Journal of Information Systems Engineering and Management
2026, 11(3s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

Research Article

Performance Evaluation of a Combined Anaerobic Pond and Constructed Wetland System for Wastewater Treatment in Sumbawanga Municipality, Tanzania

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ARTICLE INFO

Received: 02 June 2026

Revised: 18 July 2026

Accepted: 28 July 2026

ABSTRACT

Effective wastewater treatment is essential for achieving Sustainable Development Goal (SDG) 6 and 3. Despite global commitments to clean water and improved public health, access to safe sanitation remains a critical challenge in sub-Saharan Africa, including Tanzania, where inadequate wastewater management continues to pose significant threats to public health and environmental sustainability. This study evaluated the treatment performance of the combined anaerobic pond and constructed wetland system at Sumbawanga Municipal Wastewater Treatment Plant in Rukwa Region, Tanzania. A quantitative cross-sectional survey was conducted over six consecutive days, with samples collected twice daily from raw influent, anaerobic pond effluent, and constructed wetland effluent. Physical, chemical, and microbiological parameters were analyzed following Standard Methods and compared with Tanzania Bureau of Standards (TBS) effluent discharge limits (TZS 860:2019) and World Health Organization (WHO) guidelines for the safe use of wastewater. Raw influent exhibited high-organic strength characteristics, Biochemical Oxygen Demand (BOD_5) 688.8 mg/L; Chemical Oxygen Demand (COD) 1074 mg/L. Anaerobic ponds achieved substantial organic removal (BOD_5: 70.6%; COD: 71.6%) but limited nutrient reduction. The constructed wetland provided additional polishing, reducing final effluent to BOD_5 59.4 mg/L, COD 107.7 mg/L, TSS 68.8 mg/L, and faecal coliforms to 12.5×10^3 CFU/100 ml. However, only pH, temperature, TSS, and turbidity met both national and international discharge standards, while BOD_5 (59.4 mg/L), COD (107.7 mg/L), nitrate (173.8 mg/L), ammonia (122.3 mg/L), phosphate (29.7 mg/L), and faecal coliforms exceeded permissible limits set by TBS (TZS 860:2019) and WHO (2006). The study concludes that while the integrated system effectively reduces organic loads and suspended solids, critical performance gaps in nutrient and pathogen removal result in non-compliance with both national and international standards, establishing a technical baseline that justifies the investigation of enhanced tertiary treatment technologies.

Keywords: Constructed wetlands; Effluent quality; Municipal wastewater; Performance evaluation; Removal efficiency; Wastewater stabilization ponds

1. INTRODUCTION

The United Nations Sustainable Development Goals (SDGs) underscore the global commitment to ensuring clean water and sanitation (SDG 6) and reducing health risks from environmental pollution (SDG 3), both of which necessitate effective wastewater treatment (Tirkey, 2017). Wastewater, originating from domestic and industrial sources, poses significant environmental and public health challenges, including freshwater degradation, disease outbreaks, and greenhouse gas emissions (Garba Barde Bate, 2023; Ogunlade, 2021). According to the World Health

Organization, municipal wastewater comprises liquid waste from homes, businesses, and institutions collected through sewer systems.

In developing countries, inadequate wastewater management contributes substantially to disease burden. An estimated 80% of diseases and one-third of deaths in countries like Tanzania are attributed to contaminated water consumption, with corresponding losses in productive time (World Bank, as cited in Ogunlade, 2021). While Waste Stabilization Ponds (WSPs) and Construct Wetlands (CW) remain the predominant treatment technologies in these regions due to their cost-effectiveness and operational simplicity (Aluvihara et al., 2025), they frequently fail to meet effluent standards for nutrient removal and pathogen inactivation (Edokpayi et al., 2021). Al-Sa'ed et al. (2011) reported that approximately 17% of municipal wastewater collected in central sewer networks receives treatment, with most plants operating inadequately due to poor maintenance.

Sumbawanga Municipality, located in the Rukwa Region of Tanzania, operates a wastewater treatment system composed of anaerobic ponds followed by a horizontal subsurface flow constructed wetland for tertiary polishing prior to discharge. According to the Sumbawanga Environmental Action Plan (2014 – 2019), the municipality had no sewerage system providing services to the population; however, the under-construction anaerobic ponds at Makutano area under SUWASA were expected to reduce this challenge after completion. However, there are no recent studies which assess the current condition of the accomplished Sumbawanga Municipal Sewage ponds. From existing literature, most pond systems are not working properly, which means that raw sewage is discharged to surface and ground water resources (Akdim et al., 2025; Berhanu et al., 2024; Mwamlima et al., 2025). Inadequate coverage of sewerage systems in municipal areas contributes to the incidence of waterborne diseases in different parts of urban areas.

Although anaerobic ponds are theoretically efficient under tropical conditions, their performance may be compromised by hydraulic overloading, organic shock loads, sludge accumulation, and inadequate maintenance practices (Metcalf & Eddy, 2014). Similarly, constructed wetlands, while offering low-energy tertiary treatment, are vulnerable to clogging, vegetation aging, hydraulic short-circuiting, and seasonal variations in influent characteristics, which may significantly reduce treatment efficiency (Vigneswaran, 2010; Mwamlima et al., 2025). These limitations often result in inadequate removal of nutrients, suspended solids, and pathogenic organisms, thereby compromising compliance with effluent discharge standards such as those prescribed by the Tanzania Bureau of Standards (TZS 860:2019).

Several studies conducted in Sub-Saharan Africa have reported underperformance of pond-based wastewater treatment systems, particularly with respect to nutrient removal and pathogen reduction, resulting in effluent that fails to consistently meet regulatory discharge standards (Berhanu et al., 2024; Akdim et al., 2025). Evidence from similar municipal contexts in sub-Saharan Africa suggests that constructed wetlands alone may not consistently achieve the desired effluent quality required for environmental protection and public health safeguarding (Berhanu et al., 2024; Akdim et al., 2025).

A study by Ghawi (2018) using rock filters as an alternative sustainable wastewater treatment provided promising results starting from discharge quality, affordability, to compatibility. The results showed removal efficiencies of total biochemical oxygen demand (BOD), total chemical oxygen demand (COD), total nitrogen (NH_4-N), total Kjeldahl nitrogen (TKN), and total suspended solids (TSS) of 96.9%, 84.6%, 78.8%, 79.9%, and 94.3%, respectively. Despite these promising findings, there remains limited site-specific performance data for the Sumbawanga Municipal Treatment Plant, particularly concerning compliance with Tanzania Bureau of Standards effluent discharge requirements (TZS 860:2019).

A comprehensive evaluation of influent and effluent characteristics is therefore essential to quantify the current treatment efficiency, determine compliance with TZS 860:2019 discharge standards, identify operational weaknesses in primary and secondary treatment units, and establish a technical baseline for subsequent treatment optimization (TBS, 2019; Metcalf & Eddy, 2014). This study addresses these gaps by systematically characterizing wastewater quality across treatment stages and statistically evaluating system performance under existing operational conditions, if further aim to assess a feasible sustainable wastewater treatment system for Sumbawanga Municipal.

Journal of Information Systems Engineering and Management
2026, 11(3s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

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2. MATERIALS AND METHODS

2.1. Study Area

The study was conducted at the Sumbawanga Municipal Wastewater Treatment Plant located in Rukwa Region, Tanzania. The municipality lies between latitudes 07°48′ - 08°31′ South and longitudes 30°29′ - 31°49′ East, covering approximately 1,329 km² and serving a rapidly growing urban population exceeding 300,000 residents (National Bureau of Statistics [NBS], 2022). The treatment facility comprises two anaerobic ponds functioning as primary treatment units followed by a horizontal subsurface-flow constructed wetland designed to provide secondary and tertiary polishing prior to effluent discharge (Sumbawanga Municipal Council, 2019). The system represents a typical pond-wetland configuration commonly adopted in Tanzanian municipalities due to land availability and low operational cost considerations (Mara, 1993).

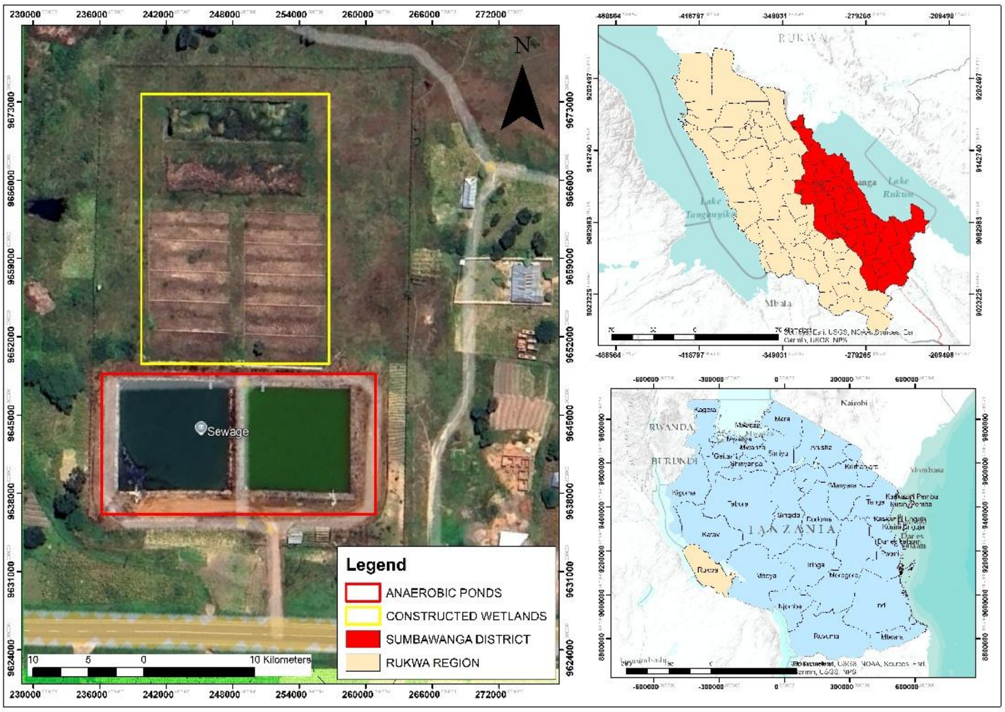

Figure 1: Location of the study area

2.2. Research Design

A quantitative cross-sectional survey design was employed to assess the wastewater quality parameters at the Sumbawanga Municipal Treatment Plant. This design was selected to enable systematic collection and analysis of influent and effluent samples across different treatment stages at a specific point in time, while allowing for statistical comparison of pollutant concentrations against national and international discharge standards (Kumar, 2010). Physical, chemical, and microbiological parameters were analyzed according to Standard Methods (APHA, 2020) and compared with Tanzania Bureau of Standards effluent discharge limits (TBS, 2019) and WHO guidelines for wastewater reuse (WHO, 2006). Treatment efficiency was calculated using percentage removal equations, and statistical significance of differences between treatment stages was evaluated using ANOVA at a 95% confidence level (Kumar, 2010).

2.3. Sampling Strategy

Wastewater samples were collected from three critical treatment points: raw influent entering the anaerobic ponds, effluent leaving the anaerobic ponds (which is also the inlet to the wetland), and final effluent from the constructed wetland. Sampling was conducted twice daily (morning and evening) for six consecutive days from 12 to 17 January 2026 capture potential diurnal variations in wastewater characteristics, consistent with recommended wastewater

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https://www.jisem-journal.com/
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monitoring practices (Metcalf & Eddy, 2014). Clean, sterilized 5-liter sampling bottles were used for sample collection, and each sample was clearly labeled with date, time, sampling location, and relevant field conditions including prevailing weather. Immediately after collection, samples were securely sealed, stored in cooled containers, and transported to the laboratory for analysis within 24 hours to minimize physicochemical and biological degradation, in accordance with standard methods for wastewater sample preservation and handling (APHA, 2020). Proper sample handling, preservation, and timely analysis were critical to ensure the accuracy and reliability of laboratory results for subsequent treatment performance assessment and design feasibility evaluation.

2.4. Laboratory Analysis

Wastewater characterization was conducted in accordance with Standard Methods for the Examination of Water and Wastewater and the Tanzania Bureau of Standards effluent discharge guidelines (APHA, 2020; TBS, 2019). Physical parameters including pH, temperature, electrical conductivity (EC), and total dissolved solids (TDS) were analyzed using calibrated meters, while total suspended solids (TSS) and turbidity were determined gravimetrically and by nephelometry, respectively, following standard protocols (APHA, 2020; Metcalf & Eddy, 2014).

Organic pollution indicators, namely five-day biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD), were determined using the standard incubation method and closed reflux titrimetric method, respectively, in accordance with established laboratory procedures (Metcalf & Eddy, 2014; TBS, 2019). Nutrient concentrations, including nitrate (NO_3^-), ammonia (NH_4^+), and phosphate (PO_4^{3-}), were assessed using spectrophotometric techniques as specified in standard methods (APHA, 2020).

Microbiological assessment of faecal coliforms was performed using the membrane filtration method, which is widely recognized as a reliable indicator of faecal contamination in wastewater systems (APHA, 2020; TBS, 2019). All analytical results were compiled and compared with permissible effluent discharge limits specified in TZS 860:2019 (TBS, 2019) and WHO guidelines for the safe use of wastewater (WHO, 2006) to provide both national and international compliance benchmarks.

2.5. Treatment Performance Evaluation

Treatment performance was evaluated using percentage removal efficiency, calculated as the difference between influent and effluent concentrations divided by influent concentration and expressed as a percentage as shown in Eq 1.

$$Percentage\ Removal\ Efficiency = \left(\frac{Influent\ Value - Effluent\ Value}{Influent\ Value}\right) \times 100 \qquad (1)$$

Where;

Influent Value - Concentration of the raw wastewater entering the system.

Effluent Value - Concentration of the wastewater after the system.

This method provides a standardized quantitative measure of treatment effectiveness and is widely applied in wastewater performance evaluation studies (Metcalf & Eddy, 2014). Removal efficiency was calculated for each parameter across treatment stages to determine pollutant reduction levels and identify performance gaps.

Statistical analysis was conducted using complementary statistical tools to assess the significance of differences between influent and effluent concentrations across treatment stages. Descriptive statistics, including mean and standard deviation, were computed to summarize the central tendency and variability of all measured parameters. A one-way ANOVA test was applied to evaluate whether observed concentration reductions between treatment stages were statistically significant at a 95% confidence level ($\alpha = 0.05$), with p-values less than 0.05 considered statistically significant (Montgomery, 2017). Additionally, Pearson correlation analysis was performed to evaluate the strength and direction of linear relationships between influent and effluent concentrations at each treatment stage, as well as between selected parameter pairs within each stage, with statistical significance similarly assessed at $\alpha = 0.05$ ($n = 6$). The statistical evaluation provided an empirical basis for determining whether observed treatment improvements were attributable to system performance rather than random variability.

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3. RESULTS

3.1. Characteristics of Raw Wastewater

The average physicochemical and microbiological characteristics of wastewater at the raw influent stage and final constructed wetland effluent, compared against TBS (TZS 860:2019) and WHO discharge standards, are presented in Table 1. The raw influent exhibited consistently high concentrations of organic matter, suspended solids, nutrients, and faecal indicators across all six sampling days.

Table 1: Summary of wastewater quality parameters at raw influent and final effluent stages compared with TBS and WHO discharge standards.

Parameter	Unit	Overall inlet	Overall outlet	TBS Limit	WHO Limits	Performance Indicator
pH		6.8 ± 0.3	7.1 ± 0.19	6.5 - 8.5	6–9	PASS
TDS	mg/L	962.2 ± 106.8	1017 ± 100.3	100	500	FAIL
EC	μ/cm	1924 ± 213.5	2034 ± 200.3	1000	–	FAIL
Temperature	°C	23.5 ± 1.6	22.9 ± 1.39	20 - 35	–	PASS
TSS	mg/L	373 ± 23.8	68.8 ± 20.5	100	50	PASS
Turbidity	NTU	47.7 ± 5	16.3 ± 5.9	300	5	PASS
BOD	mg/L	688.8 ± 95.7	59.4 ± 35.2	30	30	FAIL
COD	mg/L	1074 ± 130.5	107.7 ± 83	60	125	FAIL
Nitrate	mg/L	376.9 ± 85.5	173.8 ± 49.1	15	10	FAIL
Ammonium	mg/L	123.6 ± 18.4	122.3 ± 15.4	10	–	FAIL
Phosphate	mg/L	60.2 ± 11.5	29.7 ± 8.7	6	2	FAIL
Faecal Coliforms	$\times 10^3$ CFU/100 ml	33.5 ± 4.6	12.5	1	<1	FAIL

3.2. Performance of Anaerobic Ponds (Primary Treatment)

3.2.1. Organic Matter Removal

The anaerobic ponds demonstrated substantial removal of organic pollutants. The average BOD_5 removal efficiency was 70.6%, while COD removal averaged 71.6%. Influent BOD_5 concentrations ranging from 574 - 799 mg/L decreased to 116 - 334 mg/L in the effluent, and COD concentrations declined from 953 - 1296 mg/L to 128 - 483 mg/L (Figure 2). Statistical analysis using paired ANOVA-test confirmed that these reductions were significant ($p < 0.05$), indicating that the anaerobic ponds effectively stabilized biodegradable organic matter. Such removal efficiencies are consistent with reported performance of well-functioning anaerobic ponds under tropical temperature conditions, where elevated temperatures enhance microbial degradation rates (Metcalf & Eddy, 2014)

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2026, 11(3s)
e-ISSN: 2468-4376
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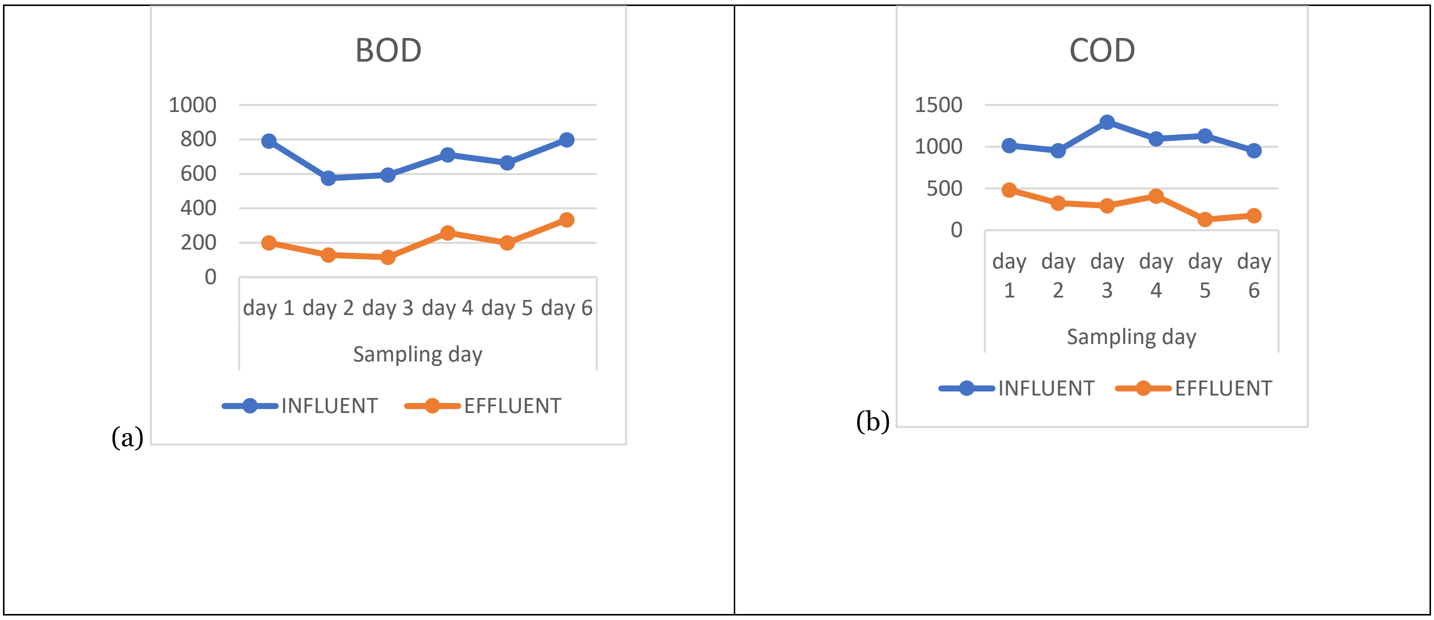

Figure 2: Variation of (a) BOD and (b) COD pollutants with time in Anaerobic Ponds at the influent and effluent

3.2.2. Suspended Solids and Turbidity

The anaerobic ponds achieved an average TSS removal efficiency of 47% and turbidity removal efficiency of 26.6% (Figure 3). The reduction in TSS was statistically significant ($p < 0.05$), demonstrating effective sedimentation of particulate matter within the pond system. The relatively lower turbidity removal compared to TSS removal suggests the persistence of fine colloidal particles that may not settle efficiently under existing hydraulic retention conditions. These findings indicate that while sedimentation processes were functional, they were insufficient to achieve complete clarification of the wastewater.

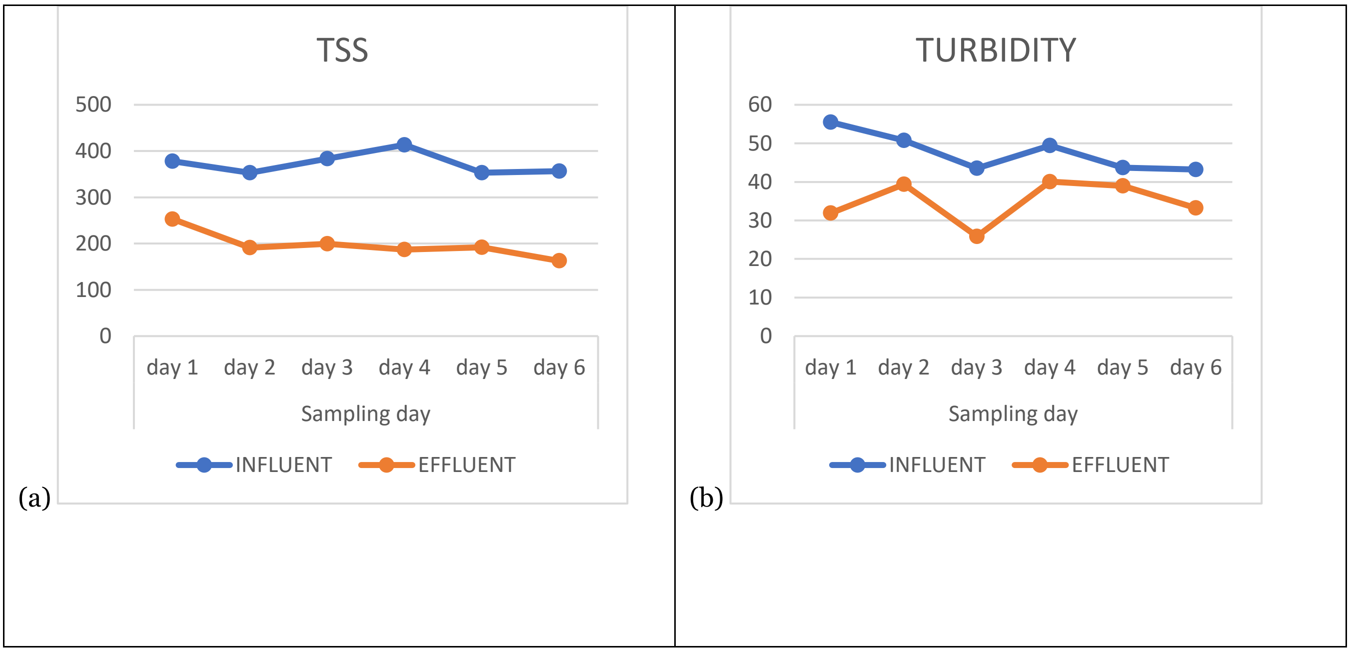

Figure 3:Variation of pollutants with time in anaerobic pond (a) TSS and (b) Turbidity

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3.2.3. Nutrient Dynamics

Nutrient removal within the anaerobic ponds was limited. The average nitrate (NO_3^-) removal efficiency was only 12%, indicating minimal denitrification activity. Furthermore, ammonia (NH_4^+) concentrations slightly increased in the effluent, resulting in a low average ammonium removal efficiency of 15.3 % (Figure 4). The increase in ammonia is attributed to anaerobic mineralization of organic nitrogen and the absence of aerobic nitrification processes within the anaerobic environment. These results confirm that anaerobic ponds primarily facilitate organic matter degradation rather than nutrient removal, as nitrification requires aerobic conditions that are absent in strictly anaerobic systems.

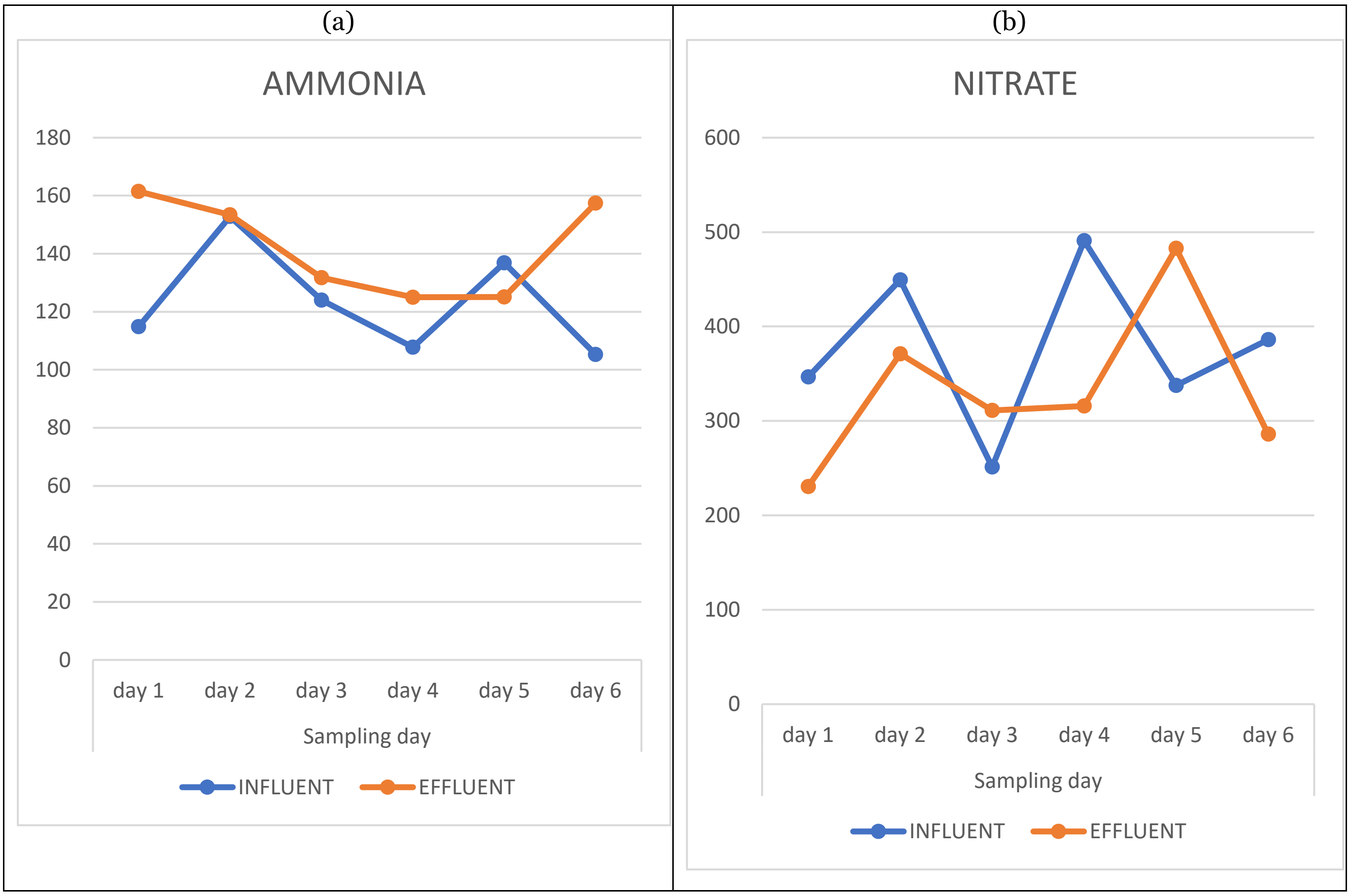

Figure 4: Variation of pollutants in anaerobic pond with time at the influent and effluent (a) $NH4^+$ and (b) NO^-_3

3.3. Performance of Constructed Wetland (Secondary / Tertiary Unit)

The horizontal subsurface-flow constructed wetland provided additional polishing of the anaerobic pond effluent. Final effluent BOD_5 concentrations averaged 59.4 ± 35.2 mg/L and COD averaged 107.7 ± 83 mg/L, representing further reductions compared to anaerobic pond effluent (Figure 5). However, despite these improvements, BOD_5 concentrations remained above the Tanzania Bureau of Standards discharge limit of 30 mg/L (TBS, 2019). This suggests that while the wetland enhanced organic matter removal, it did not provide sufficient polishing capacity to achieve full regulatory compliance.

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e-ISSN: 2468-4376
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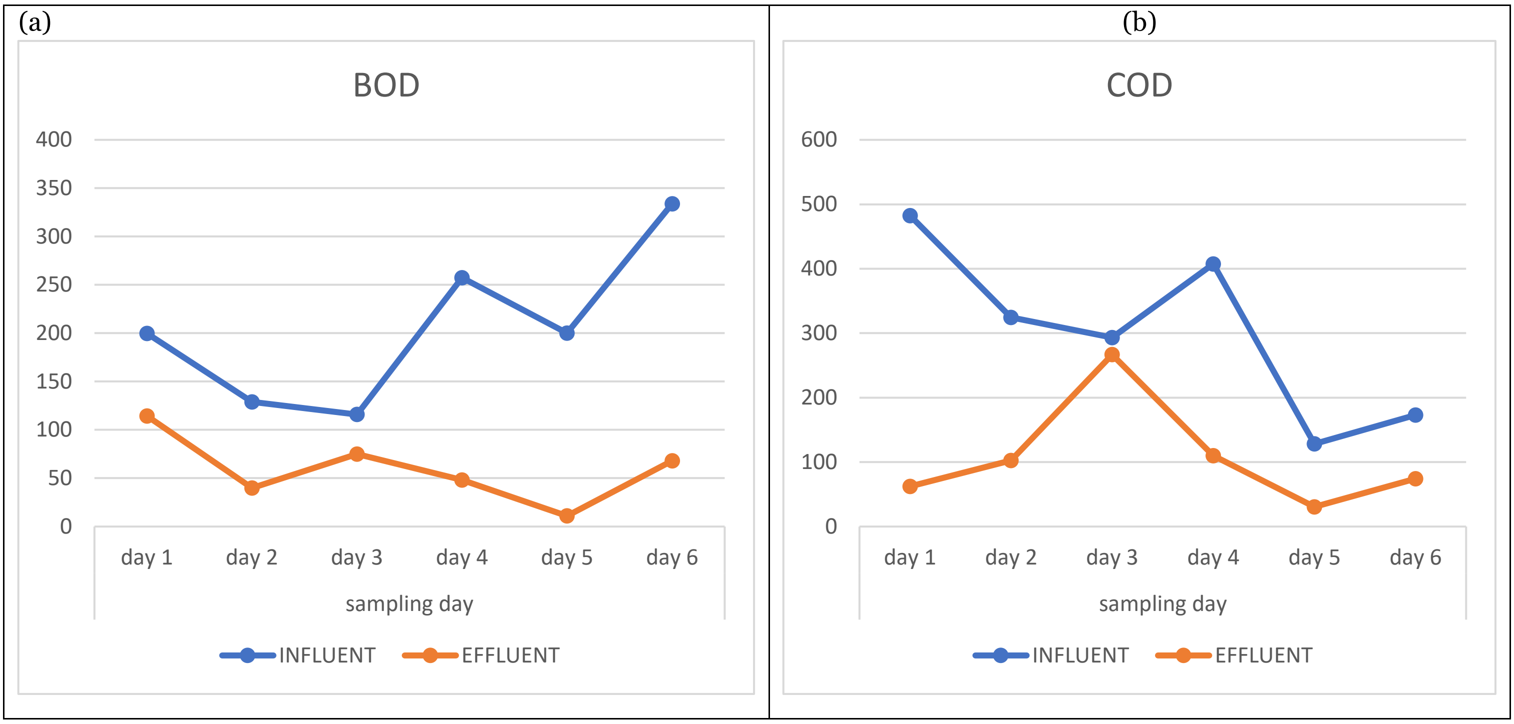

Figure 5: Variation of (a) BOD and (b) COD pollutants with time in CW at the influent and effluent

Suspended solids were reduced to 68.8 ± 20.5 mg/L, meeting the TBS limit of 100 mg/L (Figure 6). This demonstrates that the constructed wetland effectively improved clarification through filtration, sedimentation, and plant-mediated processes typical of subsurface-flow systems. The improvement highlights the complementary role of wetlands in reducing particulate matter after primary treatment.

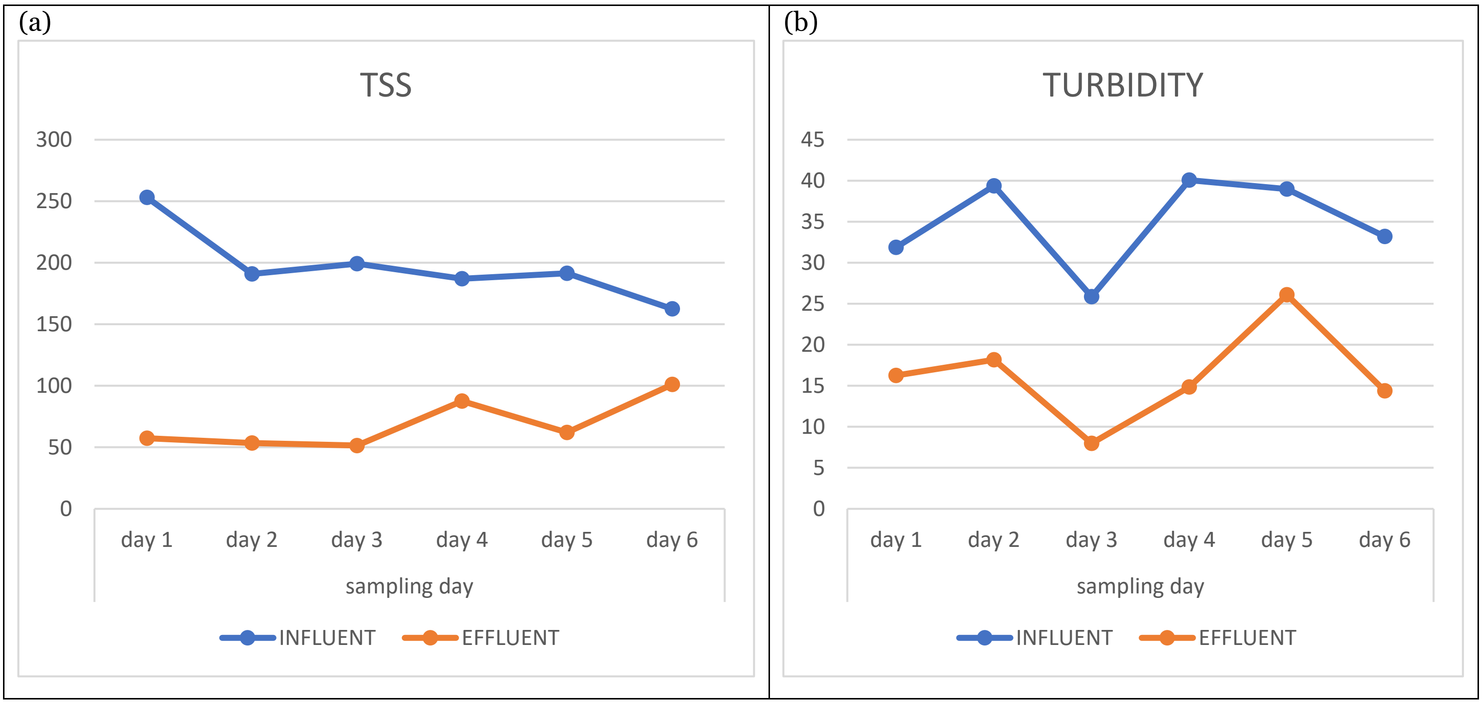

Figure 6: Variation of (a) TSS and (b) Turbidity pollutants with time in CW at the influent and effluent

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e-ISSN: 2468-4376
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Nutrient removal improved within the wetland compared to the anaerobic ponds. Nitrate removal increased to 46.8% relative to anaerobic effluent, indicating partial nitrification - denitrification processes occurring within the wetland media. Nevertheless, final nitrate concentrations remained elevated relative to environmental expectations. Phosphorus concentrations decreased from 60.2 mg/L in raw influent to 29.7 mg/L in final effluent, but this still exceeded the discharge limit of 6 mg/L established by TZS 860:2019 (TBS, 2019) (Figure 7). The limited phosphorus removal suggests insufficient adsorption capacity within the wetland substrate or absence of enhanced chemical precipitation mechanisms.

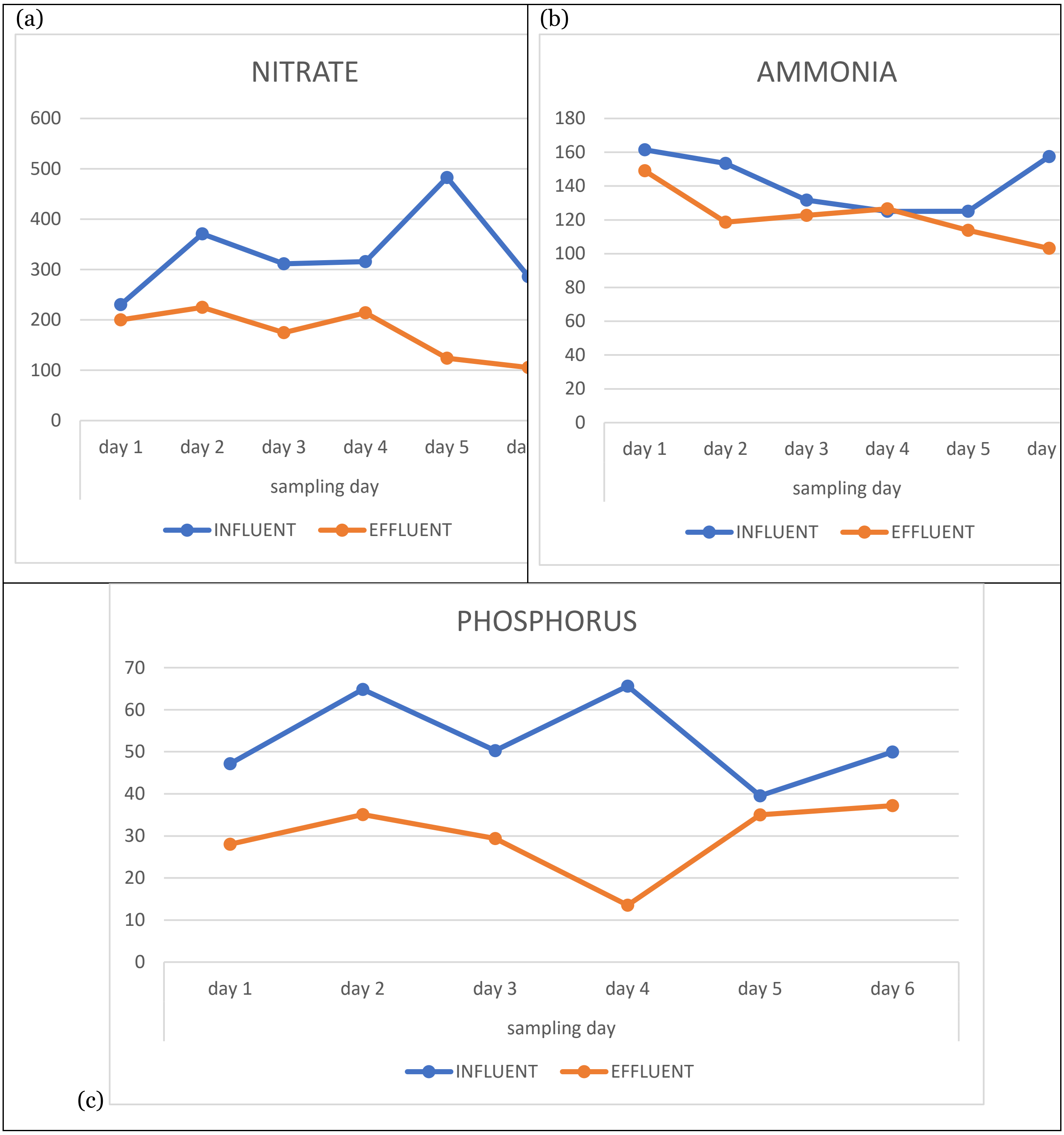

Figure 7: Variation of (a) NO_3^-, (b) NH_4^+ and (c) PO_4^{3-}pollutants with time in CW at the influent and effluent.

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e-ISSN: 2468-4376
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Faecal coliform concentrations decreased from 33.5 ×10³ CFU/100 ml in raw influent to 12.5 ×10³ CFU/100 ml in final effluent. Although this represents significant pathogen reduction, the final concentration remained substantially higher than the permissible limit of 1,000 CFU/100 ml (TBS, 2019). Subsurface-flow wetlands may have limited sunlight exposure and shorter effective retention times, which can reduce pathogen inactivation efficiency compared to maturation ponds.

3.4. Overall System Pearson Correlation Analysis

To evaluate whether raw influent loading conditions determined the quality of the final treated effluent across the entire treatment system, Pearson correlation analysis was conducted between raw influent and constructed wetland effluent concentrations for all eight measured parameters across the six sampling days. This analysis treated the anaerobic pond and constructed wetland as a single integrated unit, capturing the combined buffering effect of both treatment stages. Results are presented in Table 2.

Table 2: Pearson correlation coefficients (r). t-statistics and p-values for relationships between raw influent and final constructed wetland effluent concentrations ($n = 6$; $\alpha = 0.05$; $df = 4$)

Parameter	Unit	r	p-value	t-statistic	n
TSS	mg/L	+0.173	0.743	0.351	6
Turbidity	NTU	+0.049	0.926	0.099	6
BOD_5	mg/L	+0.491	0.323	1.127	6
COD	mg/L	+0.708	0.116	2.002	6
Nitrate	mg/L	+0.413	0.416	0.908	6
Ammonia	mg/L	−0.117	0.826	−0.235	6
Phosphorus	mg/L	−0.182	0.730	−0.370	6
FC	×10³ CFU/100 ml	+0.695	0.125	1.934	6
n = 6 sampling days; α = 0.05; df = 4; no correlations were statistically significant (all p > 0.05).					

As shown in Table 2, no statistically significant Pearson correlations were detected between raw influent and final effluent concentrations for any parameter at the 95% confidence level (all $p > 0.05$), indicating that the integrated two-stage system disrupted direct loading to effluent relationships across the overall treatment train. Physical parameters showed the weakest correlations (TSS: $r = +0.173$, $p = 0.743$; turbidity: $r = +0.049$, $p = 0.926$), reflecting consistent particulate removal independent of influent variability, consistent with the compliance of final effluent TSS (68.8 ± 20.5 mg/L) with the TBS limit of 100 mg/L (TZS 860:2019). Nutrient parameters also showed non-significant and largely negative coefficients (ammonia: $r = -0.117$, $p = 0.826$; phosphorus: $r = -0.182$, $p = 0.730$), confirming that internal biogeochemical processes; anaerobic mineralization, incomplete nitrification, and substrate adsorption governed final nutrient concentrations rather than influent loading (Tchobanoglous et al., 2014; Metcalf & Eddy, 2014).

COD and faecal coliforms showed the strongest overall correlations ($r = +0.708$, $p = 0.116$ and $r = +0.695$, $p = 0.125$, respectively), consistent with their statistically significant stage-level correlations for faecal coliforms (anaerobic pond: $r = +0.828$, $p = 0.042$; constructed wetland: $r = +0.877$, $p = 0.022$), indicating persistent but attenuated loading dependency across the full system. Overall, the results confirm that while the integrated system provided effective buffering for physical parameters and nutrients, its capacity to buffer organic matter and pathogen loading was insufficient for consistent effluent compliance, reinforcing the need for enhanced tertiary treatment.

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e-ISSN: 2468-4376
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4. DISCUSSION

The overall performance for each parameter in the treatment system at Sumbawanga Municipal has been shown below and discussed below (Figure 8);

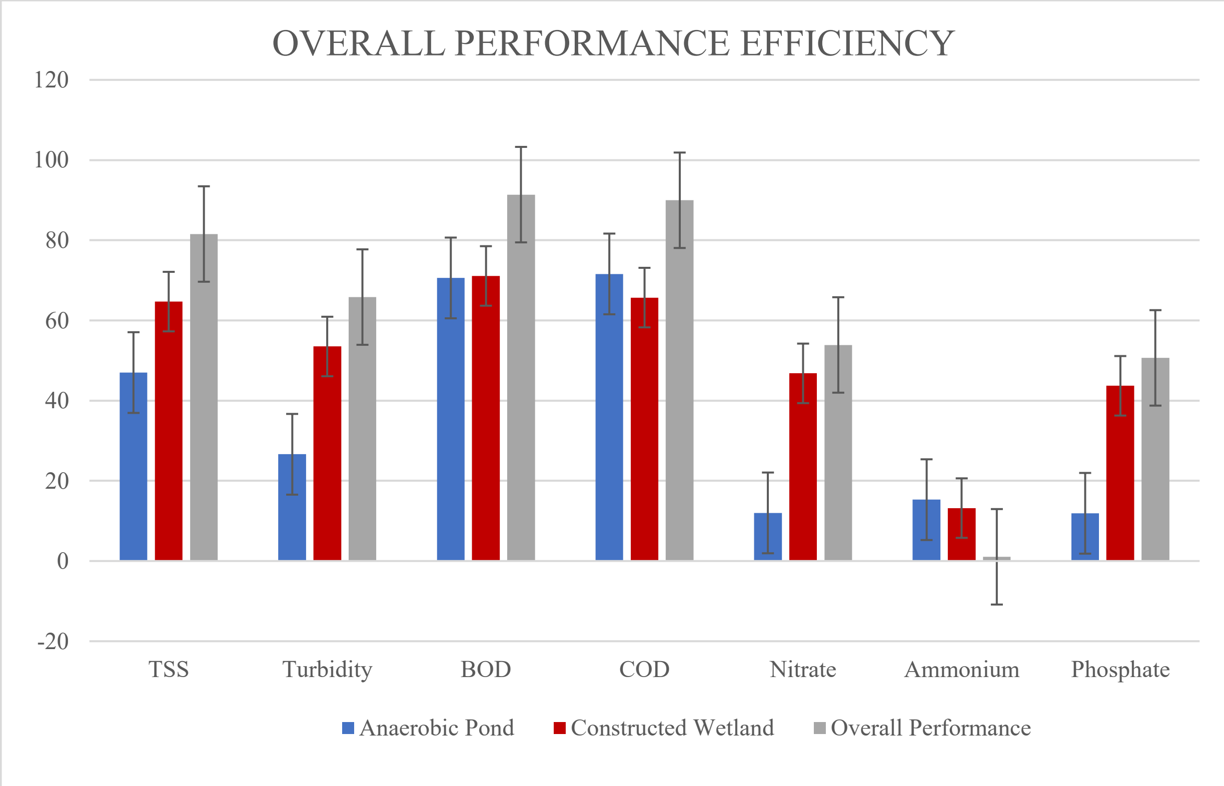

Figure 8: Average performance efficiency of the integrated system for various key parameters

4.1. Organic Matter Removal Efficiency

The anaerobic ponds achieved removal efficiencies exceeding 70% for both BOD_5 and COD, consistent with expected performance of stabilization ponds operating under tropical climatic conditions. Wastewater temperatures ranging between 21-26°C likely enhanced anaerobic microbial activity and organic matter degradation rates. However, despite significant organic removal, final effluent BOD_5 concentrations remained nearly double the regulatory limit. This indicates that the existing system lacks sufficient tertiary polishing capacity to achieve complete compliance and suggests that additional treatment enhancement is required.

4.2. Nutrient Removal Limitations

Nutrient removal performance was inadequate (46.8%) across both treatment units. Limited nitrification within anaerobic ponds and incomplete denitrification within the constructed wetland contributed to persistently high nitrate and ammonia concentrations. Effective nitrogen removal requires alternating aerobic and anoxic conditions to support nitrification and denitrification cycles, which appear insufficiently developed in the current system configuration (Tchobanoglous et al., 2014). Similarly, phosphorus removal remained minimal, likely due to limited adsorption capacity of the wetland substrate and absence of chemical dosing mechanisms. These findings confirm that the current pond-wetland configuration is not optimized for advanced nutrient control.

4.3. Pathogen Removal Challenges

Although substantial reductions in faecal coliform concentrations were observed, final levels exceeded discharge standards. This suggests inadequate retention time, potential hydraulic short-circuiting, or insufficient exposure to environmental stressors such as ultraviolet radiation, which enhance pathogen inactivation in surface systems (Mara,

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2004). Subsurface-flow wetlands, while effective for organic and suspended solids removal, may exhibit lower pathogen removal efficiencies compared to maturation ponds due to reduced sunlight penetration and limited predation effects. Consequently, public health risks remain significant if effluent is discharged into receiving water bodies without further disinfection.

4.4. Regulatory Compliance Assessment

Comparison of final effluent quality with Tanzania Bureau of Standards (TZS 860:2019) revealed that only TSS met the permissible discharge limit of 100 mg/L. BOD_5 (59.4 mg/L), COD (107.7 mg/L), phosphorus (29.7 mg/L), and faecal coliforms (12,500 CFU/100 ml) exceeded regulatory thresholds (TBS, 2019) (Table 1). This non-compliance underscores the need for targeted tertiary treatment enhancement to improve effluent quality and protect receiving water bodies from environmental degradation.

5. IMPLICATION FOR EFFLUENT OPTIMIZATION

The performance assessment of the Sumbawanga Municipal Wastewater Treatment Plant reveals critical insights for optimizing effluent quality. While the integrated anaerobic pond-constructed wetland system achieved substantial organic matter reduction (BOD_5 removal: 70.6% in anaerobic ponds; 71.1% in constructed wetland), the final effluent failed to meet Tanzania Bureau of Standards discharge limits for multiple parameters. Final effluent concentrations of BOD_5 (59.4 mg/L), COD (107.7 mg/L), nitrate (173.8 mg/L), ammonia (122.3 mg/L), phosphate (29.7 mg/L), and faecal coliforms (12,500 CFU/100 ml) all exceeded TZS 860:2019 permissible limits (TBS, 2019). Only pH, temperature, TSS, and turbidity achieved compliance.

These findings demonstrate that the current treatment configuration, while effective for primary organic removal and solids separation, possesses inherent limitations in achieving comprehensive pollutant reduction. Specifically, the system exhibits three critical performance gaps: (1) insufficient aerobic conditions to support complete nitrification, (2) inadequate denitrification capacity for nitrogen removal, (3) limited phosphorus adsorption mechanisms, and (4) suboptimal pathogen inactivation due to reduced sunlight exposure in subsurface-flow wetlands.

The persistent non-compliance with nutrient and microbiological standards poses significant environmental and public health risks. Elevated nutrient concentrations in receiving water bodies may precipitate eutrophication, while elevated faecal coliform levels indicate potential pathogen presence, threatening downstream water users and aquatic ecosystem integrity. These risks are particularly concerning given Sumbawanga projected population growth to approximately 400,000 by 2026, which will inevitably increase wastewater loading and potentially exacerbate current performance deficiencies (NBS, 2022).

The performance gaps identified in this study provide clear justification for investigating tertiary treatment enhancements. Rock-filter systems represent a promising low-cost polishing technology suitable for integration with existing pond-wetland configurations. Previous studies have demonstrated that rock filters can achieve substantial additional removal of residual BOD, suspended solids, and pathogens through attached-growth biological processes and physical filtration mechanisms (Al-Sa'ed et al., 2011; Ghawi, 2018). Ghawi (2018) reported removal efficiencies exceeding 94% for BOD, COD, and TSS in rock-filter systems, suggesting potential for achieving regulatory compliance when applied as a post-treatment unit.

The economic implications of such optimization are equally important. Given that the existing infrastructure already provides significant organic removal at low operational cost, adding a rock-filter unit could represent a cost-effective strategy for achieving compliance without complete system replacement. The passive nature of rock-filter operation, requiring minimal energy inputs and operator expertise, aligns with the operational constraints typical of municipal wastewater systems in developing regions. Therefore, systematic evaluation of rock-filter performance using site-specific effluent from Sumbawanga Municipal, coupled with comprehensive cost-benefit analysis, constitutes the logical next phase of the research.

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6. CONCLUSION

This study evaluated the treatment performance of the integrated anaerobic pond and constructed wetland system at Sumbawanga Municipal Wastewater Treatment Plant through comprehensive characterization of wastewater quality across all treatment stages. The raw influent exhibited characteristics typical of high-strength municipal wastewater, with BOD_5 averaging 688.8 mg/L, COD averaging 1074 mg/L, and substantial nutrient and pathogen loads, confirming the necessity for effective multi-stage treatment.

The anaerobic ponds demonstrated effective primary treatment, achieving BOD_5 and COD removal efficiencies of 70.6% and 71.6%, respectively, with statistically significant reductions ($p < 0.05$) attributable to enhanced anaerobic degradation under tropical temperature conditions (21–26°C). However, nutrient removal within this stage was minimal, with nitrate reduction below 12% and a net increase in ammonia concentrations due to organic nitrogen mineralization under anoxic conditions. These findings confirm that anaerobic ponds, while effective for organic stabilization, are inherently limited in nutrient removal capacity.

The horizontal subsurface-flow constructed wetland provided additional polishing, improving effluent quality across all parameters. TSS concentrations were reduced to 68.8 mg/L, achieving compliance with the TBS discharge limit of 100 mg/L, demonstrating effective filtration and sedimentation mechanisms. BOD_5 and COD were further reduced to 59.4 mg/L and 107.7 mg/L, respectively, representing substantial additional removal. Nutrient removal improved within the wetland, with nitrate and phosphate reductions of approximately 46.8% and 43.7% relative to anaerobic effluent, indicating partial nitrification-denitrification and adsorption processes. Faecal coliform concentrations decreased from 33.5×10^3 to 12.5×10^3 CFU/100 ml, reflecting pathogen reduction through filtration and biological mechanisms.

Despite these improvements, the final effluent failed to meet TZS 860:2019 discharge standards for multiple critical parameters. Only pH, temperature, TSS, and turbidity achieved compliance, while BOD_5, COD, nitrate, ammonia, phosphate, and faecal coliforms all exceeded permissible limits. This persistent non-compliance underscores the insufficient tertiary polishing capacity of the current system configuration to achieve comprehensive regulatory compliance, particularly for nutrients and pathogens.

Therefore, the study successfully established a quantitative technical baseline characterizing current system performance and identifying specific treatment gaps requiring intervention. The documented performance deficiencies provide clear justification for investigating a low-cost polishing technology as a potential optimization strategy.

Furthermore, the results highlight the broader implications for municipal wastewater management in rapidly urbanizing Tanzanian contexts. The combination of population growth projections, increasing wastewater loads, and stringent regulatory requirements necessitates proactive optimization of existing infrastructure. The performance data generated from this study contribute to the limited body of site-specific evidence on pond-wetland system performance in Sub-Saharan Africa and provide an empirical foundation for evidence-based decision-making regarding treatment upgrades.

Availability of data and materials

All relevant data are included in the paper

Declaration

I have nothing to declare

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethical approval

All work complies with ethical standards.

Journal of Information Systems Engineering and Management
2026, 11(3s)
e-ISSN: 2468-4376
https://www.jisem-journal.com/

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Consent to publication

The authors give their permission to publish

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