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ORIGINAL RESEARCH ARTICLE

Stage-wise performance evaluation of the Kalobe waste stabilization ponds in Mbeya, Tanzania: Efficiency in organic load and nutrient removal

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Abstract: Globally, waste stabilization ponds (WSPs) in warm climates have demonstrated high treatment efficiencies for organic matter and suspended solids. This study evaluates the stage-wise performance and overall treatment efficiency of the Kalobe WSPs in Mbeya city, Tanzania, which treat approximately 15,000–18,000 m^3/day of mixed domestic and industrial wastewater, compared with a design capacity of 28,800 m^3/day. The system comprises anaerobic, facultative, and maturation ponds operating in parallel. Field sampling and laboratory analysis were conducted to determine pollutant concentrations across each treatment stage, focusing on key parameters including biochemical oxygen demand (BOD), 5-day, chemical oxygen demand (COD), total suspended solids (TSSs), ammonia, nitrite, and total dissolved solids (TDS). Results revealed that while the WSP system demonstrated high removal efficiencies for organic and solid pollutants, achieving reductions of 58.1% for BOD, 87.3% for COD, and 87.2% for TSS, its performance in nutrient and dissolved solids removal remained limited. Ammonia was moderately reduced (80.5%), whereas nitrite and TDS exhibited low removal efficiencies of 17.4% and 13.7%, respectively. The final effluent BOD (39 mg/L) and COD (78 mg/L) exceeded Tanzania's national discharge standards, indicating partial non-compliance. The study also found that flow variations, particularly from industrial contributors such as Pepsi and Tanzania Breweries Limited, introduced intermittent hydraulic shocks, which may impair treatment consistency. The findings highlight the need for system upgrades, enhanced industrial pre-treatment enforcement, and the integration of post-treatment units to improve nutrient polishing. Overall, while Kalobe WSPs remain a cost-effective solution, strategic interventions are necessary to ensure sustained regulatory compliance and environmental protection.

Keywords: Waste stabilization ponds; Treatment efficiency; Organic load reduction; Nutrient removal; Anaerobic ponds; Facultative ponds; Maturation ponds

1. Introduction

Effective wastewater treatment is essential for safeguarding public health and environmental quality, particularly in urban centers of low- and middle-income countries where infrastructure expansion often lags behind population growth.[1-3] Urban wastewater management in Sub-Saharan Africa is often constrained by limited financial resources, poor planning, and outdated infrastructure, leading to frequent treatment failures and environmental contamination.[4] Waste stabilization ponds (WSPs) have gained prominence as an affordable, low-maintenance solution for municipal wastewater treatment in such contexts due to their reliance on natural treatment mechanisms, minimal operational requirements, and resilience to hydraulic and organic load fluctuations.[5,6] Their design and application follow well-established principles suited to tropical climates, making them ideal for many Sub-Saharan African countries.[7,8]

WSPs are widely adopted in developing regions because of their simple operation and ability to handle variable influent loads without the need for complex mechanical equipment.[6] In Tanzania, many urban areas rely on WSPs as the primary treatment technology. Mbeya city, located in the southern highlands of Tanzania, is served by the Kalobe WSPs, which treat a mixture of domestic and industrial wastewater. The system was designed to accommodate 28,800 m^3/day of wastewater; however, actual inflows vary between 15,000 and 18,000 m^3/day depending on rainfall and industrial activity. Major contributors to the influent load include large beverage industries such as Tanzania Breweries Limited (TBL), Coca-Cola Kwanza, and Pepsi, which are required to pre-treat their wastewater before discharging it into the municipal system.[9] However, evidence suggests that these pre-treatment processes are inconsistently effective, resulting in high influent organic and nutrient loads that compromise the WSP's performance.[10,11]

The Kalobe WSP system comprises a series of anaerobic, facultative, and maturation ponds arranged sequentially. These primary units are complemented by a preliminary screening chamber, grit channel, sludge drying beds, and a natural wetland that serves as a polishing component. Anaerobic ponds facilitate sedimentation and biological degradation under anoxic conditions, while facultative ponds support both aerobic and anaerobic processes. Maturation ponds provide final polishing, primarily targeting pathogen and nutrient reduction before discharge. While the system is theoretically capable of achieving significant reductions in biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSSs), its performance in terms of nutrient removal and final effluent quality has raised concerns in recent years.[7,12]

Globally, WSPs in warm climates have demonstrated high treatment efficiencies for organic matter (BOD, COD) and suspended solids. However, challenges persist in nutrient and pathogen removal.[6,7,13] In Sub-Saharan cities, treated effluent from WSPs is sometimes reused for irrigation and aquaculture, necessitating stricter effluent standards to protect public health.[14] Ammonia removal in WSPs is often temperature-dependent, and without adequate aeration or nitrification steps, most ammonia persists in the final effluent.[15] Regular sludge removal and continuous influent monitoring are essential to sustain WSP performance and prevent pond overloading.[7] At Kalobe WSPs, elevated levels of BOD, total dissolved solids (TDS), and nutrients in the final effluent indicate that process inefficiencies and intermittent shock loads from industrial discharges may be limiting the system's ability to meet Tanzania's effluent discharge standards.[16]

This study aims to assess the stage-wise performance of the Kalobe WSPs using field data collected at the inlet and outlet points of the anaerobic, facultative, and maturation ponds. Six key parameters, which are BOD, COD, TSS, ammonia (NH_3–N), nitrite (NO_2^-–N), and TDS, were analyzed to determine individual and cumulative removal efficiencies. The study further examines how flow variability, influent composition, and industrial contributions affect treatment outcomes. Findings from this evaluation are expected to inform future infrastructure upgrades, industrial compliance enforcement, and integration of tertiary treatment options to improve the overall system efficiency.

2. Materials and methods

2.1. Description of the study area

The Kalobe WSPs are located at 8°55'S, 33°28'E (UTM Zone 36S; Easting 9,014,865.14 m; Northing 544,767.03 m) in Mbeya city, situated in the southern highlands of Tanzania. This study was conducted during the dry season (April 2025); therefore, the results should be interpreted as baseline dry-season conditions rather than a full annual performance assessment. The facility receives wastewater from both municipal sources and major beverage industries, including TBL, Pepsi, and Coca-Cola Kwanza. The system comprises two anaerobic ponds, four facultative ponds, and one maturation pond, which operate in parallel to allow flexible hydraulic distribution and enhance treatment performance under variable loading conditions. This configuration enables the ponds to accommodate fluctuating industrial flows by distributing influent across multiple units rather than operating strictly in series.

Figure 1 presents the location of the study area. Photographs of the anaerobic, facultative, and maturation ponds are provided in Figure 2 to enhance visualization of the treatment process. In addition, Figure 3 illustrates the layout of the Kalobe WSP system.

The treatment process comprises three unit operations arranged as parallel trains, with serial flow within each train: Two units of anaerobic ponds (for primary sedimentation and anaerobic digestion under oxygendeficient conditions), four units of facultative ponds (for combined aerobic–anaerobic treatment, further organic degradation, suspended solids removal, and algal–bacterial oxygen transfer), and one unit of maturation pond (for final polishing and pathogen reduction before discharge). In addition, a screening chamber, a grit channel, sludge drying beds, and a natural wetland serve as preliminary and tertiary treatment components. This layout supports flexible influent distribution across ponds while maintaining stage-wise treatment within each train. Figure 3 shows the schematic layout of WSP.

2.2. Methods

2.2.1. Sampling strategy

To evaluate the stage-wise and overall performance of the Kalobe WSP system, a structured sampling strategy was developed to assess influent and effluent quality across each treatment stage. Composite grab samples were collected from four critical points within the system: The inlet point, located just upstream of the anaerobic ponds, representing untreated domestic and industrial influent; the anaerobic pond outlet, reflecting conditions after primary sedimentation and anaerobic digestion; the facultative pond outlet, situated downstream of the aerobic–anaerobic hybrid treatment zones; and the maturation pond outlet, representing the final effluent before environmental discharge.

Sampling followed the guidelines outlined by the American Public Health Association (APHA) for wastewater quality monitoring.[17] A total of 12 composite samples per point were collected over 4 weeks (May–June), covering Monday, Wednesday, and Friday each week, to account for weekly fluctuations and peak industrial discharges, a practice supported by previous WSP studies.[6,16] This 4-week monitoring period corresponds to the dry season baseline; while it provides robust insights under relatively stable hydraulic conditions, it does not capture wet-season variability. This limitation is therefore explicitly acknowledged

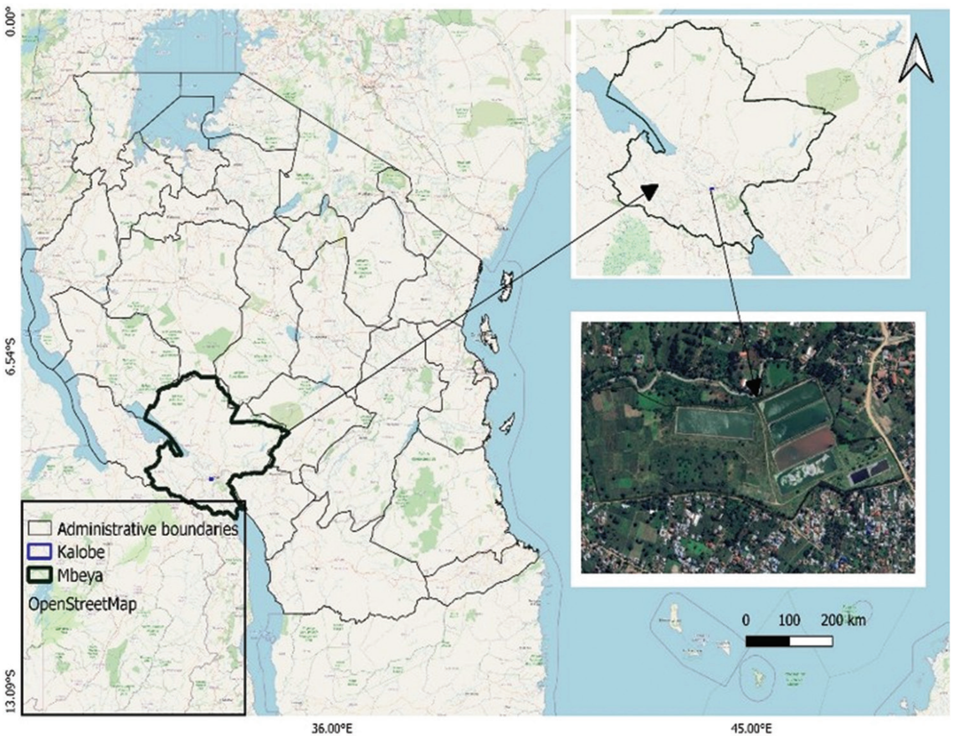

Figure 1. Location of Mbeya municipal waste stabilization ponds

in the study's conclusions. Samples were collected in sterilized high-density polyethylene bottles, stored in portable coolers at 4°C, and transported within 2 h to the Mbeya Water Quality Laboratory for analysis. Field parameters such as temperature, odor, color, and the presence of scum were also documented onsite using standardized visual indicators.[5] This strategy ensured representative and reliable data for calculating removal efficiencies and understanding temporal and spatial pollutant dynamics within the WSP system.

2.2.2. Parameters measured

The performance of the Kalobe WSP system was assessed using six key physicochemical parameters, selected based on their regulatory importance and relevance to both domestic and industrial wastewater monitoring. These parameters provide insight into organic load, solids content, and nutrient removal efficiency across the pond system.

Figure 2. Kalobe waste stabilization ponds. (A) Anaerobic ponds; (B) Facultative ponds; (c) Maturation pond.

The parameters measured included BOD, 5-day (BOD_5), which indicates the concentration of biodegradable organic matter and serves as a key measure of wastewater strength and treatment efficiency; COD, representing the total quantity of both biodegradable and non-biodegradable organic compounds; TSS, reflecting particulate matter that can settle or be filtered, and therefore indicating sedimentation performance; NH_3–N, a primary form of nitrogen relevant for assessing nitrification potential and nutrient removal; NO_2^-–N, an intermediate compound in the nitrogen cycle, whose presence can signal incomplete nitrification; and TDS, which indicate the ionic content of wastewater and may reflect industrial salt contributions or mineral solubilization.

The selection of these parameters was based on standard wastewater treatment performance indicators outlined by APHA.[17] and in accordance with Tanzanian environmental regulations.[18] Furthermore, these parameters are widely used in evaluating the efficiency of WSPs in tropical environments.[6,16] All parameters were analyzed at each of the four designated sampling points—raw influent, anaerobic pond outlet, facultative pond outlet, and final maturation pond outlet. This approach enabled the calculation of both stage-wise and overall removal efficiencies.

2.2.3. Instrumentation and laboratory methods

The physicochemical parameters (Table 1) were analyzed using standard procedures outlined in the Standard Methods for the Examination of Water and Wastewater.[17] Analyses were conducted at the Mbeya Zonal Water Quality Laboratory under controlled conditions, immediately after sample delivery, to ensure accuracy and prevent sample deterioration.

All equipment was calibrated before use using certified standards, and measurements were conducted in triplicate to ensure reproducibility. Quality assurance and control protocols were followed, including the use

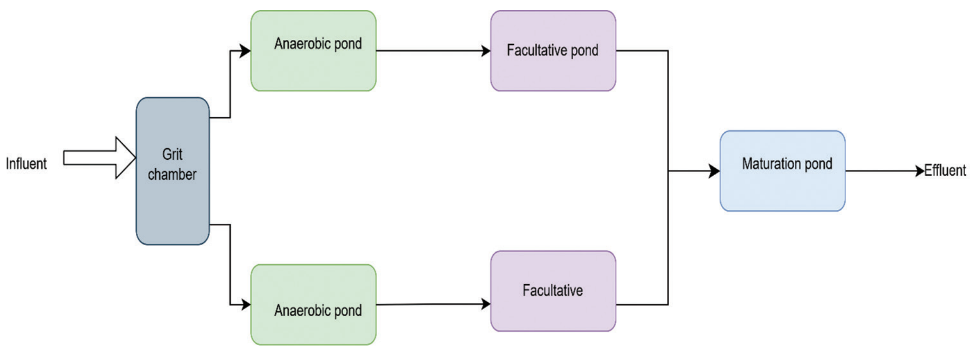

Figure 3. Schematic layout of Kalobe waste stabilization ponds.

Table 1. Analytical instruments and methods used for the analysis of wastewater quality parameters

Parameter	Analytical method	Standard method reference	Instrument used	Detection wavelength/output
BOD_5 (mg/L)	5-day incubation, dilution method	5210 B (APHA, 2017)[17]	BOD incubator+DO meter (HANNA HI9147)	DO depletion (mg/L)
COD (mg/L)	Closed reflux, colorimetric	5220 D (APHA, 2017)[17]	COD reactor (Lovibond®)+ spectrophotometer	600 nm
TSS (mg/L)	Gravimetric (drying at 105°C)	2540 D (APHA, 2017)[17]	Glass fiber filters+ Analytical balance	Mass difference (mg)
Ammonia (mg/L)	Nesslerization	4500-NH_3 C (APHA, 2017)[17]	UV-vis spectrophotometer (Hach DR 6000)	425 nm
Nitrite (mg/L)	Diazotization	4500-NO_2 B (APHA, 2017)[17]	UV-vis spectrophotometer (Hach DR 6000)	543 nm
TDS (mg/L)	Conductivity measurement	2540 C (APHA, 2017)[17]	TDS meter (Hanna HI 2300)	µS/cm converted to mg/L

Abbreviations: APHA: American Public Health Association; BOD_5: Biochemical oxygen demand, 5-day; COD: Chemical oxygen demand; DO: Dissolved oxygen; TDS: Total dissolved solids; TSS: Total suspended solids; UV-vis: Ultraviolet–visible light.

of blanks, duplicates, and spiked samples to detect contamination or analytical drift. These procedures ensured that all data collected were scientifically valid and comparable to those from other peer-reviewed studies of WSP systems in similar climatic and operational settings.[7,5]

2.3. Flow measurement and load calculations

2.3.1. Flow estimation

The Kalobe WSP system is designed to treat 28,800 m^3/day, but actual influent volumes range from 15,000 to 18,000 m^3/day, as recorded at the main inlet chamber using V-notch weirs and visual log sheets maintained by plant operators. Flow fluctuations are primarily attributed to variable domestic discharge patterns and irregular industrial loading from TBL, Coca-Cola Kwanza, and Pepsi. To estimate the average daily flow during the sampling period, recorded values over four representative weeks were averaged to obtain a typical daily influent flow of 16,500 m^3/day, aligning with seasonal operational averages reported in previous internal documents. To account for reporting variability, an uncertainty margin of ±5% was applied. These flows include contributions from the three major beverage industries (Pepsi, TBL, Coca-Cola Kwanza), which together discharged ~1,224 m^3/day during the monitoring period.

2.3.2. Pollution load calculations

Pollution load for each parameter was calculated to quantify the total mass of pollutants entering and exiting each treatment stage. This enables performance evaluation in terms of mass balance and efficiency. Pollutant loadings were calculated using the following equation.[18]

$$\text{Load}\left(\frac{\text{kg}}{\text{day}}\right)=\frac{\text{C}\times\text{Q}}{1{,}000} \tag{I}$$

Where:

- C = Concentration of the pollutant (mg/L)
- Q = Flow rate (m^3/day)
- 1,000 = Conversion factor (mg to kg)

Pollution load calculations were conducted for the six key parameters—BOD_5, COD, TSS, ammonia, nitrite, and TDS—at four defined sampling points: The inlet to the anaerobic ponds, the anaerobic pond outlet, the facultative pond outlet, and the maturation pond outlet, which represents the final discharge.

This approach allows determination of absolute removal (kg/day) at each stage and comparison against influent loads, which is more insightful than percentage removal alone, particularly under fluctuating flow regimes.[18]

2.3.3. Importance of load evaluation

Mass load evaluation is crucial in assessing real-world pond capacity, estimating sludge accumulation rates, and determining potential overload situations. Moreover, it supports long-term monitoring and decision-making related to system upgrades, desludging needs, and regulatory compliance.[18]

2.4. WSP treatment efficiency evaluation

The evaluation of treatment performance at Kalobe WSPs was conducted by analyzing the removal efficiencies of six selected parameters (BOD, COD, TSS, ammonia, nitrite, and TDS) across the three major units: Anaerobic, facultative, and maturation ponds.

2.4.1. Efficiency calculation method

The treatment efficiency for each parameter at each stage was calculated using the conventional removal efficiency formula:

$$\text{Removal efficiency}\,(\%) = \left(\frac{\text{cin-cout}}{\text{cin}}\right) \times 100 \qquad \text{(II)}$$

Where:

- Cin = Influent concentration to the unit
- Cout = Effluent concentration from the unit

This calculation was applied at two levels: (i) Stage-wise performance, covering the sequential treatment units from anaerobic to facultative to maturation ponds, and (ii) overall system performance, measured from the inlet to the final effluent. The results were expressed both as percentage removals and as mass load reductions (kg/day), using flow-weighted calculations, as described in Section 2.5.

2.4.2. Evaluation criteria

Performance was assessed against three benchmarks. First, compliance was evaluated relative to the Tanzania National Environmental Standards (URT, 2007), which specify maximum final effluent limits of BOD $\leq$ 30 mg/L, COD $\leq$ 60 mg/L, TSS $\leq$ 100 mg/L, NH_3–N $\leq$ 10 mg/L, NO_2–N $\leq$ 1 mg/L, and TDS $\leq$ 2,000 mg/L.[19] Second, results were compared to typical tropical WSP performance ranges reported in the literature, where BOD removal is generally 70–90%, COD removal 60–80%, and TSS removal 60–90%, while nutrient removals (ammonia and nitrite) tend to vary with temperature, algal activity, and hydraulic retention time (HRT).[7,20] Finally, the evaluation highlighted strengths and limitations of the Kalobe system, with particular emphasis on nutrient removal, which is often reduced in conventional WSPs that lack polishing units such as constructed wetlands or sand filtration.[18]

2.4.3. Data validation

All efficiency values were computed using the verified dataset from field measurements and laboratory analysis. Tabular summaries and graphical comparisons are presented in the results section to visually support the stage-wise trends.

2.4.4. Pollutant load contribution

Pollutant load (kg/day) for each parameter was computed using the standard mass loading equation (Equation I).

The contribution (%) of each industry to total pollutant loading was then derived by comparing each load to the total system load for BOD_5, COD, TSS, ammonia, nitrite, and TDS.

This analysis enabled the identification of industries that are primary contributors to organic, solids, and nutrient loading, helping to pinpoint the most significant sources of stress on the WSP system.

2.4.5. Application and relevance

The findings from the contribution analysis are essential for informing industrial pre-treatment compliance strategies, supporting load-based billing and regulatory mechanisms, and prioritizing pollution control interventions.

Results are presented in Section 3, alongside performance efficiency trends and compliance status.

2.5. Compliance assessment

Compliance assessment was conducted to determine whether the final effluent discharged from the Kalobe WSPs meets the 2018 Tanzanian National Effluent Discharge Standards and other international guidelines, such as the 2006 World Health Organization (WHO) recommendations for safe discharge and reuse.[19,14]

2.5.1. Standards used for compliance check

For the Tanzanian National Standards, allowable limits for key parameters include: BOD_5 $\leq$ 30 mg/L, COD $\leq$ 60 mg/L, TSS $\leq$ 100 mg/L, NH_3–N $\leq$ 10 mg/L, NO_2–N $\leq$ 1 mg/L, and TDS $\leq$ 2,000 mg/L. For WHO guidelines, parameter limits vary depending on the intended reuse (e.g., unrestricted irrigation, restricted irrigation, or discharge into surface waters).[19]

2.5.2. Approach to compliance evaluation

Compliance evaluation was performed by comparing measured effluent concentrations from the final maturation pond with the specified standards. The percentage of compliance for each parameter was determined using the following formula:

$$\text{Compliance}\,(\%) = \left(1\frac{\text{Exceedence}}{\text{Standard}}\right) \times 100 \qquad \text{(III)}$$

Where:

- Exceedance = Max (0, Effluent Concentration − Standard)

Parameters exceeding the allowable limits were flagged for further analysis, and their potential causes were investigated. These included high industrial loads, reduced HRT, or operational challenges such as sediment buildup or algal overgrowth.[5,6]

2.6. Graphical presentation

To better communicate trends and stage-wise pollutant reductions, various chart types were developed using Microsoft Excel and Python-based plotting libraries (Table 2).

These visual tools were selected to highlight treatment efficiency, assess regulatory compliance, and provide decision-makers with easily interpretable insights into system performance.

Table 2. Chart types used for graphical presentation

Chart type	Application
Vertical bar charts	For comparing influent and effluent concentrations stage-wise
Stacked bar charts	For showing cumulative removal per parameter across stages
Radar (spider) charts	For visualizing multi-parameter performance per treatment unit
Line charts	For observing seasonal/temporal variation in pollutant concentrations
Traffic-light table	To quickly indicate compliance versus non-compliance per parameter

3. Results

This section presents the validated findings from field sampling and laboratory analysis of the Kalobe WSPs in Mbeya city, Tanzania. The results are structured by treatment stage (anaerobic, facultative, and maturation) and address the core study objectives: assessing influent quality, evaluating removal efficiencies, and determining final effluent compliance with national standards.

3.1. Influent wastewater characteristics

The raw wastewater quality entering the Kalobe WSPs is summarized in Table 3. Mean influent concentrations exceeded Tanzanian discharge standards for all measured parameters, confirming the high-strength nature of the wastewater. Mean influent concentrations exceeded Tanzanian discharge standards for all measured parameters. Day-to-day variability in influent BOD and COD during the sampling campaign was statistically significant (one-way analysis of variance, $p<0.05$). These findings demonstrate the considerable organic and nutrient loads imposed on the system at the inlet.

Table 3. Influent wastewater quality characteristics entering the Kalobe waste stabilization ponds

Parameter	Influent concentration (mg/L)
Biochemical oxygen demand, 5-day	93.0
Chemical oxygen demand	612.0
Total suspended solids	320.0
Ammonia (NH_3)	15.4
Nitrite (NO_2)	0.46
Total dissolved solids	1,034.0

3.1.1. Anaerobic ponds

Samples collected at the outlet of the anaerobic ponds were analyzed to assess first-stage removal performance. The results indicate substantial reductions in COD and TSS, with moderate removal of BOD and ammonia (Table 4, Figure 4). Reductions in nitrite and TDS remained negligible.

Table 4. Performance of anaerobic ponds: Influent and effluent quality parameters

Parameter	Influent (mg/L)	Anaerobic outlet (mg/L)	% removal efficiency
BOD_5	93.0	60.60	34.84
COD	612.0	284.32	53.53
TSS	320.0	128.78	59.13
Ammonia (NH_3)	15.4	9.68	37.14
Nitrite (NO_2)	0.46	0.42	8.70
TDS	1,034.0	963.00	6.87

Abbreviations: BOD_5: Biochemical oxygen demand, 5-day; COD: Chemical oxygen demand; TDS: Total dissolved solids; TSS: Total suspended solids.

3.1.2. Facultative ponds

Following anaerobic treatment, the wastewater enters the facultative ponds for further treatment. The results show marked reductions in COD, TSS, and ammonia, while nitrite and TDS removal remained limited (Table 5 and Figure 5).

3.1.3. Maturation ponds

The final stage of treatment occurs in the maturation ponds. Effluent samples collected from the outlet of

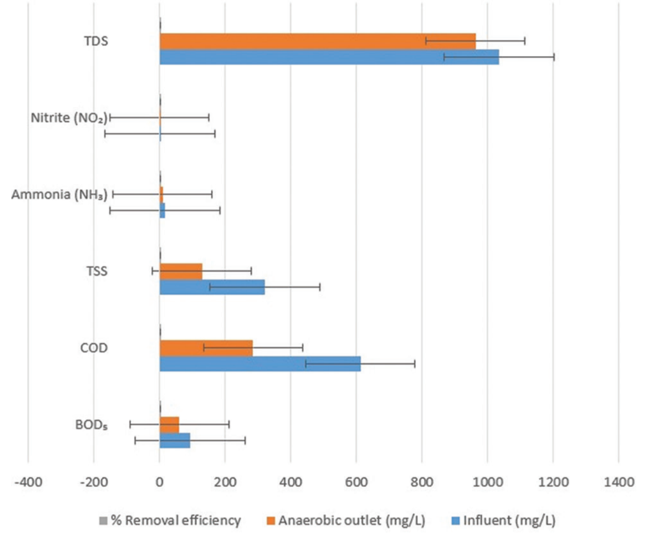

Figure 4. Anaerobic pond: Influent versus outlet concentrations

Abbreviations: BOD_5: Biochemical oxygen demand, 5-day; COD: Chemical oxygen demand; TDS: Total dissolved solids; TSS: Total suspended solids.

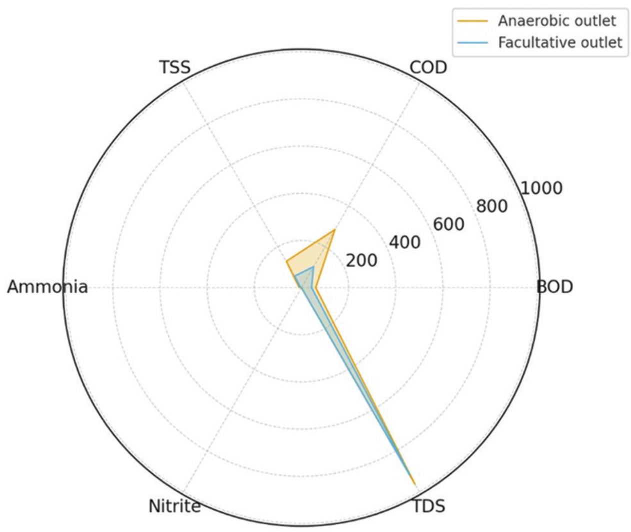

Figure 5. Facultative pond – parameter reduction

Abbreviations: COD: Chemical oxygen demand; TDS: Total dissolved solids; TSS: Total suspended solids.

this unit showed additional polishing of BOD, COD, TSS, and ammonia (Table 6 and Figure 6). Nitrite remained unchanged, while TDS removal continued to be negligible.

3.2. Overall treatment efficiency

The cumulative treatment efficiency of the Kalobe WSP system, from the anaerobic pond inlet to the maturation pond outlet, was calculated for each parameter. The

Table 5. Performance of facultative ponds: Effluent characteristics and removal efficiency

Parameter	Anaerobic outlet (mg/L)	Facultative outlet (mg/L)	% removal efficiency (this stage)
BOD_5	60.60	43.05	28.97
COD	284.32	102.27	64.02
TSS	128.78	56.67	55.99
Ammonia (NH_3)	9.68	4.91	49.28
Nitrite (NO_2)	0.42	0.38	9.52
TDS	963.00	920.40	4.42

Abbreviations: BOD_5: Biochemical oxygen demand, 5-day; COD: Chemical oxygen demand; TDS: Total dissolved solids; TSS: Total suspended solids.

Table 6. Performance of maturation ponds: Final effluent characteristics and removal efficiency

Parameter	Facultative outlet (mg/L)	Maturation outlet (mg/L)	% removal efficiency (this stage)
BOD_5	43.05	39.00	9.41
COD	102.27	78.00	23.71
TSS	56.67	41.00	27.61
Ammonia (NH_3)	4.91	3.00	38.90
Nitrite (NO_2)	0.38	0.38	0.00
TDS	920.40	892.00	3.09

Abbreviations: BOD_5: Biochemical oxygen demand, 5-day; COD: Chemical oxygen demand; TDS: Total dissolved solids; TSS: Total suspended solids.

system performed strongly in terms of COD, TSS, and ammonia removal, while BOD reductions were moderate (Table 7 and Figure 7). Nitrite and TDS removal remained poor.

3.3. Seasonal and flow variation effects

Analysis of daily industrial discharge flow data for April 2025 revealed significant fluctuations in the volumes received by Kalobe WSPs (Table 8). Peak inflows toward the end of the period coincided with temporary declines in the performance of anaerobic and facultative stages. During the highest recorded daily inflows, BOD and TSS removals were approximately 10% lower than period averages, indicating that hydraulic shocks can depress treatment efficiency.

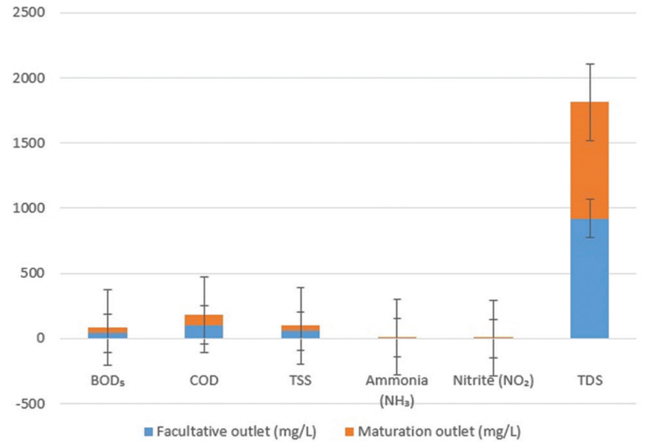

Figure 6. Maturation pond – stage-wise concentration and reduction

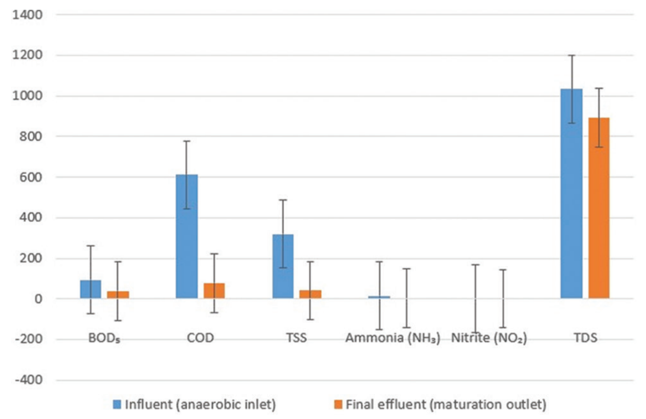

Figure 7. Overall treatment performance: Influent versus final effluent

These variations highlight that Pepsi was the largest contributor in terms of volume. Peak discharges from TBL and Pepsi were observed midweek, with certain days (e.g., April 30: TBL – 700 m^3; Pepsi – 812 m^3) showing substantial hydraulic load spikes.

Such fluctuations may lead to intermittent overloading of the treatment system, particularly affecting sedimentation and biological processes in the anaerobic and facultative stages.[21] This pattern of unregulated peak flows suggests the need to: (i) Install pre-discharge flow equalization tanks at industrial sites, (ii) coordinate discharge scheduling with the utility, and (iii) strengthen flow monitoring and regulation policies to minimize system shock-loading.

4. Discussion

The performance of the Kalobe WSPs demonstrates both the potential and the constraints of pond-based

Table 7. Cumulative removal efficiencies across the Kalobe waste stabilization pond treatment stages

Parameter	Influent (anaerobic inlet)	Final effluent (maturation outlet)	Overall removal efficiency (%)
BOD_5	93.00	39.00	58.06
COD	612.00	78.00	87.25
TSS	320.00	41.00	87.19
Ammonia (NH_3)	15.40	3.00	80.52
Nitrite (NO_2)	0.46	0.38	17.39
TDS	1,034.00	892.00	13.74

Abbreviations: BOD_5: Biochemical oxygen demand, 5-day; COD: Chemical oxygen demand; TDS: Total dissolved solids; TSS: Total suspended solids.

Table 8. Daily industrial discharge flow data for April 2025

Industry	Total flow (m^3)	Daily average (m^3/d)
Pepsi	20,108	670.3
Tanzania Breweries Limited	12,307	410.2
Coca-Cola Kwanza	4,298	143.3

treatment under mixed municipal and industrial loading conditions. Organic matter removal was strong, with COD and TSS reduced to levels typical of well-functioning tropical WSPs, confirming that anaerobic and facultative processes remain effective in high-temperature environments.[22] These results align with findings from similar systems in Ghana, Ethiopia, and Kenya, where COD reductions of 80–90% and TSS reductions of 70–90% have been reported.[13,23]

In contrast, BOD removal was modest and did not consistently achieve Tanzanian discharge standards. This partial non-compliance can be attributed to intermittent hydraulic shock loads originating from industries, particularly during peak discharge days.[21] Comparable challenges have been noted in Ethiopia, where breweries and beverage industries periodically overwhelm pond systems, depressing performance.[13,23] The link observed in this study between peak flows and efficiency declines highlights the need for flow equalization at the industrial source.

Nutrient and salt removal were especially weak. Nitrite removal was negligible, reflecting incomplete nitrification–denitrification pathways, often inhibited by fluctuating organic loads, short retention times, and limited oxygen transfer in facultative zones. Ammonia removal was moderate but fell short of benchmarks reported for tropical WSPs (60–80%), suggesting that algal–bacterial interactions were constrained by organic overload.[24] TDS reduction was minimal, consistent with evidence that conventional ponds are not designed for salt removal, which requires specific polishing processes such as wetlands or ion-exchange media.[8,25]

Ecologically, the persistence of ammonia, nitrite, and TDS in the effluent presents risks for aquatic life in receiving waters. Ammonia concentrations above 3 mg/L are toxic to sensitive fish species, while elevated nitrite interferes with oxygen transport in aquatic organisms. Dissolved solids above 1000 mg/L alter ionic balances and reduce freshwater biodiversity. The observed effluent levels at Kalobe WSPs, therefore, raise concerns about downstream ecological stress.

This study makes a novel contribution by documenting the performance of a Tanzanian WSP receiving combined domestic and industrial wastewater. Unlike most regional studies that evaluate purely municipal systems, this case illustrates the compounded challenges of mixed loading, where brewery and beverage effluents exacerbate nutrient persistence and destabilize biological processes. These findings emphasize that, while WSPs remain a viable low-cost technology in resource-constrained settings, they require complementary interventions—including industrial pre-treatment, flow regulation, and post-treatment polishing—to ensure regulatory compliance and environmental protection.

5. Limitations of the study

This study was limited in several respects that should be acknowledged. First, sampling was conducted during the dry season only; therefore, seasonal variability, particularly the influence of wet-season inflows and dilution, was not captured. Second, while composite grab sampling was applied, daily and diurnal variations in industrial discharges may not have been fully represented. Third, the analysis focused on conventional water quality indicators (BOD_5, COD, TSS, ammonia, nitrite, and TDS) but did not extend to heavy metals or emerging contaminants, which are often present in industrial effluents and may affect long-term pond performance and ecological safety. Finally, the study relied on reported flow data from industries for load calculations, which may contain uncertainties due to irregular monitoring practices.

Despite these limitations, the findings provide valuable baseline information on the functioning of Kalobe WSPs and highlight critical areas for intervention. Future research should incorporate multi-seasonal monitoring, automated flow measurement, and expanded parameter analysis to provide a more comprehensive assessment of treatment dynamics.

6. Conclusion and recommendations

The Kalobe WSPs demonstrated that, even under high-strength mixed municipal and industrial wastewater conditions, stabilization ponds can achieve meaningful reductions in organic matter and suspended solids. Nevertheless, the system did not consistently meet Tanzanian effluent discharge standards, particularly for BOD, nitrite, and TDS.

This study provides novel evidence from Tanzania, where little quantitative data exists on WSPs receiving industrial inputs. By documenting system performance under mixed loadings, the study highlights the persistence of nutrients and dissolved solids, pollutants that are not adequately treated by conventional pond configurations. These findings are important for regulators and utilities in Tanzania and across the region, as they demonstrate both the strengths of WSPs in tropical climates and the critical gaps in nutrient and salt removal.

Policy interventions are therefore needed to address these gaps. Industrial flow regulation and equalization, stricter enforcement of pre-treatment requirements, and the introduction of cost-effective polishing steps (such as constructed wetlands or sand filtration) would improve system reliability. If integrated into existing management strategies, these measures would strengthen the capacity of WSPs to meet national standards and safeguard downstream ecosystems.

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Conflict of interest

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Availability of data

Data are available from the corresponding author upon reasonable request.

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