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Research article

Performance evaluation of a brewery wastewater treatment plant: A case of Heineken Brewery, Addis Ababa, Ethiopia

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A R T I C L E I N F O

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A B S T R A C T

Untreated wastewater from the brewing industry poses significant environmental risks due to its high organic content. Therefore, this study evaluates the wastewater treatment system at Heineken Brewery in Addis Ababa, Ethiopia. Key parameters analyzed include COD, BOD_5, TSS, pH, ammonia (NH_3), total nitrogen (TN), total phosphorus (TP), electrical conductivity (EC), temperature, turbidity, and volatile fatty acids (VFA). These parameters were analyzed following the procedures of the American Public Health Association's standard. The treatment system demonstrated notable efficiency, with influent temperature decreasing from 29.37 °C to 25.35 °C, remaining well below the acceptable limit of 40 °C. The pH dropped from a mean of 9.3 to 7.5, aligning with the acceptable range of 6–9. COD and BOD_5 were significantly reduced by 97.2 %, achieving levels well below discharge limits of 250 mg/L and 60 mg/L, respectively. TSS levels decreased by 95.7 %, with a mean of 32.3 mg/L. However, TP and TN removal efficiencies were lower at 49.4 % and 57.6 %, respectively, with TP slightly exceeding the limit of 5 mg/L. The system effectively reduced VFA by 94.3 % and turbidity by 71.5 %. While parameters such as pH, temperature, TN, NH_4-N, and EC were within acceptable limits, the high nutrient concentrations in the final effluent indicate potential environmental contamination if discharged untreated. Overall, while the treatment plant shows commendable pollutant removal efficiency, further optimization is needed for improved nutrient management.

1. Introduction

Industrialization significantly impacts the environment, particularly through the generation of industrial wastewater, which varies in composition depending on the industry. This wastewater often contains toxic pollutants, such as heavy metals, dyes, and organic compounds, leading to severe water quality degradation that affects both human health and aquatic ecosystems [1]. Effective treatment of industrial wastewater is crucial, employing methods like adsorption, coagulation, and advanced oxidation processes to

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mitigate these effects [2–4]. Moreover, the reuse of treated wastewater for irrigation presents opportunities to alleviate water scarcity and support agricultural productivity; however, the presence of residual contaminants poses risks to soil health and crop safety [5–7]. Thus, while industrialization drives economic growth, it necessitates stringent wastewater management practices to protect environmental and public health [8,9]. Balancing industrial development with ecological sustainability remains a critical challenge for rapidly industrializing nations [10,11].

The brewing industry, a vital sector in Africa's economic and cultural landscape, has seen significant growth in Ethiopia over the past two decades. This expansion, fueled by substantial investments in production and marketing, underscores the sector's economic vitality [12]. However, breweries are major consumers of water and generate substantial volumes of wastewater that often exceed environmental discharge standards [13]. This wastewater is characterized by high organic content and varying concentrations of pollutants, including biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and nutrients, necessitating effective treatment methods to mitigate environmental impacts [14].

In Ethiopia, the Heineken Brewery in Kilinto, Addis Ababa, represents the largest brewery in the country, with a production capacity of 4.5 million hectoliters [15]. Despite its modern infrastructure, the brewery's wastewater management practices raise significant environmental concerns. Untreated or inadequately treated effluents are discharged into the already polluted Akaki River, posing severe risks to public health and environmental sustainability [16,17]. Furthermore, local farmers utilize this treated wastewater for irrigation without a comprehensive understanding of its composition, exacerbating potential risks to agricultural productivity and soil health [18].

Current literature highlights the critical need for effective wastewater treatment solutions within the brewing industry to mitigate these impacts and ensure compliance with environmental regulations [19,20]. Despite this, there remains a significant research gap regarding the detailed performance evaluation of wastewater treatment facilities at specific breweries. This study aims to address this gap by conducting a detailed assessment of the wastewater treatment processes at Heineken Brewery in Addis Ababa, Ethiopia. The objectives are threefold: to characterize the wastewater generated by the brewery, to evaluate the performance of its treatment plant across various operational stages, and to assess the suitability of the treated effluent for agricultural use according to FAO and EPA standards. By filling this research gap, the study aims to provide critical insights into the effectiveness of brewery wastewater management practices and their implications for industry standards, environmental protection, and public health.

2. Materials and methods

2.1. Study area

The research was carried out at the Heineken Brewery situated in Kilinto, a district of Addis Ababa, Ethiopia's bustling capital as shown in Fig. 1. Kilinto lies roughly 15 km southeast of the city center, positioned centrally within the country. The geographical coordinates of the brewery are approximately 8.9644° N latitude and 38.7718° E longitude. Addis Ababa's high altitude of about 2355 m above sea level contributes to its climate, which features an average temperature of 15.9 °C, annual rainfall of 1089 mm, and a relative humidity of 60.7 %.

The Heineken brewery compound spans approximately 3.8 ha, with 2 ha allocated to build structures. Walia Beer, produced by the Ethiopian Brewery, a subsidiary of Heineken, is one of Ethiopia's leading brands, commanding a significant share of the national

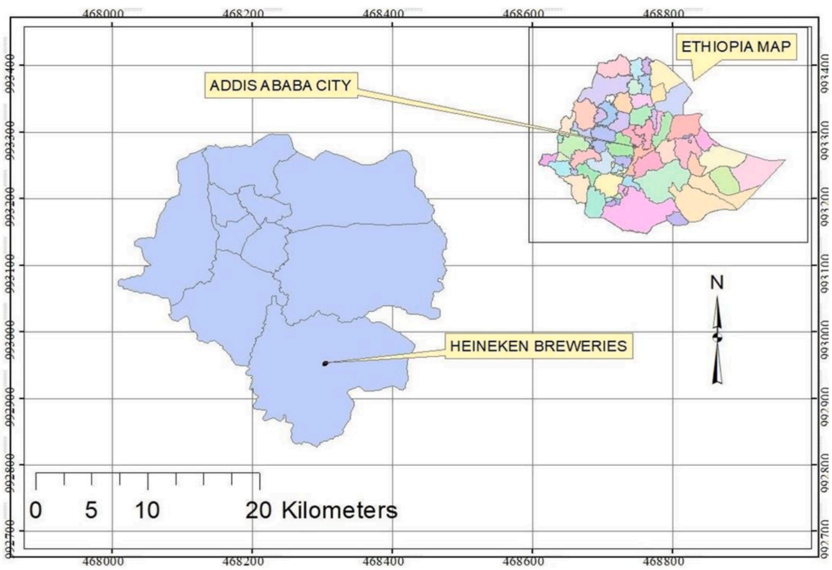

Fig. 1. Study area.

market. The brewery's primary products and byproducts include beer, discarded grains, yeast, wastewater, and carbon dioxide. The key ingredients used in production are malts, hops, yeast, and water. With an annual production capacity of 4.5 $*10^6$ L [15], the brewery relies on electric power and oil burners for energy. In line with global brewing standards, the Heineken brewery utilizes treated groundwater for its beer production.

The brewery currently employs over 600 permanent staff members, in addition to 280 contract and day laborers. The company's wastewater treatment plant has a designed capacity of 1550 m^3/day. The wastewater treatment system at the Heineken brewery includes an up flow anaerobic sludge blanket (UASB) reactor and an aeration tank. The treated wastewater is then discharged into Akaki river. Sampling points for each treatment unit's effluent were selected based on their location and retention time.

2.2. Materials and equipments

Wastewater samples were collected in 1 L polypropylene bottles. The COD digestion was performed using a COD digester (model HACH DRB 200), with results read using a spectrophotometer (model HACH DR 3900). BOD analysis was conducted using a BOD digester (model HACH BOD Incubator). Dissolved oxygen (DO) was measured with a DO meter (model Thermo Scientific Orion Star A323), and pH was determined using a portable pH meter (model Thermo Scientific Orion Star A211). Ammonium (NH_4-N), Total Nitrogen (TN), and Total Phosphorus (TP) were also measured using the spectrophotometer (model HACH DR 3900). A drying oven (model Thermo Scientific Heratherm) was used for heating during TSS analysis. Turbidity was measured using a turbidity meter (Model HACH 2100Q). Volatile fatty acids (VFA) analysis involved titration with a burette (model BRAND Burette). Samples were cooled using a desiccator (model Thermo Scientific Desiccator) and weighed with an electronic balance (model Mettler Toledo XS105). Sample temperature was measured with a thermometer (model ThermoWorks Thermapen), and conical flasks (model Pyrex) were used for sample handling and preparation. Additional essential laboratory equipment and instruments were utilized to evaluate the performance of the treatment plant [21].

2.3. Wastewater sampling and analysis

A systematic sampling approach was employed to ensure a comprehensive analysis of the wastewater treatment processes at the Heineken Brewery. Composite sampling techniques were used to gather samples from four key stages of the wastewater treatment system: influent, equalization tank, Contact Aeration Sequencing Batch Reactor (CASS), and UASB reactor. Samples were collected three times within a 24 h period from January to April 2024 to capture potential variations in wastewater composition throughout the day. Specifically, samples were gathered at 7:00 a.m., 3:00 p.m., and 11:00 p.m., with triplicate collections for each of the four sources. Grab samples were also obtained from an effluent auto sampler installed at the discharge point, providing additional data on final effluent characteristics.

All analyses were conducted following American Public Health Association (APHA) standard methods for the examination of water and wastewater. Specifically, BOD_5 was measured according to APHA Standard Method 5210B, where samples were incubated at 20 °C in the dark for five days to prevent interference from algal activity, and dissolved oxygen (DO) was measured before and after incubation to calculate BOD_5 levels. For COD, we followed APHA Standard Method 5220D, using a closed reflux colorimetric approach, in which samples were digested with potassium dichromate in a sulfuric acid medium. The remaining dichromate was quantified spectrophotometrically at 600 nm, reflecting COD levels. Total nitrogen (TN) was measured according to APHA Standard Method 4500-N, using the persulfate digestion method to oxidize nitrogen forms to nitrate, with spectrophotometric readings taken at 220 nm to capture nitrate levels accurately. Total phosphorus (TP) was assessed using APHA Standard Method 4500-P, in which all phosphorus was converted to orthophosphate through digestion, forming a blue complex read at 880 nm. For microbial analysis, total coliforms (TC) and E. coli were measured following APHA Standard Method 9222, involving membrane filtration, incubation on selective media, and colony counting based on color and morphology. Precisely, after filtering the water samples through a sterile membrane filter, the filter was placed face up on an absorbent pad soaked with membrane lauric acid broth. The membranes were then cultured for TC and E. coli at 35 °C and 44 °C, respectively. Following incubation, the number of yellow colonies on the membranes for both TC and E. coli was determined [21].

2.4. Data analysis

The statistical analysis of the sample data was performed using the SPSS Statistics Package software. The effectiveness of each treatment plant cell in removing BOD_5, COD, TN, TP, TC, and E. coli was evaluated using one-way analysis of variance (ANOVA). Differences between the inlet and outlet concentrations for each parameter in the treatment cells were assessed using multiple comparison tests with a 95 % confidence interval. Descriptive statistics, including the percentage elimination of BOD_5, COD, TN, TP, TC, and E. coli, were employed to present the results of the sample data analysis. The removal efficiency of the treatment plant for each effluent quality parameter was determined using Equation (1).

$$\text{Removal Efficiency } (\%) = \frac{C1 - C2}{C1} \times 100 \tag{1}$$

where C1 initial concentration, C2 effluent concentration.

3. Results and discussion

3.1. Characteristics of wastewater

The physicochemical characteristics of the raw brewery wastewater are summarized in Table 1. The EC of the samples ranged from 921 to 4258 μS/cm, with an average of 2459.0 μS/cm. These values align with the broader ranges reported for raw wastewater from breweries [22]. The pH ranged from 7.2 to 10.7, falling within the typical range of 2–12 pH units documented for brewery wastewater, which can vary due to the batch processing nature and chemicals used in clean-in-place (CIP) units. The temperature ranged from 18.6 to 33.6 °C, remaining below the 40 °C limit set by the National Environmental Quality Standard for brewery effluent. The TSS concentrations ranged from 290.0 to 1448.0 mg/L, which is consistent with broader ranges reported for brewery wastewater [23].

High COD values, ranging from 1980.0 to 7460.0 mg/L, are attributed to various brewery activities and housekeeping practices. These values are within the ranges reported in previous studies [24]. The BOD_5 values ranged from 2104.2 to 4923.6 mg/L, consistent with prior reports. The observed high standard deviations indicate significant variability in pollution levels, likely due to the diverse composition of brewery wastewater [25]. The high organic loads, including dissolved carbohydrates, alcohol, and suspended solids like spent grain and yeast; contribute to the high COD and BOD_5 levels. The BOD_5/COD ratio of 0.69 indicates that the organic matter in the raw wastewater is readily biodegradable [26]. Moreover, the nutritional composition of the raw wastewater, particularly nitrogen and phosphorus levels, is influenced by the use of phosphorus-containing chemicals in cleaning-in-place (CIP) units and the raw ingredients, such as malt and adjuncts. Variability in phosphorus content can be linked to the quantities of cleaning chemicals used [27]. Nitrogen sources include raw ingredients and spent yeast [28]. To address the high pollutant concentrations, it would be beneficial for the brewery to evaluate and optimize specific processes contributing to these loads. For instance, adjustments in the CIP protocols and ingredient formulations could lead to reduced phosphorus and nitrogen inputs. Additionally, implementing practices to minimize waste generation during brewing operations may further decrease the organic load entering the treatment system. Such optimizations could improve overall treatment efficiency and help meet environmental standards for nutrient levels in the effluent.

3.2. Pollutant removal efficiency

The wastewater treatment plant system comprises four sequential treatment units: an influent tank, an equalization tank, a UASB reactor, and an aeration tank. The wastewater progresses through these units before the treated effluent is discharged into the surrounding environment. Table 2 presents the recorded values of physicochemical parameters for both influent and effluent from each treatment unit.

3.2.1. Influent tank unit

The removal efficiencies of the influent tank, with a 5 min retention time, were as follows: COD at 9.8 %, BOD_5 at 62.1 %, TSS at 11.3 %, TN at 8.6 %, TP at 3.3 %, and NH_4-N at 14.6 % (Fig. 2). These efficiencies are higher than those reported by Firew et al. for BOD_5 (62.1 %), TSS (11.3 %), COD (9.8 %), NH_4-N (14.6 %), TN (8.6 %), and TP (3.3 %) [29]. However, the low removal efficiencies for COD and TP highlight the limitations of the current treatment process. The short retention time of 5 min significantly restricts the influent tank's ability to effectively reduce pollutant loads. Increasing the retention time could potentially enhance the removal efficiencies for these parameters by allowing more time for biochemical reactions and settling processes to occur. Additionally, exploring the implementation of pre-treatment technologies, such as sedimentation or advanced filtration systems, could further improve pollutant removal before the wastewater enters subsequent treatment stages. Furthermore, the concentration of temperature, dissolved oxygen (DO), and turbidity increased from the raw wastewater values of 29.4 ± 2.2 °C, 0.22 ± 0.08 mg/L, and 1134.9 ± 268.25 NTU to 30.8 ± 1.6 °C, 0.33 ± 0.07 mg/L, and 1323.7 ± 519.6 NTU, respectively. Statistical analysis indicates a significant difference ($p < 0.05$) between the mean values of these parameters in raw wastewater and the influent tank effluent.

Table 1
Characteristics of the raw Heineken brewery wastewater.

Parameters	Unit	Range	Mean ± ***SD***
Temperature	°C	18.6–33.6	29.4 ± 2.2
pH	pH	7.2–10.7	9.3 ± 0.6
COD	mg/L	1980.0–7460.0	4928.1 ± 1112.2
BOD_5	mg/L	2104.2–4923.6	3409.5 ± 832.5
TSS	mg/L	290.0–1448.0	757.13 ± 232.08
TP	mg/L	11.0–61.8	33.21 ± 10.47
TN	mg/L	12.9–58.7	39.98 ± 10.52
DO	mg/L	0.13–0.42	0.22 ± 0.08
EC	μS/cm	921.0–4258.0	2459.0 ± 1136.2
NH_4-N	mg/L	0.4–2.6	0.82 ± 0.46
VFA	mg/L	419.0–1805.0	1132.8 ± 231.65
Turbidity	NTU	658.0–1697.0	1177.5 ± 268.25

Table 2
Physicochemical characteristics of the wastewater at each treatment units.

Parameters	Unit	Influent tank	Equalization tank	UASB reactor tank	Aeration tank
Temp	°C	30.8 ± 1.6	29.4 ± 2.2	29.3 ± 1.2	25.35 ± 0.75
pH		7.6 ± 1.1	7.4 ± 0.9	7.3 ± 0.1	7.5 ± 0.25
COD	mg/L	4444.8 ± 1044	4271.0 ± 1110.5	531.2 ± 168.9	136.22 ± 85.95
BOD_5	mg/L	1292.2 ± 365	1254.0 ± 333.9	155.6 ± 48.1	38.34 ± 23.47
TSS	mg/L	671.3 ± 248	608.3 ± 222.8	416.7 ± 155.0	32.29 ± 126.54
TP	mg/L	32.1 ± 10.3	30.6 ± 10.2	25.3 ± 8.5	16.81 ± 7.96
TN	mg/L	36.5 ± 9.7	33.8 ± 9.5	31.8 ± 9.2	16.96 ± 7.78
DO	mg/L	0.33 ± 0.66	0.52 ± 0.14	0.0	4.19 ± 0.59
EC	μS/m	2337 ± 568	2112.6 ± 1139.0	777.5 ± 443.9	285.05 ± 121.31
NH_4-N	mg/L	0.7 ± 0.4	0.5 ± 0.2	0.42 ± 0.15	0.39 ± 0.34
VFA	mg/L	1101.6 ± 265.1	1102.7 ± 274.2	160.7 ± 44.4	64.07 ± 26.10
Turbidity	NTU	1323.8 ± 519.6	1050.1 ± 267.2	1129.7 ± 488	323.9 ± 125.1

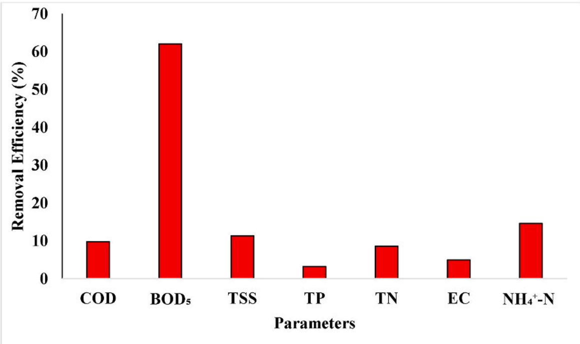

Fig. 2. Removal efficiency of influent tank.

3.2.2. Equalization tank unit

To minimize the quantity of suspended solids entering the UASB tank, the raw wastewater undergoes mechanical pre-treatment through a static fine screen, as illustrated in Fig. 3.

The equalization tank, with an 8-h retention time, is designed to manage hydraulic peaks and stabilize fluctuations in pH and organic load (COD, BOD_5, and TSS). This duration allows for effective peak shaving and facilitates the partial hydrolysis of complex organic materials into simpler compounds such as sugars, amino acids, and fatty acids (acidification). The removal efficiencies achieved in the equalization tank were as follows: COD at 3.9 %, BOD_5 at 2.9 %, TSS at 9.38 %, TP at 4.64 %, TN at 7.44 %, and NH_4-N at 24.28 %. This study demonstrates higher removal efficiencies for BOD_5 and TSS compared to those reported by Worku et al. [20], but lower for COD, TN, and TP [20]. Investigating the incorporation of additional mechanical or biological treatment processes at this stage may improve overall performance and pollutant removal. Overall, there is a significant difference ($p < 0.05$) between the mean values of influent wastewater and the equalization tank effluent, except for VFA.

3.2.3. Anaerobic Effluent Tank (UASB reactor) unit

Pretreated wastewater is pumped into the UASB reactor for biological treatment, where anaerobic sludge breaks down organic material into clean water, biogas, and a small amount of fresh biomass. The biogas generated can be utilized for energy production

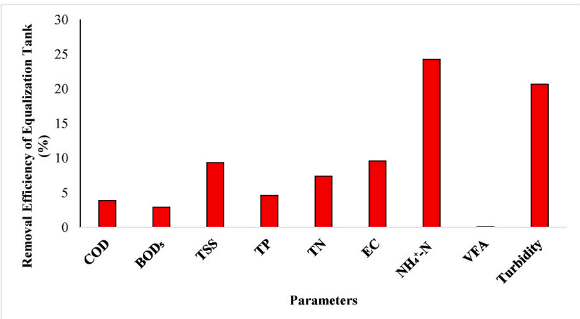

Fig. 3. Removal efficiency of Equalization Tank.

[30]. The removal efficiencies of the UASB reactor were as follows: BOD_5 at 88.0 %, COD at 88.0 %, TSS at 31.5 %, EC at 63.2 %, VFA at 85.4 %, TN at 6.1 %, TP at 17.3 %, and NH_4-N at 20.8 % as shown in Fig. 4.

This study shows lower removal efficiencies for BOD_5, TSS, and COD compared to those reported by Maleki et al. [31], but higher efficiencies for TN, EC, NH_4-N, and TP. DO analysis was not performed on the UASB reactor effluent because anaerobic bacteria do not require oxygen to decompose organic matter. The high removal efficiencies observed in the UASB reactor are likely due to optimal operational parameters and organic feeding rates. Comparison of the mean values between the equalization tank effluent and the UASB reactor effluent reveals a significant difference ($p < 0.05$) for all parameters except DO. Overall, the UASB reactor demonstrates effective removal of COD, BOD_5, and VFA.

3.2.4. Post Aeration Tank unit

The anaerobic effluent is transferred to the post-aeration tank, where it undergoes aeration to remove odor compounds and further reduce organic debris. The post-aerated effluent is then decanted, with settled sludge returned to the aeration basin. Excess aerobic sludge is periodically dewatered and disposed of in landfills [32]. The treatment efficiencies of the post-aeration tank were as follows: BOD_5 at 75.35 %, NH_4-N at 7.14 %, TSS at 92.3 %, EC at 63.3 %, COD at 74.4 %, TN at 46.6 %, TP at 34.8 %, turbidity at 71.3 %, and VFA at 60.13 % as depicted in Fig. 5.

This study shows higher removal efficiencies compared to those reported by Worku et al. [33] for BOD_5, TSS, COD, TN, EC, and TP, but lower for NH_4-N. Overall, the comparison between the UASB tank effluent and the post-aeration tank effluent reveals a strong significant difference ($p < 0.05$).

3.3. Characteristics of the effluent and overall removal efficiency

Table 3 presents the findings from the physicochemical analysis of the effluent, including a statistical summary of the brewery's treatment plant's overall effectiveness in pollutant removal, as well as the indicative discharge limits set by the Ethiopian Environmental Protection Authority (EEPA) [34].

The mean value for TP in the effluent was 16.81 mg/L, which exceeds the acceptable discharge limits set by the [35]. The temperature of the wastewater ranged from 25.4 °C to 25.4 °C, with an average of 25.4 °C. This is slightly higher than the natural stream water temperature range of 11–25 °C [22], but still within the EPA's standard temperature limitations for wastewater, suggesting minimal impact on irrigation water quality. TSS in the Heineken Brewery effluent ranged from 32.3 mg/L to 126.5 mg/L, with an average of 32.3 mg/L, which is below the mean TSS values found in other breweries [22]. Despite this, TSS levels were above the EPA's suggested threshold, indicating a need for improvement in suspended solids removal.

The pH of the effluent ranged around 7.5 ± 0.3, with a mean of 7.5, indicating a slightly basic nature that aligns with the Post and Gloria [36]. EC values ranged from 285.1 ± 121.3 μS/cm, with an average of 285.1 μS/cm. This is lower than previous studies Gemeda et al. but higher than the discharge limit of 1000 μS/cm set by regulatory agencies [37]. Elevated EC levels suggest potential issues with salinity that require further investigation to identify the sources and implement corrective measures. DO levels in the effluent ranged from 4.2 ± 0.6 mg/L, with a mean of 4.2 mg/L, which is within the USEPA [38] regulatory limit for irrigation. COD was recorded at 136.2 ± 85.9 mg/L, which exceeds the discharge limit of 250 mg/L set by EPA (2000). This indicates that the treatment plant is not effectively reducing COD levels, and further examination of treatment processes is needed.

BOD levels were measured at 38.3 ± 23.5 mg/L, lower than the EPA limits. This suggests that while BOD levels are within acceptable ranges continued monitoring is necessary to maintain compliance. TN was 16.9 ± 7.8 mg/L, which is below the EPA limit of 40 mg/L, indicating effective nitrogen management in the wastewater. TP concentration in the effluent was 16.8 ± 7.9 mg/L, which is within the regulatory standards set by EPA. This shows that phosphorus levels are being managed effectively and are lower than those found in other brewery effluents. Overall, the findings highlight areas of concern, particularly with COD, TSS, and EC levels, which suggest that improvements in the treatment process are needed to fully comply with regulatory standards and reduce potential environmental impacts.

Brewery effluent often contains high quantities of bacteria such as fecal coliforms (FC), *E. coli* (*E. coli*), and total coliforms. These

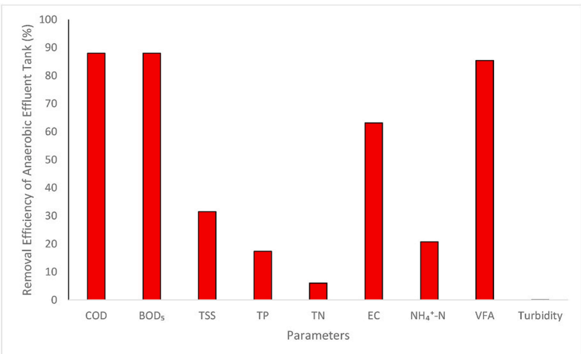

Fig. 4. Removal efficiency of Anaerobic Effluent Tank (UASB Reactor).

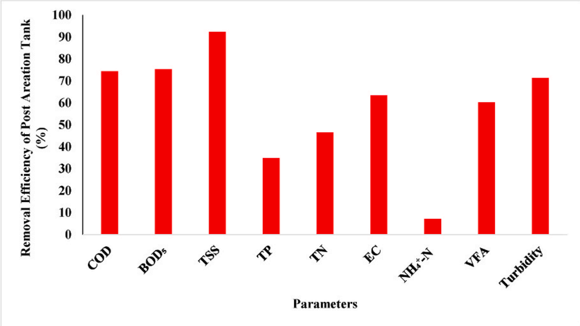

Fig. 5. Removal efficiency of Post Aeration Tank.

Table 3
Statistical summary of brewery overall pollution removal performance WWTP and EEPA's discharge limit.

Parameters	Units	Influent tank	Effluent tank	Overall removal efficiency	EEPA discharge limit
		Mean ± SD	Mean ± SD		
Temp	°C	29.37 ± 2.21	25.35 ± 0.75	40	
pH	–	9.3 ± 0.6	7.5 ± 0.3		6–9
COD	mg/L	4928.1 ± 1112.2	136.2 ± 85.9	97.2	<250
BOD_5	mg/L	3409.5 ± 832.5	38.34 ± 23.47	97.2	<60
TSS	mg/L	757.1 ± 232.1	32.3 ± 126.5	95.7	<50
TP	mg/L	33.2 ± 10.5	16.8 ± 7.9	49.4	<5
TN	mg/L	39.9 ± 10.5	16.9 ± 7.8	57.6	<40
DO	mg/L	0.22 ± 0.1	4.2 ± 0.6	−94.7	–
EC	μS/cm	2459.1 ± 1136	285.1 ± 121.3	88.4	1000
NH_4-N	mg/L	0.82 ± 0.46	0.39 ± 0.34	52.4	20
VFA	mg/L	1132.8 ± 231.7	64.1 ± 26.1	94.3	–
Turbidity	NTU	1134.0 ± 268.2	323.9 ± 125.1	71.5	–

bacteria are critical indicators of water quality, signaling fecal contamination and overall reliability of a water source [39]. Elevated levels of these bacteria in brewery effluent pose significant concerns for public health and environmental safety. Untreated or inadequately treated brewery effluent can adversely affect surface and groundwater resources and facilitate the spread of waterborne diseases [40]. Therefore, it is essential to monitor the bacteriological quality of brewery effluent before discharge to ensure compliance with national and international regulations and to protect public health and water resources.

The treatment processes at Heineken Brewery demonstrate significant effectiveness in reducing both total coliform (TC) and E. coli concentrations in the wastewater. The TC levels ranged from 8000 to 19,100 CFU/100 ml, with an average of 14,279.17 CFU/100 ml. Similarly, the E. coli counts varied between 1300 and 5966.67 CFU/100 ml, averaging 4491.67 CFU/100 ml. Importantly, these concentrations were found to be below the limits established by McKay [41] indicating compliance with safety standards.

The observed reduction in bacterial counts can be attributed to the combination of biological treatment processes employed in the wastewater treatment system. The anaerobic digestion occurring in the Upflow Anaerobic Sludge Blanket (UASB) reactor is particularly effective in removing organic matter and associated pathogens. Additionally, the subsequent aeration phase enhances the aerobic conditions that further facilitate the breakdown of bacteria.

However, while the treatment plant effectively manages coliform levels, it is essential to continuously monitor and optimize these processes to address potential fluctuations in bacterial concentrations due to varying influent qualities. Future studies should explore specific operational adjustments and advanced treatment technologies that could enhance bacterial removal efficiency, ensuring long-term compliance with health and environmental standards.

In contrast, a study on brewery wastewater in Bahirdar, northeastern Ethiopia, revealed fecal and total coliform levels exceeding acceptable limits [42]. Similarly, Adugna et al. reported high levels of coliform bacteria and fecal contamination in brewery effluent across various regions of Ethiopia [25]. These comparisons underscore the relatively better quality of Heineken Brewery wastewater in terms of coliform concentrations. The lower levels of coliform bacteria in Heineken Brewery's effluent suggest that the brewery has successfully implemented effective wastewater treatment practices to adhere to regulatory standards.

The study acknowledges the potential long-term environmental impacts associated with the discharge of treated wastewater containing elevated levels of nutrients, particularly TP and TN. Even small concentrations of these nutrients can contribute to eutrophication in nearby water bodies, leading to harmful algal blooms and the degradation of aquatic ecosystems. While the current treatment processes at Heineken Brewery demonstrate significant removal efficiencies for COD and BOD_5, the observed TP and TN levels in the effluent still exceed recommended agricultural reuse standards. This underscores the necessity for further optimization of the treatment system to enhance nutrient removal. Future research should explore advanced treatment technologies that can effectively reduce nutrient concentrations, ensuring that the effluent meets agricultural reuse criteria and minimizes ecological risks.

The wastewater treatment process at the Heineken Brewery addresses immediate environmental concerns while aligning with broader sustainability goals, including the reduction of the brewery's carbon footprint and the conservation of water resources. By implementing advanced treatment technologies, such as anaerobic digestion followed by post-aeration, the brewery effectively minimizes the organic load and greenhouse gas emissions associated with wastewater. The anaerobic phase not only generates biogas, which can be harnessed for energy production thereby reducing reliance on fossil fuels but also enhances nutrient recovery, contributing to more sustainable resource management. Furthermore, efficient wastewater treatment allows for the potential reuse of treated water in irrigation or non-potable applications, significantly decreasing the demand on local freshwater sources. By integrating sustainability practices into its wastewater management strategy, the Heineken Brewery can enhance its overall environmental performance, demonstrating a commitment to corporate social responsibility and sustainable development.

3.4. Suitability of the treated wastewater for irrigation

The treated wastewater from Heineken Brewery in Addis Ababa shows considerable potential for irrigation use, with most key parameters falling within acceptable limits. The effluent temperature of 25.35 °C and pH of 7.5 are suitable for irrigation, posing no risk to soil or plant health. Significant reductions in COD, BOD5, and TSS indicate low organic and particulate content, minimizing risks to soil and irrigation systems. The EC of 285.1 μS/cm suggests low salinity, which is beneficial for maintaining soil structure and crop health. While the removal of TN and TP is moderate, with TP slightly exceeding the recommended limit, these nutrients could benefit plant growth if managed carefully to avoid soil accumulation. Overall, the treated water is largely suitable for irrigation, though ongoing monitoring and possible adjustments may be needed to optimize nutrient levels for long-term use.

The regulatory framework and social acceptance of using treated wastewater in agriculture are critical considerations, especially in water-scarce regions like Ethiopia. While treated wastewater can provide a valuable resource for irrigation, its use must align with national health and safety standards to mitigate potential risks. Regulatory bodies, such as the Ethiopian Environmental Protection Authority, play a vital role in establishing guidelines governing the quality of treated wastewater for agricultural use. Moreover, public perception and acceptance are essential for the successful implementation of such practices. Education and awareness campaigns can inform farmers and the community about the benefits of using treated wastewater, addressing concerns about health risks and environmental impacts. Building trust through transparent monitoring and reporting can enhance community acceptance and encourage the adoption of treated wastewater as a sustainable alternative water source. Engaging stakeholders including local farmers and community leaders in discussions about the advantages and safety measures associated with treated wastewater can foster a more supportive environment for its agricultural use.

3.5. Reclamation strategies

To enhance wastewater reclamation at the Heineken Brewery treatment plant, which currently includes an influent tank, an equalization tank, a UASB reactor, and an aeration tank, several strategies could be implemented. First, integrating a tertiary treatment process, such as sand filtration or membrane filtration, could further reduce residual suspended solids and pathogens, thereby improving water quality for reuse. Additionally, implementing nutrient recovery systems such as struvite precipitation for phosphorus or ammonia stripping can reclaim valuable nutrients for agricultural use.

Optimizing the operations of the UASB reactor and aeration tank, possibly through advanced control systems or the addition of supplementary treatment stages like constructed wetlands, could enhance the removal of organic and nitrogen compounds. These strategies would not only improve the overall efficiency of the treatment plant but also increase the potential for safe and sustainable wastewater reuse in irrigation or other non-potable applications.

A structured plan for long-term monitoring is essential to ensure the sustained efficacy of the wastewater treatment processes at the Heineken Brewery. Implementing a follow-up study could focus on evaluating key performance indicators over an extended period, assessing not only treatment efficiencies but also the consistency of pollutant removal. Regular sampling and analysis of effluent quality particularly for parameters such as COD, BOD, TN, and TP should be conducted to track performance changes due to variations in influent composition or operational practices. Additionally, integrating advanced monitoring technologies, such as online sensors for real-time data collection, could provide valuable insights into process fluctuations and enable timely interventions. This longitudinal approach would benefit the brewery in maintaining compliance with environmental regulations while contributing to a deeper understanding of the long-term impacts of treatment practices on local ecosystems and public health. Engaging with local stakeholders throughout this process can foster transparency and enhance community trust in the brewery's commitment to sustainable wastewater management.

4. Conclusions

The beverage industry, known for its high-water consumption, generates substantial volumes of wastewater that often exceed environmental discharge limits. This study reveals that the final effluent from the Heineken Brewery surpasses Ethiopian beverage industry discharge standards for BOD_5, COD, and TP, indicating inefficiencies in the wastewater treatment plant. The elevated TP levels in the effluent suggest a risk of severe environmental contamination if discharged untreated. While the overall pollutant removal efficiency of the plant was commendable, with reductions of 97.2 % for COD and BOD_5, the high concentrations of nutrients in the final effluent remain problematic. Parameters such as pH, temperature, TN, NH_4-N, and EC are within acceptable limits, indicating they may be safely discharged into nearby rivers. To address the treatment inefficiencies, it is recommended that the brewery invest in advanced monitoring technologies. Specifically, the installation of online analyzers for COD, VFA, and TP in the anaerobic and effluent tanks could significantly enhance the treatment process and ensure compliance with environmental regulations. Future studies should focus on assessing seasonal variations in wastewater characteristics to understand how different production patterns influence wastewater composition and treatment efficacy. Longitudinal studies over extended periods will be crucial in evaluating the long-term performance of treatment systems. Additionally, research should explore innovative treatment methods that could enhance nutrient removal efficiency, particularly for TP and TN, to align with environmental discharge standards.

CRediT authorship contribution statement

Teklu Shumbe: Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis. **Kenatu Angassa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Israel Tessema:** Writing – review & editing, Visualization, Supervision. **Solomon Tibebu:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Mikiyas Abewaa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Data curation. **Tolesa Getu:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis.

Availability of data and material

All Data included in the manuscript.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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