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Performance Evaluation of Fayda Waste Stabilization Ponds, Duhok, Iraq: Operational Performance, Challenges and Improvement Opportunities

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Abstract

This study evaluated the operational performance of the Fayda Waste Stabilization Ponds (WSPs) in Duhok, Iraq. Sixteen grab-sampling campaigns were conducted over a 15-month monitoring period, generating 69 wastewater samples from influent sources, pond outlets, and final effluent. Field observations, physicochemical analyses, operational monitoring, and meteorological data were used to assess pollutant removal, identify operational constraints, and evaluate compliance with wastewater reuse standards. Results showed substantial seasonal and operational variability. COD removal ranged from 42.1% to 89.3%, with effluent COD concentrations of 372–926 mg/L. TSS removal ranged from 42.31% to 81.08%, while TN removal averaged approximately 65%, remaining below the recommended 70% target. TP removal ranged from 22.6% to 67.5%, indicating inconsistent nutrient removal. Effluent quality frequently failed to meet Iraqi standards for direct discharge or agricultural reuse. Performance limitations were mainly linked to variable influent characteristics, high nutrient loading, graywater inputs, temperature effects, sludge accumulation (90 cm and 85 cm in anaerobic ponds), and improper wastewater disposal. The study recommends influent equalization, controlled loading, regular desludging, improved infrastructure. This study provides the first comprehensive full-scale in situ assessments of WSP performance in Iraq and proposes practical operational measures and a category-based approach for wastewater reuse standards.

Keywords: Wastewater treatment, nutrient removal, influent characteristics, Iraqi discharge standards, seasonal variations, sludge accumulation, operation and maintenance, pollutant removal efficiency

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Graphical abstract

1. Introduction

Due to increased water contamination, population growth, and climate changes, there is a deficiency of freshwater resources worldwide (Kan. and Akalin 2025; Mishra 2023). The application of untreated wastewater is widespread in developing countries for irrigation purposes as a result of limited access to clean water thus causing adverse effects on the environment with possible related contaminants (Tariq and Mushtaq; 2023 Heyde *et al.* 2025).

Duhok City has experienced a remarkable increase in population in recent years as a result of increased numbers of internally displaced persons (IDPs) in conflict areas of Iraq and Syrian refugees fleeing Syria, as reported by the United Nations High Commissioner for Refugees (UNHCR 2018). According to the UNHCR (2018), the number of people living in Duhok City increased from about 300,000 in 2014 to more than 500,000 in 2018. This rapid population growth has put a lot of stress on local infrastructure, especially the water supply and sewage systems. The International Organization for Migration (IOM 2019) findings also stated that urban areas associated with the Kurdistan area have been severely impacted by displacement in Iraq. The study found that approximately five years after the intensification of conflicts in the region beginning in 2014, Duhok City had a population increase of around 30-40%. This population boom has changed the socio-economic landscape of the city.

The majority of countries treat or reuse wastewater before being disposed of into the environment; however, this process can be difficult for developing countries because of high growth rates in their populations, a lack of technical knowledge, and limited awareness regarding wastewater management (Shukri *et al.* 2024). Therefore, it is essential to develop adequate and cost-effective wastewater treatment technologies that can minimize water contamination while allowing the reuse of wastewater for irrigation, aquaculture, and industrial processes (Krishna *et al.* 2025; Azoulay *et al.* 2024).

Due to the absence of a wastewater treatment facility, Duhok City's total black wastewater flows directly into each resident's septic tank, where it primarily seeps through the soil until it reaches groundwater (Mizzouri *et al.* 2020). The high density of unregulated septic systems in Duhok City has proven insufficient and has had a significant impact on public health and regional groundwater quality. Numerous diseases, including diarrhea, cholera, typhoid, and others, can be brought on by bacteria, viruses, protozoa, and fungi present in sanitary wastewater (Mizzouri *et al.* 2022).

A wastewater treatment plant (WWTP) demands highly skilled workers and comes at a very high cost to design and construct. Most of the developing countries are unable to afford the costs. The WSPs are a good alternative to the conventional WWTP since they are a cheap and efficient method to treat both industrial and domestic wastewater. WSP systems have lower capital costs than conventional WWTP, lower technical manpower requirements, easier to design, operate, and maintain, and no reliance on expensive or automated equipment for treatment (Coggins *et al.* 2018; Pinheiro *et al.* 2025). These properties make WSP systems interesting. WSP is economical as it relies on natural processes to provide energy demands. It works by using sunlight and microorganisms together (GD and VA 2014; Shaheen *et al.* 2024). However, WSPs have some disadvantages such as requiring large land areas, effluent quality fluctuation, odor and mosquito problems, and may also emit greenhouse gases (Aydin Uncumusaoğlu 2018; Achag *et al.* 2023). Moreover, in contrast to other treatment systems, WSPs are influenced by environmental factors such as temperature, rainfall, wind, and evaporation, therefore, they cannot function properly in cold and cloudy regions where biological activity and sunlight for disinfection are limited (Kadri *et al.* 2021).

According to Edokpayi *et al.* (2017), effluents from WSP systems in most developing countries fail to meet acceptable discharge criteria. A research by Jagals *et al.* (2006) in South Africa's Free State Province indicated that all 60 WSP systems tested produced effluent that did not meet the recommended standards for fecal indicator organisms. Similarly, Lloyd *et al.* (2003) emphasized that inadequate operation and maintenance practices of WSPs in Mexico have caused these systems to underperform. The identified operational and maintenance challenges included significant pump malfunctions, untreated sewage bypassing treatment facilities, design flaws, wastewater short-circuiting, and other operational and design issues. Regular desludging of WSPs has been proposed as a valuable intervention technique for performance improvement because, as sludge accumulates, it can decrease effective volume, affect pond hydraulics, and alter treatment performance (Coggins *et al.* 2017). Pond modifications may improve performance. For example, Coggins *et al.* (2018) stated in their research that baffles installation improved the flow, increased hydraulic retention time (HRT) by 20% and reduced wind impacts on pond hydraulics.

The Fayda WSPs were constructed in 2020 and have a design capacity of 1052 m^3/day. The Fayda WSPs are two lines, each line is a series of four ponds that treat domestic wastewater from Domiz 1 camp, Domiz 2 camp, and the city of Duhok and its surroundings. This study differs from previous WSP investigations by providing a full-scale, in situ operational assessment of a pond system serving both refugee camps and host communities under the climatic, hydraulic, and institutional conditions of Duhok Province, rather than relying mainly on laboratory experiments, theoretical models, or conventional municipal case studies. Its scientific contribution lies in linking measured pollutant-removal performance with real operational constraints, including fluctuating influent composition, graywater inputs, sludge accumulation, seasonal loading variation. The hypothesis of this research was to test whether seasonal variations in temperature and influent loading rate have an impact on the removal of pollutants from Fayda WSPs. The objective of this study was to assess whether effluent meets standards and to diagnose performance issues. Moreover, the existing Iraqi requirements for wastewater reuse in irrigation exhibit insufficient flexibility to address the heterogeneity inherent in WSP effluents, depending on a singular effluent parameter that is frequently impracticable. This study directly addresses these gaps by conducting a comprehensive 15-month assessment of the Fayda WSPs. To our knowledge, this is the first such study in Iraq providing empirical data on WSP performance, including influent and effluent parameters, pollutant removal efficiency, and operational efficiency. The innovation of this research is the suggestion of a category-based approach to irrigation reuse, offering a more adaptable framework for wastewater management, acting as a benchmark for other areas in Iraq.

2. Methodology

To address the study objectives, the methodology was organized around four connected components: field characterization of the Fayda WSPs, wastewater sampling and laboratory analysis, operational monitoring, and climatic-data interpretation.

2.1. *Description of the study area and site visits*

The Fayda WSPs are located in the Sumel District in the Duhok Governorate in the Kurdistan Region of Iraq. It covers about 20,000 m^2 with geographical coordinates of latitude 36°45'52"N, and longitude 42°52'05"E. The plant primarily serves Domiz 1 and Domiz 2 camps in addition to many other areas including Duhok City, Fayda, Domiz, and Sharia sub-districts. The plant consists of two lines of ponds with a total design capacity of 1,052 m^3/day. Each line has a design capacity of 526 m^3/day. A series of ponds have been constructed on each line (2 anaerobic ponds, 1 facultative pond, and 1 maturation pond). The project also includes an office for the administration, sludge drying beds, and a warehouse for sludge composting (see **Figure 1**). During the monitoring period, the two treatment lines were operated either simultaneously or individually depending on incoming wastewater volume, organic loading, and operational requirements. Weekly site visits were conducted to Fayda WSP jointly with relevant staff to define the problems of the performance and to monitor the operation of the plant.

2.2. *Wastewater Sampling*

Over the 13-month study period (May 2021–May 2022), 16 grab samples were collected from the ponds and sources of black wastewater including the camps and local communities. Operational monitoring and field observations were conducted over a 15-month period. A total of 69 wastewater samples were collected from influent sources, pond outlets and final effluent points. All samples were collected between 9:00 and 11:00 AM local time to minimize the diurnal variability of the water quality parameters. Before entering the anaerobic ponds, the raw wastewater (influent) was sampled from the flow splitter chamber. Considering that one outflow served as an inflow for the following pond, samples were subsequently obtained from the outlets of each pond. The final effluent sample was collected from the outlet of the maturation pond. Samples were collected in sterilized glass or polyethylene containers, transported to the laboratory, and stored at 4°C, and analyzed within 24 hours. The raw wastewater-quality data used in the performance assessment are provided in **Table S1** as supplementary material.

2.3. *Monitoring the Performance*

Operational monitoring focused on the relationship between loading conditions, pond operation, climatic variation, and treatment performance. The organic loading, expressed as biochemical oxygen demand (BOD), was controlled, and different loading patterns were adopted throughout the research period including distributing the load on the ponds' series, operating a series on full loading, or shutting down a series of ponds. In addition, different organic loadings were applied depending on the temperature. For example, organic loading was minimized during snowfall periods to optimize treatment efficacy. The HRT was evaluated by comparing the design flow of 1,052 m^3/day with the actual applied flow during the monitoring period. Because the actual applied flow was lower than the design flow, the current HRT values were higher than the original design values. Aerial imagery was acquired during single-series operations to provide information on any potential short-circuiting in the facultative ponds (**Figure 1**).

Figure 1. Annotated aerial view of the Fayda WSPs.

2.4. *Methods of Analysis*

The sampling design was therefore intended to capture both source-water variability and treatment progression through the pond sequence, allowing influent quality, intermediate treatment performance, and final effluent quality to be compared. Physicochemical parameters were measured at the site. A HANNA instrument (model HI98199 multi-probe) was used to measure pH, temperature, conductivity, and dissolved oxygen.

The samples of wastewater were collected over a span of one year from the sources, influents and effluents of the different ponds of the Fayda WSPs. These samples were stored at 4°C and were eventually analyzed at the Directorate of Environment. The wastewater samples were analyzed for various parameters, namely BOD5, COD, TSS, TN, TP, pH, and temperature. The parameter analyses were done according to Standard Methods for the Examination of Water and Wastewater (Rice et al. 2012). COD determination of wastewater was performed by using procedure 5220 C, standard closed reflux, and titrimetric methods. BOD using method 5210 B, TSS using method 2540 D, TP using method 4500-P E, and TN using method 4500-Norg B (Rice et al. 2012). A limitation of the current assessment is the absence of microbiological data (such as fecal coliforms or helminth eggs). Due to the limitations in laboratory capacity during the study period, the analysis was restricted to physicochemical parameters. Therefore, the present assessment should be interpreted as a physicochemical evaluation of WSP performance rather than a complete sanitary-risk assessment. Microbiological indicators, including fecal coliforms, E. coli, intestinal helminth eggs, and other pathogen-related indicators, were not measured and therefore could not be used to assess the public-health safety of the treated effluent.

2.5. *Meteorological data*

The Fayda WSPs are working in the climatic conditions of Duhok governorate, where seasonal variation of temperature, precipitation and solar radiation affect the treatment performance. Heavy rainfalls characterize the climate of northern Iraq, particularly Iraqi Kurdistan, which is influenced by the mountain regions inducing the orographic heaving effect (Eklund and Seaquist 2015). The average annual precipitation in the Duhok Governorate is 530 mm based on statistics for the last 10 years (**Figure 2**). The rainy season usually extends from November to March, and little or no precipitation falls during the summer (June to September). (Eklund and Seaquist 2015). These climatic factors were taken into account in the interpretation of treatment performance since the lower winter temperatures could have reduced microbial activity and conditions in summer could have increased biological degradation and algal activity. Snowfall and snowmelt events were also operationally important as they can temporarily increase hydraulic loading and dilute wastewater entering the ponds.

2.6. *Statistical analysis*

The wastewater-quality dataset was processed using descriptive and inferential statistical analyses. For each monitored parameter, including COD, TSS, TN, and TP, the mean, standard deviation, minimum, maximum, and coefficient of variation were calculated for effluent samples where data were available.

3. Results and Discussion

The results are presented in a sequence that follows the operational pathway of the system: influent quantity, influent and effluent quality, pollutant-removal performance, operational constraints, and practical improvement measures.

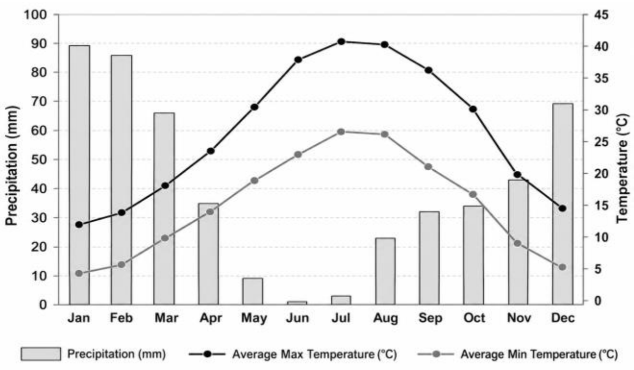


Figure 2. Climate data based on averages of the two stations in Duhok Governorate covering the period 1998-2014 (Eklund and Seaquist 2015).

3.1. *Quantity of influent*

Generally, the majority of the quantities originate from Domiz 1 camp. The quantity in Domiz 1 camp is predominantly double that of Domiz 2 camp. **Figure 3** shows the volume of wastewater received at the Fayda WSPs from January 2020 to May 2022.

Significant variations in wastewater inflow were observed over the course of a 24-month period, indicating possible fluctuations in water consumption patterns, climatic factors, or other potential challenges faced by Fayda WSPs during operation. In April 2021, there was a significant decline in wastewater intake due to the changeover of operations from UNICEF to the contracting business which led to a temporary suspension and a reduction in capacity.

The minimum wastewater inflow was recorded in December 2021, reaching a value of 5,620 m^3/month. This may result from factors such as decreased water usage in the winter months and insufficient money to facilitate the transportation of wastewater from the camps to the treatment plant. The peak wastewater inflow was recorded in June 2020, a value of 12,762 m^3/month. This may be related to the availability of money and trucks to assist the transportation of wastewater from the camps to the plant. The average wastewater inflow for the 24 months is 8,640 m^3/month which is below the design capacity of the Fayda WSPs for one line which is about 15,000 m^3/month.

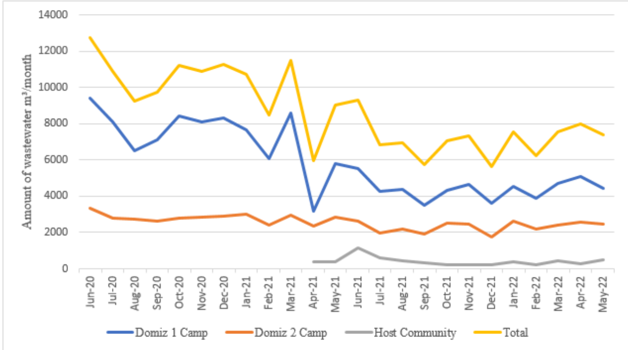


Figure 3. Monthly wastewater volumes received at Fayda WSPs from Domiz 1 camp, Domiz 2 camp, host communities, and total inflow during the monitoring period**.**

3.1.1. *Design vs operational quantities*

The data in **Table 1** show the comparison between the quantities that were considered for the design (provided by Directorate General of Municipalities of Duhok (DGoMsD) and the Environment Office of Duhok (EoD)) of the *WSPs* and the current receiving quantities from different locations that were collected during the research months on the vacuum trucks arriving at the treatment plant.

The present receiving quantities are much lower than the design quantities at the majority of places, particularly in Khanek camp, Fayda sub-district, Sharia sub-district, and Duhok City. This shows that the Fayda WSPs are functioning below their capacity and efficiency and that the collection and transportation system of the wastewater from these sites has to be improved. The sites with very low or no present receiving quantities are Khanek camp, Fayda sub-district, Sharia sub-district, and Duhok City. Increasing the present receiving amounts from these sites will not only improve the performance of the WSPs but also offer environmental and socio-economic advantages for the communities.

The observed variability in wastewater inflow is important because changes in hydraulic loading directly influence pond retention time, pollutant dilution, organic loading, and the stability of biological treatment processes.

Table 1. Comparison between design and current wastewater-receiving quantities by source.

#	Locations	Design quantity (trips/day)	Current received quantity (trips/day)
1	Domiz 1	48	16 – 30
2	Domiz 2	22	10 – 16
3	Khanek camp	16	0
4	Fayda Sub-district (Fayda and Domiz)	17	0-2
5	Sharia Sub-district	4	0-1
6	Duhok City (Urban zone)	17	0-2
7	Semel	0	0 – 1
8	Kabarto camp	0	0 – 1

3.2. *Quality of influent and effluent*

Following the assessment of influent quantity, wastewater quality was evaluated to determine how changes in organic matter, suspended solids, nutrients, pH, and temperature affected the treatment performance of the Fayda WSPs. **Table S1** for the WSP (supplementary material) presents the primary findings for the water quality parameters (COD, BOD5, TSS, TN, TP, pH, and Temperature).

3.2.1. Chemical Oxygen Demand

The influent COD mass balance fluctuates significantly from 693 mg/L to 4022 mg/L which may reflect the variations in the wastewater characteristics and flow rate entering the WSPs plant.

Figure 4(a) shows the influent COD mass balance and the effluent COD (from the B4 outlet, the maturation pond) concentrations in different periods of the year. The effluent COD values from May 2021 to August 2021 were higher than those from September 2021 to May 2022. While the lowest effluent COD value was documented in May 2021 at 372 mg/L, the highest effluent COD value was reported in May 2021 at 926 mg/L. Considerable variance in effluent COD values was observed throughout different months. This may result from multiple sources, including seasonal variations, changes in influent quality, and operational challenges. The effluent COD concentration ranges from 401 mg/L to 926 mg/L.

COD removal efficiency was calculated as

COD removal efficiency = ((Influent COD – Effluent COD)/Influent COD) *100 (1)

Figure 4(b) depicts the percentage removal of COD for the various times of the year. The average removal efficiency of COD for the entire period was 67.88% for the WSPs plant. The amounts of COD removed from wastewater by the WSP plant differ significantly from one month to another, ranging from 42.1% to 89.3%, indicating variability in the treatment efficiencies of the WSP facility. The minimum removal of 42.1% reflects unstable influent characteristics and operational loading. The removal rate was higher in September (89.3%) and November (84.4%) and lower in July (55.5%) and October (42.1%). This may be related to higher influent COD in September and November compared with July and October. Additionally, it may also be related to the effects of temperature and solar radiation on the rate of biological and photolytic degradation of organic matter in WSPs (Achag *et al.* 2021).

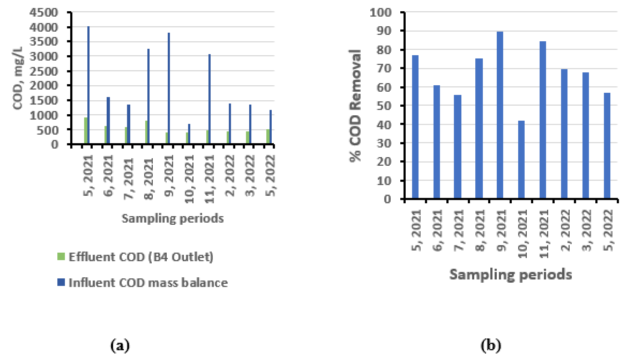


Figure 4. Temporal variation of (a) influent and effluent COD concentrations and (b) COD removal efficiency in Fayda WSPs.

Linge *et al.* (2021) studied the removal efficiency of micropollutants for different WSP configurations at a wastewater oxidation ditch treatment plant. The COD effluent concentration of 28-64 mg/l and average removal efficiency of 88-95% was reported by the authors. WSPs in the tropics with an effluent COD of 100 mg/L and a removal efficiency of 80% were studied by Ho and Goethals (2020). Despite the high removal efficiency, Gerson *et al.* (2025) specified that the final effluent COD of the Kalobe WSPs in Tanzania was still above the national discharge standard. This means that a high removal efficiency does not automatically translate into effluent compliance when the influent loads are high or variable. Similarly, Akdim *et al.* (2025) indicated that the Moroccan evaluation of seven WSP systems showed average COD reductions of ~65-70%. Lower and more variable performance in Fayda can be attributed to variable influent quality, variable truck-delivered wastewater sources, changing organic loading, sludge accumulation, and seasonal operational constraints. Thus, the Fayda results suggest that the primary limitation is not the WSP process, but the instability of influent loading and operational control under local field conditions.

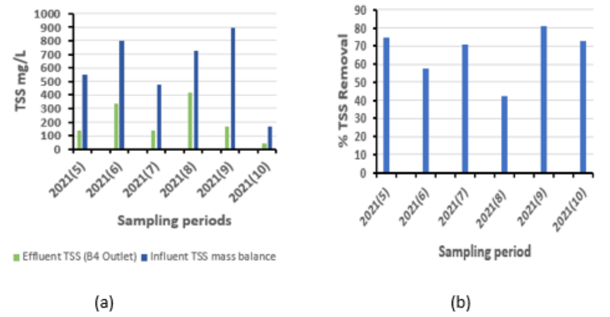


Figure 5. Temporal variation of (a) influent and effluent TSS concentrations and (b) TSS removal efficiency in Fayda WSPs.

3.2.2. Total Suspended Solids

Figure 5(a) demonstrates the influent and effluent TSS levels changed from month to month. The influent TSS mass balance values ranged from 165.39 to 898.71 mg/L, and the effluent TSS concentration ranged from 45 to 420 mg/L. This shows that the WSP plant is effective in eliminating TSS from wastewater.

Figure 5(b) represents the percentage removal of TSS in different months of the year. The percentage removal of TSS ranged from 42.31% to 81.08%. Nwankwo *et al.* (2019) investigated the kinetics of solids removal in WSPs and their results indicated that TSS removal efficiency ranged between 60 and 80% depending on hydraulic retention time. The Fayda results partly fall within this range, but the lower removal values indicate periods of reduced settling performance. This may be related to high influent solids variability, algal biomass in the facultative and maturation ponds, possible hydraulic short-circuiting, and sludge accumulation reducing the effective pond volume. Therefore, TSS performance should be interpreted as a combined indicator of influent variability, pond hydraulics, and biological activity rather than as a simple sedimentation outcome.

3.2.3. pH

Figure 6 depicts the influent pH and effluent pH values for the WSPs at different times of year. The influent pH values vary from 7.32 to 8.05 and the effluent pH values vary from

7.69 to 8.35. In most cases, results show that the effluent pH values have increased post-treatment.

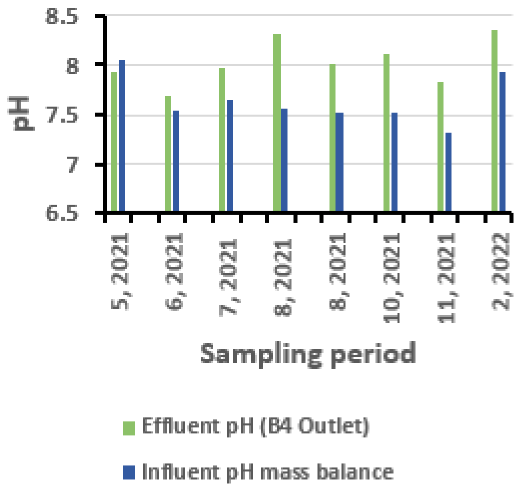


Figure 6. Temporal variation of influent and effluent pH in Fayda WSPs.

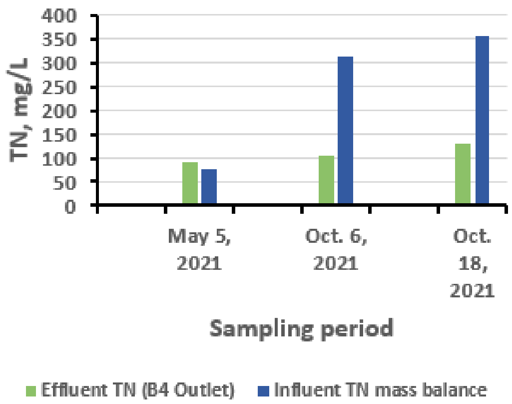


Figure 7. Temporal variation of influent and effluent TN concentrations in Fayda WSPs.

According to Kayombo *et al.* (2005), the influent pH of WSPs ranges from 6.5 to 8.5 depending on the source and composition of wastewater. WSPs have an identified optimal pH range from 7.0 to 8.5 that helps in algal and bacterial growth. Frequent checks on pH values of influent and effluent of WSPs is essential to maintain the efficiency of the treatment processes.

3.2.4. Total Nitrogen

Figure 7 shows the variation of influent and effluent TN values of the WSPs in different periods of the year. TN covers all forms of nitrogen: ammonia, nitrite, nitrate, and organic nitrogen (Scott 2012). Since the values of the effluent are lower than the values of the influent, this clearly shows that the WSP plant is able to remove nitrogen from the wastewater. The average TN removal efficiency is 65%, which is less than the 70% suggested by the World Health Organization (Desye *et al.* 2022). The influent TN mass balance values ranging between 77.1 and 357.8 mg/L are beyond the normal range of 30-100 mg/L for municipal wastewater (Chen *et al.* 2020). This indicates that the raw wastewater contains a very high nitrogen content, which may in turn affect the efficiency of the WSP plant. The highest value of influent TN mass-balance during October may be linked with a large quantity of greywater inflow coming from Domiz 1 and Domiz 2 camps. The TN concentration in the effluents varies between 92 and 130 mg/L, and the concentration is above the irrigation limit (Organization 2006). Therefore, the effluents from WSPs require some additional treatment to meet the standards.

In the study conducted in Ethiopia, Desye *et al.* (2022) measured the TN concentrations in both the influent and the effluent of one WSP system. The TN concentration for the influent was between 35.8 and 97.6 mg/L, with the mean being 83.2 mg/L. The TN removal efficiency was 79% which is larger than the 70% target allowed by the World Health Organization (Desye *et al.* 2022). To compare the results in **Figure 7** and the results in the previous study, the WSP facility in Fayda has a larger influent TN concentration than the WSP facility in Ethiopia.

This suggests that the Fayda WSPs were exposed to unusually high nitrogen loading, most likely influenced by greywater inputs from Domiz 1 and Domiz 2 camps. Unlike engineered biological nitrogen-removal systems, conventional WSPs have limited control over nitrification–denitrification pathways. Therefore, the relatively low TN removal in Fayda is consistent with the operational limitations expected for pond systems receiving nutrient-rich and compositionally variable wastewater.

3.2.5. Total Phosphorus

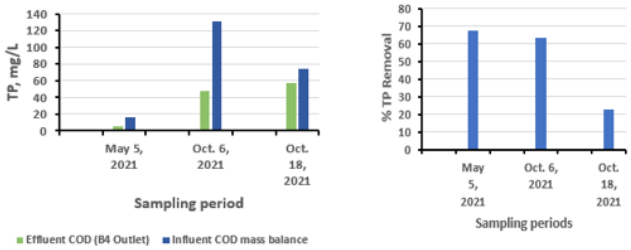
TP is a measure of the total phosphorus concentration in the water which comes from different sources such as fertilizers, detergents, organic waste, and industrial effluents. Excess phosphorus in water leads to eutrophication, defined by the overgrowth of algae and aquatic plants depleting dissolved oxygen, therefore negatively affecting water quality and aquatic life. Therefore, it is desirable to remove as much phosphorus as possible from the wastewater before discharging it into the environment (Bunce *et al.* 2018). According to **Figure 8(a)**, the influent TP concentration in the WSP plant ranged from 16 mg/L to 131 mg/L, while the effluent TP concentration ranged from 5.2 mg/L to 57.4 mg/L. The percentage of TP removed from the influent to the effluent, ranged from 22.6% to 67.5% as shown in **Figure 8(b)**. These results show that the WSP plant was able to reduce the TP concentration in the wastewater, but not consistently or sufficiently.

The typical TP removal in WSPs varies from 40% to 80% (Kayombo *et al.*, 2005); however, the studied plant depicted in **Figure 8(a) and (b)** mostly fell below this range, except on May 5, 2021, when it achieved a removal rate of 67.5%. A case study in Ethiopia (Desye *et al.* 2022) indicated a 69.2% TP removal. The effluent TP concentration exceeded the permitted discharge limit of 2 mg/L, measuring 5.2 mg/L to 57.4 mg/L. In comparison, the TP removal efficiency in the WSPs facility, illustrated in **Figure 8(a) and (b)**, corresponds with the case study but constantly demonstrates elevated effluent TP concentrations with the exception of May 5, 2021, when it attained 5.2 mg/L. Also, Linge *et al.* (2021) underlined TP removal variation (32–87%) in WSPs of different configurations and climates. Influenced by biological processes, pond setup, hydraulic regime, and weather conditions, corresponding with the plants' operational capability.

Thus, the Fayda values are within the broader range reported in the literature but show weaker consistency. This is most likely because phosphorus removal in WSPs is dependent on several processes including algal uptake, sedimentation of particulate phosphorus, adsorption to solids and the weather conditions as stated by Linge *et al.* (2021). However, such mechanisms may be unstable under conditions of sludge accumulation, variable HRT and high greywater-derived phosphorus loading. The results from the Fayda suggest that additional operational measures such as improved source control, desludging or post-treatment may be necessary for phosphorus control particularly if the effluent is to be used for agricultural reuse.

3.2.6. *Statistical Summaries for Key Parameters*

Table 2. Descriptive statistics of the final effluent quality of the Fayda WSPs. Effluent COD values ranged from 372 to 926 mg/L with mean of 550.2 ± 151.3 mg/L and CV of 27.5% indicating moderate variability. TSS was more variable with a range of 45-420 mg/L, a mean of 189.8 ± 115 mg/L and a CV of 60.6%. The TN was relatively more stable, ranging from 92 to 130 mg/L, with a mean value of 109.33 ± 19.22 mg/L and the lowest CV of 17.6%. TP had the highest variability (CV = 75.5%). Overall the results show unstable effluent quality especially for TSS and TP, requiring improved influent control, and desludging.



(a) (b)

Figure 8. Temporal variation of (a) influent and effluent TP concentrations and (b) TP removal efficiency in Fayda WSPs.

Table 2. Descriptive statistics of effluent data for the Fayda WSPs.

Parameter	Effluent range, mg/L	Effluent mean ± SD	CV (%)
COD	372–926	550.2 ± 151.3	27.5
TSS	45–420	189.8 ± 115	60.6
TN	92–130	109.33 ± 19.22	17.6
TP	5.2–57.4	36.87 ± 27.8	75.5

3.3. *Operation and Performance of Fayda WSPs*

Water Quality data alone cannot fully explain the variance found in removal rates for COD, TSS, TN, and TP; therefore, the following discussion identifies the factors of operational variables which may affect treatment performance.

Operational variables affecting performance and operation of WSPs include: influent characteristics; HRT; weather; and algae growth. The variation and time of these variables can influence the overall performance of WSPs. (Achag *et al.* 2021; Von Sperling 2007; Mara 2013). The design of Fayda WSPs was built on an average BOD5 value for the sewage as considered by the EoD. However, the actual BOD5 concentrations of the sewage inlet at the Fayda WSPs were higher than the design values, as depicted in **Table 3**. This factor has an impact on the operation and performance of the ponds and the quality of the treated effluent.

Table 3. Comparison of design and measured BOD_5 concentrations for wastewater sources.

#	Locations	Average BOD_5 that considered for the design (mg/L)			Current received average BOD_5 (mg/L)		
		Mean ± SD	**Range (Min-Max)**	**Coefficient of variation (CV%)**	**Mean ± SD**	**Range (Min-Max)**	**Coefficient of variation (CV%)**
1	Domiz 1	566 ± 125	456–703	22.21	1622 ± 1172	775–3658	72.29
2	Domiz 2	411 ± 103	339–529	25.06	811 ± 537	384–1716	66.20
3	Fayda Sub-district	3516 ± 1542	2418–5280	43.88	2993 ± 1989	1587–4400	66.45
4	Duhok City	1370 ± 660	860–2115	48.15	5064 ± 1924	3524–7221	38.00

The Domiz 1 and Domiz 2 camps, as well as Duhok City, demonstrate higher BOD_5 levels than the design values, indicating an increase in organic loading on the anaerobic ponds. Consequently, the effectiveness of the treatment may be hindered which could lead to odor problems. To improve treatment efficiency, flow rate adjustments are necessary because of the difference between the designed and actual BOD_5 levels. An equalization basin construction before the influent enters the ponds can help mitigate shock loading and stabilize the flow and character of the wastewater. At present, the removal rates of COD and BOD_5 in Fayda WSPs are around 80% and 86%, respectively, representing a good performance for WSPs (Kadri *et al.* 2021; and Mara 2013). Nevertheless, they are not meeting the design capabilities of the ponds, which could reflect higher effluent concentration than expected.

The design was based on values that assumed a certain amount of black wastewater. However, the current influent wastewater contains a high percentage of greywater that comes from Domiz 1 and Domiz 2 camps which have different characteristics than black waste. Greywater typically has higher levels of nitrogen and phosphorus due to detergent and other household chemicals. These nutrients can promote algal growth in the ponds, affecting oxygen balance, light penetration, and sedimentation processes. Algae can produce toxins harmful to aquatic life and human health. Additionally, greywater usually has a lower concentration of organic matter when compared to black wastewater, which may reduce the ponds' biodegradation limitations (Khajvand *et al.* 2022; Awasthi *et al.* 2024).

The HRT of the Fayda WSPs has undergone changes since the design phase, attributed to the variation in the applied flow. The design HRT was determined using the average daily flow anticipated by the EoD which was 1,052 m^3/d. Nonetheless, the existing applied flow is below the design flow; therefore, all ponds have longer HRTs. The current HRTs are still within the recommended ranges for each type of pond; however, for the anaerobic pond 1, it is close to the upper limit. **Table 4** illustrates the current detention times and during the design together with the criteria. Extended HRTs can provide both beneficial and detrimental effects on the performance of the WSPs. Longer HRTs can increase the interaction duration between wastewater and microorganisms, hence improving the elimination of organic matter and pathogens. However, prolonged HRTs may elevate the danger of odor generation, sludge accumulation, and nutrient leaching from anaerobic ponds. Extended HRTs might diminish the hydraulic efficiency of ponds which could cause dead zones and short-circuiting (Achag *et al.* 2021; Von Sperling 2007).

Table 4. Design and current HRT of Fayda WSP units.

#	Ponds	Designed HRT (days)	Current HRT (days)	Recommended Design Criteria (days) (Kayombo *et al.*, 2005)
1	Anaerobic pond 1	3.22	5.57	1-7
2	Anaerobic pond 2	1	1.62	1-7
3	Facultative pond	9.04	15.5	5-30
4	Maturation pond	3	5.7	Min. 3

To enhance the performance of the Fayda WSPs, control methods on the loading of the anaerobic and facultative ponds are advised. This can be accomplished by increasing the fleet of trucks used to collect black wastewater from the host communities, as this type of wastewater bears higher organic content. Additionally, the control can involve manipulating the wastewater flow through either one series of ponds or both series. Through these control measures, the effluent COD values can be reduced to values < 500 mg/L, which meet the standards for irrigation (Mizzouri *et al.* 2017; Organization 2006).

The weather conditions of the Fayda WSPs can significantly affect the operation and performance of the ponds, specifically temperature and solar radiation. The degree of temperature change has a big impact on microbial metabolic rates, gas solubility, and water density. Meanwhile, solar radiation impacts the warming of water, the disinfection of pathogens, and photosynthesis in algae (Achag *et al.* 2021; Mwamlima *et al.* 2025). Fayda WSPs, located in hot summer and cold winter regions, experience changes in performance and in temperature and solar radiation. Summer time experiences an increase in performance, and, on the contrary, winter experiences a decrease.

Another problem that could influence the operation and performance of the Fayda WSPs significantly is the algae growth, particularly in the facultative ponds. These microorganisms use sunlight to create oxygen and biomass. Algae can be beneficial because they are important for the aerobic degradation of organic material by providing oxygen and they can also eliminate certain nutrients and pathogens in the wastewater. However, algae have negative impacts too. Algae utilize oxygen at night when photosynthesis stops, and their decomposition can further increase oxygen demand. In addition, algae may reduce the amount of light that penetrates the water, therefore decreasing the rate of photosynthesis and the rate of disinfecting the water. They can also lead to problems including turbidity, color, and odor in the effluent (Kadri *et al.* 2021; Sinn *et al.* 2022). The growth of algae in the Fayda WSPs is affected by several factors, such as nutrient concentrations, HRT, temperature, and solar radiation.

The effluent quality of the Fayda WSPs does not meet the criteria for direct discharge to water resources or reuse in irrigation, an interpretation of the Iraqi standards for the use of treated wastewater in irrigation (e.g., BOD<40 mg/L, COD<100 mg/L) (Shakir *et al.* 2017; Iraqi Facts 2012).

This emphasizes the need for clear, enforceable standards for all pathways of discharge. Although the physicochemical results suggest that the final effluent did not always meet discharge or irrigation-reuse standards, the lack of microbiological data is another limitation. In addition to COD, BOD_5, TSS, nutrients and pH limits, monitoring of pathogen indicators is required to confirm safe reuse in the context of wastewater reuse. Kamel et al. (2026) reported variable bacterial and viral decreases in full-scale WSPs and emphasized the need for improved monitoring and management approaches to protect public health.

3.4. *Main Operational Problems and Recommended Improvement Framework*

The major constraints on the Fayda WSPs have been classified into six distinct areas based on the operational experiences and performance evaluation as well as the monitoring data from March 2021 to May 2022. They include: variability in loading, nutrient enrichment of the effluent, sludge accumulation, improper disposal of effluent, snow-melting drainage and limitations of the existing infrastructure; all of which have an effect on the operation of the wastewater treatment facilities to varying degrees. The list of potential challenges or problems for the Fayda WSPs include:

Seasonal loading control should be adopted as a routine operational strategy. During cold periods and snowfall events, biological degradation slows because microbial activity is reduced. Therefore, the organic loading to each pond series should be reduced during winter, while loading may be increased gradually during warmer periods when biological treatment is more active. This can be done by controlling the number of wastewater trucks discharged per day, distributing the flow between Series A and Series B, and avoiding sudden loading changes during low temperature periods. This strategy will reduce odor formation, improve the stability of COD and BOD removal and reduce the risk of effluent deterioration in winter.

In the Fayda WSPs, anaerobic and facultative ponds are subject to overload because of different hydraulic loading and the influent BOD and COD concentrations are high. The consequence of this is the establishment of odor, sludge, and nutrient problems together with a drop in the removal efficiency. One of the main improvements is the construction of an upstream equalization basin before the inflow of the wastewater in the anaerobic ponds. This basin would help regulate flow variations, reduce hydraulic shock loading, and homogenize influent wastewater quality before treatment. Such an intervention is especially important as the Fayda WSPs serve wastewater from different sources including Domiz 1, Domiz 2, host communities and other surrounding areas with highly variable influent characteristics. The equalization basin would stabilize the influent flow and pollutant concentration and would reduce sudden changes in BOD, COD, TSS, TN and TP loading and would improve the biological stability of the anaerobic and facultative ponds. However, it should be noted that this solution requires constant average flow pumping.

High nitrogen levels in both the influent and effluent are a sign that the removal of nutrients was not efficient and there is a significant risk of eutrophication.

Greywater-source management should be considered a high-priority intervention because elevated TN and TP concentrations were strongly associated with wastewater contributions from Domiz 1 and Domiz 2 camps. Greywater may contain detergents, nutrients, and household chemicals that increase nitrogen and phosphorus loads and promote excessive algal growth in facultative ponds. Therefore, source separation of greywater and black wastewater should be investigated in the camps. If full separation is not immediately feasible, practical alternatives include reducing detergent discharge, and improving awareness among camp residents. This intervention would decrease nutrient enrichment, algal overgrowth, turbidity and the risk of eutrophication.

The high level of sludge in the anaerobic ponds suggests a considerable organic load coupled with insufficient sludge removal. The level of sludge was measured using the white towel method, the sludge level in the anaerobic A1 pond was 90 cm and in the anaerobic B1 pond was 85 cm. High sludge accumulation can reduce the effective volume and HRT of the ponds and can also cause odor, nutrient, and pathogen problems (Von Sperling 2007). The solution is to remove the excess sludge from the ponds by desludging them when they are one-third full of sludge (by volume). It is important to note that timely desludging will soon be necessary to prevent further complications associated with the high sludge accumulation.

Wastewater should not be discharged directly from the facility to a pond without first going through the Intake and Grit Chamber. Bypassing the preliminary treatment process increases the amount of solids and grit, as well as damaging the geomembrane, and reduces pond performance.

To prevent this, clear discharge routes should be marked, truck drivers should receive training, and physical barriers should be installed to prevent direct dumping into the ponds. In addition, plant operators should maintain a daily log of truck arrivals, and discharge locations. This low-cost operational measure would improve influent control and protect the physical integrity of the pond system.

The excessive application of herbicides along pond embankments can have negative impacts on the organisms living there. Herbicides can leach into ponds, thus compromising water quality as well as the treatment process. The presence of herbicides usually exerts a toxic and nutrient-rich composition and a negative impact on microorganisms and algae, which are the main causes of their harmful effects on ponds. As a result, the efficiency of the pond system is reduced. To resolve this problem, it is essential to minimize the reliance on herbicides and explore alternative strategies for controlling excessive vegetation. These other ways include manual weeding, mowing, or grazing.

Snowmelt and stormwater should be diverted away from the treatment ponds because they increase hydraulic loading, dilute wastewater, and inhibits biodegradation processes. The construction of manholes equipped with gate valves between the drying beds and ponds would allow operators to control snowmelt flow during winter. Additionally, a runoff diversion channel should also be constructed to prevent clean runoff from flowing into Anaerobic Pond B1 and redirect this flow to the nearby valley. This practice will reduce hydraulic disturbance of Anaerobic Pond B1 and create a more stable treatment environment for Anaerobic Pond B1 during winter and early spring.

The following recommendations are therefore directly linked to the measured performance limitations and are intended to improve treatment stability, effluent quality, operational safety, and the feasibility of controlled wastewater reuse:

1. It is necessary to make the Iraqi regulations and criteria for treated wastewater use in irrigation more in

compliance with the World Health Organization (WHO) regional standards for wastewater reuse in the Eastern Mediterranean Region. It would also be reasonable to propose specific effluent standards that are more achievable on the basis of categories instead of a single effluent number. It is also necessary that any discharge from the Fayda WSPs intended for irrigation comply with the Jordanian Standard (JS: 893/2002) Column C regarding effluent reuse for irrigation for agricultural crops, industrial crops, and forestry (see **Table 5**).

2. Improve infrastructure to facilitate sample collection, sludge depth measurements and pond maintenance. For example, Bridge, safe egress, boats and grit chambers.
3. Increase the design volume and retention time by desludging of the first anaerobic pond. Raising the awareness of the farmers on the benefits of using the sludge as fertilizer.
4. Support community financing of sanitation projects including operation and maintenance of Fayda WSPs.
5. 5. Introduce routine microbiological monitoring of the final effluent for fecal coliforms, E.coli and intestinal helminth eggs prior to approval for any direct agricultural reuse.

4. Conclusion

The present study is a full-scale performance evaluation of the Fayda WSPs in Duhok, Iraq, based on 16 grab-sampling campaigns and 69 wastewater samples from influent sources, pond outlets and final effluent points. The results demonstrated significant variation in the performance of the treatment. COD removal ranged between 42.1% and 89.3% while the final effluent COD concentrations were high between 401 to 926 mg/L. TSS removal was between 42.31% and 81.08% indicating a moderate but inconsistent solids removal. Average TN removal was about 65% and TP removal ranged from 22.6 to 67.5%, so nutrient removal was also limited. The final effluent TN concentrations were in the range of 92 to 130 mg/L and TP concentrations were in the range of 5.2 to 57.4 mg/L, indicating that the treated effluent did not always meet the requirements for direct discharge or for agricultural reuse.

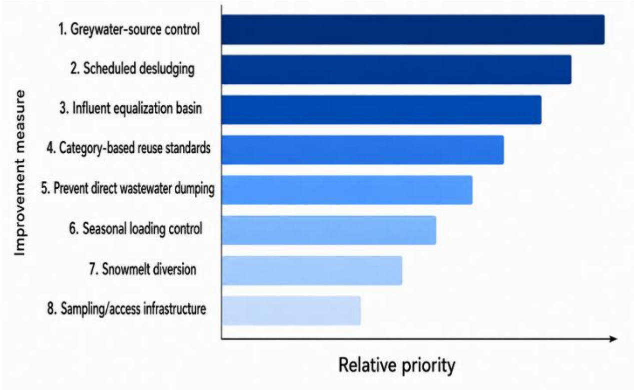


Figure 9. Prioritized improvement measures for Fayda WSPs based on observed operational problems, expected treatment benefit, and implementation urgency.

Table 5. Comparison of Jordanian wastewater reuse categories with Iraqi standards for treated wastewater reuse in irrigation.

Parameter	Unit	Cooked vegetables, parking areas, playground and side of roads inside cities	Plenteous trees and green areas, side of roads outside cities	Field crops, industrial crops and forestry	Iraqi standards for the use of treated wastewater in irrigation (Shakir *et al.* 2017; Iraqi Facts 2012)
Group		A	B	C	
BOD_5	mg/L	30	200	300	40
COD	mg/L	100	500	500	100
TDS	mg/L	1500	1500	1500	2500
TSS	mg/L	50	200	300	40
pH	unit	6.0-9.0	6.0-9.0	6.0-9.0	4-8.6
Phosphate (PO_4)	mg/L	30	30	30	25
Chloride	mg/L	400	400	400	Not specified
Total Nitrogen	mg/L	45	70	100	Not specified
Nitrates	mg/L	30	45	70	50
Sodium	mg/L	230	230	230	250
Calcium	mg/L	230	230	230	450
Magnesium	mg/L	100	100	100	80
SAR	-	9	9	9	6-9
E.coli	MPN/100 mL	100	1000	Not specified	1000
Intestinal helminth eggs	egg/L	≤1.0	≤1.0	≤1.0	Not specified

The operational assessment revealed that the system was operating below its design hydraulic capacity with an average wastewater inflow of about 8,640 m3/month against a estimated one-line design capacity of about 15,000 m3/month. Therefore, the HRT values in the present situation were higher than the original design values, reaching 5.57 days in Anaerobic Pond 1, 1.62 days in Anaerobic Pond 2, 15.5 days in the facultative pond, and 5.7 days in the maturation pond. Sludge accumulation was also considerable as the measured sludge depths were 90 cm and 85 cm in Anaerobic Ponds A1, and B1 respectively. These results confirm that the performance of the treatment was largely limited by fluctuating influent quality, high organic and nutrient loading, greywater inputs, seasonal temperature effects, sludge accumulation and operational limitations.

Results indicate that influent equalization, improved loading control, regular desludging, better control of greywater inputs and improved site infrastructure are required to enhance system stability. The study also supports the development of a category-based wastewater reuse framework in Iraq, because a single discharge limit does not adequately reflect the variable performance and potential reuse applications of WSP effluents. The study also acknowledges the important limitation of not including microbiological indicators in the performance assessment. Future studies should include microbiological monitoring, especially fecal coliforms, *E. coli*, and helminth eggs, to provide a more complete assessment of public-health risks associated with wastewater reuse. The main novelty of this study is its integration of field-based performance monitoring, operational diagnosis, and regulatory evaluation for a full-scale WSP system in a refugee-camp and host-community context, providing practical evidence for improving WSP management and wastewater reuse policy in Iraq and similar water-scarce developing regions.

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Conflict of interest

The author states that none of the work described in this publication appears to have been influenced by any known competing financial interests or personal ties.

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Table S1. Supplementary material ,raw data for the wastewater analysis.

Sample No.	Date	Test	Locations (sources for inlet)					WWTP Ponds outlets		
1	5/5/2021					*Domiz 1*	*Domiz 2*	*B1 Outlet*		*B4 Outlet*
		COD (mg/l)				4590	2750	1247		926
		TSS (mg/l)				529	440	260		140
		pH				8.18	7.8	7.84		7.92
		Temp °C				25.8	26.3	26.4		26.1
		TN (mg/l)				68.5	94.8	74.4		92
		TP (mg/l)				20	7.8	5		5.2
		SO4				160	191	143		43.3
2	16/05/2021		*Fayda*			*Domiz 1*	*Domiz 2*	*B1*	*B2 Outlet*	*B4*
		BOD	4400			1076	599	480	506	410
		COD (mg/l)	11905			1350	960	1011	712	537
		TSS (mg/l)	6485			650	528	320	316	108
		pH	6.93			7.7	7.6	7.47	7.37	7.74
		Temp °C	26.2			28.3	27.6	26.6	26.1	25.6
3	24/05/2021		*Duhok*			*Domiz 1*	*Domiz 2*	*B1*	*B2*	*B4*
		COD (mg/l)	16600			1960	1394	1820	1394	372
		TSS (mg/l)	4561			900	420	690	410	260
		pH	7.8			7.44	7.34	7.41	7.8	7.81
		Temp °C	24			24	24.2	24.3	24.1	24
4	30/05/2021		*Duhok*			*Domiz 1*	*Domiz 2*	*B1*	*B2*	*B4*
		COD (mg/l)	10221			972	783	696	612	551
		TSS (mg/l)	3583			452	285	260	235	130
		pH	7.77			7.61	7.38	7.44	7.68	7.87
		Temp °C	28.3			28	27	28.2	27.6	26.9
5	3/6/2021		*Fayda*	*Duhok*	*Domiz*	*Domiz 1*	*Domiz 2*	*B1*	*B2*	*B4*
		BOD (mg/l)	1587	3530	3191			274	238	207
		COD (mg/l)	4080	8100	12400	1103	942	734	651	639
		TSS (mg/l)	1500	6240	5020	452	285	260	170	340

		pH	7.34	7.54	7.6	7.61	7.38	7.7	8		7.69
		Temp °C	24.8	25.2	24.9			24.9	24.6		24.3
6	*July 2021*	*Test*	*Tanahi*			*Domiz 1*	*Domiz 2*	*B1*	*B2*		*B4*
		COD (mg/l)	846			1306	616	696	548		600
		TSS (mg/l)	140			420	160	360	180		140
		pH	7.7			7.7	7.5	7.7	7.94		7.97
		Temp °C	25.2			24.7	25.2	24.9	24.8		25.2
7	*August 2021*		*Domiz*					*B1*			*B4*
		COD (mg/l)	3430			3812	1860	680			792
		TSS (mg/l)	920			690	620	241			420
		pH	7.7			7.6	7.5	7.83			8.32
		Temp °C	33.6					32.9			31
8	20/09/2021					*Domiz 1*	*Domiz 2*		B2		*B4*
		COD (mg/l)				4320	2720		453		410
		TSS (mg/l)				680	1120		180		170
		pH				7.6	7.4		7.7		8
9	*Oct-21*					*Domiz 1*	*Domiz 2*	*B1 Outlet*	*B2 Outlet*	*B3 Outlet*	*B4 Outlet*
		COD (mg/l)				10400	857	774	615	659	585
		TSS (mg/l)				1835	222	380	195	165	145
		pH				7.7	7.5	7.7	7.94	7.97	8
		Temp °C				24.7	25.2	24.9	24.8	25.2	
10	*6/10/2021*					*Domiz 1*	*Domiz 2*		*B2*	*B3*	
		COD (mg/l)					890	647	601	599	587
		TSS (mg/l)				680	1120		220	230	
		pH				7.6	8		7.5	8.1	
		Temp °C				26.6	25.9		28	25.7	
		TN (mg/l)				260	410			270	106
		TP (mg/l)				142	111		125	64.5	48
11	*18/10/2021*					*Domiz 1*	*Domiz 2*		*B2*	*B3*	*B4*
		COD (mg/l)				541	699		536	497	401
		TSS (mg/l)				126	100		130	60	45
		pH				7.42	7.7		7.83	7.96	8.12
		Temp °C				27	26.5		26.6	26.8	26.5
		TN (mg/l)				410	270		180	161	130

		TP (mg/l)				82	61		80	59.8	57.4
12	*24/11/2021*		*A2 Outlet*	*A3 Outlet*	*A4 Outlet*	*Domiz 1*	*Domiz 2*	*B1 Outlet*	*B2 Outlet*	*B3 Outlet*	*B4 Outlet*
		COD (mg/l)				2860	3270	602	515	465	479
		TSS (mg/l)									
		pH				7.22	7.48	7.52	7.6	7.72	7.83
		Temp °C				25.7	25.4	25.6	25.6	25.6	24.9
13	*7/1/2022*		*A2*	*A3*	*A4*	*Domiz 1*	*Domiz 2*	*B1*	*B2*	*B3*	*B4*
		COD (mg/l)	788	547	533	2000	3260				
14	*28/02/2022*		*A1*	*A2*	*A3*	*Domiz 1*	*Domiz 2*	*B1*	*B2*	*B3*	*B4*
		COD (mg/l)	948	707	629	1430	969	831	643		429
		TSS (mg/l)									
		pH	7.75	7.9	8.2	8.05	7.75	7.95	8.1		8.35
15	*15/03/2022*		*A1*	*A2*	*A3*	*Domiz 1*	*Domiz 2*	*B1*	*B2*	*B3*	*B4*
		COD (mg/l)		880	664	1300	757		662		440
16	*10/5/2022*		*A1*	*A2*	*A3*	*Domiz 1*	*Domiz 2*	*B1*	*B2*	*B3*	*B4*
		COD (mg/l)				830	920		635	540	505