Scientific African 29 (2025) e02781

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

Assessment of urban and industrial effluents on a receiving stream using statistical and quality indices

David O. Omole [a,*], Chinemelum C. Udemezue [b], Oluranti S. Agboola [c]

[a] *School of Civil and Environmental Engineering, University of the Witwatersrand, Johannesburg, Private Bag 3, Johannesburg WITS 2050, South Africa*
[b] *Department of Civil Engineering, Covenant University, PMB 1023, Ota 112233, Ogun State, Nigeria*
[c] *Department of Chemical Engineering, Covenant University, PMB 1023, Ota 112233, Ogun State, Nigeria*

ARTICLE INFO

Editor: DR B Gyampoh

Keywords:
Water pollutants
Environmental monitoring
Heavy metals
Rivers
Wastewater
Effluent

ABSTRACT

Discharging untreated effluents into surface water bodies is a widespread practice that degrades surface water, thereby jeopardizing public health in several African countries, including Nigeria. Due to a lack of access to clean drinking water, many users rely exclusively on stream water, making stream quality monitoring very important. The Arobieye stream in Ota, Nigeria, is one such stream that is impacted by effluent discharge from an urban centre and an alcoholic beverage factory. Stream and effluent samples were obtained from known intervals for physicochemical and faecal contamination analysis. Some of the pollutants from the urban and industrial effluents that exceeded the maximum contaminant limit included COD (78.6 mg/l and 8192 mg/l), phosphate (5.087 mg/l and 6.91 mg/l), cadmium (0.016 mg/l and 0.079 mg/l), total coliform (40,000 cfu/100 ml and 180,000 cfu/100 ml), and Escherichia coliform (25,000 cfu/100 ml and 110,000 cfu/100 ml). Pearson's correlation matrix revealed strong positive correlations between the total coliform and nitrate (0.976), between the copper and nitrite (0.989), and between the *Escherichia coli* and zinc (0.910) concentrations. The stream arithmetic weighted mean water quality index (WQI_A) test also revealed that the stream depreciated from a test score of 74.13 (good) to 37.83 (bad). Pollution discharge into streams occurs year-round without any regulatory checks. Therefore, regulatory authorities need to increase their enforcement drive to protect the stream and downstream users. Additionally, a public advocacy programme should be initiated to educate downstream users on the dangers of ingesting untreated water from streams.

Introduction

Approximately 24 out of the 36 countries in East and West Africa reportedly treat <5 % of their wastewater before discharging it into the environment [1]. The remaining untreated 95 % of the generated wastewater often ends up in surface water bodies such as

Abbreviations: BOD, biochemical oxygen demand; COD, chemical oxygen demand; CW, constructed wetland; DNA, Deoxyribonucleic acid; DO, dissolved oxygen; FAO, food and agriculture organization; FGN, Federal Government of Nigeria; LDPE, light-density polyethylene; MCL, maximum contaminant limit; PMP, polluter-must-pay PRINCIPLE; SDG6, sustainable development goal; SD, standard deviation; Std. error, standard error; TDS, total dissolved solids; USEPA, United States Environmental Protection Agency; UV, ultraviolet; WQI_A, arithmetic weighted mean water quality index; WWTP, wastewater treatment plant; WHO, World Health Organization.

* Corresponding author.
E-mail address: david.omole@wits.ac.za (D.O. Omole).

https://doi.org/10.1016/j.sciaf.2025.e02781
Received 1 November 2024; Received in revised form 20 April 2025; Accepted 2 June 2025
Available online 2 June 2025

streams, rivers, lakes, and canals, thereby causing problems of eutrophication, pathogenic contamination, heavy metal pollution, and destabilization of the sensitive balance of flora and fauna in the ecosystem [1]. Furthermore, the practice of releasing untreated effluent into surface water adversely affects millions of people who use water drawn directly from streams because they have yet to have access to cleaner drinking water sources [2–4]. Therefore, addressing the problem of surface water pollution is an integral part of protecting public health and the environment.

The pollution of surface water bodies through human activities is widely reported in many parts of the world. Liu et al. [5] reported that Central, Southeast, and East Asia, including China, have the fastest-growing rate of river pollution risk in the world because of rapid population growth and increased economic and industrial activities. In Addis Ababa, Ethiopia, it is reported that 90 % of the wastewater effluents from industries are untreated before discharge into nearby rivers, thereby causing massive damage to the ecosystem and the quality of river water quality [6]. In Ghana, the Pra River is heavily contaminated by acid mine drainage because of illegal mining activities there [7]. Despite the obvious pollution of River Pra, Letheby [7]further reported that the most vulnerable people in the area use the polluted river water for cooking due to lack of access to better water sources. South Africa, one of Africa's most developed countries, is also not spared from the problems of domestic and industrial effluent pollution of rivers where pathogenic and heavy metal contaminants from informal settlements and acid mines, respectively, leach into surface water bodies [8,9]. River Msimbazi River in Tanzania, Lake Victoria (bordering Uganda, Kenya, and Tanzania), and several rivers in West African countries are also widely affected by effluents from industrial activities, as documented by Chen et al. [10] and Pare and Bonzi-Coulibaly [11]. In the United States, the government began to fight surface water pollution by establishing the Clean Water Act of 1972 and by expending over a trillion dollars to enforce the act, which eventually led to an abatement of the menace of surface water pollution in the country [12].

River pollution occurs in diverse forms, each with its own degree of consequences. Industrial effluents, which are laden with heavy metals, toxic chemicals, and other harmful substances, contaminate waterways, poison aquatic life, and endanger public health [13]. Agricultural runoff, which is characterized by toxic compounds from pesticides, fertilizers, and sediment, contributes to nutrient enrichment and eutrophication, causing algal blooms and oxygen depletion, which can asphyxiate fish and degrade water quality [14]. Moreover, untreated sewage and wastewater discharge from urban areas introduce pathogens, bacteria, and other contaminants into rivers, posing significant health risks to communities downstream [15,16]. Plastic pollution exacerbates this problem, with discarded bottles, bags, and other debris choking waterways, harming wildlife, and persisting in the environment for decades [17]. The consequences of river pollution are extensive and profound. Polluted rivers threaten the livelihoods of millions who depend on them for daily food and water. It also impacts the fishing, agriculture, and tourism industries, which rely on clean and healthy waterways.

The foregoing underscores the necessity of regularly monitoring and evaluation of surface water bodies. One of the methods that has gained widespread acceptance and application for monitoring the quality of surface water bodies among the scientific community is the water quality index (WQI) system. Nonetheless, the WQI system has its limitations, just like every other model. The basis of WQI analysis is the simplification of complex components of the analysis into a single representative number even at the risk of oversimplification. The National Sanitation Foundation Water Quality Index (NSF-WQI) method, developed in the USA, is the foundation for most WQI studies. The NSF-WQI has what can be described as the eclipsing effect [18]. This means the method can overlook one or two parameters that have exceeded the maximum contaminant level (MCL) because of its weight allocation to 'important' parameters. Also, WQI does not factor in every single contaminant. Rather, it selects. Some WQI models base their decision on as few as four parameters while some use 26 parameters [19]. Therefore, the variability in the choice of parameters that are included in any WQI constitutes a measure of subjectivity and model uncertainty. Nevertheless, the relevance of WQI analysis is that it provides a single number that describes the state of the stream or river (sparing persons who are unfamiliar with the underlying science and analysis from the technical jargon). The WQI numbers represent 0–25 (very bad), 26–50 (bad), 51–70 (fair), 71–90 (good), and 91–100 (very good) [18].

African countries where WQI studies have been carried out include Morocco, South Africa, Ethiopia, Ghana, Kenya, and Tanzania. The studies reveal pollution patterns similar to those in the Nigerian context, with most of the pollution coming from anthropogenic sources. The different studies made use of different versions of WQIs and adopted varying contaminant parameters for analysis. The study on Lake Boudaroua in Morocco made use of the Wastewater Quality Index (WWQI) to analyse thirteen parameters, namely, pH, EC, turbidity, DO, total hardness, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, Cl^{-}, SO_4^{2-} and NO_3- [20,21] Their findings show contamination by nitrogen compounds from agricultural activities was the preeminent problem. Also in South Africa, the river catchments in different parts of the country were studied. The authors tried to unify several WQIs, including the Weighted Arithmetic Water Quality Index (WAWQI or WQI_A) and the Unified Water Quality Index (UWQI) [20,22]. The parameters analysed were Ammonia, Ca, Cl, chlorophyll, EC, fluoride, hardness, Mg, Mn, NO_3, pondus hydrogenium, sulphate turbidity, alkalinity. Their findings show that NO_3, turbidity, Mn, and chlorophyll were the main contaminants from different effluent types [22]. In Ethiopia, 21 parameters were analysed with WAWQI and the Canadian Council of Ministers of the Environment (CCME-WQI) [23]. The parameters were pH, EC, TDS, temperature, turbidity, DO, BOD_5, COD, total phosphorus, soluble reactive phosphorus, Secchi depth, NO_3^{-}, NO_2^{-}, NH_4 + -N + NH_3—N, total nitrogen, Mg^{2+}, Na^{+}, K^{+}, and Ca^{2+}. They adjudged the lake unfit for domestic, recreational, or marine life as it had become eutrophic. The Aby Lagoon in Ghana was studied using CCME-WQI [24,25]. They analyzed seven parameters only, namely temperature, pH, turbidity, DO, conductivity, NO_3^{-} and PO_4^{3-} and found that Phosphate loads from wastewater effluents were the most dominant pollutants as they persisted through both the rainy and dry seasons. Phosphate often originates from agricultural and domestic effluent wastes. Although the studies in both Ethiopia and Ghana employed the use of CCME-WQI, it can be observed that the parameters used were varied. In Tanzania, researchers studied the WQI of the southern sections of the Lake Victoria basin using CCME-WQI [24,26]. They considered 23 parameters (pH, EC, Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3-, HCO_3^{-}, Cl^{-}, F, As, Ba, B, U, Mn, Fe, Ni, Cu, Zn, Cr, Pb, Cd) and the water quality in the studied section of the lake was deemed acceptable. Also, in Kenya, River Tana and different lakes were investigated for the association between the contaminants found in the water bodies and public health risks using WAWQI [27]. They identified Mn, Cl, and Al as the principal pollutants. The pollution sources were attributed to leached fertilizer and fuel leaks.

In the current study, the Arobiye stream in Ota, Nigeria, was visited to assess the impact of both industrial and domestic wastewater effluent on the stream. The aim of the study was to characterise the contaminants being released through daily effluent discharges into the stream and to quantitatively determine the consequent pollution status of the river. The aim was achieved by two main objectives namely, the determination of the arithmetic weighted mean water quality index (WQI_A) and the correlation analysis of the characterised parameters. The latter objective is useful for determining the strength of the relationship between the different characterised parameters. However, one of the observed gaps in the literature reviewed for this work shows that most WQI studies do not include correlation analysis. However, including correlation analysis sheds more insight into the wholistic reactions in polluted surface water bodies by identifying the possible causes and effects of specific contaminants.

Methods and material

Study area

The study area is a small natural stream that drains a private university campus and its environment in Ota, Nigeria. The location is 6°40′45″ N 3°08′55″. The Arobiye stream (indicated with a red line in Fig. 1) flows downstream to merge with a natural wetland in the Arobieye community, which is approximately 1.8 km away from the centre of the campus. The wetland is situated along the flow path of the Atuwara River, which is a major river in the Ota community (Fig. 1). The Arobiye stream receives wastewater from the university campus's wastewater treatment plant (WWTP), an alcoholic beverage industry and other smaller residences. The university campus has a combined resident student and staff population of approximately thirteen thousand people [16]. The wastewater from the campus is channeled to the WWTP, which uses the constructed wetland (CW) system within the campus premises (area bounded by the yellow line in Fig. 1). The campus wastewater undergoes primary treatment at the WWTP before discharge to the Arobieye stream. Every week, however, the adjoining church facility (proprietor of the university) receives worshippers numbering hundreds of

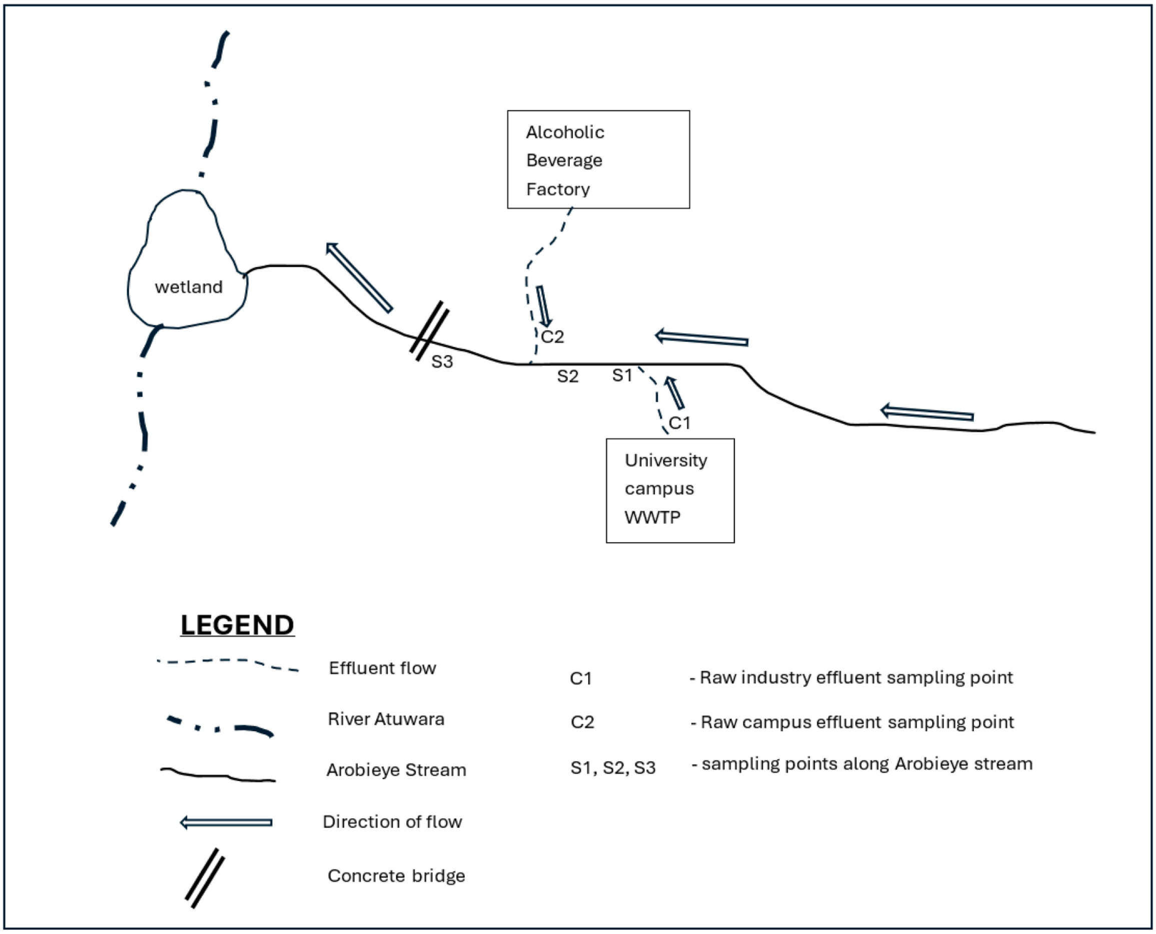

Fig. 1. Layout of the study area with respect to the sampling points.

thousands. The sewage from the church facility is also transferred to the WWTP with the aid of subterranean pipe networks.

Sewage is first received in three large concrete wastewater collection (septic) tanks to avoid overloading the WWTP. The tanks measure approximately 18 m by 15 m by 15 m (length x breadth x depth) each. Sewage digestion begins in the septic tanks. With the aid of control valves, the wastewater is gradually released into the reed beds that make up the CW. The CW is made up of two sets of concrete reed beds. Each set is connected in series. The first set of six reed beds (south of the WWTP) flows counterclockwise to the discharge outlet. The second set of five beds flows clockwise to the discharge outlet. Both sets of beds meet at a junction before discharge towards the stream.

Each reed bed, measuring 5.62 m long by 4.58 m wide and 1.2 m deep, was sown with Eichhornia crassipes (water hyacinth) to aid in the removal of nutrients from wastewater. Altogether, the WWTP discharges approximately 1.5 million litres of treated wastewater per day to the receiving stream [16].

The Arobieye stream also receives a high flow of effluent (estimated at approximately one million litres per day) from an alcoholic beverage factory through buried pipes. The alcoholic beverage factory, which is situated approximately 760 m from the stream, is at an elevation of 50 m, while the stream is at an elevation of 18 m (Fig. 1). The factory could not be accessed to verify whether there was any pretreatment of the wastewater before discharge into the environment. The factory management rebuffed all inquiries into their operations once it was established that the inquiry was for research purposes. However, the researchers observed that the effluent exuded a very strong alcoholic odour, which could be perceived from half a kilometre away from the point source. The point source, which was cleverly concealed in the undergrowth by the perpetrators, was uncovered by the researchers for sampling.

Sample collection, preservation, and transportation

The water and wastewater sampling exercise were performed between 07.00 hr and 09.00 hrs in March 2024. The sampling exercise was performed in the early hours before the sun became too hot. Increased atmospheric temperature can heat up the surface water body as well, thereby affecting the reaction rate of the physicochemical parameters of the water and wastewater samples [28–30]. When the water samples have been isolated from the stream, the rapid changes in temperature in tropical climates like Nigeria may have adverse implications on the integrity of the samples and how well the measurements represent reality. All river and wastewater effluent samples were obtained in duplicate to obtain average values. Samples were collected from five points (Fig. 1). These included effluent samples from the university campus and the alcoholic industry (samples C1 and C2, respectively). The Arobieye stream was also sampled at three points (S1, S2 and S3). Sample S1 was obtained 10 m upstream of the mixing point (before the stream merged with the campus wastewater). The purpose of this sample is to provide information on the background quality of the stream before the ingress of the wastewater effluents. Sample S2 was obtained a couple of meters from where the stream and the campus wastewater converged. Industrial wastewater joins the stream 36 m from S2. The final sample (S3) from the stream water was obtained at a distance of 151 m from S2. The water (S1, S2 and S3) and wastewater (C1 and C2) samples for physicochemical analysis were collected in 750 ml light-density polyethylene (LDPE) bottles, which had been cleaned with distilled water in the laboratory and rinsed on-site with the sample water at the point of collection. The stream water samples were collected at mid-depth in the stream. Each sample in the LDPE bottles was fixed with 1 ml of HNO_3 to prevent rapid changes in the physicochemical parameters before laboratory analysis. The water samples for biological contaminants were collected in 500 ml glass jars and sealed with aluminium foil after sample collection. As soon as each sample was collected, it was stored in a thermos cooler containing ice cubes to maintain the samples at 4 °C. The samples were immediately transported to a private analytical laboratory in Lagos, approximately one hour away from the point of collection.

Sample analysis

The parameters that were determined in situ included pH, temperature, electrical conductivity, and total dissolved solids (TDS) using a handheld Hanna multi-meter instrument (HI 98,129). The other parameters that were determined in the laboratory included dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), chloride ion, ammonia, nitrate, nitrite, phosphate, iron, copper, zinc, lead, chromium, cadmium, bacterial coliforms, and *Escherichia coli* (*E. coli*). For most WQI studies, the five parameters that are common denominators in all major WQI models include DO, BOD, total suspended or dissolved solids, temperature, and conductivity [19,31]. However, the modified National Sanitation Foundation of the USA (NSF-WQI) method upon which this study was based included temperature, total solids, pH, DO, coliform, BOD, phosphates, and nitrates [19]. All these were captured in this study. The BOD was determined using the azide modification method [32]. The COD was determined using the closed reflux titrimetric method [32]. Nitrite and nitrate were determined by the colorimetric method [32]. The phosphate content was determined using the colorimetric ascorbic acid method [32]. Dissolved oxygen (DO) was determined using the Winkler/iodometric method [32]. The biological oxygen demand (BOD) was determined using the azide modification method[32]. All the heavy metals were digested before analysis. The digestion was performed using a method [32], while the analysis was performed with an atomic absorption spectrophotometer (AAS Buck 210). The biological parameters (total coliforms and *E. coli*) were determined using the plate count method [32].

Data analysis

Descriptive statistics were performed on the physicochemical data to obtain metrics such as the mean, variance, standard deviation, and standard error. The variance test is used to analyse the differences in groups of tests while standard error informs on how accurate the mean of any given sample is, compared to the true population mean [33]. Standard deviation is a measure of how dispersed the data is in relation to the mean [33]. The statistical analysis was performed using Microsoft Excel software. Additionally, Pearson's correlation analysis was performed with IBM SPSS v29 software. Furthermore, the stream water quality index (WQI) was calculated using the modified NSF-WQI method, also known as the arithmetic weighted mean WQI_A method [34].

The formula for the modified NSF-WQI is given by Eq. (1) [34].

$$WQI_A = \sum_{i=1}^{n} W_i C_i \quad (1)$$

where W_i is the weighting factor, which ranges between 0 and 1 and is equal to 1 for all the parameters being considered. The relative weight is obtained using Eq. (2).

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (2)$$

where w_i is the weight assigned to the importance of the parameter under consideration, with weights ranging between 1 and 5 ('1′ is least important and '5' is most important).

C is the normalized subindex value, which is obtained using Eq. (3) and Table 1.

$$C = W_i . q_i \quad (3)$$

where q_i is the rating based on the concentration of the i*th* parameter, and '*i*' represents each parameter considered in the analysis, which ranges from 1 to n (where "*n*'' is the total number of parameters considered in the process).

Results and discussion

The raw physicochemical and biological data are presented in Tables 2 and 3. The maximum contaminant limit (MCL) for each parameter is also indicated in Tables 2 and 3. Usually, streams and rivers have separate water quality standards from effluent standards. The reason why the stream water quality and effluent quality standards differ is that effluent treatment is very expensive. Therefore, industries and urban wastewater treatment plants are required to treat their effluents to a certain standard with the expectation that the receiving stream will complete the breakdown of pollutants along its flow path [36]. Furthermore, different industries have different effluent discharge standards, depending on the strength of the effluent associated with the industry. In this research, Nigerian standards [35,37] were applied for both stream and effluent qualities. For parameters where no Nigerian standard limits could be obtained, the WHO [38] and FAO [37] standards were adopted.

pH

At extreme pH values (acidic or alkaline), certain pH chemical and biological reactions are triggered or catalyzed [39]. Some of these unwanted reactions may lead to unwanted byproducts. Furthermore, acidic water is deleterious to flora and fauna. For instance, algal blooms, water hyacinths, and other flora develop where there are increased nutrients (phosphate) in water. These aquatic plants act as phytoremediation agents to remove contaminants (phosphates and heavy metals) [40]. The phytoremediation process is impeded when the water is too acidic. The consequence of an impeded phytoremediation process is an accumulation of unwanted contaminants in the environment, which may be deleterious to both aquatic and land animals [41]. When humans consume fish and other edibles from such polluted rivers, public health could also be threatened [42]. Furthermore, where such polluted river water is withdrawn for municipal piped water supply, the cost of treatment could increase.

The pH of all the samples was within the acceptable range, except for the raw sample from the alcoholic beverage wastewater, which was slightly acidic at 5.7 (Table 2).

Temperature

Stream temperature could increase, especially from industrial activities and, sometimes, from climatic conditions. An elevated stream temperature is unfavourable to land and aquatic fauna [43]. This may also impact the integrity of the samples used for analysis. Hence, this parameter is important.

The temperatures of all the samples ranged between 28.8 °C and 29.7 °C, which are within standard limits (Table 2).

Conductivity

Conductivity (also known as electrical conductivity in some literature) is the ability of water to conduct electrical currents. High conductivity is indicative of dissolved salts in water [44]. In this study, the conductivity was well below the MCL (Table 2).

Table 1
Parameters, weighting, and normalization factors used in the modified WQI calculation.

PARAMETERS	Nigerian Stream MCL*	w_i	$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i}$	Normalization Factor, Ci										
				100	90	80	70	60	50	40	30	20	10	0
DO (mg/l)	4	4	0.086957	≥7.5	>7	>6.5	>6	>5	>4	>3.5	>3	>2	≥1	<1
BOD (mg/l)	6	3	0.065217	<0.5	<2	<3	<4	<5	<6	<8	<10	<12	≤15	>15
COD (mg/l)	30	3	0.065217	<5	<10	<20	<30	<40	<50	<60	<80	<100	≤150	>150
Nitrate (mg/l)	40	2	0.043478	<0.5	<2	<4	<6	<8	<10	<15	<20	<50	≤100	>100
Nitrite (mg/l)	0.08	2	0.043478	<0.005	<0.01	<0.03	<0.05	<0.1	<0.15	<0.2	<0.25	<0.5	≤1	>1
Phosphate (mg/l)	3.5	1	0.021739	<0.025	<0.05	<0.1	<0.2	<0.3	<0.5	<00.75	<1	<1.5	≤2	>2
Copper (mg/l)	0.01	2	0.043478	<0.001	<0.002	<0.003	<0.005	<0.007	<0.01	<0.02	<0.03	<0.05	≤0.75	>0.75
Lead (mg/l)	0.1	5	0.108696	<0.01	<0.02	<0.03	<0.05	<0.07	<0.1	<0.2	<0.3	<0.5	≤0.75	>0.75
Zinc (mg/l)	0.2	1	0.021739	<0.02	<0.05	<0.1	<0.15	<0.2	<0.25	<0.25	<0.3	<0.4	≤0.5	>0.5
Cadmium (mg/l)	0.01	5	0.108696	<0.001	<0.002	<0.003	<0.005	<0.007	<0.01	<0.02	<0.03	<0.05	≤0.75	>0.75
Chromium (mg/l)	0.5	5	0.108696	<0.001	<0.005	<0.01	<0.05	<0.1	<0.25	<0.5	<0.75	<1	≤1.5	>1.5
Iron (mg/l)	0.5	4	0.086957	<0.001	<0.005	<0.01	<0.05	<0.1	<0.25	<0.5	<0.75	<1	≤1.5	>1.5
T.Coli (cfu/100 ml)	10	3	0.065217	0	<2	<3	<4	<5	<6	<8	<10	<12	≤15	>15
E.COLI (cfu/100 ml)	0	5	0.108696	0	<1	<2	<3	<4	<5	<6	<7	<8	≤10	>10
pH	6.5–8.5	1	0.021739	7	7–8	7–8.5	7–9	6.5–7	6–9.5	5 or 10	4 or 11	3 or 12	2 or 13	1 or 14
		$\sum w_i = 46$	$\sum W_i$ =1.0000											

Sources: [34,35]*.

Table 2
Field results (physical data).

Sampling Point	Sample Code	Elevation (m)	pH	Temperature (°C)	Conductivity (μs/cm)	GPS Location
Treated Domestic Effluent	C1	40.51	6.6	29.7	0.26	6°40′18″ N 3°09′15″ E
10 m upstream	S1	17.36	7.4	28.8	0.26	6°40′25″ N 3°09′09″ E
Mixing Point (Reference)	S2	16.79	7.7	29.1	0.25	6°40′25″ N 3°09′06″ E
Industrial Effluent	C2	18.58	5.7	29.5	0.17	6°40′25″ N 3°09′07″ E
Bridge (Industrial+urban Effluent)	S3	16.58	6.8	29.2	0.20	6°40′25″ N 3°09′04″E
Stream Quality Standard (MCL)			6.5–8.5[a]	<40[d]		
Effluent Standard for urban/ domestic wastewater[b] (MCL)			6–9[c]		7,000[c]	

[35,37,38]FGN [35][a]; WHO ([38])[c]; FAO [37]

Dissolved oxygen

Dissolved oxygen (DO) is crucial to the survival of flora and fauna. It is also indicative of the 'health' of the stream. Dissolved oxygen is trapped from the air as the stream travels downstream [45]. Typically, fast-flowing rivers and streams trap DO at a faster rate than slow-flowing or stagnant pools [45]. However, stream DO can be depleted due to oxidation processes (in cases of inorganic contaminants) and waste digestion processes (in cases where organisms that break down the waste use up oxygen). Typically, the reaction of oxygen with contaminants begins at some distance downstream of the point at which the contaminant enters the stream [45].

The DO level in the Arobieye stream was within the proper range upstream at S1 and at S2, but it became seriously degraded at S3 (Table 3). The Nigerian Standard for stream water quality requires that the stream DO not fall below 4.0 mg/L (Table 3). However, the stream deteriorated to 1.1 mg/L at S3 (Table 3). Although the DO in the two effluents (from the urban WWTP and the industrial point source) was above the required 4.0 mg/L, the steep deterioration of the stream DO downstream may be explained by the oxidation of inorganic contaminants and the increased pathogenic population that digests organic contaminants along the stream. Researchers reported a similar steep deterioration of DO in Lake Hawassa in Ethiopia because of urban wastewater discharges. This led to several problems, including mortality in aquatic life [23].

Biochemical oxygen demand

The biochemical oxygen demand (BOD) is a pollution indicator that is determined by the amount of oxygen required by cellular organisms to completely break down organic waste [46]. A high BOD is usually indicative of a high organic waste load. If the wastewater treatment at the campus is ineffective, for instance, it could lead to effluent of greater strength, which could heavily impact the receiving stream.

In this study, the BOD of both effluents (C1 and C2) was well below the required standard (Table 3). However, the stream BOD quality measured was greater than the MCL required at point S3. This steep increase in BOD may be explained by the increased activity of the pathogenic population that digests organic contaminants along the stream.

Chemical oxygen demand

Chemical oxygen demand (COD) is also a pollution indicator that is determined by the amount of oxygen required to completely breakdown an inorganic contaminant [46]. A high COD value means that there is a high inorganic waste load in the stream. Such contaminants could be detergents from urban wastewater or alcoholic beverage waste. The COD from the urban WWTP was lower than the required MCL (Table 3). However, the COD from the alcoholic beverage factory was 5164 % higher than the MCL specified by the FAO [37]. The effect of this elevated COD load on the Arobieye stream is evident by the steep increase in the stream COD after the entrance of the effluent at C2. The studies by Lencha et al. [23] also clearly demonstrated the direct link between increased COD and industrial effluent discharges.

Nitrate and nitrite

Nitrogen contamination from organic matter such as fertilizers and human and animal wastes can increase the nitrate and nitrite parameters of water [47]. Nitrite is several times more toxic than nitrate because of its unstable nature [47]. When ingested in drinking water (especially by infants younger than five years), nitrate quickly removes oxygen from the body. This can lead to infant methemoglobinemia, also known as blue-baby syndrome [48]. This condition can lead to death by asphyxiation of infants [48].

Nitrate in all five samples was below the MCL (Table 3). However, the nitrite from the urban WWTP was much greater than the MCL required for stream quality (Table 3). Nevertheless, no nitrite contaminants were detected anywhere along the stream. Nitrite was possibly oxidized into nitrate along the flow path by the high level of DO, thus showing the capacity of a flowing stream to break down contaminants and auto-purify itself [45].

Table 3
Laboratory results (chemical data).

Sample no	LOCATION DESCRIPTION	DO (mg/L)	BOD_5 (mg/L)	COD (mg/L)	Nitrate (mg/L)	Nitrite (mg/L)	Phosphate (mg/L)	Cu (mg/L)	Pb (mg/L)	Zn (mg/L)	Cd (mg/L)	Cr (mg/L)	Fe (mg/L)	T.Coli (CFU /100 ml)	*E. coli* (CFU /100 ml)
C1	Treated Domestic Effluent	6.542	4.345	76.80	3.127	0.238	5.087	0.130	ND	0.017	0.016	0.022	0.044	40,000	25,000
S1	10 m Upstream	16.342	4.345	89.60	0.784	ND	8.195	ND	ND	0.007	0.072	0.005	0.046	ND	ND
S2	Mixing Point (C1+Stream)	13.863	2.276	51.20	1.877	ND	4.995	0.021	ND	0.011	0.086	0.019	0.041	20,000	ND
C2	Industrial Effluent	5.380	6.159	8192.00	2.929	ND	6.911	0.002	ND	0.014	0.079	ND	0.044	180,000	110,000
S3	Bridge (C1+C2+151m Downstream)	1.104	17.109	3072.00	6.673	ND	7.808	0.007	ND	0.014	0.086	0.009	0.053	95,000	20,000
Stream Quality Standards		4.0	6	30	40	0.08	3.5	0.01	0.1	0.2	0.01	0.5	0.5	10	0
Effluent Standard for alcoholic beverages[b]			50[b]	150[b]											
Effluent Standard for urban/ domestic wastewater[b]		>1[c]	50[b]	100[b]	45[c]		15[c]	0.2[c]	0.2[c]	5[c]	0.01[c]	0.02[c]	1.5[c]		1,000[c]

ND – Not Detected; C1 & C2 – Effluent samples; S1, S2, S3 – Stream samples; FGN ([35])[a]; FAO [37][b]; WHO [38][c].

Phosphate

Phosphoric compounds such as phosphates can lead to the eutrophication of water bodies [49]. Signs of eutrophication include odours emanating from the stream, plant growth midstream, and a thin, oily film covering the stream surface. When eutrophication sets in a surface water body, such a water body is said to be dying because dissolved oxygen is used up, and much of the biodiversity in the river dies off. In communities where people depend on inland waterways for travel, a river with severe eutrophication problems will cause seaweed to grow on them. Such aquatic plants can impede movement and negatively impact the socio-economic life of those who depend on such modes of travel. Sources of phosphates include sewage treatment plants, fertilizers, animal manure, and other agricultural wastes [50].

The phosphate in both effluent samples was below the MCL required for urban wastewater effluent quality (Table 3). However, the phosphate contaminants in all the stream water samples exceeded the required stream quality requirements. If the stream continues to flow unhindered, it can absorb the required atmospheric oxygen to completely break down the phosphate contaminants. However, many aquatic plants that limit stream flow speed have been observed along the river. The restricted flow along some of the stream segments can lead to eutrophication and, consequently, further deterioration of the stream water quality. A case of the increased nutrients from urban wastewater fuelling widespread algal blooms and impacting water quality was reported in South Africa [22].

Copper

Copper is a heavy metal that occurs in dissolved, particulate, or complex bonds in surface, ground, and saline water bodies [51]. Copper is also described as a trace metal because it is a micronutrient required by living organisms in trace quantities [52]. At elevated levels, however, it can be toxic when it accumulates beyond the maximum required levels [53]. Some of the sources of copper contamination include fungicides, manure from pig farms, sewage sludge, atmospheric deposition, mineral mining, industrial activities, and particulates from vehicular brakes [52]. Excessive copper intake into living tissues can alter the deoxyribonucleic acid (DNA) content, enzyme activity, and respiratory and photosynthetic activities of organisms [51]. Through phytoremediation, plant tissues can absorb copper from soil and water. When such plants are consumed by humans, copper poisoning may occur.

Table 3 shows that the effluent from the urban WWTP fell below the required effluent standard. No effluent standards were generally found for industries. However, the stream copper levels exceeded the stream quality MCL at S1 and S2. However, this effect was mitigated to the required MCL at S3.

Cadmium

Cadmium is a highly toxic heavy metal with no benefits to human or plant tissue in any quantity [54]. Cadmium is carcinogenic, and it affects human kidneys and liver when it is ingested through food or water [55]. Cadmium can leach naturally into an environment through volcanic activities or natural geological deposits [55]. It can also be released into the environment through anthropogenic activities such as waste disposal, steel and waste incineration, fossil fuel combustion, phosphate fertilizer production, and battery manufacture [55]. However, waste disposal is the most common contributor of cadmium to the environment [55]. The impact of cadmium contamination on the food chain can lead to serious public health issues and disruptions to food security. In cases where strict regulations are not observed, cadmium poisoning of whole communities can occur if contaminated wastewater is used for irrigation or when pesticides and fertilizers are applied directly to crops.

In the present study, cadmium levels were high in all the samples (both effluent and stream samples). Previous stream water quality studies in Ota corroborate this finding [54]. Water in nearly every location in Ota has cadmium contaminants exceeding the MCL, whether in the ground or surface water [54]. This suggests that natural geological deposits may be responsible [56]. There is also the possibility that the high cadmium contamination in Ota may be the consequence of anthropogenic sources since Ota hosts hundreds of manufacturing industries. Table 3 shows that the cadmium contaminant levels in the stream samples (S1, S2 and S3) exceeded the levels in the effluents (C1 and C2), which supports the theory that the elevated cadmium levels are attributable to natural geological deposits [56]. The highest value of 0.86 mg/l was measured at sampling points S1 and S2, which is 8600 % above the specified MCL. Balali-Mood et al. [57] reported the results of an experiment where people who lived in environments with high cadmium concentration were associated with high incidents of osteoporosis, nephrocarcinogenicity, and urinary cadmium compared to the control population. Much of this problem was associated with ingesting cadmium-polluted water.

Other heavy metals (lead, chromium, iron)

The other heavy metals, such as lead, chromium, and iron, were all well below the stream and effluent quality MCL. Lead was not detected in any of the samples.

Total coliforms and E. coli

Water coliforms are a health hazard, especially for infants [58]. Total coliform bacteria include all forms of both disease-causing and non-disease-causing enterobacteria (bacteria found in the guts of humans or animals) [58]. Escherichia coliform bacteria, on the other hand, is a strong indicator of faecal contamination [58]. *E. coli* can cause diarrhoeal disease [59]. *E. coli* can survive for up to four months at temperatures ranging between 15 and 18 °C in packaged water and longer in surface water [58]. Most drinking water quality standards require that the coliform count be zero as a precaution.

As shown in Table 3, the stream had no indication of *E. coli* bacteria at S1 or S2. However, the two effluents (C1 and C2) contained high counts of bacteria. The industrial effluent contained more coliform bacteria than did the effluent from the WWTP. This suggests that the industrial effluent was probably mixed with gray or black water waste as well. Subsequently, the coliform count in the stream increased significantly after the entry of the industrial effluent at C2. The *E. coli* population is lower than the total coliform population, which suggests that there are other coliform strains present in the effluents.

Correlation analyses

Table 4 presents the results of the statistical analysis of the physicochemical data. The analyses included the mean, standard deviation, variance, and standard error for thirteen parameters from the five sampling locations. Table 5 also presents the Pearson's correlation (r) matrix between the different tested parameters. Pearson's correlation measures the strength of the relationship between two parameters while also specifying direction [60]. The direction could be on either side of zero, that is, a range of $-1 < 0 < +1$. Zero means that there is no correlation between the two tested parameters. A minimum of one means that the two parameters are strongly inversely related. That is, as parameter A increases, parameter B decreases in equal proportion. A positive correlation indicates that the two parameters are strongly positively correlated. That is, as parameter A increases, parameter B increases in equal proportion. Faizi and Alvi [60] further suggested an interpretation of the positive relative strength of the correlation coefficient between parameters. A correlation coefficient of $r \geq 0.8$ means that the parameters are strongly and positively correlated. If $0.6 \leq r \leq 0.79$, then the relationship between the parameters is moderately strong. If $0.3 \leq r \leq 0.59$, then the relationship between the parameters is fair. If $r <$ 0.03, then the relationship between the parameters is poor. Due to the limitation of space for a detailed discussion of all correlated parameters, only the strongly and positively/negatively correlated (± 0.8) parameters and some moderately correlated ($0.6 \leq r \leq 0.79$) parameters were discussed.

Total coliform bacteria showed a strongly positive correlation of 0.976 with nitrate (Table 5). This strong correlation is expected considering that when a faecal mass is digested by pathogens, it releases methane (CH_4), hydrogen sulphide (H_2S), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3) [61]. Ammonia reacts with water molecules to give off nitrate (Eqs. (4) and 5). Therefore, the process begins with pathogens (total coliform) in the faecal matter, which results in the production of nitrate [61]. As the pathogen population increases, so does the gas emission.

$$NH_3 + H_2O \rightleftarrows NH_4{}^+ + OH^- \tag{4}$$

$$NH_4{}^+ + 2O_2 \rightarrow NO_3{}^- + H_2O + 2H^+ \tag{5}$$

The correlation of 0.989 between copper and nitrite was the strongest in the correlation matrix (Table 5). This finding supports the research of Turbull et al. [62], who explained that copper serves as a reducing agent in the reaction with nitrite (Eq. (6)). Eq. (6) shows that as nitrite reacts with copper, copper oxide is formed, and nitrogen gas is released. The reduction of nitrite through this process is a welcome reaction, as nitrite is toxic (the cause of blue-baby syndrome) when ingested by infants.

$$2NO_2^- \text{ (aq)} + 3Cu \text{ (s)} + 2H^+ \rightarrow N_2\text{(g)} + 3CuO\text{(s)} + H_2O \tag{6}$$

The reaction between *E. coli* and zinc also yielded a very strong positive correlation (0.910). This correlation result supports several research findings showing that the presence of zinc is deleterious to *E. coli* [63]. Rihacek et al. [63] reported that zinc exposure to *E. coli* led to an antibiotic response in the bacteria. It significantly altered the morphology and physiology of the pathogens, reduced their population, and created newer strains of the pathogen. When zinc was removed from the system, the *E. coli* pathogen returned to the status quo, confirming that the presence of zinc is toxic to the pathogen.

BOD and nitrate were also strongly and positively correlated (0.845). The BOD is an indicator of the presence of pathogens. As pathogens take up oxygen from the environment, they release other gases (Eqs. (4) and 5).

The strong but negative correlation between chromium and phosphate is an example of an inverse relationship. This strong negative correlation was confirmed by Vogel et al. [64], who reported that phosphorus-based fertilizers contain toxic elements such as hexavalent-state chromium (Cr (VI)). You et al. [65] also described the adsorptive properties of calcium phosphate in the removal of chromium (VI) with respect to contact time, pH variation, and surface area. Thus, as phosphate compounds increase under certain conditions, chromium (which is a toxic element) is depleted, thus confirming the strongly negative correlation of both elements.

BOD and total coliform content also had a strongly positive correlation at 0.845. This relationship can be explained by the fact that the total oxygen requirement of pathogens to completely break down organic waste is referred to as BOD. Therefore, it is logical that BOD will increase as the number of colony-forming units of pathogens increases.

The reaction between iron and nitrate is moderately correlated (0.76). Often, iron is used for the removal of nitrates in wastewater [66]. This is a positive reaction as it assists in reducing the concentration of nitrates that were released into the water bodies through various effluent discharges. Nitrate and *E. coli* were also found to be moderately correlated at 0.708. This is expected considering that nitrate is important for the proliferation of *E. coli*, and both contaminants are found in or produced from faecal matter [67]. It can also be seen that iron and total coliform are moderately correlated at 0.762. Studies show that the presence of iron compounds in water under anaerobic conditions is known to increase bacterial activity [68,69].

Table 4
Descriptive statistics of the physicochemical data.

C1 (Treated Domestic Effluent)								
PARAMETER	Unit	Min	Max	Mean	SD	Variance	Range	Std. Error
DO	mg/l	4.311	10.35	6.542333	2.705673	0.107256	6.039	1.562121
BOD	mg/l	1.655	7.035	4.345	2.69	7.2361	5.38	1.902117
COD	mg/l	51.2	102.4	76.8	25.6	655.36	51.2	18.10193
Nitrate	mg/l	2.035	4.575	3.127	1.067068	1.138635	2.54	0.616072
Nitrite	mg/l	ND	0.238	0.238	NA	NA	NA	NA
Phosphate	mg/l	2.431	7.743	5.087	2.656	7.054336	4.623336	1.878076
Copper	mg/l	0.028	0.231	0.1295	0.1015	0.010302	0.203	0.071771
Zinc	mg/l	0.013	0.022	0.016667	0.003859	1.49E-05	0.009	0.002228
Cadmium	mg/l	0.069	0.107	0.09	0.015769	0.000249	0.038	0.009104
Chromium	mg/l	0.004	0.04	0.022	0.018	0.000324	0.036	0.012728
iron	mg/l	0.036	0.0502	0.044067	0.005	0.000025	0.0142	0.003439
Total Coliform	cfu/100ml	30,000	50,000	40,000	10,000	1.0 × 10ˆ8	20,000	11,863.42
E. coli	cfu/100ml	20,000	30,000	25,000	5000	2.5 × 10ˆ7	10,000	3535.53
C2 (Industrial Effluent)								
DO	mg/l	2.069	8.69	5.3795	3.3105	10.95941	6.621	2.340877
BOD	mg/l	4.04	8.277	6.1585	2.1185	4.488042	4.237	1.498006
COD	mg/l	ND	8192	8192	NA	NA	NA	NA
Nitrate	mg/l	2.224	3.633	2.9285	0.7045	0.49632	1.409	0.498157
Nitrite	mg/l	ND	ND	ND	ND	ND	ND	ND
Phosphate	mg/l	6.145	7.676	6.9105	0.7655	0.58599	1.531	0.54129
Copper	mg/l	ND	0.002	0.002	NA	NA	NA	NA
Zinc	mg/l	0.011	0.016	0.0135	0.0025	6.25E-06	0.005	0.001768
Cadmium	mg/l	0.071	0.086	0.0785	0.0075	5.63E-05	0.015	0.005303
Chromium	mg/l	ND	ND	ND	ND	ND	ND	ND
iron	mg/l	0.041	0.047	0.044	0.003	0.000009	0.041	0.002121
Total Coliform	cfu/100ml	ND	18,000	18,000	NA	NA	NA	NA
E. coli	cfu/100ml	ND	11,000	11,000	NA	NA	NA	NA
S1 (10 m upstream)								
DO	mg/l	14.89	17.794	16.342	1.452	2.108304	17.794	1.026719
BOD	mg/l	1.655	7.035	4.345	2.69	7.2361	5.38	1.902117
COD	mg/l	25.6	153.6	89.6	64	4096	128	45.25483
Nitrate	mg/l	0.584	0.983	0.7835	0.1995	0.0398	0.399	0.141068
Nitrite	mg/l	ND	ND	ND	ND	ND	ND	ND
Phosphate	mg/l	8.133	8.257	8.195	0.062	0.003844	0.124	0.043841
Copper	mg/l	ND	ND	ND	ND	ND	ND	ND
Zinc	mg/l	0.006	0.007	0.0065	0.0005	2.5E-07	0.001	0.000354
Cadmium	mg/l	0.061	0.082	0.0715	0.0105	0.00011	0.021	0.007425
Chromium	mg/l	ND	0.005	0.005	NA	NA	NA	NA
iron	mg/l	0.0436	0.049	0.0463	0.0027	7.29E-06	0.0436	0.001909
Total Coliform	cfu/100ml	ND	ND	ND	ND	ND	ND	ND
E. coli	cfu/100ml	ND	ND	ND	ND	ND	ND	ND
S2 (reference/mixing point with Domestic Effluent)								
DO	mg/l	13.242	14.484	13.863	0.621	0.385641	1.242	0.439113
BOD	mg/l	2.069	2.482	2.2755	0.2065	0.042642	0.413	0.146018
COD	mg/l	51.2	51.2	51.2	NA	NA	NA	NA
Nitrate	mg/l	1.446	2.308	1.877	0.431	0.185761	2.308	0.304763
Nitrite	mg/l	ND	ND	ND	ND	ND	ND	ND
Phosphate	mg/l	2.301	7.688	4.9945	2.6935	7.254942	5.387	1.904592
Copper	mg/l	0.01	0.031	0.0205	0.0105	0.00011	0.021	0.007425
Zinc	mg/l	0.009	0.012	0.0105	0.0015	2.25E-06	0.003	0.001061
Cadmium	mg/l	0.077	0.095	0.086	0.009	0.000081	0.018	0.006364
Chromium	mg/l	0.007	0.03	0.0185	0.0115	0.000132	0.023	0.008132
iron	mg/l	0.037	0.045	0.041	0.004	0.000016	0.045	0.002828
Total Coliform	cfu/100ml	ND	20,000	20,000	NA	NA	NA	NA
E. coli	cfu/100ml	ND	ND	ND	ND	ND	ND	ND
S3 (150 m downstream)								
DO	mg/l	0.414	2.483	1.103667	0.975336	0.95128	2.069	0.56311
BOD	mg/l	13.25	20.28	17.10867	2.910847	8.47303	4.546	1.680578
COD	mg/l	3072	3072	3072	NA	NA	NA	NA
Nitrate	mg/l	4.979	8.366	6.6725	1.6935	2.867942	3.387	1.197485
Nitrite	mg/l	ND	ND	ND	ND	ND	ND	ND
Phosphate	mg/l	7.331	8.429	7.807667	0.459781	0.211398	1.098	0.265454
Copper	mg/l	0.005	0.008	0.0065	0.0015	2.25E-06	0.003	0.001061
Zinc	mg/l	0.026	0.0084	0.0142	0.008344	6.96E-05	0.0178	0.004818
Cadmium	mg/l	0.08	0.092	0.086	0.006	0.000036	0.012	0.004243
Chromium	mg/l	0.009	0.009	0.009	NA	NA	NA	NA
iron	mg/l	0.048	0.059	0.052667	0.0015	2.25E-06	0.008	37.00104

(*continued on next page*)

Table 4 (*continued*)

C1 (Treated Domestic Effluent)								
PARAMETER	Unit	Min	Max	Mean	SD	Variance	Range	Std. Error
Total Coliform	cfu/100ml	40,000	150,000	95,000	55,000	3.03E+09	110,000	38,890.87
E. coli	cfu/100ml	20,000	20,000	20,000	NA	NA	NA	NA

Water quality index analysis

The WQI_A analysis performed on the Arobieye stream before (S1) and 115 m downstream after pollution (S3) showed that the stream water quality was good before the effluent from the effluent from the WWTP and the industry mixed with it. Subsequently, the stream water quality could be classified as 'bad' following the recommendations of the WQI_A. The results of the WQI_A analysis illustrate how anthropogenic activities degrade the environment. The environmental degradation caused by the two pollutant sources could have been avoided if proper environmental monitoring had been in place to ensure compliance with the national effluent quality standards. Discharging untreated wastes into the environment reduces the cost of production and increases profitability for industries and commercial enterprises. However, when polluters disregard laid-down standards, the ultimate loser is the public. Polluters can only eliminate environmental pollution when the responsible authorities do not enforce the regulations as appropriate. There is documented evidence that people living around the Atuwara River (which receives inflow from the Arobieye stream) use it for domestic purposes without pretreatment [54]. Children swim in it, and women fetch water from it for laundry, cooking, and drinking. The continuous pollution of the stream, therefore, may lead to an epidemic if unchecked.

Spatial variability

Arobieye stream is the main natural sink for the wastewater effluent from the higher education institution that is adjacent to it. Therefore, the sampling locations along Arobieye Stream were selected primarily to track the stream's response to the impact of wastewater from the institution and its surroundings. Since the generated wastewater volume is directly correlated to changes in population, it is expected that an increase in the populated areas adjacent to the Arobieye stream can have a direct impact on stream pollution [54]. The impact of the physical developments around the stream is shown in the Land Use-Land Cover (LULC) analysis (Fig. 2; Table 6). The LULC map of the surroundings of the sampled section of Arobieye stream is presented in Fig. 2. The images show the changes in the area between 2020, when this study was conducted, and 1999, before the rapid changes in the area began. The images, which were obtained from Google Earth Engine (Landsat 5 L02 T1 for the 1999 data and Landsat 8 L02 T1 for the 2020 data, with path and row 191 and 55, and spatial resolution of 30 m), provide the LULC of the area with three distinct classes, namely built-up areas, open or bare spaces, and vegetation cover. Details of the analysis show that the built-up areas increased by 1823 % between 1999 and 2020 (Table 6). Also, the vegetation cover had reduced by one-third between 1999 and 2020, while the open spaces reduced by 61.5 % between 1999 and 2020 (Table 6). The reduced vegetation cover (Fig. 2) can cause an increase in direct storm run-off, which washes pollutants from the adjoining open spaces into the stream. The ingress of pollution from unidentified sources that can raise stream pollution is known as diffuse pollution source [30]. The population in the area went up from $<$1000 persons in 1999 to 10,000 in 2020, which explains the rapidly built-up areas [16]. It is noteworthy, however, that the institution is usually on break for about three months per year. This means that when the population of 8000 students at the intuition are on vacation, the volume of wastewater effluent is expected to reduce significantly. Therefore, the observed changes in the LULC could have had a direct and adverse impact on the adjoining stream, with the changes depending on the time of the year. This study was done while the students were on vacation, hence, the measured concentration of pollution in this study is expected to increase when the students are on campus. Therefore, the changes in stream quality, according to periods when the university is on or off session, is recommended for investigation in future studies.

Conclusion

In conclusion, this research provides insight into the intricate requirements and complex processes for monitoring and ensuring the pristine condition of surface water bodies using WQI and correlation analysis. Surface water pollution is a daunting challenge that impacts public health and the general environment in many countries, especially in developing nations.

The key findings from this research address four main themes. First, it provides insight into the global problem of surface water pollution from anthropological activities such as wastewater disposal from industrial, agricultural, and domestic activities. Surface water pollution has far-reaching consequences on the environment and public health in general when left to fester. Secondly, the study highlighted the importance of using local surface water guidelines (where available) when performing water quality index analysis. Water quality standards and guidelines are usually prepared with local conditions as the baseline [30]. Such conditions include climatic factors, hydrological factors, available waste management laws, and the applicable penalties. For example, temperature impacts the reaction rate of physicochemical and pathogenic contaminants [30,70]. Therefore, the contaminant limits and guidelines in temperate regions may not adequately address the environmental problems in tropical areas. Notwithstanding, there are countries that are yet to develop local water guidelines. In such cases, the international surface water quality guidelines may suffice for the WQI analysis. Thirdly, the correlation analysis demonstrated cause and effect between measured contaminant parameters. That is, the

Table 5
Correlation data of the means of 25 samples with respect to 13 parameters.

Parameter	COD	NO_3	NO_2	PO_4	Cu	Zn	Cd	Cr	Fe	T. Coli	*E. coli*	DO	BOD
COD	1												
NO3	0.304	1											
NO2	−0.350	0.012	1										
PO4	0.293	0.188	−0.565	1									
Cu	−0.404	0.010	**0.989****	−0.665	1								
Zn	0.284	0.645	0.629	−0.440	0.634	1							
Cd	−0.202	0.529	0.576	−0.714	0.658	0.799	1						
Cr	−0.725	−0.003	0.675	**−0.801**	0.767	0.364	0.780	1					
Fe	0.133	0.760	−0.197	0.720	−0.260	0.132	−0.032	−0.324	1				
TOTAL COLI	0.089	**0.976****	0.082	0.127	0.094	0.604	0.600	0.163	0.762	1			
E.COLI	0.154	0.708	0.677	−0.150	0.641	**0.910***	0.652	0.286	0.427	0.696	1		
DO	0.449	−0.653	−0.187	0.266	−0.268	−0.393	−0.763	−0.642	−0.397	−0.789	−0.414	1	
BOD	0.198	**0.845**	−0.457	0.374	−0.431	−0.181	0.257	−0.154	0.760	**0.845**	0.230	−0.65	1

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

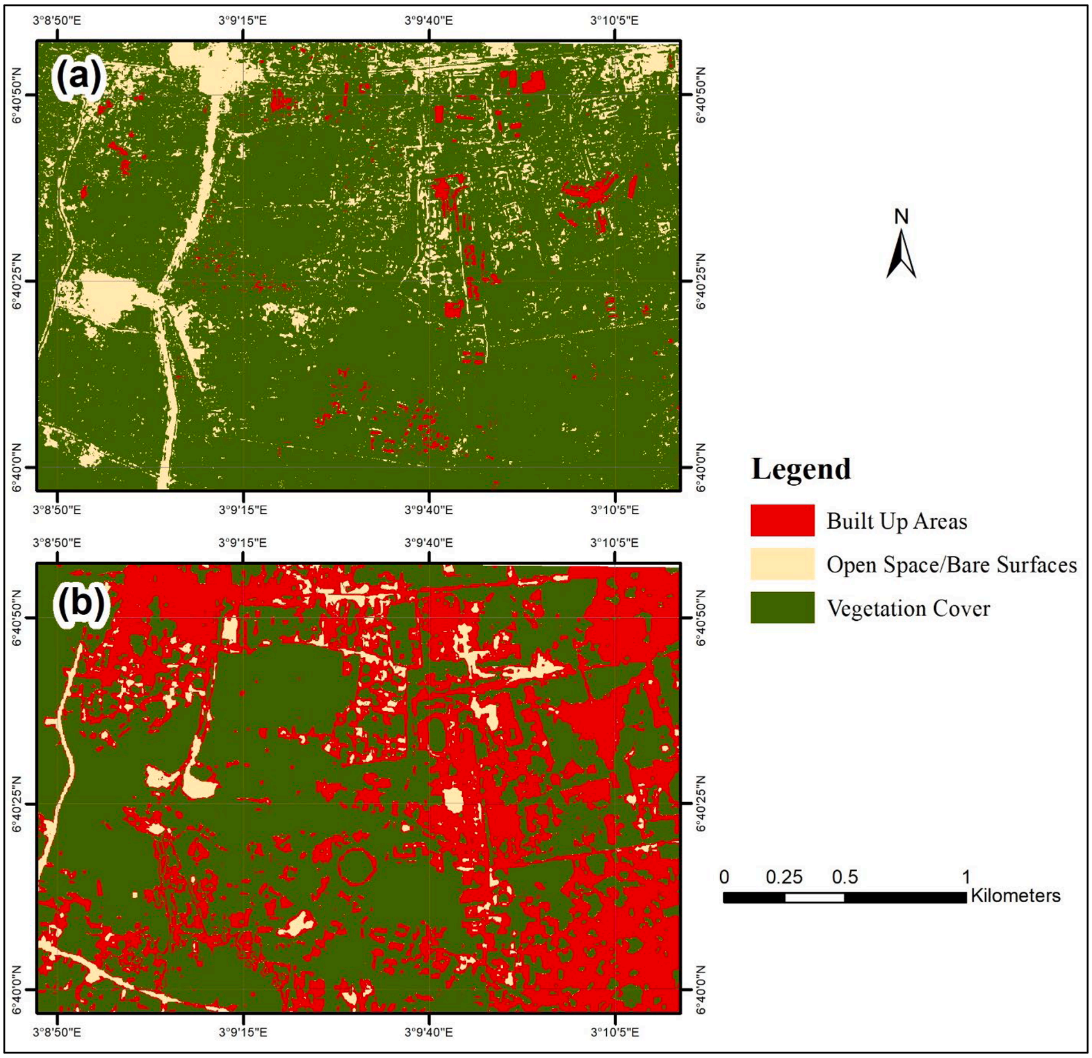

Fig. 2. LULC of the area adjacent to Arobieye Stream.

Table 6
LULC Classification Table.

LULC Class	1999 LULC		2020 LULC		Annual Change in (ha)	Annual rate in %
	Area(ha)	%	Area(ha)	%		
Built-Up Areas	10.16	1.99	195.46	38.27	8.82	86.82
Open Space/Bare Surfaces	55.86	10.94	21.51	4.21	−1.64	−2.93
Vegetation Cover	444.71	87.07	293.76	57.52	−7.19	−1.62
	510.73	100.00	510.73	100.00	0.00	0.00

presence of certain contaminants can explain the increase or decrease of others, even when they are seemingly unrelated. Finally, this research provided insight into the practical steps that must be taken to mitigate the problems of surface water pollution.

The mitigation of river pollution requires an integrated approach, which includes regulatory policies, enforcement, technological input, capacity building, adequate funding, advocacy, community engagement, and sustainable practices. The governments of countries that are affected by surface water pollution may learn much from the approach used by the United States to protect its surface water bodies. First, they set up and empowered USEPA in 1970 to help monitor the environment and enforce environmental protection laws. Next, they established the Surface Water Protection Act of 1972 [12], and very importantly, they spent more than a trillion dollars over a period of five decades to protect their surface water bodies. Such an expenditure is a demonstration of the vital importance and contribution of surface water to any economy and environment [12]. The processes of establishing and enforcing water and wastewater quality standards, regulating industrial effluent quality, and investing in wastewater collection and treatment infrastructure require much political will, commitment, and financial resources. Appropriate legislation and enforcement mechanisms should be put in place to enforce the polluter-must-pay (PMP) principle to prevent further degradation of rivers. Beyond enforcement efforts, however, collaborations among all stakeholders on the necessity of wastewater treatment could help to secure the environment. Furthermore, technological innovation is required for mitigating river pollution and restoring water quality. Rivers typically run for several thousand kilometres while passing difficult terrains and undergrowth, thereby making it almost impossible to monitor every section of the river. However, modern-day technologies such as radar, geographic information systems (GISs), satellites, and drones present options for regular monitoring. Advanced wastewater treatment technologies, such as membrane filtration, ultraviolet (UV) disinfection, and biological processes, can be used to remove contaminants and improve the safety of discharged effluents. Similarly, decentralized treatment systems, green infrastructure, and nature-based solutions, such as wetland restoration and riparian buffers, can help mitigate pollution and enhance the resilience of river ecosystems. Community engagement and public awareness are additional and essential components of any successful effort to combat river pollution. Educating individuals about the sources and impacts of pollution, promoting sustainable consumption and waste management practices, and empowering communities to act in their local watersheds are critical steps toward fostering a culture of accountability and conservation.

The main limitation of this study is that it was just a spot-check into one segment of a single receiving stream; the problem of surface water is more complex and widespread than what was captured. It should be noted that stream pollution comes all-year round into surface water bodies from diffuse and non-diffuse sources, which is a heavy burden on the environment. Nonetheless, the study limitation also serves as a pointer to future research on the problem. The procedure and discussions outlined in this research can serve as a guideline for local water monitoring and protection programmes. The dearth of wastewater collection, transportation, and treatment infrastructure makes the proper management of wastewater from municipal and industrial sources nearly impossible. The only available alternative is the release of such effluents into the nearest stream. Such practices of dumping untreated wastewater in the environment do much harm to the environment and public health. In the absence of the capital to construct a modern network of wastewater management infrastructure, however, much can be done in terms of monitoring and enforcing the on-site treatment of the generated wastewater by the polluter. Efforts should also be put in place to regularly surveil surface water bodies because they are the commonwealth of any country. Without regular monitoring and correction of the situation, the degradation may worsen. An inexpensive remediating action that can be taken urgently to protect the stream and its downstream users is to clear the stream channel of the aquatic weed that is growing midstream because of heightened phosphate levels. Weed growth limits the stream velocity and its natural capacity to absorb the needed oxygen for stream auto-purification. Another inexpensive action that can be taken to protect downstream users of stream water is public advocacy. The downstream users need to be informed of the health risks associated with drinking water from either the Arobieye Stream or the Atuwara River. Moreover, users need to be educated on inexpensive methods for removing heavy metals from water. One of the contaminants identified in every sampled segment of the stream was cadmium, which is toxic to public health when ingested. There are inexpensive adsorption methods that can be used to remove unwanted heavy metals from water before consumption. Such inexpensive and simple treatment technologies can be taught to water users. Additionally, *E. coli* and total coliform bacteria were abundant in the stream water. Downstream users can be educated on the importance of boiling water to eliminate pathogenic contamination before consumption.

Declaration of interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

There is no conflict of interest to declare. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors acknowledge Dr Chuckwueloka Okeke for assisting with the LULC data and analysis. Google Earth open source is also acknowledged for giving access to the LULC data.

CRedit authorship contribution Statement

David Omole: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, writing – review & editing. **Chinemelum Udemezue:** Formal analysis, Funding acquisition, Investigation, Resources, writing – original draft. **Oluranti Agboola**: Formal analysis, Validation, Visualization, writing – review & editing.

Funding

No funding was received to conduct this study.

Data availability

All the data that support the findings of this study are available and fully presented in this manuscript.

Ethical approval

Not applicable.

References

[1] G. Oluwasanya, D. Perera, M. Qadir, V. Smakhtin, Water security in Africa: a preliminary assessment, 2022. https://doi.org/10.53328/MUNM8683.
[2] D. Omole, J. Ndambuki, Sustainable living in Africa: case of water, sanitation, air pollution and energy, Sustainability 6 (2014) 5187–5202, https://doi.org/10.3390/su6085187.
[3] A.A. Badejo, J.M. Ndambuki, W.K. Kupolati, A.A. Adekunle, S.A. Taiwo, D.O. Omole, Appraisal of access to safe drinking water in southwest Nigeria, Afr. J. Sci. Technol. Innov. Dev. 7 (2015) 441–445, https://doi.org/10.1080/20421338.2015.1096669.
[4] C.P. Emenike, I.T. Tenebe, D.O. Omole, B.U. Ngene, B.I. Oniemayin, O. Maxwell, B.I. Onoka, Accessing safe drinking water in sub-Saharan Africa: issues and challenges in South–West Nigeria, Sustain. Cities. Soc. 30 (2017) 263–272, https://doi.org/10.1016/j.scs.2017.01.005.
[5] Y. Liu, Y. Huang, Y. Liu, Global risk assessment of river pollution stress based on nighttime light remote sensing data, Sci. Total. Environ. 949 (2024) 175146, https://doi.org/10.1016/j.scitotenv.2024.175146.
[6] S. Verma, African countries need to clean up their act on industrial pollution, Downtoearth.Org (2020). https://www.downtoearth.org.in/africa/african-countries-need-to-clean-up-their-act-on-industrial-pollution-71523 (accessed January 21, 2025).
[7] C. Letheby, Water contamination in Africa, https://storymaps.Arcgis.Com/(2021). https://storymaps.arcgis.com/stories/8d7032554bc44879be37e05f9ef0c58c (accessed January 21, 2025).
[8] A. Addo-Bediako, Comparative spatial assessment of trace metal(loid) pollution in the sediments of the Lower Olifants River Basin in South Africa, Front Env. Sci 10 (2022), https://doi.org/10.3389/fenvs.2022.882393.
[9] B. Gqomfa, T. Maphanga, B.S. Madonsela, An analysis of the effects that South Africa's informal settlements have had on the country's river systems, Nat. Environ. Pollut. Technol. 22 (2023) 1833–1843, https://doi.org/10.46488/NEPT.2023.v22i04.011.
[10] S.S. Chen, I.A. Kimirei, C. Yu, Q. Shen, Q. Gao, Assessment of urban river water pollution with urbanization in East Africa, Environ. Sci. Pollut. Res. 29 (2022) 40812–40825, https://doi.org/10.1007/s11356-021-18082-1.
[11] S. Pare, L.Y. Bonzi-Coulibaly, Water quality issues in West and Central Africa: present status and future challenges, in: IAHS Publ, Gothenburg, Sweden, 2013, pp. 87–95. https://iahs.info/uploads/dms/15573.14-87-95-361-24-H04-Pare-Bonzi_April_2013CORR.pdf (accessed January 21, 2025).
[12] D.A. Keiser, J.S. Shapiro, Consequences of the Clean Water Act and the demand for water quality, Q. J. Econ. 134 (2019) 349–396, https://doi.org/10.1093/qje/qjy019.
[13] K. Ouma, A. Shane, S. Syampungani, Aquatic ecological risk of heavy-metal pollution associated with degraded mining landscapes of the Southern Africa River basins: a review, Minerals 12 (2022) 225, https://doi.org/10.3390/min12020225.
[14] D.S. Hayes, P. Branco, J.M. Santos, T. Ferreira, Oxygen depletion affects kinematics and shoaling cohesion of cyprinid fish, Water. (Basel) 11 (2019) 642, https://doi.org/10.3390/w11040642.
[15] K.P. Neil, J. Yoder, A.J. Hall, M. Nichols, Enteric diseases transmitted through food, water, and zoonotic exposures, in: principles and practice of pediatric infectious diseases, Elsevier (2023) 408–418.e3, https://doi.org/10.1016/B978-0-323-75608-2.00058-6.
[16] V.E. Akpan, D.O. Omole, D.E. Bassey, Assessing the public perceptions of treated wastewater reuse: opportunities and implications for urban communities in developing countries, Heliyon 6 (2020), https://doi.org/10.1016/j.heliyon.2020.e05246.
[17] P.C. Emenike, O.V. Araoye, S.O. Academe, P. Unokiwedi, D.O. Omole, The effects of microplastics in oceans and marine environment on public health-a mini-review, in: IOP Conf Ser Earth Environ Sci, IOP Publishing Ltd, 2022, https://doi.org/10.1088/1755-1315/993/1/012019.
[18] D. Kumar, R. Kumar, M. Sharma, A. Awasthi, M. Kumar, Global water quality indices: development, implications, and limitations, Total Environ. Adv. 9 (2024) 200095, https://doi.org/10.1016/j.teadva.2023.200095.
[19] Md.G. Uddin, S. Nash, A.I. Olbert, A review of water quality index models and their use for assessing surface water quality, Ecol. Indic. 122 (2021) 107218, https://doi.org/10.1016/j.ecolind.2020.107218.
[20] S. Chidiac, P. El Najjar, N. Ouaini, Y. El Rayess, D. El Azzi, A comprehensive review of water quality indices (WQIs): history, models, attempts and perspectives, Rev. Env. Sci. Biotechnol. 22 (2023) 349–395, https://doi.org/10.1007/s11157-023-09650-7.
[21] H. En-nkhili, M. Najy, I. Etebaai, F.Z. Talbi, K. El Kharrim, D. Belghyti, Application of water quality index for the assessment of Boudaroua Lake in the Moroccan Pre-Rif, in: Proceedings of the 4th Edition of International Conference on Geo-IT and Water Resources 2020, Geo-IT and Water Resources 2020, New York, NY, USA, ACM, 2020, pp. 1–5, https://doi.org/10.1145/3399205.3399248.
[22] T. Banda, M. Kumarasamy, Development of a Universal Water Quality Index (UWQI) for South African river catchments, Water. (Basel) 12 (2020) 1534, https://doi.org/10.3390/w12061534.
[23] S.M. Lencha, J. Tränckner, M. Dananto, Assessing the water quality of Lake Hawassa Ethiopia—trophic state and suitability for anthropogenic uses—applying common water quality indices, Int. J. Env. Res. Public Health 18 (2021) 8904, https://doi.org/10.3390/ijerph18178904.
[24] D.K. Lukhabi, P.K. Mensah, N.K. Asare, T. Pulumuka-Kamanga, K.O. Ouma, Adapted water quality indices: limitations and potential for water quality monitoring in Africa, Water. (Basel) 15 (2023) 1736, https://doi.org/10.3390/w15091736.
[25] M.K. Miyittah, S.K. Tulashie, F.W. Tsyawo, J.K. Sarfo, A.A. Darko, Assessment of surface water quality status of the Aby Lagoon System in the Western Region of Ghana, Heliyon 6 (2020) e04466, https://doi.org/10.1016/j.heliyon.2020.e04466.
[26] F. Ligate, E. Lucca, J. Ijumulana, R. Irunde, V. Kimambo, J. Mtamba, A. Ahmad, R. Hamisi, J.P. Maity, F. Mtalo, P. Bhattacharya, Geogenic contaminants and groundwater quality around Lake Victoria goldfields in northwestern Tanzania, Chemosphere 307 (2022) 135732, https://doi.org/10.1016/j.chemosphere.2022.135732.
[27] S.M. Njuguna, J.A. Onyango, K.B. Githaiga, R.W. Gituru, X. Yan, Application of multivariate statistical analysis and water quality index in health risk assessment by domestic use of river water. Case study of Tana River in Kenya, Process. Saf. Environ. Prot. 133 (2020) 149–158, https://doi.org/10.1016/j.psep.2019.11.006.
[28] O.M. Gomez-Vazquez, L.R. Bernal-Alvarez, J.I. Velasquez-Miranda, M.E. Rodriguez-Garcia, Effects of temperature on the physicochemical properties of bioinspired, synthetic, and biogenic hydroxyapatites calcinated under the same thermal conditions, Nanomaterials 13 (2023) 2385, https://doi.org/10.3390/nano13172385.
[29] A. Aljasmi, A.S. AlJimaz, K.H.A.E. AlKhaldi, M.S. AlTuwaim, Effect of temperature and alkyl chain length on the physicochemical properties of pyridinium bis (trifluoromethylsulfonyl)imide-based ionic liquids, Chem. Thermodyn. Therm. Anal. 8 (2022) 100099, https://doi.org/10.1016/j.ctta.2022.100099.
[30] E.O. Longe, D.O. Omole, Analysis of pollution status of River Illo, Environmentalist 28 (2008) 451–457, https://doi.org/10.1007/s10669-008-9166-4.
[31] Purdue University, Simple Water Quality Index Calculator, The Nexus Institute, 2020. https://www.agry.purdue.edu/hydrology/projects/nexus-swm/en/Tools/WaterQualityCalculator.php#:~:text=The%20water%20quality%20index%20is,are%20used%20in%20the%20index (accessed January 22, 2025).
[32] APHA, Standard Methods For the Examination of Water and wastewater. - Version details - Trove, 24th ed., American Public Health Association Press, Washington DC, 2023.

[33] M.J. Hayat, A. Powell, T. Johnson, B.L. Cadwell, Statistical methods used in the public health literature and implications for training of public health professionals, PLoS. One 12 (2017) e0179032, https://doi.org/10.1371/journal.pone.0179032.
[34] D.D. Patel, D.J. Mehta, H.M. Azamathulla, M.M. Shaikh, S. Jha, U. Rathnayake, Application of the weighted arithmetic water Quality index in assessing groundwater quality: a case study of the South Gujarat region, Water. (Basel) 15 (2023) 3512, https://doi.org/10.3390/w15193512.
[35] FGN, NEQCR, Federal Government of Nigeria, Lagos, Nigeria, 2011. https://www.nesrea.gov.ng/wp-content/uploads/2020/02/Surface_and_Groundwater_Quality_Control_Regulation%202011.pdf (accessed October 15, 2024).
[36] B.J. Singh, A. Chakraborty, R. Sehgal, A systematic review of industrial wastewater management: evaluating challenges and enablers, J. Env. Manage 348 (2023) 119230, https://doi.org/10.1016/j.jenvman.2023.119230.
[37] FAO, Effluent standards, 2016. https://faolex.fao.org/docs/pdf/tw164144.pdf (accessed October 15, 2024).
[38] World Health Organization (WHO), A compendium of standards for wastewater reuse in the Eastern Mediterranean region, 2006. https://applications.emro.who.int/dsaf/dsa1184.pdf (accessed October 15, 2024).
[39] A.L. Voelker, L.S. Taylor, L.J. Mauer, Effect of pH and concentration on the chemical stability and reaction kinetics of thiamine mononitrate and thiamine chloride hydrochloride in solution, BMC. Chem. 15 (2021) 47, https://doi.org/10.1186/s13065-021-00773-y.
[40] A. Kafle, A. Timilsina, A. Gautam, K. Adhikari, A. Bhattarai, N. Aryal, Phytoremediation: mechanisms, plant selection and enhancement by natural and synthetic agents, Environ. Adv. 8 (2022) 100203, https://doi.org/10.1016/j.envadv.2022.100203.
[41] A.A. Badejo, D.O. Omole, J.M. Ndambuki, W.K. Kupolati, Municipal wastewater treatment using sequential activated sludge reactor and vegetated submerged bed constructed wetland planted with Vetiveria zizanioides, Ecol. Eng. 99 (2017) 525–529, https://doi.org/10.1016/j.ecoleng.2016.11.012.
[42] S. Muhammad, K. Ahmad, Heavy metal contamination in water and fish of the Hunza River and its tributaries in Gilgit–BALTISTAN: EVALUATION OF POTENTIAL RISKS AND PROVenance, Env. Technol. Innov. 20 (2020) 101159, https://doi.org/10.1016/j.eti.2020.101159.
[43] M. Mugwanya, M.A.O. Dawood, F. Kimera, H. Sewilam, Anthropogenic temperature fluctuations and their effect on aquaculture: a comprehensive review, Aquac. Fish 7 (2022) 223–243, https://doi.org/10.1016/j.aaf.2021.12.005.
[44] L.R.B. Rebello, T. Siepman, S. Drexler, Correlations between TDS and electrical conductivity for high-salinity formation brines characteristic of South Atlantic pre-salt basins, Water SA 46 (2020), https://doi.org/10.17159/wsa/2020.v46.i4.9073.
[45] D.R. Piatka, R. Wild, J. Hartmann, R. Kaule, L. Kaule, B. Gilfedder, S. Peiffer, J. Geist, C. Beierkuhnlein, J.A.C. Barth, Transfer and transformations of oxygen in rivers as catchment reflectors of continental landscapes: a review, Earth. Sci. Rev. 220 (2021) 103729, https://doi.org/10.1016/j.earscirev.2021.103729.
[46] J.A. Aguilar-Torrejón, P. Balderas-Hernández, G. Roa-Morales, C.E. Barrera-Díaz, I. Rodríguez-Torres, T. Torres-Blancas, Relationship, importance, and development of analytical techniques: COD, BOD, and, TOC in water—an overview through time, SN. Appl. Sci. 5 (2023) 118, https://doi.org/10.1007/s42452-023-05318-7.
[47] R. Picetti, M. Deeney, S. Pastorino, M.R. Miller, A. Shah, D.A. Leon, A.D. Dangour, R. Green, Nitrate and nitrite contamination in drinking water and cancer risk: a systematic review with meta-analysis, Env. Res. 210 (2022) 112988, https://doi.org/10.1016/j.envres.2022.112988.
[48] S.F. Johnson, Methemoglobinemia: infants at risk, Curr. Probl. Pediatr. Adolesc. Health Care 49 (2019) 57–67, https://doi.org/10.1016/j.cppeds.2019.03.002.
[49] H.M. Azam, S.T. Alam, M. Hasan, D.D.S. Yameogo, A.D. Kannan, A. Rahman, M.J. Kwon, Phosphorous in the environment: characteristics with distribution and effects, removal mechanisms, treatment technologies, and factors affecting recovery as minerals in natural and engineered systems, Environ. Sci. Pollut. Res. 26 (2019) 20183–20207, https://doi.org/10.1007/s11356-019-04732-y.
[50] B.O. Isiuku, C.E. Enyoh, Pollution and health risks assessment of nitrate and phosphate concentrations in water bodies in South Eastern, Niger. Environ. Adv. 2 (2020) 100018, https://doi.org/10.1016/j.envadv.2020.100018.
[51] M. Rehman, L. Liu, Q. Wang, M.H. Saleem, S. Bashir, S. Ullah, D. Peng, Copper environmental toxicology, recent advances, and future outlook: a review, Environ. Sci. Pollut. Res. 26 (2019) 18003–18016, https://doi.org/10.1007/s11356-019-05073-6.
[52] S. Herman, P. Lipiński, R. Starzyński, A. Bednarz, P. Grzmil, M. Lenartowicz, Molecular mechanisms of cellular copper homeostasis in mammals, Folia Biol. (Praha) 70 (2022) 201–212, https://doi.org/10.3409/fb_70-4.23.
[53] A.M. Murillo-Tovar, H. Saldarriaga-Noreña, A. Saeid (Eds.), Trace Metals in the Environment - New Approaches and Recent Advances, IntechOpen, 2021, https://doi.org/10.5772/intechopen.83504.
[54] P.C. Emenike, I.T. Tenebe, J.B. Neris, D.O. Omole, O. Afolayan, C.U. Okeke, I.K. Emenike, An integrated assessment of land-use change impact, seasonal variation of pollution indices and human health risk of selected toxic elements in sediments of River Atuwara, Nigeria, Environ. Pollut. 265 (2020) 114795, https://doi.org/10.1016/j.envpol.2020.114795.
[55] G. Genchi, M.S. Sinicropi, G. Lauria, A. Carocci, A. Catalano, The effects of cadmium toxicity, Int. J. Env. Res. Public Health 17 (2020), https://doi.org/10.3390/ijerph17113782.
[56] S. Paul, S.K. Upadhyay, N. Singh, Geogenic source of arsenic and their effect on vegetable seed germination, Trop. Plant Res. 7 (2020) 110–116, https://doi.org/10.22271/tpr.2020.v7.i1.015.
[57] M. Balali-Mood, K. Naseri, Z. Tahergorabi, M.R. Khazdair, M. Sadeghi, Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic, Front. Pharmacol. 12 (2021), https://doi.org/10.3389/fphar.2021.643972.
[58] C. Curutiu, F. Iordache, P. Gurban, V. Lazar, M.C. Chifiriuc, Main microbiological pollutants of bottled waters and beverages. Bottled and Packaged Water, Elsevier, 2019, pp. 403–422, https://doi.org/10.1016/B978-0-12-815272-0.00014-3.
[59] O. Erkmen, Isolation and counting of coliforms and *Escherichia coli*. Microbiological Analysis of Foods and Food Processing Environments, Elsevier, 2022, pp. 105–140, https://doi.org/10.1016/B978-0-323-91651-6.00051-3.
[60] N. Faizi, Y. Alvi, Correlation. Biostatistics Manual for Health Research, Elsevier, 2023, pp. 109–126, https://doi.org/10.1016/B978-0-443-18550-2.00002-5.
[61] P. Namour, The biogeochemical origin of sewage gases and control of their generation, J. Hazard. Mater. Adv. 7 (2022) 100124, https://doi.org/10.1016/j.hazadv.2022.100124.
[62] J. Turnbull, R. Szukalo, D. Zagidulin, D. Shoesmith, Nitrite effects on copper corrosion in nitric acid solutions, Corros. Sci. 179 (2021) 109147, https://doi.org/10.1016/j.corsci.2020.109147.
[63] M. Rihacek, L. Kosaristanova, T. Fialova, M. Kuthanova, A. Eichmeier, E. Hakalova, M. Cerny, M. Berka, J. Palkovicova, M. Dolejska, P. Svec, V. Adam, L. Zurek, K. Cihalova, Zinc effects on bacteria: insights from *Escherichia coli* by multi-omics approach, mSystems. 8 (2023), https://doi.org/10.1128/msystems.00733-23.
[64] C. Vogel, M.C. Hoffmann, O. Krüger, V. Murzin, W. Caliebe, C. Adam, Chromium (VI) in phosphorus fertilizers determined with the diffusive gradients in thin-films (DGT) technique, Environ. Sci. Pollut. Res. 27 (2020) 24320–24328, https://doi.org/10.1007/s11356-020-08761-w.
[65] X. You, M. Liu, X. Chen, Y. Li, Y. Yang, Mechanistic insight into the simultaneous removal of Cr(VI) and phosphate by a novel versatile bimetallic material, J. Env. Chem. Eng. 12 (2024) 114446, https://doi.org/10.1016/j.jece.2024.114446.
[66] H. Liu, W. Zeng, Z. Fan, J. Li, M. Zhan, Y. Peng, Effect of iron on enhanced nitrogen removal from wastewater by sulfur autotrophic denitrification coupled to heterotrophic denitrification under different substrate ratios, Chem. Eng. J. 421 (2021) 129828, https://doi.org/10.1016/j.cej.2021.129828.
[67] X. Zhang, Q. Zhao, C. Wu, Z. Xie, X. Ci, H. Li, W. Lin, H. Zhang, Q. Xie, Nitrate is crucial for the proliferation of gut *Escherichia coli* caused by H9N2 AIV infection and effective regulation by Chinese herbal medicine ageratum-liquid, Front. Microbiol. 11 (2020), https://doi.org/10.3389/fmicb.2020.555739.
[68] S.A. Aram, B.M. Saalidong, P.Osei Lartey, Comparative assessment of the relationship between coliform bacteria and water geochemistry in surface and ground water systems, PLoS. One 16 (2021) e0257715, https://doi.org/10.1371/journal.pone.0257715.
[69] B.M.R. Appenzeller, C. Yañez, F. Jorand, J.-C. Block, Advantage provided by iron for *Escherichia coli* growth and cultivability in drinking water, Appl. Env. Microbiol. 71 (2005) 5621–5623, https://doi.org/10.1128/AEM.71.9.5621-5623.2005.
[70] D.O. Omole, E.O. Longe, An assessment of the impact of abattoir effluents on River Illo, Ota, Nigeria, J. Environ. Sci. Technol. 1 (2008) 56–64, https://doi.org/10.3923/jest.2008.56.64.