Suitability of the Modified Bardenpho process for faecal sludge treatment in Kumasi, Ghana

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Suitability of the Modified Bardenpho process for faecal sludge treatment in Kumasi, Ghana

A thesis presented for the degree of Environmental Engineering MSc

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Abstract

The Kumasi Wastewater Treatment Plant is a recently constructed faecal sludge treatment plant located in Kumasi, Ghana. It is designed to treat 1000 m^3/d of faecal sludge. It is the first plant employing the Modified Bardenpho process for faecal sludge. A mixed-method approach was used to assess the suitability of the Bardenpho process for faecal sludge treatment. The characteristics of the received faecal sludge were examined, as well as the treatment performance in terms of removal efficiency and compliance with local effluent quality guidelines. Measurements were carried out to assess process functioning, and interviews were conducted with employees to investigate the impact of the following aspects on the performance: a) design and layout, b) operations and maintenance, c) quality control and d) data management. A high variability in quantity and quality was observed (median ± standard deviation: 917 ± 146.5 m^3/d; 4208 ± 5007 mg/L COD; 628 ± 468 mg/L TN; 40 ± 42.8 mg/L TP). Critical parameters in terms of median compliance with the Ghana EPA effluent discharge guidelines were NH_4^+-N (10.7 mg/L), NO_3^--N (122 mg/L), TP (11.3 mg/L) and E. coli (>10^5 cfu/100mL). The median removal efficiencies were 95% for COD, 99% for TSS, 96% for NH_4^+-N, 73% for TN and 71% for TP. The Bardenpho process was not taking place as designed with no actual anaerobic zone, likely caused by a high return activated sludge flow. Some of the installed technologies were not performing as anticipated and poorly planned infrastructure resulted in disturbances. The dependence on the import of high-cost materials with insufficient supply chains was found to lead to frequent shortages of the required materials for operations, maintenance and quality control, causing inconsistent operation and an impaired treatment. A lack of training and technical knowledge was identified. Standard laboratory practices are not always followed, resulting in inaccurate measurements. Data recording and storage systems were found to be insufficiently organised. Collected data is not readily available for analysis and decision making. The Bardenpho process did not seem to provide the required flexibility under highly variable conditions and was found to be not suited for faecal sludge treatment, especially in a resource-limited setting. Further research is needed to identify strategies for a sustainable and effective operation of the plant and to investigate whether biological phosphorus removal is feasible.

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Table of Contents

Abstract i

Acknowledgements ii

List of Acronyms and Abbreviations v

1 Introduction 1

1.1 Faecal Sludge Management 1

1.2 Challenges of Faecal Sludge Treatment Plants 1

1.2.1 Treatment Concerns 1

1.2.2 Management Concerns 1

1.3 The Modified Bardenpho Process 2

1.4 Scope and Objective 3

2 Materials and Methods 4

2.1 Study Setting 4

2.2 Research Approach 5

2.3 Characterisation of Received Faecal Sludge 6

2.3.1 Influent Quantity 6

2.3.2 Influent Quality 6

2.4 Performance Assessment 6

2.4.1 Treatment Performance 6

2.4.2 Measurement Campaign 7

2.4.3 System Understanding 7

2.5 Performance Limiting Factors 8

2.5.1 Semi-Structured Interview for a General Assessment 8

2.5.2 Design and Layout 8

2.5.3 Operations and Maintenance 9

2.5.4 Quality Control 9

2.5.5 Data Management 9

2.6 Data Analysis 9

3 Results and Discussion 10

3.1 Characterisation of Received Faecal Sludge 10

3.2 Performance Assessment 13

3.2.1 Treatment Performance 13

3.2.2 System Understanding 14

3.3 Limiting Factors 19

3.3.1 Design and Layout 19

3.3.2 Operations and Maintenance 21

3.3.3 Quality Control 22

3.3.4 Data Management 23

4 Conclusions and Recommendations 25

References **28**

A Effluent Discharge Guidelines **31**

B Collected Quantitative Data **32**

C Methods, Materials and Devices **35**

D Semi-structured Interview Questions for KWWTP Staff **37**

E Semi-structured Interview Questions for Truck Drivers **39**

F Additional Figures for Section 3.1 **40**

G Additional Figures for Section 3.2 **43**

H Calculation of HRT and SRT **53**

List of Acronyms and Abbreviations

AAS	Atomic Absorption Spectrometer
BOD_5	Five-Day Biochemical Oxygen Demand
Ca	Calcium
$Ca(OH)_2$	Calcium Hydroxide or Lime
COD	Chemical Oxygen Demand
Cd	Cadmium
Cr	Chromium
DO	Dissolved Oxygen
EBPR	Enhanced Biological Phosphorus Removal
EC	Electrical Conductivity
EPA	Environmental Protection Agency
$FeCl_3$	Ferric Chloride
FS	Faecal Sludge
FSM	Faecal Sludge Management
FSTP	Faecal Sludge Treatment Plant
HRT	Hydraulic Retention Time
IR	Internal Recycle
JGC	Jospong Group of Companies
KCARP	Kumasi Compost and Recycling Plant
KNUST	Kwame Nkrumah University of Science and Technology
KWWTP	Kumasi Wastewater Treatment Plant
Mg	Magnesium
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
Na	Sodium
NaOCl	Sodium Hypochlorite
NH_4^+-N	Ammonium Nitrogen
Ni	Nickel
NO_3^--N	Nitrate Nitrogen
O&M	Operations and Maintenance
PAC	Poly Aluminium Chloride
PAO	Phosphorus Accumulating Organism
PHA	Polyhydroxyalkanoate
Pb	Lead
PC	Primary Clarifier
PE	Poly Electrolyte
QA/QC	Quality Assurance/Quality Control
RAS	Return Activated Sludge
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
SRT	Sludge Retention Time
SSGL	Sewerage Systems Ghana Limited
SV30	30-Minute Settled Sludge Volume
TDS	Total Dissolved Solids
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solids
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
WWTP	Wastewater Treatment Plant

1 Introduction

1.1 Faecal Sludge Management

With less than ten years left to achieve the Sustainable Development Goals (SDGs), 46% of the world's population still lack access to safely managed sanitation and 44% of wastewater is not safely treated. In Ghana, the shares are even higher, with 87% of the population lacking access to safe sanitation services and 88% of the generated domestic wastewater not being safely treated (UN-Water, 2021). The implications for public health are severe, it is estimated that approximately 5000 annual deaths are related to unsafe water, sanitation and hygiene practices in Ghana (World Health Organization, 2014).

The sanitation service chain includes the storage, collection, transport, treatment and end use or disposal of excreta (Tilley et al., 2014). Faecal sludge (FS) consists of combinations of excreta and blackwater, with or without greywater, collected in onsite sanitation technologies, which are commonly found in lower income countries. Contrary to wastewater, FS has not been transported in a sewer. Faecal sludge management (FSM) considers the whole sanitation service chain (Strande et al., 2014).

In the city of Kumasi, 93% of the population use onsite sanitation (Peal et al., 2020). The most common toilet facilities are dry toilets with improved pit latrines or flush systems connected to septic tanks (Ghana Statistical Service, 2022). Toilets are most commonly shared within traditional compound housing (Antwi-Agyei et al., 2020) while a further 40% rely on public toilets (Ghana Statistical Service, 2013). Previously, the share of FS delivered to treatment but not treated has been found to be especially high in Kumasi (Peal et al., 2020). Groundwater is frequently contaminated with faecal coliforms (Aboagye & Zume, 2019; Appiah-Effah et al., 2021). In 2021, a new faecal sludge treatment plant (FSTP) for Kumasi was constructed, designed to use the Modified Bardenpho process in an activated sludge system.

1.2 Challenges of Faecal Sludge Treatment Plants

1.2.1 Treatment Concerns

The strength of FS is typically much higher than of wastewater transported in a sewer. The quantity and quality are found to be very variable due to a high diversity of sanitation technologies with different toilet usages (e.g., dry or flush systems), containment systems (e.g., lined or unlined pits) and storage durations. FS characteristics can also be impacted by climatic seasons and materials (e.g., solid waste or chemicals) added to the onsite system. It was established that FS behaves differently compared to wastewater and wastewater sludge. FS is usually intermittently delivered to FSTPs by collection trucks, leading to peak loads disturbing the treatment performance (Strande et al., 2014).

All these characteristics make FS harder to treat compared to wastewater. Further, there is less experience and knowledge on FS treatment compared to wastewater, and little information on the actual operation of FSTPs (Klinger et al., 2019). Despite all those factors, effluent discharge guidelines are often similar to the ones employed for wastewater treatment plants (WWTPs) in Europe or the US, although much higher removal efficiencies are required to meet the regulations (Ghana EPA, 2010; WPO, 1998; see Appendix A).

1.2.2 Management Concerns

A high frequency of failure of WWTPs and FSTPs has been observed in the past, especially in resource-limited contexts (Oakley, 2022). The reported contributing factors for failure are manifold. A lack of planning can lead to the construction of under or over designed plants in suboptimal locations. Low political prioritisation with no integrated sanitation strategy, insufficient enforcement of laws and regulations, and low stakeholder coordination can result in the lack of enabling environment for FSTPs to succeed. FSM systems can also be dependent on political situations and often lack managerial flexibility (Strande et al., 2014).

Moreover, a lack of financial resources for staffing, maintenance and other operation and management (O&M) tasks has been found to lead to the deterioration of physical structures (Oakley, 2022). The absence of effective and reliable supply chains (Tayler, 2018) and a low level of local expertise (Strande et al., 2014) can contribute to the aggravating circumstances. Lastly, a lack of operator training and technical and managerial knowledge and skills has been identified as a limiting factor for a successful operation of WWTPs and FSTPs (Tayler, 2018; Oakley, 2022).

1.3 The Modified Bardenpho Process

The Modified Bardenpho process is a particular design of an activated sludge treatment system. Activated sludge systems are sometimes used for FS treatment. Advantages include a high theoretical reduction of biological and chemical oxygen demand, pathogens and nutrients. They can be operated at a range of loading rates and can be resistant to shock loads if designed adequately. Disadvantages are the high and constant need for energy, high capital and O&M costs, dependence on the local availability of parts and a need for further sludge handling. Activated sludge systems can be prone to complicated microbiological problems and require skilled workers (Tilley et al., 2014).

Figure 1 shows a schematic flow diagram of the Modified (or Five-stage) Bardenpho process. Bardenpho stands for Barnard denitrification and phosphorus removal. It is designed for nitrogen and enhanced biological phosphorus removal (EBPR). The purpose of the anaerobic reactor is to give a selective advantage to phosphorus accumulating organisms (PAOs). They can take up and store carbon as polyhydroxyalkanoates (PHA), this conversion leads to a phosphorus release. Denitrification happens in both anoxic reactors. In the first aerobic reactor, the PHA is converted into energy in a process resulting in a net phosphorus uptake and nitrification takes place. The function of the second aerobic reactor is to strip nitrogen gas and prevent a phosphorus re-release in the secondary clarifier by increasing the dissolved oxygen (DO) concentration (Metcalf and Eddy & AECOM, 2014).

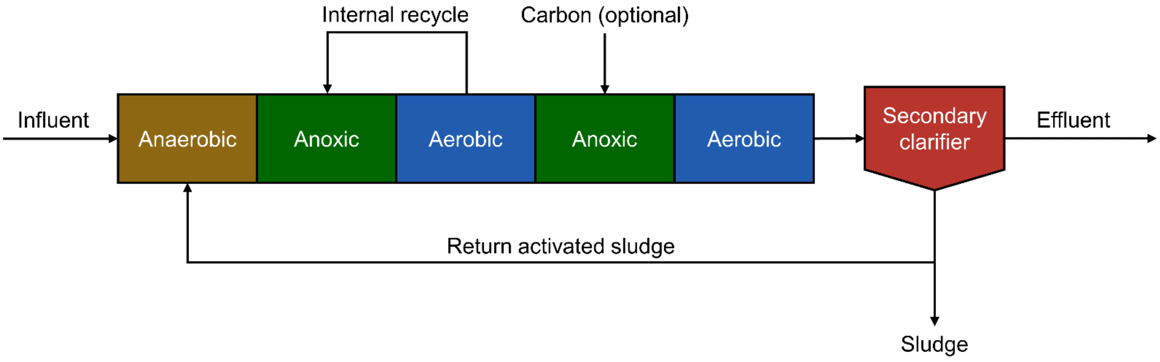

Figure 1: *Schematic flow diagram of the Modified Bardenpho process (Source: Adapted from Metcalf and Eddy & AECOM, 2014)*

The Modified Bardenpho process is a complex technology with optimal treatment performance at specific ratios of chemical oxygen demand to carbon, nitrogen and phosphorus (COD:C:N:P), hydraulic and solids retention time (HRT and SRT), DO levels and pH ranges for each stage. The internal recycle (IR) ratio should be optimised depending on the nutrient composition of the influent (Banayan Esfahani et al., 2018). The biological phosphorus removal efficiency has been found to reach over 80%, compared to approximately 10% in conventional activated sludge WWTPs (Metcalf and Eddy & AECOM, 2014). This can reduce the need for chemical phosphorus removal. Chemical phosphorus removal can be quite costly and produces more sludge. However, it is found to be less sensitive to environmental conditions than EBPR (Banayan Esfahani et al., 2018).

1.4 Scope and Objective

The Kumasi Wastewater Treatment Plant (KWWTP) is, to the best of my knowledge, the first ever treatment plant to employ the Modified Bardenpho process for FS. To date, no information is available on the use of the Modified Bardenpho process for FS treatment. Searching scientific literature with the keywords *Bardenpho* and *faecal sludge* generated no relevant results. No documentation on any other FSTP using the Modified Bardenpho could be identified.

The research objective of this work is to assess the suitability of the Modified Bardenpho process for faecal sludge treatment in the case of the FSTP in Kumasi, Ghana. Given the novel nature of this plant's design and its setting in a resource-limited environment, a multitude of factors can impact the plant's functioning. Thus, three research questions were defined:

1. What are the characteristics of the received faecal sludge at the Kumasi Wastewater Treatment Plant?
2. What is the treatment performance of the Kumasi Wastewater Treatment Plant in terms of removal efficiency and compliance with effluent quality guidelines?
3. How is the performance of the faecal sludge treatment at the Kumasi Wastewater Treatment Plant affected by a) design and layout, b) operations and maintenance, c) quality control and d) data management?

This thesis is the result of a collaboration between the Eidgenössische Technische Hochschule Zurich (ETHZ), Kwame Nkrumah University of Science and Technology (KNUST) and Sewerage Systems Ghana Limited (SSGL). The research was conducted as a part of and supported by the Network for Water and Life (NEWAL), a Cluster of Cooperation in the Global South (CLOC) in the swissuniversities Development and Cooperation Network (SUDAC). NEWAL is a network of education and research partners in West Africa and Switzerland, intending to strengthen the exchange between Swiss and West African institutions and the interface of water and life.

The practical part of the research was carried out between May and September 2022 in Kumasi, Ghana. The results presented in this thesis are specific to the examined FSTP during this period and cannot be considered generalisable to other FSTPs employing the Modified Bardenpho process. Only a limited number of factors affecting the plant's performance were assessed, as considering a wider range would have exceeded the scope of this study.

This report is divided into five sections. The preceding *Introduction* section contains background information on the topic at hand, states the identified research gap and research objectives, as well as the scope and limitations of this study. The *Methods* section describes the study setting, the research approach taken and details the applied methods. The *Results and Discussion* section presents and critically assesses the results. The *Conclusion and Recommendations* section summarises the main findings to answer the posed research questions and contains recommendations for further research and practical applications.

2 Materials and Methods

2.1 Study Setting

The Kumasi Wastewater Treatment Plant (KWWTP) is located at Adagya in the Greater Kumasi Metropolitan Area (GKMA) in the Ashanti Region of Ghana (Figure 2). Kumasi is one of the largest cities in Ghana with over 3 million inhabitants. The regional climate is classified as a tropical savanna climate (Beck et al., 2018). Kumasi receives on average 1315 mm of rainfall per year (1981 - 2010), with the driest months occurring between November and February and two rainfall peaks in June and September. February is the warmest month and August is the coldest (World Meteorological Organization, 2022).

The KWWTP was inaugurated in May 2021 and is the result of a cooperation between the Ghanaian holding company Jospong Group of Companies (JGC) and the Hungarian engineering firm Pureco Limited. It operates as a Public Private Partnership (PPP). Since the end of the trial period in March 2022, it has been fully managed by SSGL, a JGC subsidiary.

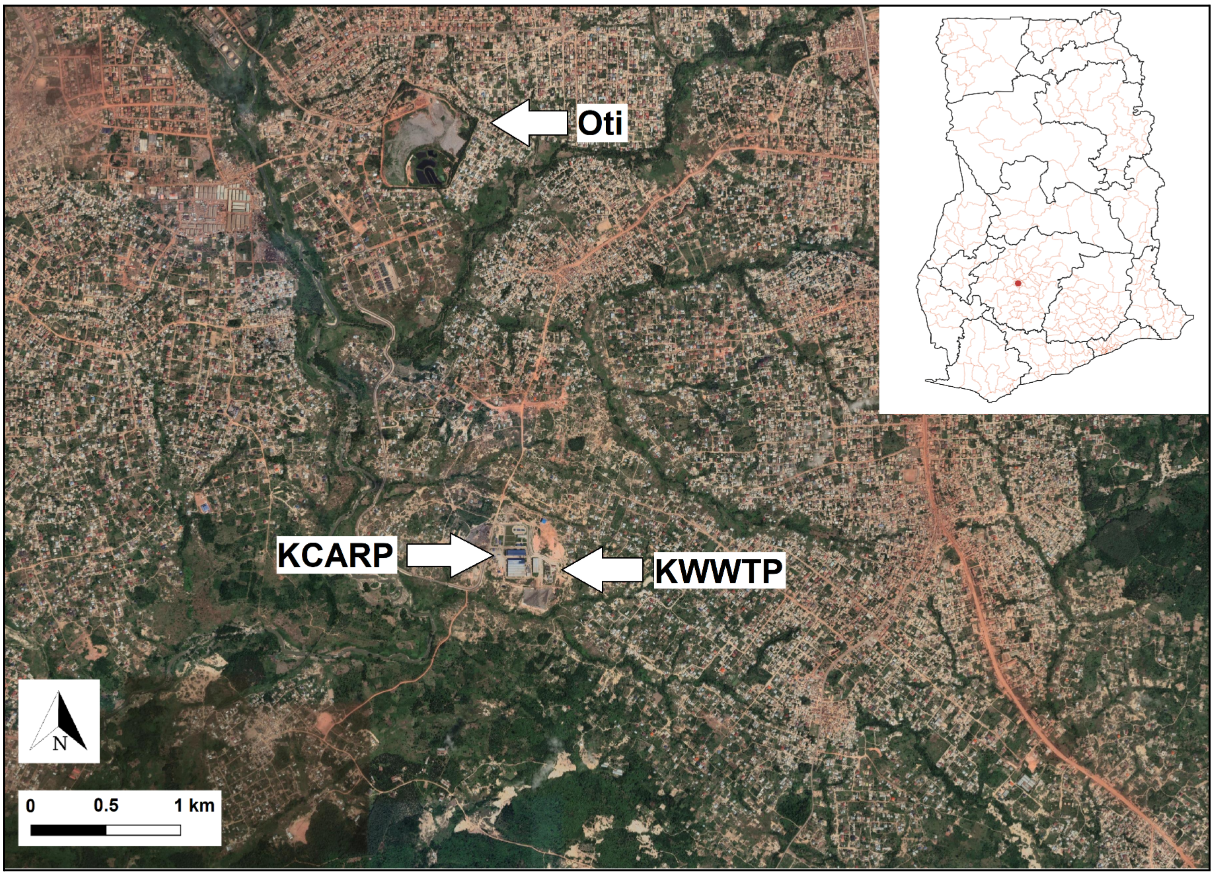

Figure 2: *Map of the study site (Source: Adapted from OpenStreetMap, Google Satellite)*

The KWWTP is designed to treat 1000 m^3/d of faecal sludge. It serves as the only legal discharge point in the area after the closure of the not fully operational Oti Septage Treatment Ponds in Dompoase. The ponds had reportedly failed due to a lack of technical staff and financial resources for O&M of the facility (WEDC et al., 2015). It is situated next to the Kumasi Compost and Recycling Plant (KCARP).

As the first plant using the Bardenpho process for FS, an additional reactor was added to the five-stage process, resulting in six biological basins. The purpose of the additional anoxic basin upstream of the five stages is to remove incoming and recycled nitrate. A schematic layout and flow diagram of the KWWTP is shown in Figure 3. The plant was designed using the software GPS-X Hydromantis for simulations.

In addition to the planned biological phosphorus removal, phosphorus is chemically removed using ferric chloride ($FeCl_3$), poly aluminium chloride (PAC) and lime ($Ca(OH)_2$). The latter also serves the purpose of increasing the alkalinity. Poly electrolytes (PE) are added to improve solid liquid separation in settling and dewatering, while sodium hypochlorite (NaOCl) was planned to be used for disinfection.

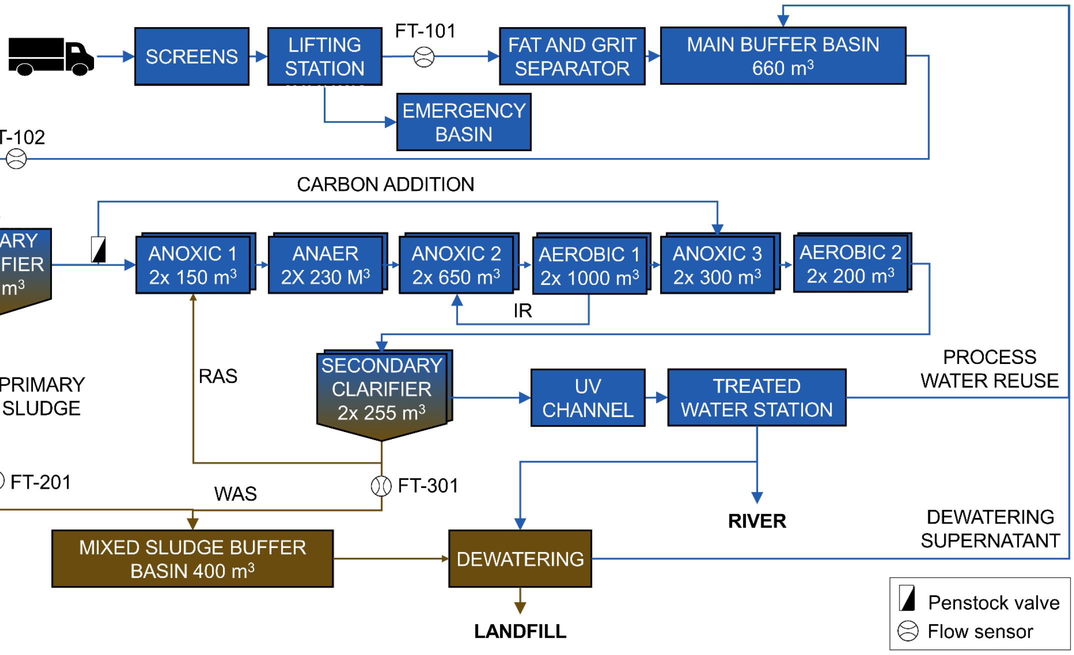

Figure 3: *Schematic layout and flow diagram of the Kumasi Wastewater Treatment Plant*

After a startup period, the plant reached its design capacity in September 2021. However, even after the influent quantity stabilised, the plant was not operated in a steady state during the observation period from May to September 2022, due to experimental optimisation and operational factors.

2.2 Research Approach

Due to the limited knowledge on the topic at hand, I applied an exploratory, mixed-method research approach for this work. Preparatory tasks such as obtaining materials had to be carried out in Switzerland without knowing the detailed layout and state of the KWWTP, as well as the locally available infrastructure and materials. Onsite, the primary goal was to gain insight into the plant's performance, day-to-day operations and challenges. This was achieved by touring the plant, making preliminary measurements, observing and asking questions. The subsequent actions were designed based on these insights.

I gathered and analysed existing monitoring data (secondary data), and carried out additional measurement campaigns (primary data) for deeper process understanding. Further, I conducted semi-structured interviews with faecal sludge truck drivers and staff members of the KWWTP to better understand their view of the plant and its challenges (see Appendix D and E). Written consent was obtained from all participants after explaining the research content. An overview of all collected quantitative data is presented in Appendix B, and the gathered files can be found in the digital appendix. All employed methods, materials, devices and softwares can be found in Appendix C, the book Methods for Faecal Sludge Analysis by Velkushanova et al. (2021) was used as a guiding reference.

The number and type of measurements was mainly limited by the available budget for this thesis. Due to this limitation, I decided to focus on one of the parallel lines in the biological treatment (line B). Certain parameters (faecal coliforms, colour, metals) could not be easily measured due to long delivery times, high import costs or unavailability of devices or materials locally, which limited the flexibility of this work.

The following sections are structured along the lines of the research questions.

2.3 Characterisation of Received Faecal Sludge

2.3.1 Influent Quantity

The influent quantity at the KWWTP is recorded in three ways: by recording the number of received faecal sludge collection trucks in a logsheet, by taking readings from flow totalizers and by exporting said flow data from the supervisory control and data acquisition (SCADA) software called Vision. I gathered the first two data sets from the Process department as Excel files and exported the inline sensor data as flows and cumulative daily volumes in the form of CSV files from Vision.

Inline flow sensors are permanently stationed after the lifting pump station (FT-101) and the main buffer (FT-102), see Figure 3. I considered these two measuring points to characterise the quantity of the received FS and the quantity going towards the primary clarifier (PC) and the biological basins. I calculated summary statistics (median, arithmetic mean, standard deviation, minimum and maximum) and produced time series plots for all data sets. Additionally, I produced graphs showing the average daily and weekly flow pattern using the exported flow sensor data. Data from 01/09/2021 to 31/08/2022 was considered (when available) to omit the startup period where fewer trucks were received.

As mentioned above in Section 2.2, an overview of the collected quantitative data can be found in Appendix B.

2.3.2 Influent Quality

Influent quality parameters are routinely measured in the KWWTP laboratory and recorded in a monthly logbook. I collected all available records from 01/07/2021 to 31/08/2022 from the Quality Assurance/ Quality Control (QA/QC) department and compiled them.

Grab samples are usually taken by KWWTP staff directly from the fat and grit separator and analysed in the laboratory within a day. Analogously to Section 2.3.1, I determined summary statistics and produced time series plots for the following parameters: temperature, turbidity, electrical conductivity (EC), pH, total dissolved solids (TDS), oxidation reduction potential (ORP), dissolved oxygen (DO), five-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), volatile suspended solids (VSS), ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), total nitrogen (TN) and total phosphorus (TP). COD, NH_4^+-N, NO_3^--N, TN and TP are usually measured without previous filtration or homogenisation.

2.4 Performance Assessment

2.4.1 Treatment Performance

Effluent quality is measured and recorded with, and analogously, to the influent (see Section 2.3.2).

Grab samples are usually taken by KWWTP staff from the treated water basin by dropping a metal container attached to a cord into the water (Figure 18 in Appendix C). I plotted the collected and compiled data as a time series with the Ghana Environmental Protection Agency (EPA) guideline values and determined summary statistics for the following parameters: temperature, turbidity, EC, pH, TDS, ORP, DO, BOD_5, COD, TSS, NH_4^+-N, NO_3^--N, TN and TP. I estimated the treatment efficiency (in %) by comparing median effluent quality to median influent quality values for all applicable parameters (turbidity, EC, TDS, BOD_5, COD, TSS, NH_4^+-N, TN and TP). Median instead of mean values were used to minimise the influence of outliers. I considered data from 01/09/2021 to 31/08/2022 to omit the startup period.

In addition to the analysis of the secondary data, I conducted one-time measurements of Escherichia coli (E. coli) and the true colour of the effluent in the Environmental Quality Engineering Laboratory at KNUST on 07/07/2022. The sample was taken and immediately transported on ice to the laboratory, where it was stored in the freezer until filtration and analysis on the next day (see Figure 18 in Appendix C).

Another one-time measurement was carried out to determine the concentration of Sodium (Na), Calcium (Ca), Magnesium (Mg), Lead (Pb), Cadmium (Cd), Chromium (Cr) and Nickel (Ni). A sample from 28/06/2022 was analysed by Atomic Absorption Spectroscopy (AAS) in the Central Laboratory at KNUST after previous digestion at the Chemistry Department at KNUST. The values were again compared to the Ghana EPA guidelines when applicable.

2.4.2 Measurement Campaign

To assess the functioning of the Modified Bardenpho process and to increase process understanding, I sampled from a total of nine compartments on six occasions over the span of three weeks in August 2022. The grab samples were taken with the same technique as described in Section 2.4.1. In case of thick foam, the container is dropped onto the surface a few times to break up the foam before taking a sample.

I determined TN_{sol}, NH_4^+-N_{sol}, NO_3^--N_{sol}, TP_{sol} and COD_{sol} for the influent, primary clarifier effluent, all six biological basins in line B and the effluent. Only soluble compounds were analysed since it was not possible to homogenise samples locally. The samples were filtered through a coffee filter and an MN GF-5 glass fibre filter as soon as possible to prevent degradation processes, and stored in the refrigerator until analysis within the same day. The analysed parameters are labelled with the subscript $_{sol}$ for *soluble* to differentiate from the unfiltered samples analysed by KWWTP staff. Additionally, I determined TSS or mixed liquor suspended solids (MLSS) and VSS or mixed liquor volatile solids (MLVSS) for the influent, primary clarifier effluent, aerobic basins and the effluent. The samples were filtered through a 934-AH glass fibre filter into a vacuum flask, the filter was then dried. To assess volatile solids, the filters were put in a 550° C furnace for 30 minutes at the closeby KCARP laboratory.

I produced boxplots showing the nutrient concentrations in each compartment. For the influent and effluent samples, I calculated summary statistics and removal efficiencies analogous to the secondary data in Section 2.4.1. Further, I produced time series plots to better understand the change of nutrients in the biological basins over time.

I collected additional secondary data on primary clarifier effluent characteristics (temperature, turbidity, EC, pH, TDS, ORP, DO, BOD_5, COD, TSS, NH_4^+-N, NO_3^--N, TN and TP) and MLSS from the Process department to compare the determined TSS concentration in the primary clarifier and the MLSS in the aerobic basins to available data points. I compared the summary statistics of the solids and produced summary plots for a better understanding of the data.

2.4.3 System Understanding

I gathered further existing records for increased understanding of the system and the data quality. From the QA/QC department I collected available data on pH in all biological basins (usually recorded with handheld field measurements) and the 30-minute settled sludge volume (SV30) in both aerobic basins. I produced time series plots of the pH during the measurement campaign (15/08/2022 to 29/08/2022) and boxplots using the available data up to 31/08/2022.

From the SCADA software Vision I exported inline sensor data on pH and conductivity in the lifting station and the main buffer basin, DO in both aerated basins and temperature and TSS/MLSS in the second aerated basin and COD, NH_4^+-N and NO_3^--N in the treated water basin. I produced time series plots for all the above mentioned data and assessed the data quality of the inline sensor measurements.

Lastly, I exported data on the daily removed primary sludge (FT-201) and the wasted activated sludge (FT-102) volume (see Figure 3). I produced time series plots showing the daily volumes for the time span from 01/09/2021 to 31/08/2022. I used the mean and standard deviation to display in and calculate values for a simplified flow diagram, together with flow estimations based on data provided on the installed pumps (extracted from the piping and instrumentation diagram in the digital appendix) and on the volumes of the skips containing dewatered sludge provided by the Process department.

The hydraulic retention time (HRT) and the solids retention time (SRT) were calculated using the layout information, the previously calculated mean daily flows (FT-101, FT-102, FT-201, FT-301) and mean measured MLSS concentration in the second aerobic reactor (from 01/09/2021 to 31/08/2022) with Equation (1) and (2).

$$HRT = \frac{V_R}{Q_I} \quad (1) \qquad SRT = \frac{V_R \cdot X_R + M_{SC}}{Q_{WAS} \cdot X_{WAS} + Q_E \cdot X_E} \quad (2) \qquad X_{WAS} = \frac{Q_R \cdot X_R - Q_E \cdot X_E}{Q_{WAS} + Q_{RAS}} \quad (3)$$

V_R is the total reactor volume of the biological basins, Q_I is the influent flow rate, X_R is the suspended solids concentration in the biological basins, M_{SC} is the mass of solids in the secondary clarifier, Q_{WAS} is the flow rate of the waste activated sludge, X_{WAS} is the suspended solids concentration in the waste activated sludge, Q_E is the effluent flow rate, X_E is the suspended solids concentration in the effluent and Q_{RAS} is the return activated sludge flow rate. X_{WAS} was estimated with Equation (3). The aerobic SRT was calculated by multiplying the overall SRT with the ratio of aerated basin volume. M_{SC} was considered as negligible.

2.5 Performance Limiting Factors

To identify factors which affect the treatment performance, I depended on field observations. Based on the findings of my observations, I then designed a semi-structured interview questionnaire for a general assessment (see Section 2.5.1) to help me better comprehend the ways in which the identified factors affect the performance. I relied mainly on the data collected in these interviews to answer my third research question. Sections 2.5.2 to 2.5.5 describe additional actions I took to gain an improved understanding of the impact of the factors a) design and layout, b) operations and maintenance, c) quality control, d) data management or to collect data to document my findings.

2.5.1 Semi-Structured Interview for a General Assessment

I carried out semi-structured interviews with a total of eleven KWWTP staff members to assess their opinion on the functioning of the treatment plant and identify challenges and possible performance limiting factors. To gain broad insight, I interviewed staff from different departments (Process, QA/QC, Mechanical, Electrical, Health and Safety Executive) and hierarchy levels (officer, assistant officer and junior staff). The staffs' answers were used to better understand how they experience and cope with challenges they face in their daily work, as well as how they think their performance is impacted by the design and layout, operations and maintenance, quality control and data management.

The interviews were divided into the following sections: *General plant functioning*, *Treatment performance*, *Design and layout*, *Chemical dosage/process monitoring, Maintenance, Power consumption, Quality control* and *Data management* (see Appendix D). To reduce the duration of the individual interviews, only the subsections relevant to the interviewed staff members were considered. The interviews were conducted in English towards the end of the onsite research. The participation was voluntary and I did not collect any personal information. The participants were willing to have their answers utilised in this research. During the interviews, I took summary notes to record information, I did not record any audio.

2.5.2 Design and Layout

A separate set of semi-structured interviews (see Appendix E) were conducted with 14 drivers of faecal sludge collection trucks to assess the functioning of the receiving facilities and identify potential issues that can occur during the waste docking process. The interviews were conducted in English and Twi with the assistance and translation by Mark Arthur.

Based on observations and findings from the staff interviews (see Section 2.5.1), I gathered existing inline sensor data on the fill level of the main buffer basin and the mixed sludge basin and used the time series plot to analyse the utilisation of the capacity between 01/09/2021 and 31/08/2022.

2.5.3 Operations and Maintenance

I gathered existing operations records on chemical dosage from the Process department. The daily amounts of added lime ($Ca(OH)_2$), ferric chloride ($FeCl_3$), poly aluminium chloride (PAC) and poly electrolyte (PE) were displayed over time. Due to irregular dosage, I refrained from calculating summary statistics. Possible interrelations between dosage and treatment quality were examined.

The daily volumes of consumed water from the onsite wells and the treated water station were plotted in time series plots and analysed. Further, operational highlights that are noted daily in a physical logbook by the Process department were analysed onsite to better understand how operational decisions and extraordinary events can impact the treatment.

2.5.4 Quality Control

When measuring nutrients with Hach Lange reagents, high levels of certain ions or oxidisable organic substances can cause interference (Hach Lange GmbH, 2019). I assessed the impact of filtration and dilution on the NO_3^--N measurement by measuring one sample taken from the main buffer basin on 28/06/2022 after combining different filtration modes (unfiltered, coffee filter, MN GF-5 glass fibre filter) and dilutions (undiluted, 1:5). The COD was determined for each filtration mode. The Ca concentration of the sample was also measured using AAS (analogously to Section 2.4.1)

2.5.5 Data Management

I created exemplary Python coding scripts in Jupyter Notebook with the goal of reporting and displaying relevant daily operations data, as well as quality control data, in a clear manner for an improved overview and easier decision-making. As input I used the data that was provided to me in the form of separate monthly Excel documents, which I compiled into overview files, as well as exported CSV files from the SCADA software Vision.

2.6 Data Analysis

Analysis of quantitative data was carried out by coding Python using Jupyter Notebook. I used the python libraries *pandas*, *numpy*, *matplotlib.pyplot*, *matplotlib.ticker*, *datetime*, *dill*, *scipy.stats*, *cycler* and *matplotlib.dates*. Data was read in from the out of the software Vision exported CSV files (for inline sensor data) or from compiled or created Excel files (see Section 2.5.5). The collected data was cleaned before quantitative analyses were carried out. The scripts used to produce plots and calculate summary statistics can be found in the digital appendix. The types of data analysis I carried out for each data set, listed by section, are listed in Appendix B.

The collected qualitative data was analysed by sorting the recorded summary notes taken during the interviews and recorded field observations by topics and as much as possible along the lines of the research questions. Possible contradictions were further investigated by asking additional questions.

3 Results and Discussion

3.1 Characterisation of Received Faecal Sludge

Table 1 presents an overview of the influent quantity after the start up period. The median average quantities lie below the design capacity of 1000 m^3/d. However, the variability is relatively high. Considering Kumasi's annual population growth rate of 4.02% (World Population Review, 2022), the delivered FS quantity might increase rapidly. The daily volume going towards the primary clarifier (PC) is almost a third higher than the received volume due to the substantial recycle flows.

There are significant differences between the totalizer readings and the directly out of the SCADA software Vision exported data. The standard deviation of the totalizer reading is significantly higher than the one of the exported data. This leads to the assumption that inaccuracies are caused by errors when digitising the manual readings. More outliers can also be seen in the time series of the data in Figure 4 and Figure 20 in Appendix F. Further, the totalizer readings in Figure 20 feature a jump after the new year which compromises the plausibility of the data from 2021 (cf. Figure 19 in Appendix F). However, there is a large data gap of almost two months for the exported data on the received volume, which lowers the number of days (n) used for calculating the summary statistics. Seasonality is not clearly identifiable but faecal sludge collection truck drivers reported to receive more business in the wet season, which are likely caused by floodings of unlined containment systems (Strande et al., 2014).

Table 1. *Influent quantity: summary statistics for available data from 01/09/2021 to 31/08/2022*

Parameter	**Unit**	**Med**	**Mean**	**SD**	**Min**	**Max**	**n**
Daily number of trucks	-	72	72.7	11.7	29	102	363
Daily received volume (totalizer reading)	m^3	876.5	868.8	186.1	55	1810	356
Daily received volume (exported CSV)	m^3	917.5	909.7	146.5	366	1249	301
Daily volume to PC (totalizer reading)	m^3	1226	1109	396.0	255	1973	359
Daily volume to PC (exported CSV)	m^3	1359	1324	214.7	630	1839	361

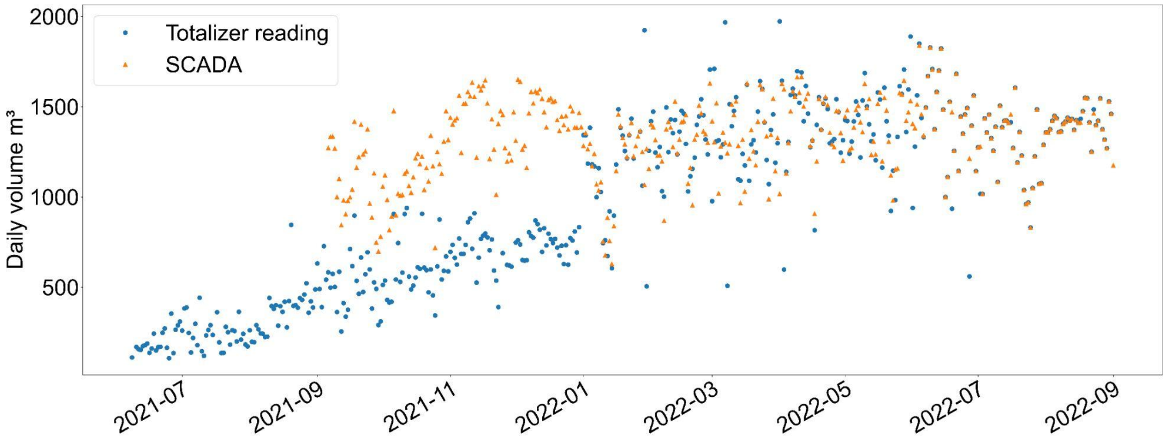

Figure 4: *Time series of daily volumes going to the primary clarifier recorded by a reading of the flow totalizer and exported from the SCADA software Vision*

Figure 5 shows the average daily and weekly pattern of the received FS. A clear peak is identifiable in the morning, with the vast majority of volume received between 6am and 6pm, the hours when staff reported to be receiving trucks at the discharging bay. On Sundays, less FS is received but the difference to the other days is not extreme. A drop from the otherwise less variable flow is identifiable for the flow going towards the PC in the daily pattern around 8pm, reportedly caused by the programming of the SCADA (Figure 6).

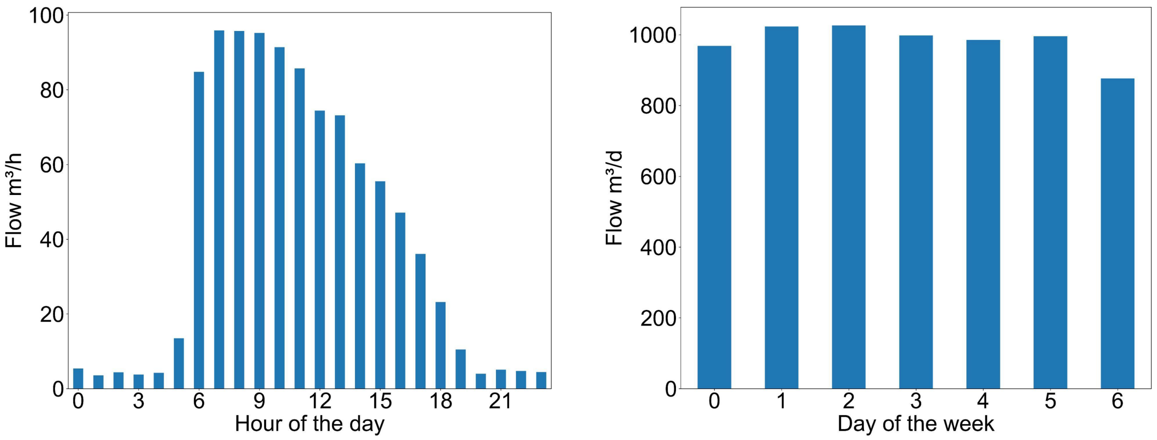

Figure 5: *Average daily and weekly pattern of the received influent flow (n = 301 days; Day of the week: 0=Monday, 1=Tuesday, 2=Wednesday, 3=Thursday, 4=Friday, 5=Saturday, 6=Sunday)*

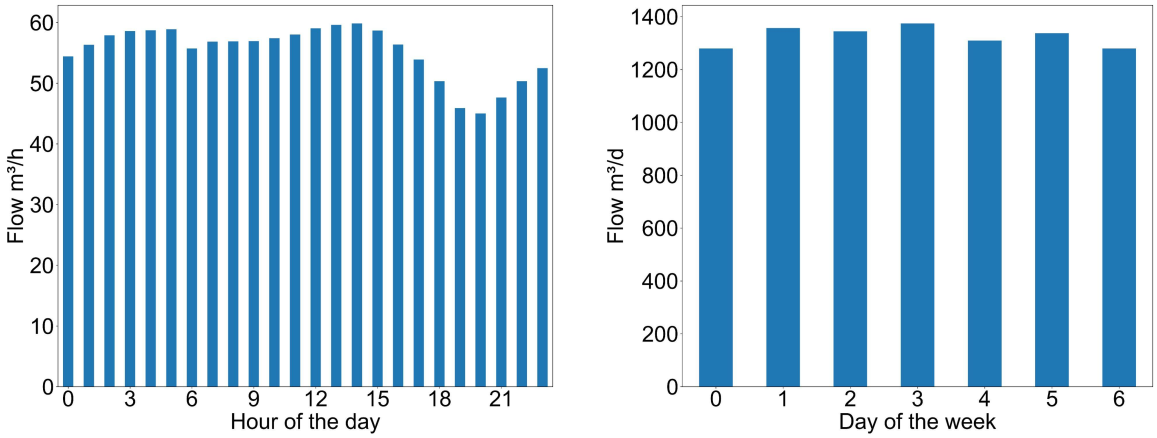

Figure 6: *Average daily (left) and weekly (right) pattern of the flow going to the primary clarifier (n = 361 days; Day of the week: 0=Monday, 1=Tuesday, 2=Wednesday, 3=Thursday, 4=Friday, 5=Saturday, 6=Sunday)*

An overview of the influent quality is presented in Table 2, while time series visualisations can be additionally viewed in Figure 21 and Figure 22 in Appendix F.

Compared to typical domestic wastewater, the strength of the measured parameters is definitely higher. However compared to literature ranges given for FS, the values are found to be rather on the low end (cf. Strande et al., 2014), as well as compared to samples with average COD values between 9495 and 45’612 mg/L COD, taken directly from onsite containment systems in and around Kumasi (Fanyin-Martin et al., 2017; Appiah-Effah et al., 2014). The FS collection truck drivers reported that they oftentimes dilute the FS with one to three barrels of water when pumping out the sludge from onsite containment systems, so the received FS is almost always in a diluted and rather fluid state. In addition, the composition of the influent sample taken from the fat and grit separator can differ from what is delivered in the trucks, as it can be diluted with process water used for cleaning the receiving bay, as well as with rain which can enter the drains at the bay.

As expected for FS due to the wide range of onsite technologies, the found variability is very high, as can be seen especially with the secondary data on the influent solids and nutrient concentrations. On top of that, staff reported that industrial waste is sometimes received at the KWWTP. Some residents in Kumasi have also stated that they add chemicals to the onsite containment systems to reduce the needed frequency for emptying (Appiah–Effah et al., 2020). These large fluctuations could lead to shock loads impacting the microbiological treatment if not equalised sufficiently in the mixed buffer basin.

Table 2. *Influent quality: summary statistics for available secondary from 01/07/2021 to 31/08/2022 (top) and primary data from 15/08/2022 to 29/08/2022 (bottom). Italic: likely erroneous*

Parameter	**Unit**	**Median**	**Mean**	**SD**	**Min**	**Max**	**n**
Temperature	°C	29.75	29.35	2.56	*21*	33.8	304
Turbidity	NTU	3740	4619	4739	64.2	*56'233*	303
EC	µS/cm	3260	3454	1538	784	11'500	317
pH	-	7.67	7.66	0.30	6.13	8.95	301
TDS	mg/L	1679	1781	859	*3.14*	6300	317
ORP	mV	-242.3	-207.2	153.1	-549.2	334.1	259
DO	mg/L	0.30	0.66	0.98	0.04	*6.29*	289
BOD$_5$	mg/L	2150	2188	1457	461	5120	11
COD	mg/L	4280	5603	5007	263	21'200	40
TSS	mg/L	3375	5164	5532	640	38'600	56
VSS	mg/L	749	-	-	-	-	1
NH$_4^+$-N	mg/L	270	378.1	377.9	10.3	1622	39
NO$_3^-$-N	mg/L	31.1	81.1	162.6	3.29	800	51
TN	mg/L	628	727	468	51	2411	62
TP	mg/L	40	50.3	42.8	10.2	248.5	59
TSS	mg/L	2230	3838	3954	1020	11'340	6
VSS	mg/L	*6225*	-	-	*1620*	*10'830*	2
COD$_{sol}$	mg/L	640.5	701.3	269.3	380	1055	6
NH$_4^+$-N$_{sol}$	mg/L	339.5	378.7	118.7	273	595	6
NO$_3^-$-N$_{sol}$	mg/L	4.0	3.9	1.0	2.4	4.97	6
TN$_{sol}$	mg/L	354	399	108	319	598	6
TP$_{sol}$	mg/L	38.9	40.0	9.5	28.6	53.6	6

Measurement or recording errors might also contribute to the high observed variability, e.g. the maximum turbidity value of 56'233 NTU could be caused by an inadvertently double typed '3'. Still, these types of judgments of the data quality are more difficult to make for secondary data without access to background information on the sample and the measurement. The samples might not have been immediately analysed in the laboratory, which implicates that continued degradation could distort the measured composition values. Prolonged storage in a cold environment might explain the minimum temperature of 21° C.

Some differences are noticeable when comparing the primary data from the measurement campaign to the compiled secondary data. Unsurprisingly, the soluble fractions of COD and TN are lower than the total concentrations. The median soluble fraction of TP is however in a similar range as the median of the total. The majority of the phosphorus could be in soluble form. It might also be caused by the low number of samples in the measurement campaign and the high variability of the received FS, which can make it hard to compare two different subsets of samples. It is also hard to estimate a typical ratio of the soluble fractions to the total concentrations, as the ratios have been found to be highly variable for different FS samples. Ratios of COD:N:P for FS show generally large ranges as well (Schöbitz et al., 2016), which could make the operation of the Bardenpho process more difficult.

The nitrate concentrations I measured are lower than the concentrations measured by KWWTP staff. This is unexpected since it is a soluble compound. The difference is likely caused by interferences from high concentration of oxidisable organic substances in the unfiltered samples. According to the working procedure guidelines for the cuvette test LCK 339 used for the measurement of both the primary and secondary data, the COD concentration must be below 200 mg/L (Hach Lange GmbH, 2019). Even if the samples were diluted, some of the COD concentrations were likely higher.

Further limitations of the results are caused by laboratory practices. The spectrophotometer continued to be used although it required servicing, while handheld probes were continuously used without calibration (see the effect of calibration events in Figure 23c in Appendix G). The dilution of samples using materials with large uncertainties and the lack of homogenisation contribute to inaccurate results. During the measurement campaign the scales in both the KWWTP and KCARP laboratories were not measuring stable values and only in two cases the VSS was estimated to be lower than the TSS.

3.2 Performance Assessment

3.2.1 Treatment Performance

Table 3. *Effluent quality: summary statistics for available secondary from 01/07/2021 to 31/08/2022 (top) and primary data from 15/08/2022 to 29/08/2022 (bottom), effluent discharge guidelines (Ghana EPA, 2010) and median removal efficiencies. Italic: likely erroneous or high uncertainty; Underlined: EPA guideline not met*

Parameter	**Unit**	**Med**	**Mean**	**SD**	**Min**	**Max**	**n**	**EPA**	**Eff**
Temperature	°C	31.2	31.0	2.08	24.5	35.1	270	≤ 3 [1]	-
Turbidity	NTU	26.3	223	753	6.4	*5558*	267	75	99%
EC	µS/cm	*1615*	*1740*	*443*	*1012*	*3050*	282	1500	50%
pH	-	6.65	6.55	0.63	4.51	7.88	280	6 - 9	-
TDS	mg/L	*801.5*	*867*	*234*	*502*	*1861*	280	1000	52%
ORP	mV	*95.2*	*74.5*	*77.7*	*-304.3*	*206.9*	192	-	-
DO	mg/L	5.56	4.99	1.41	0.15	7.07	281	-	-
BOD_5	mg/L	27.8	32.1	14.0	13.8	49.5	5	50	99%
COD	mg/L	223.5	423	877	137	4320	40	250	95%
TSS	mg/L	47	270	906	11	5705	99	50	99%
NH_4^+-N	mg/L	10.7	33.0	70.9	0.18	360	56	1	96%
NO_3^--N	mg/L	122.2	112.4	58.7	1.21	220	46	50	-
TN	mg/L	169.5	296.9	557.1	71	3390	44	-	73%
TP	mg/L	11.3	12.0	8.2	1.58	32.8	50	2	71%
TSS	mg/L	57	51.8	22.5	16	80	6	50	97%
COD_{sol}	mg/L	161.5	163.7	17.0	144	192	6	-	75%
NH_4^+-N_{sol}	mg/L	0.21	0.31	0.35	0.02	0.88	5	-	99.9%
NO_3^--N_{sol}	mg/L	92.7	100.6	31.8	60.8	153	6	-	-
TN_{sol}	mg/L	110.3	122.0	46.5	80.5	207.6	6	-	69%
TP_{sol}	mg/L	28.3	32.3	17.8	16.7	67.3	6	-	27%

Secondary and primary data of the effluent quality is presented in Table 3. The variability of the effluent quality appears to be considerable for most parameters. No steady state operation seems to have been achieved, which is also apparent when looking at the time series in Figure 23 and Figure 24 in Appendix G. The median removal efficiencies calculated from the secondary data are found to be quite high for most compounds (99% for BOD_5, 95% for COD, 99% for TSS, 96% for NH_4^+-N, 73% for TN and 71% for TP), also compared to many values provided in other literature on FS treatment (as low as 62% for BOD_5, 70% for COD, 31% for TSS and 20% or PO_4^-. However, even higher TP removal has been identified in other systems such as moving bed biofilm reactors (MBBR), anaerobic baffled reactor (ABR) or a combination

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[1] above ambient

of planted drying beds and vertical flow constructed wetlands (cf. Jain et al., 2022; Vijayan et al., 2020; Kengne et al., 2014). It has to be considered that it is very difficult to adequately compare the performance of FSTPs since the influent composition and the scales vastly differ. No information on treatment performance from other centralised FSTPs treating a comparable daily amount of FS could be identified.

When comparing the median treatment performance with the Ghana EPA guideline values, we find that in spite of the comparatively high removal efficiencies, the requirements are not routinely fulfilled for EC, NH_4^+-N, NO_3^--N and TP. The required removal efficiency to meet the guidelines for TP considering the high median influent concentration would be over 95%. Comparatively, in Switzerland, the Water Protection Ordinance would only require an estimated removal of 84% for TP, assuming a TP concentration of 5 mg/L in municipal wastewater (Gujer, 2002), applicable only in the case of sensitive receiving waters (see Appendix A). Therefore, using similar guidelines for FSTPs modelled after EU or US guidelines for WWTPs might not be sensible. Different locations require different priorities, pathogen removal might be considered more relevant in countries where excreted infections are common (Oakley, 2022). At the KWWTP, pathogen concentrations are neither measured in the influent nor the effluent.

The one-time measurements of colour and E. coli found that both did not meet the EPA requirements (see Table 4). The effluent usually looks dark and yellow (Figure 14 in Section 3.3.1), even after filtration. The concentration of E. coli was found to be much higher than the guidelines and than expected, resulting in an insufficient dilution of the sample which made it difficult to accurately count the pathogens (Figure 14 in Section 3.3.1). The measurement of the metals did not indicate any problematic levels, some measurements even rendered implausible, negative concentration values. The Central Laboratory at KNUST also reported having problems with the AAS device, and especially with the Ca measurement, resulting in a delayed analysis only several weeks later after repair works, which is likely to impact the accuracy of the results.

Table 4. *Effluent quality for one-time measurements and effluent discharge guidelines (Ghana EPA, 2010). Italic: likely erroneous; Underlined: EPA guideline not met*

Parameter	**Unit**	**Value**	**SD**	**EPA**
Colour	TCU	446	-	200
E. coli	cfu/100mL	$>10^5$	-	10
Ca	mg/L	*0.1019*	0.0072	-
Na	mg/L	0.5911	0.0520	-
Mg	mg/L	16.60	0.0631	-
Pb	mg/L	*-0.2484*	0.0086	-
Cd	mg/L	*-0.0815*	0.1622	0.1
Cr	mg/L	*-0.2917*	0.1214	0.5
Ni	mg/L	*-0.6039*	0.1844	-

The same limitations concerning the laboratory practices apply for the effluent quality measurements as discussed in Section 3.1. Further, the effluent quality data might be skewed because more measurements are reportedly taken during periods when the treatment is facing difficulties.

3.2.2 System Understanding

Figure 7 and Figure 8 (left) show an overview of soluble nutrient concentrations measured in different compartments during the measurement campaign. For COD_{sol} we find a rapid decrease followed by a slower and seemingly tangential approach towards the median value of 161.5 mg/L. Most of the rapidly biodegradable soluble COD seems to be depleted fast and latest in the first aerobic reactor (Compartment 6). For NH_4^+-N_{sol} a similar pattern can be observed, a large share of the ammonium concentration is already reduced in the first anoxic reactor. A slightly higher concentration was measured in the third anoxic reactor

(Compartment 7) because the Process department started redirecting some of the primary clarifier effluent to this basin as a carbon source to aid denitrification during the measurement campaign.

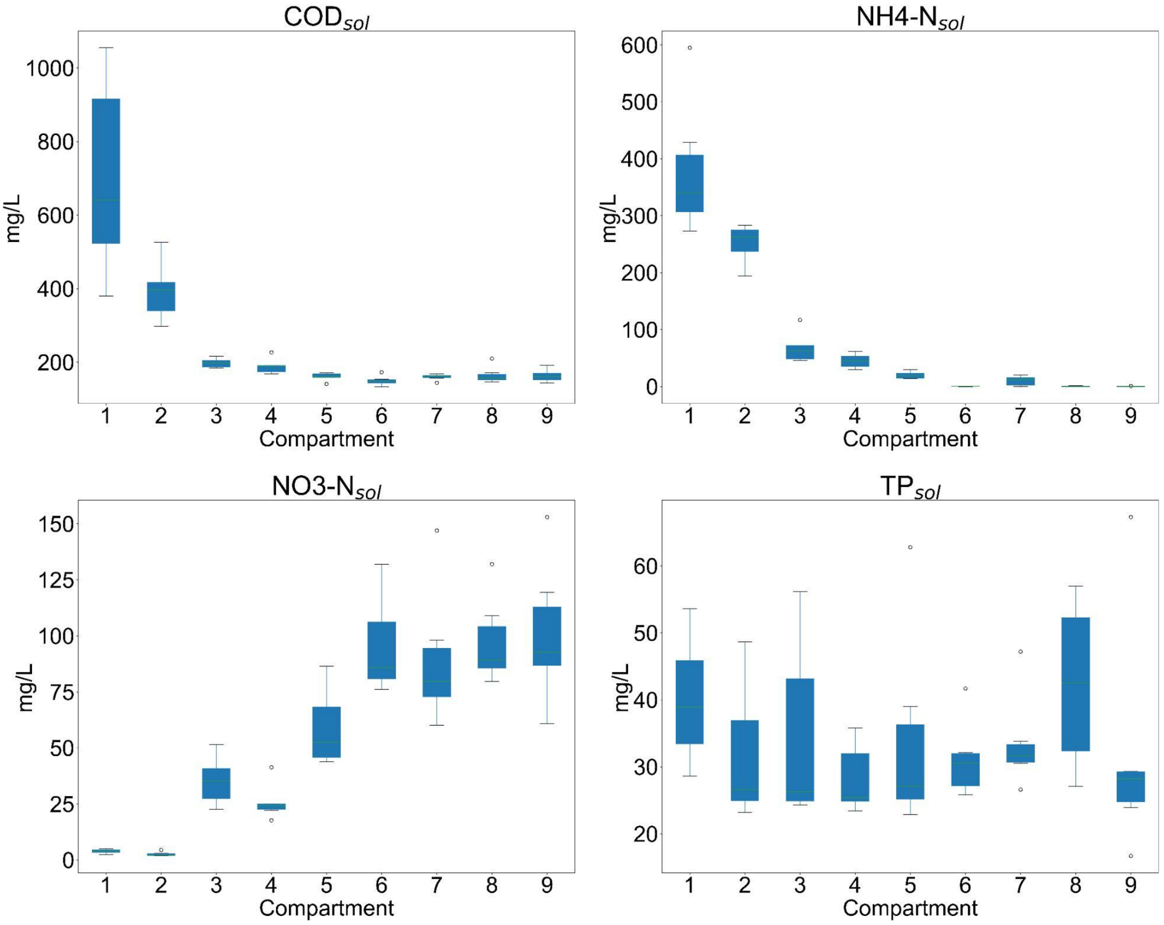

Figure 7: *Boxplots of dissolved ($_{sol}$) nutrient concentrations (COD, NH_4^+-N, NO_3^--N, TP) measured in a measurement campaign (n=6) from 15/08/2022 to 29/08/2022 (1: Influent, 2: Primary clarifier effluent, 3: Anoxic 1B, 4: Anaerobic B, 5: Anoxic 2B, 6: Aerobic 1B, 7: Anoxic 3B, 8: Aerobic 2B, 9: Effluent)*

For NO_3^--N$_{sol}$ the concentration increases overall as a result of the nitrification. The concentration in the anaerobic reactor (Compartment 4) is not found to be negligible. The conditions in this basin are not actually anaerobic, indicating that the Modified Bardenpho process is not taking place as designed. This is supported by the fact that the TP$_{sol}$ concentration does not seem to reduce during the biological treatment. Denitrification can be observed in the anaerobic and the third anoxic reactor (Compartment 4 and 7). To quantify the amount of denitrification taking place in the first and second anoxic reactor (Compartment 3 and 5) accurate information on the return activated sludge (RAS) flow and internal recycle would be needed.

The nitrate in the first anoxic reactor (Compartment 3) could have two origins: Firstly, it can result from the RAS. Figure 9 shows that the estimated flow of the RAS is significantly higher than the flow coming from the primary clarifier (2160m^3/d compared to 1203.5m^3/d). However, this data is based on provided information on the RAS pump and not backed up by flow measurements. Secondly, the high DO concentration in the RAS can enable nitrification taking place in the first anoxic reactor (Compartment 3). Again, to accurately quantify the sources of the nitrate, more certain information on all flows would be required. Nitrate does not seem to significantly stem from the effluent recycled as process water going back into the main buffer, since the concentration in the primary clarifier effluent is very low. This indicates however that denitrification is happening either in the main buffer basin and/or in the primary clarifier, which is plausible considering the relatively high amount of easily biodegradable substrate available.

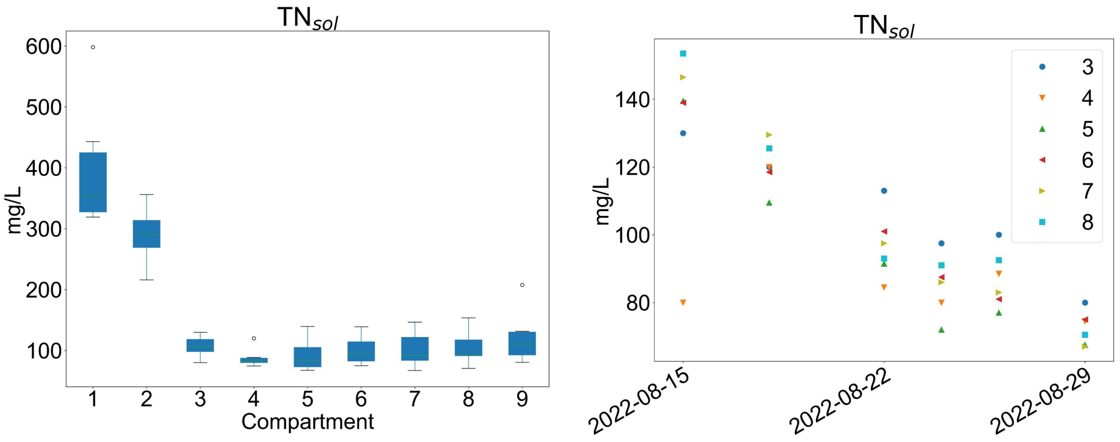

Figure 8: *Boxplot (left) and time series (right) of dissolved ($_{sol}$) TN concentrations measured in a measurement campaign (n=6) from 15/08/2022 to 29/08/2022 (1: Influent, 2: Primary clarifier effluent, 3: Anoxic 1B, 4: Anaerobic B, 5: Anoxic 2B, 6: Aerobic 1B, 7: Anoxic 3B, 8: Aerobic 2B, 9: Effluent)*

In contrast to that, denitrification within the biological reactors is likely to be limited by the amount of available substrate. This is demonstrated by the fact that the start of the addition of substrate to the third anoxic reactor (Compartment 7) in the form of primary clarifier effluent is likely to have caused a decrease in the TN$_{sol}$ concentration over the duration of the measurement campaign (Figure 8, right). Figure 25 and Figure 26 in Appendix G display analogous data for the other nutrients but only NO$_3^-$-N$_{sol}$ showed a comparable downwards trend as expected. It can also be noticed in Figure 7 that the TP$_{sol}$ concentrations show a large variability over the six conducted measurements which could be caused by an inconsistent addition of chemicals (lime, FeCl$_3$ and PAC) for chemical phosphorus removal.

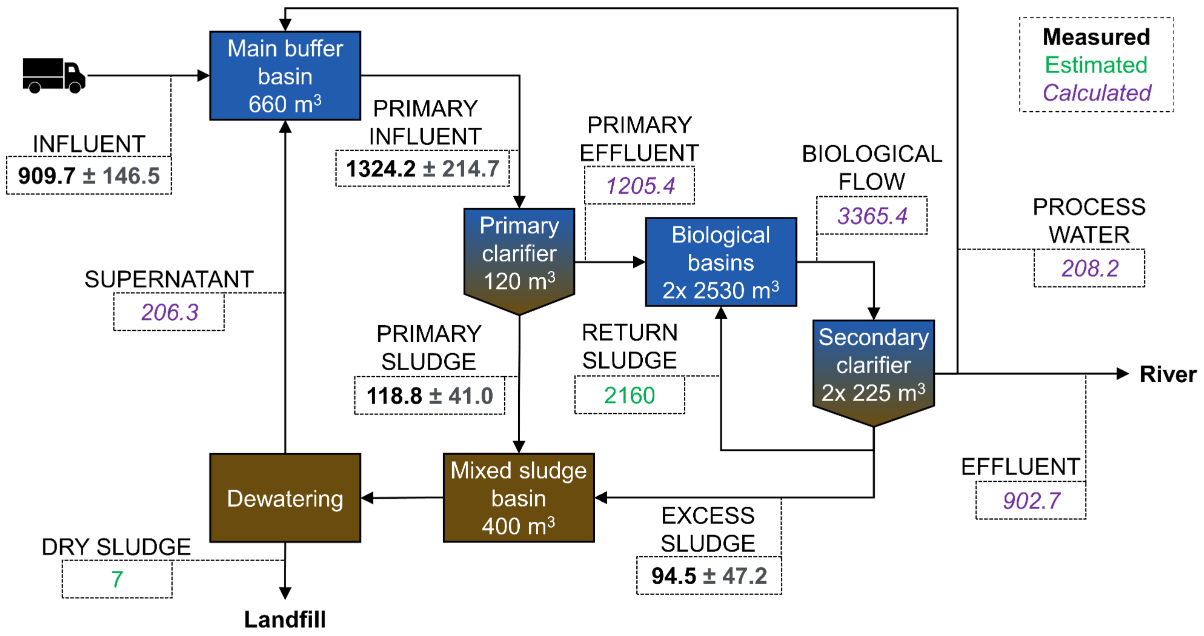

Figure 9: *Simplified flow diagram of the KWWTP*

If we look at the pH in the biological basins (Figure 10), we can see a general decrease over the course of the reactors, with the lowest concentrations in the aerobic reactors (Compartment 6 and 8). This indicates that nitrification is taking place and consuming alkalinity. Very low pH values below 5 appear to be sometimes observed. This is suboptimal for nitrification since nitrifying microorganisms require a pH between 6 and 9 (Metcalf and Eddy & AECOM, 2014). Even over the two week span of the measurement campaign, a considerable variation in pH is noticeable. This illustrates further that the plant is not running in a steady state. The variation might be due to changes in chemical dosage, the addition of carbon to the third anoxic reactor or changing influent composition.

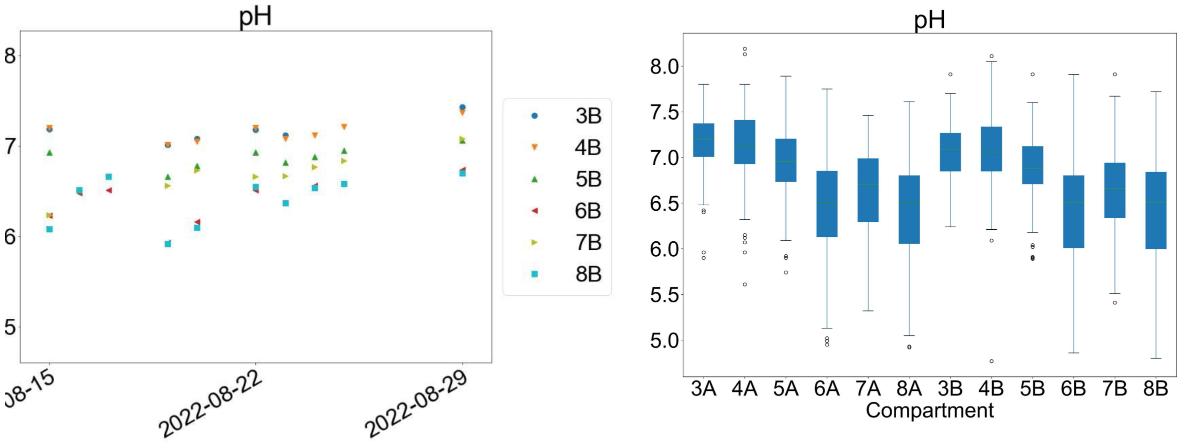

Figure 10: *Secondary data on handheld pH measurements over the course of the measurement campaign (left) and boxplot (right) for available data from 01/09/2022 to 31/08/2022 (3: Anoxic 1, 4: Anaerobic, 5: Anoxic 2, 6: Aerobic 1, 7: Anoxic 3, 8: Aerobic 2)*

In Table 5, an overview over suspended solids in the primary clarifier and in the aerobic basins is presented. The median removal of suspended solids in the primary clarifier compared to the influent suspended solids is found to be 78% for the secondary data and 77% during the measurement campaign. This is less than 90%, which was estimated by the contractor in the design process. This might be due to a high share of public toilet sludge, for which the solid liquid separation has been found to be more difficult (Ward et al., 2019). However, the performance also seems to vary substantially, potentially caused by a changing chemical dosage of precipitants and coagulants.

The MLSS concentrations are found to be highly variable as well (see also Figure 11). The MLSS in the second aerobic reactor (Compartment 8A/8B) is higher than in the first one. This could be caused by additional growth of the biomass or by the denser foam which was observed. The denser foam in the second aerobic reactor might distort the results. With the available sampling materials, it was not possible to sample below the foam.

Table 5. *Suspended solids in primary clarifier and aerobic reactors: summary statistics for available secondary from 01/09/2021 to 31/08/2022 (top) and primary data from 15/08/2022 to 29/08/2022 (bottom)*

Parameter	**Unit**	**Median**	**Mean**	**SD**	**Min**	**Max**	**n**
TSS in PC effluent	mg/L	730	957	1182	160	5840	21
MLSS in 6A	mg/L	5618	5707	1727	3066	8790	20
MLSS in 6B	mg/L	5153	5853	2719	2516	14’140	21
MLSS in 8A	mg/L	7892	8172	2495	5470	16’390	20
MLSS in 8B	mg/L	7577	8235	2563	4560	15’800	20
TSS in PC	mg/L	505	573	274	360	1120	6
MLSS in 6B	mg/L	6272	6387	964	5233	7853	6
MLSS in 6B	mg/L	8767	9121	2966	5467	13’790	6

The 30-minute settled sludge volume is one of the parameters which is most often recorded and the time series is displayed in Figure 12. The characteristics of the sludge (SV30 and MLSS) appear to be ever changing. The variation could be explained by several factors, such as operational changes of the WAS, RAS and IR flows, or changing microbial communities caused by changing conditions (e.g., pH, alkalinity, substrate concentrations, DO) in the biological basins.

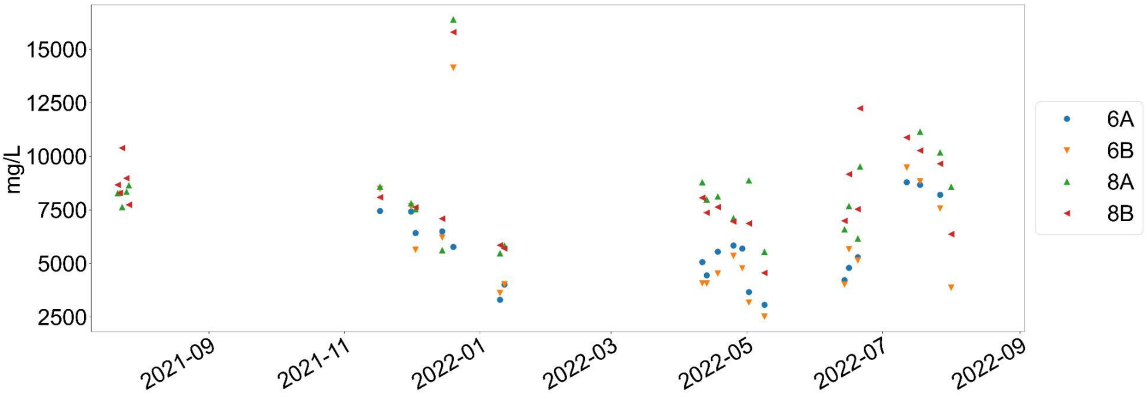

Figure 11: *Time series of all available secondary data on MLSS in the aerobic reactors (6: Aerobic 1, 8: Aerobic 2)*

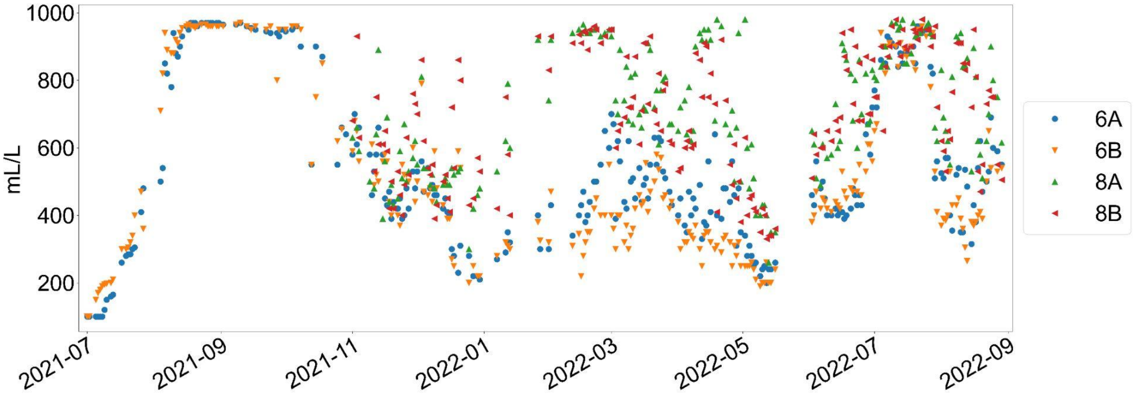

Figure 12: *Time series of all available secondary data on SV30 in the aerobic reactors (6: Aerobic 1, 8: Aerobic 2)*

The calculated total HRT was 5.6 days and the total SRT 34.4 days (see Table 13 in Appendix H). Followingly, the aerobic HRT was estimated to be 2.6 days and the aerobic SRT 16.3 days. In comparison, typical HRT for activated sludge WWTPs are normally below 24 hours (Metcalf and Eddy & AECOM, 2014), however the influent concentrations are also lower and the flows higher. Still, it seems to be a stark difference and raises the question if such a long HRT is necessary for the received loads or if the plant was overdesigned.

Similarly, the SRT seems to lie also on the high end compared to Metcalf and Eddy & AECOM (2014), which gives a range of 3 to 18 days for the aerobic SRT for complete nitrification and a range of 2 to 4 days, depending on the temperature. Considering the tropical climate, a shorter SRT might theoretically also suffice to remove ammonium nitrogen to a desirable level, and be advantageous for EBPR. However, since the ammonium concentration was oftentimes not meeting the guidelines, it might be beneficial to use a longer SRT to keep more nitrifiers in the system. Suitable literature values for WWTPs were most likely not defined with FS in mind. They might not be appropriate for FSTPs due to the high strength and different composition of FS.

It has to be noted that the uncertainty of the estimated SRT values is high. Firstly, the operation of the WAS pump is variable (Figure 13). Secondly, as mentioned previously, the measurement of MLSS especially in the second aerated reactor might be inaccurate. Thirdly, measurements of the RAS are not available, so the calculation was carried out on the assumption that the pump was running on full capacity, which was reported by the KWWTP staff.

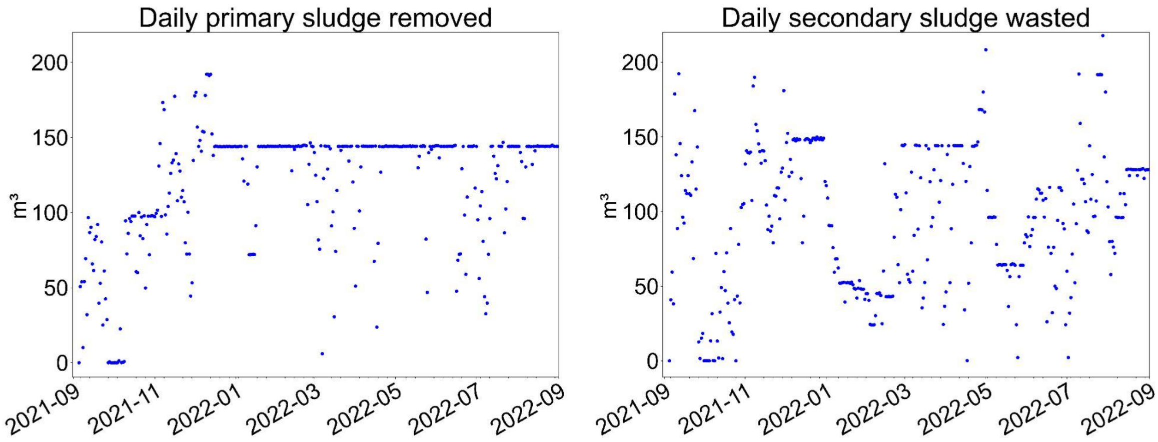

Figure 13: *Daily volumes of primary sludge (left) and waste activated sludge (right)*

Figure 29 to Figure 33 in Appendix G display partially cleaned inline sensor data exported from Vision for completeness. Without gathering more information on calibration and maintenance of these systems, it is hard to gauge the reliability of the data. A more detailed analysis would have exceeded the scope of this study. It is however visible that data gaps and outliers are frequent.

3.3 Limiting Factors

3.3.1 Design and Layout

In the following section, it is described how the design (planning, configuration and sequence of treatment stages, installed components) and layout (dimensioning of basins, spatial arrangement) was found to impact the performance of the treatment.

Figure 14: *Photo of typical effluent colour (left) and Chromocult Coliform Agar plate (right)*

Some staff were of the opinion that the plant was overdesigned, while others thought it was underdesigned. They did not have access to estimations used in the design and the simulation software. It is likely that the estimation of the expected quantity and quality of the received faecal sludge was not accurate, since it was reportedly only based on three days of data collection before the construction of the plant. The expected quality and quantity of FS could have also been estimated using data on FS generation and collection rates (Strande et al., 2018; Yesaya & Tilley, 2021; Sagoe et al., 2019).

Staff mentioned that, as a result of the strong effluent colour, the UV disinfection is not effective (Figure 14). The colour should be below 20 mg/L PtCo for a functioning disinfection (DWQR, 2021). The different colour characteristics of FS might not have been considered during the process design. This has the consequences that one of the main treatment goals (removal of pathogens) does not seem to be met. Foaming in the biological basins has also been a problem reported by the staff. They mentioned that they had to lower the DO so the foam would not go over the walls of the biological basin. Furthermore, the density of the foam in the third anoxic basin leads to a blockage of the inlet. The mixer in the third anoxic basin is frequently raised up to cope with the blockage. This can impair the mixing in the basin and lower the treatment efficiency.

The reuse of the effluent for cleaning in dewatering has also led to impaired performance. When it is too turbid, it leads to clogging of the dewatering system, which then has to be halted. One staff member expressed the wish to have the flexibility to redirect the flows, e.g. from the treated water station back to the primary or secondary clarifier if it is too turbid.

Staff and drivers reported that the main buffer basin gets full often. Trucks cannot be received and have to wait. As a consequence, dewatering has to be stopped as well, since the dewatering supernatant goes into the main buffer as well. Figure 15 illustrates that the basin frequently reaches capacity.

The skips where the dewatered sludge is stored are found difficult to access when it's raining due to a bad condition of the road. Followingly, emptying trucks get stuck or don't show up at all. If the skips are full, the dewatering has to be halted, which can cause the mixed sludge basin to get full (see Figure 15). The removal of sludge from the clarifiers is then also stopped and impairs the treatment.

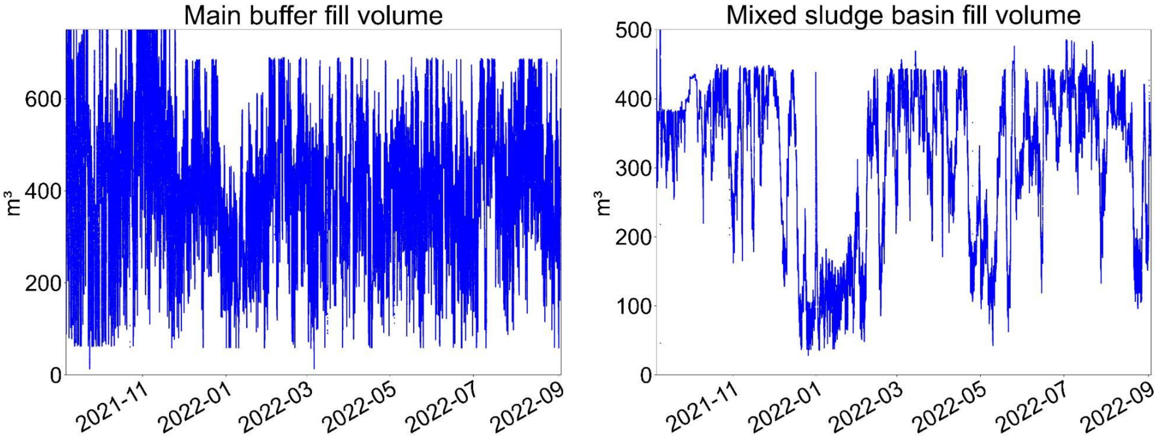

Figure 15: *Fill volumes of the main buffer basin (left) and the mixed sludge basin (right)*

Drivers also complained about poorly lit and bad roads on the way to the KWWTP, especially during rain, as well as the rather remote location of the plant. Although they did not mention discharging FS anywhere else, it could imply that they might be tempted to discharge at a location closer to the collection point. Further, the slope of the discharging ramp is very steep, which can damage their vehicles when not careful enough. Drivers and staff also expressed the wish for a washroom and weather protection shelter near the receiving bay.

3.3.2 Operations and Maintenance

Staff reported frequently facing difficulties accessing the needed chemicals. This is apparent when looking at the chemical dosage displayed in Figure 16. Reasons mentioned are high costs and insufficient supply chains. Since the materials have to be ordered through the head office in Accra and imported from Europe, they have to cope without chemicals for up to several weeks. As a consequence, the pH has been found to drop below 6, which can impact the nitrification. Precipitation, settling and dewatering are also impacted by the lack of chemicals, leading to higher phosphorus levels and solids concentrations in the effluent. In addition, the inefficient management structure and low local decision-making powers have been identified as a risk factor for the successful operation (Strande et al., 2014).

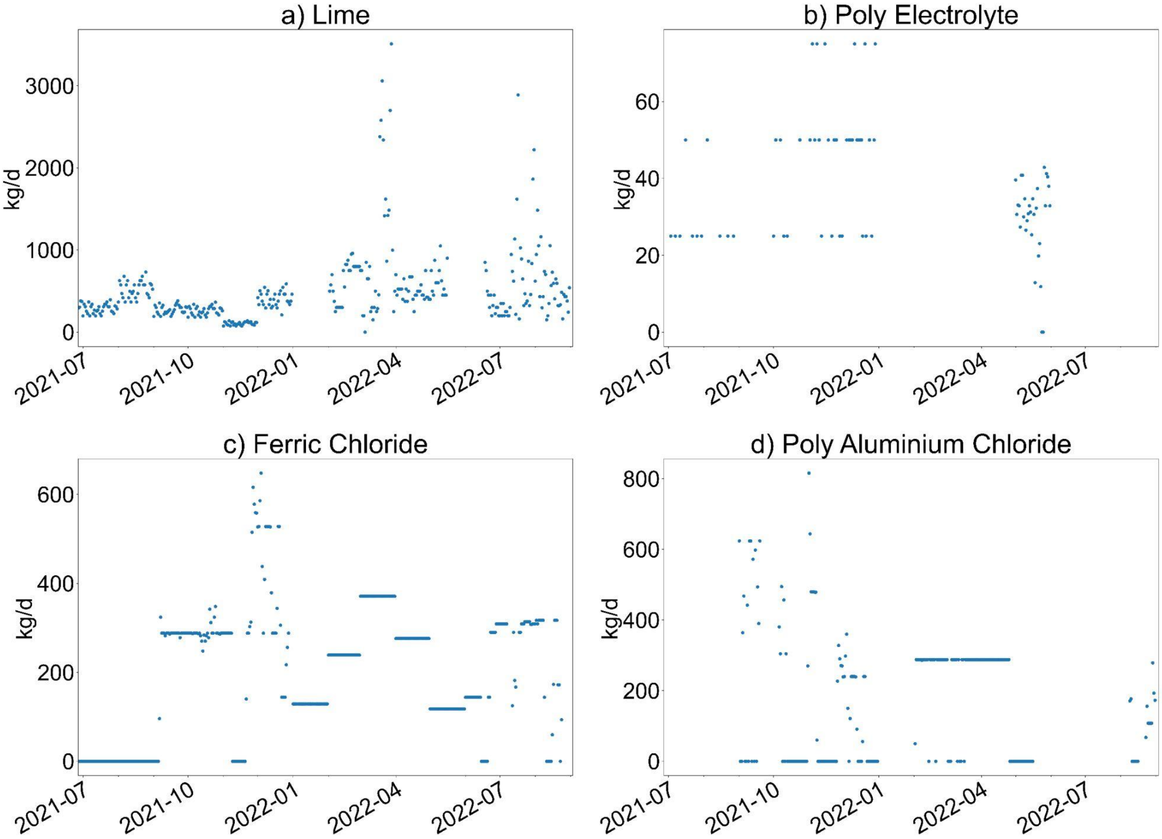

Figure 16: *Daily chemical dosage for a) Lime, b) Poly electrolyte, c) Ferric chloride, d) Poly aluminium chloride*

Compared to ferric chloride which can lower the pH significantly, PAC has been found to have less of an impact. However, it is more expensive than other coagulants (Wei et al., 2015). To cope with this dilemma, staff reported often switching between different chemicals, as well as the location of the dosage. This inconsistent operation makes it harder to understand the interrelationships of the process functioning and make informed decisions based on those.

Access to enough water (e.g., used for mixing chemicals) has also been listed as an issue. Some of the wells of the boreholes onsite have been found to run dry (see Figure 17). As a consequence, water had to be bought from outside at a high cost and a new borehole had to be installed. Staff did not know if any groundwater table analysis was conducted before the construction. Also the water required for the operation of the dewatering system was found to be higher than anticipated.

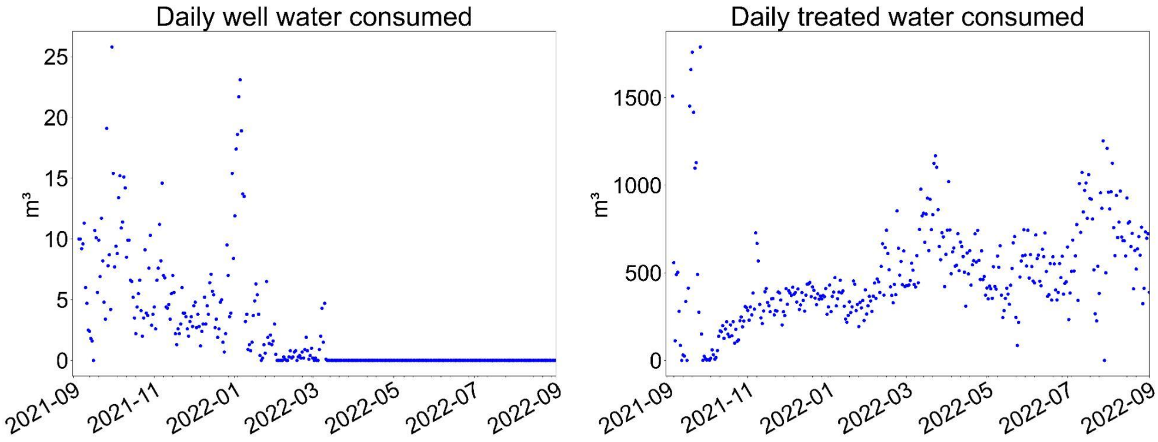

Figure 17: *Daily volumes of well water (left) and treated water (right) consumed*

When it comes to maintenance activities, staff reported difficulties accessing spare parts. Similarly to the chemicals, they are not locally available and have to be commonly imported from Europe for high costs. Delayed maintenance and repair activities can have a negative impact on the treatment efficiency and lead to deterioration of the infrastructure in the long run. Moreover, it can be difficult to find local contracting firms with specific skills.

Some members of the staff also wished that they would have received more training before starting to work at the plant and mentioned that they need to rely on trial and error strategies to optimise their operation instead of deeper process knowledge.

Staff members also voiced safety concerns. There is a shortage of personal protective equipment such as coveralls and gloves. Some of the smaller couplings used to discharge FS from the trucks at the receiving bay do not fit, which can lead to spillages. The consequence is increased exposure to pathogenic materials and an increased health risk.

Power consumption to operate the aerated treatment system is not generally seen as an issue by the staff and they do not see the need to reduce the energy usage for the treatment. However, frequent power cuts can lead to higher costs when needing to rely on generators.

The high costs for operations and maintenance are seen as a high-risk factor for the long-term sustainability of the plant. As a PPP, they also rely on financial support from the government to run their operations. An economic recession could endanger the continued operation of the plant. Consequently, staff members suggested that some form of cost- or resource-recovery might be beneficial.

3.3.3 Quality Control

Monitoring practices at the KWWTP laboratory are impacted by a few limiting factors. Similarly to chemicals and spare parts, access to reagents and other laboratory materials is difficult. High costs and long and complicated import procedures are seen as prohibitive by the staff. As a result, devices could not be adequately and timely calibrated due to a shortage of calibration solutions, leading to inaccurate results. A shortage of potassium hydroxide has led to discontinued BOD_5 measurements. To cope with the shortage of certain reagents to measure nutrients, out of range test kits are sometimes used, contributing to high uncertainties.

The lack of locally available expertise and repair services impacts the quality control practices as well. Instruments such as the spectrophotometer and the laboratory scale are not routinely serviced, and defect measuring probes cannot be easily repaired or replaced. Knowledge on the maintenance of the inline sensors is missing according to the staff. The trust in the reliability of the measured values is rightfully low, so the inline sensor data is mostly not used for decision-making.

The staff is currently not measuring certain potentially relevant parameters, such as faecal coliforms, colour, alkalinity, metals, total nutrients and free chloride. As a reason, they again state the difficulty to access the required materials. However, the prioritisation of those parameters seemed to be rather low. This is especially surprising for the pathogen concentrations, since it is a principal objective of a safe sanitation service chain management.

Table 6. *Results of the assessment of the impact of high COD concentrations on the* NO_3^-*-N measurement by combining filtration and dilution modes using a sample taken from the main buffer on 28/06/2022.*
Italic: diluted measured concentration; Underlined: COD meas. > 200 mg/L; ***Bold:*** NO_3^-*-N values for sample*

Dilution		Unit	Unfiltered		Coffee filter		Microfiber filter	
			NO_3^--N	**COD**	**NO_3^--N**	**COD**	**NO_3^--N**	**COD**
undiluted	measured	mg/L	**5.6**	7175	**2.68**	1096	**1.71**	456
1:5 diluted	*measured*	*mg/L*	*4.23*	*1435*	*0.605*	*219.2*	*0.365*	*91.2*
	calculated	mg/L	**21.15**	7175	**3.025**	1096	**1.825**	456

The results of the assessment of the impact of oxidisable substances on the nitrate measurement is displayed in Table 6. It was found that only the sample which was filtered with a microfiber filter and diluted had a concentration of COD below 200 mg/L (91.2 mg/L) and should have reliable nitrate results according to Hach Lange GmbH (2019). Independent of the filtration mode, all undiluted samples had a COD concentration above the guideline, however it is apparent that a large amount can be removed by filtration. The sample with the highest COD concentration also gave the highest reading for nitrate (5.6 mg/L compared to 1.71 for the microfiber filtered sample). The impact on the resulting nitrate values is even larger for the unfiltered but diluted sample. The reading of 4.23 mg/L is distorted by the high COD (1435 mg/L) of the sample and even more so after multiplying by 5. It is evident that a simple filtration with a coffee filter can already have a big positive effect on the accuracy of the nitrate measurement.

As already mentioned in the discussion of the influent and effluent quality, some laboratory practices can also have a negative impact on the measurement results. The lack of homogenisation can lead to inconsistent results for unfiltered samples. The utensils used for volume measurements can lead to inaccurate dilutions. Substrate can be degraded if samples are not immediately filtered and cooled. On top of that, some methods require the sample to be at a certain temperature to be (e.g., 20 to 24° C for the nitrate measurement discussed before).

Additionally, sampling practices could be improved especially for the samples taken from the biological reactors containing foam. Appropriate specialised sampling devices can help getting a more homogenous and representative sample.

The combinations of the above mentioned factors lead to a poor data basis and low system understanding, making it more difficult to make appropriate operational decisions.

3.3.4 Data Management

A heavy reliance on paper records was observed in several departments, e.g. for the truck logsheets, noting down quality control measurements and the daily process logbook. This data was then often found to be digitised either delayed or not at all, meaning that the collected data is not easily available for data analysis.

If the records are digitised, they were found to be stored in inconsistent forms and varying locations. Often they were transferred into Excel files which were saved locally. As a consequence, there were often different versions of the same excels found in different storage locations. Also, digitised data for some months seemed to be missing altogether and the written records had to be re-entered in an Excel file for the compilation of the data. The storage of the hardcopies also did not seem to be organised and some were missing, as the contractor reportedly took them and did not return them to the plant.

Several staff reported that the data management and storage practices made their work more difficult and made it hard to get a good understanding of the collected data. They were mostly in favour of a centralised data storage system compared to storing them locally, however, internet access might be a problem.

Further, a staff member reported that the laptops they received from the contractor were very slow, it can reportedly take over 30 minutes to open certain files and they have frequently experienced data losses.

Similarly to the previous section, these data management practices impair the system understanding and negatively impact the decision making.

4 Conclusions and Recommendations

The median amount of faecal sludge of 917.5 m^3/d received at the Kumasi Wastewater Treatment Plant was found to be just below the designed capacity of 1000 m^3/d. Considering the high standard deviation of 146.5 m^3/d and a rapid growth rate of Kumasi's population, there is not much buffer space. The variability of the quality of the incoming sludge is also considerable, with values ranging from 263 to 21'000 mg/L COD, 51 to 2411 mg/L TN and 10.2 to 248.5 mg/L TP.

Critical parameters in terms of median compliance with the Ghana EPA guidelines are EC (1615 µS/cm), NH_4^+-N (10.7 mg/L), NO_3^--N (122 mg/L), TP (11.3 mg/L), colour (446 TCU) and E.coli (>105 cfu/100mL). However, the median removal efficiencies appear to be relatively high (99% for BOD_5, 95% for COD, 99% for TSS, 96% for NH_4^+-N, 73% for TN and 71% for TP). A prioritisation of the most important effluent quality parameters leading to an adverse impact on public health and the environment could be conducted to guide the further optimisation of the treatment process.

Several factors have been identified to negatively impact the treatment performance of the plant:

a) Design and layout: The chosen process using the Modified Bardenpho system in a complex series of six stages does not seem to provide the required flexibility for the treatment of highly variable influent under highly variable conditions. Some of the installed technologies appear to not perform as anticipated and can lead to impaired functioning of other system components, resulting in a suboptimal treatment. Poorly planned infrastructure results in disturbances and interruptions of the treatment.

b) Operations and maintenance: The dependence on the import of high-cost materials from abroad with insufficient supply chains and low decision-making powers leads to frequent shortages of the required chemicals and spare parts. These shortages cause inconsistent operation and an impaired treatment. A lack of training and specific technical knowledge has been identified, as well as the lack of local access to specialised services.

c) Quality control: The monitoring practices are negatively impacted by the difficult access to laboratory materials required for analyses and maintenance and repair services for the laboratory equipment. The costs and the lack of local availability have been found to be prohibitive. Standard laboratory practices are not always followed, resulting in inaccurate measurements. A solid data basis on the performance and functioning of the system is missing, making it more difficult to make operational decisions.

d) Data management: Data collection and storage systems are found to be decentrally and insufficiently organised. Collected data is not readily available for analysis and decision making.

It can be concluded that the Modified Bardenpho process is not suitable for faecal sludge treatment in Kumasi, Ghana, especially given the local circumstances and the resource limitations. However, the achieved treatment performance is relatively good and there is much potential to further optimise the technical and managerial operation of the plant. In the following paragraphs, recommendations are listed for the practical implementation in this plant, for further research needed to optimise the treatment performance and for the planning of other FSTPs in similar settings.

Practical recommendations:

General

- Prioritise the improvement of critical parameters for environment and health
- Improve the communication to the head office in Accra
- Improve management flexibility by increasing decision making powers at KWWTP
- Improve the relationship to research institutions
- Increase community engagement
- Carry out a systematic assessment of the success or failure as proposed by Bassan et al. (2015)
- Carry out a systematic optimisation program (e.g. as proposed by National Research Council, 2003: define objectives, identify performance limiting factors, prioritise performance limiting factors)

Design and layout

- Improve the condition of the access roads in the vicinity of the plant
- Improve the condition of the road to the dewatered sludge skip
- Explore the feasibility of an extension of the main buffer and the mixed sludge basin
- Improve the mixing conditions in the third anoxic reactor
- Quantify unknown flows by installing flow sensors
- Optimise the operation by adjusting the RAS flow
- Optimise the operation by adjusting the IR flow
- Optimise the operation by using the SRT as a guideline value

Operations and layout

- Implement more specialised staff training (technical and managerial)
- Monitor the inventory
- Bulk order materials ahead of time
- Set up direct and long term contracts with suppliers
- Set up automated ordering systems when the inventory is low
- Keep a stock of spare parts
- Keep a stock of safety equipment

Quality control

- Keep a stock of laboratory materials
- Establish connections with local laboratory equipment specialists
- Acquire specialised sampling equipment
- Regularly service laboratory equipment
- Use simple filtration equipment before analysis of soluble parameters
- Use test strips to estimate concentration ranges or for rapid testing
- Regularly analyse MLSS
- Get specialised training for maintenance of inline sensor
- Acquire laboratory equipment for measuring alkalinity, colour and pathogens
- Focus on relevant and easy to measure parameters

Data management

- Record results of laboratory experiments
- Record results of operational experiments
- Record operational changes in flow rates (RAS, IR, carbon addition to the third anoxic basin)
- Routinely document the location of chemical dosage

- Establish well understood procedures for record keeping
- Switch from paper records to electronic where possible
- Employ an IT consultant to set up a central data storage system (server, cloud)

Resource and cost recovery

- Explore the possibility of collecting tipping fees for cost recovery (see Tanoh et al., 2022)
- Explore the potential of resource recovery of dewatered sludge
- Explore the potential of reuse of the effluent for irrigation
- Explore the local availability of biodegradable flocculants (see Maćczak et al., 2020)

Outlook and future research:

- Conduct a microbial analysis of the activated sludge and investigate changes related on the operation (chemical dosage, recycle flows)
- Compare different biodegradable polymers in terms of dewatering performance, costs, local availability and suitability
- Investigate the potential of producing chitosan local from shrimp waste (Gold et al., 2016), also recommended by (Moto et al., 2018)
- Investigate the potential of co-composting of the dewatered sludge with the solid waste from KCARP and determine suitable mixing ratios
- Identify factors of demand for sanitation services and make projections for the future
- Evaluate models and contractual arrangements of PSP in sanitation services and assess performance and shortcomings
- Assess the impact of the collection of tipping fees on the received sludge
- Assess the suitability of the effluent for reuse in agriculture
- Assess the market demands for the recovered products (irrigation water, compost)

Recommendations for planning other plants:

- Focus on pathogen removal
- Use locally available and replaceable materials in construction
- Engage all stakeholders during and before planning
- Choose resilient and low maintenance systems
- Choose a system with low O&M costs
- Choose a system with resource recovery
- Conduct a thorough analysis of the expected quantity and quality of the FS

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Appendix

A Effluent Discharge Guidelines

Table 7. *National guidelines for effluent discharge from municipal wastewater treatment plants*

Parameter	**Unit**	**Ghana (Ghana EPA, 2010)**	**Switzerland (WPO, 1998)**
Colour	TCU	200	-
EC	µS/cm	1500	-
pH	-	6 - 9	6.5 - 9 [2]
Temperature	°C	≤3 above ambient	-
Turbidity	NTU	75	(Snellen transparency: >30cm)
TDS	mg/L	1000	-
TSS	mg/L	50	15 [3]
BOD_5	mg/L	50	15 [4, 4]
COD	mg/L	250	45 [4, 5]
NH_4^+-N	mg/L	1	2 [6]
NO_3^--N	mg/L	50	(TN: as low as possible)
TP	mg/L	2	0.8 [7]
Oil and Grease	mg/L	5	-
Cadmium	mg/L	0.1	0.1
Chromium	mg/L	0.5	2
Total Coliform	cfu/100mL	400	-
E. coli	cfu/100mL	10	-

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[2] For industrial wastewater treatment plants, no value for municipal wastewater

[3] For WWTPs serving more than 10’000 inhabitants

[4] Required removal efficiency: 90%

[5] Required removal efficiency: 85%

[6] Required removal efficiency: 90% compared to Kjeldahl nitrogen in influent

[7] Applicable for sensitive waters, required removal efficiency: 80%

B Collected Quantitative Data

Table 8. *Collected quantitative data for the characterisation of received faecal sludge (Section 2.3)*

Item	**Parameters**	**Type**	**Source**	**Method**	**Analysis**
Truck logsheet records	Daily number of trucks	Secondary	Received as · *KWWTP Operations Data 2022 Draft.xlsx* · *TRUCK DATA 2021 - KWWTP.xlsx*	Manual data entry	Summary statistics Time series
Influent volume	Volume (influent and inflow to primary clarifier)	Secondary	Exported from Vision as · *inflow-cum.csv* · *inflow-pc-cum.csv*	Inline Sensor	Summary statistics Time series
Influent flow	Flow (influent and inflow to primary clarifier)	Secondary	Exported from Vision as · *inflow.csv* · *inflow-pc.csv*	Inline sensor	Daily pattern Weekly pattern
Influent totalizer reading	Daily volume (influent and inflow to primary clarifier)	Secondary	Received as · *KWWTP Operations Data 2022 Draft.xlsx* · *TRUCK DATA 2021 - KWWTP.xlsx*	Manual data entry	Summary statistics Time series
Influent quality	Temperature, turbidity, EC, pH, TDS, ORP, DO, BOD_5, COD, TSS, VSS, NH_4^+-N, NO_3^--N, TN, TP	Secondary	Received as · *07.2021 TRIAL OPERATION.xlsx* · *08.2021 TRIAL OPERATION.xlsx* · *09.2021 TRIAL OPERATION.xlsx* · *10.2021 TRIAL OPERATION.xlsx* · *12.2021 TRIAL OPERATION.xlsx* · *02.2022 TRIAL OPERATION.xlsx* · *03.2022 TRIAL OPERATION.xlsx* · *04.2022 TRIAL OPERATION 1.xlsx* · *MAY.2022 TRIAL OPERATION new.xlsx* · *June, 2022.xlsx* · *JULY, 2022.xlsx* · *AUGUST, 2022.xlsx*	Laboratory measurement	Summary statistics Time series

Table 9. *Collected quantitative data for the performance assessment (section 2.4)*

Item	**Parameters**	**Type**	**Source**	**Method**	**Analysis**
Effluent quality	Temperature, turbidity, EC, pH, TDS, ORP, DO, BOD_5, COD, TSS, NH_4^+-N, NO_3^--N, TN, TP	Secondary	Same as for influent quality	Laboratory measurement	Summary statistics Time series
Effluent characteristics	E. coli, true colour, Na, Ca, Mg, Pb, Cd, Cr, Ni	Primary	-	Laboratory measurement	-
Measurement campaign (nutrients)	TN_{sol}, NH_4^+-N_{sol}, NO_3^--N_{sol}, TP_{sol}, COD_{sol} (influent, primary clarifier, biological basins B, effluent)	Primary	-	Laboratory measurement	Summary statistics Boxplot Time series
Measurement campaign (solids)	TSS/MLSS, VSS/MLVSS (influent, primary clarifier, aerobic 1B and 2B, effluent)	Primary	-	Laboratory measurement	Summary statistics
PC effluent quality	Temperature, turbidity, EC, pH, TDS, ORP, DO, BOD_5, COD, TSS, NH_4^+-N, NO_3^--N, TN, TP	Secondary	Same as for influent quality	Field/laboratory measurement	Summary statistics (TSS) Time series
Activated sludge properties	MLSS,SV30 (aerobic 1 and 2)	Secondary	Same as for influent quality	Laboratory measurement	Summary statistics (MLSS) Time series
pH conditions	pH (biological basins)	Secondary	Same as for influent quality	Field/laboratory measurement	Boxplot Time series (Aug 22 campaign)
Sludge flows	Daily volume (primary sludge, waste activated sludge)	Secondary	Exported from Vision as · *pc-sludge-vol.csv* · *sc-sludge-vol.csv*	Inline sensor	Mean, min (for flow diagram) Time series
Inline measurements	pH and EC (lifting station, main buffer), DO (aerobic 1 and 2), temperature, TSS/MLSS (aerobic 2), COD, NH_4^+-N and NO_3^--N (effluent)	Secondary	Exported from Vision as *mb-ph.csv, raw-ph.csv, mb-cond.csv, raw-cond.csv, do-1a-1.csv, do-1a-2.csv, do-1a-3.csv, do-1b-1.csv, do-1b-2.csv, do-1b-3.csv, do-2a.csv, do-2b.csv, temp-2a.csv, temp-2b.csv, tss-2a.csv, tss-2b.csv, cod.csv, nh4.csv, no3.csv*	Inline sensor	Time series

Table 10. *Collected quantitative data for the identification and documentation of performance limiting factors (Section 2.5)*

Item	**Parameters**	**Type**	**Source**	**Method**	**Analysis**
Fill volume	Fill level (main buffer basin, mixed sludge basin)	Secondary	Exported from Vision as · *mb-level.csv* · *msb-level.csv*	Inline sensor	Time series
Chemical dosage	Daily amount of $Ca(OH)_2$, $FeCl_3$, PE, PAC, NaOCl	Secondary	Received as · *KWWTP Operations Data 2022 Draft.xlsx* · *chemical dosage for 2021.xlsx*	Manual data entry	Time series
	Consumed well and treated water		Exported from Vision as · *treated.csv* · *well-consumed.csv*	Inline sensor	Time series
Nitrate measurement method	NO_3^--N (filtration: unfiltered, coffee filter, MN GF-5 glass fibre filter; dilutions: undiluted, 1:5)	Primary	-	Laboratory measurement	-

C Methods, Materials and Devices

Table 11. *List of employed methods and materials for sample analysis*

Parameter	Methods and materials
pH	WTW Multi 3320, Hanna Instruments HI991001, Palintest Micro 800 MULTI
DO, EC	WTW Multi 3320, Hach HQ30d
ORP, TDS	Hach HQ30d
Colour	Grade 1 qualitative filter, Hach DR3900 Spectrophotometer (True Colour Pt-Co 465 nm)
E. coli	Membrane filtration (0.45 µm pore size), Water Jet Pump, Memmert Incubator 100-800, Chromocult Coliform Agar
TSS	Whatman 934-AH Glass Microfiber Filters, Millipore Chemical Duty Pump 6122050, Cole-Parmer PA 124I (120g ± 0.1mg), Faithful 202-1AB Drying Oven
VSS	Faithful Electric Ceramic Fibre Laboratory Muffle Furnace
NO_3^--N	Hach DR3900 Spectrophotometer, Hach LCK339 Cuvette, range estimation with Mquant Test Strips (10-500 mg/L)
NH_4^+-N	Hach DR3900 Spectrophotometer, Hach LCK302/303 Cuvette, range estimation with Mquant Test Strips (10-400 mg/L)
TN	Hach DR3900 Spectrophotometer, Hach LT200 Thermostat, Hach LCK238 Cuvette
TP	Hach DR3900 Spectrophotometer, Hach LT200 Thermostat, Tests LCK348 Cuvette
COD	Hach DR3900 Spectrophotometer, Hach LT200 Thermostat, Hach LCK014/114/514 Cuvette
Ca, Na, Mg, Pb, Cd, Cr, Ni	Digestion of 50 mL sample with 10 mL of 1:1 mix of nitric acid (HNO_3, 70%) and perchloric acid ($HClO_4$, 70%) and 10 mL of sulfuric acid (H_2SO_4, 98%), measurement with Atomic Absorption Spectrometer at KNUST Central Laboratory

Table 12. *List of employed materials and softwares for sample preparation and data analysis*

Activity	Materials and Software
Filtration	Macherey-Nagel MN GF-5 Filter Paper, House of Coffees Filter Paper (Size 102)
Dilution	Hach QH82797 Pipette (0.2 - 1.0 mL), Measuring Cylinder 100 mL (± 0.5 mL)
Data analysis	Python Jupyter Notebook, Microsoft Excel

Figure 18: *Photo of sampling procedure (left) and coliform analysis preparation (right)*

D Semi-structured Interview Questions for KWWTP Staff

1. *General plant functioning*

A. What is your opinion on the new plant?
B. What is the main challenge you face in your daily work?
C. What risks for long-term sustainability of the plant operation do you see?
D. What do you see as the most financially unsustainable part of your operation?
E. What were the best parts of the training you received? Which parts were missing?
F. Describe the working with the contractor. What was good? What could have been better?
G. How would you improve the security/safety conditions at KWWTP?

2. *Treatment performance*

A. What effluent quality parameters are of concern?
B. What are your main barriers for achieving better results?
C. Improving the quality of which parameter is your top priority?

3. *Design and layout*

Compartment	**Main issue (past/now)**	**Frequency**	**Still occuring?**	**What are the reasons?**	**What are the effects?**	**Layout suitable?**
Waste docking station						
Screening						
Lifting pump station + emergency basin						
Fat and grit separator						
Main buffer basin						
Primary clarifier						
Biological basins						
Secondary clarifier						
UV disinfection						
Mixed sludge basin						
Dewatering						
Treated water reuse						
Well water use						
Chemical dosage						

A. If you could, what would you change in the layout of the plant?
B. If you could, what would you change in the process design/treatment stages?

4. *Chemical dosage/process monitoring*

A. What is the main challenge you face in process/operations?
B. What challenges do you face regarding access to chemicals? What are the reasons?
C. For what chemicals have you faced difficulties to access?
D. What are the consequences of the difficulties to access?
E. In your opinion, how could the access to chemicals be improved so you don't run out anymore?
F. How do you make use of the inline sensor data?
G. What types of decisions do you make using the inline sensor data?

5. Maintenance

A. What challenges do you face regarding maintenance work?
B. What challenges do you face regarding access to repair services?
C. In your opinion, how could the maintenance be improved?

6. Power consumption

A. What challenges do you face regarding electricity and energy usage?
B. How do power cuts affect the treatment? What are the consequences?
C. In case of negative effects: In your opinion, how could the situation be improved?
D. What is the share of energy used for aeration?
E. What is your opinion on the current power consumption?
F. What is your opinion on the current power consumption for aeration?
G. What strategies do you plan to use to reduce the power consumption?

7. Quality control

A. What challenges do you face regarding access to materials needed for QC? What are the reasons?
B. For what materials have you faced difficulties to access?
C. In your opinion, how could the access to materials be improved so you don’t run out anymore?
D. Why do you not filter the samples before nutrient analysis?
E. Why do you not measure pathogens?

8. Data management

A. How do you store your data?
B. What challenges do you face regarding data management?
C. How do you think current data management impacts your decision-making?
D. In your opinion, how could data management be improved?
E. Would you prefer to save monitoring data on a server or cloud service?

E Semi-structured Interview Questions for Truck Drivers

A. What is your opinion on the new treatment plant?
B. What was the situation like before the construction of the new plant?
C. What do you think of the layout and accessibility of the docking facilities?
D. Is there anything you would change?
E. What is your opinion on the turnaround times/waiting times?
F. What would you change to improve the efficiency?
G. How would you improve the safety/security conditions?
H. What suggestions do you have to make your job easier or better?
I. At what discharge fee would you stop coming here?
J. How does your business change between seasons?
K. Normally, how much water do you use to dilute the faecal sludge before pumping?
L. What types of onsite technologies and origins do you encounter?

F Additional Figures for Section 3.1

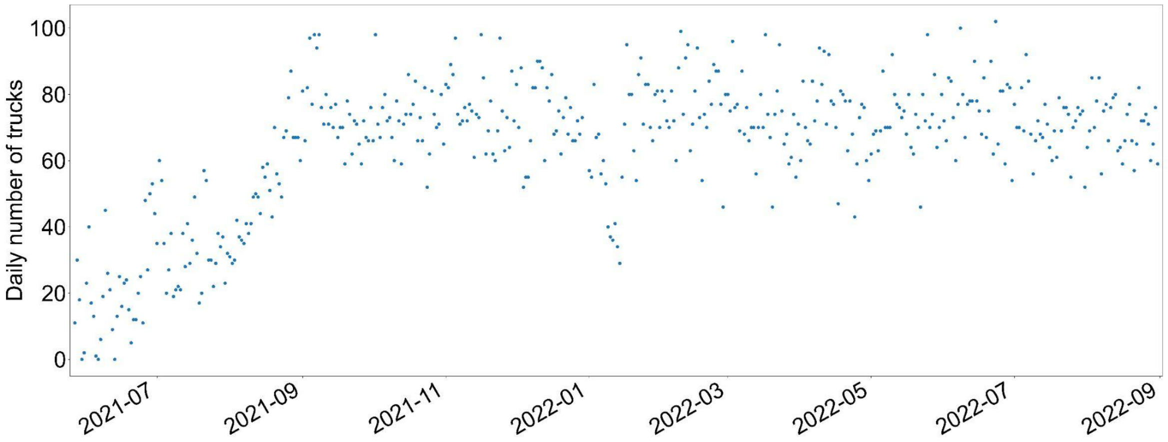


Figure 19: *Time series of daily number of received faecal sludge collection trucks*

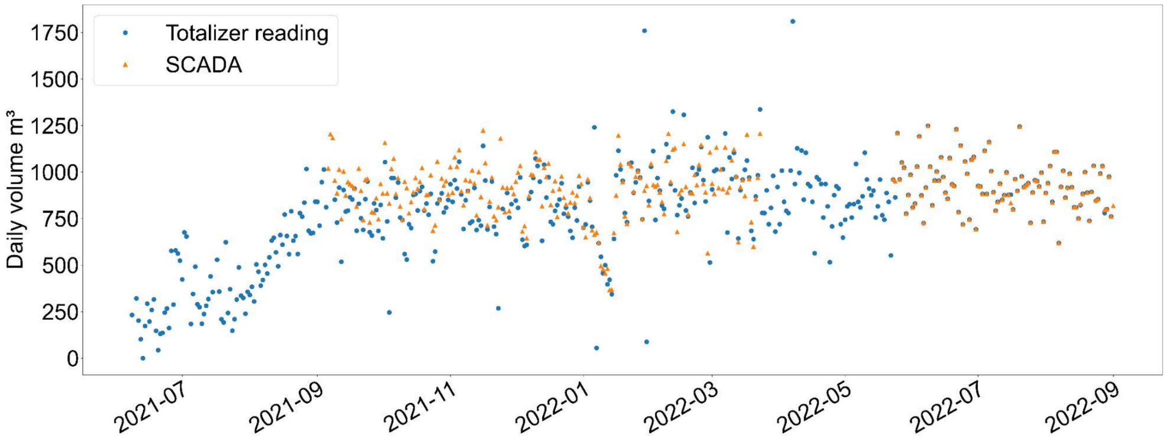


Figure 20: *Time series of daily received volumes recorded by a reading of the flow totalizer and exported from the SCADA software Vision*

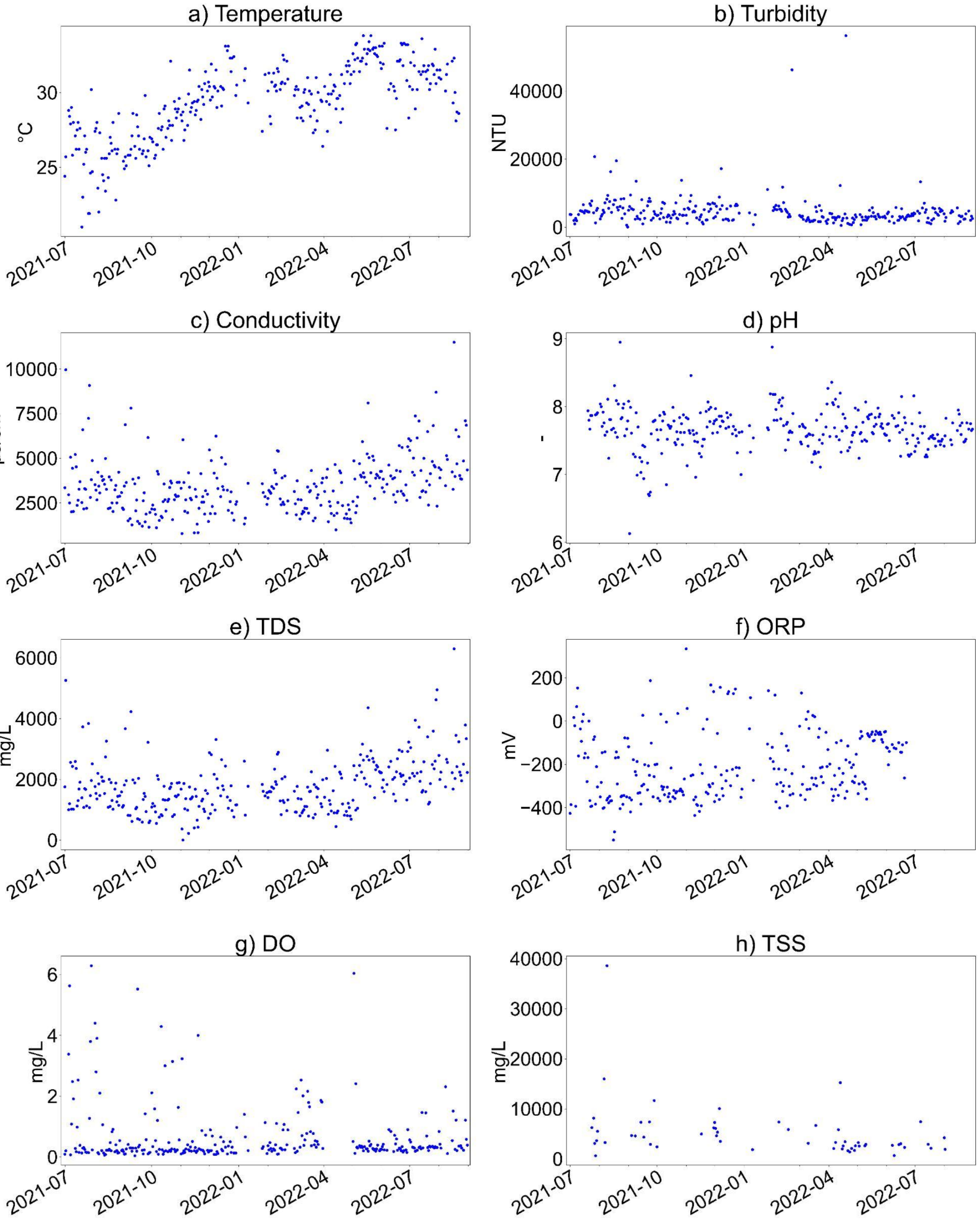
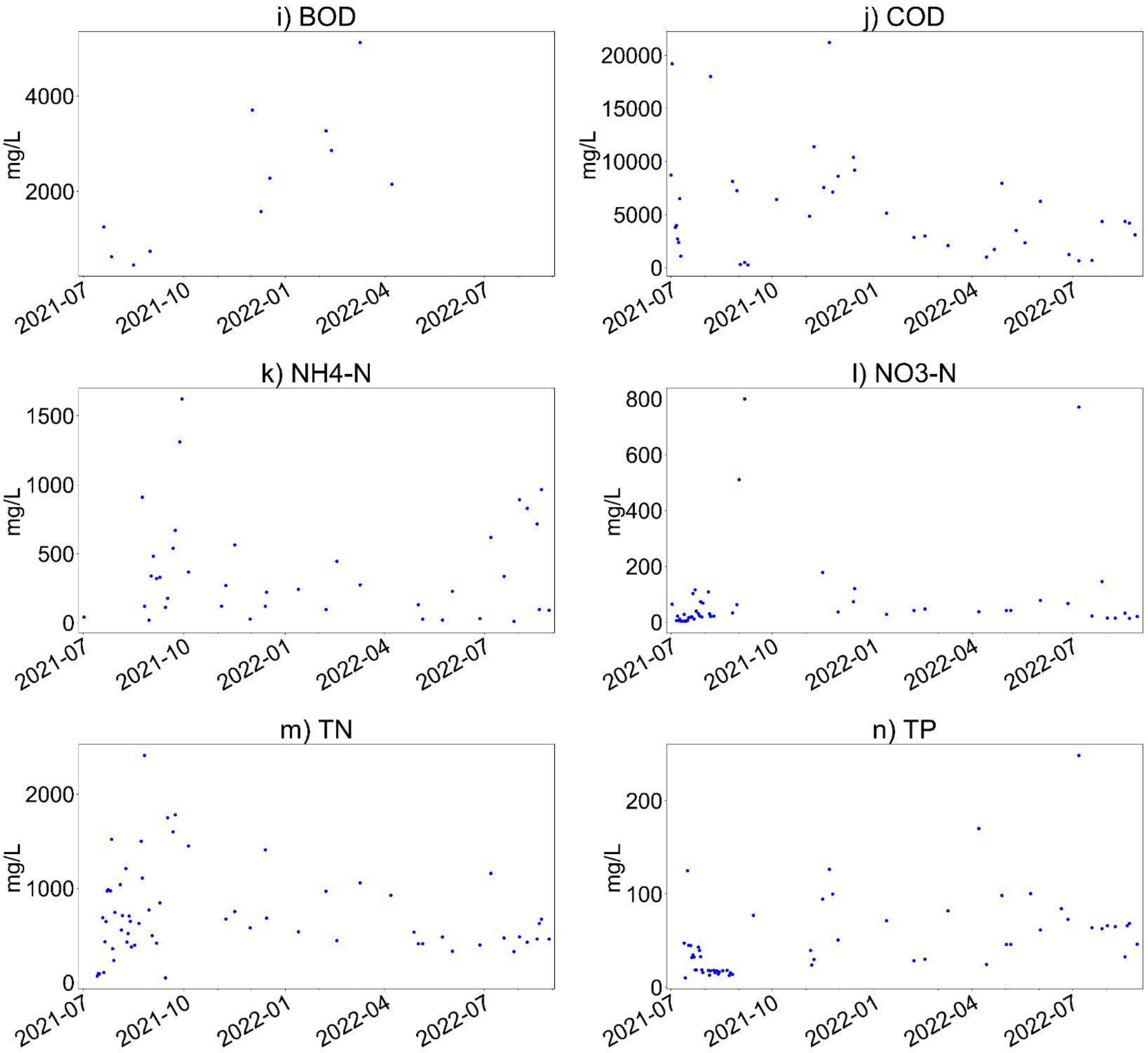


Figure 21: *Time series of available secondary influent quality data for a) Temperature, b) Turbidity, c) EC, d) pH, e) TDS, f) ORP, g) DO, h) TSS*


i) BOD

j) COD

k) NH4-N

l) NO3-N

m) TN

n) TP

Figure 22: *Time series of available secondary influent quality data for i) BOD$_5$, j) COD, k) NH$_4^+$-N, l) NO$_3^-$-N, m) TN, n) TP*

G Additional Figures for Section 3.2

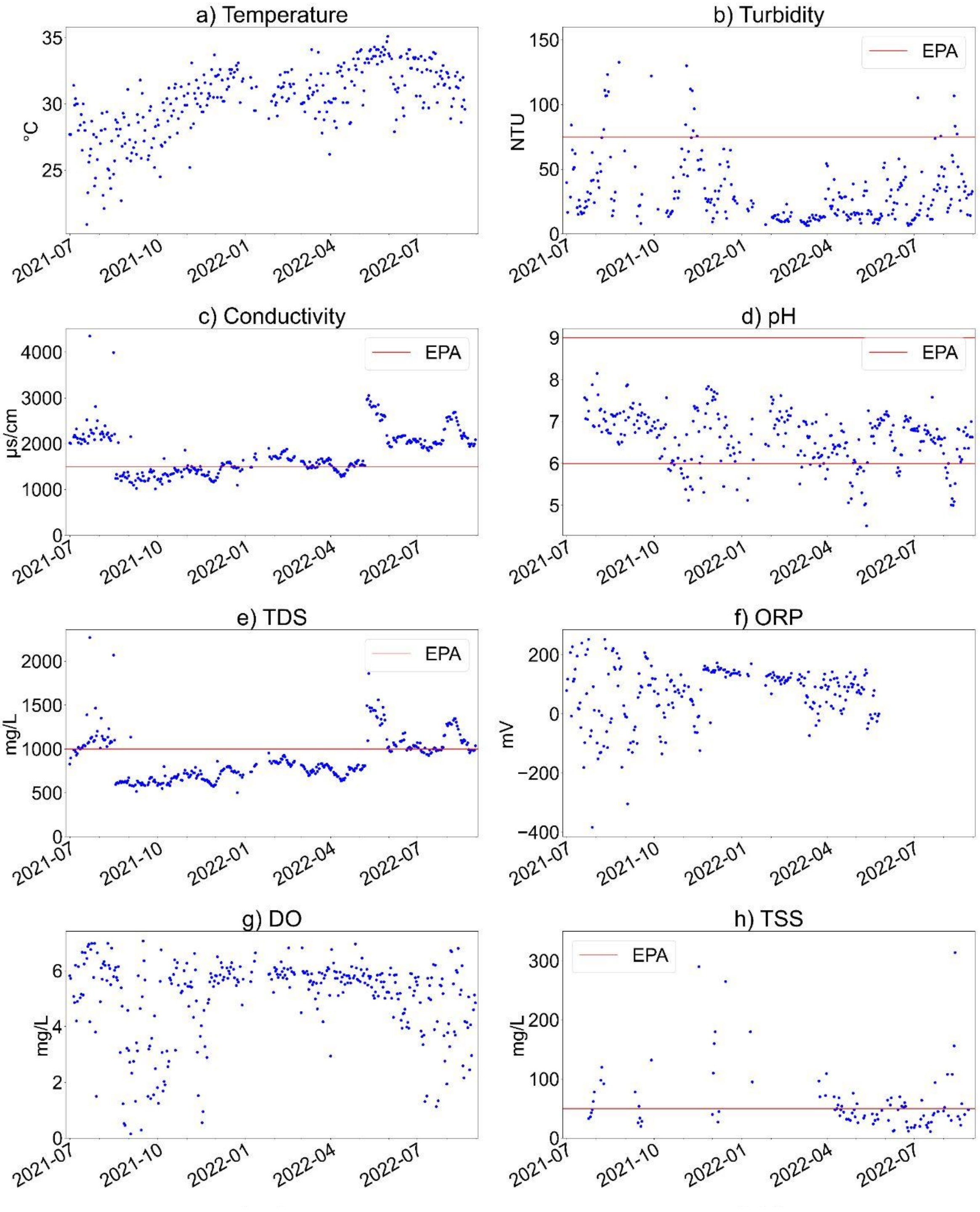


Figure 23: *Time series of available secondary effluent quality data compared to effluent discharge guidelines (Ghana EPA, 2010) for a) Temperature, b) Turbidity, c) EC, d) pH, e) TDS, f) ORP, g) DO, h) TSS*

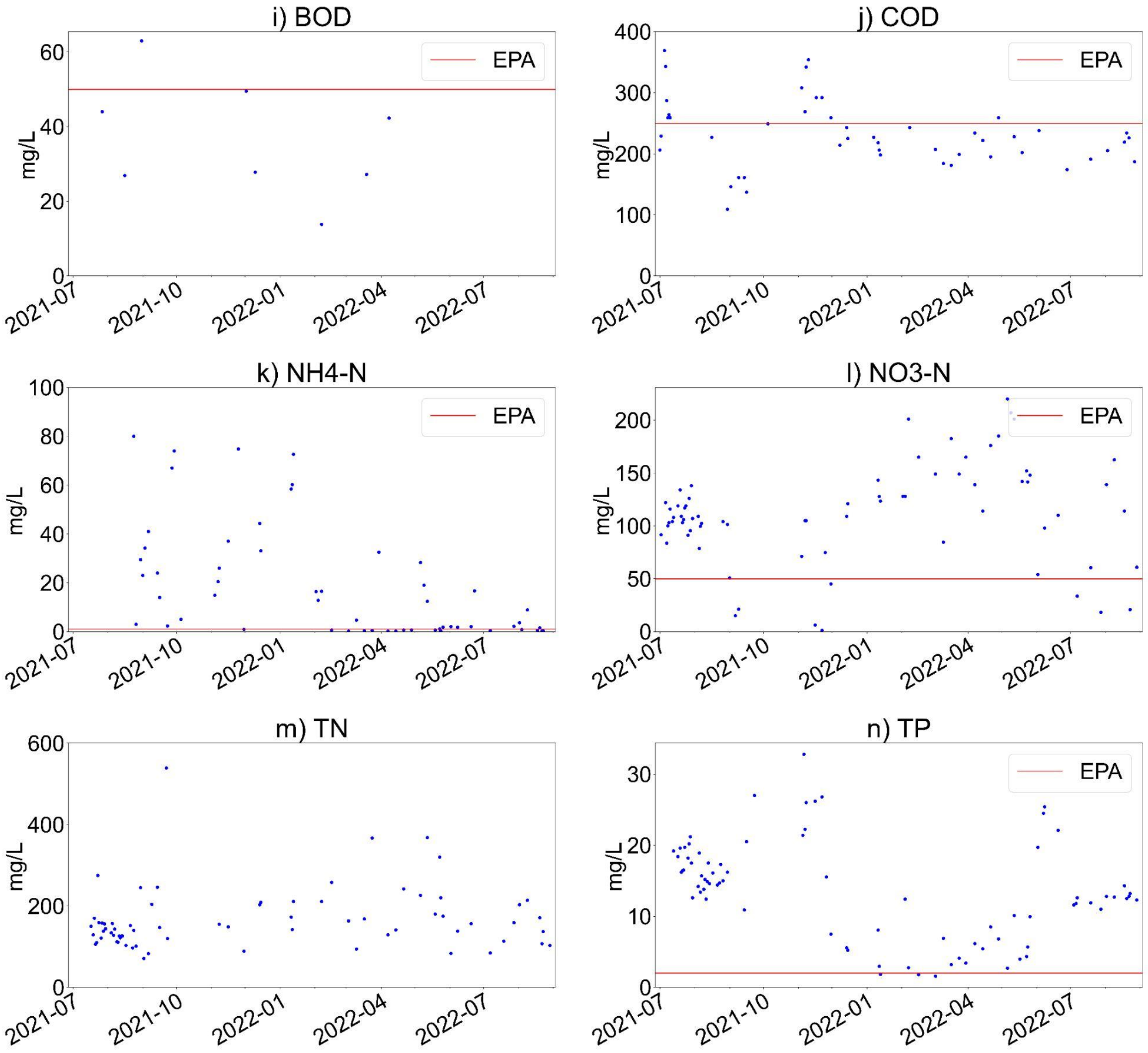


Figure 24: *Time series of available secondary effluent quality data compared to effluent discharge guidelines (Ghana EPA, 2010) for i) BOD$_5$, j) COD, k) NH$_4^+$-N, l) NO$_3^-$-N, m) TN, n) TP*

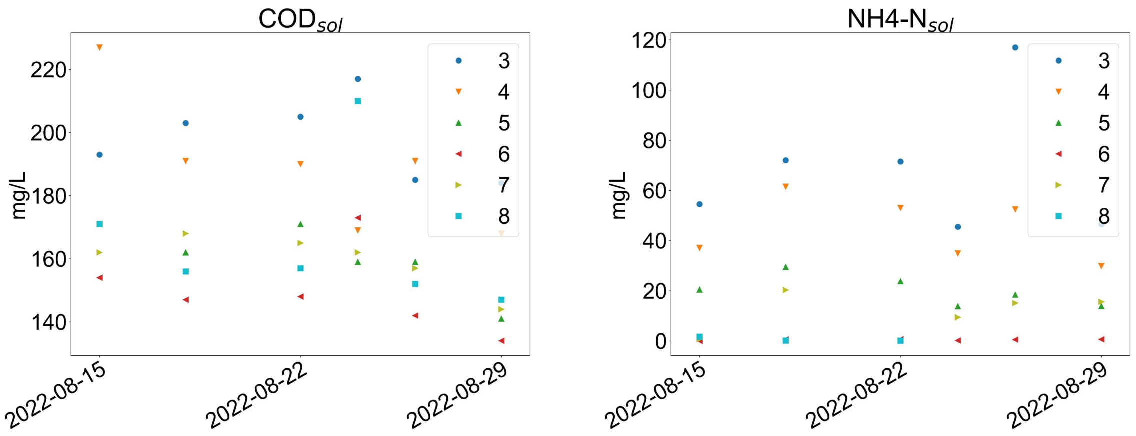


Figure 25: *Time series of dissolved (*$_{sol}$*) COD (left) and* NH_4^+*-N (right) concentrations measured in a measurement campaign (n=6) from 15/08/2022 to 29/08/2022 (3: Anoxic 1B, 4: Anaerobic B, 5: Anoxic 2B, 6: Aerobic 1B, 7: Anoxic 3B, 8: Aerobic 2B)*

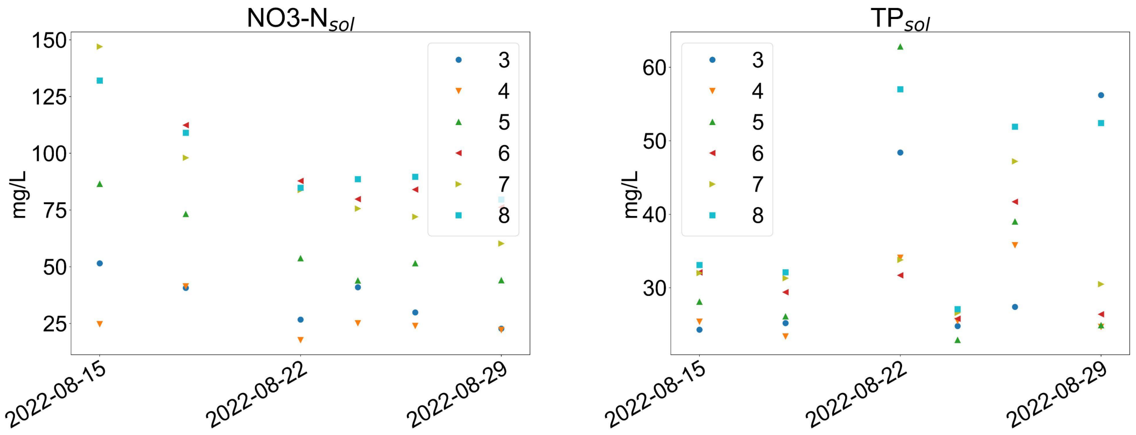


Figure 26: *Time series of dissolved (*$_{sol}$*)* NO_3^-*-N (left) and TP (right) concentrations measured in a measurement campaign (n=6) from 15/08/2022 to 29/08/2022 (3: Anoxic 1B, 4: Anaerobic B, 5: Anoxic 2B, 6: Aerobic 1B, 7: Anoxic 3B, 8: Aerobic 2B)*

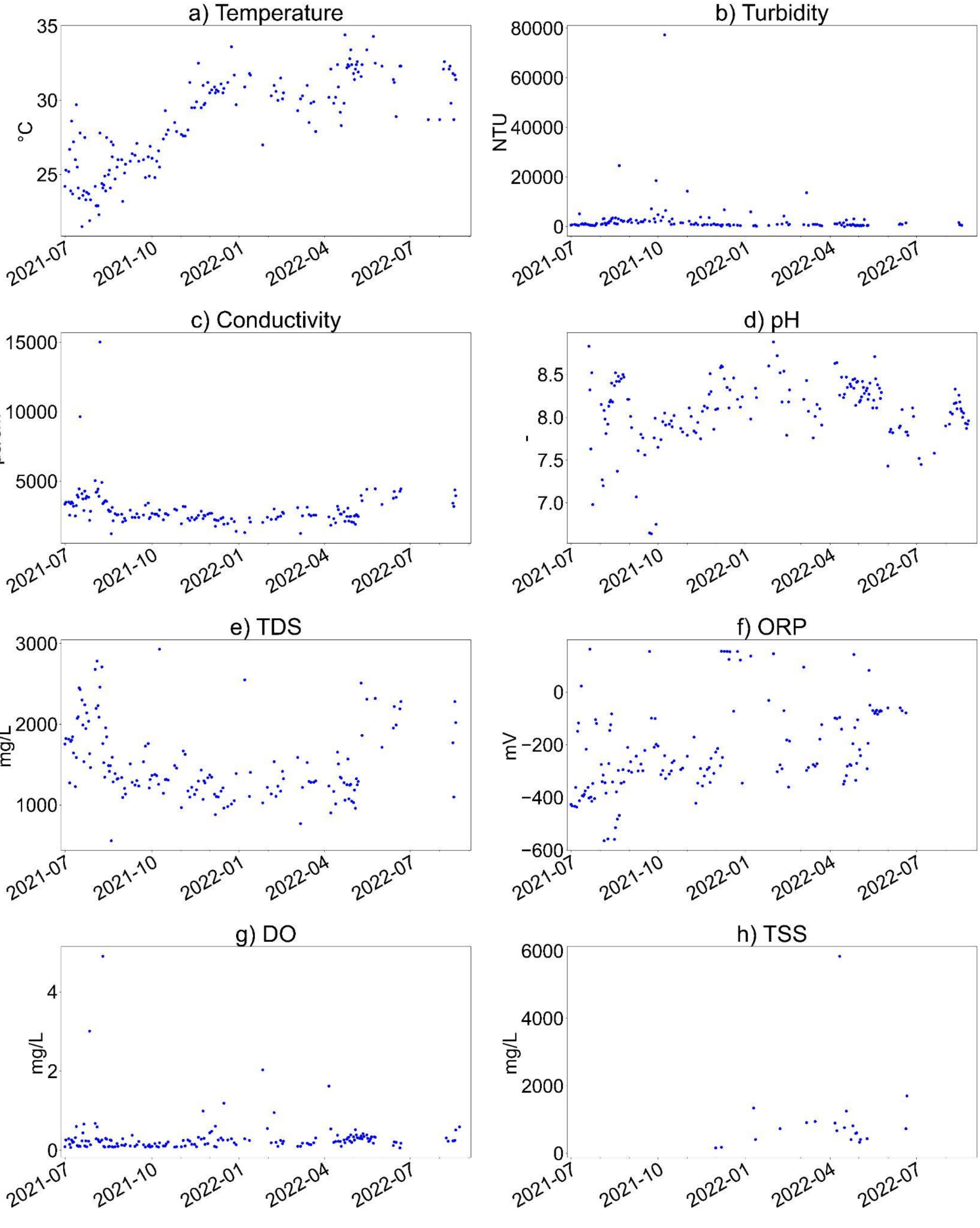


Figure 27: *ime series of available secondary primary clarifier effluent quality data for a) Temperature, b) Turbidity, c) EC, d) pH, e) TDS, f) ORP, g) DO, h) TSS*

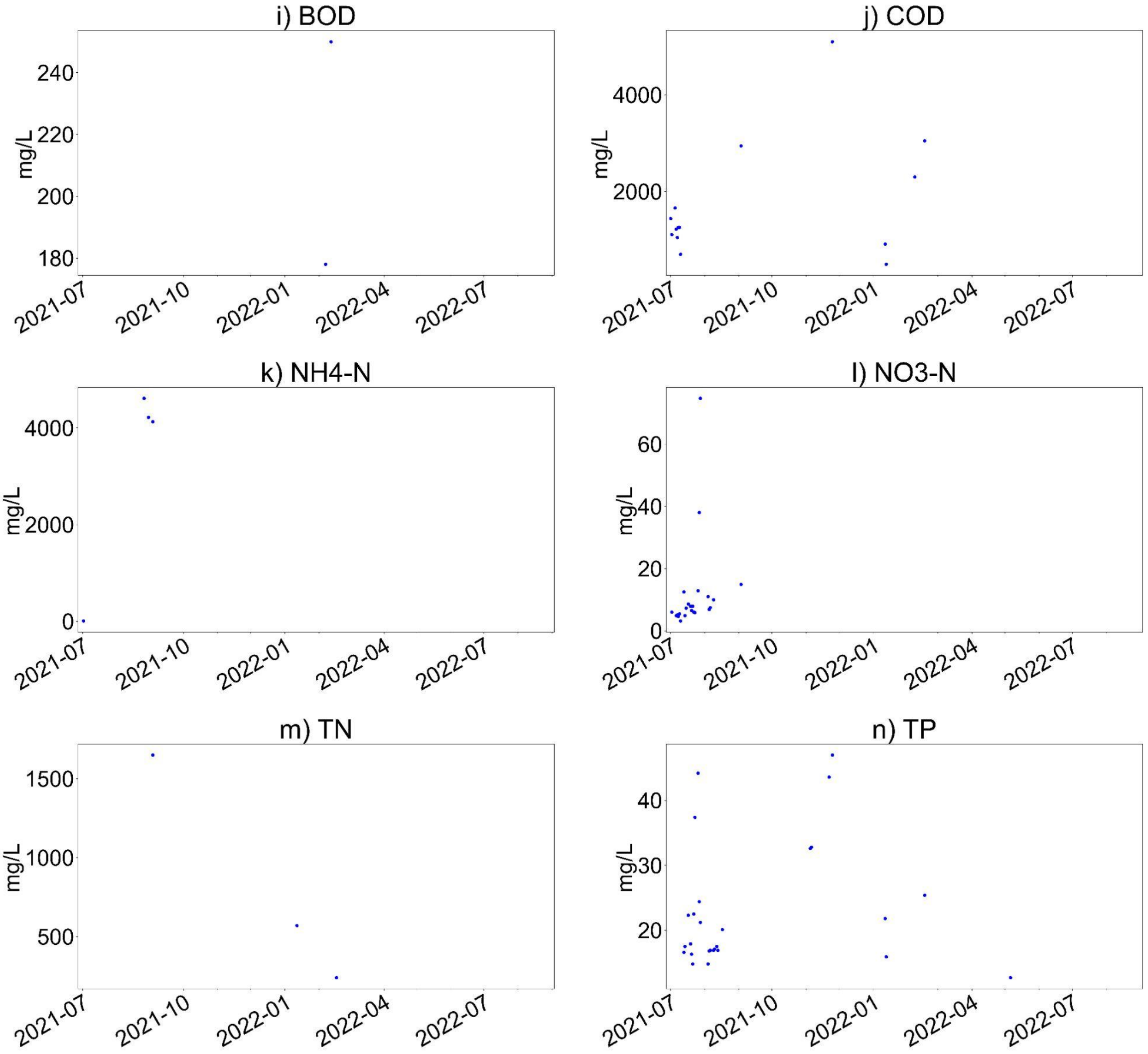


Figure 28: *Time series of available secondary primary clarifier effluent quality data for i) BOD$_5$, j) COD, k) NH$_4^+$-N, l) NO$_3^-$-N, m) TN, n) TP*

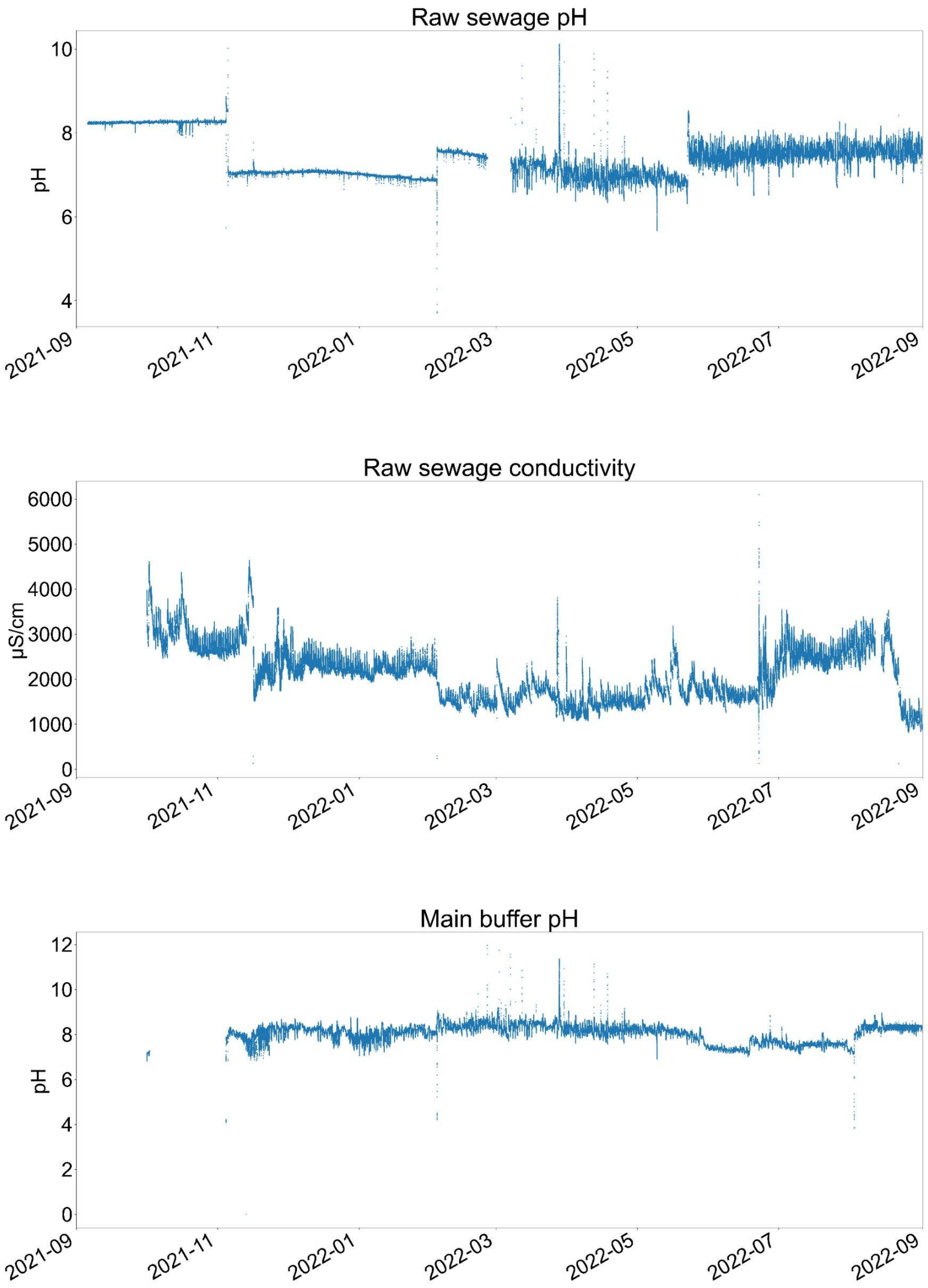


Figure 29: *Available inline sensor data for pH and EC in the lifting pump station and pH in the main buffer*

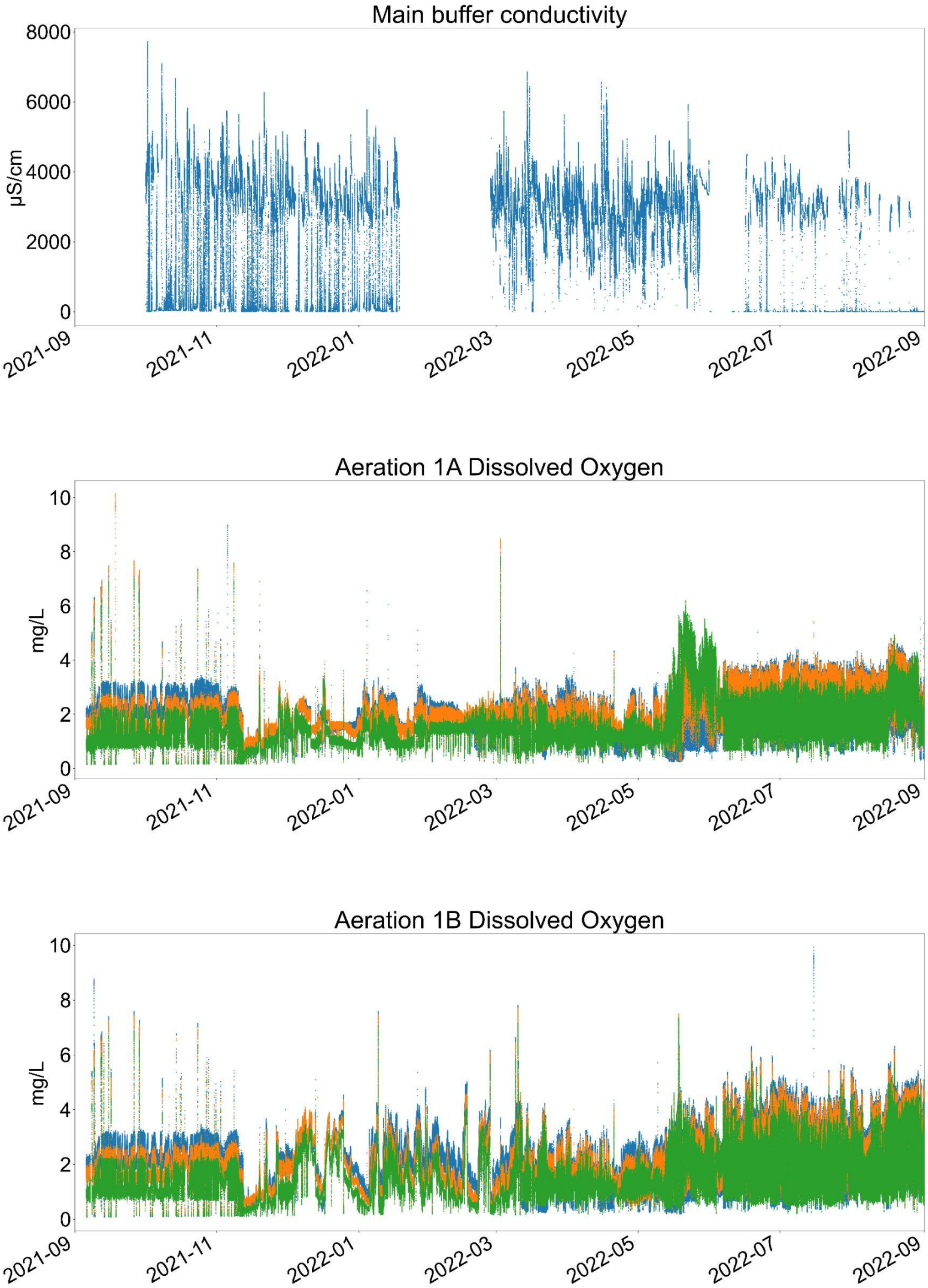


Figure 30: *Available inline sensor data for EC in the main buffer and DO in the first aerobic reactors, measured by 3 separate DO probes each*

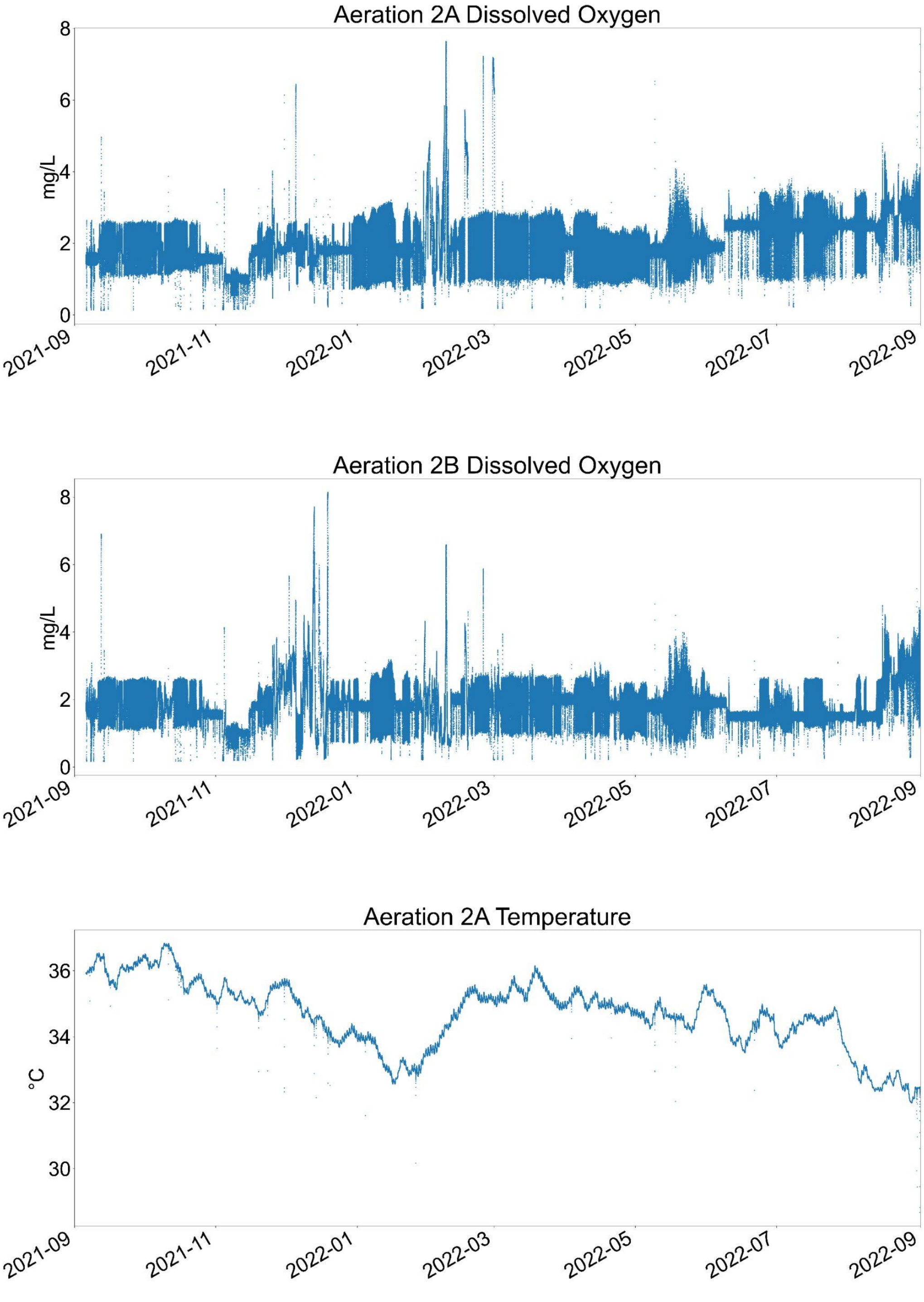


Figure 31: *Available inline sensor data for DO in the second aerobic reactors and temperature in the second aerobic reactor (A)*

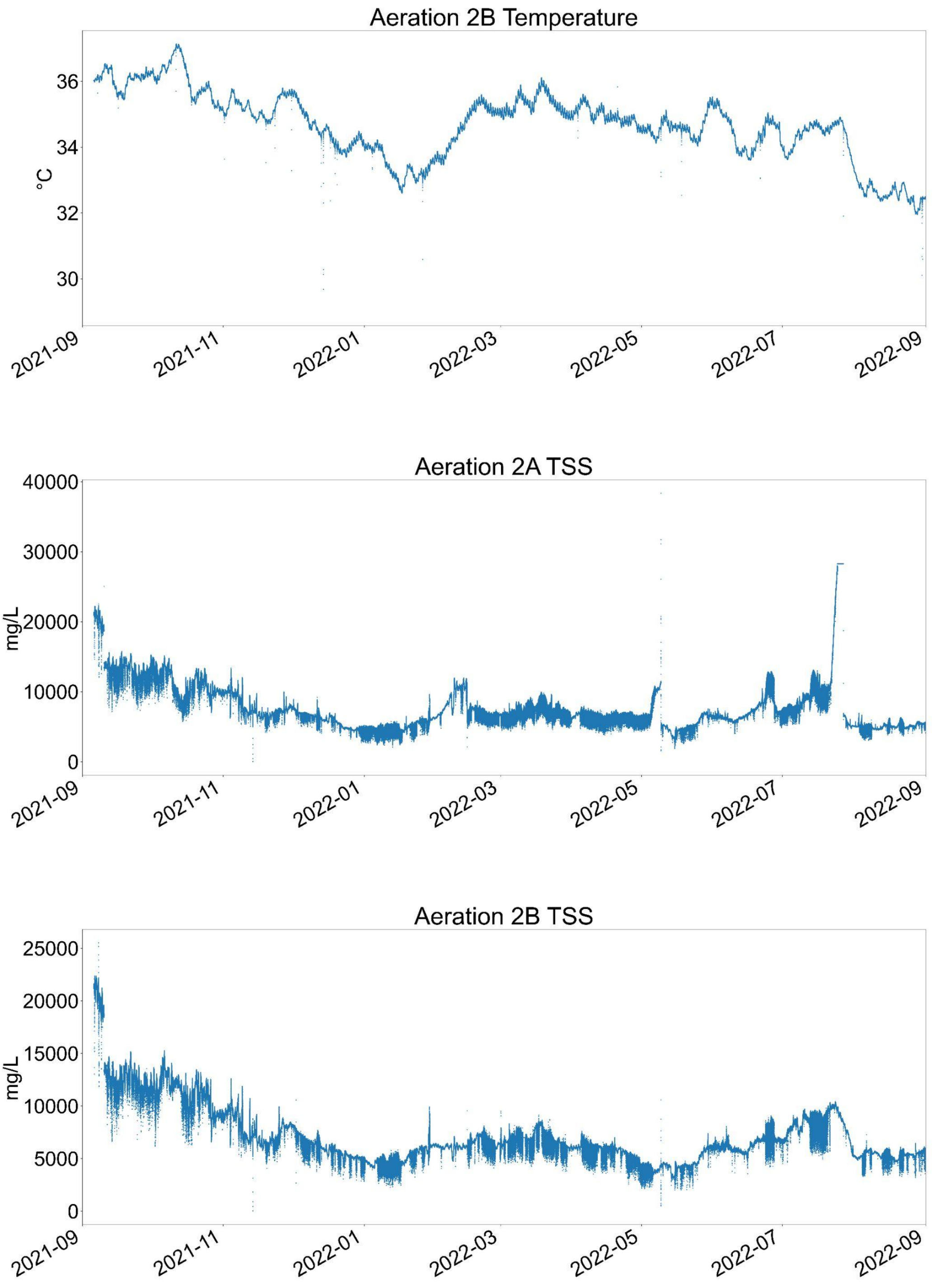


Figure 32: *Available inline sensor data for temperature in the second aerobic reactor (B) and TSS in the second aerobic reactors*

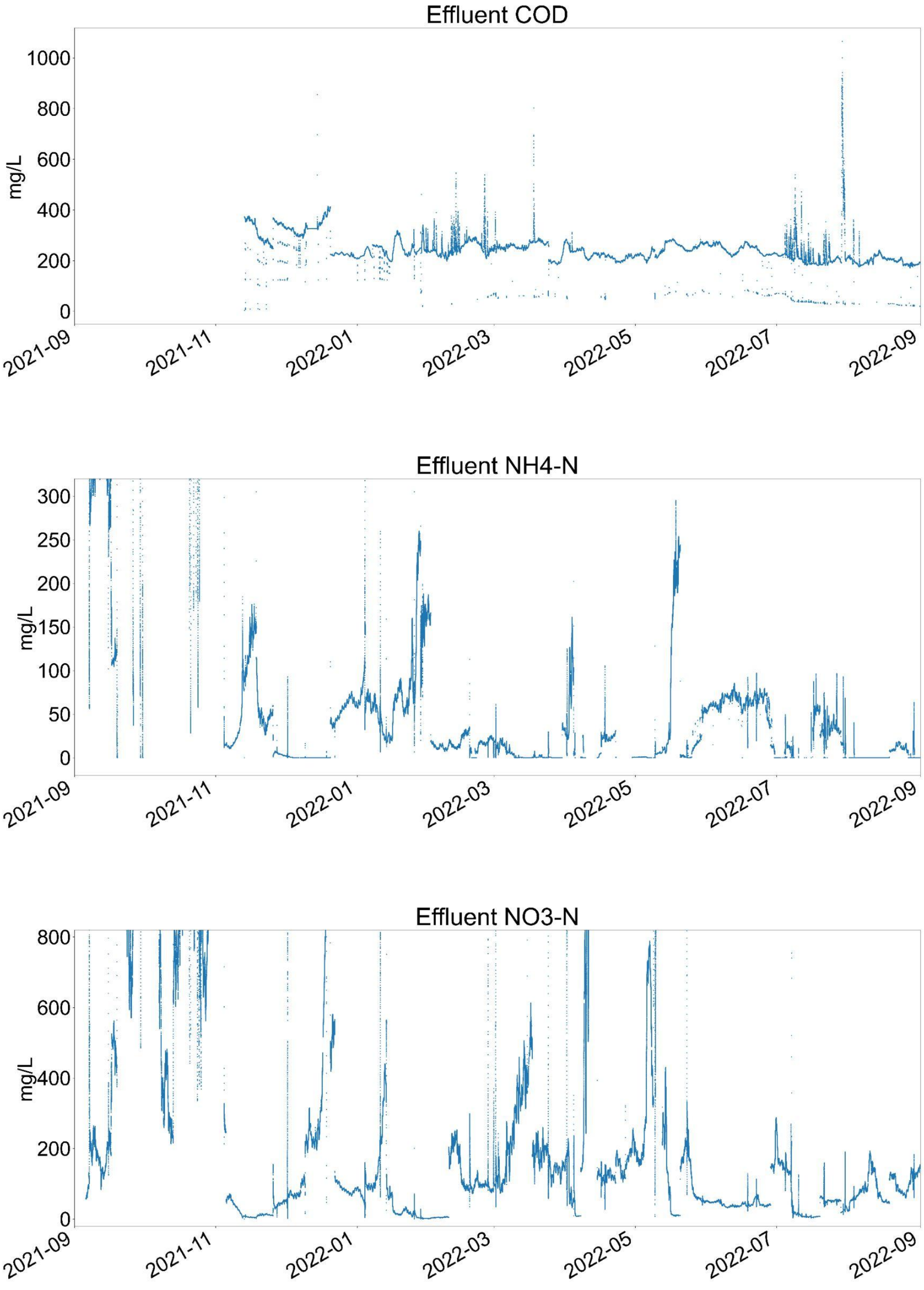


Figure 33: *Available inline sensor data for COD, NH_4^+-N and NO_3^--N in the treated water station*

H Calculation of HRT and SRT

Table 13. *Auxiliary values used for the calculation of HRT and SRT*

Flow	**Flow rate Q** m^3/d	**TSS X** g/m^3	**Solids load** g/d
Influent raw I	909.7		
Influent to biology I	1205.4		
Biology flow R	3365.4	8204	27609742
Excess sludge WAS	94.5		
Return sludge RAS	2160		
Secondary sludge	2254.5	12223	27557529
Effluent	1110.9	47	52212.

Compartment	**Volume per line** m^3	**Total volume** m^3	**HRT** d
Anoxic 1	150	300	0.33
Anaerobic	230	460	0.51
Anoxic 2	650	1300	1.43
Aerobic 1	1000	2000	2.20
Anoxic 3	300	600	0.66
Aerobic 2	200	400	0.44
Total	2530	5060	5.56
Aerobic	1200	2400	2.64

Calculation 1: neglecting X E

V R	5060	m^3
X R	8204	g/m^3
Q WAS	94.5	m^3/d
X WAS	12223	g/m^3
SRT	35.94	d
Aerobic SRT	17.05	d

Calculation 2: with X E

X E	47	g/m^3
Q E	1110.9	m^3
SRT	34.4	d
Aerobic SRT	16.3	d
HRT	5.6	d
Aerobic HRT	2.6	d