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Evaluation of Treatment Efficiency in a Conventional Sewage Treatment Plant in Semi-Arid Urban Region: Physicochemical Records from Al-Muameera WWTP, Iraq

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Abstract
Wastewater treatment plants (WWTPs) are of prime importance for the protection of aquatic environments and public health, especially in semi-arid regions where water availability is scarce leading to an increased demand for eco-friendly wastewater treatment plant management and further use. The present work investigates the physicochemical efficiency of a conventional Al-Muameera wastewater treatment plant in urban Hilla City, central Iraq. A surveillance plan was carried out in 6 months (November 2024 – April 2025) with bi-monthly sampling of sewage, treated and influent, to evaluate the efficiency of treatment.
Temperature, pH, DO (dissolved oxygen), TSS (total suspended solids,), BOD_5 (biochemical oxygen demand at 5 days), COD (chemical oxygen demand) and nutrients [NH_3-N, NO_2-N, NO_3-N], total nitrogen and total phosphorus), were determined by a standard procedure as well as the concentrations of sulfates, chlorides and hydrogen sulfide. The findings indicated that influent water was rich with high organic and nutrient levels which represented the mainly domestic nature of the sewage. After treatment, there were significant decreases in TSS, BOD_5 and COD, which indicated that the organic matter that could be degraded was effectively removed by biological treatment units.
Although treatment system performance was generally improved after the process enhancements, nutrient removal (both nitrogen and phosphorus) remained incomplete due to inherent limitations in a non-enhanced secondary treatment system. The seasonal influence was observed on several parameters, among which the highest organic loads were measured during warmer seasons, highlighting the plant performance dependence on climatic and operation conditions. The results indicate that, although Al-Muameera WWTP accomplishes an efficient organic load removal, yet more improvement is necessary to improve nutrient removal and meet water reuse and environmental discharge limits. The work gives valuable baseline data to help performance optimization, as well as for sustainable wastewater management planning in semi-arid urban areas.
Keywords: Wastewater treatment plant; Physicochemical properties; Treatment performance; Nutrients removal; Semi-arid climate; Iraq

Introduction
Water resources are increasingly threatened across the globe as rising population, urbanization, climate change and water demand continues to accelerate. They are especially intense in semi-arid and arid areas where freshwater resources are scarce and rats have high

sensitivity to degradation of water quality. In this context, wastewater is not thought of as waste any longer; it is increasingly seen as a potential second water resource, if appropriately treated first to alleviate environmental and public health risks (WHO, 2020; Shemer, 2023).

City sewage is one of the main sources of pollution in surface waters, because it contains high levels of biodegradable organic matter, suspended solids, nutrients and other chemicals. The discharge of untreated or insufficiently treated municipally derived wastewater can result in oxygen consumption, eutrophication, toxicity for aquatic biota and degradation of downstream uses (Varma *et al.*, 2021; Van Vliet *et al*., 2017). Therefore, wastewater treatment plants (WWTPs) are scaffolds for reducing pollutant loads and maintaining the balance of aquatic ecosystems in order to protect public health.

Traditional waste water treatment options that predominate in many developing countries use primary settlement followed by secondary biological treatment to remove organics and suspended solids. Although these systems are effective in BOD_5 and TSS removal, nutrient removal (nitrogen and phosphorus) is generally low without advanced treatment processes (Lin *et al*, 2023; Ganji *et al*., 2024). This constraint is becoming more urgent since nutrient enrichment is a key factor for the eutrophication of freshwater systems, especially in rivers that receive effluents from urban areas after wastewater treatment.

Physicochemical parameters such as temperature, pH, dissolved oxygen (DO), organic indicators (BOD_5 and COD), nutrients, and main ions are used extensively to estimate the efficiency of WWTPs processes in addition to the environmental acceptability of treated effluent. These indices give a good direct insight into treatment efficiency, operational stability and potential effects on receiving water media (Lin *et al.*, 2023; Sangamnere et al., 2023). In addition, there are the interactions among these parameters which may indicate principal pollution sources and effectiveness of specific treatment methods.

In semiarid regions, WWTP efficiency is highly sensitive to the climate and operation conditions. High ambient temperatures can promote the biochemical activities and microbiological processes, which may benefit to organic matter degradation. Meanwhile, high temperatures and evaporation losses as well as varying hydraulic loads can destabilize the treatment processes and decrease overall operational efficiency especially in peak loading times (Jones *et al.*, 2022; Alevizos *et al.*, 2023). Even in hot climate areas, seasonality of wastewater characteristics have been well documented and confirmed, calling for site-specific performance evaluations rather than using engineered assumptions.

Iraq provides a significant case study on the nexus of water scarcity, diminished river flow and aging infrastructure. Urban wastewater treatment, in the Iraqi cities is continuously confronted with a lot of bottlenecks for insufficient treatment capacity, operational failures as well as no application of advanced nutrient removal technology. It is worth noting that it has been demonstrated in some studies (e.g., Todd, 2024, Shehab, & Alsultani, 2025) that effluents of conventional WWTPs in Iraq frequently attained organic load reduction but insufficient nutrient removal, with potential risks to the downstream ecological systems and reuse requirements. However, systematic and current assessment of WWTP performance is scarce, in particular based on thorough physicochemical examination under present day climate and operating circumstances.

The Al-Muameera WWTP is a municipal station positioned in Hilla City, central Iraq at coordinates about from the Euphrates River. This facility is designed to operate as any conventional WWTP and receive entirely domestic wastewater loads which constitutes an excellent example of typical treatment plants established within semi-arid urban zone. Due to the fact that local water resources are more and more constraint for potable use, and that wastewater reuse trends toward infection treatment, restriction irrigation or environmental discharge, it is of great interest to learn about the physicochemical performance of the plant. Comparison of influent and effluent properties gives an indication about the degree of treatment, operational constraints, and area to be optimized.

The objective of this study is thus to evaluate the physicochemical efficiency of Al-Muameera WWTP in terms influent versus effluent water quality over period of 6 months, which is intended as one phase in an ongoing research project. Through a focus on the principal physical and chemical criteria (i.e., organic matter, suspended solids, nutrients and major ions), this work aims at evaluating treatment performance while identifying limitations faced by these treatments; which will then be compared to regional as well as global wastewater management benchmarks. The outcome is aimed to inform evidence-based decision-making for optimising wastewater treatment processes and sustainable water reuse in semi-arid metropolitan areas.

Materials and Methods

2.1 Wastewater Treatment Plant and Study Area Description

The present investigation was performed in Al-Muameera WWTP which is situated at Hilla City, Babylon Province of central Iraq. The area has a semi-arid climate, with hot summer seasons and mild winter ones, that affects wastewater qualities and wastewater treatment performance. The plant has mainly residential catchment, and the influent wastewater is of domestic origin with little industrial determination.

The Al-Muameera WWTP is a traditional treatment plant with a physical and biological treatment process. Preliminary screening and sedimentation are the unit processes in primary treatment that remove coarse suspended solids, as well as settleable solids. Aerobic biological systems are used for secondary treatment to further reduce biodegradable organic matter and solids in suspension. The plant consists of no tertiary treatment or advanced nutrient removal; a common design in many municipal WWTPs located in developing and semi-arid areas.

2.2 Sampling Design and Collection

The study was conducted over 6 months from November, 2024 to April, 2025 in order to account for potential seasonally-dependent differences in wastewater composition. Wastewater was sampled bimonthly from two fixed sampling sites, the influent (before treatment) and effluent (after secondary treatment).

Samples were stored in pre-cleaned polyethylene containers. Containers were washed with sample water before collection. Upon collection all samples were stored in insulated cool boxes at about 4 °C and delivered to the laboratory for analyses immediately. Sensory and physicochemical analyses which are sensitive to especially storage time were carried out on the same day or within a short period according to the holding times.

2.3 Physicochemical Analyses

Relevant physicochemical parameters were evaluated to determine the treatment performance and effluent quality. Temperature, pH and dissolved oxygen (DO) were determined in situ by portable meters (Hach, USA). TSS were analysed spectrophotometrically as per standard method and manufacturer procedure.

Parameter determinations The characteristic parameters of organic pollution, BOD_5 and COD, were determined according to standard incubation and closed-reflux digestion methodologies. The nutrient parameters including ammonia nitrogen (NH_3-N), nitrite (NO_2-N, nitrate (NO_3-N), total nitrogen (TN) and total phosphorus(TP) were determined according to the procedures of distillation, combined-colorimetry and persulfate digestion. Common ions, such as sulfate (SO_4^{2-}), chloride (Cl^-), and hydrogen sulfide gas (H_2S) were analysed by gravimetric, titrimetric or iodometric methods when applicable.

Analysis followed international standard methods for water and wastewater examination (APHA, 2017), and quality assurance/quality control included blanks, calibration checks, replicate-measurements to guarantee data reliability.

Results

3.1 Composition of Sewage and Treated Wastewater - Physical properties

The specified physical wastewater properties before and after the Al-Muameera WWTP during the study period are given in Table 1. Influent wastewater temperatures varied between 26.2 and 30.8 °C with a mean value of 29.1 ± 1.1 °C, temporal equivalent temperatures were obtained for the effluent (26.0–30.7 °C; average = 28.8 ± 1.0 °C), due to this the treatment process had no significant effect on the temperature of the treated wastewater during the sampling period.

Influent wastewater pH was maintained in a narrow neutral range (7.16–7.51) with the mean value of 7.31 ± 0.12. Upon treatment, effluent pH values slightly decreases and varied between 7.11 and 7.44 (average value: 7.22 ±0.11). The pH value before and after the treatment was environmentally accepted.

Values of dissolved oxygen (DO) were low in the influent wastewater, between 8.17 and 10.98 mg/L (average = 9.3 ± 0.9 mg/ L). The DO concentrations significantly rose after the treatment, varying from 7.32 to 9.21 mg/L with an average of 8.6 ± 0.7 mg/L and indicating improved aerobic condition at the effluent.

Table 1. Physical properties of the influent and effluent wastewater at Al-Muameera WWTP during investigation period (mean ± SD, ranges; n = 12).

Parameter	Influent (Mean ± SD, Min–Max)	Effluent (Mean ± SD, Min–Max)
Temperature (°C)	29.1 ± 1.1 (26.2–30.8)	28.8 ± 1.0 (26.0–30.7)
pH	7.31 ± 0.12 (7.16–7.51)	7.22 ± 0.11 (7.11–7.44)
DO (mg/L)	9.3 ± 0.9 (8.17–10.98)	8.6 ± 0.7 (7.32–9.21)

Principal component analysis (PCA) The results of PCA performed on physicochemical data before/after treatment statistics standardisation were illustrated in Figure (3-1). Results of the analysis indicate that highest amount total variance was explained by the 1st principal component. This factor was strongly related to organic load and suspended solids variables (BOD_5, COD, SST, among others) as well as with some nitrogen compounds.

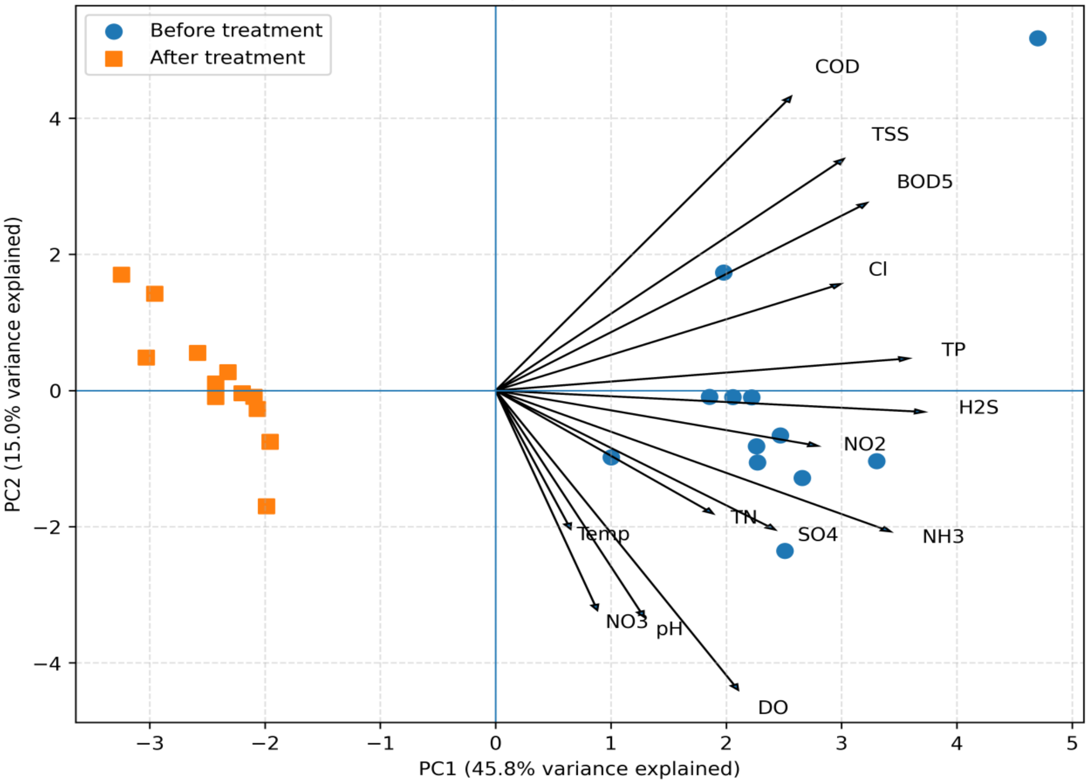

Figure (3-1): Biplot of Principal Component Analysis (PCA) showing the spread of wastewater samples, before and after treatment with respect to analyzed physicochemical variables in Al-Muameera WWTP..

On the other hand, the second principal component was correlated with nutrient and ionic parameters such as TN, TP, sulphate, chlorides as well as some physico-chemicals factors like pH and temperature.

The PCA plot of pre-treatment and post-treatment samples also showed that they were spatially separated. Pre-treatment samples showed numbers clustered on one side of the plot and post treatment on the other side. This behaviour indicates different physicochemical profile of wastewater in the two filling states and clear statistical separation of two data sets.

3.2 Chemical Characteristics of Wastewater

Influent and effluent wastewater chemical properties are shown in Table 2. The influent wastewater was rich in organic matter, nutrients, suspended solids and specific inorganic impurities with a typical domestic nature of the inflow.

Influent wastewater TSS concentrations varied between 94 and 863 mg/L with an average of 292 ± 203 mg/L while the treated effluent TSS reached values in the range of 6-23 mg/L with a mean value of 15 ±7mg/L.

Influent BOD_5 values were elevated (74-455 mg/L and average of 150 ± 110 mg/L), but after treatment the removal was substantial with effluent concentrations ranging from 10-27 mg/L (average = 17 ± 6 mg/L); COD removal also followed the similar pattern from the ranges of

137-2166 mg/L (average = 463 ± 506 mg/L) in the influent wastewater to the ranges of18-62mg/L (mean=41±15mg/L) in the effluent samples.

Nutrients were also found to decrease after treatment, although removal efficiencies differed between parameters. The NH_3-N concentrations in influent were between 14.6 and 24.3 mg/L, with an average of 19.9 ± 4.3 mg/L, and in effluent decreased to a range of 5.3–9.1 mg/L (mean = 7.6 ± 1.6 mg/L). In the effluent, total nitrogen (TN) levels dropped from an average influent level of 11.3 ± 6.7 mg/L to 4.7 ± 3.6 mg /L.

Nitrite (NO_2-N) and nitrate (NO_3-N) displayed relatively less variation after treatment. NO_2-N went down from 0.30 ± 0.20 mg/L in influent water to 0.04 ± 0.06 mg/L for effluent samples, with NO_3-N concentrations not changing significantly pre- and post treatment period.

The concentration of TP in the influent wastewater (2.3–11.6 mg/L, mean = 8.3 ± 3.1 mg/L) was decreased to 0.6–2.5 mg/L (mean = 1.7 ± 0.7 mg/L) in effluent samples.

For the major ions, (SO_4^{2-}) and (Cl^-) concentrations decreased slightly after treatment. Concentrations of hydrogen sulfide (H_2S) decreased remarkably from influent by 16.2 to 21.3 mg/L (average = 18.8 ± 2.1 mg/L) to effluent by 1.3-2.7 mg/L (average = 2.0 ± 0.6 mg/L).

Table 2. Composition of influent and effluent wastewater to Al-Muameera WWTP during the observation period (mean ± SD, min–max; n = 12).

Parameter (mg/L)	Influent (Mean ± SD, Min–Max)	Effluent (Mean ± SD, Min–Max)
TP	8.3 ± 3.1 (2.3–11.6)	1.7 ± 0.7 (0.6–2.5)
TN	11.3 ± 6.7 (4.6–22.0)	4.7 ± 3.6 (0.3–12.4)
NH_3-N	19.9 ± 4.3 (14.6–24.3)	7.6 ± 1.6 (5.3–9.1)
NO_2-N	0.30 ± 0.20 (0.013–0.567)	0.04 ± 0.06 (0.005–0.188)
NO_3-N	3.6 ± 2.4 (0.9–9.3)	3.0 ± 2.5 (0.5–7.9)
SO_4^{2-}	1053 ± 116 (879–1231)	866 ± 90 (722–990)
Cl^-	561 ± 58 (449–629)	470 ± 38 (398–492)
H_2S	18.8 ± 2.1 (16.2–21.3)	2.0 ± 0.6 (1.3–2.7)
TSS	292 ± 203 (94–863)	15 ± 7 (6–23)
COD	463 ± 506 (137–2166)	41 ± 15 (18–62)
BOD_5	150 ± 110 (74–455)	17 ± 6 (10–27)

Altogether, the results clearly evident the ameliorated wastewater quality after treatment in Al-Muameera WWTP. Suspended solids and organic pollution indicators showed great reductions, whereas nutrient removal was incomplete with some residual concentrations in the treated effluent.

Discussion

4.1 General Performance of the Treatment System in Semiarid Environment

This work represents an in-depth physicochemical characterization of a Al-Muaamery WWTP operating within semi-arid climatic conditions located in central Iraq. The findings clearly indicate that the existing treatment system is highly effective in organic matter/suspended solids removal, but relatively less efficient nutrient elimination. This reproductive performance is similar to those of many secondary effluent treatment plants in arid and semi-arid areas, where the performance of a treatment plant is highly climate dependent and the hydraulic load effect on organic removal is sensitive, lacking any advanced treatment phases.

High removal efficiencies of TSS, BOD_5, and COD show the working efficiency of sedimentation tank, biological tanks. Equivalent rates of COD removal have been previously reported for traditional WWTPs in other semi-arid regions, e.g., the Middle East and North Africa, as well as several South Asian countries where domestic wastewater is also predominant (Jones *et al.*, 2022; Alevizos *et al*., 2023). These results suggest that traditional biological treatment in developing country context, despite being restricted by operation and infrastructure, can be an effective solution for organic pollution control.

4.2 Physical Parameters and Operation Stability

Wastewater temperatures tracked with air temperature, and there were no significant differences between influent and effluent samples. This is characteristic of open warm climate treatment systems where the treatment influence over thermal conditions is insignificant. Similar temperature patterns have been detected in WWTPs from Egypt, Iran and southern part of Asia, where influent/effluent temperatures are also, mostly related to properties of air temperature between seasons (Dias *et al*., 2024; Alsulaili et al., 2020).

The pH of influent before and after treatment were in a narrow neutral range, suggesting a consistent influence composition and expected buffering capacity within the treatment system. At a neutral pH, biological treatment processes generally perform well which is reflected in the performance of conventional WWTPs across the globe (Lin *et al.*, 2023). The elevation of DO concentrations after colour removal reflects the good aeration during secondary treatment and confirms the decrease in organic matter content. Comparable DO enhancements have also been reported for warm climate (Ganji *et al.,* 2024).

4.3 Organic Matter Removal Efficiency

After treatment, the substantial reduction of BOD_5 and COD concentration demonstrates the effectiveness of biological treatment process to eliminate biodegradable organic matter. The effluent BOD_5 values are in line with other values reported for secondary treated municipal wastewater in the developing countries (Sabliy *et al.*, 2017; Zhao et al., 2023). This indicates that the microbial population in the treatment units were metabolising organic substrates as an energy source, which resulted in significant pollutant loads reduction.

But the presence of high COD/BOD_5 ratio in the treated effluent indicates non biodegradable or slowly biodegradable organic portions. The pattern observed has been documented in literature and occurs when conventional systems are unable to include advanced oxidation or other type of tertiary treatment (Sangamnere *et al.,* 2023). The correlation between COD and

BOD_5 found in this study is consistent with international data, highlighting the inefficiency of biological processes in obtaining complete mineralization of organic components.

4.4 Nutrient Transport and Removal Constraints

Nutrient removal was identified as the primary constraint on performance of the Al-Muameera WWTP. Partial nitrification (PNA) was achieved as indicated by low ammonia nitrogen (NH_3-N) concentration, yet total nitrogen (TN) removal was not satisfied. The rise in oxidized nitrogen species (NO_2-N and NO_3-N) observed after treatment of the effluent indicates that the ammonia is transformed but not removed entirely. Similar alteration of nitrogenous transformation in traditional WWTPs without such nitrification–denitrification units has also been seen (Hu *et al.*, 2023).

TP removal was restricted as well, and concentrations of TP in the effluent were relatively high. This is in line with similar observations from studies outside the EU, demonstrating that conventional biological treatments are highly variable and inefficient to remove phosphorus through biomass uptake (Tiwari & Pal, 2022). Phosphorus persistance in treated effluent is anticipated without chemical or biological P precipitation.

By contrast, WWTPs with tertiary treatment or nutrient removal facilities exhibit much higher nitrogen and phosphorus removal rates. Yet, these systems entail high capital cost, operational complexity, and technical training that are not available in many developing areas (Muzioreva *et al.*, 2022). Thus, the nutrient removal efficiency obtained in this work represents a real operation practice condition for WWTPs widely used at semi-arid urban areas.

4.5 Major Ions and Sulfur Species

The slight shifts of SO_4^{2-} and Cl^- concentrations indicate their mostly conservative behavior during treatment, which is congruent with other research findings (Elmansour *et al.*, 2022). Chloride in particular has a long history of invariance to traditional treatment processes, and mainly depends influent composition than on the process used.

The significant decrease in hydrogen sulfide (H_2S) levels post-treatment, however, indicates that the system's aerobic activity is enhanced while analytics show a reduced anaerobic regime now present. Comparable decreases in the sulfide levels after biological treatment were observed also in WWTPs located in warm climate zones, when improved aeration inhibits activity of sulfate-reducing bacteria (Aib *et al*, 2024).

4.6 Implications for Environmental Discharge and Reclamation

The general amelioration of physico-chemical water quality implies that the treated effluent at Al-Muameera WWTP is potentially applicable for controlled environmental discharge and perhaps even specific reuse applications including irrigation of non-food crops. Nevertheless, residual nutrients in the effluent may pose eutrophication hazards if it is discharged to the more sensitive receiving waters.

International standards highlight the need that wastewater reuse should manage the water scarce environment effectively, while taking care of the environment too (Ehalt Macedo *et al.*, 2022). The results of this analysis suggest that the currently operating treatment system would be sufficient to reduce organic load, but that further treatment or operational enhancements would be needed for reducing nutrient impacts on the environment.

4.7 Comparison with studies within the region and worldwide

Compared with neighboring countries, its performance in organic matter removal is quite similar while it is a bit less efficient in nutrient removal. Similar findings were reported in studies from Jordan, Iran and Egypt where secondary level treatment has demonstrated dependable BOD_5 and TSS reductions but not always nutrient discharge compliance (Todd, 2024; Alevizos *et al*., 2023).

These commonalities point to a common regional problem of traditional wastewater infrastructure in semi-arid conditions. Consequently, findings of this work also add valuable empirical support to an emerging literature that argues not for the wholesale importation of high-cost advanced treatment technologies, but instead calls attention to the importance of stepwise improvements and the contextual optimization of treatment approaches.

To conclude, this paper offers an extensive physicochemical evaluation of the performance of the Al-Muameera WWTP when exposed to semi-arid urban conditions in Iraq. The results show that the conventional process is efficient in removal of organic pollution and SS, clearly evidencing its functional "efficiency" under the conditions of a mainly domestic wastewater treatment.

Marked decreases in TSS, BOD_5, and COD were achieved all over the monitoring period. These decreases are evidence that both the primary and secondary treatment works, especially the biological phases, efficiently remove biodegradable organic substances providing good level quality effluent. The rise of DO concentration in treated wastewater also indicates a good condition of aerobiosis and sufficient operational efficiency.

Yet nutrient removals were relatively inefficient despite the high treatment performance. Partial conversion of ammonia to oxidized nitrogen species was detected, in treated effluent but the total nitrogen (TN) and total phosphorus (TP) concentrations were still somewhat high. This result demonstrates the limitations of traditional secondary treatment systems that do not have advanced nutrient removal technologies. The persistence of nutrients in effluent represents a potential environmental risk, especially eutrophication of receiving waters (due to the limited capacity for dilution)in semi-arid areas.

The observed performance of the Al-Muameera WWTP is similar to other conventional treatment works that are found in arid and semi-arid zones across the globe. The findings highlight good performance of non-point control in controlling organic pollution, while also indicating the importance of strengthening point source and nutrient control.

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