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PERFORMANCE ASSESSMENT AND PRELIMINARY REUSE SUITABILITY OF A HOSPITAL-BASED WASTE STABILIZATION POND SYSTEM IN GHANA

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Abstract

Hospital wastewater in Ghana is frequently treated using waste stabilization ponds (WSPs); however, their treatment efficiency and reuse potential remain poorly characterized. This study conducted a six-month assessment of the Cape Coast Teaching Hospital WSP using an integrated framework that combined physicochemical, microbial, hydrochemical, and heavy metal analyses with predictive modeling and reuse suitability indices. The system achieved notable reductions in suspended solids (54.5%) and heavy metals, including Pb (0.001 mg/L) and Cr (0.002 mg/L), which complied with WHO (2006) discharge standards. Fecal coliform concentrations decreased by 21.7%, yet remained above acceptable thresholds for direct reuse. In contrast, salinity and nutrient levels accumulated, with electrical conductivity reaching 1565 µS/cm, ammonia rising to 59.4 mg/L, and nitrate and phosphate concentrations indicating elevated eutrophication risk. Corrosivity indices (LSI −98; RSI >200) suggested strong potential for metal corrosion, while sodium hazard (SAR up to 155.9) and Kelly's ratio (>9) rendered the effluent unsuitable for irrigation without dilution or tertiary treatment. This study introduces a novel integrated framework that combines pollutant attenuation assessment with reuse potential analysis, offering a comprehensive approach rarely applied in hospital-based waste stabilization pond systems. The findings demonstrate that, although the effluent contains nutrients beneficial for crops, its high salinity and sodium hazard necessitate controlled reuse strategies and post-treatment interventions to prevent soil degradation, thereby informing sustainable wastewater management and reuse planning.

Keywords

Hospital wastewater, Waste stabilization ponds, Predictive modelling, Effluent reuse, Corrosion indices, tropical wastewater treatment

Introduction

The global demand for potable water has risen sharply in recent years. This increase is driven by rapid population growth and the contamination of freshwater sources by untreated domestic, industrial, and hospital wastewater (Alao et al., 2023; Jahan and Singh, 2023).

Hospital wastewater is of particular concern because it contains a complex mixture of pollutants. These include heavy metals, nutrients, pharmaceuticals, pathogens, and detergents (Appenroth, 2010; Jadaa and Mohammed, 2023). When discharged without adequate treatment, these contaminants pose serious risks to public health and ecosystems.

Hospital wastewater typically has a low biodegradability index, which limits the effectiveness of conventional biological treatment methods (Wen et al., 2004). Continuous release of antibiotics also promotes antimicrobial resistance in environmental microbial communities (Sanaa et al., 2019; Verlicchi et al., 2010). Heavy metals further disrupt biological treatment processes, undermining long-term sustainability (Appenroth, 2010; Jadaa and Mohammed, 2023).

Several treatment technologies exist, including activated sludge systems, trickling filters, aerated lagoons, constructed wetlands, and waste stabilization ponds (WSPs) (Jadaa and Mohammed, 2023). WSPs are particularly suitable for resource-limited settings like Ghana because they require low operational costs, minimal energy, and effectively reduce organic and microbial loads (Okoh et al., 2010). These systems typically consist of anaerobic, facultative, and maturation ponds that remove pollutants through combined anaerobic and aerobic microbial processes.

Studies show WSPs can achieve up to 99.9% reduction in fecal coliforms and near-complete elimination of helminth eggs (Bajpai et al., 2019). In contrast, conventional systems often fail to remove pathogens effectively (Jordan and Eaton, 2024; Pennellini, 2022). Despite these advantages, hospital-based WSP systems in Ghana, especially the Cape Coast Teaching Hospital (CCTH) WSP remain under evaluated.

The CCTH WSP, operational since 1996, has not undergone systematic performance assessment (Tornyi, 2017). Minimal maintenance, inadequate vegetation control, and lack of integrated monitoring hinder understanding of its capacity to remove microbial and chemical contaminants. This gap is vital because Ghana's Environmental Protection Agency (EPA) and Ministry of Sanitation and Water Resources mandate compliance with WHO and national effluent discharge standards for healthcare facilities, yet enforcement and monitoring remain limited. Strengthening evidence on WSP performance is essential for aligning hospital wastewater management with these regulatory frameworks.

This study addresses these gaps by conducting a detailed evaluation of pollutant removal efficiency and reuse potential of the CCTH WSP system. Unlike previous studies that focus on single dimensions such as microbial removal or basic chemical characterization, this research introduces a novel, integrated framework that combines multiple assessment indices, physicochemical, microbial, hydrochemical, heavy metals, predictive modeling, water stability indices, and agronomic suitability into one holistic evaluation. This multi-dimensional approach provides decision-ready insights for optimizing decentralized wastewater treatment and developing safe reuse strategies in resource-constrained healthcare settings, a perspective not previously documented for hospital-based WSPs in tropical environments.

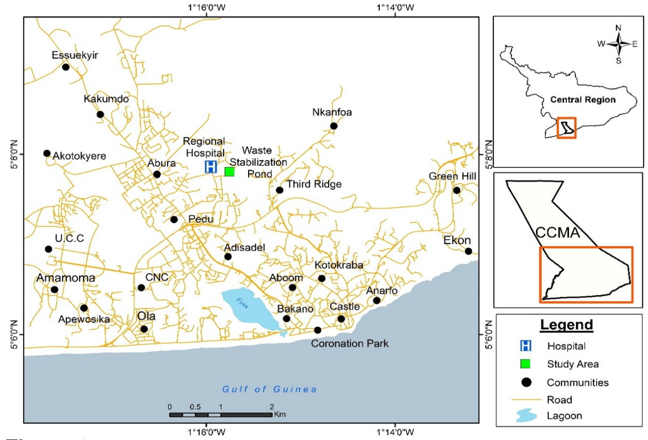

Figure 1. Topographical map of Cape Coast indicating the location of the hospital-based Waste Stabilization Pond (WSP) system. The map highlights proximity to sensitive areas such as the Gulf of Guinea and surrounding districts, emphasizing potential environmental exposure pathways.

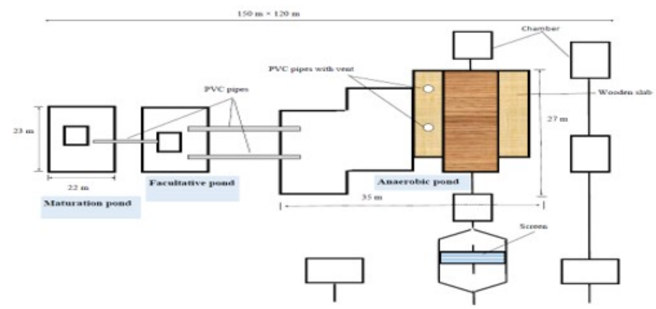

Figure 2. Conceptual layout of the Cape Coast Teaching Hospital WSP system, showing the sequential arrangement of anaerobic, facultative, and maturation ponds. This configuration illustrates the treatment flow and retention times critical for pollutant attenuation and pathogen reduction.

Materials and Methods

Study Area

Geographically, CCTH is bounded to the south by the Gulf of Guinea, to the west by the Komenda-Edina-Eguafo-Abrem Municipality, to the east by the Abura-Asebu-Kwamankese District, and to the north by the Twifo-Heman-Lower Denkyira District (Figure 1; Baah-Boateng (2015)). The study area lies at approximately 5°06′ N latitude and 1°15′ W longitude and spans an area of about 122 square kilometres. The hospital's wastewater treatment ponds which were constructed in 1996 cover a total surface area of approximately one hectare (Figure 2), and consist of three ponds, that is the Anaerobic (1,500 m^2, depth 3.5 m, volume 5,250 m^3, Hydraulic retention time = 10 days), Facultative (4,500 m^2, depth 1.5 m, volume 6,750 m^3, Hydraulic retention time = 14 days), and Maturation (4,000 m^2, depth 1.0 m, volume 4,000 m^3, Hydraulic retention time = 8 days). These estimates are based on previous works conducted by Tornyi (2017), and verified against the system's total footprint. The climatic condition of the area is humid with an annual rainfall between 900 and 1,200 mm and an average temperature between 24–30°C (Tornyi, 2017).

Study Design

A six-month field-based monitoring study evaluated pollutant attenuation, effluent quality, and the potential for reuse of wastewater treated by the Cape Coast Teaching Hospital (CCTH) Waste Stabilization Pond (WSP) system. The assessment spanned from November 2021 to April 2022 and was performed under standard operational conditions of the treatment system. Throughout the study period, the WSP received continuous inflow of wastewater generated by Cape Coast Teaching Hospital. The treatment system comprised three sequential stages: anaerobic, facultative, and maturation ponds. Wastewater passed through these stages under the existing operational configuration, enabling assessment of progressive changes in water quality from influent to final effluent.

The study utilized an integrated assessment framework that included physicochemical, microbiological, hydrochemical, nutrient, and heavy metal analyses. Additionally, pollutant attenuation calculations, effluent quality assessments, time-series analyses, anomaly detection, and indices related to irrigation and corrosion were applied to evaluate treatment performance and the suitability of effluent for potential reuse.

Waste Stabilization Pond System and Sampling Design

The CCTH wastewater stabilization pond (WSP) system consists of three primary treatment units arranged in sequence: an anaerobic pond, a facultative pond, and a maturation pond. This system receives wastewater generated by hospital activities and treats it through sedimentation, anaerobic degradation, facultative biological processes, algal activity, and natural pathogen reduction.

A separate experimental or control pond was not utilized, as the objective was to assess the performance of the existing operational hospital WSP under real-world conditions. Wastewater entering the anaerobic pond was designated as the influent and served as the baseline or reference condition for evaluating pollutant attenuation. The outlet of the facultative pond represented the intermediate treatment stage, while the outlet of the maturation pond represented the final treated effluent. The treatment sequence evaluated in this study was as follows:

Hospital wastewater $\rightarrow$ *Anaerobic pond influent* $\rightarrow$ *Facultative pond* $\rightarrow$ *Maturation pond* $\rightarrow$ *Final effluent*.

This design enabled assessment of changes in water quality along the treatment train and facilitated determination of the overall attenuation efficiency of the WSP system by comparing the influent with the final effluent.

Sampling Strategy and Sample Collection

Monthly sampling occurred from November 2021 to April 2022, resulting in six distinct sampling campaigns. Samples were obtained from three primary treatment stages: anaerobic pond influent, facultative pond outlet, and maturation pond outlet.

For each pond, samples were collected from three locations—namely, the inlet, centre, and outlet—to address spatial variability within the treatment units. Samples from these locations were combined to produce a single composite sample for each pond during each monthly event. Over the six-month monitoring period, this approach yielded 18 composite samples. Each composite sample was analysed in triplicate, resulting in 54 analytical determinations.

To assess overall pollutant attenuation, the anaerobic pond influent was designated as the initial wastewater condition, and the maturation pond outlet as the final treated effluent. The facultative pond outlet represented the intermediate treatment stage.

Sampling was performed between 09:00 and 11:00 AM on each sampling day to ensure consistency and minimize potential diurnal variations in parameters including pH, dissolved oxygen, temperature, and algal activity.

All samples were collected using clean high-density polyethene (HDPE) sampling bottles in accordance with the guidelines of the American Public Health Association (American Public Health Association, 2017). Samples designated for physicochemical, hydrochemical, nutrient, heavy-metal, and microbiological analyses were handled and preserved following the requirements of the respective analytical procedures (UNDP, 2021).

Sample Handling and Preservation

Cation and heavy-metal samples were collected in 1-L high-density polyethylene (HDPE) bottles that had been thoroughly acid-washed with nitric acid (HNO_3), rinsed with deionized water, and dried before use. Acid-washed containers minimized the risk of contamination and adsorption of trace metals onto container surfaces. After collection, samples for cation and heavy-metal analysis were preserved by acidification with nitric acid to pH ≤ 2, following established procedures for aqueous sample preservation for trace-element analysis (USEPA Method 200.8).

Samples for anion analysis were collected in similarly cleaned 1-L HDPE bottles without acidification, since acidification could alter the chemical forms or concentrations of certain anionic constituents. Microbiological samples were collected separately in 500-mL sterile bottles to minimize contamination and maintain microbiological integrity during transportation.

Alkalinity was measured in the field using the titrimetric method, following the Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 2017); Method 2320 B. Field measurements were conducted immediately after sample collection to prevent changes in alkalinity due to carbon dioxide exchange and other chemical processes during storage.

All samples were immediately placed in insulated ice chests and maintained at approximately 4 °C during transportation. Samples were delivered to the respective laboratories within six hours of collection and analyzed within the recommended holding times specified by the relevant analytical methods. Collection, preservation, transportation, and handling procedures followed American Public Health Association (2017) and applicable USEPA methods.

Field Measurements

Selected physicochemical parameters were measured *in situ* immediately following sample collection. Parameters assessed included pH, temperature, total dissolved solids (TDS), and electrical conductivity (EC). All measurements were obtained using a calibrated multiparameter meter (Hanna HI98194).

Turbidity was measured using a calibrated portable turbidity meter. Calibration was conducted prior to measurement in accordance with the manufacturer's specifications and American Public Health Association (2017) guidelines.

Field measurements were performed consistently during each sampling campaign to minimize variability due to differing measurement conditions and to ensure that recorded values accurately reflected wastewater conditions at the time of sampling.

Laboratory Analysis

Hydrochemical, physicochemical, nutrient, biochemical, and heavy-metal analyses were conducted at the Ghana Atomic Energy Commission (GAEC) laboratory in Accra, while microbiological analyses were performed at the Department of Laboratory Technology, University of Cape Coast. Analytical procedures followed the Standard Methods for the Examination of Water and Wastewater, 23rd Edition (American Public Health Association, 2017), together with applicable United States Environmental Protection Agency (USEPA) methods.

Biochemical oxygen demand (BOD_5) was determined using the five-day incubation method (APHA 5210 B), while chemical oxygen demand (COD) was determined using the closed reflux dichromate method (APHA 5220 D). Total suspended solids (TSS) were determined gravimetrically using the total suspended solids method (APHA 2540 D). Turbidity was measured using the nephelometric method (APHA 2130 B).

Nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+-N), and total phosphorus (TP) were determined using appropriate colorimetric/spectrophotometric procedures within the APHA 4500 series. Alkalinity was determined by titration to the appropriate endpoint (APHA 2320 B). These methods were selected to provide standardized and reproducible measurements of the nutrient and buffering characteristics of wastewater.

Calcium (Ca^{2+}) was determined using the EDTA titrimetric method, while chloride (Cl^-) was determined using the argentometric titration method. Sodium (Na^+) and potassium (K^+) concentrations were determined by flame photometry using appropriate calibration standards. Magnesium (Mg^{2+}) and selected trace metals were quantified instrumentally following appropriate digestion and analytical procedures.

Heavy metals, including cadmium (Cd), lead (Pb), chromium (Cr), zinc (Zn), and copper (Cu), were determined by atomic absorption spectrophotometry (AAS) following acid digestion. Sample preservation and preparation for trace-element analysis followed applicable USEPA procedures, including USEPA Method 200.8, where appropriate. USEPA Method 200.8 specifies nitric-acid preservation of aqueous samples for total recoverable elements to pH <2.

Microbiological analyses focused on total coliforms, faecal coliforms, and *Escherichia coli* (*E. coli*). Total coliforms were enumerated using the membrane filtration technique following APHA 9222 B, while faecal coliforms were determined using APHA 9222 D. Appropriate selective culture media and incubation conditions were employed, with results expressed as colony-forming units per 100 mL (CFU/100 mL) (American Public Health Association, 2017).

All analytical methods were performed according to the applicable standard procedures, and laboratory results were subjected to the QA/QC procedures described below.

Quality Assurance and Quality Control (QA/QC)

Rigorous QA/QC measures were implemented throughout sampling and analysis to ensure accuracy and reproducibility. All field and laboratory instruments were calibrated before each session using certified standard solutions, following American Public Health Association (2017) and U.S. Environmental Protection Agency (USEPA) (2007) guidelines. Hydrochemical and nutrient analyses included procedural blanks, duplicate samples, and spiked controls, with recovery rates consistently within 85–115%, confirming analytical reliability (Ris, 2007). Heavy metal determinations employed multi-element standard solutions for calibration, verified through certified reference materials (CRMs) and replicate measurements in compliance with International Organization for Standardization/International Electrotechnical Commission (2017). Method detection limits (MDLs) were established for all parameters, and results below MDLs were flagged according to standard reporting protocols.

Microbiological QA/QC involved sterility checks of media and filtration apparatus, negative controls, and duplicate plate counts to prevent contamination and ensure consistency (American Public Health Association, 2017; World Health Organization, 2006). All microbiological samples were processed within recommended holding times to minimize microbial growth and preservation (American Public Health Association, 2017).

Data Analysis and Performance Evaluation

This study primarily employed descriptive analysis and predictive modeling to evaluate effluent quality. Data processing and analyses were conducted using Python (SciPy, NumPy, and statsmodels) and R (base and stats packages), with analytical procedures guided by American Public Health Association (2017) and World Health Organization (2006) standard methods. Temporal trends and anomalies in effluent quality were assessed using time-series techniques. Advanced inferential statistical tests (e.g., ANOVA or multivariate analyses) were not applied because the dataset comprised 18 composite samples collected over six months, which limits statistical power for robust seasonal or spatial inference. Instead, ARIMA-based time-series analysis and rule-based anomaly detection were used as exploratory tools to identify short-term trends and operational disturbances. These outputs are intended for hypothesis generation and preliminary insights, not for robust forecasting or generalizable predictions. Compliance of the treated effluent was assessed by comparing the measured physicochemical, microbiological, nutrient, and heavy-metal concentrations with applicable national and international wastewater discharge and reuse guidelines. For wastewater reuse assessment, the WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater: Volume 2 – Wastewater Use in Agriculture (World Health Organization, 2006) were consulted where applicable, together with relevant Ghanaian environmental standards and other appropriate regulatory guidelines. Parameters exceeding the applicable guideline values were identified and their potential environmental and public-health implications evaluated.

Furthermore, a pollutant attenuation efficiency model was developed to quantify the treatment performance of the WSP system. The model calculated the percentage reduction of selected pollutants by comparing their mean concentrations at the anaerobic pond influent (initial stage) and the maturation pond effluent (final stage) using the following formula (Ghazy et al., 2008):

$$\text{Reduction (\%)} = \frac{C_{\text{anaerobic}} - C_{\text{maturation}}}{C_{\text{anaerobic}}} \times 100 \qquad (1)$$

where $C_{\text{anaerobic}}$ and $C_{\text{maturation}}$ represent the mean concentrations at the anaerobic pond influent and maturation pond effluent, respectively. Mean values were used instead of individual measurements to reduce bias from short-term fluctuations and provide a more representative performance estimate. Parameters below method detection limits (MDLs) were excluded from calculations to avoid distortion.

Water stability indices

In this study, the corrosion indices, including LSI, RSI, PSI, and AI were used to assess the corrosion and scaling potential of the maturation pond since it is the final system of the WSPs. The indicators used are briefly described below:

1. **Langelier Saturation Index (LSI):** LSI was developed by Langelier in 1936, which is an estimated indicator of the saturation degree of $CaCO_3$ in water (Choi, 2016). LSI considers the effects of Ca^{2+}, total alkalinity, TDS, and temperature to obtain pHs.
2. **Ryznar Stability Index (RSI):** This is an observed method to estimate water tendency to precipitate $CaCO_3$ (Alsaqqar et al., 2014; World Health Organization, 2006).
3. **Aggressiveness Index (AI):** This was developed for Asbestos-made pipes with water temperatures ranging from 4 to 27 °C (40–80°F).

These indices were computed using the following empirical formulas and interpreted according to international water stability standards:

$$LSI = pH - pH_s \tag{2}$$

where pH = measured pH of the maturation pond, and pH_s = saturation pH at which water is in equilibrium with calcium carbonate, calculated as:

$$pH_s = (90.3 + A + B) - (C + D) \tag{3}$$

where:

- $A = (\log_{10}(TDS) - 1)/10$
- $B = -130.12 \times \log_{10}(C + 273) + 340.55$
- $C = \log_{10}(\text{Ca}^{2+} \text{ as } \text{CaCO}_3) - 0.4$
- $D = \log_{10}(\text{Total Alkalinity as CaCO}_3)$

Maturation pond with a positive LSI is capable of depositing calcium carbonate scale from solution. In addition, strong corrosivity would be observed when LSI is smaller than -0.2. RSI is calculated as:

$$RSI = 2 \times pH_s - pH = pH_s - LSI \tag{4}$$

When RSI is less than 5.5, the scale is generated; if RSI is within the range of 5.5–7, the maturation pond saturates and Calcium carbonate is in equilibrium; in the case that RSI is from 7 to 8.5 the maturation pond moderately tends to dissolve Calcium carbonate; and finally when RSI is larger than 8.5, it shows high corrosiveness.

The Aggressiveness Index (AI) is calculated as:

$$AI = pH + \log_{10}(A \times H) \tag{5}$$

where A and H are Ca^{2+} and alkalinity, respectively (Fazlzadeh Davil et al., 2009; Gholizadeh et al., 2017). The maturation pond with AI <10 is considered highly aggressive, 10<AI<12 as relatively aggressive and AI>12 represents that the maturation pond is non-aggressive.

The above analysis was conducted to evaluate the suitability of treated effluent from the maturation pond for reuse in cleaning hospital equipment, floors, and windows. This assessment focused on identifying parameters that may contribute to material corrosion, which is key for maintaining the safety, hygiene, and operational integrity of cleaning processes in healthcare environments. Understanding the corrosive potential of the wastewater is essential for ensuring that reuse practices do not compromise equipment longevity or surface sanitation, especially in hospital settings in Ghana and similar environments.

Predictive Modeling and Anomaly Detection

Predictive modeling in this study was applied as an exploratory analytical approach rather than as a robust forecasting tool. Time-series data were collected for key microbial indicators (*Escherichia coli*, faecal coliforms, and total coliforms), as well as physicochemical parameters, including electrical conductivity, total dissolved solids, ammonia, nitrate, phosphate, chemical oxygen demand, and biochemical oxygen demand.

To assess temporal trends, simple linear regression was applied independently to each parameter using the standard form:

$$y = mx + c \tag{6}$$

where y = predicted parameter value, x = time (in months), m = slope of the trend line, and c = y-intercept.

This analysis was used to evaluate the direction and magnitude of linear changes over the monitoring period. Following trend analysis, the Isolation Forest algorithm (an unsupervised machine learning technique for anomaly detection) was employed to identify outliers and episodic deviations within the dataset. The method operates by recursively partitioning the data through random feature selection and random split values within the observed range, thereby isolating observations that differ markedly from most of the data. By integrating linear trend analysis with anomaly detection, the approach enabled the identification of short-term disturbances, temporal variability, and potential operational inefficiencies within the waste stabilization pond system over the monitoring period. These insights provide valuable evidence for strengthening system monitoring and improving the operational robustness of waste stabilization ponds, particularly in dynamic hospital wastewater treatment environments.

Time-Series Modeling of BOD Using ARIMA

To support operational decision-making and generate hypotheses regarding potential disturbances within the Cape Coast Teaching Hospital (CCTH) waste stabilization pond (WSP) system, an exploratory time-series analysis was conducted on Biochemical Oxygen Demand (BOD) data from the maturation ponds using the Autoregressive Integrated Moving Average (ARIMA) framework (Box and Jenkins, 1976; Harvey, 1990). Given the limited duration of the monitoring record, the analysis was not intended to produce robust or generalizable forecasts, but rather to examine short-term temporal patterns, variability, and episodic deviations in organic loading. Monthly BOD measurements collected over a six-month period (n = 6 per pond) from three maturation ponds (Pond 1C, Pond 2C, and Pond 3C) were extracted and analysed independently in order to preserve pond-specific dynamics. Although the dataset is insufficient for reliable long-term time-series forecasting, it is adequate for exploratory trend analysis and preliminary characterization of temporal structure, particularly within resource-constrained monitoring contexts where extended datasets are often unavailable (Harvey, 1990). Given the limited sample size (n = 6 per pond), a parsimonious ARIMA(1,1,1) model was selected as a minimum-order specification capable of capturing short-term temporal dependence and non-stationarity without introducing excessive parameter uncertainty. More complex model formulations were thoughtfully avoided, as the small sample size would increase the risk of overfitting, unstable parameter estimates, and reduced interpretability. The ARIMA(1,1,1) model incorporates a first-order autoregressive component to represent short-term dependence, a first-order differencing term to address non-stationarity, and a first-order moving average component to account for residual autocorrelation. Prior to model fitting, each pond-specific BOD series was first differenced to improve stationarity, and model parameters were estimated using maximum likelihood estimation. Model outputs were interpreted qualitatively, with emphasis placed on identifying temporal tendencies, variability, and episodic deviations rather than generating precise or predictive forecasts.

Biochemical Oxygen Demand (BOD) was selected for this exploratory analysis because it is a primary indicator of organic pollution, a key operational parameter for evaluating wastewater treatment performance, and a central metric in World Health Organization (WHO) guidelines for effluent discharge and reuse. Analysis of BOD dynamics therefore provides a practical basis for generating hypotheses related to treatment efficiency, short-term disturbances, and operational variability within the maturation pond system. Overall, this exploratory and parsimonious modeling approach adds value by highlighting temporal patterns and potential system disturbances that may warrant targeted investigation or enhanced monitoring, while remaining methodologically appropriate for the available data.

Effluent Suitability for Agricultural Reuse

The suitability of the pond water for irrigation purposes was assessed using sodium adsorption ratio (SAR), salinity (EC), Kelly's ratio (KR), and magnesium ratio (MR), as suggested by Richards (1954), Szabolcs and Darab (1964), Kelley (1963), and Eaton (1950). These agronomic chemical parameters are extensively used in different parts of the world (Kouakou et al., 2017; Mukate et al., 2020; Rao, 2018; Rao et al., 2021), which were computed following the equations below, and taking the ions in milligrams per liter (mg/L):

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \tag{7}$$

$$MR = \frac{Mg^{2+}}{Ca^{2+}+Mg^{2+}} \times 100 \tag{8}$$

$$KR = \frac{Na^{+}}{Ca^{2+}+Mg^{2+}} \tag{9}$$

All results were interpreted according to the World Health Organization (World Health Organization, 2006) guidelines for irrigation water quality. This comprehensive assessment provided a basis for determining the safe and sustainable reuse of treated hospital effluent in agricultural applications, while highlighting potential risks that may require mitigation through dilution, blending, or additional treatment.

Results and Discussions

Generalized WSP chemistry

This study presents a detailed chemical parameter across the anaerobic, facultative, and maturation ponds of the Cape Coast Teaching Hospital (CCTH) Waste Stabilization Pond (WSP) system. The results revealed dynamic inter-pond transitions and seasonal influences, offering critical insights into the system's treatment efficiency and effluent reuse potential. Among the parameters assessed, pH exhibited a consistent upward trend across the pond sequence, with mean values increasing from 7.2 in the anaerobic pond to 8.1 in the facultative and maturation pond.

pH Trends and Biological Implications

The observed pH values (Tables 1 to 3) across all three ponds remained within the World Health Organization (World Health Organization, 2006) recommended range for treated wastewater effluent and reuse (typically pH 6.0–9.0) indicating a chemically stable environment conducive to microbial activity. The gradual increase in pH from the anaerobic to the maturation pond is driven by ammonia volatilization, algal photosynthesis, and organic matter degradation. These biological and chemical processes are enhanced in the facultative and maturation ponds due to longer hydraulic retention times and higher solar exposure. Notably, the elevated pH in the maturation pond is not merely a byproduct of treatment but plays an active role in pathogen inactivation by disrupting microbial membranes and enzymatic systems (Liu et al., 2018). These findings align with previous studies that have documented similar pH dynamics in WSP systems. For instance, Kumari (2025), and Duku et al. (2024) reported comparable pH increases along pond treatment sequences in tropical climates. The dual role of the maturation pond, as both a final polishing stage and a disinfection zone, has also been emphasized in the literature (Alao et al., 2023; Shilton, 2006; Wood et al., 2022), reinforcing the importance of maintaining optimal pH conditions for effective microbial reduction. The consistent pH elevation observed in this study suggests that the maturation pond at CCTH is functioning effectively in terms of

Table 1. Statistical Summary of the chemical composition of Anaerobic Pond

Chemical Parameter	Minimum	Maximum	Mean
pH	7.2	8.0	7.7
HCO_3^{2-} (mg/L)	10.3	73.5	36.2
T (°C)	23.7	28.1	26.1
EC (μS/cm)	716.0	2320.0	1570.8
TDS (mg/L)	394.0	1153.0	787.1
TSS (mg/L)	0.0	578.0	121.4
T (NTU)	37.0	249.0	124.1
NH_3 (mg/L)	0.0	0.6	0.2
Cl^- (mg/L)	107.9	377.9	217.1
NO_3^- (mg/L)	0.0	4.0	1.4
PO_4^{3-} (mg/L)	0.0	0.1	0.03
SO_4^{2-} (mg/L)	2.1	44.4	18.1
DO (mg/L)	0.5	2.8	1.14
COD (mg/L)	56.9	101.1	72.4
BOD (mg/L)	0.1	2.8	0.6
Ca^{2+} (mg/L)	18.4	38.9	26.6
Mg^{2+} (mg/L)	7.3	14.0	9.9
Na^+ (mg/L)	211.2	692.1	468.1
K^+ (mg/L)	18.98	56.9	38.7

Table 2. Statistical Summary of the chemical composition of Facultative Pond

Chemical Parameter	Minimum	Maximum	Mean
pH	7.1	8.1	7.7
HCO_3^- (mg/L)	10.8	78.8	39.2
T (°C)	23.8	28.1	26.3
EC (μS/cm)	1022.0	2180.0	1753.9
TDS (mg/L)	518.0	1083.0	879.8
TSS (mg/L)	5.0	303.0	114.1
T (NTU)	30.0	397.0	122.9
NH_3 (mg/L)	0.0	0.31	0.10
Cl^- (mg/L)	213.0	337.2	271.9
NO_3^- (mg/L)	0.0	0.6	0.2
PO_4^{3-} (mg/L)	0.0	0.1	0.04
SO_4^{2-} (mg/L)	1.0	17.8	8.4
DO (mg/L)	0.2	3.3	0.96
COD (mg/L)	56.9	107.4	72.3
BOD (mg/L)	0.0	3.3	0.5
Ca^{2+} (mg/L)	20.7	38.8	29.1
Mg^{2+} (mg/L)	8.3	13.95	10.9
Na^+ (mg/L)	302.6	650.2	522.7
K^+ (mg/L)	25.1	53.4	43.3

Table 3. Statistical Summary of the chemical composition of Maturation Pond

Chemical Parameter	Minimum	Maximum	Mean
pH	7.6	8.1	7.8
HCO_3^{2-} (mg/L)	23.6	86.5	46.3
T (°C)	24.7	28.1	26.4
EC (μS/cm)	827.0	2180.0	1565.4
TDS (mg/L)	55.0	1071.0	700.7
TSS (mg/L)	11.0	119.0	55.2
T (NTU)	0.01	154.0	58.5
NH_3 (mg/L)	0.0	285.4	59.4
Cl^- (mg/L)	0.02	316.1	186.5
NO_3^- (mg/L)	0.01	8.97	2.03
PO_4^{3-} (mg/L)	0.0	18.3	2.5
SO_4^{2-} (mg/L)	0.5	20.1	6.2
DO (mg/L)	0.5	68.1	15.9
COD (mg/L)	0.1	104.3	60.1
BOD (mg/L)	0.1	3.1	0.7
Ca^{2+} (mg/L)	10.0	40.0	25.9
Mg^{2+} (mg/L)	0.0	15.7	8.9
Na^+ (mg/L)	247.1	651.0	466.6
K^+ (mg/L)	2.4	52.8	34.4

both chemical stabilization and pathogen control. However, future research could explore the seasonal variability of pH in greater detail, especially in relation to algal dynamics and sunlight intensity.

Electrical Conductivity (EC) and Ion Accumulation

As illustrated in Tables 1 to 3, electrical conductivity (EC) values exhibited a consistent upward trend across the treatment sequence, increasing from a mean of 716 μS/cm in the anaerobic pond to 2180 μS/cm in both the facultative pond and maturation pond. Notably, EC levels in both ponds exceeded the WHO (2006) recommended discharge limit of 1500 μS/cm, indicating elevated ionic concentrations in the treated effluent. The progressive increase in EC suggests ion accumulation throughout the WSP system. This trend is driven by the presence of dissolved inorganic ions such as Na^+, K^+, Ca^{2+}, Cl^-, and SO_4^{2-} many of which are introduced through pharmaceutical residues, disinfectants, and other chemical inputs associated with hospital operations. The persistence of high EC values in both facultative and maturation pond (Tables 2 and 3) raises concerns about the suitability of the wastewater for agricultural reuse and aquifer recharge, particularly in salinity-sensitive environments. These findings are consistent with those reported by Duku et al. (2024), and Kinnunen et al. (2025), who observed similar EC elevations in hospital-based WSP systems. The obtained results underscore the need for context-specific effluent standards, as highlighted by Hashem and Qi (2021) and Lemessa et al. (2023), who advocate for tailored post-treatment strategies in healthcare settings where chemical inputs differ significantly from domestic wastewater sources. Given the elevated EC levels observed in the final effluent, future studies should explore advanced or hybrid post-treatment options, such as carbon constructed wetlands, membrane filtration, or ion exchange systems, to mitigate salinity risks.

Total Dissolved Solids (TDS) Dynamics and Implications

As shown in Tables 1 to 3, TDS concentrations increased from 394–1153 mg/L in the anaerobic, 518–1083 mg/L in the facultative pond, and 55–1071 mg/L in the maturation pond.

Although some values remained below the WHO (2006) discharge limit of 1000 mg/L, the consistent increase across the treatment sequence is significant. The increase TDS levels across the pond system suggest probable cumulative mineralization and ionic enrichment as wastewater progresses through the treatment stages. This trend indicates that while the WSP system is effective in removing suspended solids and microbial contaminants, it is less efficient at eliminating dissolved salts. The accumulation of TDS is driven by hospital-derived inputs, including pharmaceuticals, disinfectants, and saline solutions, which are not readily removed through natural sedimentation or biological degradation processes. These findings align with the observations of Wang et al. (2020), who reported similar ionic enrichment in healthcare effluents. The limited removal of dissolved solids in WSP systems has also been highlighted by Rukoro (2018) and Edokpayi et al. (2021), who noted that WSPs are generally more effective at removing particulate matter than dissolved ions. This underscores a fundamental limitation of passive treatment systems when dealing with chemically complex effluents such as those from hospitals. The upward trend in TDS levels raises concerns for long-term reuse, specifically in agricultural applications involving salt-sensitive crops or soils prone to salinization. Future research should implement source control strategies within hospital facilities which could help reduce the input of non-biodegradable dissolved substances into the WSP system.

Total Suspended Solids (TSS) Dynamics and Treatment Efficiency

TSS concentrations (Tables 1 to 3) exhibited a clear decreasing trend from the anaerobic pond to the maturation pond. The anaerobic pond recorded the highest variability (0–578 mg/L; mean: 121.4 mg/L), followed by the facultative pond (5–303 mg/L; mean: 114.1 mg/L), while the maturation pond showed the lowest TSS levels (11–119 mg/L; mean: 55.2 mg/L). The observed decline in TSS concentrations across the pond sequence indicates effective particulate matter removal through natural sedimentation and biological processes. The high variability in the anaerobic pond is due to sludge disturbance, biogas release, and high organic loading, which contribute to fluctuations in suspended solids. In the facultative pond, the range narrows slightly, reflecting partial stabilization. The maturation pond demonstrates the most consistent and lowest TSS values, suggesting enhanced settling efficiency and biological stabilization at the final treatment stage. These findings are consistent with previous studies where El-Aassar (2003) and Adu-Ofori (2019) reported similar TSS reduction patterns in WSP systems. The elevated TSS levels in the anaerobic and facultative ponds may also be attributed to microbial floc formation and algal biomass, which contribute to suspended solids but are eventually settled or degraded in the maturation pond (Dey et al., 2025). Furthermore, the low TSS levels in the maturation pond are critical for disinfection efficiency, as reduced turbidity enhances UV penetration and facilitates pathogen inactivation (Nwankwo et al., 2019; Yelindo, 2023). The substantial reduction in TSS across the WSP system highlights the potential of hospital-based ponds to effectively manage particulate pollution, even under high organic and chemical loading conditions.

Turbidity Trends and Treatment Implications

The turbidity levels (Tables 1 to 3) remained consistently high throughout the system, significantly exceeding the WHO (2006) guideline of 5 NTU. The anaerobic pond recorded values ranging from 37 to 249 NTU (mean: 124.1 NTU), the facultative pond ranged from 30 to 397 NTU (mean: 122.94 NTU), and the maturation pond showed slightly lower values between 0.01 and 154 NTU (mean: 58.52 NTU). The persistently elevated turbidity levels across all pond stages suggest a high concentration of suspended solids, biological activity, and algal proliferation. The high values in the anaerobic and facultative ponds are driven by biomass turnover, sludge disturbance, and microbial dynamics. Although the maturation pond exhibited a reduction in turbidity, the levels remained well above recommended thresholds, indicating incomplete settling and flocculation. This may be due to short-circuiting, insufficient retention time, or high organic loading, all of which are common in hospital effluents. These findings are consistent with the work of Cowan et al. (2016), who reported similar turbidity patterns in WSPs influenced by biological and operational factors. The results highlight the need for design enhancements and post-treatment interventions to improve turbidity reduction in hospital-based WSP systems.

Temperature Stability and Biological Optimization

As shown in Tables 1 to 3, temperature remained relatively stable across all three stages of the Waste Stabilization Pond (WSP) system during the monitoring period. The anaerobic pond recorded temperatures ranging from 23.7 to 28.1 °C (mean: 26.1 °C), the facultative pond ranged from 23.8 to 28.1 °C (mean: 26.3 °C), and the maturation pond exhibited slightly higher values between 24.7 and 28.1 °C (mean: 26.36 °C). These warm and consistent temperature conditions are mainly advantageous in tropical WSP systems. They support optimal microbial metabolism, enzymatic activity, and algal photosynthesis, all of which contribute to enhanced organic matter degradation and nutrient cycling. The slightly elevated temperature in the maturation pond may be attributed to reduced shading and increased sun exposure, which promote aerobic microbial processes and natural disinfection. The observed temperature ranges align with the optimal operational window for tropical WSPs, as reported by Zhao et al. (2022), Samal et al. (2025), and López et al. (2019). These authors highlighted the importance of thermal inactivation in pathogen reduction, reinforcing the significance of temperature stability in achieving effective disinfection in maturation ponds. The thermal consistency observed across the pond system suggests a degree of resilience to seasonal fluctuations, which is critical for maintaining reliable treatment performance in healthcare facilities with variable wastewater loads.

Ammonia (NH_3-N): Transformation and Remineralization
Ammonia (NH_3-N) concentrations (Tables 1 to 3) remained relatively low across the treatment sequence. Mean concentrations were 0.16 mg/L in the anaerobic pond, 0.10 mg/L in the facultative pond, and increased to 59.4 mg/L in the maturation pond. The observed trend suggests that ammonification and partial nitrification occurred effectively in the anaerobic and facultative ponds, which are consistent with microbial processes. The increase in ammonia concentration in the maturation pond may be attributed to remineralization of organic nitrogen, algal biomass decay, or reduced nitrification efficiency, potentially due to fluctuating dissolved oxygen levels or shifts in microbial community structure. Despite this increase, ammonia levels remained well below the WHO (2006) discharge guideline of 1.5 mg/L in the anaerobic and facultative pond, indicating a low toxicity risk in both effluent but a high toxicity risk in the final effluent. These findings align with the work of Valero (2008), who described similar nitrogen transformation pathways in WSP systems. The potential for ammonia accumulation in the maturation pond due to algal decay and microbial shifts has also been noted by Valero et al. (2009) and more recently by Ma et al. (2025). The results reinforce the understanding that while WSPs are generally effective in reducing ammonia, biological feedback mechanisms in the maturation stage can lead to localized increases.

Nitrate (NO_3^-): Aerobic Conversion and Environmental Risk
Nitrate concentrations across the Cape Coast Teaching Hospital (CCTH) Waste Stabilization Pond (WSP) system exhibited an inverse trend relative to ammonia, with comparatively low levels in the anaerobic (1.42 mg/L) and facultative ponds (0.21 mg/L) and a noticeable increase in the maturation pond (2.03 mg/L). This trend reflects the progressive transition from anaerobic and facultative conditions to a predominantly aerobic treatment environment that controls nitrogen transformation processes in WSP systems. In the upstream ponds, nitrogen occurs mainly in reduced forms, particularly ammonia, released through the microbial mineralization of organic nitrogen under oxygen-limited conditions. These environments restrict nitrification, resulting in low nitrate concentrations. In contrast, the maturation pond is designed to promote aerobic processes through shallow depth, longer hydraulic retention times, and enhanced oxygen availability arising from atmospheric diffusion and algal photosynthetic activity. These conditions are favorable for aerobic nitrification, whereby ammonia is oxidized to nitrate by nitrifying microorganisms. The observed increase in nitrate in the maturation pond indicates effective ammonia oxidation but also suggests limited nitrogen removal. Under the predominantly aerobic conditions prevailing in maturation ponds, denitrification is constrained by the lack of anoxic zones and the reduced availability of readily biodegradable organic carbon. Although algal uptake may temporarily assimilate nitrate, subsequent biomass decay and sediment–water interactions can re-release nitrogen into the water column, allowing nitrate to persist in the final effluent. From an effluent quality and reuse perspective, this nitrogen transformation is consistent with the intended function of maturation ponds, which prioritize pathogen reduction and effluent stabilization rather than complete nutrient removal. The conversion of ammonia to nitrate is a recognized indicator of aerobic microbial efficiency in WSP systems (Paul et al., 2020). However, elevated nitrate concentrations in treated effluent warrant consideration in line with WHO guidelines for wastewater discharge and reuse, particularly for irrigation, where nutrient loading may contribute to eutrophication of receiving environments or require controlled application rates.

Dissolved Oxygen (DO): Gradient and Microbial Support
As shown in Tables 1 to 3, dissolved oxygen (DO) concentrations increased progressively across the WSP system: from 1.14 mg/L in the anaerobic pond, to 0.96 mg/L in the facultative pond, and reaching 15.86 mg/L in the maturation pond. This increasing mean DO in the maturation pond reflects the influence of surface aeration, algal photosynthesis, and oxygen diffusion. The higher DO levels in the maturation pond support aerobic microbial processes such as organic matter degradation, nitrification, and pathogen inactivation. These findings are consistent with the work of Ho et al. (2018) and Huang (2017), who highlighted the critical role of dissolved oxygen in WSP performance, particularly in facultative and maturation ponds where algal photosynthesis provides oxygen that supports aerobic biological processes. The observed DO profile confirms the functional zoning of the pond system, where anaerobic, facultative, and aerobic conditions are maintained to optimize treatment processes.

COD and BOD: Organic Load and Treatment Efficiency
Across all pond stages, Chemical Oxygen Demand (COD) remained elevated (Tables 1 to 3), with mean values ranging from 60.1 in the maturation pond to 72.4 mg/L in the anaerobic pond, exceeding the WHO (2006) discharge limit of 10 mg/L. In contrast, Biochemical Oxygen Demand (BOD) values were lower, ranging from a mean of 0.48 in the facultative pond to 0.71 mg/L in the maturation pond. The persistently high COD levels suggest the presence of refractory organic compounds, such as pharmaceuticals and disinfectants, which are characteristic of hospital wastewater. The slight increase in COD observed in the maturation pond is attributed to algal exudates or ongoing mineralization of organic matter. Meanwhile, the relatively low BOD values indicate that a significant portion of the biodegradable organic load has been effectively removed, although some residual biodegradable matter remains in the final effluent. These results align with findings by Duku et al. (2024), who reported similar trends in hospital-based WSP systems. The discrepancy between COD and BOD levels is a common observation in healthcare effluents, where non-biodegradable organics persist despite biological treatment. This highlights the limitations of WSPs in fully addressing complex organic pollutants without additional treatment stages.

Calcium (Ca^{2+}) and Magnesium (Mg^{2+}): Stability and Functional Roles

Both Ca^{2+} and Mg^{2+} concentrations (Tables 1 to 3) remained relatively stable throughout the pond sequence, with mean Ca^{2+} ranging from 25.9 to 29.13 mg/L and mean Mg^{2+} from 8.86 to 10.86 mg/L. The slight increase in calcium in the maturation pond is due to evapoconcentration. Ca^{2+} and Mg^{2+} ions are essential for pH buffering, microbial flocculation, and phosphate precipitation, contributing to the chemical stability and treatment efficiency of the WSP system. The observed stability of Ca^{2+} and Mg^{2+} aligns with findings by Boyd and McNevin (2014), who emphasized their role in maintaining alkaline conditions favourable for microbial activity and pathogen reduction. Their presence supports the resilience of the CCTH WSP system under variable loading conditions.

Sodium (Na^+), Potassium (K^+) and Bicarbonate (HCO_3^- expressed as mg/L $CaCO_3$)

In Tables 1 to 3, it was observed that Na^+ levels were highest in the facultative pond, with a mean of 522.7 mg/L, indicating active mineral dissolution and ionic exchange. The maturation pond showed comparable maximum values, suggesting continued mineral presence even in later treatment stages. Similarly, potassium was most concentrated in the facultative pond (K^+ = 43.3), due to organic matter breakdown and microbial activity. The maturation pond had a wider range, with a notably low minimum (2.44 mg/L), possibly reflecting dilution or uptake by algae. Likewise, bicarbonate (Total Alkalinity) peaked in the maturation pond, with a mean of 46.35 mg/L and a maximum of 86.53 mg/L, indicating strong buffering capacity and advanced biological stabilization. These trends reflect the progressive nature of treatment where facultative ponds showed peak nutrient release, while maturation ponds stabilize and buffer the pond chemistry. Additionally, the bicarbonate trends align with findings from Metcalf et al. (2004), which highlight increased alkalinity in maturation ponds due to CO_2 uptake and photosynthesis. Sodium and potassium dynamics are consistent with Mara and Pearson (1999), who observed elevated cation concentrations in facultative ponds due to microbial decomposition and organic matter turnover.

Chloride (Cl^-): Conservative Behaviour and Hospital Signature

The mean chloride concentrations (Tables 1 to 3) were consistently high, ranging from 217.1 mg/L in the anaerobic pond to a peak of 271.9 mg/L in the facultative pond, with a slight decline to 186.5 mg/L in the maturation pond. The high chloride values reflect the conservative nature and its prevalence in hospital effluents, likely due to saline solutions, disinfectants, and pharmaceutical residues (Wang et al., 2020). The persistence of chloride across the pond system is consistent with previous studies (Edokpayi et al., 2021; Fitzgerald and Rohlich, 1958; Wang et al., 2020) and highlights the limitations of biological treatment in removing conservative ions.

Phosphate (PO_4^{3-}): Nutrient Cycling and Algal Uptake

Phosphate concentrations across the Cape Coast Teaching Hospital (CCTH) WSP system remained relatively low but showed clear spatial variability, with the lowest mean concentrations observed in the anaerobic pond (0.03 mg/L) and a marked increase in the maturation pond (mean: 2.52 mg/L). This pattern reflects the combined effects of organic matter mineralization, microbial metabolism, and internal nutrient cycling within the pond system rather than simple attenuation along the treatment train. In the anaerobic and facultative ponds, phosphate is released primarily through the microbial degradation of organic matter and the dissolution of phosphorus associated with particulate material under reducing conditions. As wastewater progresses toward the maturation pond, changes in redox conditions, pH, and biological activity influence phosphate partitioning between the dissolved phase, algal biomass, and sediments. Although algal uptake and chemical precipitation with calcium, iron, or aluminum can temporarily reduce soluble phosphate under favorable conditions, these processes are often reversible. Phosphorus may be re-mobilized through algal senescence, sediment resuspension, or shifts in redox conditions, contributing to elevated concentrations in the final pond. From an effluent discharge and reuse perspective, the persistence of phosphate in maturation pond effluent is consistent with the functional design of WSP systems, which prioritize pathogen reduction and organic matter stabilization rather than complete nutrient removal. Elevated phosphate concentrations in treated effluent therefore warrant consideration under World Health Organization (WHO) wastewater reuse and environmental protection frameworks, particularly where discharge occurs into nutrient-sensitive receiving waters or where effluent is reused for irrigation with limited nutrient assimilation capacity. Similar phosphate dynamics have been reported in other WSP systems operating under comparable climatic and hydraulic conditions (Lahiri et al., 2018). While the concentrations observed do not imply unsuitability for controlled reuse, they highlight the potential for nutrient enrichment in downstream environments. Where stricter nutrient control is required, supplementary management strategies such as algal biomass harvesting, targeted chemical precipitation, or enhanced biological phosphorus removal may be considered as post-treatment options to improve effluent quality.

Sulphate (SO_4^{2-}): Microbial Reduction and Biogeochemical Cycling

Sulphate concentrations decreased from a mean of 18.06 mg/L in the anaerobic pond to 8.39 mg/L and 6.19 in the facultative pond and maturation ponds, respectively. This decline indicates active microbial sulphate reduction under anaerobic conditions, where sulphate-reducing bacteria convert SO_4^{2-} to hydrogen sulphide (H_2S), contributing to organic matter degradation and redox balance. This trend supports the concept of functional stratification in WSP systems, where anaerobic zones facilitate reductive processes and aerobic zones promote stabilization. The observed sulphate reduction aligns with established biogeochemical models (D'Aoust, 2016) and confirms the efficacy of anaerobic ponds in initiating sulphur cycling. Although all sulphate values remained below WHO (2006) limits, further research could investigate the fate of hydrogen sulphide and its potential impacts on odour, infrastructure corrosion, and effluent toxicity.

Heavy Metal Dynamics and Attenuation in Waste Stabilization Ponds (WSPs)

As shown in Figure 3, the dynamics of trace metals (Pb, Cr, Cd, Hg, Fe, and Mn) were influenced by pond-specific conditions such as redox potential, pH, hydraulic retention time, and biological activity. The relatively stable pH range across all ponds provided a chemically favorable environment for assessing metal transformation and attenuation across the three pond stages: anaerobic, facultative, and maturation.

Anaerobic Pond

In this pond, partial removal of heavy metals was observed, though episodic spikes indicated intermittent inputs from medical waste, stormwater inflow, or sediment resuspension. Pb averaged 0.001 mg/L, below WHO (2006) limits, likely precipitating as $PbCO_3$ or PbS under reducing conditions. Cr remained stable at 0.002 mg/L, likely in the less toxic Cr (III) form. Cd ranged from 0.002–0.005 mg/L, slightly exceeding WHO limits of 0.003 mg/L, due to high solubility and weak sediment affinity, though CdS formation may occur under sulfate-reducing conditions. Hg remained within safe limits, stabilized as HgS. Fe and Mn showed variability, with Mn exhibiting high skewness, suggesting episodic releases linked to sludge disturbance or microbial cycling.

Facultative Pond

Complex redox gradients influenced metal mobility in this pond. Pb remained low (mean = 0.001 mg/L) but showed occasional spikes, possibly due to flow disturbances. Cr remained consistent (0.002–0.002; mean = 0.002). Mean Cd value (0.003 mg/L) was the same as WHO (2006) limits of 0.003 mg/L, reflecting reduction under neutral pH (Deng et al., 2023; Wang et al., 2013). Hg levels (0.003–0.008) increased slightly, due to re-release from sediments or formation of mercury-organic complexes. Fe showed the widest variation (0.06–1.34 mg/L), often exceeding WHO limits of 0.3 mg/L, due to microbial iron reduction (Swami et al., 2024). Mn exhibited high kurtosis of 17.2, indicating rare but intense spikes from anaerobic microenvironments or seasonal sediment dynamics.

Maturation Pond

Metal concentrations generally stabilized in the maturation pond with Pb remaining low (Figure 3), besides occasional spikes. Cr remained stable (Figure 3), with no signs of remobilization. Cd persisted near WHO limits of 0.003 mg/L, reflecting solubility and weak binding sediment (Leleko et al., 2025). Hg clustered near the upper safe limit; aerobic conditions stabilized inorganic mercury and reduced methylmercury formation. Fe levels declined, due to precipitation as $Fe(OH)_3$.

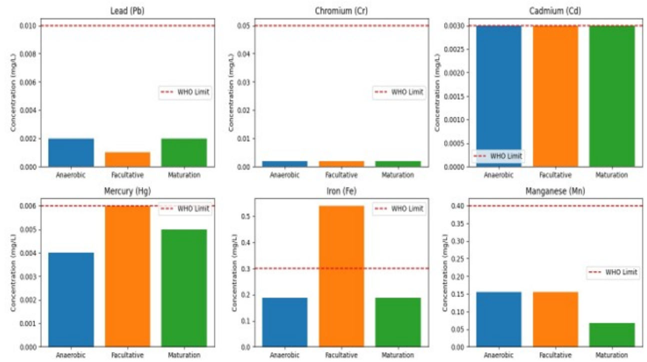

Figure 3. A chart illustrating the descriptive statistics of heavy metals across Waste Stabilization Pond Treatment Stages (Nov 2021 – Apr 2022)

Mn showed occasional spikes, with high kurtosis of 1.47 suggesting episodic releases due to slow oxidation kinetics. These findings align with broader literature (Hu et al., 2024; Xia et al., 2024; Yu et al., 2021) on metal behavior in WSPs. Redox conditions, pH, and biological activity are key drivers of metal speciation and removal efficiency. The persistence of Cd and Mn despite treatment reflects challenges noted by Wang et al. (2013) and Swami et al. (2024), particularly for metals with high solubility or weak sediment affinity. The stabilization of Hg and Pb in the maturation pond supports findings by Sun et al. (2015) on the role of oxygen and pH in metal immobilization.

Microbiological Assessment and System Performance

As shown in Figures 4 and 5, microbial concentrations varied across the anaerobic, facultative, and maturation ponds, reflecting the influence of pond design, environmental conditions, and hydraulic dynamics on pathogen attenuation.

Anaerobic Pond (Figure 4)

The anaerobic pond exhibited high microbial variability, particularly for faecal coliforms (mean: 96.44 CFU/100 mL), with pronounced skewness indicating sporadic contamination spikes. These were driven by fluctuating organic loads and limited pathogen die-off under low-oxygen conditions. Total coliforms showed moderate variability, suggesting partial stabilization. *E. coli* averaged 14.33 CFU/100 mL, exceeding WHO (2006) thresholds for unrestricted reuse. These results confirm the anaerobic pond's primary role in organic matter breakdown, rather than effective pathogen removal (Abd-Elmaksoud et al., 2021).

Facultative Pond (Figure 4)

The facultative pond showed intermediate microbial reduction, benefiting from partial oxygenation and solar exposure. Faecal coliforms increased to a mean of 115.4 CFU/100 mL, and *E. coli* rose slightly to 17.56 CFU/100 mL, suggesting microbial regrowth under microaerobic conditions. Total coliforms exhibited the highest variability and skewness, with extreme values due to biofilm sloughing, sediment resuspension, or

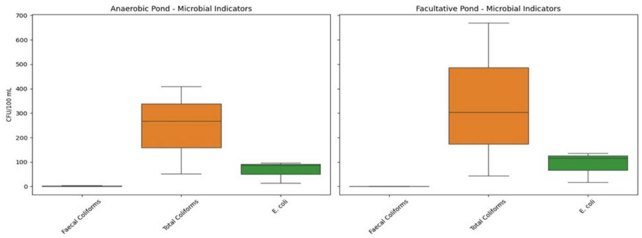

Figure 4. Box plot of the microbial indicator distributions in the anaerobic and facultative ponds, from November 2021 to April 2022

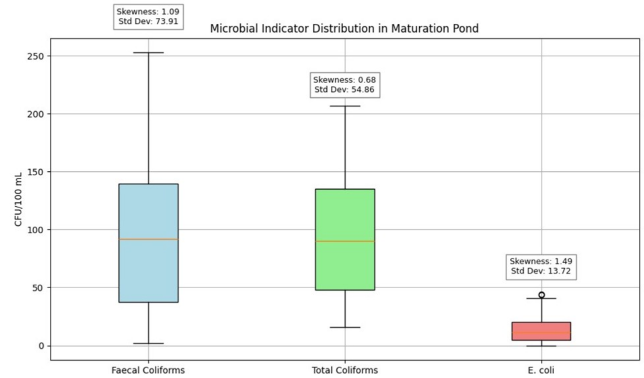

Figure 5. Box plot showing the distribution of fecal coliforms, total coliforms, and *E. coli* in the maturation pond from November 2021 to April 2022

episodic contamination. These patterns reflect the transitional nature of the facultative pond, where environmental fluctuations and retention time significantly influence microbial dynamics (Chambonniere et al., 2021).

Maturation Pond (Figure 5)

The maturation pond demonstrated the most consistent microbial attenuation, with symmetrical distributions and lower mean values across all indicators. *E. coli* declined to 14.64 CFU/100 mL, reflecting the pond's polishing role through extended retention, solar disinfection, and natural die-off. Occasional spikes (up to 50 CFU/100 mL) suggest incomplete disinfection or external contamination events. The decreased standard deviation for total coliforms (55.23 CFU/100 mL) indicates greater stability and predictability in microbial removal. These outcomes align with expectations for maturation ponds operating under aerobic, sunny conditions (Dahl, 2017; Dias et al., 2017). The observed microbial trends are consistent with established WSP performance patterns. These findings reinforce the importance of pond sequencing, environmental control, and hydraulic optimization in pathogen removal. Across the CCTH WSP system, microbial indicators showed a general downward trend, affirming the cumulative effect of staged treatment. However, none of the ponds achieved microbial concentrations below WHO (2006) thresholds for unrestricted reuse, highlighting the need for additional disinfection measures. High variability was observed across all stages, with standard deviations ranging from 73.91 to 92.45 CFU/100 mL, indicating the system's sensitivity to environmental and operational factors. The downward trend in microbial concentrations confirms the effectiveness of sequential pond treatment in reducing pathogen loads. However, the inability to meet reuse standards suggests that passive treatment alone is insufficient for complete microbial safety. The high variability across stages reflects the influence of rainfall, wastewater composition, and hydraulic loading, which can cause episodic spikes in microbial counts. These fluctuations underscore the importance of downstream processes, mostly the maturation pond, in achieving more stable microbial attenuation. These findings are consistent with existing literature on WSP performance (Oruganti et al., 2022). The observed variability aligns with studies (Akpor et al., 2014; Liu et al., 2023; Shilton, 2006) that emphasize the dynamic nature of microbial behaviour in open pond systems and the need for supplementary treatment to ensure effluent safety.

Pollutant Attenuation Efficiency in the Waste Stabilization Pond System

Table 4 presents the attenuation efficiencies (%) of selected physicochemical, nutrient, and microbiological parameters as wastewater from CCTH progressed from the anaerobic to the maturation pond. The efficiency values represent the degree of reduction (positive) or increase (negative) in mean concentrations between the two units, reflecting the functional performance and internal dynamics of the WSP treatment system.

Microbial and Particulate Pollutants

Microbial indicators displayed mixed responses. Faecal and total coliforms declined by 21.7% and 23.4%, respectively, reflecting the solar disinfection and oxidative stress characteristic of maturation ponds. However, *E. coli* showed a slight increase (−2.2%), suggesting possible regrowth or shielding within suspended particulates. The persistence of *E. coli* aligns with emerging evidence that antibiotic-resistant strains in hospital effluents may survive longer under environmental stressors, thereby posing residual public health risks even after secondary treatment.

Physicochemical Transformations

The pH showed a marginal increase from 7.7 in the anaerobic pond to 7.8 in the maturation pond, corresponding to an attenuation of −1.30%. This transition toward alkalinity is indicative of enhanced photosynthetic activity, during which algal uptake of CO_2 reduces carbonic acid concentration and shifts the equilibrium toward carbonate species. The increase in HCO_3^- (−27.9%) further supports this observation, suggesting active carbon cycling and mineralization of organic compounds in the more oxygenated maturation environment. Electrical conductivity (0.34%) and total dissolved solids (10.98%) exhibited minor reductions, implying limited ionic removal across the treatment train. However, total suspended solids (54.53%) and turbidity (52.86%) declined significantly, confirming that sedimentation and natural flocculation remain dominant removal pathways in the maturation pond, improving light penetration and supporting photosyn-

Table 4. Attenuation Efficiency (%) from Anaerobic to Maturation Pond

Chemical parameters	Anaerobic Mean	Maturation Mean	Reduction (%)
pH	7.7	7.8	−1.30
HCO_3^- (mg/L)	36.2	46.3	−27.90
T (°C)	26.1	26.4	−1.15
EC (μS/cm)	1570.8	1565.4	0.34
TDS (mg/L)	787.1	700.7	10.98
TSS (mg/L)	121.4	55.2	54.53
T (NTU)	124.1	58.5	52.86
NH_3 (mg/L)	0.2	59.4	−29600.00
Cl^- (mg/L)	217.1	186.5	14.09
NO_3^- (mg/L)	1.4	2.03	−45.00
PO_4^{3-} (mg/L)	0.03	2.5	−8233.33
SO_4^{2-} (mg/L)	18.1	6.2	65.75
DO (mg/L)	1.14	15.9	−1294.74
COD (mg/L)	72.4	60.1	16.99
BOD (mg/L)	0.6	0.7	−16.67
Ca^{2+} (mg/L)	26.6	25.9	2.63
Mg^{2+} (mg/L)	9.9	8.9	10.10
Na^+ (mg/L)	468.1	466.6	0.32
K^+ (mg/L)	38.7	34.4	11.11
Fe	0.2	0.2	7.9
Mn	0.067	0.067	−93.317
Pb	0.002	0.002	−99.761
Cr	0.002	0.002	−99.8
Cd	0.003	0.003	−99.725
Hg	0.005	0.005	−99.517
Fecal Coliform	96.4	75.6	21.7
Total Coliform	85.6	65.6	23.4
E. coli	14.3	14.6	−2.2

Note: Negative values indicate an increase in concentration from anaerobic to maturation pond. Positive values indicate percentage reduction.

thetic oxygen production (Prasse and Ternes, 2010). Temperature exhibited a marginal increase from 26.1 °C in the anaerobic pond to 26.4 °C in the maturation pond, corresponding to a −1.15% change. This slight increase is consistent with enhanced solar exposure and reduced shading in the maturation pond and falls within the normal thermal range for tropical waste stabilization pond systems. As temperature is not a treatment target parameter, this variation reflects natural environmental conditions rather than process inefficiency.

Major Ions and Trace Metals

Major cations such as calcium, magnesium, sodium, potassium, and iron showed modest reductions (2.63%, 10.10%, 0.32%, 11.11% and 7.9%, respectively), due to co-precipitation and adsorption on settling particles. In contrast, manganese increased significantly (−93.3%), which may indicate reductive dissolution or sampling variability near sediment-water interfaces. The negative attenuation recorded for trace metals such as lead, chromium, cadmium, and mercury (Table 4) suggests sporadic hospital discharge influences or analytical uncertainties. Such extreme increases highlight the importance of metal speciation and temporal monitoring to differentiate between actual mobilization and episodic contamination events.

Nutrient Dynamics and Oxygenation

The transition from anaerobic to aerobic conditions was characterized by notable shifts in nitrogen and phosphorus species. The recorded increase in ammonia (−29600%) may result from ammonification of organic nitrogen or localized accumulation zones. Conversely, nitrate increased by −45%, indicating nitrification under aerobic conditions in the maturation pond. Dissolved oxygen (DO) rose from 1.14 mg/L to 15.9 mg/L (−1294.74%), confirming a strong oxygenic photosynthesis regime driven by algal activity. This elevated DO supports further oxidation of organics and promotes nitrification. Phosphate (PO_4^{3-}) exhibited a striking increase (−8233.33%), reflecting internal recycling and solubilization of sediment-bound phosphorus (an effect commonly reported in mature pond systems). Conversely, sulphate (SO_4^{2-}) decreased by 65.75%, which may be attributed to precipitation as metal sulphides or uptake by microbial consortia. These observations reveal that the maturation pond functions not merely as a clarifier but as a biogeochemical reactor, balancing mineralization, uptake, and regeneration processes.

Organic Load and Redox Processes

The chemical oxygen demand (COD) decreased by 16.99%, confirming further oxidation of organic matter, whereas biochemical oxygen demand (BOD) increased slightly (−16.67%). The latter suggests release of labile organic matter from algal exudates or resuspension of decaying biomass. This dual behaviour signifies that the maturation pond is a metabolically open system, where organic production and degradation occur concurrently rather than sequentially. The attenuation trends reveal that the maturation pond performs a dual ecological function, acting as both a polishing unit for suspended solids and a biogeochemical hub where nutrients and trace elements are cycled through microbial and algal mediation. Unlike conventional stabilization systems that are viewed as linear treatment sequences, the hospital-based pond system in this study demonstrates cyclic pollutant dynamics, where processes of oxidation, mineralization, and nutrient regeneration coexist.

This finding introduces a conceptual understanding of waste stabilization ponds as self-regulating ecological reactors, rather than passive treatment units. Such systems achieve effluent clarification and oxygenation but simultaneously promote nutrient recycling that supports internal productivity. For practical applications, the enhanced oxygen regime and moderate removal of solids and organics suggest that the effluent may be suitable for controlled reuse (e.g., irrigation, aquaculture, or landscape restoration), provided that nutrient and metal concentrations are regularly monitored to prevent long-term accumulation or ecological imbalance.

The above findings align with previous studies (Duku et al., 2024; Sun et al., 2015) that emphasize the strong performance of waste stabilization ponds (WSPs) in microbial and heavy metal removal, but also their limitations in nutrient and ionic attenuation. The persistence of Fe, Mn, NH_3, and NO_3^- has been reported in similar systems (Duku et al., 2024; Sun et al., 2015). Additionally, the sharp increases in EC and TDS highlight the conservative nature of dissolved salts, consistent with observations by Rukoro (2018) and Edokpayi et al. (2021).

Corrosivity Index Assessment

Langelier Saturation Index (LSI)

From the computed values (Table 5), the LSI ranged from −98.7 to 10.3 across the maturation pond samples. These values indicate a wide spectrum of water stability conditions. Negative LSI values suggest that the pond water is undersaturated with calcium carbonate, making it corrosive and potentially aggressive toward metal infrastructure. Such water can dissolve protective scales and increase the risk of pipe degradation (Fazlzadeh Davil et al., 2009). On the other hand, positive LSI values reflect supersaturation, implying a tendency for scale formation due to calcium carbonate precipitation (Fazlzadeh Davil et al., 2009). An LSI as high as 10.3 suggests a strong scaling potential (Fazlzadeh Davil et al., 2009), which may impair reuse applications such as irrigation, washing of hospital equipment, mopping of floors and windows as well as industrial use. These findings are consistent with previous studies on WSP effluent chemistry, which emphasize the importance of pH, alkalinity, and calcium concentration in determining water stability (Edokpayi et al., 2021; Prathapar et al., 2015). The dual risk of corrosion and scaling has been documented in reuse systems, particularly in tropical climates where temperature and evaporation rates amplify chemical fluctuations.

Ryznar Stability Index (RSI)

The RSI values (Table 5) for the maturation pond effluent ranged from −12.9 to 205.2, indicating a wide range of chemical stability conditions. RSI values above 7 typically signify that water is unlikely to form protective calcium carbonate scales, making it corrosive to metal surfaces over time. The elevated RSI values suggest a high potential for infrastructure degradation, especially in reuse systems such as irrigation networks or industrial piping, where metal components are exposed to treated effluent. The extreme upper range of RSI values further highlights the aggressive nature of the effluent under certain conditions. These findings align with established water chemistry principles and previous studies that emphasize the importance of RSI in predicting long-term corrosion risks. Research by Prathapar et al. (2015) and Edokpayi et al. (2021) similarly identified high RSI values in WSP effluents, particularly in tropical climates, where temperature, evaporation, and mineral dissolution contribute to chemical instability.

Aggressiveness Index (AI) Assessment

The Aggressiveness Index (AI) values for the maturation pond effluent were consistently above 10, as shown in Table 5, indicating that the water is non-aggressive toward concrete infrastructure. This result is favourable for reuse scenarios involving concrete-lined irrigation channels, aquaculture ponds, or holding tanks. AI values above 10 suggest that the effluent is chemically stable regarding concrete, reducing the risk of surface degradation, erosion, or structural weakening over time. This stability supports the safe use of treated wastewater in applications where concrete is a primary material, enhancing the longevity and reliability of reuse infrastructure. While the effluent is not highly corrosive, its mildly aggressive nature toward metals, as indicated by RSI values, suggests the need for material selection favouring non-metallic options such as PVC or HDPE. These findings align with the interpretation provided by Edzwald (2011), who emphasized that while LSI is a useful indicator of scaling or corrosive tendencies, it should be viewed as a qualitative guide rather than a precise predictor of calcium carbonate precipitation. The observed RSI values are consistent with studies (Dehghan Dehnavi et al., 2025; Gholizadeh et al., 2017) from similar climatic and infrastructural contexts, such as the Yazd-Ardakan Plain, where high RSI values have been linked to metal corrosion risks in aging water distribution systems. This analysis represents the first documented application of LSI, RSI, and AI

Table 5. Corrosivity indices summary

Location	LSI	Status	RSI	Status	AI	Status
POND 1C	−98.6	strong corrosivity	205.2	high corrosiveness	10.8	relatively aggressive
POND 2C	−98.7	strong corrosivity	205.1	high corrosiveness	10.6	relatively aggressive
POND 3C	−98.4	strong corrosivity	204.5	high corrosiveness	10.9	relatively aggressive
POND 1C	−98.3	strong corrosivity	204.4	high corrosiveness	10.7	relatively aggressive
POND 2C	−98.1	strong corrosivity	203.7	high corrosiveness	10.8	relatively aggressive
POND 3C	−97.9	strong corrosivity	203.4	high corrosiveness	11.0	relatively aggressive
POND 1C	−98.2	strong corrosivity	204.1	high corrosiveness	11.1	relatively aggressive
POND 2C	−98.3	strong corrosivity	204.3	high corrosiveness	10.9	relatively aggressive
POND 3C	−98.1	strong corrosivity	204.1	high corrosiveness	11.2	relatively aggressive
POND 1C	−98.4	strong corrosivity	204.7	high corrosiveness	11.2	relatively aggressive
POND 2C	−98.2	strong corrosivity	204.1	high corrosiveness	11.2	relatively aggressive
POND 3C	−98.0	strong corrosivity	204.1	high corrosiveness	11.2	relatively aggressive
POND 1C	−98.3	strong corrosivity	204.5	high corrosiveness	11.1	relatively aggressive
POND 2C	−98.3	strong corrosivity	204.3	high corrosiveness	11.1	relatively aggressive
POND 3C	6.6	Scaling	−5.1	Scaling	10.5	relatively aggressive
POND 1C	9.4	Scaling	−11.0	Scaling	10.5	relatively aggressive
POND 2C	10.3	Scaling	−12.9	Scaling	10.2	relatively aggressive
POND 3C	6.5	Scaling	−4.9	Scaling	10.5	relatively aggressive

Note: LSI = Langelier Saturation Index; RSI = Ryznar Stability Index; AI = Aggressiveness Index.

indices for a hospital-based WSP system in Ghana offering a valuable framework for assessing effluent-infrastructure compatibility.

The above corrosivity indices (LSI, RSI, AI) indicate mild to strong corrosive tendencies toward metal infrastructure, which could lead to long-term degradation of pipes and fittings in reuse systems. To address these risks, CCTH WSP management should incorporate corrosion-resistant materials such as PVC or HDPE, apply protective coatings to metal surfaces, and establish routine monitoring of water stability indices. Periodic maintenance and replacement schedules should also be implemented to prevent structural failures. The above when undertaken, will provide a practical framework for managing both chemical and physical risks associated with effluent reuse in the hospital.

Predictive Modeling and Anomaly Detection in Maturation Pond Water Quality

The predictive modeling and anomaly detection results (Figure 6) revealed that *E. coli* levels remained relatively low and stable, with a slight downward trend, while faecal coliforms showed moderate variability and total coliforms exhibited the highest variability with multiple anomalies. These patterns suggest that although *E. coli* attenuation is generally effective, episodic spikes in faecal and total coliforms result from biofilm disruption, sediment resuspension, or external loading events. This highlights the limited reliability of time as a sole predictor of water quality behaviour, with short-term disturbances such as rainfall, algal blooms, and hydraulic shifts playing a more significant role. These findings are consistent with previous studies (von Sperling, 2007), which emphasize the vulnerability of maturation ponds to transient environmental factors.

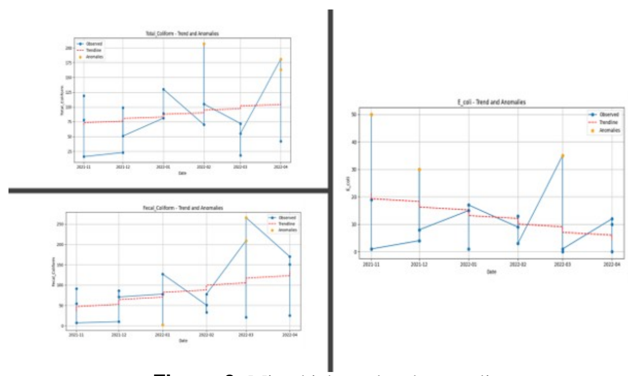

Figure 6. Microbial trend and anomalies

Predictive Modeling Insights

Anomaly detection revealed episodic spikes in microbial indicators and nutrient concentrations, coinciding with rainfall events and algal blooms. These disturbances suggest hydraulic short-circuiting and biological feedback loops that compromise effluent stability. ARIMA trend analysis indicated potential variability in BOD across maturation ponds, highlighting the need for adaptive operational strategies such as flow equalization and algal biomass control. Integrating these predictive insights into routine monitoring can help anticipate performance dips and guide proactive interventions, improving reliability in resource-limited hospital wastewater systems.

Hydrochemical Parameters and Temporal Dynamics in the Maturation Pond

The chemical profile of the maturation pond effluent was analysed to assess temporal trends, episodic fluctuations, and residual pollutant behaviour. Electrical Conductivity (EC) and Total Dissolved Solids (TDS) (Figure 7) showed consistent upward trends, indicating ion accumulation. Nitrogen species (Figure 7) increased over time, suggesting internal generation. Phosphate and nitrate concentrations (Figure 8) fluctuated, with anomalies linked to biological and geochemical processes. Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) (Figures 8 and 9, respectively) revealed persistent organic loads and episodic spikes.

Regression models applied to these parameters yielded low coefficients of determination (R^2), indicating that time alone explains only a small fraction of the observed variability in chemical behaviour within the waste stabilization pond (WSP) system. This outcome highlights a fundamental limitation of univariate, time-based regression approaches when applied to WSPs, which operate as complex, open bioreactors influenced by non-linear biological processes, physicochemical transformations, and external environmental forcing. As such, the low R^2 values do not reflect poor data quality but rather demonstrate that temporal progression alone is insufficient to capture the dominant drivers of water-quality dynamics in WSPs. Within this context, the observed upward trends in electrical conductivity (EC) and total dissolved solids (TDS) are consistent with the accumulation of dissolved ions driven by evaporation, mineral dissolution, and the limited capacity for ionic removal inherent to WSPs. Episodic deviations from these trends likely reflect short-term influent variability, including fluctuations in hospital discharge and seasonal changes. Increases in nitrogen species indicate ongoing organic matter degradation, with the presence of nitrate suggesting partial nitrification under intermittently oxic conditions, while persistent ammonia points to incomplete nitrification–denitrification, potentially resulting from insufficient anaerobic zones or short hydraulic retention times. Variability in phosphate concentrations is similarly influenced by internal pond processes, including algal uptake and release, seasonal nutrient cycling, and sediment–water interactions. Binding and release of phosphate under changing redox conditions involving iron and calcium may further contribute to the observed fluctuations. Trends in chemical oxygen demand (COD) and biochemical oxygen demand (BOD) underscore the continued influence of biological activity even in the final treatment stages, with anomalies potentially arising from algal by-products, biofilm sloughing, or intermittent external organic inputs. These interpretations are consistent with previous studies of WSP systems (Kayombo et al., 2010), which emphasize the dominant role of environmental and operational controls over simple temporal drivers.

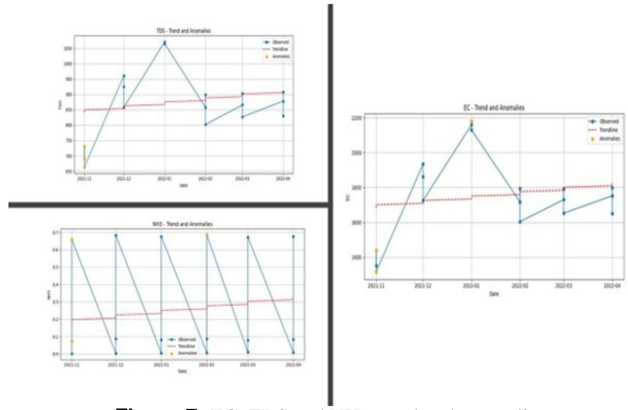

Figure 7. EC, TDS and NH_3 trend and anomalies

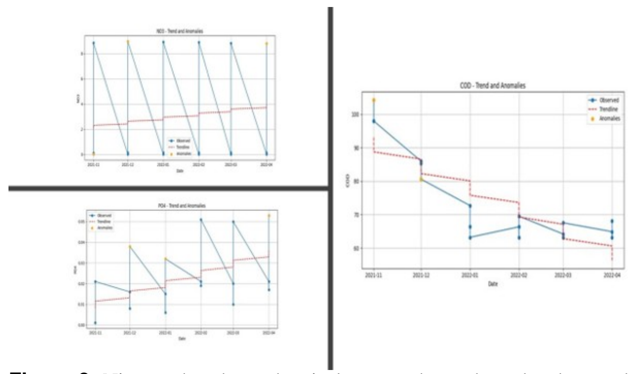

Figure 8. Nitrate, phosphate, chemical oxygen demand trend and anomalies

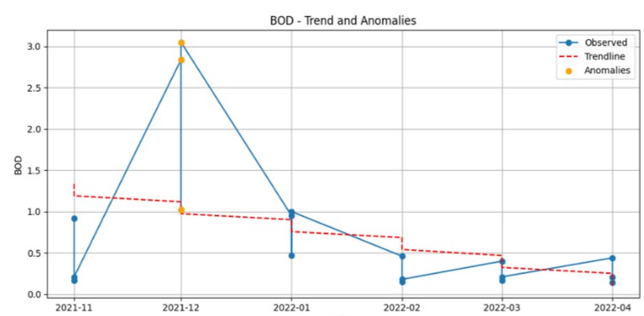

Figure 9. Biochemical Oxygen Demand trend and anomalies

Algal and Biofilm Contributions in the Maturation Pond

To evaluate biological drivers of pollutant variability, the maturation pond was analysed using COD and BOD as proxies for algal activity (Figure 10), and coliform variability as indicators of biofilm sloughing and microbial regrowth (Figure 11). From Figure 10, it is observed that COD and BOD levels had moderate variability with mean values of 78.6 mg/L and 1.18 mg/L, respectively. Additionally, the COD peaks rose to 104.28 mg/L, suggesting the likely presence of non-biodegradable organic matter, probable from algal metabolic by-products. The observed outliers and skewness were indicative of episodic algal blooms or organic load surges. The decoupling of COD and BOD implies that much of the organic matter is refractory, resisting biological degradation.

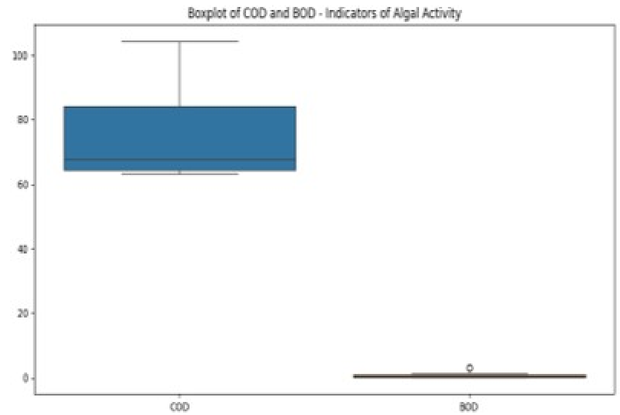

Figure 10. Box plot of COD and BOD of algal activity

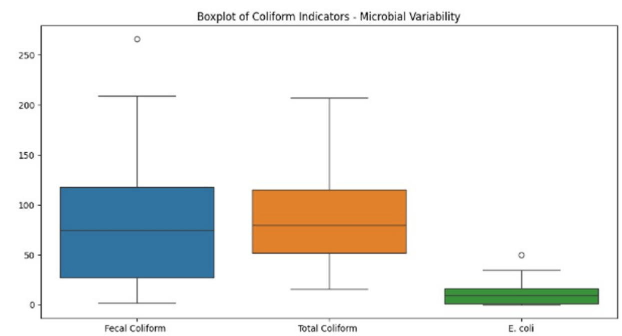

Figure 11. Box plot of microbial indicators

Microbial indicators (Figure 11) showed significant variability with total coliforms ranging from 16 to 207 CFU/100 mL, and faecal coliforms ranging from 2 to 266 CFU/100 mL, but *E. coli* remained relatively stable (1 to 50 CFU/100 mL). The presence of outliers and spikes in total and faecal coliforms suggests the likelihood of biofilm sloughing events, where microbial communities detach from surfaces and re-enter the water column. *E. coli*'s lower variability reinforces its reliability as a specific faecal contamination indicator, while total coliforms' sensitivity reflects their broader ecological niches. These findings align with existing research (Dias et al., 2017; Liu, 2018; von Sperling, 2007) on WSP systems, which highlights the role of algal blooms and biofilm dynamics in influencing effluent quality. The obtained results emphasize the need for seasonal monitoring of algal activity and biofilm dynamics.

Time-Series Modeling of BOD Using ARIMA

From Figure 12, it is observed that POND 1C exhibited relatively stable BOD values, while POND 2C and POND 3C showed greater variability, likely reflecting differences in hydraulic loading, microbial activity, or influent composition. The six-month forecasts (Figure 12) indicated that POND 1C is expected to maintain low BOD levels, suggesting consistent treatment performance. In contrast, POND 2C may experience moderate increases, and POND 3C shows potential for further variability, warranting operational adjustments. These findings are consistent with previous applications of ARIMA (Chaoui et al., 2023; Lee and Ko, 2011; Reagan, 1984) in wastewater systems, where time-series modeling has proven effective for forecasting pollutant trends and informing management decisions. Studies (Aparna et al., 2024; Dai et al., 2025; Lai, 2025; Lotfi et al., 2019) have shown that ARIMA models can accurately predict BOD and COD levels, supporting proactive control strategies in wastewater treatment systems.

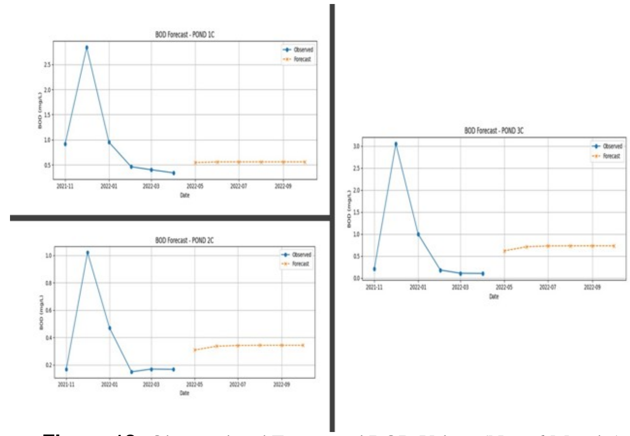

Figure 12. Observed and Forecasted BOD Values (Next 6 Months)

Table 6. US Salinity classification (After Richards (1954)) table for the maturation pond at CCTH

SAR	EC (μS/cm)	EC (dS/m)	Class
92.7	1351	1.35	C3-S4
103.0	1438	1.44	C3-S4
86.7	1316	1.32	C3-S4
125.7	1934	1.93	C3-S4
127.1	1863	1.86	C3-S4
106.0	1725	1.73	C3-S4
123.9	2160	2.16	C3-S4
155.9	2180	2.18	C3-S4
152.5	2130	2.13	C3-S4
97.6	1717	1.72	C3-S4
127.5	1795	1.80	C3-S4
113.2	1604	1.60	C3-S4
98.1	1730	1.73	C3-S4
127.4	1792	1.79	C3-S4
110.3	827	0.83	C3-S4
94.3	878	0.88	C3-S4
120.5	908	0.91	C3-S4
109.5	830	0.83	C3-S4

Note: SAR = Sodium Adsorption Ratio; EC = Electrical Conductivity; C3-S4 class indicates high salinity and very high sodium hazard.

Effluent Suitability for Agricultural Reuse

Sodium Adsorption Ratio (SAR)

The US Salinity Laboratory (USSL) diagram was employed to evaluate the combined effects of salinity (as indicated by Electrical Conductivity, EC) and sodium hazard (as indicated by Sodium Adsorption Ratio, SAR) for the maturation pond. The plot (Figure 13) reveals the distribution of the water samples across different salinity–sodium hazard zones (C1–C4 and S1–S4), thereby providing insights into their suitability for irrigation purposes. The EC values of the samples range from approximately 827 to 2180 μS/cm, placing most of the samples within the C3 (high salinity) to C4 (very high salinity) categories of the USSL classification. Water in these classes is typically associated with salinity hazards, meaning that special management practices (such as good drainage, leaching, or salt-tolerant crops) are required to prevent soil salinization and maintain crop productivity. Such high EC levels suggest the presence of considerable dissolved ions (e.g., Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-), likely influenced by evaporative concentration, mineral weathering, and possibly anthropogenic inputs from pond management activities.

The SAR values of the samples range from 86.7 to 155.9, which clearly fall within the S4 (very high sodium hazard) category. Water with such high sodium concentrations poses a serious risk to soils, as sodium tends to replace calcium and magnesium ions on the soil exchange complex, leading to soil dispersion, reduced infiltration, and poor aeration. The dominance of S4 classification implies that none of the samples are suitable for irrigation under normal conditions without treatment. The diagram (Figure 13) also represents pond water of very high salinity and very high sodium hazard, which are unsuitable for irrigation, but suitable for salt-tolerant crops. The high SAR relative to EC indicates that sodium hazard predominates over the total salinity hazard, intensifying the potential for soil structure degradation. The elevated SAR and EC values point to processes such as intense evaporation, ion exchange reactions, and mineral dissolution. If such waters are used for irrigation, soil alkalinity and salinity buildup may rapidly impair soil fertility and crop yield.

To make the effluent suitable for reuse, several mitigation measures such as dilution, advanced treatment, chemical amendments, crop selection and drainage management should be considered. These strategies can significantly reduce salinity hazards and enable safer reuse of treated effluent for irrigation purposes. The findings underscore the need for regular water quality monitoring, management of saline inflows, and possibly use of alternative water sources for sustainable agricultural practices in the study area.

Magnesium Ratio (MR) and Kelly Ratio (KR)

In this study, the MR values ranged from approximately 0.01 to 30.6 (Table 7), with several samples exceeding the recommended threshold of 0.5, indicating a significant magnesium hazard. Similarly, KR values ranged from approximately 9.4 to 26.7 (Table 7), far exceeding the safe limit of 1.0, suggesting a dominant sodium presence relative to calcium and magnesium. Elevated MR values affect soil structure, leading to reduced permeability, poor aeration, and ultimately lower crop performance. High KR values indicate sodium accumulation in the soil, which impairs its physical properties and fertility. These findings imply that the effluent, in its current state, poses a substantial risk to agricultural soils and crops, making it unsuitable for direct irrigation reuse without intervention.

The observed MR and KR values are consistent with established research (Ayers and Westcot, 1985; Rhoades et al., 1992) on irrigation water quality. High magnesium concentrations have been linked to soil compaction and reduced hydraulic conductivity, while elevated KR values are known

Table 7. Agricultural indices for the maturation pond

Sample Number	MR	KR
1	27.77	10.68
2	30.60	12.39
3	25.40	9.60
4	28.42	13.71
5	26.46	14.54
6	26.52	10.94
7	25.77	11.94
8	26.63	18.66
9	26.44	18.28
10	28.15	9.33
11	28.61	15.17
12	28.01	13.39
13	28.57	9.35
14	28.56	15.18
15	0.01	24.63
16	0.01	16.98
17	0.01	26.73
18	0.01	24.19

Note: MR = Magnesium Ratio; KR = Kelly's Ratio.

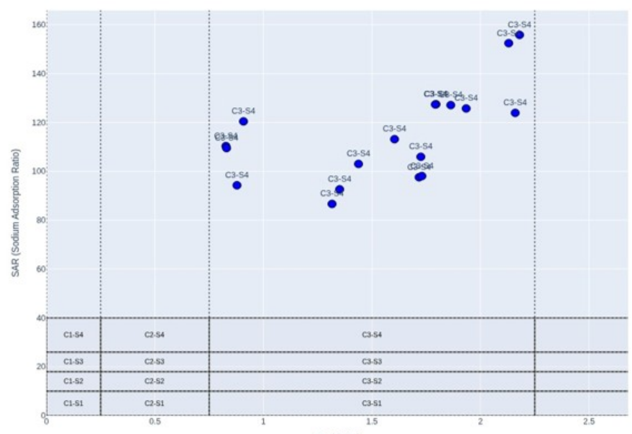

Figure 13. The plot of maturation pond data on the US salinity diagram (After Richards 1954)

to degrade soil fertility (Alao et al., 2025; Ayers and Westcot, 1985; Rhoades et al., 1992). These ratios are widely used in agricultural water management to assess the balance of cations and their impact on soil health.

Conclusion

The Cape Coast Teaching Hospital Waste Stabilization Pond (WSP) system demonstrates mixed performance after 26 years of operation. The system achieved strong attenuation of suspended solids (54.5%) and selected heavy metals (Pb and Cr), meeting WHO discharge standards. However, nutrient concentrations (ammonia up to 59.4 mg/L), salinity indicators (EC up to 1565 μS/cm), and microbial indicators remained above WHO thresholds for unrestricted reuse. Corrosivity indices revealed risks to metal infrastructure, and irrigation suitability analysis classified the effluent as unsuitable without intervention (SAR 86.7–155.9; S4 category). These findings underscore that while the WSP system effectively reduces particulate matter and some metals, it is inadequate for complete nutrient and microbial removal. Practical implications include the need for tertiary treatment options such as constructed wetlands, membrane filtration, or blending with freshwater, alongside controlled reuse strategies to mitigate salinity and sodium hazards. This integrated assessment provides critical evidence for improving hospital wastewater management and designing safe, sustainable reuse frameworks in resource-limited settings.

Recommendations

1. To address the elevated levels of nutrients, dissolved ions, and organic pollutants in the maturation pond effluent, tertiary treatment methods such as carbon constructed wetlands, membrane filtration, or activated carbon systems should be considered to enhance effluent quality before reuse.
2. Regular desludging, vegetation control, and hydraulic flow management should be instituted to reduce short-circuiting, improve retention time, and minimize episodic spikes in microbial and chemical parameters.
3. Specific reuse protocols should be developed for hospital effluent, especially for applications such as cleaning, irrigation, or aquaculture, with consideration for corrosivity, salinity, and microbial safety.
4. Hospitals should adopt source reduction strategies, including proper disposal of pharmaceuticals and saline solutions, to minimize the input of refractory and conservative pollutants into the WSP system.

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Authors' Contribution

E. K. A. A. – Supervision of the entire research work, fund acquisition, read and approved the manuscript. J. M. T. – Sampling, laboratory analysis, read and approved the manuscript. A. K. E. – Conceptualization, methodology, data analysis, interpretation, writing, read and approved the manuscript. F. S. – Statistical analysis, read and approved the manuscript. I. M. B. – Data analysis, read and approved the manuscript. M. T. – Data analysis, read and approved the manuscript. H. P. – Proofread the manuscript, read and approved the manuscript. D. A. – Sampling, laboratory analysis, read and approved the manuscript.

Ethical Approval

The study involved only environmental sampling and laboratory analysis; therefore, no human or animal subjects were used. Permission for wastewater sampling was obtained from the hospital management, and all research activities complied with institutional safety and environmental ethical guidelines.

Consent to Participate

This study did not involve human participants; therefore, individual consent was not required. Permission for environmental sampling and data collection was obtained from the management of the hospital hosting the waste stabilization pond system.

Consent to Publish

This study did not involve human participants or personal data; therefore, consent for publication was not required. The author(s) consented to the publication of this manuscript and its associated data.

Competing Interests

The authors declare that there are no known competing financial or personal interests that could have appeared to influence the work reported in this manuscript.

Data Availability Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Availability of data and materials

All data analyzed during this research work are summarized and included in this published work but contact the first author for all detailed data.

Clinical trial number

Not applicable.

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