

Performance Assessment of the Mabogini Integrated Wastewater Treatment Plant for Treated Effluent Reuse in Irrigation, Moshi, Tanzania

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ABSTRACT

Combined waste stabilization ponds and constructed wetlands are widely adopted as wastewater treatment technologies in tropical regions but still face challenges in meeting recommended standards. This study assessed the performance of the Mabogini integrated wastewater treatment plant (IWTP) for the reuse of treated effluent in irrigation in Moshi, Tanzania. Wastewater sampled during the dry and wet seasons was analysed using APHA standard methods. Results showed high removal efficiencies for organic pollutants, with COD (mg/L) reaching 93.3% and BOD₅ (mg/L) 86.1%. Nutrient removal efficiencies were high, with Ammonia (NH₃/NH₄⁺) (mg/L) reaching 85.8% and nitrate (NO₃⁻) (mg/L) 73.6%, while Phosphate (PO₄³⁻) (mg/L) had low removal at 53.1%. Likewise, the effluent limits for phosphate and bacteriological contamination occasionally exceeded the reuse limits set by the Tanzania Bureau of Standards and the World Health Organization. Heavy metal removal was moderate, with detectable concentrations of Pb (mg/L), Cd (mg/L), and Hg (mg/L) remaining in the final effluent. Therefore, the Mabogini IWTP effectively removes organic pollutants, but nutrient and toxic contaminant removal remains incomplete under current operational conditions.

Keywords: Wastewater reuse, IWTP, Mabogini, pollutant removal efficiency, heavy metals.

1 INTRODUCTION

Reuse of wastewater has become an increasingly important alternative water source for agricultural and other environmental activities, particularly in fast growing areas of developing countries (UN, 2021; Angelakis *et al.*, 2023). In tropical regions, the natural waste treatment system combining waste stabilization ponds (WSPs) and constructed wetlands (CWs) has been adopted for its low operating and maintenance costs (Jaramillo and Restrepo, 2017; Omidinia and Shayannejad, 2021). The system has been reported to be effective in reducing organic pollutants and suspended particles, thereby supporting water reuse (Waly *et al.*, 2022; Tuyisenge, 2022).

Despite the advantages of water reuse, many systems have experienced declining efficiency due to hydraulic loading, sludge buildup, wetland degradation, and inadequate maintenance, especially in older systems (Edokpayi *et al.*, 2021; Outwater *et al.*, 2019). Past research in Rwanda, Kenya, Tanzania, and Uganda has indicated that while the removal of organic pollutants by WSP and CW is quite effective, nutrient stabilization and pathogen reduction may not be consistent, especially when overloaded and during rainy seasons (Kirumba *et al.*, 2024; Pennellini, 2022; Ngoboka, 2024; Wawa, 2020). The issue of seasonality has raised concerns about high concentrations of ammonia and phosphorus that exceed the set standards for reuse in farming and environmental protection (Zhang *et al.*, 2021; Sohoulade *et al.*, 2023). Moreover, growing concerns have emerged regarding the persistence of toxic heavy

metals such as Lead (Pb), Cadmium (Cd), Chromium (Cr), Copper (Cu), and Mercury (Hg) in treated wastewater reused for irrigation (Fazekašová *et al.*, 2021; Kinuthia, 2020).

The use of wastewater treatment through natural and integrated methods is common in cities of Tanzania owing to its low cost and adaptability to tropical conditions (Outwater *et al.*, 2019; Hance, 2020). Nevertheless, most systems did not demonstrate consistent compliance with standards set by TBS (2019) and WHO (2006) for wastewater reuse, particularly regarding nutrient levels, bacteriological contamination, and presence of toxic chemicals (Msuya *et al.*, 2025; Hance, 2020). In addition, the lack of proper monitoring and ageing-treatment infrastructure raises questions about the future sustainability of water reuse practices and environmental protection (Hance, 2020).

The Mabogini IWTP, run by the Moshi Urban Water Supply and Sanitation Authority (MUWSA), is among the early models of integrated natural wastewater treatment systems in Tanzania that combine WSPs with horizontal subsurface constructed wetland (HSSFCW) and fishpond systems, prior to the utilization of treated effluent for agricultural irrigation (MUWSA, 2023). The MUWSA data on wastewater characteristics between 2021 and 2025 show that the wastewater received at this treatment facility is highly polluted with nutrients and organic pollutants, with average influent COD and BOD₅ levels usually exceeding 1,000 mg/L and 800 mg/L, respectively. Despite the system exhibiting high removal efficiency of organic pollutants (COD and BOD₅), effluent levels of COD, BOD₅, nutrients, and bacteriological parameters sometimes exceed TBS (2019) and WHO (2006) guidelines for reuse, especially under high hydraulic loading. Existing empirical studies in Mabogini by Nyangwi and Seria (2023) and Tarimo (2013) have focused on specific aspects of the treatment process rather than on the overall performance of the existing wastewater treatment plant. In particular, the work carried out by Tarimo (2013) focused on the nitrogen transformation dynamics, indicating operational challenges such as sludge build-up, hydraulic short-circuiting, and reduction in retention time, while the research carried out by Nyangwi and Seria (2023) raised concerns about heavy metal concentration in sludges reused for agricultural purposes in Moshi Municipality. However, no recent research has examined the overall performance of the IWTP with considering seasonal variations. Therefore, this research examines the current performance of the Mabogini IWTP with respect to seasonal variations of physicochemical parameters, bacteriological contaminants, and heavy metals.

2 MATERIALS USED AND METHOD

2.1 Study area

The study was conducted at the Mabogini Integrated Wastewater Treatment Plant (IWTP) in the Mabogini area, Moshi Municipality, Kilimanjaro Region, Northern Tanzania, as shown in Figure 1. The IWTP is owned and operated by the Moshi Urban Water Supply and Sanitation Authority (MUWSA) and serves as the main municipal wastewater treatment facility for Moshi Municipality. The treatment system comprises waste stabilization ponds (WSPs), horizontal subsurface flow constructed wetlands (HSSFCWs), and a fishpond, arranged sequentially to progressively remove organic pollutants, nutrients, and pathogens before the final effluent is reused for irrigation. The pond system includes an anaerobic pond, facultative ponds, and maturation ponds, while the constructed wetlands provide additional treatment through filtration, microbial degradation, adsorption, and macrophyte uptake. According to MUWSA (2024), the WSP system has an average treatment capacity of approximately 4,500 m³/day, whereas the constructed wetlands treat about 528 m³/day under normal conditions. The entire IWTP consists of partially treated effluent from maturation pond two (MP2) entering the horizontal subsurface constructed wetland (HSSFCW), then the fishpond, before the final effluent is released for reuse. About 70 farmers, each owning an average of 1 acre, use treated effluent for agricultural irrigation, particularly in paddy-farming areas surrounding the treatment plant. The system was selected for this study because increasing wastewater loading, seasonal hydraulic variations, and growing wastewater reuse activities have raised concerns about treatment efficiency and

final effluent quality. Seven points were sampled, which were the inflow at MP2 (SP1), outflow at MP2 (SP2), inflow at HSSFCW (SP3), outflow at HSSFCW (SP4), inflow at Fishpond (SP5), outflow at Fishpond (SP6), and final effluent after reuse (SP7)

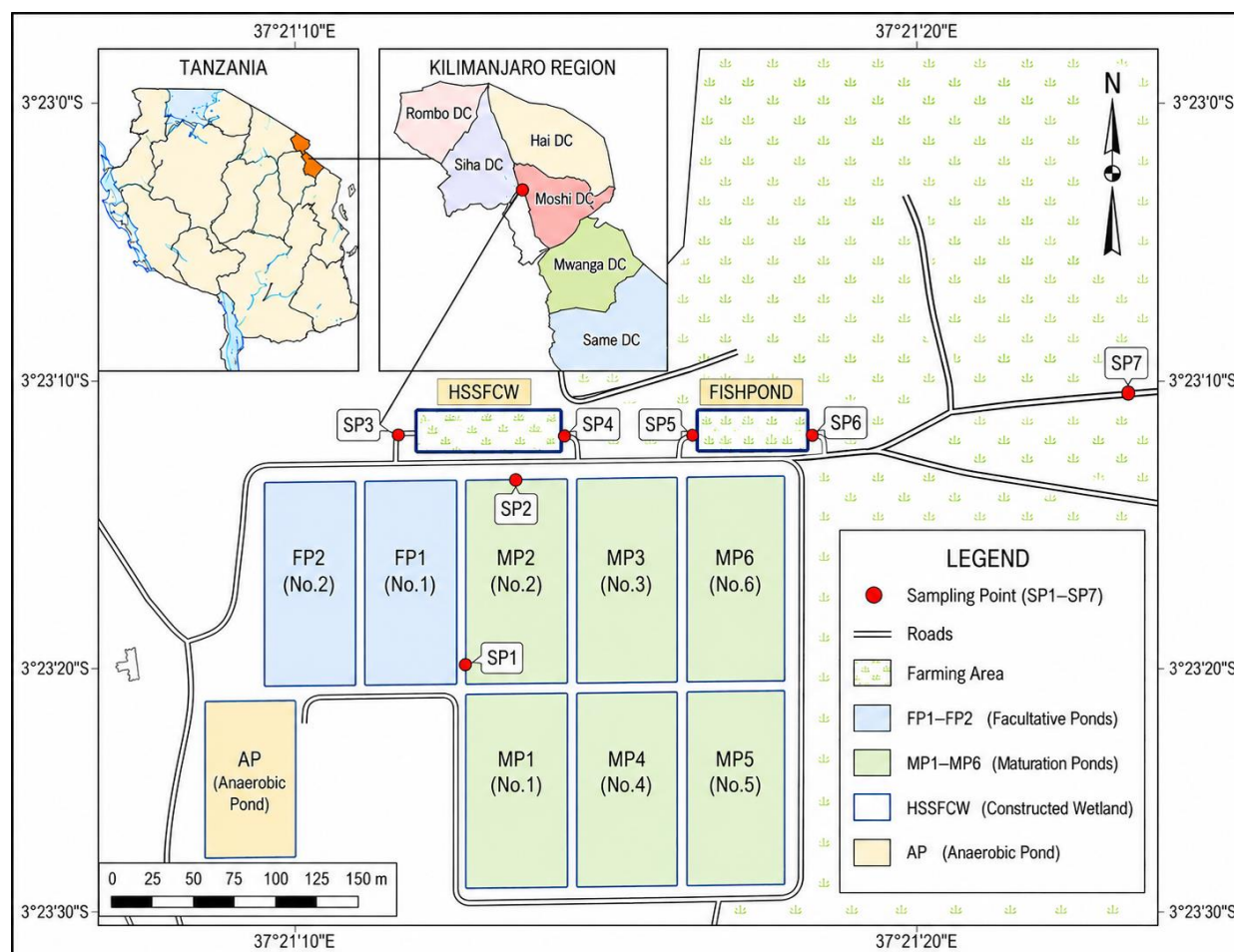


Figure 1: Location of the Mabogini Integrated Wastewater Treatment Plant in Moshi Municipality, Tanzania

2.2 Sampling Procedure and Sampling Points

Wastewater sampling was conducted in both the dry and wet seasons to account for seasonal changes in pollutant concentrations at the Mabogini IWTP. Wastewater samples were collected from seven sampling points along the treatment train at the Mabogini IWTP to assess pollutant reductions throughout the treatment process. Sampling points included the major treatment processes and polishing units, including the influent of the downstream maturation ponds (SP1), maturation ponds outlet (SP2), horizontal subsurface flow constructed wetlands (SP3), outlet of horizontal subsurface flow constructed wetlands (SP4), inlet to fishponds (SP5), outlet of the fishponds (SP6) and discharge outlet (SP7). The sequential placement of sampling points along the treatment units was intended to measure variation and the efficiency of pollutant removal in each unit. Before sampling, sample bottles were rinsed with distilled water and wastewater from each sampling point to avoid contamination. Samples intended for physicochemical analysis were packed and kept in cool boxes until they arrived at the laboratory, while those for heavy metals were preserved with concentrated nitric acid to prevent chemical changes before analysis.

2.3 Physical parameter data collection and analysis

The in situ measurement process was employed to record physical parameters that could provide direct information on operating conditions in the treatment process system, and that would affect biological and chemical reactions (Ndikumana et al., 2021). These

physical parameters were recorded by taking samples directly at each sampling location using field-calibrated equipment to prevent changes during transport. Physical parameters measured include temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), and dissolved oxygen (DO). They were chosen due to their influence on microbial growth, reaction rate, and the effectiveness of the wastewater stabilization ponds and constructed wetlands treatment systems (Juneidi et al., 2022).

2.4 Laboratory analysis of chemical, bacteriological, and heavy metals parameters

The analysis of the samples took place according to the APHA standard methods for wastewater characterization. The chemical composition of the samples consisted of Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD₅), ammonia (NH₃/NH₄⁺), nitrate (NO₃⁻), and phosphate (PO₄³⁻). For the determination of the levels of COD and BOD₅, APHA standard laboratory procedures were employed. Spectrophotometric methods were applied for nutrient analysis, while bacteriological contaminants were evaluated based on the presence of total coliforms and *Escherichia coli* (E. coli) bacteria. The microbiological analysis used membrane filtration and incubation procedures carried out under standardized conditions of 37 °C. Heavy metals (Pb, Cd, Cr, Cu, Hg) analysis used Atomic Absorption Spectrophotometry (AAS) due to its sensitivity.

2.5 Data Analysis Techniques

Data analysis of physicochemical, bacteriological, and heavy-metal parameters was conducted using descriptive statistics and linear regression models to evaluate changes in pollutant concentrations along the treatment units as shown in Equation (1). The coefficient of determination (R²) was used to assess the strength and consistency of pollutant reduction trends. The value of R² above 0.70 indicates a strong removal trend, values between 0.50 and 0.70 indicate a moderate trend, and values below 0.50 indicate a weak trend (Edokpayi *et al.*, 2021; Hitimana *et al.*, 2025). Finally, the final effluents were compared with the allowable standards set out in TBS (2019) and WHO (2006)

$$\gamma = \beta + \delta X \dots \dots \dots (1)$$

γ = pollutant concentration

X = treatment unit sequence (SP1–SP7)

β = intercept

δ = regression coefficient (slope)

Likewise, pollutant removal efficiency of the IWTP was calculated to evaluate contaminant reduction across treatment units using Equation (ii).

$$RE(\%) = \left[\frac{C_{in} - C_{out}}{C_{in}} \right] \times 100 \dots \dots \dots (2)$$

Where;

RE(%) = the removal efficiency in percentage

C_{in} = the concentration of the pollutant in the influent

C_{out} = the concentration of the pollutant in the effluent

Furthermore, building on Juneidi et al. (2022), microbiological parameters (Total Coliforms and E. coli) removal performance was assessed using log removal values to account for the exponential nature of microbial concentrations, as shown in Equation (ii)

$$\text{"Log removal"} = \log_{10}(C_{in}/C_{out}) \dots \dots \dots (3)$$

Where;

Log Removal = Logarithm of the reduction of pollutant concentration across the treatment unit

C_{in} = the concentration of the pollutant in the influent

C_{out} = the concentration of the pollutant in the effluent

$\log_{10}$ = base 10 Logarithm

3 RESULTS AND DISCUSSION

3.1 Physical parameters removal along the IWTP

Results presented in Table 1 show the mean concentration and standard deviation of each physical parameter at the influent and effluent of the treatment train during both wet and dry seasons. Temperature remained stable across all seasons and complied with the TBS (2019) and WHO (2006) ranges of 20-35 °C. pH changes were stable, with minimal variation, while complying with the 6-9 recommended ranges by TBS (2019) and WHO (2006). Although EC and TDS during the wet season were within the recommended TBS and WHO standards, records of EC during the dry season showed higher concentrations than recommended limits, indicating higher salinity due to less dilution. DO was recorded below 5 mg/L, as recommended by TBS and WHO; however, it showed a progressive increase across the treatment units, indicating aeration and improved treatment performance. The removal trend across the entire treatment units, as illustrated in Figure 3, shows a strong reduction, with R^2 values of 0.986 for EC in the dry season and 0.984 in the wet season, and 0.982 for TDS in the dry season and 0.974 in the wet season. This shows the strong consistency in the decrease in dissolved ions from the influent to the final effluent pond-wetland system. Likewise, Figure 2 shows a positive increase in DO in both seasons, with an R^2 of 0.988 indicating that the aeration and polishing process is taking place across the units. PH was relatively stable with minimal variations in all seasons, indicating a stable and favourable condition for microbial stabilization.

Overall, the results indicate that the Mabogini IWTP is progressively becoming hydraulically and biologically functional, underscoring its suitability for tropical climates. The progressive reduction in EC and TDS, together with an increase in DO, has been reported in similar tropical climates by Edokpayi et al. (2021) in South African stabilization ponds and by Tuyisenge (2022) in hybrid pond-wetland systems in Rwanda, where the systems exhibit strong reductions in EC and TDS and increases in DO along the entire treatment system. The findings of the Mabogini IWTP, therefore, complement similar studies that the natural treatment mechanism under warm tropical climatic conditions plays a significant role in improving the quality of the final treated effluents

Table 1 Physical Parameters and Removal Efficiency

Parameter	Dry Season (Mean ± SD)	Wet Season (Mean ± SD)	TBS/WHO Guideline
Temperature (°C)	29.46 ± 0.18	28.64 ± 0.18	–
EC (µS/cm)	1821.6 ± 47.6	1698.1 ± 64.0	1700

TDS (mg/L)	856.2 ± 75.1	817.6 ± 63.4	1000
pH	7.46 ± 0.13	7.38 ± 0.16	6–9
DO (mg/L)	3.26 ± 0.83	2.98 ± 0.78	≥ 5

Source: Field data,2026

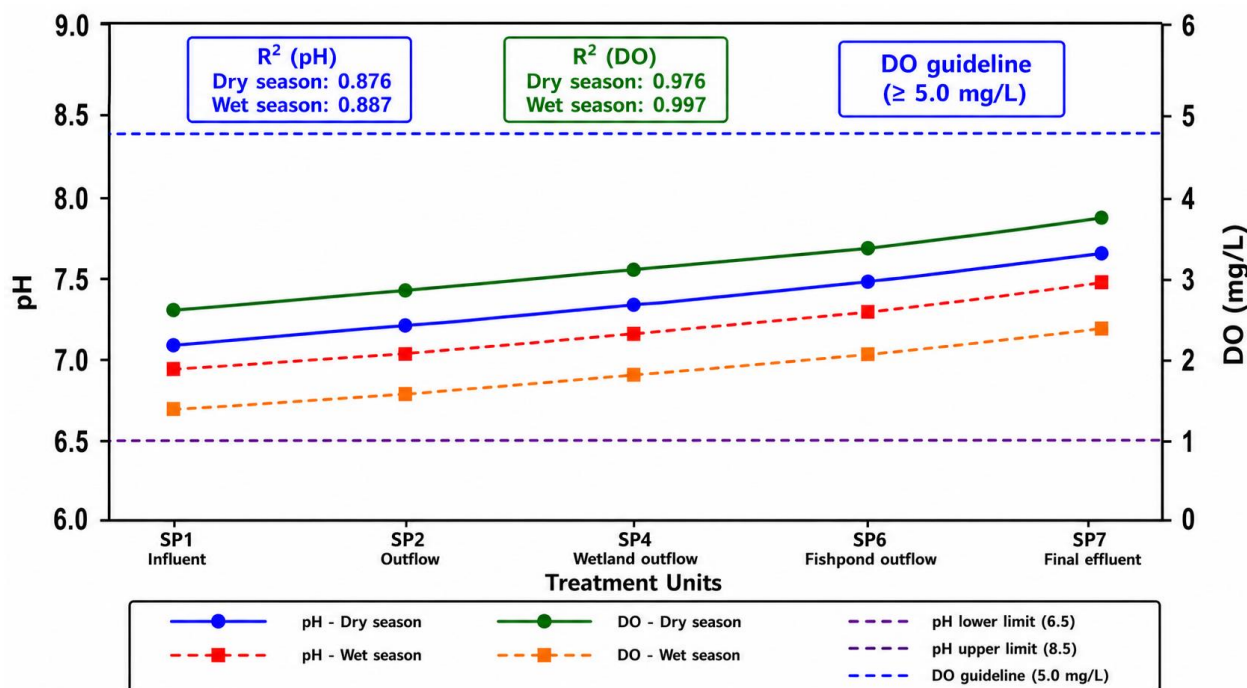


Fig 2 DO and PH removal trends along the treatment units

Source: (Field data,2026)

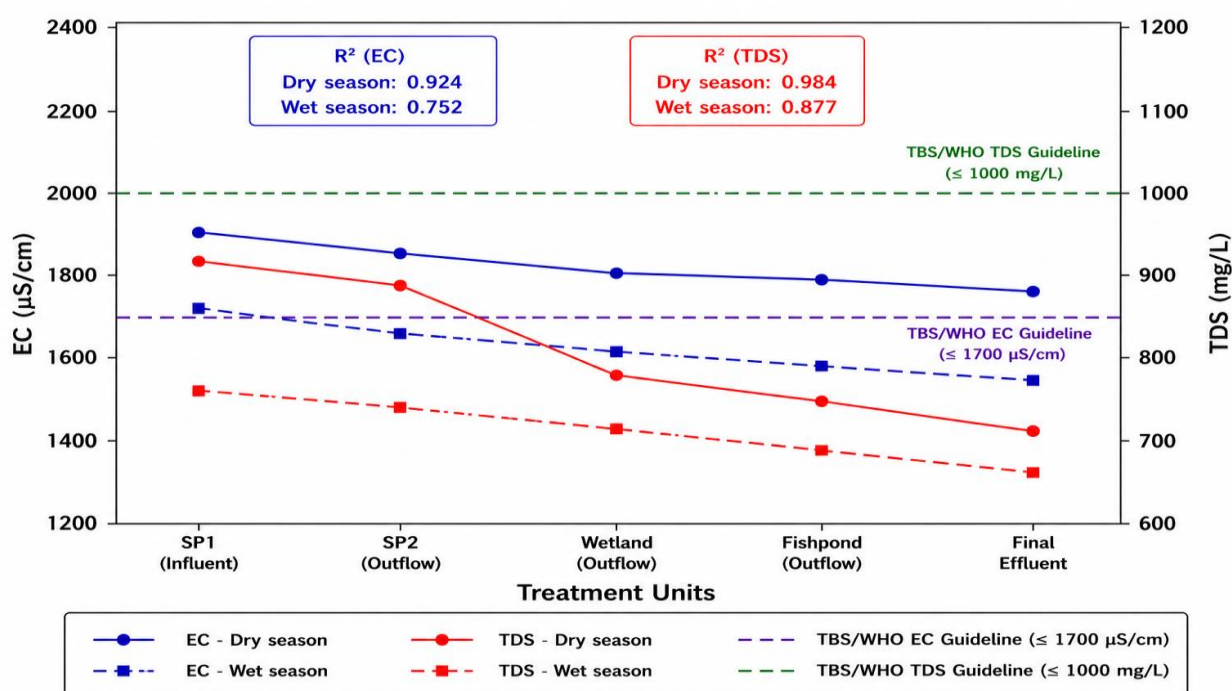


Fig 3 EC and TDS removal trends along the treatment units

3.2 Chemical parameters along the IWTP

Illustrations in Figures 4 and 5 show reductions in the concentrations of organic contaminants and nutrients throughout the treatment system during both the dry and wet seasons. COD and BOD₅ levels consistently decreased from the inlet to the outlet, and high coefficients of determination (R^2) indicate that this trend is significant and steady throughout the treatment process. Likewise, nutrient levels decreased consistently across each unit throughout the treatment process. However, the overall level of pollution varied with the season. The mean concentrations of chemical parameters in Table 2 indicate high organic pollution during the wet season, implying seasonal fluctuations in wastewater loading. Also, the table 2 shows that the removal efficiency of organic pollutants was high in the dry season, with COD removal efficiency of 93.3% and BOD₅ removal efficiency of 86.1%, while in the wet season, COD removal efficiency was 86.9% and BOD₅ removal efficiency was 71.1%. This shows that the pond-wetland system remains effective at removing biodegradable organic matter despite seasonal variation in loading. Such high levels of pollutant removal can mainly be attributed to sedimentation, anaerobic digestion, oxidation, and stabilization in each unit.

The high removal efficiencies (above 80%) have been documented in wastewater stabilization ponds and hybrid wetland systems operating under the same tropical conditions in Kenya, Tanzania, and Uganda (Kirumba et al., 2024; Ngoboka, 2024; Wawa, 2020). Such effective removal observed in the upstream pond units suggests that, under these conditions, anaerobic and facultative ponds play a vital role in stabilizing organic pollution in the Mabogini IWTP. Nonetheless, relatively low efficiencies recorded in wet seasons could imply increasing hydraulic stress within the treatment system. Such results have been noted in earlier works conducted in Kenya and Rwanda by Hitimana et al. (2025) and Kirumba et al. (2024), which associated decreased treatment performance during wet seasons with stormwater entry, hydraulic overloading, and declining HRT.

The efficiency of nutrient removal ranged from moderately effective to relatively inefficient, depending on the season and the parameters considered. While the removal of ammonia and nitrate was more than 70%, the removal of phosphate was relatively low, especially in the wet season. This may be attributed to inefficient phosphorus adsorption, an inadequate hydraulic retention period, and ineffective downstream polishing. Nutrient removal inefficiencies of similar magnitudes have been reported in Tanzania and other sub-Saharan countries (Sohoulande Djebou et al., 2023; Hance, 2020; Outwater *et al.*, 2019 et al., 2019). The studies attributed the decrease in phosphorus removal capacity to ageing and overload conditions of the treatment system. Furthermore, phosphate concentrations above TBS (2019) and WHO (2006) guidelines for reuse suggest incomplete nutrient polishing by downstream treatment units. Moreover, high ammonia concentrations during the wet season may indicate interference with the nitrification process due to excessive hydraulic loads. This has similarly been reported by Zhang et al. (2021), who found that ineffective ammonia removal was due to insufficient oxygen supply, shorter retention periods, and wetland clogging.

Moreover, although the results indicate that the Mabogini IWTP continues to demonstrate high efficiency in removing organic pollutants, the increased hydraulic pressure and reduced effectiveness of downstream polishing processes limit its ability to consistently remove nutrients.

Table 2 Chemical Parameters, Removal Efficiency, and Standards Compliance

Parameter	Dry Season (Mean ± SD)	Wet Season (Mean ± SD)	RE (%) Dry	RE (%) Wet	WHO/TBS Limit
COD	291.3 ± 305.4	304.6 ± 207.3	93.3	86.9	60
BOD ₅	83.0 ± 66.5	96.4 ± 47.0	86.1	71.1	30
NO ₃ ⁻	82.7 ± 46.6	71.4 ± 33.4	73.6	69.7	50

$\text{NH}_3/\text{NH}_4^+$	47.6 ± 27.9	49.2 ± 18.3	85.8	72.4	10
PO_4^{3-}	49.7 ± 13.9	45.1 ± 9.6	53.1	40.7	5

Source: (Field data,2026)

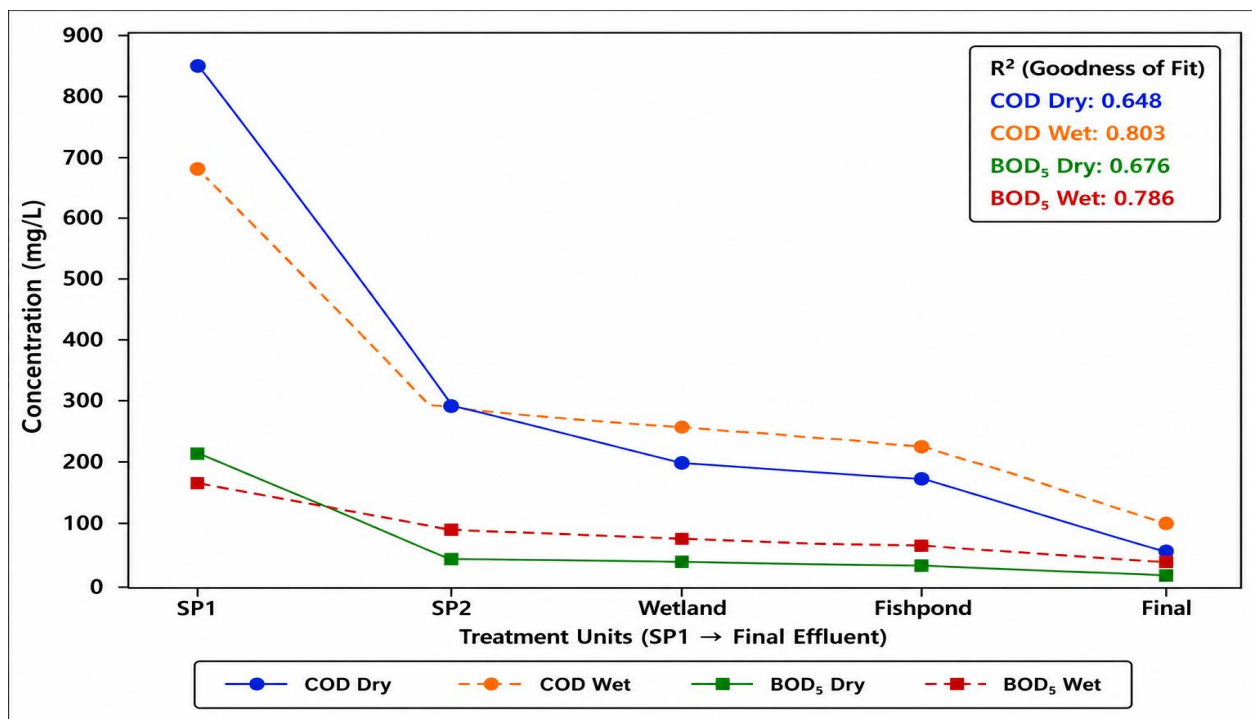


Figure 4: Organic Loading removal trend along the treatment units

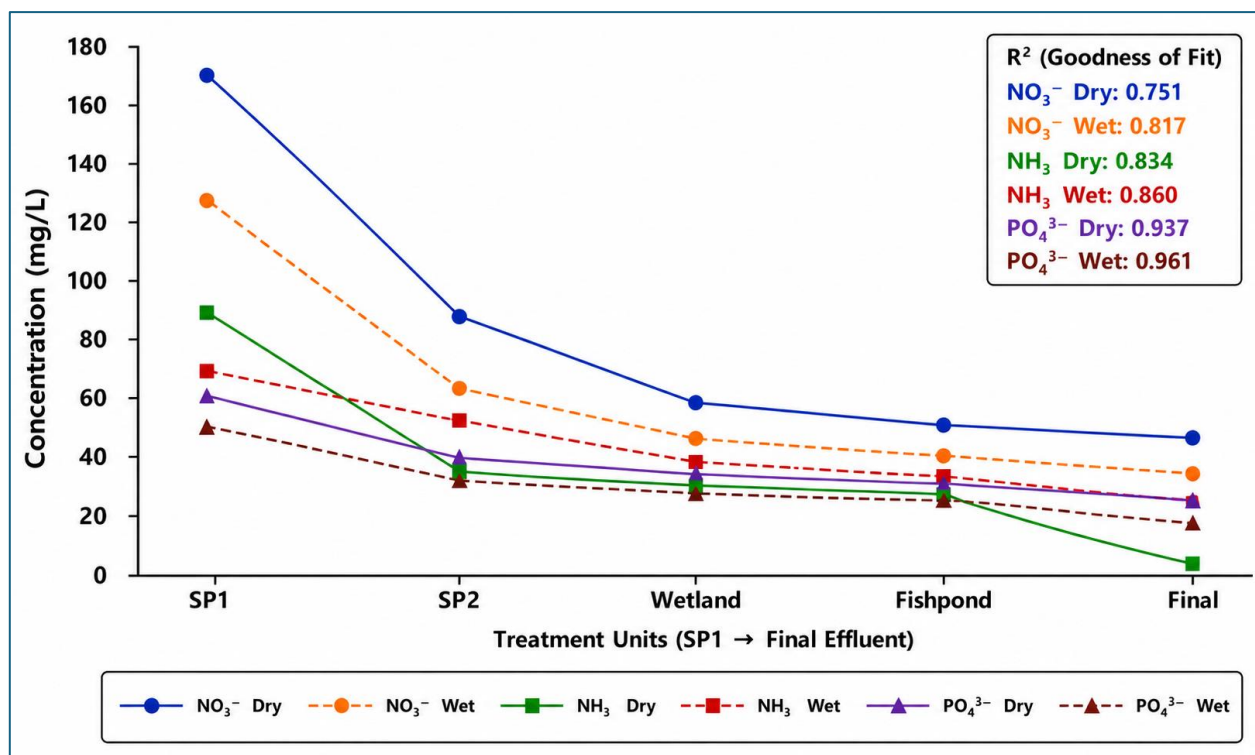


Figure 5: Nutrient removal trend along the treatment units

3.3 Bacteriological Parameters along the IWTP

The mean concentrations of both microbial parameters, as shown in Table 3, were higher in the wet season than in the dry season. This implies that seasonal variations influence the level of microbial contamination in the treatment units. Also, compliance with TBS (2019) and WHO (2006) was high in the wet season, exceeding the recommended limits. This indicates relatively low performance during wet seasons, likely due to high hydraulic loads that reduce exposure to sunlight and other biological processes, such as filtration. Although seasonal effects had an impact on performance, removal along the treatment system achieved more than 2 log units in both wet and dry seasons. This shows that the integrated treatment plant's removal efficiency exceeded 99%, indicating excellent microbial activity driven by sedimentation, solar inactivation, filtration, and biological processes within the pond wetland system. The relatively high coefficients of determination (R^2) ranged from 0.982 to 0.985 for both *E. coli* and total coliform, as shown in Figure 6, indicating a high degree of consistency and predictability in the reduction patterns of bacteria across the different stages of the treatment units in both dry and wet seasons. This implies relatively stable microbial reduction in this hybrid treatment system.

The situation in warm tropical climatic regions has been documented by Outwater *et al.* (2019), Hance (2020), and Msuya *et al.* (2025). For instance, Outwater *et al.* (2019) reported that during the rainy season, most of the wastewater stabilization ponds in Tanzania underperform due to high hydraulic load and reduced retention time. Hance (2020) noted that increased flow during the rainy season leads to solar disinfection and slower settling in the municipal wastewater treatment chain in Moshi, resulting in high concentrations of microbes in the final effluents. The recent findings of Msuya *et al.* (2025) on Wastewater management challenges in Dar es Salaam reported high bacterial removal during dry seasons and low removal during rainy seasons due to shorter retention times and system overload. The findings of this study also document that the performance of the treatment systems is highly influenced by seasonal variations.

Table 3: Mean concentration and removal efficiency of bacteriological parameters

Parameter	Mean $\pm$ SD Dry	Mean $\pm$ SD Wet	Log Removal Dry	Log Removal Wet	WHO/TBS limit
<i>E. coli</i>	2037 $\pm$ 1075	3490 $\pm$ 1802	2.76	2.49	< 1000
Total Coliforms	3383 $\pm$ 1824	6320 $\pm$ 3410	2.76	2.55	< 1000

Source: (Field data,2026)

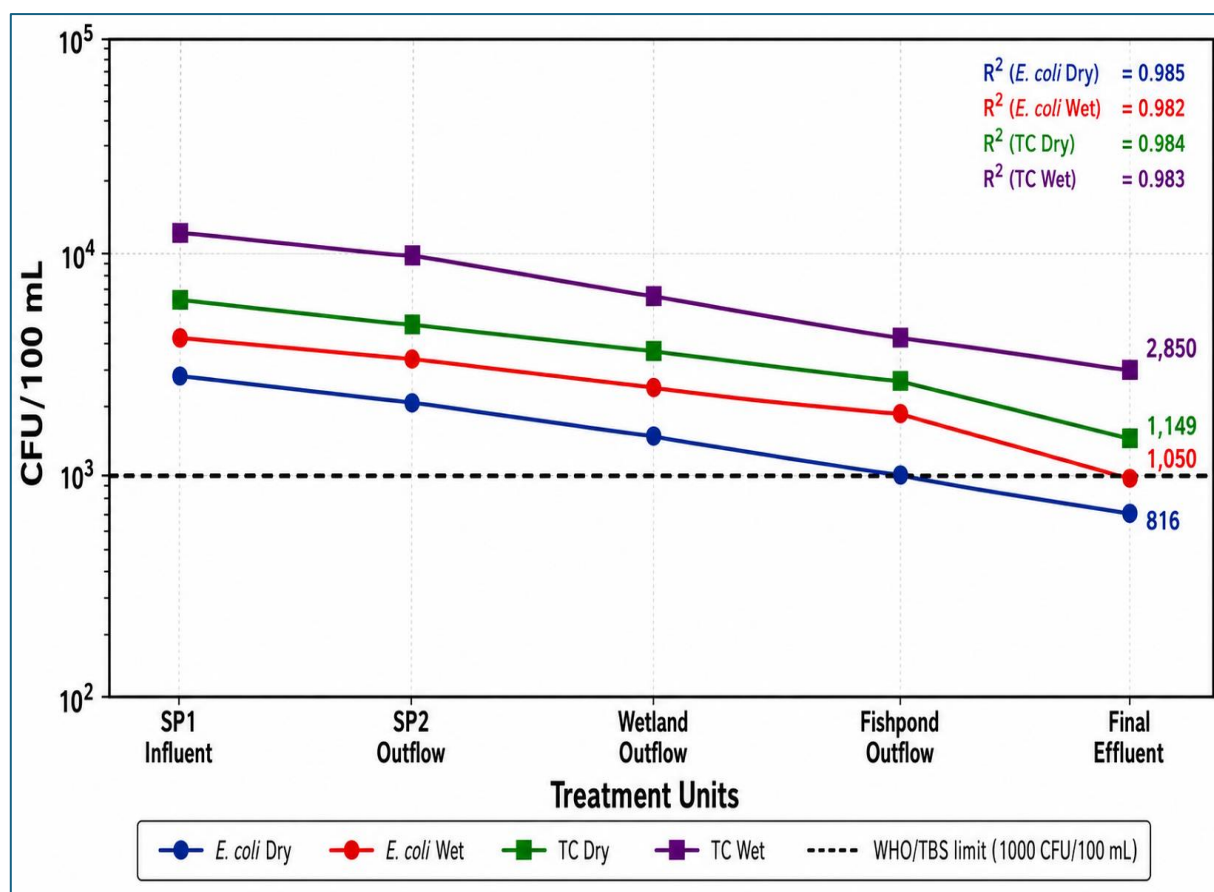


Figure 6: Bacteriological removal trend along the treatment units

3.4 Heavy metal concentrations along the IWTP

Mean concentrations of Pb, Cd, Cr, Cu, and Hg in Table 4 seem to be higher in dry seasons than in wet seasons, although the variations are slight. The observed removal efficiency across the system ranged from 40% to 62.5% during the dry season and from 20% to 51.7% in the wet season. This gradual reduction indicates a partial decrease in metal concentration across the units due to sedimentation, absorption, filtration, and biological uptake in the constructed wetland system. The high R^2 values in Figure 7 indicate very strong and consistent heavy metal reduction trends across both seasons in the treatment units, indicating a positive reduction in concentration from one unit to another. Although the treatment system indicates progressive removal of trace amounts of heavy metals, residual heavy metals remained in the final effluent, indicating that the current treatment process is ineffective at completely removing them.

Studies conducted in East Africa by Fazekašová et al. (2021), Kinuthia (2020), and Nyangwi and Seria (2023) observed residual concentrations in the final effluents of combining waste stabilization ponds and a constructed wetland were due to hydraulic overloading and ineffective polishing caused by seasonal variability. Further, at the Mabogini IWTP, the levels of Pb, Cd, and Hg exceeded the WHO (2006) and TBS (2019) recommended limits, indicating that not all toxic contaminants have been adequately removed. The studies by Fazekašová et al. (2021) and Kinuthia (2020) indicate that the system experiences high concentrations above the limit, likely due to hydraulic overloading, wetland degradation, and reduced polishing capacity in downstream polishing units. The authors further emphasized that the high concentration of heavy metals may have a potential effect on the soil under long-term irrigation. The same scenario applies to Mabogini IWTP, where heavy metal contamination of soil and crops may occur with

continued use of wastewater for irrigation. Based on these findings, the Mabogini IWTP requires more polishing units downstream to improve effluent quality for reuse in agriculture

Table 4 Heavy Metal Concentrations and Removal Efficiency

Heavy Metal	Dry Season (Mean ± SD)	Wet Season (Mean ± SD)	RE (%) Dry	RE (%) Wet	WHO/TBS Limit (mg/L)
Pb	0.156 ± 0.035	0.146 ± 0.030	62.5	51.7	0.1
Cd	0.030 ± 0.012	0.024 ± 0.010	62.5	42.9	0.01
Cr	0.138 ± 0.040	0.134 ± 0.038	57.1	44.4	0.1
Cu	0.504 ± 0.068	0.496 ± 0.055	64.4	52.5	0.2
Hg	0.015 ± 0.004	0.015 ± 0.003	40	20	0.001

Source:(Field data,2026)

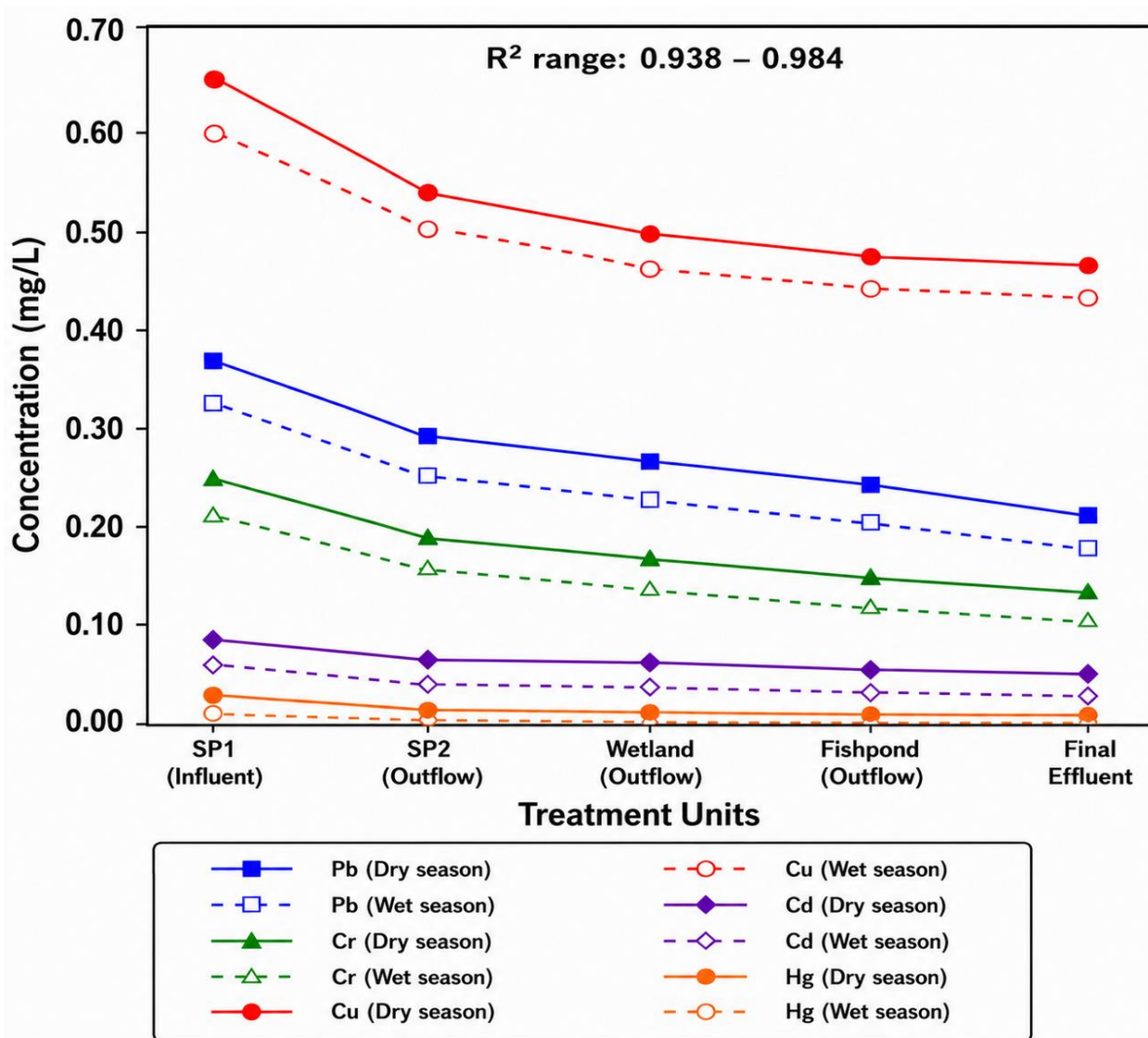


Figure 7: The heavy metal reduction trend across the treatment units

4 CONCLUSION

Results show that the Mabogini IWTP remains capable of effectively removing pollutants under tropical climate conditions, despite limitations in nutrient and heavy-metal removal. Removal efficiency of COD, BOD₅, nitrate, and bacteriological parameter values were high, which shows that the integrated ponds and wetlands still play an important role in the stabilization of organic pollutants and bacterial reduction. However, phosphate levels, ammonia, and bacteriological parameters during wet seasons, as well as the presence of Pb, Cd, and Hg, still exceeded the WHO (2006) and TBS (2019) limits for reuse. These indicate that nutrients and toxic contaminants are not completely removed under the current operating conditions of this IWTP. In addition, rising hydraulic loads, wetland degradation, and decreased efficiency of the polishing units downstream of the wetland may lead to a gradual deterioration in effluent composition over time. Therefore, for future sustainability of the treatment plant, rehabilitation and optimization of the downstream units are required to strengthen removal of nutrient, bacteriological, and heavy-metal removal for safe agricultural reuse

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Conflict of Interest

The authors declare that there is no conflict of interest

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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