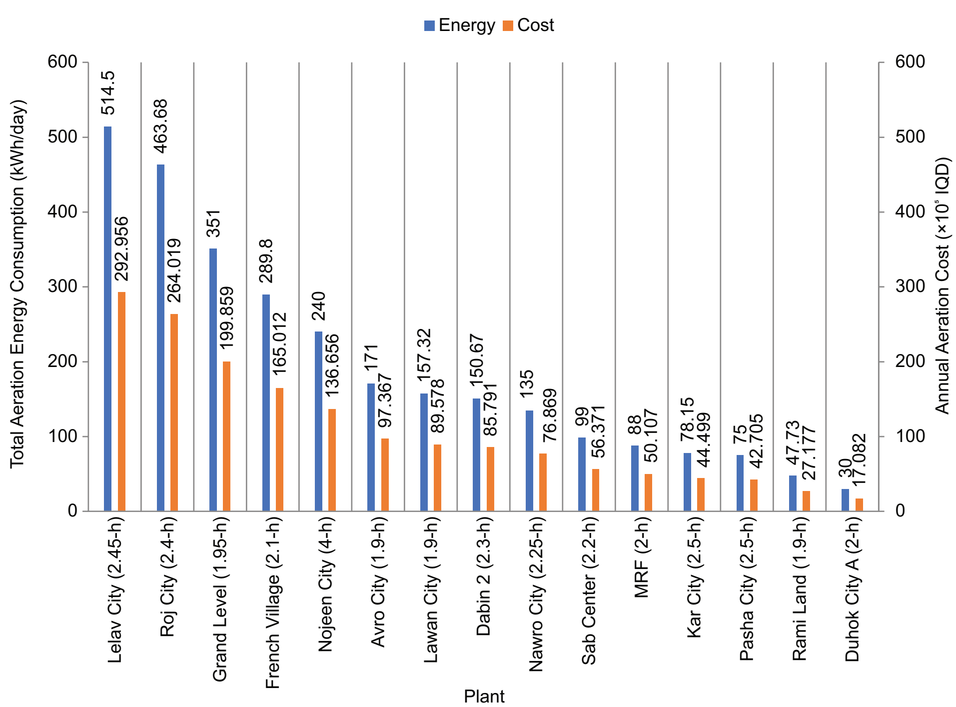

Fig. 8. Optimized aeration results for Duhok city functional sequencing batch reactor plants.

MBR will most probably be more, since it will be used for biotreatment, floc agitation, and membrane scouring, while, MABR will probably require less aeration time, since it has 100% oxygen transfer efficiency, resulting in less pressure on blowers and reducing energy consumption (Rahimi et al., 2011, Li et al., 2023). As for MBBR, the aeration time might be slightly more, as it will be used for biotreatment and biofilm mixing.

This research's findings highlight the importance of using optimized aeration time for decentralized SBR plants in Duhok, which will result in more than 50% reductions in OPEX and CO_2 emissions. The optimized aeration can also have a positive effect on nutrient removal. Plus, plant engineers can use the extra time gained from optimization to increase settling time or reduce cycle time, thus treating a greater quantity of wastewater per day, or have more plant shutdowns for applying preventive maintenance. Moreover, the saved costs can be used as an extra resource to enhance the plant's performance.

Although reduced aeration time is effective under stable conditions, real-world operation may be affected by shock loads and seasonal variability, which can temporarily increase oxygen demand. Therefore, flexible aeration control and routine monitoring are required to ensure consistent performance.

IV. Conclusion

This study presents the first successful application of BioWin as a tool for optimizing the aeration time of decentralized SBR plants treating domestic wastewater. A city-wide assessment of all functional SBR plants was conducted using empirical operational, laboratory, and field data rather than design assumptions. The simulation results indicate that the SBR systems in Duhok City are over-aerated and that aeration time can be reduced while maintaining compliance with Iraqi discharge standards. These findings have important implications for sustainable wastewater treatment, as optimized aeration reduces energy demand, operational costs, and associated CO_2 emissions, and the proposed approach is transferable to similar decentralized SBR plants operating under comparable conditions. The study is subject to limitations, including the use of default BioWin kinetic parameters and the exclusion of long-term operational variability. Future work should include complete field validation and investigate the impact of seasonal variability on aeration optimization.

References

Abed, A., Wahab, B., and Salman, A., 2024. Estimating the carbon footprint of civil electrical diesel generators in Baghdad City. *The Iraqi Geological Journal*, 57, pp.138-148.

Altin, S., and Yildiz, A., 2025. A study on CO_2 emissions of a small-scale port. *Journal of Agroforestry and Environment*, 18, pp.24-32.

Arbabi, M., Akbarzadeh, A., and Khodabakhshi, A., 2012. Optimization of SBR system for enhanced biological phosphorus and nitrogen removal. *International Journal of Environmental Health Engineering*, 1, p.49.

Barnard, J., 2001. Design and operational considerations for the largest SBR plant. *Proceedings of the Water Environment Federation,* 2001, pp.346-361.

Bianco, F., Giuliani, A., Martucci, I., Pucci, L., and Race, M., 2024. Comparing continuous and intermittent aeration using BioWin™ model simulation in a full-scale wastewater treatment plant. *Journal of Water Process Engineering,* 68, p.106530.

Bournazou, M.N.C., Hooshiar, K., Arellano-Garcia, H., Wozny, G., and Lyberatos, G., 2013. Model based optimization of the intermittent aeration profile for SBRs under partial nitrification. *Water Research,* 47, pp.3399-3410.

Briggs, C., Gilfillan, D., Hefner, M., Marland, E., and Marland, G., 2023. Annual estimates of global and national CO_2 emissions from fossil fuels: Tracking revisions to the United Nations energy statistics database input energy data. *Environmental Data Science*, 2, p.e40.

Brown, J., Vaccari, C., and Vaccari David, A., 2023. Numerical optimization of wastewater treatment plant design for a high-nitrate industrial waste. *Journal of Environmental Engineering*, 149, p.04023087.

Chen, Z.M., Xie, W., and Zhang, H.Y., 2013. Study status and focus about CO_2 from municipal wastewater treatment. *Advanced Materials Research*, 610-613, pp.1556-1559.

Cheng, H.H., Huang, P.W., and Whang, L.M., 2024. Optimization of biological nitrogen removal in full-scale municipal WWTPs using activated sludge model simulation. *Chemosphere*, 362, p.142939.

Duhok Sewerage, 2024. KRI. Investment Residential Projects Information. In: *Planning*. Duhok Sewerage Directorate, Duhok.

EPA, 2004. *Local Limits Development Guidance (EPA 833-R-04-002A)*. United States Environmental Protection Agency, Office of Wastewater Management 4203. Available from: https://www.epa.gov/sites/default/files/2015-10/documents/final_local_limits_guidance.pdf [Last accessed on 2025 Jul 17].

Insel, G., Sin, G., Lee, D., Nopens, I., and Vanrolleghem, P., 2006. A calibration methodology and model-based systems analysis for SBRs removing nutrients under limited aeration conditions. *Journal of Chemical Technology and Biotechnology*, 81, pp.679-687.

Ismael, S., and Aziz, S.Q., 2024. Solar energy application for erbil municipal wastewater treatment and reusing. *Journal of Civil Engineering Researchers*, 6, pp.49-59.

Izadi, P., Izadi, P., and Eldyasti, A., 2021. Enhancement of simultaneous nitrogen and phosphorus removal using intermittent aeration mechanism. *Journal of Environmental Sciences*, 109, pp.1-14.

Johannessen, E., Samstag, R., and Stensel, H.D., 2005. Effect of process configurations and alum addition on EBPR in membrane bioreactors. *Proceedings of the Water Environment Federation*, 2005, pp.5144-5166.

Kim, H., Hao, O.J., and Mcavoy, T.J., 2001. SBR system for phosphorus removal: Linear model based optimization. *Journal of Environmental Engineering*, 127, pp.105-111.

Kochary, S., Byl, T., and Noori, B., 2017. Modeling the movement of septic water chloride through a soil profile. *Sustainability*, 9, p.501.

Li, J., Tao, T., Li, X.B., Wang, L.M., and Zheng, H., 2013. Effect of anaerobic time on biological nitrogen removal in a modified SBR. *Desalination and Water Treatment*, 51, pp.3691-3699.

Li, X., Bao, D., Zhang, Y., Xu, W., Zhang, C., Yang, H., Ru, Q., Wang, Y.F., Ma, H., Zhu, E., Dong, L., Li, L., Li, X., Qiu, X., Tian, J., and Zheng, X., 2023. Development and application of membrane aerated biofilm reactor (MABR)-a review. *Water*, 15(3), p.436.

Lovibond® Water Testing, Tintometer® Group, 2019. *Manual of Methods: Analytical procedures for Analysis of Water and Wastewater*. Lovibond® Water Testing, Germany.

Muloiwa, M., Dinka, M., and Nyende-Byakika, S., 2022. Modelling and optimization of energy consumption in the activated sludge biological aeration unit. *Water Practice and Technology*, 18, pp.140-158.

Nabi Bid Hendi, G., Daryabeigi Zand, A., and Rabiee Abyaneh, M., 2021. Assessing the life-cycle greenhouse gas (GHG) emissions of renewable and fossil fuel energy sources in Iran. *Environmental Energy and Economic Research*, 5, pp.1-9.

Okan, B., Erguder, T.H., and Aksoy, A., 2022. Plant-wide modeling of a metropolitan wastewater treatment plant to reduce energy consumption and carbon footprint. *Environmental Science and Pollution Research*, 30, pp.16068-16080.

Ozturk, M.C., Martin Serrat, F., and Teymour, F., 2016. Optimization of aeration profiles in the activated sludge process. *Chemical Engineering Science*, 139, pp.1-14.

Rahimi, Y., Torabian, A., Mehrdadi, N., Habibi-Rezaie, M., Pezeshk, H., and Nabi-Bidhendi, G.R., 2011. Optimizing aeration rates for minimizing membrane fouling and its effect on sludge characteristics in a moving bed membrane bioreactor. *Journal of Hazardous Materials*, 186, pp.1097-1102.

Rice, E.W., Bridgewater, L., Association, A.P.H., Association, A.W.W., and Federation, W.E., 2012. *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, Washington, DC.

Robescu, L.D., Bondrea, A.D., Radosavlevici, I., and Stoicescu, A., 2018. Comparative study on sequential batch reactor and granular sequencing batch reactor. *AIP Conference Proceedings*, 2022, p.020021.

Shi, W., Satoh, H., and Mino, T., 2013. The effect of reduction of aeration period on organic pollutants removal in sequencing batch activated sludge reactors. *Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research)*, 69, pp.III_427-III_434.

Šikić, T., Welles, L., Rubio-Rincón, F.J., Matošić, M., and Brdjanovic, D., 2019. Assessment of enhanced biological phosphorus removal implementation potential in a full-scale wastewater treatment plant in croatia. *International Journal of Environmental Research*, 13, pp.1005-1013.

Soliman, M., and Eldyasti, A., 2017. Long-term dynamic and pseudo-state modeling of complete partial nitrification process at high nitrogen loading rates in a sequential batch reactor (SBR). *Bioresource Technology,* 233, pp.382-390.

Tchobanoglous, G., Metcalf, E., Stensel, H.D., Tsuchihashi, R., Burton, F.L., Abu-Orf, M., Bowden, G., and Pfrang, W., 2014. *Wastewater Engineering: Treatment and Resource Recovery*. McGraw-Hill Education, United States.

Tyagi, R., Pandey, A., Drogui, P., Yadav, B., Pilli, S., and Wong, J., 2024. *Decentralized Sanitation and Water Treatment: Concept and Technologies*. CRC Press, United States.

Weiss, B., 2016. *Evaluating the Anaerobic Codigestion Potential of Stillage and Dairy Manure in a Tubular Digester*, Open Access Master's Report, Michigan Technological University.

 http://dx.doi.org/10.14500/aro.12487

SUPPLEMENTARY TABLE I
Physicochemical parameters and analysis methods

Parameters	Measuring instruments	Analysis method
DO (mg/L)	DO 9100	Direct measurement
pH	HI 931401	Direct measurement
BOD5 (mg/L)	Lovibond BD 600	5210 B, following Standard Methods for the Examination of Water and Wastewater, 22nd Edition, 2012.
COD (mg/L)	HACH COD Reactor	M131, as per Lovibond manual 2019.
VSS (mg/L)	According to Standard Method 2540 E.	2540 E, following Standard Methods for the Examination of Water and Wastewater, 22nd Edition, 2012.
TSS (mg/L)	According to Standard Method 2540 D.	2540 D, following Standard Methods for the Examination of Water and Wastewater, 22nd Edition, 2012.
TP (mg/L)	MultiDirect 660 nm.	M318, as per Lovibond manual 2019.
TN (mg/L)	MultiDirect 430 nm.	M280, as per Lovibond manual 2019.

SUPPLEMENTARY TABLE II
Energy Consumption, CO_2 Emissions, and Annual Aeration Costs in SBR-Based WWTPs in Duhok

No.	Plant	EQ Blower energy usage (kWh/day)	Bioreactor Blower energy usage (kWh/day)	Total aeration energy usage (kWh/day)	Annual CO_2 emissions (kg/year)	Annual Aeration Cost (IQD/year)	Annual operational cost (IQD/year)	Aeration % of total OPEX costs
1	Nojeen City	153	240	393	100,412	22,377,420	41,981,573	53.30
2	Lawan City	0	414	414	105,777	23,573,160	38,558,687	61.14
3	Roj City	244.42	966	1210.42	309,264	68,921,600	83,262,765	82.78
4	Lelav City	450	514.50	964.50	246,430	54,918,630	128,400,000	42.77
5	Duhok City A	0	60	60	15,330	3,416,400	4,868,720	70.17
6	Rami Land	0	100.50	100.50	25,678	5,722,470	21,992,780	26.02
7	Nawro City	0	240	240	61,320	13,665,600	21,698,100	62.98
8	Sab Center	95.08	225	320.08	81,780	18,225,355	26,065,348	69.92
9	MRF	0	176	176	44,968	10,021,440	25,939,629	38.63
10	Kar City	114	125.25	239.25	61,128	13,622,895	18,478,191	73.72
11	Grand Level	128.55	900	1028.55	262,795	58,565,637	100,308,558	58.39
12	Dabin 2	150	262.50	412.50	105,394	23,487,750	32,868,719	71.46
13	Pasha City	99	90	189	48,290	10,761,660	15,555,464	69.18
14	French Village	203.50	690	893.50	228,289	50,875,890	86,412,895	58.88
15	Avro City (SBR)	0	360	360	91,980	20,498,400	111,787,735	18.34

SUPPLEMENTARY TABLE III

Influent Profile used in All BioWin Simulation Runs for Duhok City SBRs, Including Wastewater Characteristics, Cycle Time, and Filling Time

Plant	Influent (m^3/day)	Cycle time (h)	Filling time (h/cycle)	COD_{tot} (mg/L)	BOD_{tot} (mg/L)	TSS (mg/L)	VSS (mg/L)	TP (mg/L)	TN (mg/L)	pH
Nojeen City	280	6	2	1670	789.41	768	460	16	52	6.65
Lawan City	465	8	2	489	231.15	176	54.56	18.2	30	7.3
Roj City	7460	8	1.5	818	386.67	482	149.42	84	65	6.5
Lelav City	1132.5	6	0.75	1427	674.54	324	149.04	31.4	98	6.7
Duhok City A	300	6	2	887	419.28	112	90.5	13.5	29	6.7
Rami Land	560	6	2	384	181.52	132	40.92	17.1	49	6.9
Nawro City	1188	6	2	912	431.10	364	112.84	21.3	39	6.65
Sab Center	306	8	2	971	458.99	162	99.1	31.7	60	6.75
MRF	288	6	2	1157	546.91	459	142.29	23.2	64	6.7
Kar City	666.25	6	1	718	339.40	164	73.5	21.7	37	6.8
Grand Level	1248	8	1.5	574	271.33	100	59	23.6	67	6.95
Dabin 2	1450	6	2	958	452.85	152	98	20.8	39	6.8
Pasha City	360	9	2	1424	673.12	528	163.68	23.3	50	7.4
French Village	850	8	2	761	359.72	352	109.12	27.1	40	8.2
Avro City (SBR)	800	6	1	429	202.79	112	44	21.1	53	6.7

SUPPLEMENTARY TABLE IV

Optimized Aeration Results and Associated Reductions in Energy Consumption, CO_2 Emissions, and OPEX for Functional SBRs in Duhok City

Plant	Optimized aeration time (h)	Total aeration energy usage (kwh/day)	Annual CO_2 emissions (kg/year)	Annual Aeration Cost (IQD/year)	% Reduction in Energy, Aeration Cost, & CO_2 Emissions	Cost savings within annual aeration expenditure (IQD/year)
Nojeen city	4	240	61,320	13,665,600	38.93	8,711,820
Lawan city	1.9	157.32	40,195	8,957,801	62.00	14,615,359
Roj city	2.4	463.68	118,470	26,401,939	61.69	42,519,660
Levav city	2.45	514.5	131,455	29,295,630	46.66	25,623,000
Duhok city A	2	30	7,665	1,708,200	50.00	1,708,200
Rami land	1.9	47.73	12,195	2,717,746	52.51	3,004,724
Nawro City	2.25	135	34,493	7,686,900	43.75	5,978,700
Sab center	2.2	99	25,295	5,637,060	69.07	12,588,295
MRF	2	88	22,484	5,010,720	50.00	5,010,720
Kar city	2.5	78.15	19,967	4,449,861	67.34	9,173,034
Grand level	1.95	351	89,681	19,985,940	65.87	38,579,697
Dabin 2	2.3	150.67	38,496	8,579,150	63.47	14,908,600
Pasha city	2.5	75	19,163	4,270,500	60.32	6,491,160
French village	2.1	289.8	74,044	16,501,212	67.57	34,374,678
Avro city (SBR)	1.9	171	43,691	9,736,740	52.50	10,761,660