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Research Paper

Performance of four wastewater treatment plants serving Ethiopia's capital city, Addis Ababa

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ABSTRACT

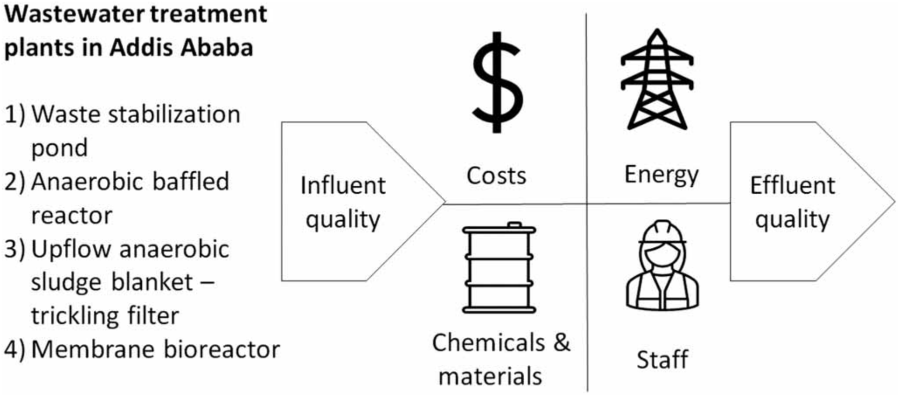
There is an urgent need to expand wastewater treatment on the African continent. To help choose appropriate technologies for this task, we evaluated the efficiency, energy and chemical demands, and costs of four wastewater treatment plants (WWTPs). These plants represent the main wastewater treatment technologies operated by the Addis Ababa Water and Sewerage Authority (AAWSA): waste stabilization pond (WSP), anaerobic baffled reactor (ABR), up-flow anaerobic sludge blanket with trickling filter (UASB-TF), and membrane bioreactor (MBR) technologies. Principal component analysis revealed that season significantly impacts the raw and treated wastewater quality (ANOSIM, $R = 0.3126$, $p = 0.001$), while the type of treatment plant did not significantly affect the measured effluent characteristics (ANOSIM, $R = 0.1235$, $p = 0.2000$). In contrast, construction and operational costs, as well as energy and chemical demands per m^3 of treated wastewater, varied starkly between the WWTPs. Total costs of wastewater treatment in 2022 ranged from $0.045 to 0.546 per m^3 of wastewater treated, being 6–12 times higher for MBR compared with the other WWTP technologies. Real-world performance data as reported in this study are essential for choosing appropriate technologies that meet Africa's wastewater treatment needs.

Key words: economic analysis, sanitation, sustainability, wastewater treatment, water quality

HIGHLIGHTS

- Four distinct wastewater treatment plants in Addis Ababa were investigated.
- Costs, energy demand, chemical demand, and water quality were evaluated.
- Season significantly shaped influent and effluent water quality.
- Treatment technology had no significant overall effect on effluent quality.
- Membrane bioreactor technology had the highest costs and operational demands.

GRAPHICAL ABSTRACT



INTRODUCTION

According to the indicators for progress on the United Nation's Sustainable Development Goal 6 (SDG6), safe water and sanitation, globally, only 56% of household wastewater is safely treated (UN 2022b). The sanitation infrastructure development challenge is most acute in countries like Ethiopia, where in 2020 only 7% of its 120 million people used safely managed sanitation services (UN 2022a). Given the magnitude of this challenge, assessing the performance of existing wastewater treatment technologies on the African continent is important. Such a performance evaluation needs to consider the local context and resulting operational challenges (Cossio *et al.* 2020). For example, the rapid growth of African cities can increase influent contaminant loads beyond the existing WWTP design capacity and result in poor pollutant removal (Teklehaimanot *et al.* 2015). The robust performance of WWTPs depends on context-appropriate treatment technology that is chosen based on local skills and costs, operational resilience, efficiency, and priority pollutants (Wang *et al.* 2014; Onu *et al.* 2023).

Much of Ethiopia's existing wastewater treatment infrastructure is within the catchment of the Akaki Rivers. The Akaki catchment encompasses Ethiopia's capital Addis Ababa, which is one of Africa's fastest-growing cities (Hiruy *et al.* 2022). Water supply for Addis Ababa City is managed by the Addis Ababa Water and Sewerage Authority (AAWSA), which, in 2023, provided about 515,000 m^3/day drinking water (personal communication with AAWSA). To treat the resulting wastewater, Addis Ababa City currently has 36 wastewater treatment plants (WWTPs) that are managed by the AAWSA and have a total design capacity of 163,080 m^3/day (Figure 1 and Table S1 in Supplementary Information).

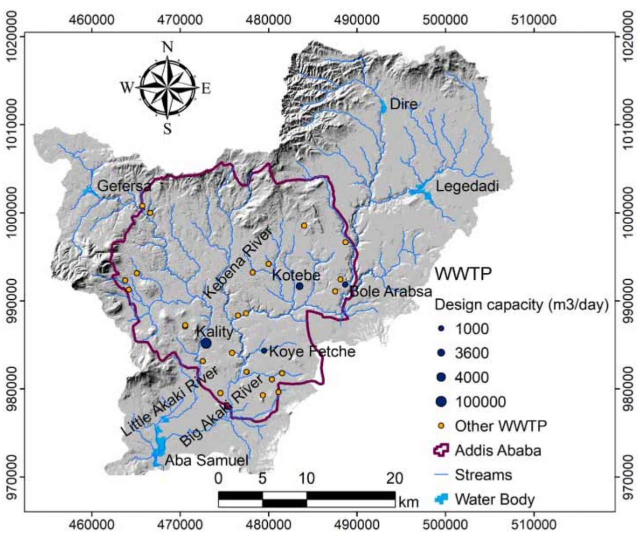


Figure 1 | Water bodies of the Akaki catchment and WWTPs in Addis Ababa City.

The actual discharge is 112,039 m^3/day, which shows that many WWTPs operate below their design capacity. The WWTPs in Addis Ababa use a wide range of technologies with the main ones being up-flow anaerobic sludge blanket reactors with trickling filters (UASB-TF), membrane bio-reactors (MBR), anaerobic baffled reactors (ABR) and waste stabilization ponds (WSP). The total design capacity of UASB-TF, MBR, ABR and WSP plants is 100,000, 26,760, 21,200 and 13,500 m^3/day, respectively (Figure 1 and Table S1 in Supplementary Information). The discrepancies between water supply, wastewater treatment capacity and actual wastewater discharge are explained by limitations of the sewerage system, which only covers about 23% of residential houses in Addis Ababa (Tadesse 2021). Accordingly, a substantial amount of sewage is discharged untreated into local water bodies with detrimental impacts in the Akaki and Upper Awash sub-basins (Getachew *et al.* 2021).

Impacts of treated and untreated wastewater discharges on river water quality in the Akaki catchment include elevated concentrations of pathogenic microorganisms such as *Aliarcobacter butzleri* (formerly *Arcobacter butzleri)* and *Vibrio cholerae* (Acharya *et al.* 2020; Hiruy *et al.* 2022), antimicrobial-resistant bacteria (Hiruy *et al.* 2022), resistance genes (Yitayew *et al.* 2022), heavy metals (Dessie *et al.* 2022), nutrients (Dessie *et al.* 2024), and pesticides and herbicides (Getachew *et al.* 2021). A public health study suggested that a significant risk factor associated with *V. cholerae* infection in Ethiopia is drinking river water (Bitew *et al.* 2024). Ethiopia has drafted policies, legislations, and laws to better protect and manage its water resources and public health, such as the Environmental Pollution Control Proclamation 300/2002, the Ethiopian Water Resources Management Proclamation No. 197/2000, and the Public Health Proclamation No. 200/2000 (UNEP 2023). Public Health Proclamation No. 200/2000 states in article 12 that 'no person shall dispose solid, liquid or and other waste in a manner which contaminates the environment or affects the health of the society'.

Previous studies have evaluated the performance of municipal and industrial WWTPs in Addis Ababa with a focus on water quality (Abate *et al.* 2021; Dessie *et al.* 2022; Hiruy *et al.* 2022). Our study aim was to understand the performance of municipal WWTPs in Addis Ababa more comprehensively by comparing distinct technologies in terms of their construction and operational costs, energy and chemical demands, and microbial and chemical effluent water quality observed in different seasons. Our study is aligned with the United Nations SDG 6.3 to improve water quality by finding cost-effective and resilient ways to reduce pollution. Our hypotheses were that (1) the season is influential in determining the untreated wastewater quality, (2) wastewater treatment technology shapes the effluent water quality, and (3) more expensive and energy-intensive treatments result in better pollutant removal.

MATERIAL AND METHODS

WWTPs and operational data collection

We investigated four WWTPs in Addis Ababa, Kotebe, Koye-Feche, Kality, and Arabsa WWTP (Figure 1, with photos in Figures S1–S4 in Supplementary Information). The Kotebe WWTP was constructed in 1998 with a design capacity of 4,000 m^3/day and WSP technology. The Koye-Feche WWTP was constructed in 2017 with a design capacity of 1,000 m^3/day and ABR technology. The Kality WWTP was constructed in 2018 with a design capacity of 100,000 m^3/day and UASB-TF technology. The Arabsa WWTP was constructed in 2018 with a design capacity of 3,600 m^3/day and MBR technology. Kality and Kotebe WWTPs receive wastewater from the city's sewer system and vacuum trucks that empty septic tanks. Arabsa and Koye-Feche WWTPs receive wastewater from the sewer system only.

WWTP operational data were collected from staff interviews and records of the AAWSA. Data collected comprised construction costs, operational costs, operational energy, chemicals, material demands, and a number of staff employed to run each facility. Chemical demand and costs were based on the use of NaOCl for chlorination, $Na_2S_2O_5$ to quench residual chlorine, odour neutralizer, and laboratory reagents for wastewater testing. Material costs comprised the costs of hand tools and purchasing costs of dumper/roller/skip trucks spread over a budgeted lifetime of 15 years. Energy demand and associated costs were derived from the electricity and fuel consumption in the year 2022. For electricity, the year 2022 costs were $0.04526/kWh. For fuel consumption, the litres of petrol or diesel used by vehicles and generators were added up for each WWTP in the year 2022, and costs were calculated based on a price of $1.24/L of fuel. Personnel costs comprised salary, water allowance, sewerage allowance, milk allowance, pension contribution, life insurance payments, health care, and the annual cost of personal protective equipment (clothes, shoes, soap, and disinfectants). Operational costs were then calculated as the sum of personnel, fuel, electricity, chemical, and materials costs. For a total of wastewater treatment cost estimation, we added 1/35th of the WWTP construction costs at year 2022 prices to the operational costs. The assumed plant lifetime of 35 years was an intermediate value between the expected 20-year lifetime of WWTP equipment and the 50-year lifetime of WWTP structures (Corominas *et al.* 2020). The year 2022 prices were calculated by accounting for US $ inflation between the construction year and the year 2022. Costs were normalized per m^3 of wastewater discharged (or treated) and added up to compare the total costs of wastewater treatment with different technologies.

Wastewater sample collection and analysis

Composite grab samples from the influent and the effluent of each WWTP were collected into 1 L polypropylene bottles in December 2020, April 2021, and August 2021. The three sampling dates were chosen to cover variable meteorological conditions in Ethiopia, namely the dry (December), small rains (April), and primary rainy season (August). Physicochemical parameters (water temperature, pH, and conductivity) were immediately measured in the field using a portable meter (Hach, Manchester, UK). All samples were then stored in cold boxes and transported to the AAWSA laboratory for examination of nutrients and coliform bacteria within 24 h of collection.

Total coliform (TC) and faecal coliform (FC) bacteria were enumerated by membrane filtration after dilution of an appropriate wastewater volume in a sterile normal saline solution. Filters were placed on m-endo or m-FC broth (Hach, Manchester, UK) soaked into sterile pads in Petri dishes and incubated for 24 h, at 35 and 44.5 °C, respectively. For the enumeration of total coliforms with ESBL resistance traits (ESBL TC), Coliform ChromoSelect Agar (Sigma-Aldrich, St. Louis, USA) was prepared using an ESBL ChromoSelect Agar supplement (Sigma-Aldrich, St. Louis, USA) containing antibiotics Ceftazidime, Cefotaxime, Ceftriazone, Aztreonam, and Fluconazole, following the manufacturer's instructions. Then, 50 μL of an appropriately diluted wastewater sample was spread on agar plates and incubated for 24 h at 35 °C. Helminth eggs were enumerated by a commercial provider at the School of Chemical and Biological Engineering, Addis Ababa University, using a sedimentation and suspension method, as previously described by Moodley *et al.* (2008). Various nutrients were quantified using colorimetric methods with Hach reagents and following the manufacturer's methods before evaluating samples on a DR5000 spectrophotometer (Hach, Manchester, UK). Ammonia was quantified with the Nessler method 8038, nitrate was quantified with the cadmium reduction method 8171, nitrite was quantified with the diazotization method 8507, phosphate was quantified with the PhosVer 3 ascorbic acid method 8048, sulphate was quantified with the Sulfaver 4 method 8051, and sulphide was quantified with the methylene blue method 8131. Turbidity was measured with a laboratory turbidity meter (2100AN, Hach, Manchester, UK). Standard solutions with known concentrations were used to validate the nutrient analysis results (Hach, Manchester, UK). Sterile saline solution and distilled water served as blank controls for the coliform and nutrient analysis, respectively. The analysis of each parameter value was repeated in duplicate to assess precision except for the coliform counts in August when a lack of reagents meant that only one plate could be prepared per sample.

Data curation and analysis

Mean parameter values for each sample were first calculated from duplicate analysis, resulting in a multivariate data matrix of 384 entries (16 mean parameter values determined in 24 samples). These samples comprised the influents and effluents of four WWTPs from three sampling dates. From these data, log removal rates were calculated as

$$\log \text{removal rate} = \log C_{\text{Influent}} - \log C_{\text{Effluent}}$$

From the effluent samples, two of the FC and two of the ESBL TC plates grew no visible colonies, and in these cases, the detection limit was substituted based on the volume of sample analysed to enable the calculation of minimum log removal rates. We also calculated the mean and standard deviation of concentration and log concentration values and log removal rates across the three sampling dates. We used the z-test function in Excel© (Microsoft Corporation, Redmond, WA, USA) to assess if log removal rates were significantly greater than zero. Matlab© version 2019 (Mathworks, Natick, MA, USA) was used for multivariate data analysis. We performed principal component analysis (PCA) using z-score-transformed log parameter values and Euclidean distance as the (dis)similarity metric. Analysis of normality (ANOSIM) was used as a non-parametric statistical test to assess the significance of (dis)similarity between samples grouped according to wastewater type (influent versus effluent), treatment plant (Kality versus Kotebe versus Arabsa versus Koye-Feche), and sampling data (December versus April versus August).

RESULTS AND DISCUSSION

Infrastructure and operational costs

Three of the WWTPs evaluated in this study, Koye-Feche, Kality, and Arabsa, were built within 5 years of the sample collection. They operated below their design capacity at the time of sampling, while the oldest WWTP at Kotebe operated above its design capacity (Figure 2). Table 1 compares the four WWTPs in terms of the wastewater treatment costs per m^3 of wastewater treated (i.e. discharge volume) in the year 2022. In this calculation, infrastructure costs were considered at 1/35th of the year 2022 prices following adjustment for inflation. The Arabsa WWTP with MBR technology had by far the highest treatment cost per m^3 of wastewater discharge, which was explained by high operational costs that were 5.5–18.5 times higher than at the other WWTPs (Table 1). High capital and operational costs are well-known disadvantages of MBR technology (Al-Asheh *et al.* 2021). The pumps, membranes, and other associated components of the MBR had high operational demands and frequent maintenance requirements causing higher costs. Furthermore, the MBR WWTP at Arabsa operated at only 1/5th of its design capacity, which meant that the infrastructure construction costs were also high per volume of wastewater treated.

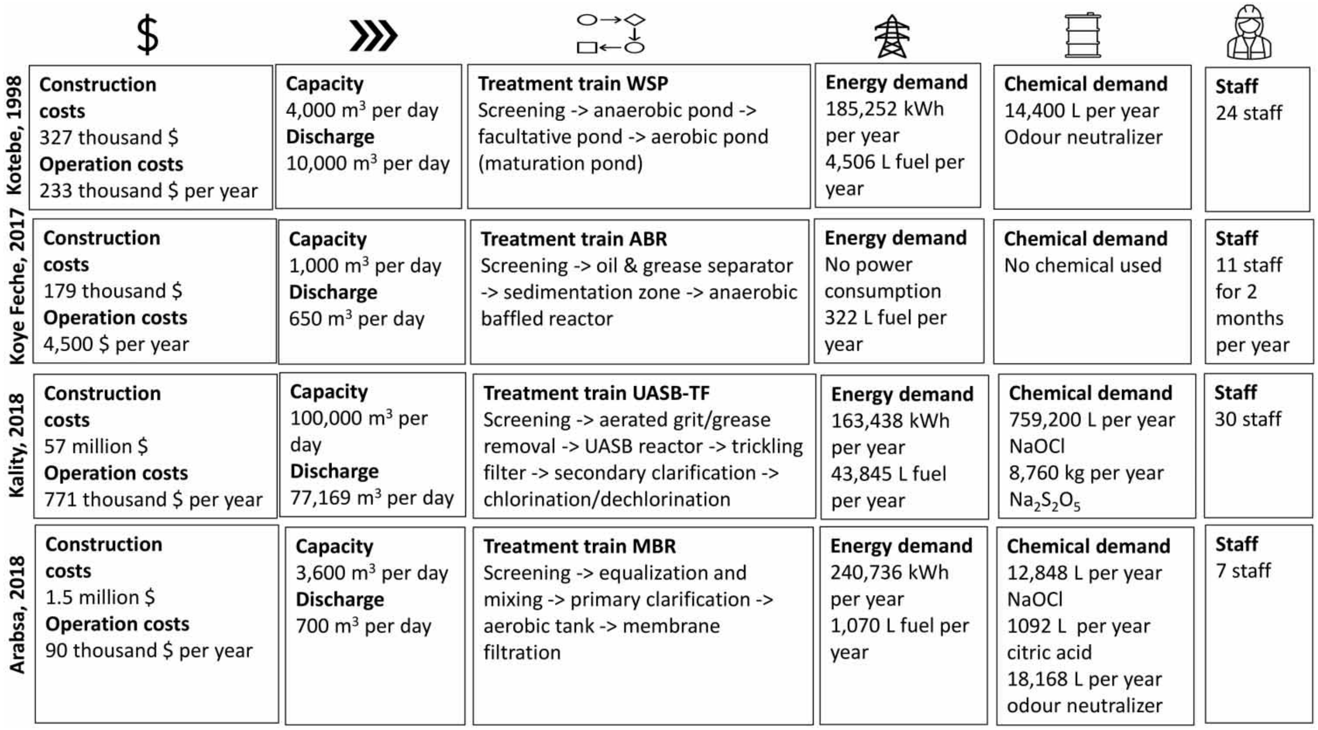


Figure 2 | Summary of key construction cost, design, and operational metrics of the four WWTPs investigated in this study.

Table 1 | Cost comparison of four WWTPs at year 2022 prices in US dollars per m^3 of wastewater treated

	Construction at 1/35th of year 2022 prices ($ per m^3)	Electricity ($ per m^3)	Fuel ($ per m^3)	Chemicals ($ per m^3)	Personnel ($ per m^3)	Materials ($ per m^3)	Operational costs ($ per m^3)	Total costs ($ per m^3)
Kotebe (WSP)	0.0046	0.0023	0.0015	0.0293	0.0205	0.0102	0.0638	0.0684
Koye-Feche (ABR)	0.0258	0.0000	0.0017	0.0005	0.0161	0.0007	0.0190	0.0448
Kality (UASB-TF)	0.0671	0.0003	0.0019	0.0178	0.0057	0.0016	0.0274	0.0945
Arabsa (MBR)	0.1940	0.0426	0.0052	0.1206	0.1249	0.0589	0.3523	0.5463

Energy and chemical demands

The Arabsa WWTP with MBR technology had a high energy and chemical demand for the aeration and membrane filtration and maintenance (Figure 2 and Table 1). The electricity demand of the Arabsa WWTP per volume of wastewater treated was 0.94 kWh/m^3, in the mid-range of values ranging from 0.4 to 2.4 kWh/m^3 reported for municipal MBR systems in Europe and the USA (Krzeminski *et al.* 2012). Sodium hypochlorite and citric acid were needed for periodic backwashing and chemical cleaning of the membranes. With the inclusion of deodorizer, the chemical demand amounted to 0.13 L/m^3 of wastewater treated. In the operational manual of the MBR treatment plant, the addition of aluminium sulphate as a coagulant is recommended to facilitate phosphorus removal by precipitation. However, this flocculation step was omitted from the treatment because the dewatering system at Arabsa WWTP was not working. The Kality WWTP with UASB-TF technology used sodium hypochlorite for disinfection and $Na_2S_2O_5$ to quench residual chlorine in the effluent, amounting to a chemical demand of 0.03 L/m^3 of wastewater treated. The Kotebe WWTP also used chemicals for odour control, amounting to 0.004 L/m^3 of wastewater treated. The Koye-Feche WWTP with ABR technology had the lowest energy demand and no chemical demand. Energy consumption at the Koye-Feche WWTP was solely due to the fuel consumption of vehicles needed for occasional site visits and maintenance.

Operational issues

The frequency of typical maintenance issues as reported by WWTP operators is summarized in Table 2. Blockages were frequent maintenance issues at Kality and Arabsa WWTPs. The operator at Kality WWTP pointed out that pump blockages occurred mainly in the rainy season when more grit from urban runoff accumulated at the inlet. Foaming was an issue that frequently occurred at the Kotebe WWTP in the mornings. Flooding was another issue that frequently affected Kality, Arabsa, and Kotebe WWTPs. The fewest issues were reported for the Koye-Feche WWTP with ABR technology due to its simple design, which required operator visits only six times a year to clean the screening chamber, manholes, top of the septic tanks, and the surrounding areas. Additionally, the frequency of desludging the ABR depended on the accumulation of sludge and could be completed in 10 days during a single visit. A lack of good road access was an issue at the Arabsa WWTP and required staff to carry the chemicals for systems maintenance onto the site during the rainy season. Given the high maintenance requirements of MBR technology, road access should become an important consideration for MBR site selection in the future. Contrary to previous reports on wastewater treatment challenges in Africa (Wang *et al.* 2014), lack of chemicals was not a major issue for the operators interviewed in this study (Table 2).

Factors shaping untreated and treated wastewater characteristics

It is well known that different types of WWTPs have a wide range of operational energy and chemical demands (Arroyo & Molinos-Senante 2018). An important consideration is therefore if higher costs, energy, and chemical usage can be justified by substantially improved wastewater treatment outcomes (Ravina *et al.* 2021). In a PCA of log-transformed concentration values using the entire wastewater data set (Figure 3), the first two principal components (PC 1 and PC2) together accounted for 54.75% of the overall variability in wastewater quality metrics. PC1 had positive loadings of log concentrations of faecal bacteria and helminth eggs, turbidity, conductivity, total dissolved solids, and nutrients with a low oxidation state like ammoniacal nitrogen and sulphur in sulphides. Contrariwise, nutrients with a higher oxidation state like nitrogen in nitrite and nitrate, phosphorus in phosphate, and sulphur in sulphate had negative PC1 loadings. Accordingly, effluent samples (empty symbols) were shifted in a negative sign direction along PC1 away from their respective influent samples (filled symbols). These shifts show how a reduction of faecal bacteria and helminth eggs and mineralization of nitrogen, phosphorus, and sulphur, resulted from the wastewater treatment. ANOSIM confirmed a significant overall effect of treatment on the wastewater characteristics (influent versus effluent, $R = 0.4396$, $p = 0.001$). Furthermore, all influent and effluent samples from the dry season in December (circles) had more positive PC1 scores than the respective samples from the wet seasons in August (diamonds), with samples from the small rains season in April (triangles) falling in between, except for the effluent sample from the Arabsa WWTP (green triangles). One-way ANOSIM confirmed a significant seasonal effect on the wastewater characteristics (December versus April versus August, $R = 0.3126$, $p = 0.001$). Being located close to the equator, Addis Ababa experiences only limited variation in monthly average temperatures, but there is substantial variation in monthly rainfall, which likely explains the observed effects. The observed seasonal shifts likely reflected a lesser pollutant concentration and higher oxygenation state during rainy weather conditions, when wastewater from households, commerce, and industry was mixed with rainwater from roof and road runoff, as compared to dry weather conditions (Zan *et al.* 2023).

Table 2 | Frequency of reported operational issues on a scale of never, daily, weekly, monthly, or once a year, according to operators at the WWTPs

Issues	WWTP Kotebe (WSP)	Koye-Feche (ABR)	Kality (UASB-TF)	Arabsa (MBR)
Lack of fuel (diesel)	Never	Never	Never	Monthly
Lack of chemicals (sodium hypochlorite, and odour neutralizer)	Never	Once a year	Never	Once a year
Blockages (blocked screens, and pumps)	Never	Monthly	Daily (this happens in the rainy season only)	Daily
Flooding (due to rain or overflowing tanks)	During the rainy season	Once a year	Daily	Monthly
Foaming (excessive amounts of foam)	Daily in the morning	Monthly	Never	Monthly
Failure of instruments (monitors, sensors, pumps, valves etc)	Never	Monthly	Never	Monthly
Vandalism/theft (damaged or stolen tools, infrastructure components)	Once a year	Once a year	Never	Never
Are there any other issues affecting the smooth operation of your treatment works?	The stabilization pond is affecting the smooth operation of the treatment plant. Maintaining the water bodies needs large manpower and there is a shortage of drying beds	–	Due to urban flooding during the rainy season, there is too much silting in the grit chamber which causes blockage of the grit pumps	The treatment plant is inside farmland and there is no proper access road. In the rainy season, the AAWSA vehicles cannot go to the treatment plant. In the rainy season, workers carry the chemicals on their shoulders for long distances, and the treatment plant operation becomes tough for the workers

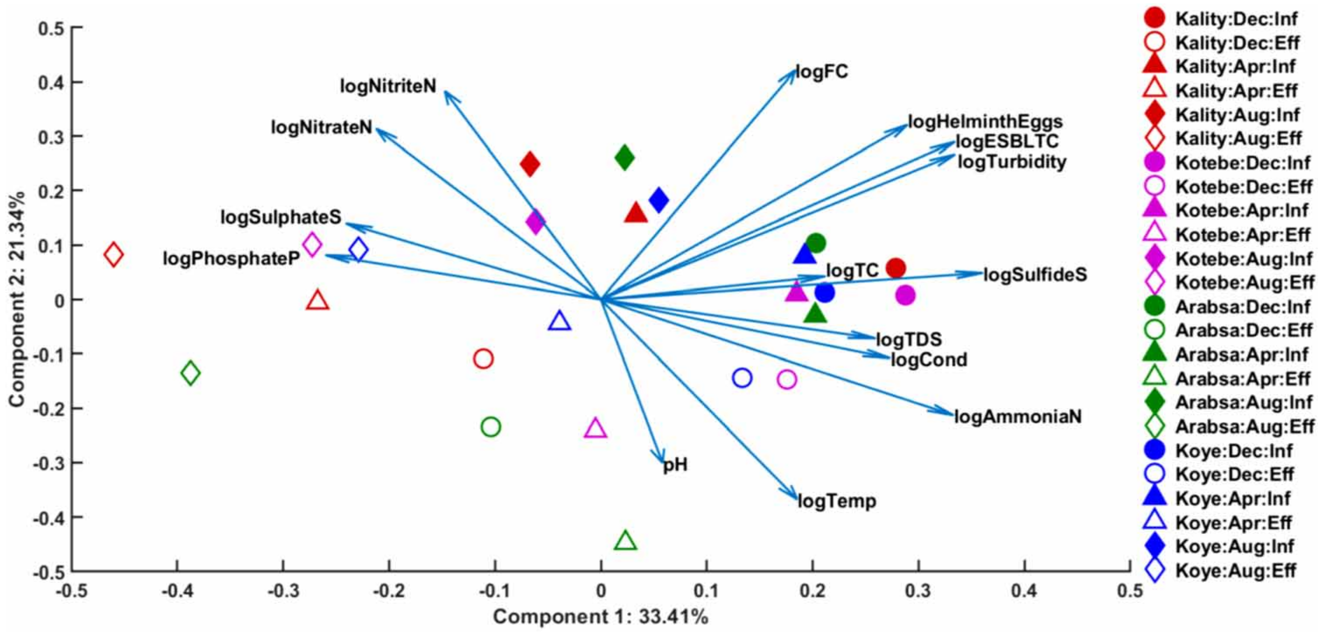


Figure 3 | PCA of *z*-score-transformed influent and effluent quality metrics (mean values of duplicates) of the four WWTPs investigated in this study: symbols represent the score of each sample and the proximity of scores indicates high sample similarity as measured by Euclidean distance. The percent sample variation each principal component captures from the data are indicated on the axes. The arrows show the loadings and illustrate how strongly each variable influences the principle components. Arrows forming a close angle illustrate variables which are positively correlated.

Contrary to our research hypothesis, no significant effect of the treatment plant type on the overall wastewater characteristics was observed in this study (ANOSIM, Kotebe versus Koye-Feche versus Kality versus Arabsa, $R = 0.0148$, $p = 0.3660$). When analysing similarities for the influent data only, there was no significant difference between WWTPs that receive waste from vacuum trucks in addition to sewage and those that only receive inputs via the sewer system (ANOSIM, Kotebe and Kality versus Koye-Feche and Arabsa, $R = -0.0796$, $p = 0.7381$). When analysing similarities for the effluent data only, there was also no significant effect of the wastewater treatment system (ANOSIM, Kotebe versus Koye-Feche versus Kality versus Arabsa, $R = 0.1235$, $p = 0.2000$), while a significant overall seasonal effect was confirmed (ANOSIM, December versus April versus August, $R = 0.3727$, $p = 0.005$). These observations suggest that the season was more influential than the wastewater treatment technology in shaping the characteristics of the effluents discharged into the water bodies of the Akaki catchment.

Tables S2 and S3 in the Supplementary Information compile the observed influent wastewater quality characteristics for each season and each WWTP, respectively. As already discussed, untreated wastewater had a higher content of bacteria, ammonia, and sulphite, and lower content of oxidized nutrients such as nitrate, sulphate, and phosphate, in the dry season (December) as compared to the wet season (August). The average values across all seasons mostly fell within the range of values reported by other authors for the inflows of other WWTPs in Sub-Saharan Africa (Table S2). Tables S4 and S5 in the Supplementary Information compare the WWTP effluent characteristics observed in each season and WWTP with literature reports from the African continent. For the effluents, seasonal differences were less apparent in the bacterial water quality, but the trends mirrored those observed in the influents. The average values across all seasons mostly fell within the wide range of values reported for the effluents of other WWTPs in sub-Saharan Africa (Table S4).

Pollutant removal efficiency in different WWTPs

Figure 4 compares the treatment efficiency of the four WWTPs investigated in this study in terms of log removal rates for bacteria, helminth eggs, salts, and nutrients. Bacterial removal was positive but ranged widely from 0.27 to 2.81 log units (i.e. 46–99.8% reduction). One mechanism of bacterial removal from wastewater is the sedimentation of bacteria attached to solids to form sludge (Curtis 2003). This removal by sedimentation would occur in all investigated WWTPs. In the PCA

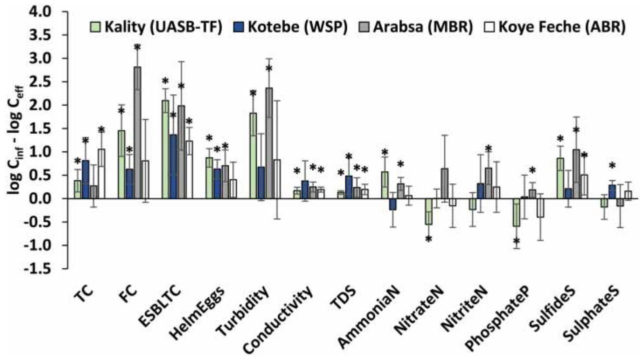


Figure 4 | Mean log removal efficiency plus/minus standard deviation of 13 biological and physicochemical wastewater constituents in the four WWTPs investigated in this study across three sampling events (December, April, and August). Refer to Figure 2 for the treatment process description. Removal rates with are significantly different from zero (*z*-test, $p < 0.05$) are indicated by *.

plot, the close alignment of the arrows for biological variables with the arrow for turbidity shows the correlation between the levels of bacteria/helminth eggs and suspended solids in untreated versus treated wastewater. An Ethiopian WWTP with WSP technology reportedly had a 1.7 log removal of total coliforms (i.e. 98% reduction) and a 2.6 log removal of faecal coliforms (i.e. 99.7% reduction) (Teshome *et al.* 2020). In comparison, Kotebe WWTP with WSP technology achieved only 0.8 log removal of total coliforms and 0.6 log removal of faecal coliforms (i.e. 84 and 75% reduction, respectively). The poor performance of the Kotebe WWTP could be caused by overloading and short hydraulic retention time, as the Kotebe WWTP currently treats 10,000 m^3/year versus a design capacity of 4,000 m^3/year. Similar operational challenges with high influent loads have been reported for a WSP system in Kenya (Wang *et al.* 2014). Pathogen removal in WSPs can vary by 3–4 orders of magnitude and depends, amongst other factors, on how long wastewater is retained in the ponds (Curtis 2003). In a report from Ghana, 3.35 log removal of faecal coliforms (i.e. 99.96% reduction) by a WWTP with a UASB reactor and biological filter occurred mostly in the final settling tank (Ahmed *et al.* 2018). In comparison, the Kality WWTP with UASB-TF technology achieved only 1.5 log FC removal (i.e. 96.8% reduction). According to Khan *et al.* (2012) FC removal by UASB systems is typically 1 log unit (i.e. 90% reduction), but can be enhanced to 2 log units (i.e. 99% reduction) with optimization of hydraulic retention time and diffuse aeration. Reduction of faecal coliforms is often used as a proxy for the removal of related pathogens like enterovirulent *Escherichia coli*, *Shigella*, and *Salmonella* species (Curtis 2003). In our study, the highest FC removal of 2.8 log units (i.e. 99.8% reduction) was observed for the Arabsa WWTP with MBR technology. In theory, the membrane filtration should remove all bacteria by size exclusion (Curtis 2003), but while MBR had by far the best removal of FC bacteria, we detected the notable presence of TC bacteria in the Arabsa WWTP effluent. Due to a highly variable performance, the Koye-Feche WWTP with ABR technology did not achieve a statistically significant FC and helminth egg removal, but removal rates of 1.1 and 1.2 log units (i.e. 92 and 94% reduction) were noted for total coliforms, without and with ESBL resistance traits, respectively.

Regarding nutrients, statistically significant removal was mostly observed for reduced species such as ammonia-N and sulphide-S, with a statistically significant net formation or negative log removal of nitrate-N and phosphate-P in the Kality WWTP that combines UASB technology with a trickling filtration step (Figure 4). Similarly, net formation of nitrate-N (−37.7% or −0.14 log removal) and phosphate-P (−8.4% or −0.04 log removal) was reported for a WWTP in Accra, Ghana, with the same UASB-TF configuration (Arthur *et al.* 2022). The Ghanian study showed how nitrification occurred in the trickling filters but was incomplete and resulted in only moderate total-N (27.0% or 0.14 log removal) and ammonium-N removal (9.0% or 0.04 log removal). Ammonium-N removal is less than observed at the Kality WWTP (73% or 0.57 log removal). Optimization of trickling filter media might be an avenue for improved nitrogen removal from UASB reactor effluents (Forbis-Stokes *et al.* 2018). Kotebe WWTP even had net formation of ammonia-N with high effluent concentrations of 121 ± 55 mg/L likely because of the organic overloading of the ponds. Similarly, a WSP on a university campus in Juja town, Kenya, failed to meet ammonium-N effluent quality guidance set by the Kenya National Environmental Management Authority, and even poorer performance in terms of ammonium-N removal was observed in a pilot-scale horizontal subsurface flow constructed wetland established at the site (Mburu *et al.* 2013). In a WSP at the University of Dar es Salaam, Tanzania, net ammonium-N removal occurred mainly in the maturation pond (48.1% or 0.28 log removal) and was attributed to uptake by microorganisms, with lesser contributions from nitrification and only minor losses from volatilization (Mayo & Abbas 2014). The Arabsa WWTP with MBR technology achieved statistically significant ammonia-N removal (52% or 0.32 log removal). There may be room for process optimization as MBRs reportedly remove over 90% of the ammonia under optimum conditions (Gander *et al.* 2000). Arabsa was the only WWTP with significant phosphate-P removal (35% or 0.19 log removal), likely because phosphate adsorption onto sludge is enhanced by the high biomass concentration in MBRs.

Impacts on receiving rivers

A comparison was made between the design capacity of the WWTPs and the discharge of the major rivers that receive the WWTP effluent. The discharge data were obtained from citizen science data and rainfall–runoff modelling (Negash *et al.* 2023). The discharge of Kotebe and Arabsa WWTPs ranged between 0.3 and 10.3%, and less than 0.9% of the discharge of the main river receiving their effluents, respectively. As Koye-Feche is a small WWTP situated at the most downstream part of the Big Akaki River, its discharge is a negligible fraction of the river discharge suggesting a significant dilution effect. Contrariwise, the discharge of Kality WWTP varies from 2.2 to 125.6% of the discharge of the Little Akaki River showing large variation with the seasons. Its treated waste discharge exceeds the natural river discharge in the driest month (February). Climate change is expected to change precipitation patterns in the Awash Basin with more intense, but less frequent rainfall increasing current pressures on freshwater resources (Legass *et al.* 2025). During periods of drought, treated and untreated wastewater discharges already contribute substantially to stream flows and poor water quality in the Akaki catchment (Hiruy *et al.* 2022), which emphasises the need for more effective pollution control measures in the future.

Table S4 in the Supplementary Information compares the treated wastewater concentrations with reports on water quality in the receiving Little and Big Akaki Rivers. Effluents from the WWTPs contained much higher levels of faecal bacteria, salts, and nutrients than the rivers in the upstream of the Akaki catchment. The comparison shows that WWTP discharge is a pollution source into freshwater bodies, where the rivers flow through the central, urbanized part of the watershed. However, some of the pollutant concentrations previously reported for urban river sampling locations within and downstream of Addis Ababa City exceed those reported here for the treated WWTP effluent. This comparison shows the importance of additional pollution sources in the catchment, such as untreated and industrial wastewater discharges (Dessie *et al.* 2024), and the potential benefits of expanding wastewater treatment coverage in Addis Ababa.

CONCLUSIONS

By comparing the performance of four WWTPs in Addis Ababa City with WSP, ABR, UASB-TF, and MBR technology, respectively, we found that MBR had the highest costs, energy, and chemical demands due to the high maintenance needs of membrane filtration technology. Contrary to our hypothesis, we found that WWTP technology was not a statistically significant factor in shaping the effluent quality. The season was more influential in determining untreated and treated wastewater characteristics. Consequently, close attention should be paid to balancing benefits and costs when choosing an appropriate technology for expanding wastewater treatment capacity in Ethiopia and beyond. Imbalances between sewerage and WWTP design capacity, lack of road access, and problems with sludge dewatering systems were real-world performance issues encountered in this study. More WWTP performance data needs to be reported from the African continent to inform robust investment strategies for the region and achieve the United Nations SDG6, safe water and sanitation for all.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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