Assessment of Sewage Sludge Generation, Characteristics, and Potential Treatment Methods in Rapidly Expanding Population Regions

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Abstract–**This study assesses sewage sludge generation, characterizes its physicochemical properties, and evaluates viable treatment strategies tailored to local conditions. Grab samples were collected from two operating wastewater treatment plants (Shariya and Avro City). Sludge and wastewater were analyzed for total solids, total dissolved and suspended solids, biochemical oxygen demand, chemical oxygen demand (COD), and selected heavy metals. 35 years of climatic data were reviewed, and a socioeconomic survey was conducted. Results indicated substantial current and projected sludge volumes, about 19,895 tons of dry matter for the study area and about 51,268 tons for the governorate per year. The estimated sludge generation rate was 32.9 kg/capita/year. The sludge shows high organic content and extremely elevated COD (for example, Shariya ≈115,800 mg/L). These characteristics indicate significant potential for energy recovery via anaerobic digestion. Chemical analyses revealed localized heavy metal enrichment (notably aluminum and lead in Shariya) that constrains direct land application without pretreatment. Socioeconomically, whereas 90% of respondents reported connections to a water supply, 40% reported insufficiency. Comparison of treatment scenarios indicates that the most viable near-term options for resource recovery and pathogen reduction are low-cost sludge treatment wetlands and mesophilic anaerobic digestion. This study constitutes the first research conducted on sewage sludge management in Duhok City. The results serve as an important database that can be used by policymakers and engineers to develop a sludge management system not only for Duhok but also for other growing Iraqi cities and similar regions.**

Index Terms—**Anaerobic digestion, Duhok governorate, Sewage sludge management, Sludge characterization, Sludge treatment wetlands.**

1. Introduction

The management of sludge as a byproduct of wastewater treatment is a major global concern. Sludge production and its quality are dependent upon the characteristics of the influent and techniques applied to treat the sludge (Zeynali, et al., 2025; Vali, et al., 2025). In the Duhok Governorate in the Kurdistan Region of Iraq, where rapid development of urban areas takes place due to a lack of adequate water resources and facilities, proper sludge management is one of the technical ways that can be considered to resolve the problems.

The population of Duhok city has been growing significantly due to internally displaced persons (IDPs), increasing from 300,000 people in 2014 to over 500,000 people in 2018 (United Nations High Commissioner for Refugees, 2018). This growth has put further strains on water and sanitation services, which makes it vital to find sustainable solutions for dealing with sludge. The expansion of wastewater treatment plants (WWTPs) worldwide also means increased global sludge generation.

The main goal of traditional sludge treatment methods is to reduce sludge volume and stabilize it using methods such as thickening, dewatering, anaerobic digestion, and composting (Andreoli, Von Sperling and Fernandes, 2007). Solutions such as sludge treatment wetlands (STWs) for dewatering and stabilization through evapotranspiration (Semiyaga, et al., 2015) are ideal for Duhok, where land availability and cost are concerns, but low-cost options still exist. While anaerobic digestion requires less external energy and has lower costs to stabilize and digest the sludge, thermal treatments (e.g., incineration and supercritical water oxidation, SCWO) effectively reduce pathogens and sludge volume but require high investments and economic resources (Garrido-Baserba, et al., 2015).

In Duhok Governorate, weak regulation and a lack of centralized treatment lead to many households depending on septic tanks with unsafe disposal to land or water, leading to environmental pollution and loss of the potential for nutrient and energy recovery. This illustrates the necessity for a quickly implementable, cost-effective, flexible, and localized solution.

Many studies have been conducted on the quality of wastewater treatment and reuse in Duhok City to date (Dawud, Abdi and Umer, 2024; Mizzouri, Algabban and Hassan, 2047; Mizzouri, Kochary and Barwari, 2020, 2022; Shukri, et al., 2024; Rekani and Dohuki, 2024). However,

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there are no studies, to our knowledge, that attempt to measure the volume of sewage sludge and characterize the components of sewage sludge in Duhok Governorate. No previous research has evaluated sludge quantity, characteristics, and treatment options in this region. This study addresses that gap. Therefore, the purpose of this study was to evaluate the sewage sludge, its generation, and physicochemical characteristics as well as treatment methods potentially applicable in Duhok Governorate, Iraq. This study examines the quantity and quality of sludge produced in wastewater treatment facilities. Another goal of this study is to assist policymakers, engineers, and other interested parties by providing recommendations for sewage sludge management in Duhok and elsewhere. The authorities might be able to use the findings from Duhok and apply them in the rest of Iraq.

II. Methodology

A. Study Area and Site Description

The study area comprised the subdistricts of Sharya and Fayda, as well as Duhok City. Five camps were also involved: Kaberto 1 IDP Camp, Kaberto 2 IDP Camp, Domiz 1 Refugee Camp, Domiz 2 Refugee Camp, and Sharya IDP Camp.

To assess the environmental impact of wastewater treatment and sludge management in Duhok, the variables of climatic conditions in Duhok were analyzed using a 35-year historical climate database. Climatic conditions examined included temperature extremes, evaporation rates and precipitation. As summer evaporation rates are high and annual precipitation is low, it is vital to develop solutions for sludge handling that are environmentally sustainable.

B. Site Visits

Many site visits were conducted to the IDP and refugee camps as well as to governmental bodies such as the Sewerage Directorate, the Environment Directorate, and the Investment Directorate. This allowed for an in-depth evaluation of the state of the sanitation facilities and sludge disposal.

C. Sampling Strategy

Grab sampling was used to collect sludge samples directly from the WWTPs for accurate determination of sludge properties. For black wastewater, composite sampling was performed during discharge events of desludging trucks at the Fayda WSPs, where three incoming desludging trucks originating from the Fayda, Shariya, and Domiz districts were received and sampled. Black wastewater samples were collected following the extraction of wastewater from septic tanks and subsequent transportation by vehicles. A composite sample was taken as three distinct subsamples of 500 mL each were collected at the start, middle, and end of the vehicle discharge process. Optimal handling practices were followed, with samples preserved at low temperatures (4 ± 2°C) to inhibit microbial activity, and the analyses were performed within 8 h after collection. Monthly volumes of the black wastewater generated by the camps were calculated from recorded truck trips and the truck capacity (8–10 m^3). A total of 38 complexes were surveyed; 22 had operational treatment facilities, and effluent samples were collected from the 11 plants that held official operating licenses during 1 month.

Two WWTPs (Shariya Camp and Avro City) provided sludge samples; these sites were selected on the recommendation of the Directorate of Environment as the most successful local facilities for sludge production. A total of 6 sludge samples were collected over 3 weeks, 3 per plant, and the frequency was every week. A limitation that must be considered is that at the time of the research being carried out, there were only two WWTPs in Duhok City that had sludge produced by them, which constrained the sampling scope. As additional facilities become operational in the future, broader sampling should be undertaken. Moreover, this research paper did not explore the seasonal variations in the quality of wastewater as well as the quantity of sludge generated, which is a significant and promising subject for future research. Influent and effluent wastewater samples were analyzed alongside sludge samples to link plant performance with sludge generation.

D. Analytical Procedures

The wastewater and sludge samples were analyzed according to the Standard Methods for the Examination of Water and Wastewater (Rice, et al., 2012). Chemical oxygen demand (COD) was estimated using the 5220 C. Closed reflux titrimetric method: placing the digestion tubes in a block digester preheated to 150 ± 2°C and digesting for 2 h. Biochemical oxygen demand (BOD) was determined using the 5210 B method (5-day BOD test). Total dissolved solids (TDS) using method 2540°C with the drying method at 180°C, total suspended solids (TSS) using the 2540 D method (drying at 105°C), volatile suspended solids (VSS) through ignition at 550°C according to Method 2540 E, and total solids (TS) using Standard Methods 2540 B. pH was analyzed using HANNA (model HF 931401) (Method 4500 H+ B). Heavy metals (aluminum [Al], cadmium [Cd], chromium [Cr], copper [Cu], iron [Fe], lead [Pb], zinc [Zn], and others) were analyzed using an atomic absorption spectrophotometer (model HF 931401). Calibration standards were prepared from certified reference materials. Quality control was maintained by ensuring that all analyses were performed within 8 h of collection and that samples were stored at 4 ± 2°C to inhibit microbial activity.

E. Socioeconomic Evaluations

A targeted cohort of 19 key institutional stakeholders, including public schools, hospitals, and municipal directorates, received a standardized questionnaire. Stratified sampling was utilized to select nineteen individuals who represented the demographics of Duhok. Future work should include comprehensive household surveys to gain wider public input. There were 17 questions on sludge use and sanitation practices in the questionnaire. The Survey of the Study (Table SI) collected quantitative and qualitative data (i.e., household demographics and income, willingness to pay, and perception of health risks due to poor environmental health related to current disposal practices) on the sanitation practices. Survey responses were analyzed using descriptive statistics (frequencies, averages).

III. Results and discussion

A. Production of Black Wastewater

Black wastewater production in Duhok Governorate depends on factors including population density and soil permeability. A combination of inferences from our field measurements and assessments confirms that urban areas, particularly Zakho and Shekhan, generate significantly higher amounts of black wastewater compared to rural or camp settings. The highest black wastewater-producing cities were Zakho and Shekhan, aligning with trends from previous regional studies (Mizzouri, Kochary and Barwari, 2020; Dawud, Abdi and Umer, 2024).

The Chamishko IDP camp produced the highest volume of black wastewater (7740 m^3/month). The highest value in the refugee camps was 8000 m^3/month at Domiz 1 camp. Figs. 1 and 2 illustrate the black wastewater results.

B. Evaluation of Wastewater Treatment Facilities

Comparing the performance of WWTPs in Duhok Governorate is necessary for the reduction of the environmental impacts of wastewater disposal. The data extracted from 38 residential complexes, recognizing that not all facilities were fully operational, show a remarkably wide range in treatment plant performance. Evidence of treated wastewater generation from 22 residential complexes shows that some developments, such as in Avro City and War City, have generated large volumes of effluent wastewater (Fig. 3). Avro City, for example, has projected effluent discharges as high as 4500 m^3/d, which ties directly to the occupancy rate and completed residential units.

According to COD tests of effluent samples from 11 residential complexes, the majority of WWTPs are not achieving the Iraqi allowable limit for wastewater effluent disposal into receiving water bodies for COD set at 100 mg/L

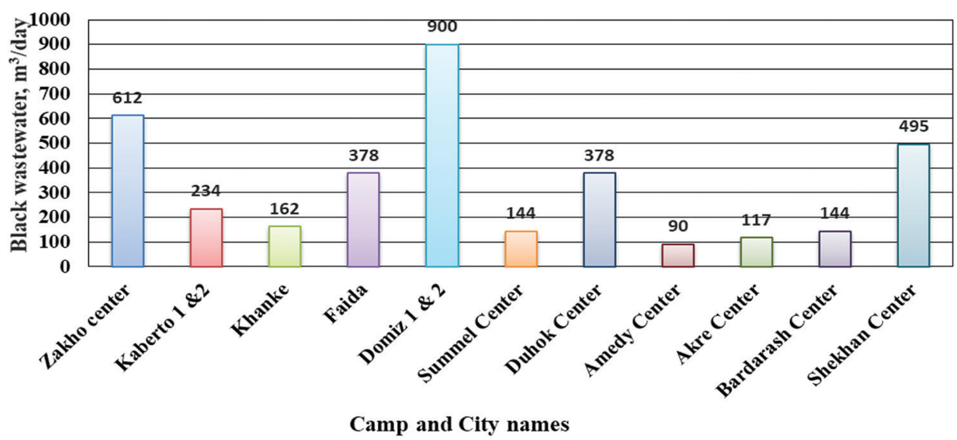

Fig. 1. Comparative analysis of daily black wastewater production (m^3/d) across major cities and camp settlements in Duhok Governorate.

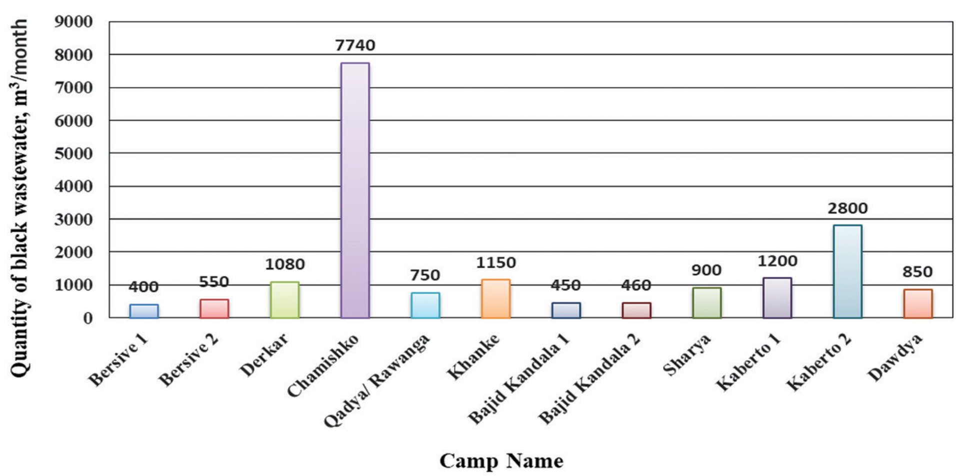

Fig. 2. Quantified monthly black wastewater generation (m^3/month) from internally displaced persons camps in Duhok Governorate.

(Iraqi regulation for the preservation of water resources [act no. B (2) 2001 amendment]) (Mizzouri, Kochary and Barwari, 2022). Only Avro City and the New Zakho project achieved COD levels below this limit (Fig. 4).

The constant exceedance of the COD values recorded in the majority of complexes indicates that there are systemic problems in the management and maintenance of these treatment facilities.

To further illustrate these deficiencies, the organic loading rate was calculated from integrated flow and COD data collected (Fig. 5). The Lelav City project, New Jin City, and Dabin had the highest organic loading rates collected from each project, with rates of 665, 470, and 332 kg/day, respectively. In addition, inadequate treatment often results from short hydraulic retention time or solid retention time. Optimizing these (along with operator training and maintenance) is a potential remedy.

C. Sludge Production

Sewage sludge is an organic and inorganic byproduct of the treatment of wastewater. It is derived from the solids that have been removed during primary clarification, the organic solids generated during the secondary treatment, and the excess biological material from suspended growth or fixed-film operations. McGhee and Steel (1991) pointed out that primary treatment removes about 60% of the suspended solids in raw wastewater. The rest of the solids are processed in the secondary treatment, producing sludge at a rate of 0.4–0.5 kg per kg of applied BOD in fixed growth processes.

In Duhok Governorate, sludge production is related to wastewater characteristics and treatment methods, as well as the population's water consumption patterns. The estimated BOD levels for domestic sewage (combined black and grey wastewater) average 400 mg/L (McGhee and Steel, 1991). With water consumption rates of 300 L/capita/day in cities and 200 L/capita/day in sub-districts, 80% of which is converted to wastewater (Finley, Barrington and Lyew, 2009), the region generates substantial sludge volumes. Fig. 6 clarifies the expected sludge production in the study areas. Fig. 7 shows the expected sludge production from different cities in Duhok governorate.

Anticipated future WWTPs will generate around 19,895 t of annual dry matter sludge (1,785 t/month) from the study

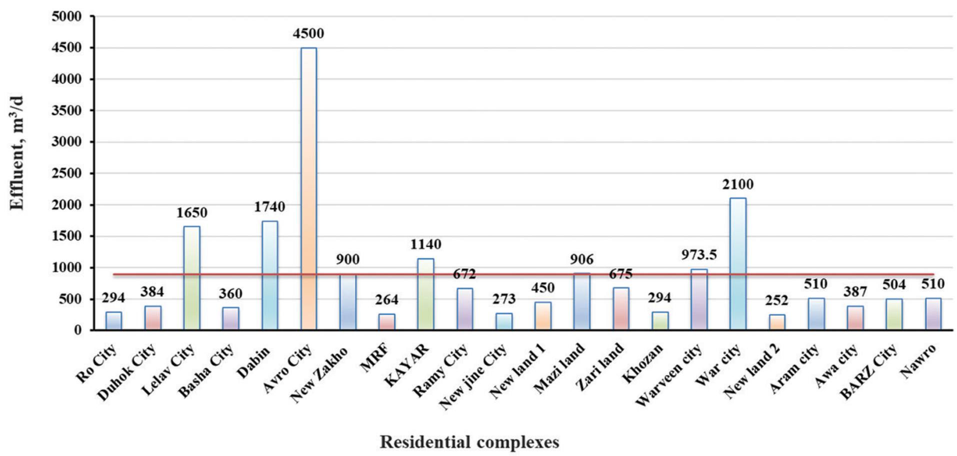

Fig. 3. Daily wastewater effluent generation (m³/d) across monitored residential complexes in Duhok governorate, with mean reference line (897 m³/d).

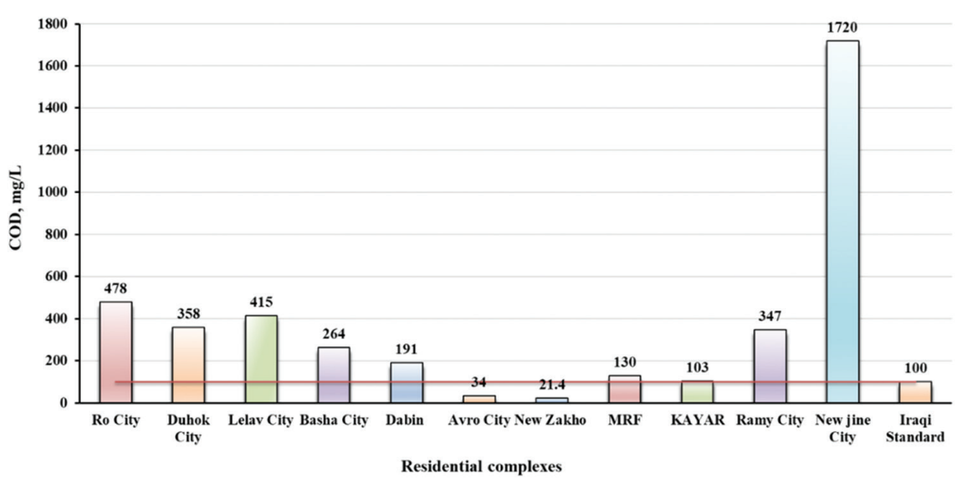

Fig. 4. Comparison of the chemical oxygen demand levels from residential complexes' effluent against the Iraqi National Standard (100 mg/L, shown as a solid red line).

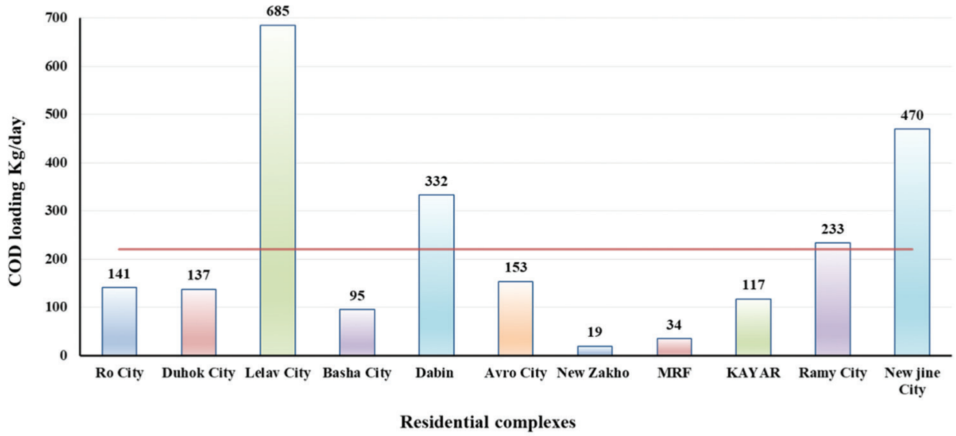

Fig. 5. Daily organic loading rates (kg chemical oxygen demand/day) entering wastewater treatment facilities at residential complexes, with mean reference line (220 kg/day).

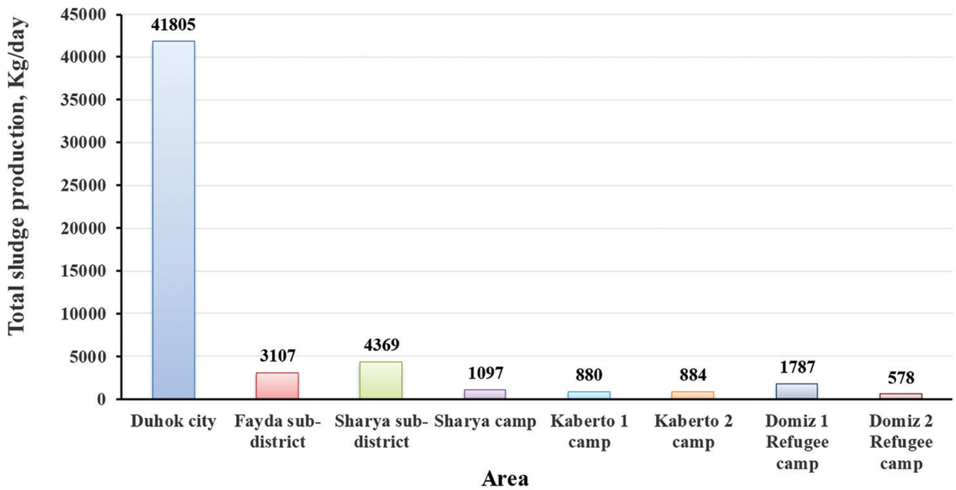

Fig. 6. Estimated daily sludge production (kg/day) for specific camps and districts within the designated study area.

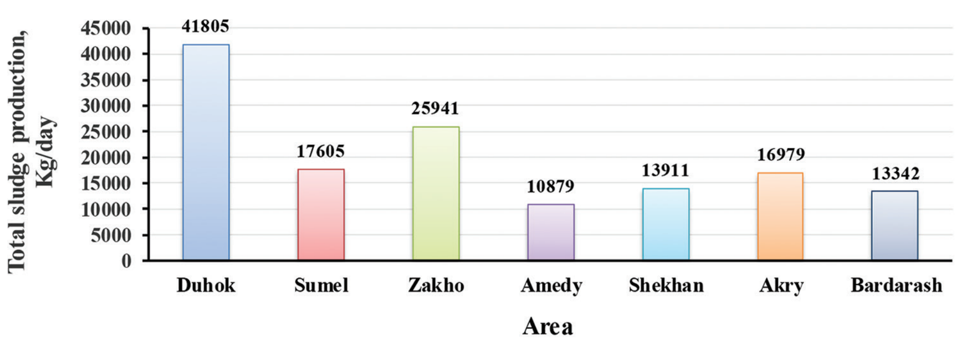

Fig. 7. Expected daily sewage sludge production (kg/day) from major urban cities in Duhok governorate.

area only. At the Duhok governorate level, the total production reaches 51,268 t of dry sludge per year. A comprehensive mass-balance sample of calculation with a detailed breakdown of the methodology and assumptions used to project future sludge production for the Duhok Governorate and study area is provided in Table SII of the supplementary material. However, we note that these projections depend partly on some literary assumptions concerning the levels of per-capita water consumption, wastewater conversion ratios, and typical BOD values rather than extensive local measurements. Whereas these assumptions suffice at this preliminary stage of the investigation, future studies need to employ more local data.

To gain insight into the significance of the rates of sludge production observed in our work, the rates of sludge production obtained in some Middle Eastern cities were compared to those observed. In the city of Greater Amman, having a population of 4.6 million people, about 85,000 tons of dry sewage sludge are produced annually, amounting to 18.5 kg/capita/year (Albtoosh, Alnsour and Abu Hajar, 2023). Similarly, Uddin et al. (2024) reported that approximately 18 kg of dry sludge is generated per person annually in Kuwait. In comparison, the projected sludge generation for Duhok Governorate, estimated at about 51,268 tons of dry matter per year for a population of approximately 1.557 million, corresponds to roughly 32.9 kg/capita/year. This comparison shows that Duhok has a much larger sludge burden per person than either Greater Amman or Kuwait. The difference is partly because the Duhok estimate is for future sludge production across the whole governorate, including both urban and rural areas, whereas the reported values for Amman and Kuwait, on the other hand, primarily reflect sludge produced by existing, fully operational WWTPs.

D. Sludge Characteristics

This study shows that sewage sludge characteristics from Duhok Governorate vary, reflecting differences in wastewater influent and treatment efficiency, as shown in Table I.

Sludge from Shariya showed significantly higher levels of TS, TDS, TSS, and organic matter (expressed in terms of mixed liquor VSS [MLVSS]) compared to Avro City. The TS for Shariya (19,900 mg/L) was more than double that for Avro City (9,160 mg/L). Notably, the 95% confidence intervals for TS at the two sites do not overlap (Shariya: 13,970-25,830 mg/L; Avro City: 6,952–11,367 mg/L), indicating a statistically significant difference. The waste sludge from Avro City yielded an MLVSS/MLSS ratio of ~0.80 (5800/7260), which meets the typical target, whereas the ratio for that from Shariya was only ~0.63 (7500/11900); the lower ratio for Shariya may indicate differences in operational or wastewater conditions between the two locations. For organic load, this trend is also applicable as Shariya's BOD (15,706 mg/L) and COD (115,800 mg/L) are higher than those from Avro City (12,664 mg/L and 107,400 mg/L, respectively). These significant differences highlight that the sludge management of the city of Duhok poses great challenges. Sludge could be used for agricultural applications after stabilization because of the high organic matter and nutrients. The COD levels in Duhok (107,400–115,800 mg/L) are high compared to benchmarks from similar climates. According to Atilla et al. (2003), the primary sludge from the Tuzla WWTP in Istanbul, Turkey, was recorded at 36,500 mg/L, whereas the secondary sludge from the Eastern Alexandria WWTP in Alexandria, Egypt, was tested at 35,355 mg/L (Nakhla et al., 2022). Based on these differences, Duhok has highly concentrated waste streams. The likely reason is that the city is expanding quickly, and the wastewater is not sufficiently diluted.

The results of chemical analysis of the black wastewater (Table II) indicate even more issues with regard to heavy metal pollution. The concentration of Al was highest in Shariya with 0.325 mg/L compared to Fayda (0.0655 mg/L) and Domiz (0.0636 mg/L). Shariya also had the highest concentration of Pb with 0.01033 mg/L, which is almost double that of Fayda with 0.00505 mg/L. The presence of high Al levels in sewage sludge is typically associated with increased human activities, i.e., the use of Al-based coagulants (like alum) in drinking water treatment facilities that then get diverted to the sewage system. Moreover, other contributing factors include runoff at construction sites (dust from cement/concrete), certain industrial effluents, and leachate from cookware. Lead contamination of sludge is man-made and emanates mainly from human actions due to the following factors: Leaching from plumbing systems, residue from previous leaded fuel use, and small-scale industrial operations such as battery refurbishment and metallurgy (Camargo, et al., 2016).

The concentrations of heavy metals in black wastewater (in mg/L) were converted to dry weight (mg/kg) for comparison with international sludge reuse standards (EU Directive 86/278/EEC, U.S. EPA 40 CFR Part 503). The conversion was performed using the TS content of the samples according to the standard equation (Rice, et al., 2012):

$$Concentration\left(\frac{mg}{kg}\right)=\frac{Concentration\left(\frac{mg}{L}\right)\times 1000}{Total\,Solids\left(\frac{g}{L}\right)} \quad (1)$$

TABLE I

A Comparative Analysis of Sludge Characteristics Against Various Statistical Parameters between Avro City and Shariya (TS, TSS, TDS, MLVSS)

Characteristics	Avro city				Shariya			
	Mean±SD	Range (Min-Max)	Coefficient of variation (CV%)	Confidence intervals (95% CI)	Mean±SD	Range (Min-Max)	Coefficient of variation (CV%)	Confidence intervals (95% CI)
pH	7.8±0.17	7.7–8	2.2	7.61, 7.99	8±0.1	7.9–8.1	1.2	7.89, 8.11
TS, mg/L	9160±1950.4	7420–11310	21.6	6952, 11367	19900±5240.2	14000–24100	26.4	13970, 25830
TDS, mg/L	1900±351.8	1650–2300	18.4	1502, 2298	8000±1585.5	6210–9140	19.6	6206, 9794
TSS, mg/L	7260±1904.5	5340–9140	26.1	5105, 9415	11900±1297.8	10390–12740	11.0	10431, 13369
MLVSS, mg/L	5800±360.6	5500–6200	6.2	5392, 6208	7500±889.9	6480–8190	12.0	6493, 8507
BOD_5, mg/L	12664±1507	10910–13822	12.2	10959, 14369	15706±2339.8	14290–18370	14.7	13052, 18348
COD, mg/L	107400±8880.8	96310–113490	8.9	97351, 117449	115800±2153.2	113400–117700	1.9	113364, 118237

Values are presented as mean±SD, and ranges and 95% confidence intervals (95% CI) are shown. All concentration-type measurements are in mg/L (unless otherwise indicated). Coefficient of variation (CV) is in percent (%). pH is dimensionless. TS: Total solids, TSS: Total suspended solids, TDS: Total dissolved solids, BOD: Biochemical oxygen demand, COD: Chemical oxygen demand, MLVSS: Mixed liquor volatile suspended solids, SD: Standard deviation

TABLE II
Chemical Examination of Black Wastewater

S. No.	Characteristics	Fayda	Shariya	Domiz
1.	Aluminum, mg/L	0.0655	0.325	0.0636
2.	Cadmium, mg/L	0.00065	0.00088	0.00084
3.	Calcium, mg/L	94.4	74.6	81.5
4.	Chromium, mg/L	0.0053	0.01715	0.0024
5.	Cobalt, mg/L	Nil	Nil	Nil
6.	Copper, mg/L	0.4282	0.4272	0.4152
7.	Iron, mg/L	0.1832	0.1781	0.4902
8.	Lead, mg/L	0.00505	0.01033	0.00846
9.	Lithium, mg/L	0.3	0.2	0.2
10.	Manganese, mg/L	0.1978	0.2760	0.1436
11.	Nickel, mg/L	Nil	Nil	Nil
12.	Potassium, mg/L	160	77	41
13.	Sodium, mg/L	530	337	168
14.	Zinc, mg/L	0.2417	0.2445	0.2160
15.	Magnesium, mg/L	26.26	37.85	28.25

All values are concentrations in mg/L. "Nil" indicates concentration below detectable limits

Using the Shariya sample as an example (TS = 19,900 mg/L; Table I), the converted concentrations are Al ≈ 16.3 mg/kg dry weight and Pb ≈ 0.52 mg/kg dry weight (other converted values: Cd ≈ 0.044, Cr ≈ 0.86, Cu ≈ 21.5, Zn ≈ 12.3 mg/kg; all dry-weight basis). These values were compared with the EU Directive 86/278/EEC and US EPA 40 CFR Part 503 pollutant concentration thresholds (both reported on a dry-weight basis). The EU Directive prescribes member-state limit ranges for several metals (e.g., Cd ~20–40 mg/kg; Cu ~1,000–1,750 mg/kg; Pb ~750–1,200 mg/kg; Zn ~2,500–4,000 mg/kg), and the US EPA Part 503 gives ceiling/benchmark concentrations (e.g., Cd 39, Cu 1,500, Pb 300, Zn 2,800 mg/kg) (Snyman, Herselman and Tesfamariam, 2024). In conclusion, all converted metal concentrations (including Al, Pb, Cd, Cr, Cu, and Zn in the Shariya sample) fall well below the EU 86/278/EEC and US EPA (40 CFR Part 503) concentration thresholds for land application (i.e., they do not exceed the directive or Part 503 limits). Furthermore, the calculated dry-weight metal concentrations are also compliant with the Republic of Iraq's national Instruction No. 1 (2016) limits for agricultural use (e.g., Pb: 300, Cu: 1500, Zn: 2800, Cd: 39 mg/kg) (Al-Obaidi, Al-Anbari and Hassan, 2021).

The analyzed sludge shows potential for agricultural use after stabilization due to its high organic matter and nutrient content. Nonetheless, since heavy metals were found to be detectable in the liquid sludge, particularly Al (0.325 mg/L) and Pb (0.01033 mg/L) in Shariya, the data must be treated with care. Although the dry-weight concentrations were lower than those stipulated by EU Directive 86/278/EEC and US EPA 40 CFR Part 503 (Al ≈ 16.3 mg/kg, Pb ≈ 0.52 mg/kg), direct application of untreated liquid sludge on land is not recommended because metals may accumulate in soils over time. At the same time, cultivated crops and popular vegetables and fruits need specific pretreatment or additional management strategies to remove heavy metals instead of entering the food chain. A second approach to controlling heavy metals in the soil is the use of phytoremediation, where non-edible, purpose-grown plants are used. For example, sunflowers (Helianthus annuus) are known to be effective in accumulating Pb and other metals from contaminated soil and, therefore, can also be used for phytoextraction or phytostabilization if properly utilized (Chauhan, et al., 2020).

The COD value in Shariya's sludge (115,800 mg/L) was significantly high. This indicates that the sludge in Duhok possesses significant potential for energy recovery via anaerobic digestion. However, its elevated heavy metal levels indicate that biological treatment should be used with other methods, such as thermal hydrolysis, to ensure safe reuse.

E. Socioeconomic Impacts

The socioeconomic questionnaire provided important information about the household characteristics in Duhok Governorate, the state of the water supply, and how people feel about dealing with wastewater and sludge. For the results of the socioconomic questionnaire (Table SI).

The average household size of 4.47, which is relatively small, has a direct effect on the amount of sludge and sewage produced. Most people had moderate incomes. There is potential to create cost-recovery mechanisms for wastewater and sludge treatment programs, given the 19 respondents' positive willingness to pay for improved water and sanitation services.

The data show that most households use septic tanks for fecal sludge management, and only two individuals stated they were linked to WWTPs. Relying on septic tanks is hard to justify because poorly processed or managed sludge will affect the environment. Thirteen respondents did not identify any significant environmental problems, although some did identify problems, such as odors from open sewage and pollutants from power plants. The water supply situation varied significantly from house to house, with 90% of homes connected to a water distribution system; however, 40% of homeowners perceived that their water supply was insufficient for their households.

F. Sludge Treatment Technologies and Integrated Management Strategies for Duhok Governorate

Choosing the right technology is critical for reducing sludge production at wastewater treatment facilities, stabilizing organics and pathogens, and recovering resources from sludge. Dewatering and stabilization are complementary processes, with dewatering removing water to minimize the volume to be transported and disposed of and stabilization dealing with the reduction of biodegradable organics and the pathogens to ensure safe reuse or disposal (Andreoli, Von Sperling and Fernandes, 2007). Table III presents a comparative evaluation of the treatment of sewage sludge systems with regards to the performance and cost parameters.

In Duhok, the consideration of cost-effectiveness is vital. The STWs incur lower operational and administrative costs. Another major consideration is that mesophilic anaerobic digestion provides an excellent method for recover nutrient and biogas, whereas thermophilic anaerobic digestion could

TABLE III
Comparative Assessment of Sewage sludge Treatment Technologies Based on Key Performance and Economic Criteria

Technology	Capital cost	O&M Cost	Pathogen reduction	GHG emissions	References
Sludge treatment wetlands	Very Low	Very Low	Moderate	Neutral to low	(Uggetti, et al., 2010)
Anaerobic digestion (Mesophilic)	Medium	Medium	Moderate	Negative	(Appels, et al., 2011; Cao and Pawłowski, 2012)
Anaerobic digestion (Thermophilic)	High	High	High	Negative	(Cao and Pawłowski, 2012; Suryawanshi, Chaudhari and Kothari, 2010)
Incineration	Very High	Very High	Very High (Complete)	High	(Garrido-Baserba, et al., 2015; Moharir, Gautam and Kumar, 2019)
Gasification	Very High	High	Very High (Complete)	Medium	(Fericelli, 2011; Garrido-Baserba, et al., 2015)
Supercritical water oxidation	Extremely High	High	Very High (Complete)	Low	(Garrido-Baserba, et al., 2015; Marrone, 2013)

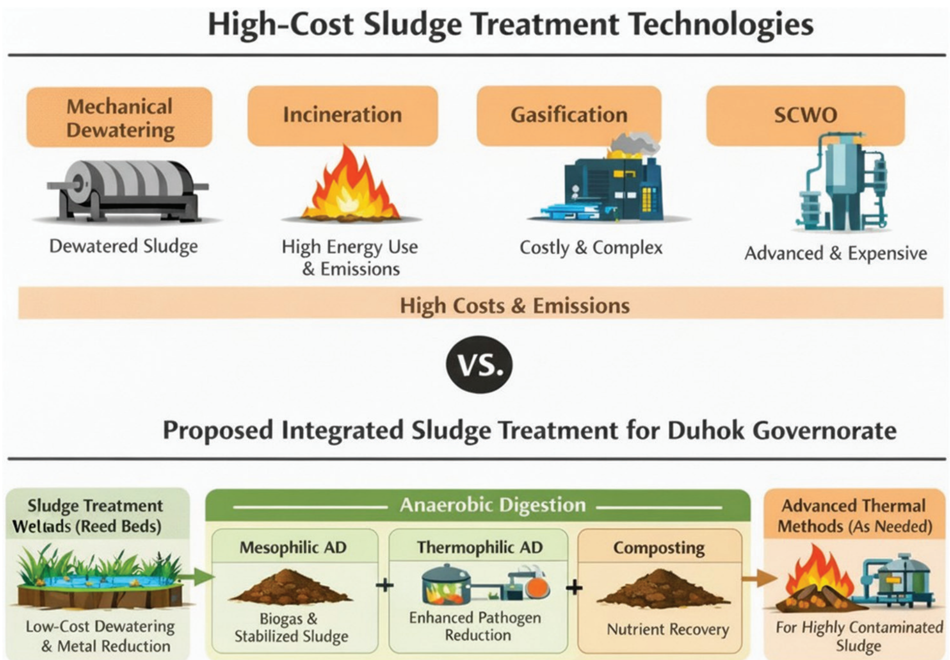

Fig. 8. Schematic comparison of conventional high-cost sludge treatment technologies and the proposed integrated sludge management framework for Duhok governorate.

enhance performance at the expense of increased capital investment (Cao and Pawłowski, 2012).

There are several factors impacting the amount of sewage sludge in Duhok Governorate, including: High volumes, inconsistent composition, financial constraints, and particular/immediate concerns such as heavy metals in Shariya. An integrated solution is recommended; STWs with separate facilities for dewatering processes, stabilization processes, and removing pathogens/metals, along with both types of anaerobic digestion (mesophilic for cost-effectiveness, thermophilic if concerns about pathogens) for volume reduction, biogas energy recovery, and stabilization. If heavy metals are severely contaminated, thermal methods (gasification preferred over incineration) may be a solution, but only if economically built upon via partnerships or funding from elsewhere. STWs and AD were identified as the most viable based on economic, technical, and environmental criteria. STWs provide low capital and operational costs as well as heavy metal immobilization. Technically, AD efficiently manages the identified high organic loads whereas providing environmental benefits through energy recovery. This approach balances resource recovery with local financial constraints better than advanced thermal alternatives. Fig. 8 presents a conceptual diagram of high-cost sludge treatment options versus the proposed low-cost, integrated sludge management strategy in Duhok Governorate.

G. Recommendations for Improved Sewage Sludge Management in Duhok Governorate

This study offers the following recommendations to enhance sewage sludge management in Duhok Governorate:

- In the short-term, establish STWs (reed beds) to stabilize sludge and produce biosolids that are safe from heavy metals and pathogens
- A single authority, preferably the Directorate of Environment, should be designated to regulate sludge management
- Focus on Technologies that work well in the local context, thus ensuring the economic feasibility, environmental sustainability, and social acceptance

- Encourage private sector investment in WWTP and sludge treatment projects. Improve the economic feasibility of sludge reuse, particularly for agricultural applications, by encouraging on-site processing and local partnerships
- Cities with high black wastewater production, such as Zakho and Shekhan, should be prioritized in future sludge management plans.

IV. Conclusion

This study offers a comprehensive evaluation of sewage sludge management challenges in Duhok Governorate and examines potential solutions. The principal finding is that the governorate faces a considerable and growing sludge management crisis. The annual production exceeds 51,000 t of dry sludge. Characterization of this sludge reveals its high organic matter and nutrient content, which present opportunities for resource recovery. However, elevated levels of heavy metals such as Al and Pb may pose significant environmental and public health risks.

The findings collectively support an integrated, tiered management framework.

First, deploy low-cost STWs for decentralized dewatering, stabilization, and partial metal immobilization. Second, combine wetlands with mesophilic anaerobic digestion to achieve biogas energy recovery and enhanced stability. Finally, reserve the advanced thermal option (SCWO) for metal-impacted streams where financing and technical capacity permit. This combination balances cost, performance, pathogen control and resource recovery.

This study demonstrates that integrating low-cost, land-intensive technologies such as STWs with energy recovery systems provides a viable model for sustainable sludge management in rapidly urbanizing regions with similar climatic and economic constraints.

References

Albtoosh, A.F., Alnsour, M.A., and Abu Hajar, H.A., 2023. *Sustainable Management of Sewage Sludge in Jordan - as-Samra Wastewater Treatment Plant. A Case Study*. [MSc Thesis, ISRA University].

Al-Obaidi, A.R., Al-Anbari, R.H., and Hassan, M.S., 2021. Sewage sludge reuse in concrete industry: A review. *IOP Conference Series Earth and Environmental Science*, 779(1), p.012010.

Andreoli, C.V., Von Sperling, M., and Fernandes, F., 2007. *Sludge Treatment and Disposal*, IWA Publishing, London.

Appels, L., Lauwers, J., Degrève, J., Helsen, L., Lievens, B., Willems, K., Van Impe, J., and Dewil, R., 2011. Anaerobic digestion in global bio-energy production: Potential and research challenges. *Renewable and Sustainable Energy Reviews*, 15, pp.4295-4301.

Atilla, B., Yangin-Gomec, C., Altinbas, M., and Ozturk, I., 2003. Anaerobic digestion of municipal sludges with high silt content using granular seed. *Journal of Environmental Science and Health Part A*, 38(10), pp.2369-2379.

Camargo, F.P., Sérgio Tonello, P., Dos Santos, A.C.A., and Duarte, I.C.S., 2016. Removal of toxic metals from sewage sludge through chemical, physical, and biological treatments-a review. *Water Air and Soil Pollution,* 227, p.433.

Cao, Y., and Pawłowski, A., 2012. Sewage sludge-to-energy approaches based on anaerobic digestion and pyrolysis: Brief overview and energy efficiency assessment. *Renewable and Sustainable Energy Reviews*, 16, pp.1657-1665.

Chauhan, P., Rajguru, A.B., Dudhe, M.Y., and Mathur, J., 2020. Efficacy of lead (Pb) phytoextraction of five varieties of *Helianthus annuus* L. From contaminated soil. *Environmental Technology and Innovation*, 18, p.100718.

Dawud, K.I., Abdi, S.I., and Umer, M.I., 2024. Assessment of municipal waste water of Duhok district and its usefulness for irrigation. *Indonesian Journal of Social and Environmental Issues*, 5(2), pp.171-181.

Fericelli, P.D., 2011. *Comparison of Sludge Treatment by Gasification vs. Incineration*. University of Central Florida, Florida.

Finley, S., Barrington, S., and Lyew, D., 2009. Reuse of domestic greywater for the irrigation of food crops. *Water, Air, and Soil Pollution*, 199(1-4), pp.235-245.

Garrido-Baserba, M., Molinos-Senante, M., Abelleira-Pereira J.M., Fdez-Güelfo, L.A., Poch, M., and Hernández-Sancho F., 2015. Selecting sewage sludge treatment alternatives in modern wastewater treatment plants using environmental decision support systems. *Journal of Cleaner Production*, 107, pp.410-419.

Marrone, P.A., 2013. Supercritical water oxidation-current status of full-scale commercial activity for waste destruction. *The Journal of Supercritical Fluids,* 79, pp.283-288.

McGhee, T.J., and Steel, E.W., 1991. *Water Supply and Sewerage*. McGraw-Hill, United States.

Mizzouri, N.S., Algabban, M.M.J., and Hassan, H.M., 2017. Assessment of grey water disposal and different treatment options for Domiz camp in Duhok City. *Journal of Duhok University*, 20, pp.184-195.

Mizzouri, N.S., Kochary, S.A., and Barwari, N., 2022. Decentralized sanitation solutions for temporal internally displaced people (IDPs) and refugees camps and residential complexes in Duhok province-case study. *Ain Shams Engineering Journal*, 13, p.101706.

Mizzouri, N.S., Kochary, S.A., and Barwari, N., 2020. Decentralized/semi-centralized sanitation solutions in Duhok governorate-case study. In: *6th International Engineering Conference "Sustainable Technology and Development" (IEC)*. IEEE, United States, pp.1-6.

Moharir, R.V., Gautam, P., and Kumar, S., 2019. Waste treatment processes/technologies for energy recovery. In: *Current Developments in Biotechnology and Bioengineering*. Elsevier, Netherlands, pp.53-77.

Nakhla, S.F., Arafa, A., Naga, I.S., Mohamed, M., Alsherbeny, H.A., Fahmi, N.M., Hosny, H., and Moussa, S., 2022. Primary and secondary sludge treatment using ionizing radiation technology in Alexandria, Egypt. *Applied Radiation and Isotopes*, 181, p.110101.

Rekani, O.A.O., and Dohuki, M.S.M., 2024. Assessment of filter efficiency in recycling wastewater for irrigation purposes using physicochemical processes in Semel district/Duhok-KR, Iraq. *Annals of Forest Research*, 67(1), pp.41-54.

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, United States.

Semiyaga, S., Okure, M.A.E., Niwagaba, C.B., Katukiza, A.Y., and Kansiime, F., 2015. Decentralized options for faecal sludge management in urban slum areas of Sub-Saharan Africa: A review of technologies, practices and end-uses. *Resources Conservation and Recycling*, 104, pp.109-119.

Snyman, H.G., Herselman, J.E., and Tesfamariam, E.H., 2024. *The Development of a Framework for the Review of the Sludge Management Guidelines*, *Water Research Commission*, [WRC Report No. 3164/1/24].

Shukri, A.H., Mizzouri, N.S., Saifadeen, A., Saleem, D., and O'Malley, M., 2024. Assessing and improving the sanitation services in Kabarto 2 IDP camp using the smart sanitation approach. *Ain Shams Engineering Journal*, 15, p.102593.

Suryawanshi, P.C., Chaudhari, A.B., and Kothari, R.M., 2010. Thermophilic anaerobic digestion: The best option for waste treatment. *Critical Reviews in Biotechnology*, 30, pp.31-40.

Uddin, S., Zaman, M., Martínez-Guijarro, K., Al-Murad, M., Behbehani, M., Habibi, N., and Al-Mutairi, A., 2024. Sewage sludge as soil amendment in arid soils - a trace metal, nutrient and trace organics perspective. *Emerging Contaminants*, 11, p.100420.

Uggetti, E., Ferrer, I., Llorens, E., and García, J., 2010. Sludge treatment wetlands: A review on the state of the art. *Bioresource Technology*, 101, pp.2905-2912.

United Nations High Commissioner for Refugees (UNHCR)., 2018. Iraq: UNHCR Operational Update. Available from: https://www.unhcr.org/iraq.html [Last accessed on 2025 Jul 15].

Vali, N., Zabihi, S., Shamim, S., Mohsenzadeh, A., and Pettersson, A., 2025. Slow-pyrolysis of municipal sewage sludge: Biochar characteristics and advanced thermodynamics. *Biomass Conversion and Biorefinery*, 15, pp.21045-21065.

Zeynali, R., Asadi, M., Ankley, P., Mahoney, H., Brinkmann, M., Acharya, B., Mcphedran, K., and Soltan, J., 2025. Smart municipal wastewater treatment sludge management: Enhancement of biogas production from anaerobic digestion amended by optimized sludge-derived biochar. *Science of The Total Environment*, 989, p.179860.

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Supplementary Tables

TABLE S1
The Results of the Socioeconomic Questionnaire

Socioeconomic impacts	Responses
Number of persons per household	Average 4.47
Household income level	4 good, 15 medium, and 1 poor
Willingness and ability to pay of the households for water and sanitation services.	19 positive and one blank
Current migration patterns of household members	2 no, and 18 blank
Current type of water supply, current quantities and costs for water per household	2 wells, 18 water supply network/7 mentioned 10000, and the rest mentioned depending on area
Is there a sewage system in the area? Where is it discharged to? If no, how do you deal with the wastewater? Are you experiencing any problems with wastewaters/sewage?	5 yes. 8 no and the rest mentioned septic tanks
Current fecal sludge management practices at the household and community level.	Two referred to WWTP, and the rest referred to septic tanks
Current use of drinking water for other than human purposes, e.g., watering small gardens, livestock farming, others	6 no, and 14 mentioned for the garden
What are the main sources of water? Is it enough?	10 yes, 8 no and 2 blank
How is the solid waste handled? Do you experience any problems regarding solid waste disposal?	Municipality/19 mentioned no, and one mentioned that they leave some solid waste behind
Are you aware of any widespread and/or contagious diseases in the area (for the last 5 years)?	19 no and 1 blank
Do you have any environmental problems in your area? If so, what are they?	13 no, 2 odor from the smoke of the electrical production plant, 2 bad odor, 1 unpaved roads, 1 open sewers, and 1 burning the garbage
Do you have any agricultural problems in your area, if so what are they?	19 no and 1 mentioned irrigation using black wastewater
Are there any people who are very poor/dependent upon benevolent support from others? If yes, how many	5 mentioned no, and the rest yes and the numbers mentioned are from 4 to 50000
Do you think there are any groups that could particularly benefit from the sludge treatment project?	11 yes, 1 no, and the rest don't know
Do you think there are any groups that could particularly be prone to the adverse effects of the sludge treatment project?	10 yes, 7 no, 3 don't know
Are there any people whose lands will be deducted in this area?	4 no, 3 yes, and the rest don't know

WWTP: Wastewater treatment plants

Sample of calculations for the expected sludge production

Assuming 90 g/day per capita of suspended solids in raw domestic wastewater, and 60% will be removed in primary clarification. In addition, 0.5 kg/kg BOD_5 applied to secondary treatment will be produced as sludge and assume average BOD_5 is 400 mg/L for the future sewerage system that combines black and grey wastewater. The water consumption inside the cities was assumed to be 300 L/c.d, and the water consumption inside the subdistricts was assumed to be 200 L/c.d, and according to 80% to be converted to wastewater (Finley, et al., 2009). Table SII(A) and Fig. 6 clarify the expected sludge production in study areas. Table SII(B) and Fig. 7 show the expected sludge production from different cities in Duhok governorate.

The expected annual quantity of sewage sludge from the assumed WWTP for the study area is 19895 tons of sludge (dry matter). At the same time, the expected annual quantity of sewage sludge from the assumed WWTPs for all Duhok governorate is 51268 tons of sludge.

Sludge production in primary clarification for Duhok City, kg/day = $90 \times 409854 \times 0.6/1000 = 22132.12$ kg/d

Sludge production in secondary clarification for Duhok City, kg/day = $409854 \times 300 \times 400 \times 0.8 \times 0.5/1000000 = 19672.99$ kg/d

Total sludge production for Duhok City, kg/d = $22132.12 + 19672.99 = 41805.11$ kg/d

Total sludge production for the study area = $(54508 \times 365)/1000 = 19{,}895$ tons/year

Total sludge production for Duhok governorate = $(140461 \times 365)/1000 = 51{,}268$ tons/year

TABLE SII (A)
Expected Sludge Production in Study Areas

Area	Population	Water cons. LPCD	Sludge production in primary clarification, kg/day	Sludge production in secondary clarification, kg/day	Total Sludge production, kg/day
Duhok city	4,09,854	300	22,132.12	19673	41805
Fayda sub-district	36,129	200	1,950.97	1156	3107
Sharya sub-district	50,800	200	2,743.20	1626	4369
Sharya camp	16,420	80	886.68	210	1097
Kaberto 1 camp	13,504	70	729.22	151	880
Kaberto 2 camp	13,565	70	732.51	152	884
Domiz 1 Refugee camp	26,884	78	1,451.74	336	1787
Domiz 2 Refugee camp	8,750	75	472.50	105	578
Total	5,75,906		31,098.92	23409	54508

TABLE SII (B)
Expected Sludge Production from Different Cities in Duhok Governorate

Area	Population, end of 2018	Water cons. LPCD	Sludge production in primary clarification. Kg/day	Sludge production in secondary clarification, Kg/day	Total Sludge production, kg/day
Duhok	4,09,854	300	22,132.13	19673	41805
Sumel	2,04,706	200	11,054.15	6551	17605
Zakho	3,01,635	200	16,288.29	9652	25941
Amedy	1,26,504	200	6,831.19	4048	10879
Shekhan	1,61,751	200	8,734.56	5176	13911
Akry	1,97,431	200	10,661.25	6318	16979
Bardarash	1,55,140	200	8,377.56	4964	13342
Total	15,57,021		84,079.13	56382	140461
					51,268 tons/year