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Seasonal and spatial variations of physicochemical parameters and heavy metals in surface water of interconnected Nigeria lagoons experiencing distinct anthropogenic disturbances

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Lagoon systems in Nigeria serve as essential ecosystems for fisheries and local livelihoods, yet, they face increasing threats from industrial discharges, agricultural runoff, and urban pollution, which may degrade water quality and pose health risks to coastal communities. This study comparatively assesses how varying anthropogenic activities influence the physicochemical properties and heavy metal levels in surface waters of Nigeria's interconnected coastal lagoons and also evaluates the contamination indices, pollution sources, and human health risks. The physicochemical parameters were; pH (6.86–6.97), dissolved oxygen (4.39–5.91 mg/L), total suspended solids (20.81–21.74 mg/L), electrical conductivity (26.28–217.11 uS/cm), and total dissolved solids (61.82 mg/L) and were within the recommended limits, except for TDS. The distribution trends and average levels of heavy metals were as follows: Zn (1.98–4.60 mg/L) > Fe (0.59–3.79 mg/L) > Cu (0.18–3.10 mg/L) > Cr (0.02–0.785 mg/L) > Pb (0.30–0.50 mg/L) > Cd (0.15–0.41 mg/L) > As (0.05–0.06 mg/L) > Ni (0.02–0.06 mg/L). Heavy metal concentrations were highest during the dry season, and the spatial analysis revealed that the concentrations of Cd, Pb, and As were highest at stations LE6 and LE9 in Lekki Lagoon, indicating areas primarily influenced by agriculture, tourism, and dredging activities. In Lagos Lagoon, stations LA1, LA3, and LA5 presented the highest levels, mostly contaminated with Cd, Cr, and Pb, corresponding with locations dominated by industrial wastewater discharge, crude oil processing, shipping activities and leaching oil from abandoned power plants. The integrated pollution and water quality indices revealed that approximately 90% of the sampling stations of both lagoons presented moderate to extreme contamination levels, rendering the water unsuitable for drinking, with potential uptake, accumulation, and ecological risks for important ecosystem functions. Multivariate analysis revealed that the elevated heavy metal concentrations in both lagoons originated primarily from diverse anthropogenic activities. The health risk assessment revealed that ingestion of Cd, Cr, and As poses the highest threat to human health, with most of the sampling stations, especially in Lagos Lagoon, presenting potential non-cancer and carcinogenic health risks, with children being the most vulnerable group. Our findings showed that both lagoons are highly contaminated irrespective of the varying anthropogenic influences. Thus, we recommend stringent monitoring of land use and contaminant sources, implementation of targeted remediation at high-risk sites, and development of integrated coastal-zone management strategies to protect the lagoon ecosystems and human health.

Keywords Lagos lagoon, Heavy metal pollution, Water quality index, Spatial distribution, Multivariate analysis, Health risk assessment

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The presence and accumulation of heavy metals in aquatic ecosystems, such as lagoons, lakes, and rivers, have emerged as significant global environmental issues because of their persistent nature, stability, and prolonged retention under natural conditions[1–8]. These toxic elements tend to frequently accumulate in organisms over time and eventually biomagnify in the food chain, causing serious health risks for humans and aquatic organisms[9], depending on several factors such as specific toxicity forms (Cu, Zn, Fe, and Co; some of which are co-enzymes) and behaviour under certain environmental conditions. Trace elements such as Cu, Zn, Cu and Fe (in appropriate levels) are considered micronutrients that are essential for enzymatic functions in biological systems[3]. The knowledge and comprehension of heavy metal toxicity and its ability to cause havoc in human body systems and the aquatic environment are widely known, although awareness is limited in some developing nations[10]. In highly populated developing nations, including Nigeria, the concentrations of contaminants in environmental matrices, including surface water, have been linked with a high likelihood of harmful health effects on human populations[1,2,5,11,12].

The increased levels of toxic metals and other emerging contaminants in West Africa Lagoons, often above acceptable thresholds, have been traced primarily to industrial activities, coupled with improper municipal waste management. In Nigeria, several manufacturing industries release untreated effluents that contain toxic metals into aquatic environments without abiding to environmental regulation[2,5,13]. In addition, contemporary farming systems, where agrochemicals, including fertilizers and fungicides, are indiscriminately applied on farms, are typically followed by processes where harmful elements are concentrated, absorbed and amplified in soil, which are then washed down into aquatic ecosystems[14]. Aquatic-based activities such as sand dredging, mineral ore mining, and industrial shipping are prevalent in most West African ecosystems[12]. This results in water quality deterioration due to the accumulation of contaminants in aquatic ecosystems, thus making this essential resource unfit for drinking, agricultural and industrial purposes, recreational activities, and even for the productivity of aquatic organisms[6].

Potentially toxic elements can trigger several adverse health risks. For example, exposure to Pb could potentiallycause hypertension, renal damage, red blood cell dysfunction, and encephalon impairment[5]. Even at low concentrations, inorganic As, especially the trivalent form has been reported to be among the most dangerous heavy metals, and is capable of causing several adverse health issues, such as liver and coronary artery disease, inconsistent skin appearance, cancer, and hyperglycemia[15]. Similarly, high-level exposure to Cd has been linked with extreme toxicity; an example of this is the 1970 itai-itai acute syndrome in Japan[16]. This condition could lead to negative health consequences in individuals, including kidney tubule and heart system damage, bone weakening, increased risk of breast and lung tissue cancers, impaired body sugar metabolism, and paralysis from insufficient blood supply to the brain[9,16]. Conversely, maintaining proper levels of vital trace elements such as Zn and Fe is widely recognized to be beneficial to both human health and aquatic organisms[9]. These elements play important roles in ensuring maximum growth, development, and metabolism, as well as in physiological, reproductive, and neurological functions. Conversely, exposure to high amounts of these elements can cause acute toxicity, hypotension, nausea, and convulsions[5,17]. At elevated levels, other trace elements, such as Cu, Cr, and Fe, have been linked to numerous gastrointestinal disorders, diarrhea, and renal problems, whereas Ni has been shown to be responsible for respiratory system impairment and dermatitis[9]. These associated toxicity and health implications imply the need for monitoring and assessing their properties to prevent adverse ecological risks.

A number of modelling indices for determining water pollution and overall quality status as well as the associated human health implications have been developed and utilized by several researchers[5,18–21]. These methods include indexical, geospatial, and multivariate techniques[2,19,20]. Among the various indexical approaches, several play essential roles in evaluating the drinkability and contamination levels of water. For example, the water quality index (WQI) synthesizes complex quality data into an aggregated value, thus simplifying the assessment of water suitability for purposes such as consumption and irrigation[7]. Also, the single factor pollution index quantifies the contribution of individual heavy metals to water contamination at a given site[20]. For comprehensive assessments, the contamination degree (C_{deg}) and heavy metal evaluation index (HMEI) are used to evaluate the modified pollution level and the toxicity of all detected toxic elements in water from certain locations. Similarly, the heavy metal pollution index (HPI) is a globally adopted metric used not only to quantify and indicate contamination levels but also to provide a detailed assessment of the health adversities posed by toxic elements to human populations[2,5,19,20,22]. Geospatial techniques are often employed for continuous monitoring of water pollution levels at a particular location and for predicting or visualizing spatially occurring data. Multivariate analysis is often conducted to decipher the potential sources and the linear relationships among heavy metal variables. Deterministic health risk assessment uses fixed metrics such as hazard quotients (HQs), hazard indices (HIs), and lifetime target cancer risks (TCRs) to estimate health-related implications, with population dimensions, toxicological data and exposure routes considered[2,5,19]– [20].

Coastal lagoon systems in Nigeria are essential for the ecosystem services they provide, including fisheries, transportation, and other socioeconomic activities; however, they are subjected to increasing anthropogenic

pressure[1,2,11,12]. Interestingly, Lekki and Lagos lagoons are interconnected West African coastal systems and are predominantly fed by Ogun, Yewa, and Osun rivers[23]. However, these lagoons significantly differ with respect to the types and natures of anthropogenic inputs received, primarily due to distinct levels of human-induced processes and land use interference. For example, Lekki Lagoon is predominantly surrounded by coastal communities, which results in numerous residential and other human-sourced contaminants. These include urban development, land reclamation, small-scale sand dredging, landfilling, discharge of household sewage systems, municipal waste disposal and agricultural practices that involve the application of agrochemicals for crop cultivation[24] (Table S1). Lekki Lagoon is also bordered by numerous tourist beaches, and the associated recreational activities, which significantly contributes to the deposition of waste materials or litters. Tourism often results in careless disposal of waste products, such as plastics, food packaging, and other debris by visitors[25]. Lagos Lagoon, on the other hand, is the most impacted coastal system within the Atlantic Gulf of Guinea[26], primarily due to the presence of various industries, combined with dense human population. This lagoon is significantly vulnerable to ceaseless effluent discharge from industries like petrochemical factories, crude oil spill during transportation; shipping operations, which involves the use of antifouling agents, automobile facilities, coating and electroplating activities, power plant projects, mineral mining, textile warehouses, pharmaceuticals, agrochemical, logging and metal factories, breweries, sawmills[27], leathers, and food processing factories (Table S1). Lagos lagoon also receives nutrient inputs, particularly from dry deposition and roadside dust, creating conditions described as eutrophic, with notable bottom water hypoxia during the harmful season[28]. As a result, the hydrochemical and hydrobiological dynamics, as well as the overall ecological diversity of this coastal lagoon have been profoundly altered[26].

Several studies have reported varying concentrations and forms of heavy metals in environmental matrices in water bodies across different locations, but only a few have examined interconnected lagoon systems with differing pollution sources. For example, Jolaosho et al.[9] reported that surface waters in dredged-mined Badagry and Ojo creeks contained elevated levels of Cd and Mn compared with those in non-dredged Gbaji river, in Lagos, Nigeria. Similarly, a long-term study revealed increased concentrations of Cd, Cu, and Zn in peanut farmlands subjected to fertilizer application in Jiangxi province, China[29]. Li et al.[30] attributed the elevated levels of As, Pb and Zn in the surface sediments of Dongting Lake, China, to industrial and mining effluent deposits from nearby plants. Zhang et al.[31] reported substantial levels of Cu, Pb, and Zn in blast furnace operations in steel and iron industries, China. Antifouling particles, which are commonly used in the shipping industries, increased Cu leaching rates but reduced Zn leaching under conditions of increased salinity[32]. In addition, both oil extraction and eventual spillage significantly influenced the speciation of several metals, including Ni, Cu, Mn, Mo, Pb, V, Cr, Zn, and Co, in the marine surface waters around Weizhou Island[33]. Based on the above studies, we hypothesize that varying nature and intensity of anthropogenic activities will result in distinct spatial and temporal patterns of physicochemical profiles and heavy metal concentrations, solubilization, and mobilization. Moreover, we expect that these differences will lead to divergent water quality profiles and varying degrees of metal contamination in the lagoons, regardless of their interconnectedness. These complex situations present research gaps, which suggest the need to investigate these interconnected ecosystems. This study aims to (i) examine the impacts of varying anthropogenic activities on the spatial and seasonal distributions of physicochemical parameters and heavy metals in surface waters from Lekki and Lagos Lagoons, with a view of determining the contamination dynamics (ii) examine the water quality level in terms of suitability for usage and the degree of contamination via indexical techniques. (iii) evaluate the non-cancer and carcinogenic health implications of water contaminants in exposed populations. The seasonal and spatial results of this study have the potential to provide empirical data essential for establishing targeted water quality standards and discharge limits at the regional level. Moreover, our findings can contribute to policy dialogues on heavy metal pollution, aid harmonization of monitoring protocols, risk assessment frameworks, and remediation strategies in coastal lagoon ecosystems facing similar anthropogenic pressures.

Materials and methods

Geographical, land use, geological profiles of the study area

The study sites are interlinked West African lagoons situated on the southwestern coast of Nigeria (Fig. 1: map was created with ArcGIS Pro version 3.4). This area experiences both tropical dry and wet periods annually. To its northern boundary, Lagos Lagoon is connected to Lekki Lagoon, with Mahin creeks joining at the southern end. Lekki Lagoon is situated between 6°27'N and 6°59'N (latitude) and 4°03′E and 4°16′E (longitude) and has an area of approximately 247 km². Lagos Lagoon, on the other hand, is located between 6°15′N and 6°36′N (latitude) and 3°10′E and 3°45′E (longitude), occupying an estimated area of 6,354 km². Precise global positioning system (GPS) coordinates were utilized to identify the sampling sites in each lagoon system, as presented in Table S1. Despite being situated within the same climatic zone, Lagos Lagoon, Lekki Lagoon, and associated ecosystems exhibit local environmental differences driven by distinct land use, urban development, and water exchange patterns, which may influence microclimatic and ecological conditions (See Table S1). However, both lagoon systems experience approximately 80% annual humidity and average temperatures ranging from 24 °C to 34 °C. The precipitation estimates within these areas are between 1200 and 1600 mm annually, with the highest and least abundant occurring from April to August and September to November, respectively, while a long-term dry spell is experienced between December and March[19].

Lagos State is a coastal region characterized by unique hydrological features considered regions of deposition[19]. Upstream waterways, mainly rivers, springs, lagoons, creeks, swamps, and drainage systems, drain largely into Lekki and Lagos Lagoons prior to final discharge into the Atlantic Ocean (Fig. S1). The coastal zones are separated from the open ocean by a sandy barrier that ranges in width from 2 to 16 km. Approximately 12% of the land area of the state experiences seasonal flooding. Both lagoons are influenced by the dual rainfall pattern of the region, which results in a wetland environment. This distinct ecological characteristic has resulted

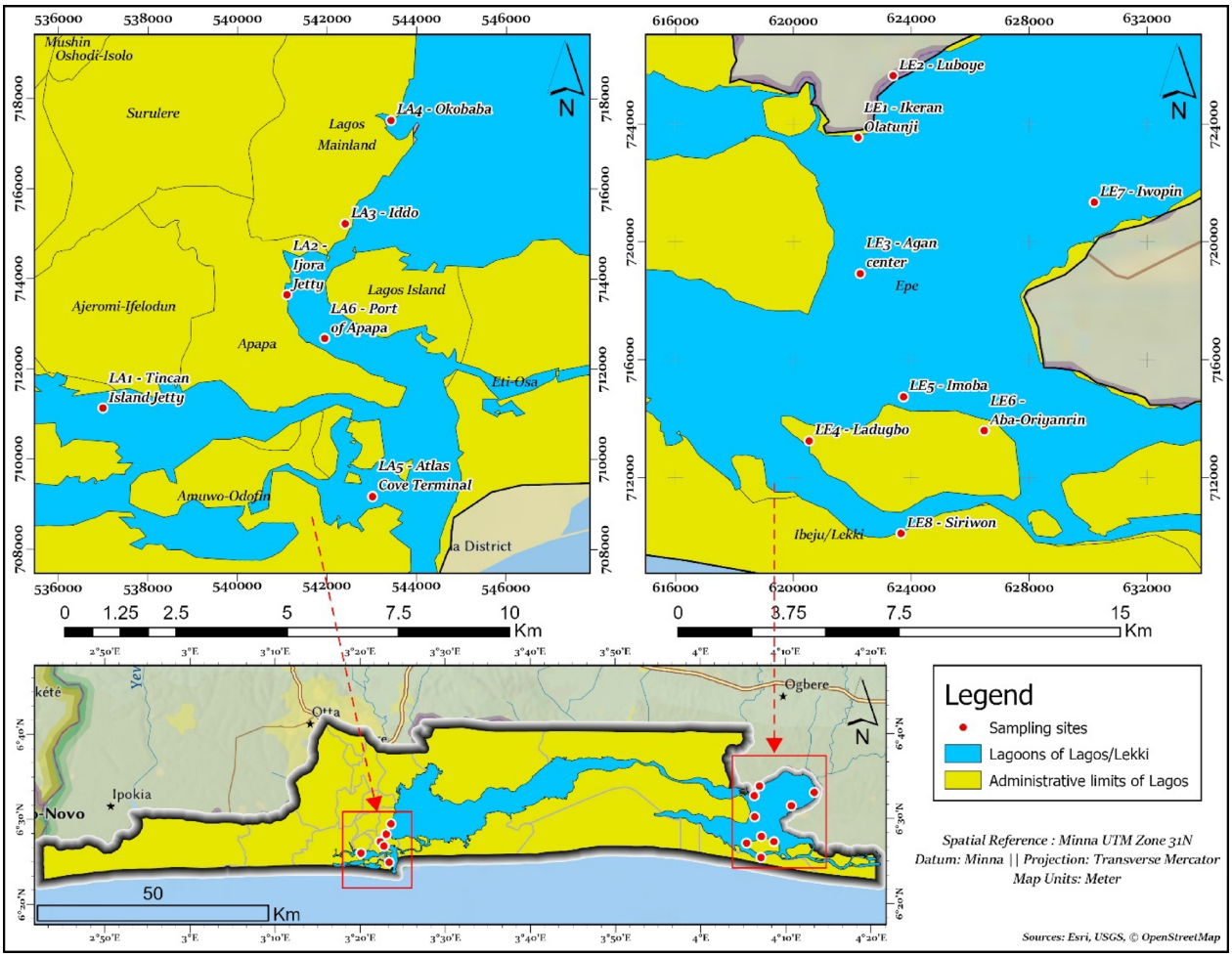

Fig. 1. Map of Lagos State showing the sampling stations within the Lekki and Lagos Lagoon systems. *Source* Map was created with ArcGIS Pro version 3.4 (https://www.arcgis.com).

in Lagos being commonly perceived as a realm of aquatic splendor. Geologically, the study area is situated within the Dahomey watershed and is characterized by multilayered sedimentary rock formations composed of diverse mineral types, including clayey soils, gravel, consolidated sandstone, and unconsolidated sand-sized grain deposits[20]. The Volta Delta in southwestern Ghana and the Okitipupa Ridge, otherwise referred to as the Ilesha Spur in southwestern Nigeria, are both part of the Dahomey Basin[19]. This basin contains a substantial level of geological structures, including basement complex (Precambrian), Ewekoro deposits (Paleocene), Oshosun and Ilaro deposits (Eocene) and Abeokuta rocky formations (cretaceous), which rise at the onshore border of the basin[19] (Fig. S1). These geological formations act as crucial reservoirs for aquifers and crude oil accumulation while also playing a role in mineralization processes. These geological materials, which are predominantly clastic in nature, extend offshore, where cretaceous rocks are overlain by finely grained Cenozoic deposits[20]. Additionally, the surface sand in the study area primarily consists of fine-grained, porous deposits formed by littoral beaches and barrier systems. As illustrated in Fig. S1, the geological composition of the studied lagoon and its surrounding areas consists primarily of coastal plain and alluvial deposits that is characteriezed by clay lenses, coarse sand, and small pebbles[19,20]. These deposits rest upon sedimentary rock formations within a coastal plain that features predominantly flat topography, with an average elevation of less than 15 m above sea level[19].

Water sample collection, preservation and digestion

The field sampling was carried out for 12 months, from December 2021 to November 2022, and included the wet and dry seasons. Each period lasted 6 months, with the dry season spanning from December to May and the wet season from June to November. Prior to field sampling and data collection, all necessary permissions and approvals to conduct the study were granted by the Lagos State University Research and ethical committee and relevant Lagos State regulatory bodies. The sampling approach considered both temporal and spatial stratification. Temporal stratification encompassed 2 dry and 2 wet seasons, whereas spatial stratification followed the methodology outlined by Opadokun et al.[34]. In this method, the interconnected lagoon systems are systematically divided into 5 distinct areas: the mouth, upper, middle, lower, and head. The site selections were determined based on the proximity as well as land use characteristics of each zone. 15 sampling points

were strategically chosen, of which 9 sampling points were from Lekki Lagoon, whereas the remaining six were in Lagos Lagoon (Fig. 1; Table S1). The positioning of these stations was determined via reference points such as vulnerability to specific anthropogenic inputs, prominent landing areas, distinct coastline attributes, fisher poles, and wreckage within the lagoon. Surface-water grab (single) samples were obtained directly from the selected stations in well-labeled pre-cleaned 2 L plastic containers that were washed with HNO_3 and subsequently rinsed with demineralized water to remove contaminants prior to sampling. Water samples were collected three times per month, yielding a total of 36 samples at each station. To avoid sampling the surface microlayer, samples were collected at depths of 10 cm and 30 cm. After collection, the samples were pretreated with the appropriate reagent (HNO_3 at 65%) to prevent the adsorption of toxic elements onto the walls of the plastic containers. The samples collected were immediately stored at 4 °C to preserve their physicochemical integrity during transportation to the laboratory for analysis. Deionized water was used during sample processing and preparation. This step was essential to prevent contamination and ensure the accuracy of the results during sample digestion and analysis. The experimental equipment was washed in deionized water and dried at 100 °C for 10 min. Sample digestion follows the methods of USEPA[35]. Following heating on a hot plate within a sealed cabinet, 50 mL of the digested solution was transferred to a graduated beaker after being reduced to 20 mL via evaporation. The sample was left to cool for approximately 15 min, filtered through filter paper (Whatman No. 42) and then measured in a calibrated volumetric flask, which was filled with 50 mL of demineralized water.

Analyses of the physicochemical and heavy metal parameters

This study incorporates several methods to determine the physicochemical properties of unfiltered surface water samples. The pH and temperature were determined via a thermometer (mercury-in-glass) and pH electrode (IONIX PC-50) from a multiparameter test meter, respectively. The dissolved oxygen (DO) content and alkalinity were measured following the titration methods described by Boyd[36]. Before the pH reading, the electrode was thoroughly rinsed with distilled water and dried with tissue paper. The BOD level was measured by analyzing the DO levels in 60 ml sample portions both before and after a 5-day incubation period at 20 °C in complete darkness. For the chemical oxygen demand (COD), a sealed reflux method combined with colorimetric analysis was employed. A 2 ml portion of the homogenized sample was treated with a dichromate-sulfuric acid reagent and digested at 150 °C for 2 h via a Grant QBD 2 reactor. Other parameters, such as total hardness (TH), electrical conductivity (EC), and total dissolved solids (TDS), were also measured with a multiparameter test meter. The heavy metals, namely, As, Cd, Cr, Cu, Fe, Pb, Ni, and Zn, in the surface water were quantified in mg/L. A graduated glass cylinder was used to measure 35 mL of the digested water sample, which was then analyzed with an atomic absorption spectrophotometer (AAS, Buck Scientific model 225ATS). For the analysis, specific absorption wavelengths (See Table S2) were maintained to facilitate the detection and quantification of various elements.

Quality control and assurance

To maintain quality assurance during the analysis, rigorous measures were put in place, particularly in handling sample blanks. Each analysis was conducted in triplicate to enhance accuracy and reliability. The testing process was organized into batches via an internal quality control method, with subsequent validation to confirm compliance with internal standards. Blank samples were incorporated to prevent potential contamination throughout the analytical process. Certified reference material (CRM), specifically DORM-2 (dogfish muscle), which is recommended by the National Research Council of Canada, was employed as an internal standard for the analysis. This is important for ensuring precision, eliminating errors, and enhancing the overall accuracy of the test batches. Replicate analyses of the CRM demonstrated satisfactory consistency between the certified and observed values (Table S2). For the calibration curves, a stock solution containing 1000 mg/L of the target element was diluted with ultrapure acidic water (5% v/v HNO_3). For sample processing and standard preparation, high-purity analytical-grade reagents (E-Merck or BDH; certified purity > 99.99%) along with deionized water were utilized. Calibration curves and blanks were established using six distinct concentration points and the resulting correlation coefficients (r^2) are provided in Table S2. The validation process for the heavy metal assessment followed the methodology outlined by Jolaosho et al.[20] (2020). To ensure the reliability of the analysis, blank samples were examined, and rigorous washing procedures were consistently applied to maintain high analytical quality. Instrument detection limits were established by analyzing raw intensity data from both standard and blank samples. The limit of detection and limit of quantification values (mg L^{-1}) are Cd = 0.0067 and 0.0258; Cu = 0.0041 and 0.0280; Cr = 0.0005 and 0.0017; Fe = 0.0072 and 0.0460; Pb = 0.0033 and 0.0091; Ni = 0.0017 and 0.0069; Zn = 0.0095 and 0.015; and As = 0.00028 and 0.00146, respectively. The recovery rates for each heavy metal are presented in the supplementary material (Table S2).

Water quality and contamination risk assessment

Single pollution index (Pi)

The Pi technique was employed to estimate the extent to which individual heavy metals contribute to the contamination of water in a particular location. The Pi values of the eight heavy metals were computed via Eq. (1), as described in Jolaosho et al.[5]

$$Pi = \frac{Cx}{Si} \tag{1}$$

Cx = analyzed concentration of one metal: Si = maximum permissible limit for drinking water quality [As = 0.05, Cd = 0.005, Cr = 0.041, Cu = 1.5, Fe = 0.3, Pb = 0.01, Ni = 0.002, Zn = 5.00]. The pollution level of each metal was classified into the following classes.

Pi ≤ 1 = negligible pollution; 1 < Pi ≤ 2 = low pollution level; and 2 < Pi ≤ 3 (moderate pollution degree). Conversely, a Pi value above 3 implies an extremely high degree of contamination and could lead to environmental risk. It is also unadvisable to use such water except when it is treated[20].

Contamination degree (Cdeg)

Cdeg is a commonly utilized index for evaluating the overall impact of toxic substances in various freshwater resources[19,20]. Its calculation involves a 2-step process: initially, the contamination factor (Cfn) of each pollutant is determined by comparing its concentration to its regulatory standard, and subsequently, these individual factors are summed for all pollution variables assessed. In this study, Cdeg was applied to gauge the level of surface water contamination in Lekki and Lagos Lagoons, with computations based on Eqs. (2) and (3).

$$Cfn = \frac{Cn}{Si} - 1 \tag{2}$$

$$C_{\deg} = \sum_{i=1}^{n} [Cfn] \tag{3}$$

Cfn (contamination factor); Cn (measured heavy metals in surface water); Si (recommended limits, as shown in Table 2); n (numbers of heavy metals considered in the study). Cdeg values are categorized into 3 groups: Cdeg < 40 minimal or no contamination; Cdeg between 40 and 80 = moderate contamination level; and Cdeg > 80 = extreme contamination level.

Heavy metal evaluation index (HMEI)

The HMEI is another crucial index used for estimating the modified pollution level of all the heavy metals in a water sample from a particular location. The HMEI was computed from the formula provided below.

$$HMEI = \sum\nolimits_{i=1}^{n} \frac{Ci}{Si} \tag{4}$$

Ci = measured heavy metal levels in water; Si = recommended values of the ith heavy metal.

To assess the toxicity levels in water, HMEI values were classified via an established classification scale. An HMEI value lower than 40 implies low contamination and safe water, whereas a value between 40 and 80 suggests that the water is moderately polluted. However, HMEI values above 80 indicate extreme water pollution levels and are rated as "unsuitable" for utilization[19,20].

Heavy metal pollution index (HPI)

HPI is a widely recognized approach for assessing water quality[2,5,19,29]. It serves as a contamination indicator that provides comprehensive water evaluation and monitoring in terms of contamination levels. To calculate the HPI, each element was assigned a weighted value (Wp) in accordance with its relative impact on aquatic ecosystems. The HPI values were computed via the mathematical formulas outlined below.

$$HPI = \frac{\sum_{i=1}^{n} [Wu \cdot Qi]}{\sum_{i=1}^{n} Wu} \tag{5}$$

Wu represents the calculated relative weight, with further details provided in the supplementary material (Table S3). Qi denotes the subindex for the ith parameter, determined from the equation below, whereas n represents the total number of heavy metals analyzed.

$$Qi = \frac{(Cx - Zi)}{(Si - Zi)} x100 \tag{6}$$

Cx represents the measured heavy metals; Zi is the ideal value and is considered 0 for all the heavy metals; and Si refers to the standard recommended limits (as outlined in Table 2). The HPIs were categorized based on the criteria provided below.

HPI < 100 (negligible pollution); HPI = 100 (moderate pollution level); and HPI > (extreme pollution level and is rated unfit for utilization).

Water quality index (WQI)

The WQI was employed to determine the purity of water in reference to its suitability for consumption. These essential techniques are interrelated and are often employed as water contamination indices. In this study, thirteen (13) of the eighteen (18) analyzed water variables (water quality parameters and heavy metals) were considered for the WQI assessment. The water parameters were selected based on the available recommended

limits established by international standards, as provided in supplementary Table S3. The procedures and formulas provided in Jolaosho[19] were used to estimate the WQI.

Step A: Use the suitable scale, as indicated below, to rate each metal.

$$Qi = \frac{(Cv - Ii)}{(Si - Ii)} \times 100 \tag{14}$$

Cv= measured content of one parameter; Ii = ideal value of one parameter and is considered 0 except for the pH (7); Si = standard recommended limits in drinking water.

Step B: Computation of the weightage unit of each parameter (Wx).

$$Wx = \frac{Wu}{\sum_{i=1}^{n} Wu} \tag{13}$$

Wx = the relative weight unit of each water parameter. Wu = assigned value of each parameter. The computed Wx and Wu values are provided in Table S3.

Step C: Calculation and classification of WQI values.

$$\mathrm{WQI} = \sum (W_x \times Q_i) \tag{vi}$$

The WQI values are categorized as follows: Class (0–25) = excellent (pure water); Class B (26–50) = good (clean water); Class C (51–75) = poor (moderately unclean water); Class D (76–100) = very poor (highly unclean water); and Class E (> 100) = extremely unclean (unfit for usage)[20].

Assessment of human health implications

Humans are exposed to environmental pollutants through multiple pathways, the aftermath of which is associated with health implications. Thus, it becomes essential to subject the potentially toxic elements found in surface waters from the sampling locations to health risk evaluations to provide clear insight into the associated carcinogenic and non-carcinogenic risks.

Average daily doses (ADDs)

To determine the extent to which children and adults are exposed daily to toxic metals in surface water from the sampling areas, ADDs via two exposure pathways (ingestion and dermal contact) were employed[12]. The ADD was computed via the equations below.

$$\mathrm{ADD_{ingestion}} = \frac{\mathrm{Ce} \times \mathrm{Cri} \times \mathrm{ABSi} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \tag{10}$$

$$\mathrm{ADD_{dermal}} = \frac{\mathrm{Ce} \times \mathrm{SA} \times \mathrm{KPi} \times \mathrm{ABS} \times \mathrm{EF} \times \mathrm{ET} \times \mathrm{CF} \times \mathrm{ED}}{\mathrm{BW} \times \mathrm{AT}} \tag{11}$$

Ce (Mg/L) = measured concentration of each heavy metal; Cri (L/day) = daily water intake rate and is given as 2.2 (adults) and 1.0 (children)[37]. SA (cms^2) = exposed skin factor and is 18,000 (adults) and 6,600 (children)[5,20]. ET (hrs/day) = exposure time and is 0.58 (adults) and 1.00 (children). ED = the duration at which an individual is likely to be exposed to a toxicant and is 30 years (adults) or 6 years (children) for the non-carcinogenic risk assessment, whereas the cancer risk assessment considers 70 years for all age groups[19,37]. EF (years) describes the frequency of exposure and is given as 365 years for ingestion and 350 years for dermal contact[12,19]. AT = ED × EF while BW = body weight (adult = 70 kg; children = 15 kg)[5,20]. Kpi = coefficient of dermal permeability of heavy metals (Table S4). Absi = absorption factor of one element (Table S4). CF = quality conversion coefficient (1 L/1000 cm^3 = 0.001).

Non-carcinogenic risk assessment

The hazard quotient (HQ) and hazard index (HI) were adopted to estimate the health implications associated with exposure to heavy metals in water samples from the sampling locations. The non-cancer risk values were computed via the equations stated below. A toxic element with an HQ value > 1 suggests the likelihood of non-cancer risks of such an element. Similarly, a water's likelihood of posing a non-cancer risk is indicated by an HI value > 1[38].

$$\mathrm{HQi_{ingestion}} = \left(\frac{ADDi}{RfDi}\right)_{\mathrm{ingestion}} \tag{12}$$

$$\mathrm{HQi_{dermal}} = \left(\frac{ADDi}{RfDi}\right)_{\mathrm{dermal}} \tag{13}$$

$$\mathrm{HI} = \sum_{i=1}^{n} \mathrm{HQi} \tag{14}$$

ADDi = average daily dose of heavy metals; HQi = hazard quotient; RfDi = reference dose of each provided in Table S4; HI = hazard index.

Carcinogenic risk assessment

The carcinogenic risk assessment determines whether heavy metals in surface water could trigger cancer risks in children and adults due to exposure over a period of time. This study ensured that this assessment was performed to ascertain the carcinogenic potential of the five (5) heavy metals (As, Cd, Cr, Ni, and Pb) identified by the Cancer Research Agency[39]. Thresholds of 1 × 10–6 and 1 × 10–4 were established for single and lifetime target cancer risks, respectively. Thus, values above the thresholds in water could result in cancer risks in exposed human populations[37,38].

$$\mathrm{CRi}_{\mathrm{ingestion}} = \mathrm{ADDi}_{\mathrm{ingestion}} \times \mathrm{CSF} \tag{15}$$

$$\mathrm{CRi}_{\mathrm{dermal}} = \mathrm{ADDi}_{\mathrm{dermal}} \times \mathrm{CSF} \tag{16}$$

$$\mathrm{MCR} = \sum_{i=1}^{n} \mathrm{CRi}\ (\mathrm{ingestion} + \ \mathrm{dermal}) \tag{17}$$

CRi stands for single-cancer risk; TCR stands for lifetime target cancer risk. CSF (mg/kg) represents the slope factor values (see Table S4).

Multivariate and statistical evaluations

This study employed four (4) multivariate indices to further evaluate the water quality and heavy metal characteristics of the examined lagoons. First, the coefficient of variation (CV%) technique was adopted to evaluate the spatial distribution patterns of the analyzed surface water parameters. Second, the correlation matrix (r) was computed to determine the linear associations between the analyzed water variables. Third, factor analysis via principal components was carried out to determine the source of origin as well as the relationships between the identified variables[12,20]. The extracted Kaiser–Meyer–Olkin (KMO) and Bartlett tests of sphericity values were used to quantify the suitability of the datasets for the PCA. Fourth, hierarchical cluster analysis (HCA) was employed to categorize the produced clusters into homogeneous groups on the basis of their common chemical characteristics[5,19]. Both the PCA and HCA were preferred for this study because they directly address our dual goals of data reduction, pattern discovery and grouping of sampling sites by using methods that are broadly understood, and well-validated in aquatic-geochemistry studies[19]. To test for significant differences, one-way analysis of variance (ANOVA) established at 95% significance ($P < 0.05$) was used. All the analyses were performed with SPSS software (IBM version 23.0), except for correlation heatmap that was developed in R (version 4.5.1). In addition, spatial trends of physicochemical and heavy metal concentrations in surface waters were mapped exclusively using the Inverse Distance Weighting (IDW) method within ArcGIS Pro 3.4, licensed through the University of Groningen Geoportal. The two interconnected coastal lagoons were delineated using supervised classification of Sentinel-2 satellite imagery, with the connecting water canals (unsampled areas that lacking data points) excluded from interpolation. Georeferenced datasets from all sampling stations were used as input for the interpolation process. Final raster maps for each physicochemical and heavy metal parameter were generated to illustrate the distance-weighted spatial representations of water quality and heavy metal distributions across the study area.

Results and discussion

Seasonal variations and Spatial distributions of physicochemical parameters in surface water

Table 1 summarizes the seasonal changes observed in the ten measured physicochemical parameters of water from Lekki and Lagos Lagoons. Figure 2 shows the spatial distributions of the water parameters across the 15 sampling stations. The physicochemical characteristics of the water varied, showing significant differences ($P < 0.05$) between the two lagoon systems during both the dry and wet seasons.

pH

pH values ranging between 6.99 and 8.01, with a mean value of 7.37 ± 0.37, were obtained in surface water from Lekki Lagoon, whereas values ranging from 7.20 to 7.80, with an average of 7.51 ± 0.22, were recorded in Lagos Lagoon (dry season). During the wet season, Lekki had a pH range between 6.15 and 7.05, with a mean of 6.58 ± 0.40, whereas Lagos Lagoon had pH values between 5.63 and 6.74, with an average of 6.22 ± 0.38. The significantly higher pH values observed during the dry season than during the wet season ($P < 0.05$) may be attributed to the influx of sewage effluents rich in carbonates and bicarbonates. This outcome is in line with the previous reports[40–42]. The low pH observed in both lagoons during the wet season may be attributed to terrestrial runoffs containing organic acids, humic substances and anthropogenic acidifying pollutants, leading to water acidity[43]. Excessive rainfall, often slightly acidic may also lead to diluting effects, thus lowering water pH[42]. Wilbers et al.[44] reported relatively low pH levels during the wet season in contaminated surface water of the Mekong Delta, Vietnam. The spatial plot revealed that most of the sampling stations in the Lekki (LE) (Fig. 2a) and Lagos (LA) (Fig. 2b) lagoons had average pH values near neutral (pH = 7), which are well within the guideline limits for drinking (5.5–9.0)[45,46] and are favorable for aquatic life and irrigation purposes (6.5–8.0)[47,48], except for stations LE2 (6.22), LE4 (6.49), LE9 (6.25) and LA2 (6.43) (slightly acidic). The observed pH variations among the sampling sites of both lagoons may be attributed to differences in salinity and temperature, along with the degradation of organic matter in the respective aquatic areas. Saha et al.[49] reported mean pH

SN	Parameters	Lekki Lagoon						Lagos Lagoon						Permissible limits		
		Dry season			Wet season			Dry season			Wet season					
		Min	Max	Mean ± S.D	Min	Max	Mean ± S.D	Min	Max	Mean ± S.D	Min	Max	Mean ± S.D	Si (Drinking water quality)	Sz (Irrigation)	Sx (Aquatic live survival)
1	pH (at 25 °C)	6.99	8.01	7.37 ± 0.37^{a}	6.15	7.05	6.58 ± 0.40^{b}	7.20	7.80	7.51 ± 0.22^{a}	5.63	6.74	6.22 ± 0.38^{b}	5.5–9.0	8.5	6.5–8.5
2	Temperature (°C)	30.15	30.94	30.46 ± 0.27^{a}	27.54	29.71	28.44 ± 0.75^{b}	28.45	30.98	29.66 ± 0.86^{a}	26.25	27.75	27.15 ± 0.59^{c}	–	–	8–28
3	DO (mg/L)	3.77	4.65	4.05 ± 0.32^{d}	4.55	5.12	4.74 ± 0.21^{bc}	4.95	5.55	5.21 ± 0.21^{b}	6.25	7.10	6.61 ± 0.31^{a}	> 4	–	> 5
4	TSS (mg/L)	6.78	16.44	11.58 ± 3.17^{d}	28.95	35.57	31.90 ± 2.98^{a}	15.25	18.64	17.44 ± 1.17^{c}	22.87	26.05	24.20 ± 1.45^{b}	10–50	100	100
5	BOD (mg/L)	21.08	30.45	26.43 ± 3.23^{b}	154.28	197.81	176.88 ± 6.72^{a}	7.25	8.99	8.27 ± 0.56^{d}	10.25	12.75	11.52 ± 1.05^{c}	50	–	50
6	COD (mg/L)	104.85	120.45	106.41 ± 3.87^{d}	284.85	371.45	339.25 ± 11.73^{c}	1015.03	1089.98	1058.52 ± 29.16^{b}	2753.90	2887.60	2815.48 ± 52.48^{a}	250	–	–
7	EC (uS/cm)	203.84	238.63	217.29 ± 12.36^{a}	103.98	133.45	117.72 ± 16.94^{b}	40.73	51.75	47.02 ± 3.94^{c}	4.33	6.35	5.16 ± 0.74^{d}	250	3000	–
8	TDS (mg/L)	403.56	574.56	492.03 ± 50.28^{b}	1278.58	1660.76	1417.28 ± 106.45^{a}	14.65	27.43	21.95 ± 4.30^{d}	55.27	65.85	61.84 ± 4.17^{c}	< 1000	2000	500
9	Salinity (ppt)	4.98	5.98	5.55 ± 0.37^{a}	3.60	4.58	4.01 ± 0.39^{b}	3.78	6.45	5.12 ± 1.00^{a}	0.89	2.59	1.65 ± 0.68^{c}	–	–	–
10	Alkalinity (mg/L)	70.36	85.66	78.63 ± 6.03^{c}	9.78	14.71	12.18 ± 1.01^{d}	105.19	167.65	129.51 ± 21.69^{a}	71.25	96.95	86.40 ± 8.58^{b}	200	600	250

Table 1. Seasonal changes in water physicochemical parameters and permissible limits for drinking, irrigation practices and aquatic life. All the values are expressed in duplicate. Within the same row, values marked with identical superscripts do not differ significantly. *Si[45,46]; Sz[47]; Sx[48,54,56,58].

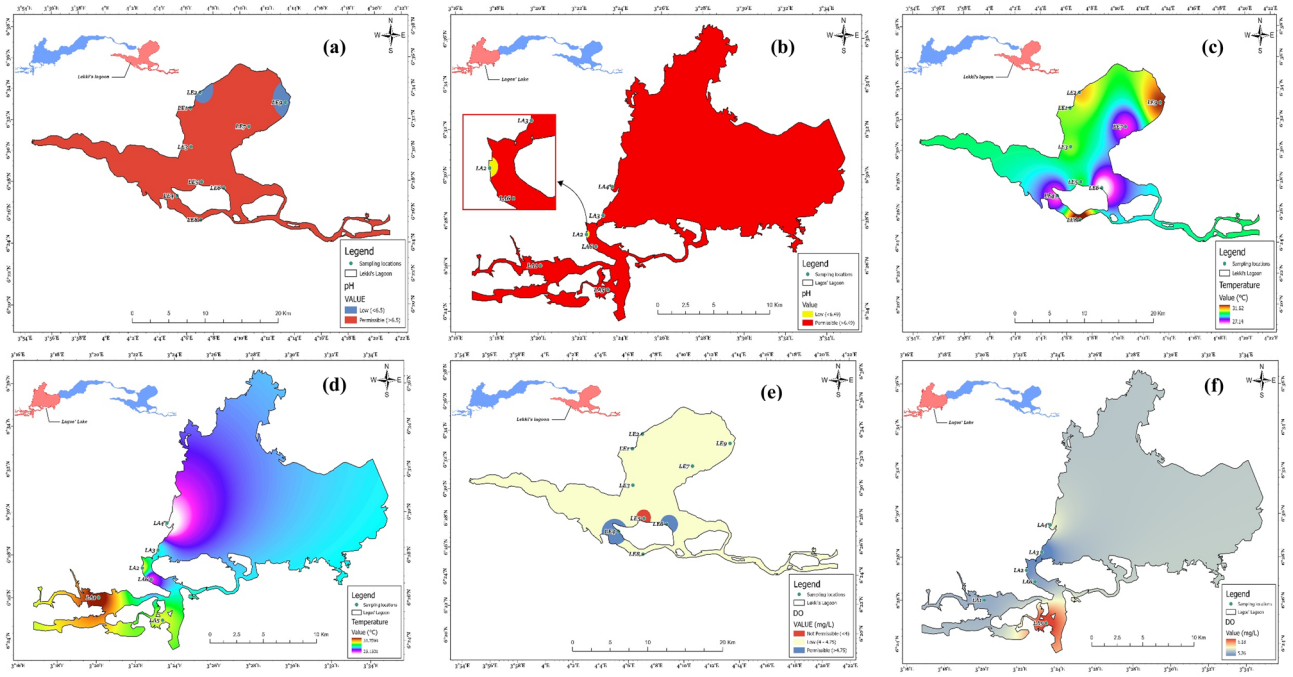

Fig. 2. Spatial variations of the physicochemical variables in surface water from interconnected coastal lagoons: (**a**,**b**) pH; (**c**,**d**) Temperature; (**e**,**f**) Dissolved oxygen; (**g**,**h**) Total suspended solids; (**i**,**j**) Biological oxygen demand; (**k**,**l**) Chemical oxygen demand; (**m**,**n**) Electrical conductivity; (**o**,**p**) Total dissolved solids; (**q**,**r**) Salinity; (**s**,**t**) Alkalinity. *Source* Map created with ArcGIS Pro version 3.4 (https://www.arcgis.com).

values of 8.41 (pre-monsoon), 8.29 (monsoon), and 8.42 (post-monsoon), which are slightly greater than those reported in our study.

Temperature

The temperature level ranges between 30.15 and 30.94 °C, with a mean of 30.46 ± 0.27 °C (dry season), and between 27.54 and 29.71 °C, with an average of 28.44 ± 0.75 °C (wet season) in Lekki Lagoon. In Lagos Lagoon, the values ranged from 28.45 to 30.98 °C, with a mean of 29.66 ± 0.86 °C (dry season), and from 26.25 to 27.75 °C, with a mean of 27.15 ± 0.59 °C during the wet season. The temperatures of both lagoons were highest during the dry season, and the differences between the temperature values with respect to seasons between the two lagoons were found to be significant ($P < 0.05$). Our results are consistent with the low temperature levels obtained by Koledoye et al.[50] in Lekki and Lawson[51] in Lagos lagoon during the rainy season. Spatially, with the exception of LA4 and LA6, all the sampled stations of both lagoon systems presented relatively high temperature values (Fig. 2c and d), which exceeded the 25 °C recommended by NESREA for aquatic life survival. However, the temperature levels of some of the sampled stations (LE8, LE9, and LA1) were within the permissible range limit (31–35 °C) recommended by the WHO, which is favorable for the productivity of aquatic species. Rahman et al.[52] asserted that temperature in aquatic ecosystems may not be a critical variable for the survival of aquatic organisms and biotic communities, as tolerance levels may differ among species. However, elevated temperatures can pose a major challenge due to their inverse relationship with DO, which is crucial for the growth and survival of aquatic organisms[52].

Dissolve oxygen (DO)

The DO values for Lekki Lagoon ranged from 3.77 mg/L to 4.65 mg/L, with a mean of 4.05 ± 0.32 mg/L (dry season), and from 4.55 mg/L to 5.12 mg/L, with an average of 4.74 ± 0.21 mg/L (wet season). In Lagos Lagoon, the DO levels ranged from 4.95 mg/L to 5.55 mg/L, with an average value of 5.21 ± 0.21 mg/L (dry season), whereas the DO levels during the wet season ranged from 6.25 mg/L to 7.10 mg/L, with an average value of 6.61 ± 0.31 mg/L. The DO levels in the examined lagoons varied significantly from one season to another ($P < 0.05$). The average DO values observed in Lekki Lagoon across both seasons were slightly below the 6.0 mg/L suggested for the optimum survival and productivity of aquatic organisms[52]. The DO levels in both lagoons were highest during the wet season, which could be due to air saturation, which increases the oxygen content as it rains. Conversely, nitrification processes in both lagoon systems could be responsible for the low DO obtained during the dry season[53]. Our findings align with previous studies that observed high DO levels in freshwater systems during the wet season[41,53]. Spatially, all the sampled stations of Lekki Lagoon (Fig. 2e), except for LE4 (5.05 mg/L), presented average DO values lower than the minimum recommended limit of 5.0 mg/L suggested by FEPA[54] in surface waters for the sustenance of fish but within the 4–6 mg/L suggested by the WHO[45,46]. Excessive organic contaminants, runoff from farmlands, sewage systems and municipal waste discharges from nearby areas could be the reasons why low DO levels were obtained from Lekki Lagoon. On the other hand, the

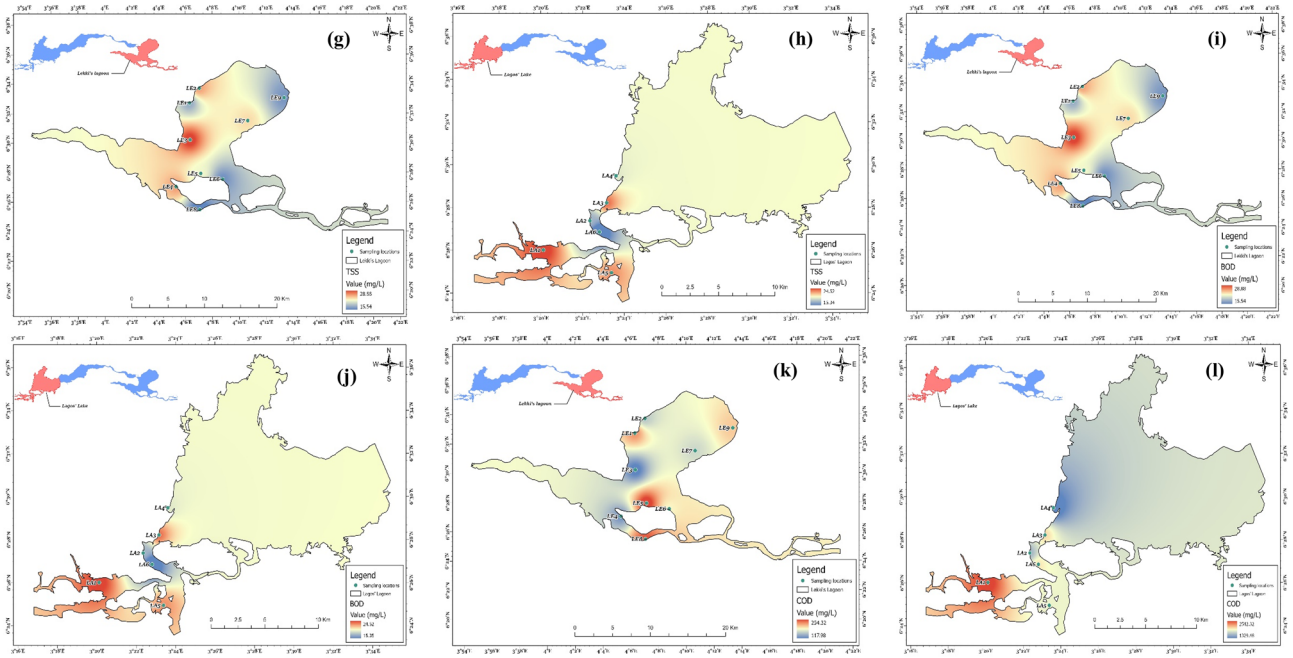

Fig. 2. (continued)

DO levels in all the sampled stations in Lagos Lagoon meet the requirements for drinking, and productivity of aquatic lives (Fig. 2f).

Total suspended solids (TSS)

In Lekki Lagoon, the TSS values ranged from 6.78 to 16.44 mg/L, with an average of 11.58 ± 3.17 mg/L (dry season), whereas these values increased during the wet season, ranging from 28.95 to 35.57 mg/L, with a mean of 31.90 ± 2.98 mg/L. Similarly, in Lagos Lagoon, the dry season TSS values ranged between 15.25 and 18.64 mg/L (average of 17.44 ± 1.17 mg/L), whereas in the wet season, they ranged from 22.87 to 26.05 mg/L, with an average of 24.20 ± 1.45 mg/L, and the results were significantly different ($P < 0.05$). Our results were lower than the average values of 44.83 mg/L (dry season) and 50.17 mg/L (wet season) previously reported in surface water from Lekki lagoon[34]. The increased TSS level during the wet season could be due to intensive precipitation, which enhances water flow, thus resulting in greater deposition of sediments and other anthropogenic particles through runoff. Although, our findings contradict those of Rahman et al.[52], who reported lower TSS levels during the wet period. Furthermore, the observed variations of TSS levels across different sampling stations in both lagoons (Fig. 2g and h) suggest differences in the levels of anthropogenic inputs, including organic deposition and sedimentation. However, the reported results were within the acceptable limits of 10–50 mg/L for drinking water[45,46], irrigation practices (25 mg/L)[47], and freshwater species (100 mg/L)[48]. Notably, station LE3 recorded the highest TSS levels, a trend that can be attributed to dredging activities and ongoing land reclamation for urban development in this location (Table S1), thus leading to sedimentation within the lagoon.

BOD and COD

In Lekki Lagoon, the BOD ranged from 21.08 to 30.46 mg/L, with a mean of 26.43 ± 3.23 mg/L (dry season). During the wet season, the BOD levels increased significantly, ranging from 154.28 to 197.81 mg/L, with an average of 176.88 ± 6.72 mg/L. In Lagos Lagoon, the dry season BOD ranged from 7.25 to 8.99 mg/L (mean of 8.27 ± 0.56 mg/L), whereas the BOD ranged between 10.25 and 12.75 mg/L and a mean of 11.52 ± 1.05 mg/L during the wet season. The differences in the BOD values with respect to season between the two lagoon systems were found to be significant ($P < 0.05$). The BOD levels for Lagos Lagoon were within the recommended limits of 50 mg/L for the sustenance of aquatic organisms[48] but were above the acceptable 5 mg/L in drinking water[45,46]. However, the increased BOD levels recorded during the wet season are most likely due to the presence of organic matter, such as decayed plants, as well as manure deposits and fertilizers used for agricultural activities, which eventually flow down into the lagoon system due to excessive rainfall. This could have also contributed to the extremely high levels of COD observed during the wet season, given the direct correlation between the two parameters, such that higher levels of organic matter led to increased COD contents. Interestingly, the spatial plots showed that BOD levels were higher in all the nine sampling stations in Lekki Lagoon (Fig. 2i) than those observed in the six stations in Lagos Lagoon (Fig. 2j). Conversely, COD levels in surface water of Lagos Lagoon were significantly higher (Fig. 2l) relative to those in Lekki Lagoon (Fig. 2k), which highlights the differences in the anthropogenic inputs within the two study areas (see the study area description in Table S1). The average COD levels across the sampling stations of Lagos Lagoon ranged from 1329.45 to 2542.35 mg/L and were 4 to 10 times above the maximum allowable limits (Table 1). The extremely low BOD-to-COD ratios observed

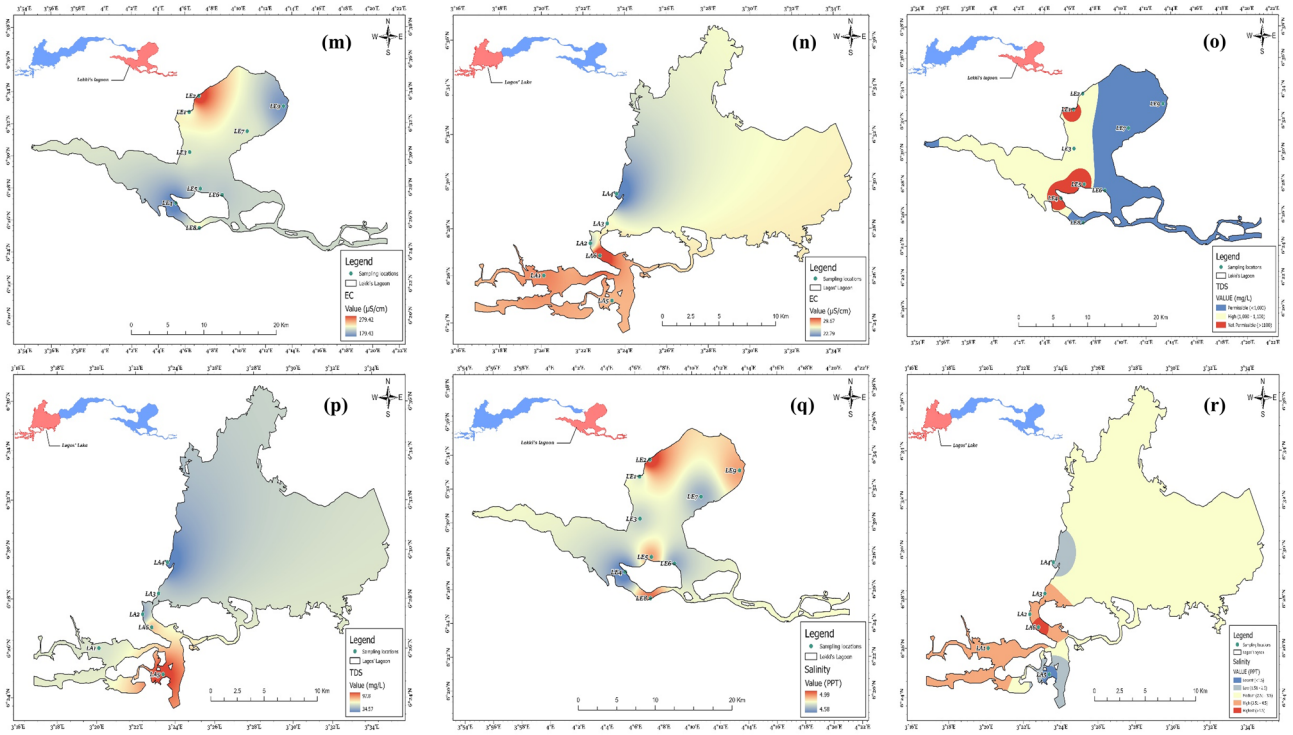

Fig. 2. (continued)

across all the sampling stations in Lagos Lagoon suggest that the wastewater discharged from surrounding industries (notably, distillers, organic chemical manufacturers, agrochemical facilities, and dyeing, painting, and crystal factories) either degrades more slowly or contains a substantial amount of non-biodegradable materials that inhibit microbial activity[55]. It can therefore be inferred that surface water from the Lagos lagoon is COD contaminated, which could alter its suitability for drinking, irrigation, and industrial uses.

Electrical conductivity (EC)

The EC ranged between 203.84 and 238.63 uS/cm, with a mean of 217.29 ± 12.36 uS/cm (dry season) and a range of 103.98 and 133.45 uS/cm, with an average of 117.72 ± 16.94 uS/cm (wet season) in Lekki Lagoon. In Lagos Lagoon, the EC values ranged between 40.73 and 51.75 uS/cm, with an average of 47.02 ± 3.94 uS/cm (dry season), and the values ranged from 4.33 to 6.35 uS/cm, with an average of 5.16 ± 0.74 uS/cm (wet season). Aquatic habitats promote the optimal growth and population density of fish species, provided that the EC levels fall between 200 and 1000 µS/cm, but it is advisable to maintain the EC level within 400 µS/cm (high morpho-edaphic index)[56]. The EC levels in this study were within the standard limits for aquatic life productivity, as well as for drinking water (1000 uS/cm) and irrigation purposes (1000 uS/cm). During the wet season, both lagoons experienced very low values of EC, which could have been caused by the dilution of dissolved concentrations of salt and ionized minerals due to heavy rainfall[52]. The dilution effect caused by external water influx reduces the concentration of nutrient-rich minerals and thus lowers the EC, an assertion that is consistent with the low concentration of salinity in across all the sampling stations in both lagoons (Fig. 2q and r). Conversely, the relatively high EC values obtained in the dry season ($P < 0.05$) are in agreement with Ewa et al.[57] that runoff from farmlands (high in nutrients) and industrial wastewater are responsible for high levels of EC in aquatic environments. The spatial distribution maps revealed that EC levels across all the stations in Lekki Lagoon (Fig. 2m) were significantly higher than those in Lagos Lagoon (Fig. 2n). The extremely low EC levels observed at all six (6) sampling stations in Lagos Lagoon most likely reflect the predominant freshwater inflow from nearby Ogun, Yewa, and Osun tributaries, leading to dilution of salt and dissolved ion pools[23].

Total dissolved solids (TDS)

The TDS values ranged from 403.56 mg/L to 574.56 mg/L, with a mean of 492.03 ± 50.28 mg/L (dry season), whereas they ranged from 1278.58 mg/L to 1660.76 mg/L, with a mean of 1417.28 ± 106.45 mg/L in Lekki Lagoon during the wet season. In Lagos Lagoon, the TDS values ranged from 14.65 mg/L to 27.43 mg/L, with an average of 21.95 ± 4.30 mg/L (dry season), whereas during the wet season, the TDS values ranged from 55.27 mg/L to 65.85 mg/L, with an average of 61.84 ± 4.17 mg/L. Statistical analysis revealed differences ($P < 0.05$) between the lagoons as well as across the seasons. According to NESREA[58], the ideal TDS limit is 450 mg/L, whereas the WHO[56] sets the standard at 600 mg/L for proper aquatic growth and 1000 mg/L for drinking water. The TDS levels observed in Lekki Lagoon during the wet season exceeded the acceptable limits for aquatic life productivity and consumption purposes. The elevated TDS levels recorded during the wet season likely reflect the

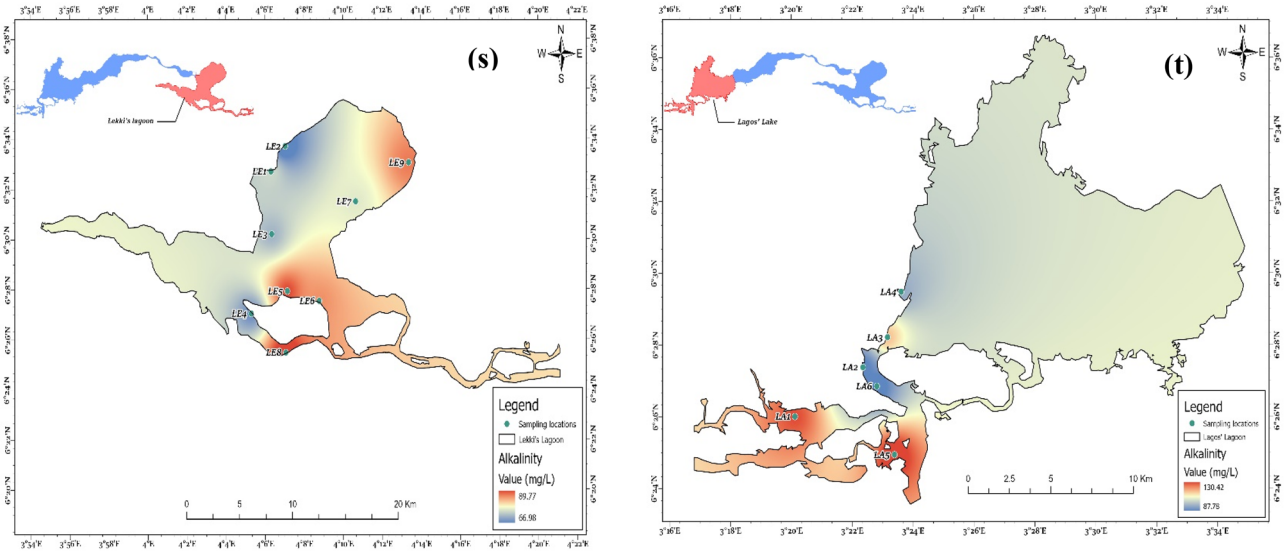

Fig. 2. (continued)

increased influx of municipal waste, residential and agricultural runoff, and suspended particulate matter into these aquatic systems. This is supported by the significantly high TDS concentrations observed in Lekki Lagoon than in Lagos Lagoon. Lekki Lagoon is particularly impacted by intense human activities, such as household waste disposal, landfilling, and dredging, all of which contribute to enhanced sedimentation and dissolution of solids into the water column[5,12]. During periods of heavy rainfall, runoff effectively transports contaminants from urbanized areas into lagoon systems, which tends to further elevate TDS levels, corresponding with the high levels of TDS observed during wet season. These observations align with previous research where urban runoff increased the TDS levels in freshwater systems during the wet season[59]. Our findings contradict other report where elevated TDS levels were reported during the dry season[42]. The relatively low TDS recorded in Lagos Lagoon, where industrial activities prevail, suggests that the water body experiences direct inputs mainly from manufacturing industries. The spatial distribution trends showed that the average TDS levels across all the sampled locations in Lekki Lagoon (Fig. 2o) were significantly higher than those in Lagos Lagoon (Fig. 2p), with stations LE1–LE5 exceeding the standard limit of 1000 mg/L for drinking[45,46] and 500 mg/L for aquatic live survival[48,56]. Such outcome is expected due to the nature of anthropogenic activities (such as municipal waste disposal, land reclamation, and dredging), within the Lekki lagoon. Conversely, all sampling locations in Lagos Lagoon presented extremely low concentrations, which suggests minimal levels of ionic materials that could be traced to the limited environmental resource activities in the area.

Salinity and alkalinity

The average salinity levels of both lagoons were slightly above 5 ppt during the dry season, which suggests fresh-brackish water systems. During the wet season, the average salinity levels were less than 5 ppt. Akintola et al.[60] suggested that elevated salinity levels during the wet season could be attributed to saltwater intrusion or deposition in inland waters, which contradicts our findings. Similarly, the average alkalinity levels of the Lekki (78.63 ± 6.03 mg/L) and Lagos (129.51 ± 21.69 mg/L) lagoons were highest during the dry season. The high alkalinity during the dry season may be due to increased disintegration rates, where CO2 builds up, which subsequently reacts with water to produce bicarbonate and thus accounts for the elevated alkalinity during this season[61]. Conversely, the low alkalinity levels during the wet season may be explained by the naturally acidic nature of uncontaminated rain (pH 5.0-5.5), or even SO_2 and NO_2 emissions from automobiles and power plants that generate suspended aerosol particles, all of which deplete carbonate buffering and reduce surface water alkalinity through wet and dry deposition[62]. The alkalinity levels across the sampled stations of both lagoon systems were the 250 mg/L and 200 mg/L standard allowable limits for freshwater fish and for domestic uses, respectively (Fig. 2s and t).

Seasonal variations and Spatial distributions of heavy metals in surface water

Table 2; Fig. 3 provide a summary of the heavy metals distributed in surface water from Lekki and Lagos Lagoons. A total of eight (8) metals were distributed in the following patterns: Lekki Lagoon ranged from [Zn (1.37–3.15) > Fe (0.35–1.08) > Pb (0.38–1.05) > Cu (0.15–0.48) > Cd (0.11–0.34) > As (0.07–0.12) > Cr (0.01–0.07) > Ni (0.005–0.08) mg/L] during the dry season and [Zn (0.86–1.15) > Fe (0.22–0.65) > Pb (0.22–0.65) > Cu (0.05–0.12) > Cd (0.03–0.012) > Cr (0.02–0.10) > As (0.01–0.03) > Ni (0.001–0.010) mg/L] during the wet season. Lagos Lagoon had [Zn (3.75–10.55) > Fe (3.66–8.25) > Cu (3.15–5.89) > Cr (0.56–1.17) > Cd (0.27–1.38) > Pb (0.31–0.65) > Ni (0.05–0.15) > As (0.03–0.10) mg/L during the dry season and Zn (1.46–6.57) > Cu (0.41–3.38) > Fe (1.45–1.92) > Cr (0.58–0.75) > Cd (0.08–0.21) > Pb (0.06–0.18) > Ni (0.01–0.07) > As (0.01–0.05) mg/L during the wet season. The forms of heavy metals detected in both lagoons were similar but at different

SN	Parameters	Lekki lagoon								Lagos lagoon							
		Dry season				Wet season				Dry season				Wet season			
		Min	Max	Mean ± SD	CV (%)	Min	Max	Mean ± SD	CV (%)	Min	Max	Mean ± SD	CV (%)	Min	Max	Mean ± SD	CV (%)
1	Cd	0.11	0.34	0.23 ± 0.09^{b}	41.57	0.03	0.12	0.07 ± 0.04^{d}	50.25	0.27	1.38	0.69 ± 0.39^{a}	56.36	0.08	0.21	0.14 ± 0.04^{c}	31.10
2	Cu	0.15	0.48	0.28 ± 0.13^{c}	46.59	0.05	0.12	0.08 ± 0.03^{d}	35.58	3.15	5.89	4.46 ± 1.59^{a}	35.66	0.41	3.38	1.75 ± 1.18^{b}	67.28
3	Cr	0.01	0.07	0.04 ± 0.02^{c}	52.44	0.02	0.10	0.05 ± 0.03^{c}	122.21	0.56	1.17	0.91 ± 0.43^{a}	47.08	0.58	0.75	0.66 ± 0.33^{b}	49.27
4	Fe	0.35	1.08	0.73 ± 0.26^{c}	36.03	0.22	0.65	0.44 ± 0.17^{d}	39.31	3.66	8.25	5.91 ± 1.63^{a}	27.55	1.45	1.92	1.68 ± 0.19^{b}	11.19
5	Pb	0.38	1.05	0.71 ± 0.28^{a}	39.74	0.22	0.35	0.30 ± 0.12^{c}	40.68	0.31	0.65	0.49 ± 0.19^{b}	39.18	0.06	0.18	0.12 ± 0.05^{d}	39.79
6	Ni	0.01	0.08	0.03 ± 0.03^{c}	69.41	0.00	0.01	0.01 ± 0.00^{d}	69.71	0.05	0.15	0.09 ± 0.04^{a}	40.41	0.01	0.07	0.04 ± 0.02^{b}	52.44
7	Zn	1.37	3.15	2.55 ± 0.61^{b}	24.05	0.86	1.15	1.01 ± 0.12^{c}	12.18	3.75	10.55	5.95 ± 2.56^{a}	42.95	1.46	6.57	3.26 ± 2.28^{b}	70.16
8	As	0.07	0.12	0.09 ± 0.02^{a}	20.02	0.01	0.03	0.02 ± 0.01^{c}	44.72	0.03	0.10	0.06 ± 0.03^{b}	42.16	0.01	0.05	0.03 ± 0.02^{c}	59.62

	Cd	Cu	Cr	Fe	Pb	Ni	Zn	As	References
Lekki Lagoon	0.148	0.181	0.023	0.585	0.503	0.022	1.779	0.056	Present study
Lagos Lagoon	0.414	3.103	0.788	3.794	0.302	0.063	4.604	0.045	
Permissible limits for drinking water quality (Si)	0.005	1.5	0.03	0.30	0.01	0.02	5.0	0.01	WHO[45,46]
	0.01	1.0	0.05	1.0	0.01	0.1	3.0	0.01–0.02	NESREA[58]
Permissible limits for Irrigation practices (Sz)	0.01	0.2	0.10	5.0	5.0	0.2	2.0	0.10	FAO[47]
Permissible criteria for freshwater fish survival (Sx)	0.03	0.05	0.016	1	0.065	0.470	0.09	0.07	USEPA[65,66]
Previous studies reported worldwide									
Mangla Lake, Pakistan	0.032	0.026	0.085	0.135	0.337	0.114733	0.025	–	Saleem et al.[6]
Major River (Misiones), Argentina	–	0.0016–0.0065	0.0006–0.0029	0.044–0.477	0.0003–0.0043	0.0006–0.0029	0.014–0.042	–	Avigliano & Schenone[75]
Gomti River, Bangladesh	–	0.01–0.22	–	4.25–67.43	–	0.07–0.46	0.68– 10.42	–	Yasmin et al.[42]
Yellow Estuary, China	0.0007	0.012	–	–	0.006	–	0.015	0.0026	Wang et al.[68]
Naivasha Lake, Kenya	0.10	–	0.03	–	0.16	0.15	0.65	3.26	Yang et al.[77]
Ajayi River, India	0.030	0.072	–	1.951	0.053	0.017	0.242	–	Singh & Kumar[22]
Legnica Lake, Poland	0.002	0.029	0.001	0.006	0.0002	0.068	0.204	–	Samecka-Cymerman & Kempers[76]
Ojo River, Nigeria	0.001	0.019	0.041	0.099	0.006	0.003	0.452	0.010	Jolaosho et al.[5]
Nhezelele River, South Africa	0.001	0.394	0.266	4.054	0.109	–	0.076	–	Edokpayi et al.[63]
Awash River, Ethiopia	0.10	0.95	0.69	2.77	0.70	0.08	0.89	–	Eliku & Leta[67]
Sirsa River, India	0.003	0.027		1.18	0.018	0.065	0.096		Herojeet et al.[69]
Tinto River, Spain	0.118	18.9	0.071	574	0.372	0.170	48.0	0.521	Cánovas et al.[73]
Changjiang, China	0.0009–0.001	0.002–0.005	–	–	0.002–0.015	0.0009–0.0014	0.002–0.014	–	Li et al.[4]
Ologe lagoon, Nigeria	0.02	0.02	0.02	0.14	0.02	0.03	1.04	–	Ndimele et al.[2]

Table 2. Seasonal distributions and previous studies on heavy metals (Mg/L) in major freshwater systems. All the values are expressed in replicate. Within the same row, values marked with identical superscripts do not differ significantly.

accumulation levels. The mean concentrations of metals obtained during the dry season were notably higher than those observed in the wet season, with the differences being statistically significant ($P < 0.05$). These results may be attributed to frequent and high anthropogenic inputs facilitated by stable and low water levels during the dry season[6]. Previous studies have reported elevated levels of heavy metals in surface water during the dry season[6,63,64]. However, the low metal levels during the wet season could be due to dilution of pollutants, where large volumes of relatively less contaminated water, either directly from rainfall or influx from nearby catchments into the lagoon systems, thus lowering the toxic metal concentrations in the water column. Although, elevated metal levels may also be observed during the wet season, as inland contaminants from various anthropogenic sources are transported into aquatic ecosystems through runoff or drainage from smaller catchments.

The variabilities of the metals were assessed via the coefficient of variation (CV%) (Table 2). Jolaosho et al. (2024) reported that a CV value above 30% for individual metals indicates extreme spatial variability in the distribution pattern, primarily due to both geogenic processes (such as climate change effects, precipitation, and weathering) and anthropogenic events, especially industrial activities. On the other hand, a value less than 30% suggests stable distribution trends and could primarily be attributed to natural sources. In Lekki Lagoon, all the heavy metals had CV values higher than 30%, except for Zn during both seasons (24.05%–12.18%) and As (20.01%). Similarly, in Lagos Lagoon, seven of the eight metals had CV values above 30, except for Fe, which had lower CV levels during both seasons. Our findings indicate that anthropogenic inputs are the primary driver

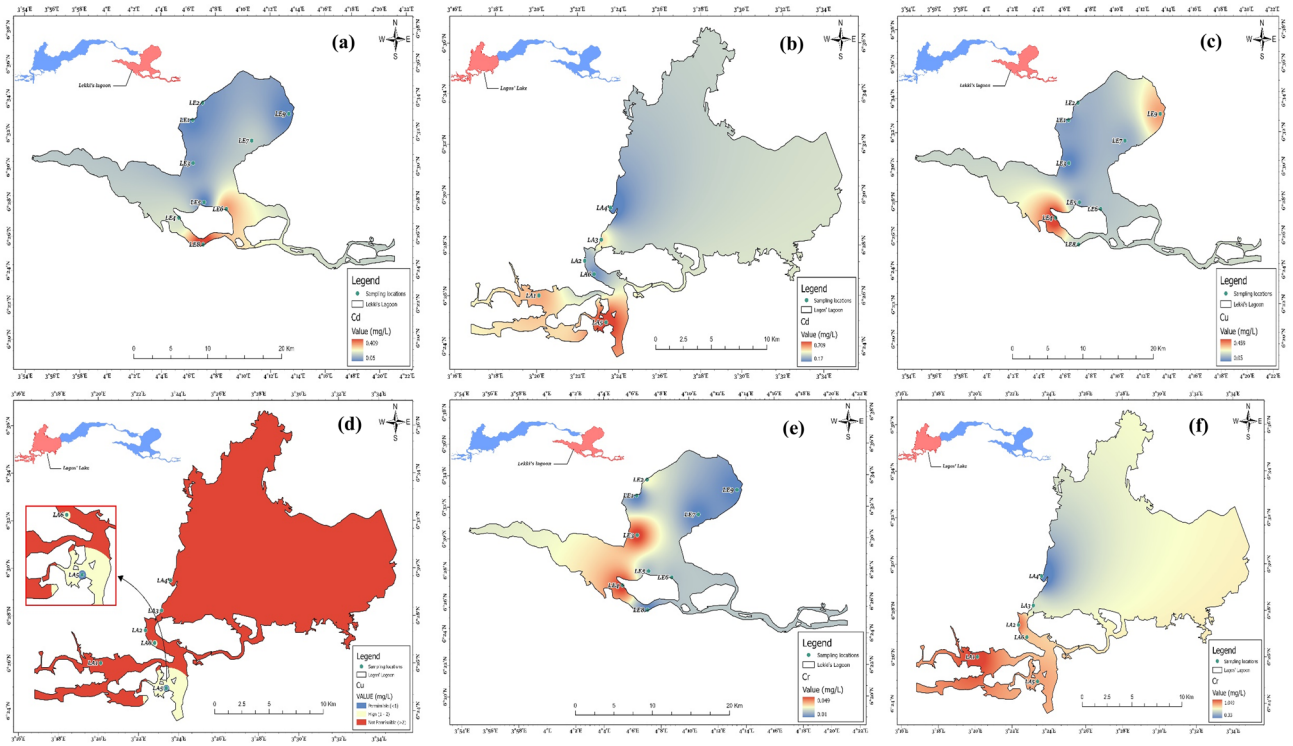

Fig. 3. Spatial distributions of heavy metals in surface water from interconnected coastal lagoons: (**a,b**) Cd; (**c,d**) Cu; (**e,f**) Cr; (**g,h**) Fe; (**i,j**) Pb; (**k,l**) Ni; (**m,n**) Zn; (**o,p**) As. *Source* Map created with ArcGIS Pro version 3.4 (https://www.arcgis.com).

of elevated metal concentrations in the examined lagoons, with little contribution from natural sources. This outcome aligns with the previous reports on water resources in other parts of the study regions[2,5,19,20].

Cadmium (Cd)

The average Cd levels in surface water from Lekki and Lagos Lagoons were 148 mg/L and 0.414 mg/L, respectively (Table 2). Generally, Cd occurs in the environment at background levels; however, the Cd levels obtained significantly exceeded both the local allowable limits in drinking water (0.01 mg/L)[58] and international guideline (0.005 mg/L)[45,46]. They were also above the standard threshold for irrigation practices (0.01 mg/L)[47], and the survival for aquatic organisms (0.03 mg/L)[65,66]. Cd can impair reproductive organs, if ingested and subsequently bioaccumulates in human and aquatic organisms. Toxic elements can also damage the pulmonary and immune systems as well as prevent bone mutilation[9]. The mean level of Cd in Lagos Lagoon was 3–4 times higher than that reported in Lekki Lagoon. This difference is likely attributable to the industrial nature of Lagos Lagoon, which hosts numerous industrial establishments. Elevated Cd levels in aquatic ecosystems are primarily linked to the discharge of wastewater enriched with Cd ions from industries operating in this region, as Cd is a common component of chemicals used in the manufacturing of various industrial products[12]. The Cd concentrations in this study were higher than the 0.032 mg/L recorded in Mangla Lake, Pakistan[6], 0.10 mg/L in Awash tributary, Ethiopia[67], 0.0007 mg/L in Yellow Estuary, China[68], 0.001 mg/L in Ojo River, Nigeria[5] and 0.118 mg/L in Sirsa River, India[69]. Spatially, the average levels of Cd in the surface waters across all the sampling locations of both lagoons exceeded the permissible limits, especially in areas dominated by land reclamation and construction projects [LE6 (0.30 mg/L)], agricultural activities [LE8 (0.41 mg/L)] (Fig. 3a), crude oil transport routes [LA1 (0.59 mg/L)], a propane terminal and an abandoned power transformer [LA2 (0.31 mg/L)], auto-mechanic workshops [LA3 (0.49 mg/L)], and pipelines and maritime oil companies [LA5 (0.71 mg/L)], which had the highest levels of Cd contamination (Fig. 3b). Our findings corroborate a prior long-term monitoring report that Cd concentrations in Lagos coastal lagoons have significantly increased over the past two decades, particularly in pollution hotspots adjacent to industrial and urban regions[70].

Copper (Cu)

Cu is geologically abundant and is mostly detected at considerable levels in the environment. However, in the present study, Cu was the third most predominant metal, with averages of 0.181 and 3.103 (mg/L) reported in Lekki and Lagos Lagoons, respectively. The mean Cu level in surface water from Lagos Lagoon significantly exceeded those in Lekki Lagoon and was at least 2 times above the local and international standard limits (Table 2) for drinking, agricultural uses, and sustenance of freshwater species[45–47,58,65,66]. The high Cu levels in Lagos Lagoon suggests the presence of a point source of contamination from effluent discharge by nearby electrical and home appliance industries[71]. Also, shipping activities, characterized mainly by using antifouling materials

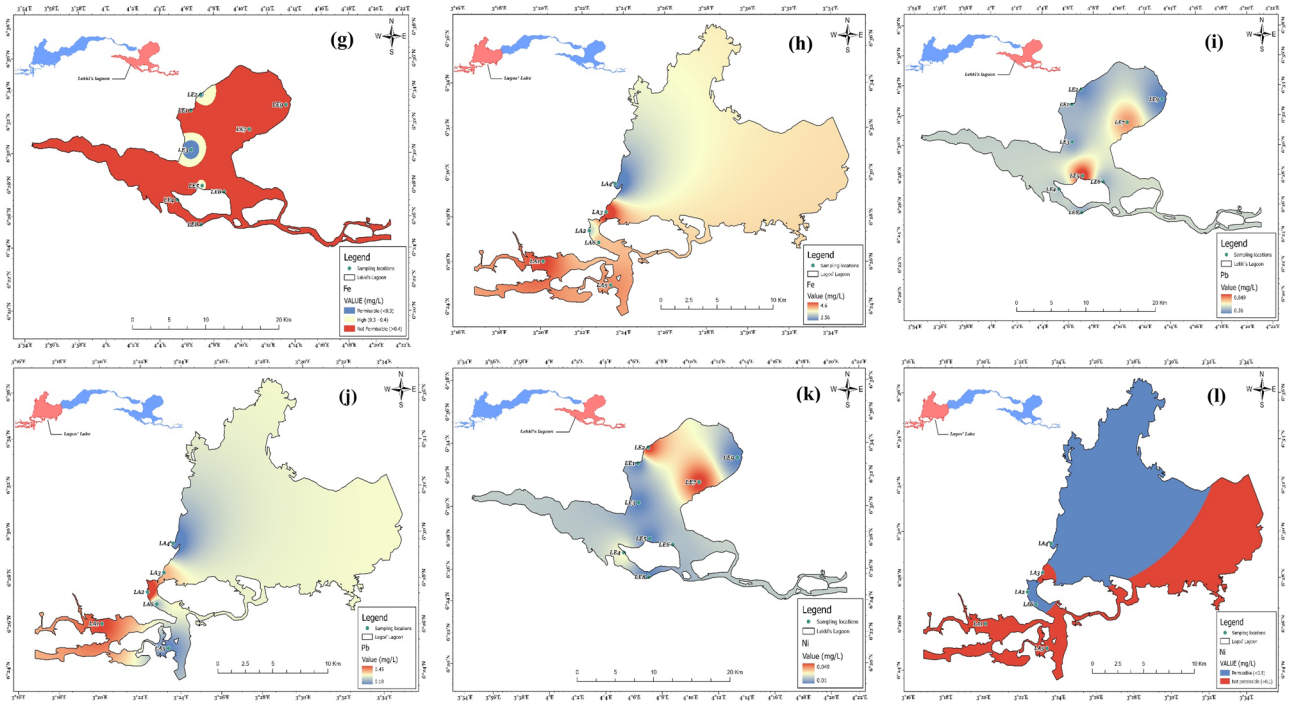

Fig. 3. (continued)

for painting ship hulls at the banks of Lagos Lagoon, could also be responsible for the release of Cu in this ecosystem[72]. The average Cu levels reported in this study were higher than most of the values determined in earlier studies (Table 2), except for 0.394 mg/L (Nhezelele River, South Africa)[63], 0.950 mg/L (Awash River)[67], and 18.90 mg/L (Tinto River)[73], which were higher than those reported in our study. The spatial distributions of Cu in surface water across all nine the sampling locations (LE1–LE9) in Lekki Lagoon were considerably low, although those of LE4 (0.49 mg/L) (an area dominated by small-scale sand dredging and farming practices) and LE9 (0.36 mg/L) (a region known for huge waste generation from tourist activities and agriculture) were still higher than the 0.2 mg/L suitable for irrigation (Fig. 3c)[47]. In contrast, all the sampling locations dominated by several industrial and shipping activities in Lagos Lagoon (See Table S1) were highly contaminated with Cu, except for LA5 (0.97 mg/L), a site near a stationary oil depot (Fig. 3d). Basheeru et al.[74] also recorded elevated Cu levels in Lagos Harbour water and attributed the high contamination degree to several industrial processes, including effluent discharges and shipping in the harbor area.

Chromium (Cr)

The average Cr level of 0.023 mg/L recorded in surface water from Lekki Lagoon was significantly lower than the 0.788 mg/L observed in Lagos Lagoons. The Cr in Lagos lagoon exceeded both local and international guideline limits of 0.03 mg/L and 0.05 mg/L, respectively, in drinking water; 0.10 mg/L for irrigation[47]; and 0.016 mg/L for the productivity of aquatic organisms[65,66]. Environmental Cr is mostly derived from anthropogenic sources; hence, the elevated level of Cr in Lagos Lagoon can be attributed primarily to local industrial activities such as steel and alloy productions, thermal power stations, chrome plating, dye and pigment manufacturing, and industrial welding[12]. Excessive exposure to Cr has been associated with cancer and may lead to impairment of internal tissues, including the intestines, liver, and cardiovascular system[5,9,12]. In comparison with previous studies, Avigliano & Schenone[75] and Samecka-Cymerman & Kempers[76] reported lower ranges of 0.0006–0.0029 mg/L and 0.0001 mg/L in Misiones Lake, Argentina, and Legnica Lake, Poland, respectively. In contrast, the Cr concentrations reported in the Awash River, Ethiopia (0.690 mg/L)[67], Mangla Lake, Pakistan (0.001 mg/L)[6], Naivasha Lake, Kenya (0.03 mg/L)[77], Ojo River, Nigeria (0.041 mg/L)[5], Nhezelele River, South Africa (0.266 mg/L)[63], and Tinto River, Spain (0.071 mg/L)[73] were all higher than those reported in Lekki Lagoon but remained lower than the levels measured in Lagos Lagoon. The spatial plots revealed that three (LE2–LE4) of the nine sampling sites in Lekki Lagoon presented the highest Cr levels (between 0.03 mg/L and 0.05 mg/L) that are well above the permissible limits for aquatic life survival (Fig. 3e). Coincidentally, these three locations are commonly characterized by intensive sand dredging, unsustainable municipal waste management, and agricultural practices that involve the use of pesticides and inorganic fertilizers (Table S1). Additionally, all the sampling sites of Lagos Lagoon had considerably high levels of Cr, with the highest concentration (1.05 mg/L) recorded at station 1 (LA1), situated near the second busiest port in Nigeria and a major crude oil transport route complemented by bunkering vessels operated by several reputable oil companies (Table S1; Fig. 3f). These spatial patterns support the previous report where elevated Cr was documented in sediment and water from near industrial and port areas[74].

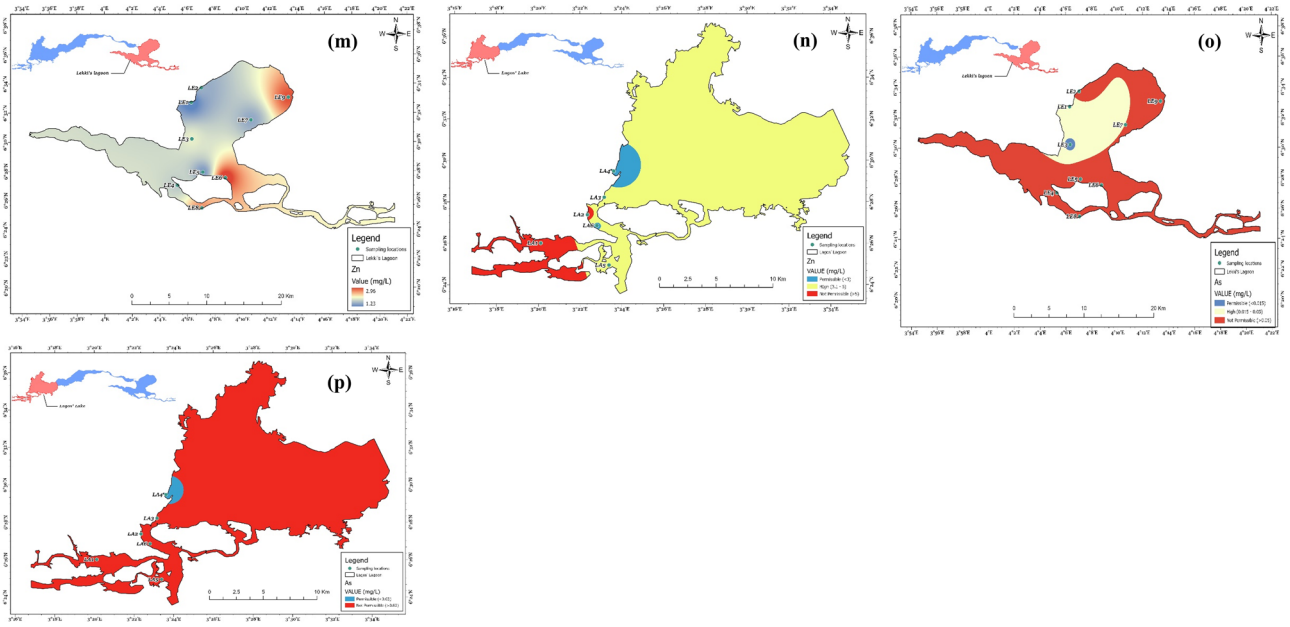

Fig. 3. (continued)

Iron (Fe)

The average Fe concentrations were 0.585 mg/L in Lekki Lagoon and 3.794 mg/L in Lagos Lagoon, with the latter nearly 8 times more Fe-enriched. The Fe level in Lagos Lagoon exceeded the local standard limit of 1.0 mg/L[58], while both lagoons surpassed the 0.3 mg/L recommended limit in drinking water[45,46]. However, the Fe levels remain suitable for aquatic life (1.0 mg/L) and irrigation practices (5.0 mg/L). The elevated Fe levels in Lagos Lagoon may be due to the naturally elevated background Fe levels in tropical soils or the prevailing intensive industrial processes in the study locations. According to Ndimele et al.[2], Nigeria's soils are typically rich in Fe due to geogenic processes, which may lead to its release into other environmental matrices. In contrast, low Fe levels have been previously reported in freshwater bodies in Nigeria[5,12]. Fe concentrations in the surface water from all the sampling stations in Lagos Lagoon were high (Fig. 3h) compared with those from Lekki Lagoon (Fig. 3g), which further highlights the impact of distinct anthropogenic inputs between the study locations. High levels of Fe have also been reported in previous studies. The Fe levels between 4.25 and 67.43 mg/L reported in the Gomti River, Bangladesh[42] and the 574.0 mg/L obtained in the Tinto River, Spain[73] were higher than those reported in the current study.

Lead (Pb)

Pb is a metallic element without any positive biological function, and elevated levels of Pb cause environmental pollution and have significant health implications for aquatic organisms and human populations[9]. Elevated levels of Pb pose serious threats to human bone health and can lead to increased muscle stiffness, which in turn can cause neurotoxicity, disrupt kidney and liver functions, cognitive impairment, rapid onset of behavioral and metabolic abnormalities, cardiovascular disease, and stunted growth[5,9,12]. The average Pb levels of 0.503 and 0.302 (mg/L) obtained in Lekki and Lagos Lagoons, respectively, significantly exceeded the acceptable values of 0.01 mg/L[46,47,58] and 0.0065 mg/L[65,66] in drinking water and for aquatic life, respectively. The elevated levels of Pb in both types of Lagoons could be attributed to several sources. Singh and Kumar[22] argued that the presence of lead (Pb) at low levels is mainly from natural sources, such as geological weathering; however, the exceedingly high concentration of Pb is due to anthropogenic inputs. In Lekki Lagoon, where urban and environmental resource activities are more prevalent, Pb could be attributed to landfill activities, inorganic manures and pesticides for agricultural practices, dredging-mining, land reclamation, and construction or building activities. Conversely, the increased Pb level in Lagos Lagoon could be attributed to discharge from abandoned thermal plants, gasoline additive leakage, and discharge from coating industries in this location[22]. The Pb pollution observed was due to mobilization processes with respect to the anthropogenic activities described earlier, which resulted in surface water enrichment. In this study, the average Pb concentrations were higher than those reported in the global studies provided in Table 2, except the 0.700 mg/L reported in surface water of the Awash River[67]. Spatially, two sampling stations in Lekki Lagoon [LE5 (0.85 mg/L) and LE7 (0.71 mg/L)] exhibited the highest Pb levels (Fig. 3i), of which both sites are heavily impacted by unsustainable agricultural and dredging activities. In addition, the Pb levels in surface water across all sampled locations in Lagos Lagoon exceeded the thresholds in drinking water and for aquatic life productivity. The highest Pb contaminations were observed at sites (LA1, LA2, and LA3) that are commonly vulnerable to oil spills from numerous sources (Fig. 3j). These findings are consistent with previous studies where Pb exceeded the thresholds in surface sediments of six Mediterranean lagoons due to agricultural runoffs[78] and in mangrove lagoons along the Red Sea, a site influenced by industrial and port-related effluent discharges[79].

Nickel (Ni)

Ni compounds are recognized as toxic elements because of their potential to cause lung and nasal cancers in humans. Elevated Ni levels can negatively harm aquatic life because it tends to persist in the environment and accumulate through the food chain[5,9]. The average levels of Ni in Lekki (0.022 mg/L) and Lagos Lagoons (0.063 mg/L) were within the local standard limit of 0.1 mg/L[63] but exceeded the 0.02 mg/L recommended by the WHO (2017; 2022) in drinking water. Conversely, the Ni values were within the recommended limits of 0.20 mg/L[47] and 0.47 mg/L[65,66] for aquatic life and for irrigation purposes, respectively. The average Ni concentration in Lagos Lagoon surface water was almost 3 times higher than that observed in Lekki Lagoon. Ni is an element that is generally formed from hydrogeochemical processes, particularly Ni rock-bearing weathering, and is commonly found in lateritic soil and terrigenous deposits[20,22]. The high Ni levels recorded in this study, particularly in Lagos Lagoon, appear to be linked to a variety of anthropogenic activities, which include industrial wastewaters that are byproducts of paint, ceramic, and glass production; exhaust from automobiles; battery disposal; and the activities of crude oil power stations, with runoff ensuring the transport of these contaminants to lagoon environments[20,22]. Compared with previous studies, the average Ni concentrations reported in the Naivasha River, Kenya (0.15 mg/L)[77], and Tinto River, Spain[73], were higher than those obtained across all the sampling locations. However, the surface water from other Nigerian ecosystems reported 0.006 mg/L[5] and 0.02 mg/L[2], which were lower than our results. Spatially, about 67% of the sampling stations in Lekki Lagoon had Ni concentrations between 0.01 and 0.02 mg/L, which are within the acceptable limits for consumption (Fig. 3k). However, three stations [LE2 (0.05 mg/L), LE4 (0.03 mg/L), and LE7 (0.05 mg/L)] heavily dominated by farming and sand dredging exceeded these limits. Similarly, within Lagos Lagoon, several sampling points had elevated Ni levels that are well above the drinking water guideline of WHO[45,46]. For example, LA1 (situated near crude oil transport routes), LA3 (an area with auto mechanics and engine oil workshops), and LA5 (dominated by pipelines and maritime oil operations) had the Ni concentrations ranging from 0.05 to 0.12 mg/L (Fig. 3l). These elevated Ni levels likely reflect the impact of extensive industrial activity in the region. Globally, similar contamination patterns have been observed, with elevated Ni in Nador Lagoon, Morocco linked to industrial and agricultural runoff[80].

Zinc (Zn)

Zn serves as a trace metal required for growth and supports metabolic and biochemical processes in humans. It also functions as a catalyst for approximately 300 enzymes in aquatic life[9]. However, excessive consumption of Zn above the required limits results in toxicological effects. The mean Zn levels were 1.779 mg/L (Lekki Lagoon) and 4.606 mg/L (Lagos Lagoon), both of which are within the 5.0 mg/L recommended in drinking water[45,46], although the latter was above the 3.0 mg/L allowable limit of NESREA[58]. The mean Zn level in Lagos Lagoon was nearly three times higher than that in Lekki Lagoon, a difference that may be attributed to several anthropogenic factors. Singh and Kumar[22] noted that the disintegration and mobility processes of Zn are complex, which allows its persistence in the environment for extended periods. In Lekki Lagoon, Zn levels might be influenced by the influx of fertilizers and fungicide residues from agricultural lands. Conversely, the higher concentrations in Lagos Lagoon are likely linked to industrial processes such as metal plating and the discharge of untreated wastewater from the automobile industry[12,20]. Similarly, the average Zn levels reported in this study were much higher than those previously reported in Nigerian natural water bodies, such as those reported by Jolaosho et al.[5] in the Ojo River (0.452 mg/L) and Ndimele et al.[2] in Ologe Lagoon (1.04 mg/L). Similarly, the Zn levels in our findings exceed those provided in Table 4, except the 48.0 mg/L reported in the Tinto River, Spain[73]. The spatial plots revealed that in Lekki lagoon, the highest Zn contents were obtained at stations LE9 (2.79 mg/L), a site characterized by a steady influx of tourists, farming, aquaculture, and mining activities (Fig. 3m). In Lagos lagoon, the site LA1 dominated by crude oil mining and processing companies had the highest Zn concentration (8.74 mg/L), exceeding the limit suitable for irrigation, drinking, or aquatic life. In fact, approximately 33% of the sampling stations in Lagos Lagoon had Zn concentrations unsafe for any of these uses (Fig. 3n). Given that LA1 measures nearly three times the WHO threshold for drinking water, irrigation and well above levels toxic to aquatic species, it could be inferred that industrial activities, especially associated with oil handling are the main drivers of these elevated Zn concentrations[81].

Arsenic (As)

As is considered a toxic element that can cause detrimental effects on aquatic organisms and human health, even at low exposure levels. Elevated levels of As, especially inorganic As, are linked with the likelihood of lung and dermal cancers; disruption of the endocrine system; hyperpigmentation; dermatitis; anemia; gastrointestinal disorders; impairment of the reproductive, circulatory, and respiratory systems; and even death[9,15]. The average levels of As in the Lekki (0.056 mg/L) and Lagos (0.045) lagoons were 4–5 times higher than the 0.01 mg/L recommended limits for drinking water[45,46,58], although the concentrations are still suitable for aquatic life and irrigation purposes. Generally, As in the environment is formed through geological rock weathering and the dissolution of sulfide minerals; however, its elevated level can be attributed to various human-induced activities. Given the human-induced activities around Lekki, pollution sources could be mainly from agriculture containing pesticides and dredging activities, whereas in Lagos Lagoon, industrial activities such as operations from hydrothermal power plants, smelting, combustion of fuel materials, and discharges from nearby industries are the main contributors. Our results were lower than the 3.26 mg/L and 0.521 mg/L reported in Naivasha Lake, Kenya[77], and Tinto River, Spain[73], respectively. In Nigeria's estuarine systems, Jolaosho et al.[5] reported an even lower level of 0.010 mg/L in the Ojo River, whereas Ndimele et al.[2] reported As levels below the detectable limit in Ologe Lagoon. About seven of the nine sampling stations of Lekki Lagoon had the As concentrations above the threshold limit in drinking water[45,46]. Only surface waters from sites LE1 and LE3 (areas dominated by rapid urban expansion, land reclamation, agriculture, and improper waste management) remain within the

permissible limits (Fig. 3o). Similarly, in Lagos lagoon, all the sampling stations except one had elevated As levels. The site (LA4), dominated by the wood industry and characterized by logging, cutting, and processing, had the As level within the permissible limits in drinking water. In addition, the As concentrations measured in surface water at LE4 (0.10 mg/L), LE8 (0.08 mg/L), and LA2 (0.09 mg/L) exceed thresholds deemed safe for aquatic productivity and survival (Fig. 3p). Rendón-Martínez et al.[82] reported high sedimentary As (13–48 mg/kg) in Urías Lagoon, Mexico, near industrial zones, while Mirlean et al.[83] also obtained high bioavailable As (50 mg/kg) in the Patos Lagoon, Brazil, impacted by agricultural runoff and fertilizer use. These findings suggest that significant As contamination across both lagoons is most likely linked to both environmental and industrial-related activities.

Relationships between pH and metalloid elements in surface water

Given that metallic ions are freely released in surface water in the presence of low pH, this study examines the interactions between pH and toxic metals through Ficklin plots[19,84]. The occurrence of heavy metals in aquatic environments, particularly at their background levels, is largely influenced by geological processes such as the interaction between weathered rocks, as well as environmental factors and the degree of mineralization, where pH is an important factor[19]. To assess the spatial distribution and source specificity of heavy metals in relation to geological phenomena and mineralogical deposits, the Ficklin Caboi plot was utilized. As shown in the figures below, the pH values were plotted against the cumulative loads of eight metalloids in surface water from Lekki (Fig. 4a) and Lagos (Fig. 4b) Lagoons. In both Lagoon systems, all the samples had pH values within the "near-

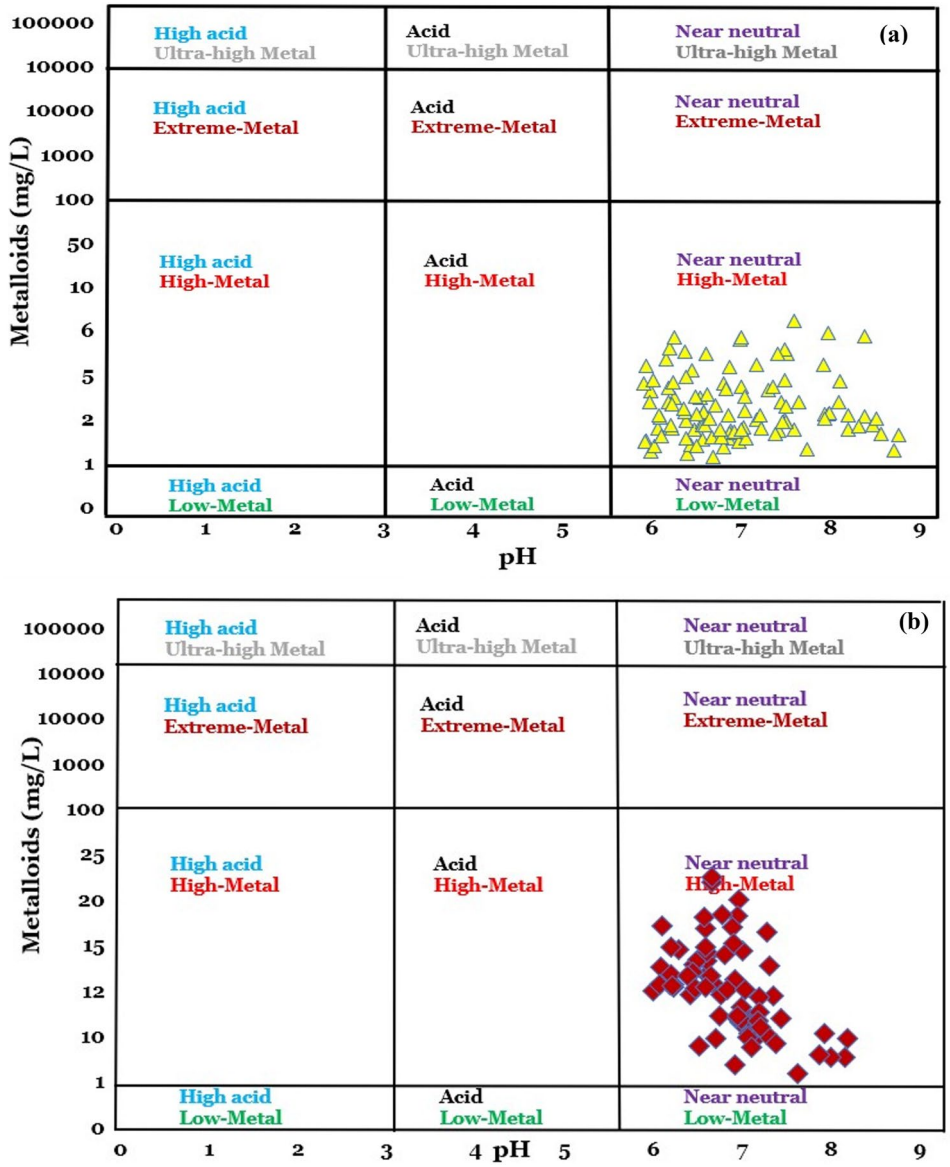

Fig. 4. Ficklin–Caboi plots showing the mutual relationship between pH and metalloid elements: (**a**) Lekki lagoon; (**b**) Lagos Lagoon.

neutral" class, with corresponding "high metal," which suggests that the metal solubilities may not be completely correlated with pH acidity. However, in Lagos Lagoon, the pH between 6 and 7 resulted in more heavy metals, whereas a drastic reduction was observed in surface water with a pH > 8. These varying outcomes suggest that the solubilization of some of the evaluated metals increased with decreasing redox potential. Singh and Kumar[22] argued that the bioavailability and mobilization processes of some trace and heavy metals, such as Cu, Mn, Pb, and Zn, are influenced primarily in acidic aqueous environments. However, this study could only deduce that the pH alkalinity restricted the mobilization of some and not all the heavy metals in the aqueous phases. This suggests that the influence of high anthropogenic inputs in the study areas may have overridden or suppressed the geological processes typically governing metal speciation within the lagoon systems.

Integrated water contamination and quality index assessment

Figure 5 presents the Pi values of eight heavy metals in surface water from 15 sampling locations (Lekki and Lagos Lagoons) in the dry and wet seasons. This index was employed to determine the contribution of each toxic element to water contamination at the study sites rather than the aggregated effects of all the metals on pollution loads[5,19,20]. The Pi values for Cd across all the sampling stations were above 3 in both the dry and wet seasons, suggesting extreme Cd contamination (Fig. 5a). Conversely, the Pi values for Cu across all the sampling stations in Lekki Lagoon during both seasons were less than 1 (not polluted), whereas in Lagos Lagoon, only LA5 had Pi values lower than 1 (not polluted) across both seasons, with most of the samples in the category of low-extreme Cu contamination (Fig. 5b). As shown in Fig. 5c, the Pi values for Cr in more than 80% of the sampling locations of Lekki Lagoon fell into the class of "not polluted," except for LE3 and LE4, which were slightly contaminated by Cu. On the other hand, all the sampling points in Lagos Lagoon presented Pi values greater than 3, indicating extreme Cr pollution. A negligible - moderate pollution levels was obtained for Fe in Lekki lagoon, with only LE6 being extremely contaminated by Fe (dry season), whereas all the sampling stations of Lagos Lagoon (LA1-LA6) had high Pi values (> 3) during the dry and wet seasons, which implies extreme Fe contamination, a phenomenon explainable by the naturally high background levels of Fe in Nigeria's tropical waters (Fig. 5d). Both lagoons were extremely contaminated by Pb irrespective of the sampling location and season (Fig. 5e). The Pi values for Ni across all the sampling points during both seasons suggest extreme water pollution levels (Pi > 3), except for LE1, LE9, and LA4 in the class "low-moderate pollution" during the wet season (Fig. 5f). In the Lekki and Lagos lagoons, none of the samples were contaminated by Zn during both seasons, except for LA1 and LA2, whose Pi values were ≤ 2 during the dry season, which implies low water contamination by Zn (Fig. 5g). Most of the samples were extremely contaminated by As (Pi > 3), except for LE3 (not polluted) in both seasons and a few other samples (LE1, LA1, LA4, and LA6) that were slightly to moderately contaminated during the wet season (Fig. 5h).

This study further employed four integrated contamination indices (Cdeg, HEI, HPI, and WQI) to comprehensively assess the overall pollution and quality levels of surface water from Lekki and Lagos Lagoons across two different seasons (Table 3). This helps to determine the contamination status and suitability ofthe examined surface water for utilization[7,19]. The Cdeg scores during the dry season suggest that about 67% of the water samples were extremely contaminated, whereas the others were moderately contaminated. During the wet season, the Cdeg values at 4 sampling stations (LE1, LE2, LE3, and LE9) of the Lekki system and 1 station (LA4) of the Lagos Lagoon system fell into the class of negligible contamination. The HEI values revealed that approximately 87% of the water samples were highly polluted (HEI > 80) during the dry season, except at 2 sampling stations (LE1 and LA1), with 1 each from both lagoons that were moderately polluted. During the wet season, approximately 20% of the samples had HEI scores classified as "not polluted," while 40% were categorized as moderately polluted and the remaining 40% as highly polluted. Irrespective of the season, the HPI scores across all the sampling stations were above 100, which suggests extremely polluted surface water. Similarly, the water quality index (WQI) was employed to evaluate the quality of water in terms of purity level, such that all the water parameters were aggregated and eventually converted into a single value[19]. The WQI scores across all the sampling locations of both lagoons during both seasons were above 100 (WQI > 100). These findings demonstrate that the water samples from these lagoons are extremely unclean and thus unfit for utilization, except if properly treated.

Source analyses of surface water variables from the Lekki and Lagos lagoons

Given that the study areas experience varying degrees and natures of anthropogenic processes, which influence the concentration levels and mobility of toxic elements in the surface waters of the examined lagoons, identifying the specific sources of these pollutants is important. Therefore, source analyses were conducted with the application of multivariate analytical techniques.

Pearson's correlation matrix (PCM)

The relationship between the physicochemical and heavy metal variables in surface water from Lekki and Lagos Lagoons was examined through the PCM. As shown in Fig. 6, pH and salinity were strong-positively correlated with some of the heavy metals in both lagoons. The bioavailability of metals in water depends on the water pH[85]. For example, when the surface water pH is high, raindrops in the form of OH^- or CO_3^{2-} predominate. A gradual decrease in pH reduces the influence of rainfall, consequently increasing the capacity of water-holding cations. Hence, toxic metals are retained, provided that the buffering capacity of water is passable to maintain a stable pH[86]. Similarly, salinity tends to increase the retention and mobility of metallic ions in water[40]. Temperature was positively correlated with DO ($r = 0.62$; $r = 0.87$) and TSS ($r = 0.84$; $r = 0.83$) in both lagoons; and with TDS ($r = 0.89$) in Lekki and with BOD ($r = 0.80$) and COD ($r = 0.89$) in Lagos Lagoon. This finding aligns with the claim that some water parameters are interdependent, such that a higher temperature results in lower DO[87]. The strong correlations of DO with TSS ($r = 0.73$; $r = 0.86$) in both lagoons correspond with the assertion that high levels of

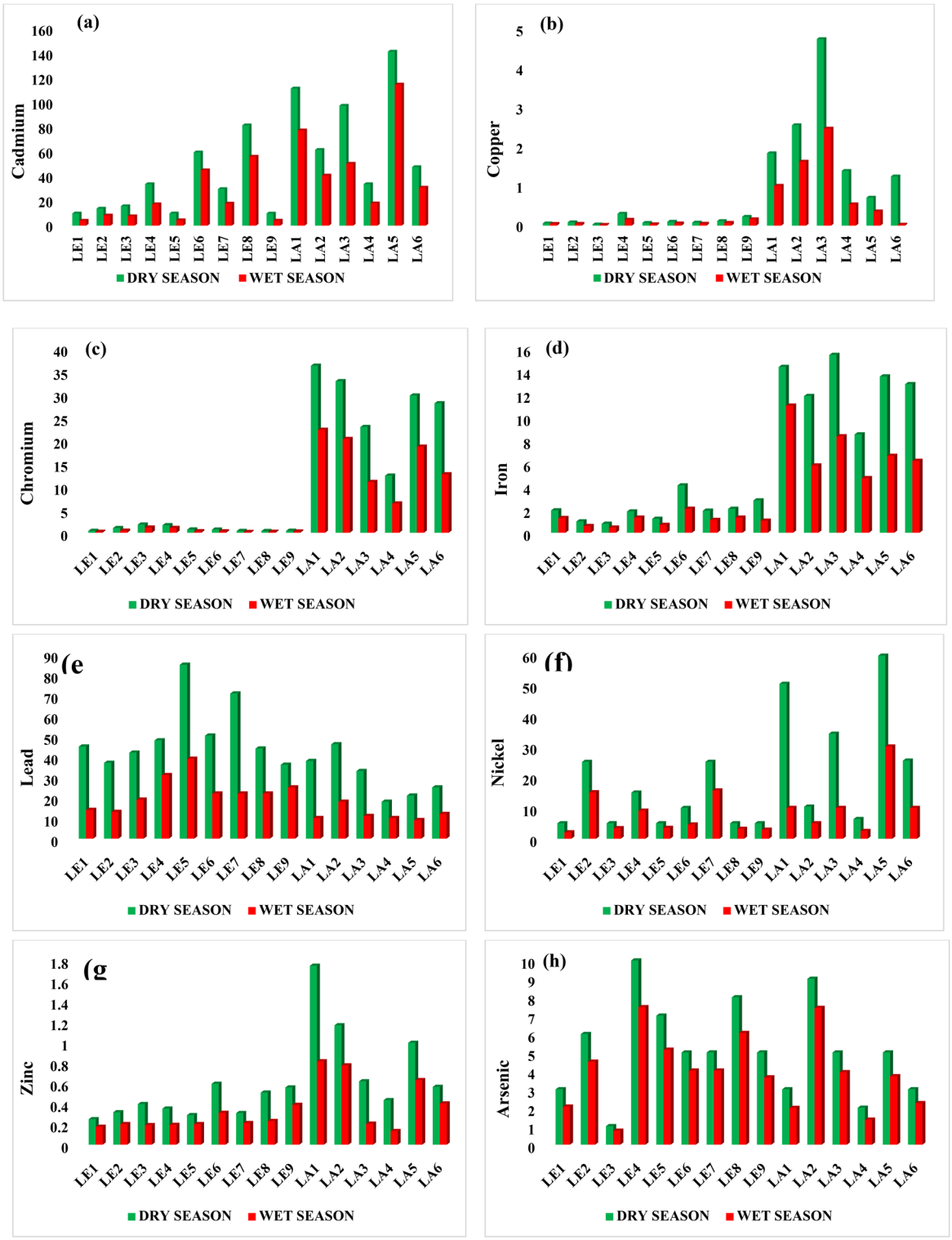

Fig. 5. Contributions of heavy metals to surface water contamination in Lekki and Lagos Lagoons: (**a**) Cd; (**b**) Cu; (**c**) Cr; (**d**) Fe; (**e**) Pb; (**f**) Ni; (**g**) Zn; (**h**) As.

TSS negatively impact the DO levels in water[88]. The positive correlations observed between all the metals suggest their identical geochemical sources, most likely due to anthropogenic impacts. This outcome corresponds with the claim that strong correlations of toxic metals imply similar geochemical sources[12], which are mostly traced to multiple anthropogenic processes. The differences in the correlated water variables of the two lagoons suggest the need to identify their main sources. To achieve this, we used factor analysis (FA) and hierarchical cluster analysis (HCA) to clarify the underlying relationships.

Indices	C_{degree}		HEI		HPI		WQI	
	Score	Status	Score	Status	Score	Status	Score	Status
Dry season								
LE1	57.61	Moderate contamination	65.61	Moderately polluted	881.27	Extremely polluted	609.33	Unsuitable for usage
LE2	76.37	Moderate contamination	84.37	Highly polluted	1137.34	Extremely polluted	778.90	Unsuitable for usage
LE3	58.95	Moderate contamination	66.95	Moderately polluted	902.57	Extremely polluted	634.52	Unsuitable for usage
LE4	103.10	Extreme contamination	111.10	Highly polluted	1495.61	Extremely polluted	1024.00	Unsuitable for usage
LE5	101.24	Extreme contamination	109.24	Highly polluted	1472.79	Extremely polluted	1010.99	Unsuitable for usage
LE6	122.79	Extreme contamination	130.79	Highly polluted	1756.01	Extremely polluted	1201.834	Unsuitable for usage
LE7	125.57	Extreme contamination	133.57	Highly polluted	1799.68	Extremely polluted	1232.26	Unsuitable for usage
LE8	134.04	Extreme contamination	142.04	Highly polluted	1913.54	Extremely polluted	1302.92	Unsuitable for usage
LE9	52.07	Moderate contamination	60.06	Moderately polluted	803.531	Extremely polluted	553.94	Unsuitable for usage
LA1	249.58	Extreme contamination	257.58	Highly polluted	3436.93	Extremely polluted	2319.45	Unsuitable for usage
LA2	177.99	Extreme contamination	175.99	Highly polluted	2339.28	Extremely polluted	1580.23	Unsuitable for usage
LA3	205.92	Extreme contamination	213.92	Highly polluted	2836.20	Extremely polluted	1918.46	Unsuitable for usage
LA4	75.12	Moderate contamination	83.12	Highly polluted	1096.44	Extremely polluted	753.03	Unsuitable for usage
LA5	264.65	Extreme contamination	272.65	Highly polluted	3645.81	Extremely polluted	2463.94	Unsuitable for usage
LA6	136.24	Extreme contamination	144.24	Highly polluted	1910.85	Extremely polluted	1298.76	Unsuitable for usage
Wet season								
LE1	15.84	Negligible contamination	23.84	Not polluted	318.66	Extremely polluted	226.78	Unsuitable for usage
LE2	34.19	Negligible contamination	42.19	Moderately polluted	568.50	Extremely polluted	392.73	Unsuitable for usage
LE3	24.68	Negligible contamination	32.68	Not polluted	440.33	Extremely polluted	314.17	Unsuitable for usage
LE4	59.78	Moderate contamination	67.78	Moderately polluted	912.00	Extremely polluted	625.33	Unsuitable for usage
LE5	45.31	Moderate contamination	53.31	Moderately polluted	718.56	Extremely polluted	496.29	Unsuitable for usage
LE6	70.71	Moderate contamination	78.71	Moderately polluted	1057.95	Extremely polluted	726.01	Unsuitable for usage
LE7	53.36	Moderate contamination	61.36	Moderately polluted	826.01	Extremely polluted	570.80	Unsuitable for usage
LE8	81.55	Extreme contamination	89.55	Highly polluted	1206.43	Extremely polluted	820.33	Unsuitable for usage
LE9	29.55	Negligible contamination	37.55	Not polluted	504.21	Extremely polluted	347.93	Unsuitable for usage
LA1	127.09	Extreme contamination	135.09	Highly polluted	1792.99	Extremely polluted	1209.21	Unsuitable for usage
LA2	92.06	Extreme contamination	100.06	Highly polluted	1331.97	Extremely polluted	897.68	Unsuitable for usage
LA3	89.76	Extreme contamination	97.76	Highly polluted	1291.80	Extremely polluted	874.41	Unsuitable for usage
LA4	35.86	Negligible contamination	43.86	Moderately polluted	578.37	Extremely polluted	396.50	Unsuitable for usage
LA5	176.28	Extreme contamination	184.28	Highly polluted	2471.26	Extremely polluted	1670.12	Unsuitable for usage
LA6	66.75	Moderate contamination	74.75	Highly polluted	993.61	Extremely polluted	678.86	Unsuitable for usage

Table 3. Pollution metrics for holistic evaluations of water quality and contamination.

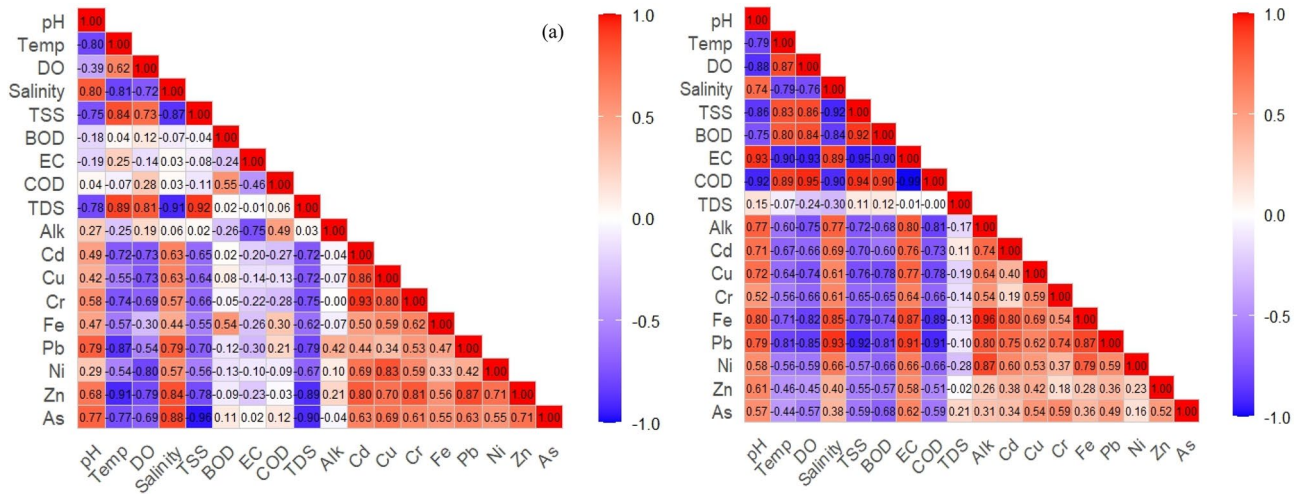

Fig. 6. Heat maps showing the correlations of surface water variables in (**a**) Lekki lagoon and; (**b**) Lagos Lagoon.

Factor analysis (principal components and hierarchical clusters)

This study employs PCA, which is part of the FA technique, to reduce the size of the complex dataset to a substantially smaller magnitude without influencing dimensions or losing a sizable portion of the original datasets. It was essential to compress the datasets to ensure that only a small but crucial set of variables would be used to determine the associations among the groups of related components, with clear identification of the important parameters across all the datasets[2,19,20]. Additionally, PCA was also used to estimate the commonalities, distinct features, and sources of origin of the correlated parameters identified earlier. The eigenvalues, along with the variances, are essential factors that best explain the substantiality of the identified component matrix of a dataset. An eigenvalue of 1 or higher is considered substantial enough to be retained among its pairs[89]. In Fig. 7a, the trend of the screen plot shows that four of the eighteen components produced for Lekki Lagoon had eigenvalues of at least 1. In Lagos Lagoon, three of the components had eigenvalues of 1 or above, (Fig. 7b). The suitability of the datasets for PCA assessment was validated by the KMO (0.672) and BTS ($P < 0.001$) values of this study (Table 4). These obtained values demonstrate the non-identical nature of the correlated factors and also the adequacy and quality of the sampling datasets[5].

Table 4 shows the variances and component matrices for the Lekki and Lagos lagoons. In PCA assessment, the factor loading scores are categorized as follows: PC < 5 = not sufficient; PC > 5 = sufficient; and PC > 0.750 = very high, which suggests a strong correlation among the correlated components[19,20]. The rotated spaces represented in Fig. 7c and d illustrate the geochemical associations between the principal components of the analyzed parameters in Lekki and Lagos Lagoon, respectively. In Lekki Lagoon, PC1 was loaded with the factors of pH (0.867), salinity (0.880), Pb (0.850), Zn (0.696), and As (0.826), explaining 55.29% of the total variance. This trend confirmed that the solubilization of these heavy metals was mutually dependent on pH and salinity. High loadings of Zn and As (naturally occurring elements) in Lekki lagoon implies formation through numerous geological events, including sedimentary deposition, rock weathering, fossil fuels, and volcanic events[20]. For example, phosphate rocks are naturally enriched in Zn, and their weathering has been reported in African soils and riverine systems[8]. However, their correlation with high Pb loads indicates anthropogenic sources, which could be primarily due to the runoff of animal waste, agrochemicals such as fungicides and pesticides used on farmlands, and the discharge of wood preservatives by sawmills around the Lagoon system[12]. PC2 explained 14.58% of the total variance and was loaded with Cd (0.934), Cu (0.876), Cr (0.831), Ni (0.781), and Zn (0.634), which clearly denotes human-induced processes. A number of human activities, including landfilling, disposal of municipal waste, sewage sludge plants, and the absorption of unsterilized furnace grease from dredgers used for extracting mineral ores, are responsible for the speciation of Cd, Cr, and Cu[5,9,12,20], whereas Ni could be from fertilizer runoff from agricultural soils, as it is one of the essential elements used in commercially produced fertilizers in Africa[6,8]. This result aligns with the prevailing human activities in Lekki Lagoon, where agricultural practices, landfilling, land reclamation, and dredging are the most common activities near the sampling sites. The third PC explained approximately 10.23% of the aggregated variance obtained and was loaded with a single strong factor (alkalinity = 0.995). PC4 explained approximately 10.23% of the cumulative variance and was loaded with the factors BOD (0.959), COD (0.645), and Fe (0.689). This result corresponds with the outcome of the heatmap correlated factors. In Lagos Lagoon, PC1 accounts for approximately 70% of the total variance and was loaded with the component factors pH (0.900), salinity (0.931), EC (0.988), alkalinity (0.804), Cd (0.717), Cu (0.816), Cr (0.792), Fe (0.672), Pb (0.729), Ni (0.729), Zn (0.899), and As (0.912). The high loadings of EC and salinity observed in water from Lagos Lagoon could be explained by the presence of conductive ions originating from dissolved salts and inorganic materials (Ullah et al., 2022). Moreover, the high loading of all the heavy metals in Lagos lagoon suggests anthropogenic activities, primarily from industrial sources. The deposition of effluents, anticorrosive materials, antifouling wastes from the ship industry, coating materials, leather tanning, pigments, batteries, printed wiring boards, and electroplating has been identified as the primary source of Cd, Cu, and Cr, all of which corresponds with the industrial activities near Lagos lagoon. Smelting, fossil combustion, and ore mining are the major industrial sources of As in water[5,12]. Both PC2 and PC3 were loaded with one factor of TDS (0.941) and alkalinity (0.556) each and explained only 8.68% and 6.82% of the total variance, respectively.

The results obtained in the PCA assessment were validated via HCA via centroid linkage and the squared Euclidean distance method. HCA ensures the allocation of large physicochemical and heavy metal clusters into small but corresponding groups based on chemical properties[20]. The dendrograms show the rescaled distance clusters of the water parameters and explain the correlations between these variables. In Lekki Lagoon, three clusters were generated within the rescaled distance of 0–5 (Fig. 7e), whereas in Lagos Lagoon, two clusters were generated within a rescaled distance of 0–5 (Fig. 7f). Xu & Li (2015) noted that a strong association of variables could be demonstrated if the clusters generated are within a short distance. This suggests that there is a strong relationship between the physicochemical and heavy metal variables. In Lekki Lagoon (Fig. 7e), cluster 1 contains all eight (8) heavy metals, salinity, pH, and DO, corresponding with the PC1 and PC2 trends, whereas subcluster I contain BOD, TSS, and alkalinity. Cluster 2 included only EC, COD, and TDS. In Lagos Lagoon (Fig. 7f), Cluster 1 contains all the variables except for the COD, which formed a distinct class similar to Cluster 2. This outcome also corresponds with PC1 for Lagos Lagoon (Table 4). This suggests that the generated clusters have similar characteristics and are geochemically dependent on each other.

Health risk assessment of heavy metals in surface water

Average daily doses (ADDs) of heavy metals

The rates at which human populations are exposed to eight (8) heavy metals in surface water from Lekki and Lagos Lagoons, either through ingestion or dermal contact, were evaluated via the average daily dose assessment provided in Fig. 8. In Lekki Lagoon, the average ADDs were in the following descending order of exposure: Cd > Zn > As > Cr > Fe > Pb > Cu > Ni for children and Zn > As > Fe > Pb > Cu > Cd > Cr > Ni for adults. The order

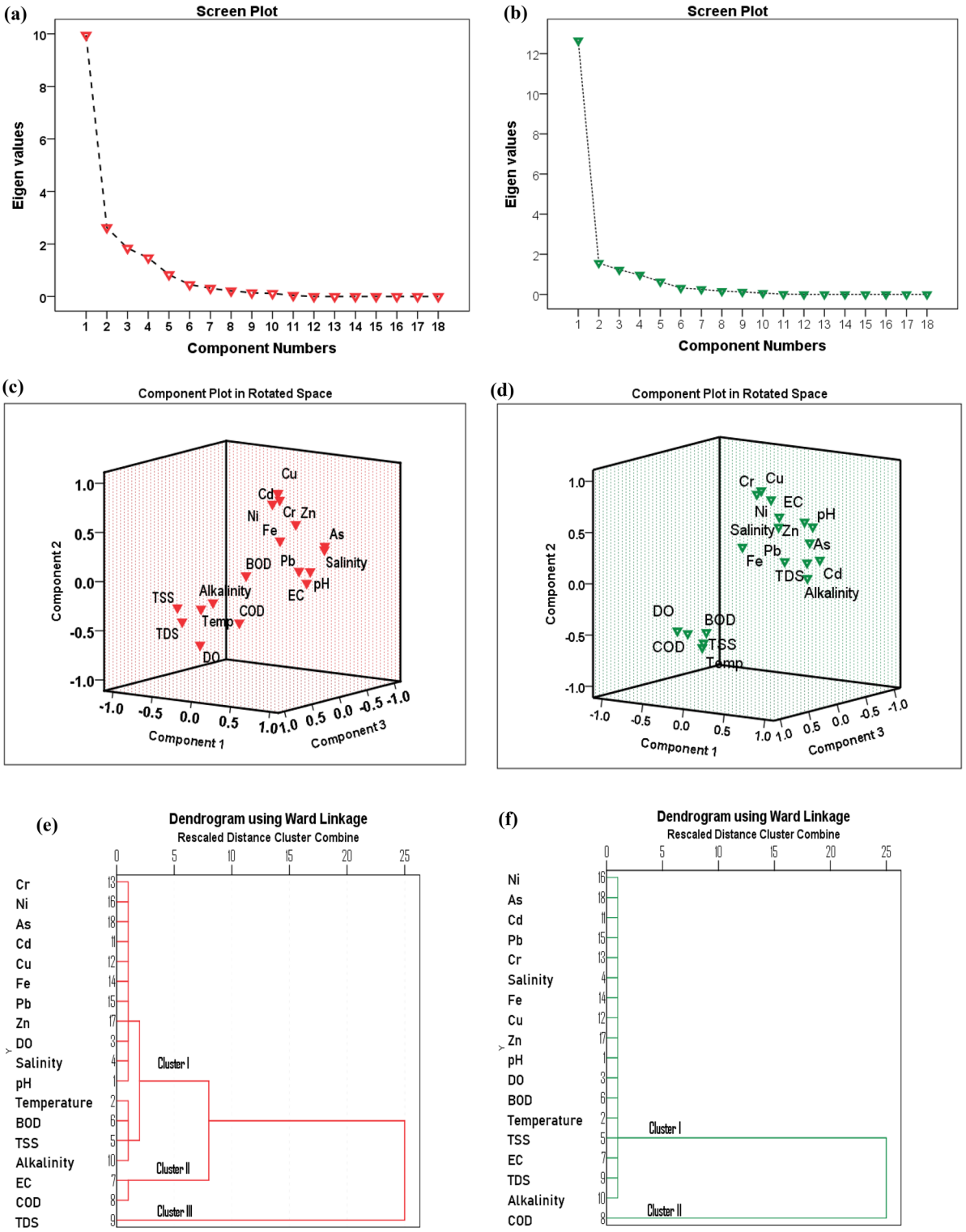

Fig. 7. Screens plots showing the eigenvalues for (**a**) Lekki, (**b**) Lagos; rotated spaces showing the components in (**c**) Lekki and (**d**) Lagos; dendrograms showing the rescaled distant clusters (**e**) Lekki, (**f**) Lagos Lagoons.

of ADDs of heavy metals in Lagos Lagoon is as follows: Cr > Cd > Zn > Fe > Cu > As > Pb > Ni for children and Zn > Fe > Cu > As > Cr > Cd > Pb > Ni for adults. The ADD values for both the ingestion and dermal pathways were generally higher in Lagos Lagoon, except for one sampling location (LE2) in Lekki Lagoon. In the children's category, Cd was the predominant heavy metal in Lekki Lagoon, with the highest ADD ingestion value observed at station LE8 (8.00E-04). Conversely, in Lagos Lagoon, Cr was the dominant heavy metal, with five out of the six sampling stations recording an ADD ingestion value of 2.00E-03. For adults, Zn was most prevalent in

Variables	Lekki Lagoon				Lagos Lagoon		
	PC1	PC2	PC3	PC4	PC1	PC2	PC3
pH	**0.867**	0.169	0.183	−0.042	*0.900*	0.255	0.048
Temperature	−0.808	−0.440	−0.219	−0.056	−0.905	−0.085	0.162
DO	−0.500	−0.709	0.238	0.119	−0.920	−0.276	−0.068
Salinity	**0.880**	0.355	−0.057	0.004	*0.931*	−0.212	0.023
TSS	−0.860	−0.380	0.137	−0.161	−0.960	0.019	0.079
BOD	−0.120	−0.007	−0.058	**0.959**	−0.904	0.065	0.000
EC	0.058	−0.188	−0.907	−0.259	*0.988*	0.092	0.037
COD	0.179	−0.378	0.493	**0.645**	−0.989	−0.091	−0.064
TDS	−0.829	−0.527	0.093	−0.078	−0.069	*0.941*	−0.137
Alkalinity	0.160	−0.109	**0.945**	−0.172	*0.804*	−0.050	*0.556*
Cd	0.342	**0.887**	0.026	0.043	*0.717*	0.315	0.319
Cu	0.302	**0.876**	−0.041	0.174	*0.816*	−0.079	−0.472
Cr	0.397	**0.831**	0.068	0.037	*0.792*	−0.133	−0.455
Fe	0.396	0.416	0.060	0.689	*0.672*	−0.536	0.041
Pb	**0.850**	0.197	0.363	−0.024	*0.729*	−0.152	0.294
Ni	0.301	**0.781**	0.064	−0.069	*0.729*	0.077	−0.411
Zn	**0.696**	**0.634**	0.202	−0.016	*0.899*	−0.106	−0.107
As	**0.826**	0.376	−0.141	0.225	*0.912*	0.099	0.230
Variance	55.291	14.580	10.230	8.1795	70.282	8.684	6.816
Total variance	55.291	69.870	80.100	88.280	70.282	78.966	85.782
KMO sampling adequacy						0.672	
Bartlett's Test of Sphericity (Sig)						0.001	

Table 4. Principal component matrix of surface water variables in the two lagoon systems. Rotation Method: Varimax with Kaiser Normalization.

Lekki Lagoon, reaching its highest ADD ingestion value at station LE6 (3.00E-07), whereas Cu predominated in Lagos Lagoon, with the highest ADD ingestion value reported at station LA3 (1.00E-06). With respect to dermal contact, station LE2 in Lekki Lagoon recorded the highest ADD value for children (1.0E−05), with iron as the dominant metal. In Lagos Lagoon, station LE3 presented the highest dermal ADD value for children (2.00E-06), with copper being the predominant metal. For adults, the highest dermal ADD values were observed at station LE4 in Lekki Lagoon (9.00E-05) and station LA1 in Lagos Lagoon (3.00E-04), with zinc being the most prevalent element. In both lagoons, the ingestion route accounted for approximately 95% of the total ADDs in the exposed populations. This outcome aligns with a previous report on health risks indicating that the oral pathway is the most important route by which humans are chronically exposed to contaminants in water. Singh and Kumar[22] reported ADD values between 6.18E-04 and 6.97E-02 (children) and between 9.0E-04 and 1.01E-01 (adults), which were higher than the dermal ADD values between 1.37E-03 and 1.18E-01 (children) and between 2.09E-03 and 1.80E-01 (adults) obtained for both age groups. Similarly, Jolaosho et al.[20] reported higher ADD values between 3.41E-09 and 4.05E-05 via the ingestion route than via dermal contact, ranging from 2.28E-11 to 1.07E-07. This implies that ingestion, rather than dermal contact, is the most likely route by which children and adults within the study areas could be exposed primarily on a daily basis to water toxicity.

Non-carcinogenic health risk of heavy metals in surface water

The non-carcinogenic human health implications of exposure to eight heavy metals in surface water from 15 sampling stations in Lekki and Lagos Lagoons were estimated via the hazard quotient (HQ) and hazard index (HI). In Lekki Lagoon, the HQ values (ingestion and dermal contact) across all the sampling stations for the children and adult categories were less than 1 (Table S5). In Lagos Lagoon, only the HQ-Cd values (ingestion) of LA1 (1.10) and LA5 (1.40) exceeded 1 in the children's category. This implies that Cd in surface water from Lagos Lagoon could pose adverse non-cancer health concerns to children, particularly via the ingestion route. Cd is highly retained in body tissues throughout life, irrespective of the routes through which humans and organisms are exposed[9]. Immediately after birth, Cd gradually accumulates and eventually increases in the human body as age increases but attenuates at the age of 60–70[9]. Cd can bioaccumulate in body tissues, especially the kidney and liver, because these organs synthesize metallothionein, which explains the overall Cd toxicity in body tissues[90]. The effects of Cd exposure include damage to the liver and pulmonary glands, bone brittleness, paralysis, coronary heart and peripheral artery disease, atherogenic alteration of the lipid profile, and osteoporosis[20,90]. Cd can also impair the viability of the cellular system, and cause numerous pathological issues[90].

Figure 9 presents the aggregated hazard quotient (HQ ingestion + dermal contact) values, referred to as the hazard index (HI). An HI value exceeding 1 indicates that exposure to a combination of heavy metals may lead to significant non-carcinogenic health risks, whereas an HI value below 1 suggests negligible risk[2,6,12,38]. Figure 9a shows that for children, three sampling stations (LE4 = 1.048, LE8 = 1.37, and LE9 = 1.37) in Lekki

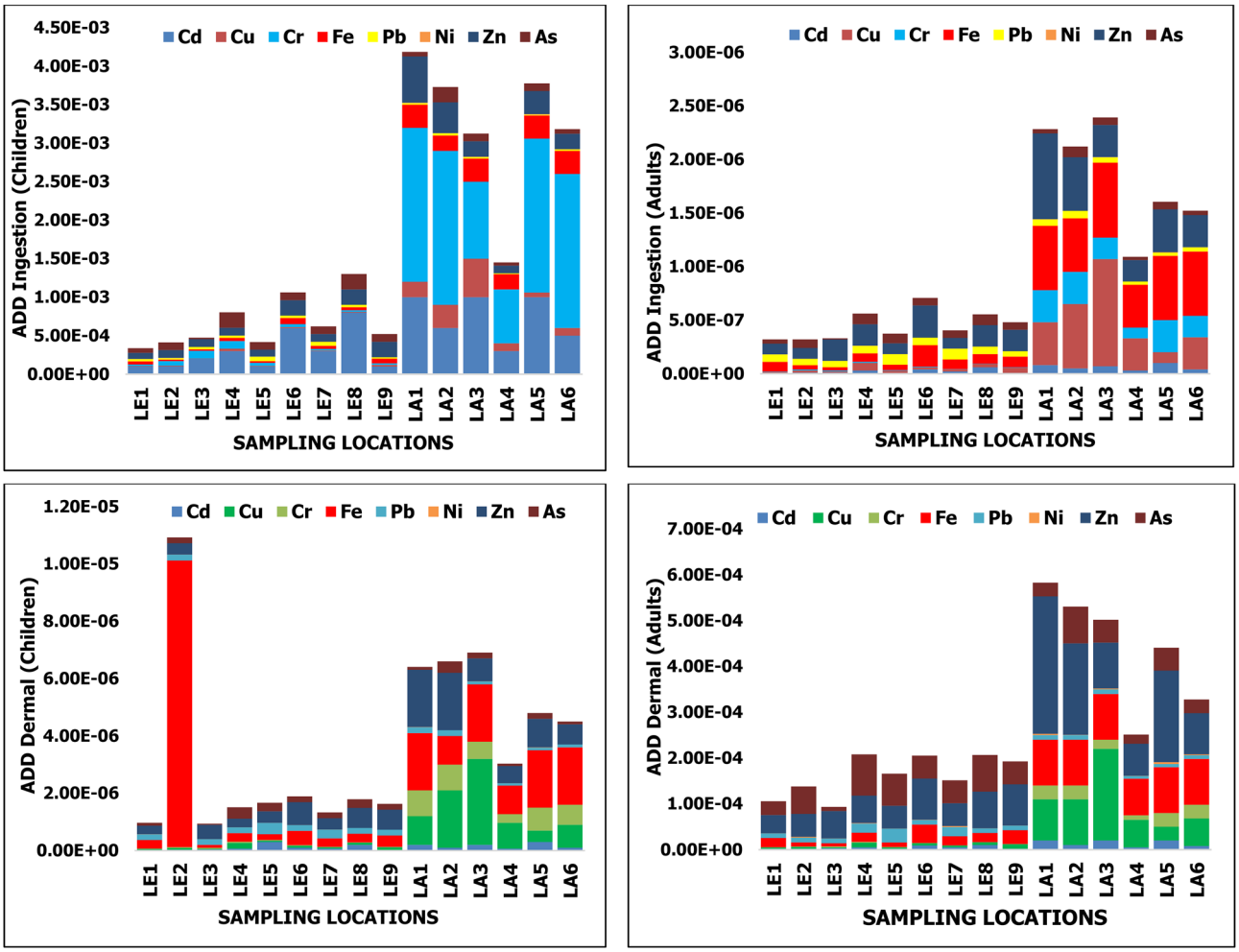

Fig. 8. Average daily intake of heavy metals in surface water from Lekki and Lagos Lagoons.

Lagoon presents HI values > 1, whereas none of the HI values reported for adults exceeded 1. Similarly, five out of six sampling stations recorded HI values above 1 for children (LA1 = 2.05, LA2 = 1.89, LA3 = 1.78, LA5 = 2.37, and LA6 = 1.24), yet none of the HI values reported for adults exceeded 1. This could be attributed to the elevated HQ values obtained for Cd, Cr, and As. The elevated HI values (HI > 1) obtained for children in the above sampling locations indicate the ability of surface water from these areas to cause non-carcinogenic health issues in children, especially via the ingestion route, whereas adult exposure to all the samples indicates negligible adverse non-carcinogenic risk. Many coastal villages around both lagoons still depend on surface water from systems for daily uses, including drinking and household chores, due to limited access to clean water and regular portable water supply[91]. Moreover, children frequently swim and play in the lagoons, which increases their exposure through dermal contact and accidental ingestion. Given this locally relevant exposure, the high risk of non-carcinogenic health values for children are particularly concerning. It has been previously reported that children are more susceptible to the adverse effects of toxic elements than adults are[5,6,9,20], which corresponds with the outcome of this study. This could be attributed to the fact that the blood–brain barrier, which regulates the movement of molecules and ions between the blood and the brain, is yet to fully develop in children, thus allowing a ceaseless movement of these elements in their organs. Similarly, the rate of intake via the gastrointestinal tract of children is 4–5 times higher than that of adults[9].

Carcinogenic risk assessment

The likelihood that children and adults will develop cancer within a specific period due to exposure to carcinogens was evaluated in this study. Five (5) of the eight (8) heavy metals classified by the "agency for research on cancer" as number 1 carcinogens were considered for the carcinogenic risk assessment (IARC)[39]. A threshold of 1.0E-06 (single cancer risk) to 1.0E-04 (target lifetime risk) has been established for cancer health risk[9,20,38]. This indicates that a cancer risk ranging from 1 in 1,000,000 to 1 in 10,000 people is deemed acceptable. The CR values (ingestion and dermal contact) of children and adults from Lekki and Lagos Lagoons are provided in Table S6. For children, the ingestion-based cancer risk (CR) values for Cd ranged from 6.0E-04 to 5.0E-03 in Lekki Lagoon and from 2.0E-03 to 9.0E-03 in Lagos Lagoon. In adults, the Cd CR values varied between 1.0E-05 and 8.0E-05 in Lekki Lagoon and between 3.0E-05 and 1.0E-04 in Lagos Lagoon. Additionally, the CR

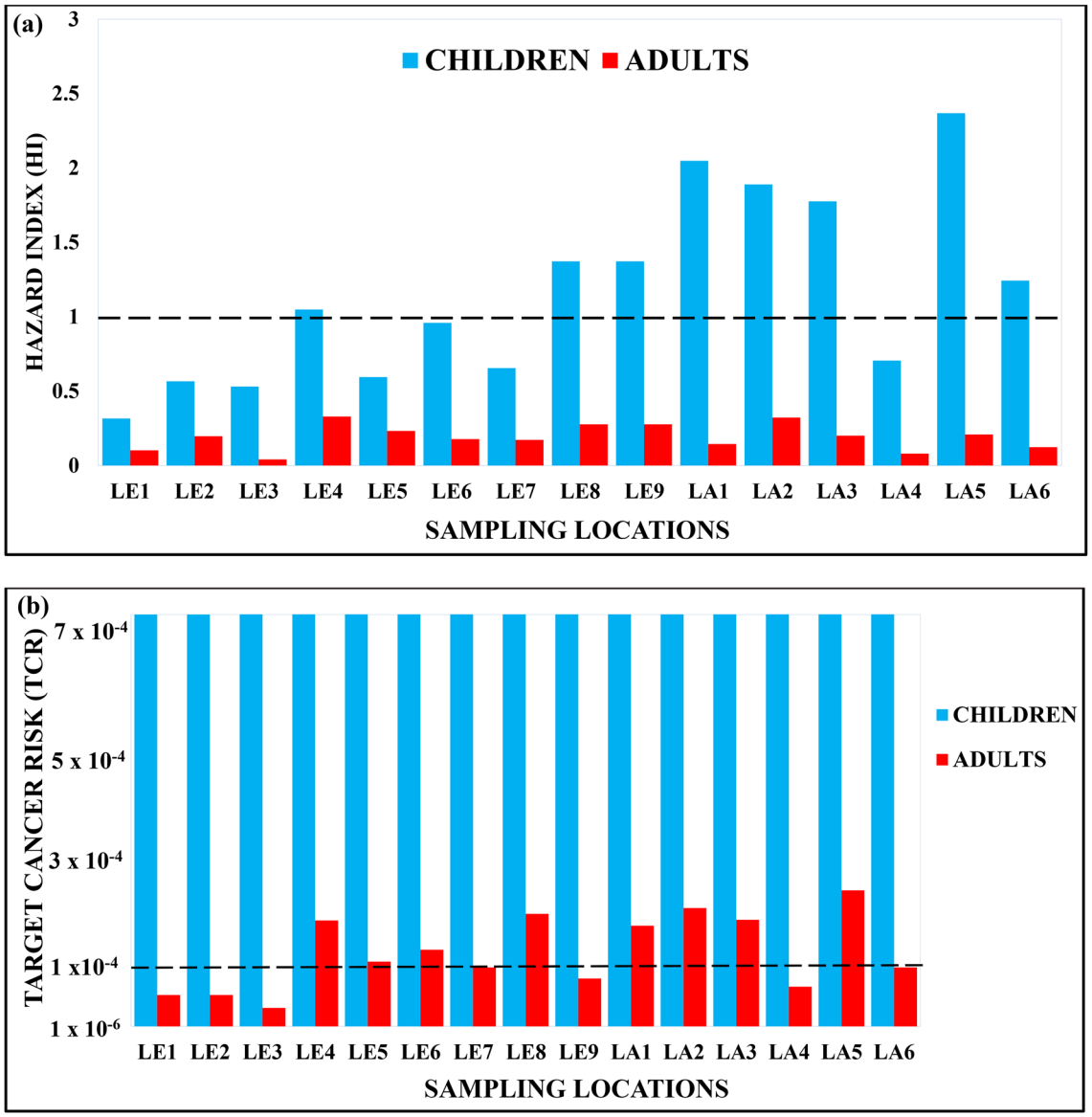

Fig. 9. Health risk evaluations for the children and adult groups: (**a**) hazard index and (**b**) target cancer risk.

values for Cr at all sampling stations in both age groups surpassed the minimum threshold of 1.0E−06 for single carcinogens, indicating that both Cd and Cr exceeded this guideline for a single cancer risk across all locations. In contrast, none of the ingestion-based CR values for Pb exceeded the threshold for either children or adults. For Ni, the CR values for children range from 1.0E-07 to 3.0E-04 in Lekki Lagoon and from 6.0E-05 to 3.0E-04 in Lagos Lagoon, with stations LE2 (3.0E-06), LE4 (2.0E-06), LE7 (3.0E-06), LA1 (6.0E-06), LA3 (4.0E-06), LA5 (7.0E-06), and LA6 (3.0E-06) exceeding the minimum cancer risk limit. For adults, all sampling stations in Lekki Lagoon recorded Ni-CR values below 1.0E-06. In Lagos Lagoon, three of the six locations (LA3 = 1.0E-06, LA4 = 2.0E-06, and LA5 = 3.0E-06) surpassed the minimum risk threshold for Ni. Furthermore, the CR values for As exceeded the minimum cancer risk threshold in all the sampling stations of both lagoons in the children and adult categories. Conversely, the dermal route CR values of all the carcinogens across all the sampled locations were below the minimum threshold (1E-06) for children and adults, except for Cd in LA1 (2E-06), LA5 (2E-06), and As in LA1 (5E-06). This study illustrates that those individual carcinogens, specifically Cd, Cr, Ni, and As, can cause serious cancer risks to populations exposed (primarily via the ingestion route). Notably, children appear to be the most vulnerable group to these cancer health hazards. As shown in Fig. 9b, the children's lifetime target cancer risk (TCR) values, ranging from 0.0007 to 0.0053 (Lekki Lagoon) and 0.0025 to 0.0099 (Lagos Lagoon), were above the 1E-04 threshold for lifetime carcinogenic health risks. This implies that water from every sampling site may pose a cancer risk to children. In addition, for adults, the TCR values range between 3.11E-05 and 1.91E-04 (Lekki Lagoon) and between 6.73E-05 and 2.31E-04 (Lagos Lagoon), with LE4, LE5, LE8, and four of the 6 sampling stations of Lagos Lagoon, except for LA4 and LA6, which exceed the recommended threshold limits for lifetime carcinogenic health risks. The outcome clearly demonstrates that exposure to water

from the Lekki and Lagos lagoons may ignite lifetime cancer risk in both age groups. Although the trend of the TCR assessment suggests that between 7 and 53 (Lekki Lagoon) and 25 to 99 (Lagos Lagoon) of every 10,000 children are likely to develop cancer risks due to exposure to water resources. This is higher than the 1 and 2 of every 10,000 adults that are likely to develop cancer due to ingestion-based exposure.

Recommendations and future research directives

This study demonstrates the need for targeted remediation measures to mitigate ecosystem contamination, health risks and safeguard environmental quality. Given that both lagoons exhibit relatively high pollution levels despite differing land uses and anthropogenic activities, it is essential to establish long-term monitoring programs, specifically targeting the specific contamination sources such as wastewater discharges from industries, as well as mining operations. This would help to effectively identify the most significant contributors to water contamination. Regulatory agencies can then enforce strict mitigation measures, such as improving wastewater treatment infrastructure, enforcing industrial compliance, and mandating remediation protocols for mining runoff. These targeted interventions will form the scientific foundation for evidence-based policy, and ultimately help to protect water quality and ensure the long-term health and resilience of these complex aquatic ecosystems. Efforts should also expand into track emerging contaminants beyond heavy metals like pharmaceuticals, personal care products, and microplastics to detect potential pollutants and understand the spatial and temporal trends. Given that the study is limited to quantification of heavy metals in surface waters only, it is highly important that future studies consider analyzing heavy metals in sediment. This is because sediments serve as both repository and long-term sources of heavy metals due to their sorption properties[92]. Moreover, they accumulate contaminants transported from rivers, runoff, and groundwater, with high levels of heavy metals in aquatic systems bound to sediment particle. This would help to further provide more information on the trends and sources of the contaminants, thus enabling researchers to distinguish recent pollution from historical baseline levels.

To address heavy metal contamination, it is imperative to explore innovative remediation strategies that best mitigate the observed contaminants in both lagoon systems. This is pertinent, as exposure to the assessed heavy metals could pose both non-cancer and cancer risks, especially in children. Previous research has highlighted several methods such as microbial and phytoremediation, nanotechnology-driven adsorbents, engineered in-situ capping, and novel material applications such as metal-organic frameworks and zero-valent Fe nanoparticles[93]. This could be achieved by engaging environmental scientists, policymakers, socioeconomic analysis, and stakeholders to co-design regulatory tools, best-practice frameworks, and incentive-based mechanisms that curb contaminant inputs at their sources. Future comparative studies should assess performance, environmental compatibility, economic feasibility, and scalability to comprehensively examine the hydrology, salinity, and sediment dynamics of the lagoons.

Conclusion

This study evaluates the effects of varying anthropogenic disturbances on the physicochemical properties and heavy metal contamination in surface water from interconnected coastal lagoons across space and time. The findings clearly demonstrate that seasonal variations have a significant effect on the ecological profiles of both freshwater systems, such that the results of the physicochemical variables, particularly DO, TSS, BOD, COD, and TDS, were highest during the wet season. Conversely, the heavy metal levels were highest in both lagoons and peaked during the dry season. Interestingly, the types and accumulations of heavy metals in both lagoons were distinct despite their interconnection. Lekki lagoon was predominantly impacted by Cd, Pb, and As, likely reflecting agricultural runoff and dredging activities, whereas Lagos lagoon presents elevated levels of Cd, Cr, Cu, Ni, and Zn, indicative of intensive industrial effluent discharge and crude oil processing. This suggests that the nature of anthropogenic activities significantly impacts the forms of heavy metals accumulated in the lagoons. Both lagoons were more or less contaminated by some similar heavy metals factors such as Cd, Cr, Pb, and As, which could either be due to their hydrological connection, as both lagoons flow into each other or probably due to various nearby rivers, creeks and streams draining into both lagoons. Although, the greater deposition of heavy metals in more water samples from Lagos than in those from Lekki Lagoons could reflect the greater degree of anthropogenic inputs, mainly industrialization in the surrounding areas. The Ficklin-Caboi index demonstrated that pH could be a driver of the solubilization of some of the evaluated metals. More importantly, the water quality and integrated pollution indices indicate that 80% of the sampling sites of both lagoon systems, either during the dry or wet seasons, were unclean or moderately to extremely polluted, making them unsuitable for consumption except when properly treated. Multivariate analyses confirmed that anthropogenic activities ranging from dredging, agricultural practices, and municipal waste discharge in Lekki Lagoon to wastewater discharge, shipping, oil spills, mineral extraction, and electroplating in Lagos Lagoon are the primary drivers of heavy metal accumulation. The average daily dose assessment revealed that Cd, Cr, Fe, and Zn are the most consumed elements, with ingestion responsible for approximately 95% of the total exposure route. With respect to human health risk, approximately 35% and 80% of the sampling sites in Lekki and Lagos Lagoons, respectively, have the potential to trigger severe non-cancer health risks in exposed children. Similarly, the carcinogenic risk evaluation implies that exposure of the children to all the water samples will likely result in lifetime cancer risks, whereas approximately 40% of the surface water from the sampling sites may trigger long-term cancer risks in adult populations, with Cr, As and Cd having the highest carcinogenic risk potential.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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References

1. Rehman, K., Fatima, F., Waheed, I. & Akash, M. S. H. Prevalence of exposure of heavy metals and their impact on health consequences. *J. Cell. Biochem.* **119** (1), 157–184 (2018).
2. Ndimele, P. E., et al. Source apportionment, ecological and health risk assessment of potentially toxic elements in Water, sediment and Blackchin tilapia {Sarotherodon melanotheron (Rüppell 1852)} from Lagos and Ologe Lagoons, Lagos State, Nigeria. *J. Trace Elem. Miner.* 100173 (2024).
3. Bawa-Allah, K. A. Assessment of heavy metal pollution in Nigerian surface freshwaters and sediment: A meta-analysis using ecological and human health risk indices. *J. Contam. Hydrol.* **256**, 104199 (2023).
4. Li, R. et al. Spatiotemporal distribution dynamics of heavy metals in water, sediment, and zoobenthos in mainstream sections of the middle and lower Changjiang river. *Sci. Total Environ.* **714**, 136779 (2020).
5. Jolaosho, T. L. et al. Occurrence, distribution, source apportionment, ecological and health risk assessment of heavy metals in water, sediment, fish and Prawn from Ojo river in Lagos, Nigeria. *Environ. Monit. Assess.* **196** (2), 109. https://doi.org/10.1007/s10661-023-12148-y (2024).
6. Saleem, M., Iqbal, J. & Shah, M. H. Seasonal variations, risk assessment and multivariate analysis of trace metals in the freshwater reservoirs of Pakistan. *Chemosphere* **216**, 715–724 (2019).
7. Hammoumi, D. et al. Seasonal variations and assessment of surface water quality using water quality index (WQI) and principal component analysis (PCA): a case study. *Sustainability* **16** (13), 5644 (2024).
8. Githaiga, K. B., Njuguna, S. M., Gituru, R. W. & Yan, X. Water quality assessment, multivariate analysis and human health risks of heavy metals in eight major lakes in Kenya. *J. Environ. Manage.* **297**, 113410 (2021).
9. Jolaosho, T. L. et al. Bioaccumulation dynamics, noncarcinogenic and carcinogenic risks of heavy metals in commercially valuable shellfish and finfish species from the world largest floating slum, Makoko, Nigeria. *Mar. Pollut. Bull.* **207**, 116807 (2024a).
10. Ali, H., Khan, E. & Ilahi, I. Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. *J. Chem.* **2019** (2019).
11. Ajah, K. C., Ademiluyi, J. & Nnaji, C. C. Spatiality, seasonality and ecological risks of heavy metals in the vicinity of a degenerate municipal central dumpsite in Enugu, Nigeria. *J. Environ. Health Sci. Eng.* **13**, 1–15 (2015).
12. Jolaosho, T. L. et al. Comprehensive geochemical assessment, probable ecological and human health risks of heavy metals in water and sediments from dredged and nondredged rivers in Lagos, Nigeria. *J. Hazard. Mater. Adv.* **12**, 100379 (2023).
13. Ado, A. et al. A review on industrial effluents as major sources of water pollution in Nigeria. *Chem. J.* **1** (5), 159–164 (2015).
14. Nana, A. S. et al. Farming practices and disease prevalence among urban lowland farmers in Cameroon, central Africa. *Agriculture* **12** (2), 230 (2022).
15. Ahmed, S. et al. Heavy metals contamination in shrimp and crab from Southwest regions in bangladesh: possible health risk assessment. *Toxicol. Rep.* **10**, 580–588 (2023).
16. Aoshima, K. Itai-itai disease: renal tubular osteomalacia induced by environmental exposure to cadmium—historical review and perspectives. *Soil. Sci. Plant. Nutr.* **62** (4), 319–326 (2016).
17. Mishra, S. et al. Heavy metal contamination: an alarming threat to environment and human health. *Environmental Biotechnology: Sustainable Future* 103–125 (2019).
18. Tyagi, S., Sharma, B., Singh, P. & Dobhal, R. Water quality assessment in terms of water quality index. *Am. J. Water Resour.* **1** (3), 34–38 (2013).
19. Jolaosho, T. L. Characterization of potentially toxic elements in leachates from active and closed landfills in Nigeria and their effects on groundwater systems using spatial, indexical, chemometric and health risk techniques. *Chemosphere* **369**, 143678 (2024).
20. Jolaosho, T. L., Mustapha, A. A. & Hundeyin, S. T. Hydrogeochemical evolution and heavy metal characterization of groundwater from southwestern, Nigeria: An integrated assessment using spatial, indexical, irrigation, chemometric, and health risk models. *Heliyon* **10** (19) (2024).
21. Zakir, H. M., Sharmin, S., Akter, A. & Rahman, M. S. Assessment of health risk of heavy metals and water quality indices for irrigation and drinking suitability of waters: a case study of Jamalpur Sadar area, Bangladesh. *Environ. Adv.* **2**, 100005 (2020).
22. Singh, U. K. & Kumar, B. Pathways of heavy metals contamination and associated human health risk in Ajay river basin, India. *Chemosphere* **174**, 183–199 (2017).
23. Nubi, O. A., Oyatola, O. O. & Adeleye, A. O. Hydrological distribution of physicochemical parameters, heavy metals, and their ecotoxicological implications in Lagos Lagoon, off the Gulf of Guinea basin. *Sustainable Water Resour. Manage.* **10** (2), 84 (2024).
24. Adesalu, T. A. & Nwankwo, D. I. Successional pattern of phytoplankton (>55µm) in Lekki lagoon, Nigeria. *Revista De Biología Trop.* **60** (1), 143–155 (2012).
25. Perkumienė, D., Atalay, A., Safaa, L. & Grigienė, J. Sustainable waste management for clean and safe environments in the recreation and tourism sector: a case study of Lithuania, Turkey and Morocco. *Recycling* **8** (4), 56 (2023).
26. Nkwoji, J. A., Ugbana, S. I. & Ina-Salwany, M. Y. Impacts of land-based pollutants on water chemistry and benthic macroinvertebrates community in a coastal lagoon, Lagos, Nigeria. *Sci. Afr.* **7**, e00220 (2020).
27. Fajemila, O. T. et al. Contamination levels of potentially toxic elements and foraminiferal distribution patterns in Lagos lagoon: A correlation analysis. *Water* **14** (1), 37 (2021).
28. Oladosu, N. O., Abayomi, A. A., Olayinka, K. O. & Alo, B. I. Wet nitrogen and phosphorus deposition in the eutrophication of the Lagos Lagoon, Nigeria. *Environ. Sci. Pollut. Res.* **24**, 8645–8657 (2017).
29. Wang, X. et al. Effects of long-term fertilizer applications on peanut yield and quality and plant and soil heavy metal accumulation. *Pedosphere* **30**, 555–562 (2020).
30. Li, F. et al. Spatial risk assessment and sources identification of heavy metals in surface sediments from the Dongting Lake, Middle China. *J. Geochem. Explor.* **132**, 75–83 (2013).
31. Zhang, X. et al. Evaluation and analysis of heavy metals in iron and steel industrial area. *Environment, Development and Sustainability* 1–14 (2021).
32. Singh, N. & Turner, A. Leaching of copper and zinc from spent antifouling paint particles. *Environ. Pollut.* **157** (2), 371–376 (2009).
33. Xie, S. et al. Interannual variation and sources identification of heavy metals in seawater near shipping lanes: Evidence from a coral record from the northern South China Sea. *Sci. Total Environ.* **854**, 158755 (2023).
34. Opadokun, I. O., Falaye, A. E. & Ajani, E. K. Seasonal variation in physicochemical parameters of Lekki lagoon and the conservation of its ecosystem. *J. Geoscience Environ. Prot.* **3**, 11–17. https://doi.org/10.4236/gep.2015.39002 (2015).
35. United States Environmental Protection Agency (USEPA). *SW Method 3005. Acid Digestion of Waters for Total Recoverable or Dissolved Metals for Analyses by Flame Atomic Absorption Spectroscopy* 35 (U.S. Gov. Print Office, 1987).
36. Boyd, C. E. *Water Quality in Warm Water Fish Ponds* (Alabama Agricultural Experimental Station, Auburn University, 1981).
37. United States Environmental Protection Agency, USEPA. *USEPA Regional Screening Level (RSL) Summary Table*. http://www.epa.gov/regshwmd/risk/human/Index.htm (2011).
38. United States Environmental Protection Agency, USEPA. Risk assessment guidance for superfund (RAGS). *Human Health Evaluation Manual (HHEM). Part E: Supplemental Guidance for Dermal Risk Assessment*, vol 1 (2004).
39. International Agency for Research on Cancer. *Review of Human Carcinogens*, Vol. 100 (IARC Monographs on the Evaluat, 2012).

40. Jia, P., Shang, T., Zhang, J. & Sun, Y. Inversion of soil pH during the dry and wet seasons in the Yinbei region of Ningxia, China, based on multisource remote sensing data. *Geoderma Reg.* **25**, e00399 (2021).
41. Islam, M. S., Kabir, M. H., Sifat, S. A., Meghla, N. T. & Tusher, T. R. Status of water quality from the Padmariver at Bheramara point of Kushtia in Bangladesh. *Bangladesh J. Environ. Sci.* **27**, 110–115 (2014).
42. Yasmin, F., Hossain, T., Shahrukh, S., Hossain, M. E. & Sultana, G. N. N. Evaluation of seasonal changes in physicochemical and bacteriological parameters of Gomti river in Bangladesh. *Environ. Sustain. Indic.* **17**, 100224 (2023).
43. Li, A. et al. Excessive use of chemical fertilizers in catchment areas raises the seasonal pH in natural freshwater lakes of the subtropical monsoon climate region. *Ecol. Indic.* **154**, 110477 (2023).
44. Wilbers, G. J., Becker, M., Sebesvari, Z. & Renaud, F. G. Spatial and Temporal variability of surface water pollution in the Mekong Delta, Vietnam. *Sci. Total Environ.* **485**, 653–665 (2014).
45. World Health Organization. *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First Addendum, 38* 104 (WHO, 2017).
46. World Health Organization. WHO global water, sanitation and hygiene: annual report 2021. In *WHO Global Water, Sanitation and Hygiene: Annual Report 2021* 114 (2022).
47. Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. FAO irrigation and drainage paper 56. *Rome: Food Agric. Organ. United Nations* **56** (97), e1561998).
48. DOE (Department of Environment). *Bangladesh Gazette, No. DA- 1; Department of Environment* 1324–1327 (Ministry of Environment and Forest, 1997).
49. Saha, A. et al. Evaluation of spatiotemporal changes in surface water quality and their suitability for designated uses, Mettur Reservoir, India. *Nat. Resour. Res.* **30**, 1367–1394 (2021).
50. Koledoye, T. Y., Akinsanya, B., Adekoya, K. O. & Isibor, P. O. Physicochemical parameters of the Lekki lagoon in relation to abundance of Wenyonia Sp Woodland, 1923 (Cestoda: Caryophyllidae) in synodontis Clarias (Linnaeus, 1758). *Environ. Challenges*. **7**, 100453 (2022).
51. Lawson, E. O. Physico-chemical parameters and heavy metal contents of water from the Mangrove swamps of Lagos Lagoon, Lagos, Nigeria. *Adv. Biol. Res.* **5** (1), 8–21 (2011).
52. Rahman, A., Jahanara, I. & Jolly, Y. N. Assessment of physicochemical properties of water and their seasonal variation in an urban river in Bangladesh. *Water Sci. Eng.* **14** (2), 139–148 (2021).
53. Nienie, A. B. et al. Seasonal variability of water quality by physicochemical indices and traceable metals in suburban area in Kikwit, Democratic Republic of the Congo. *Int. Soil Water Conserv. Res.* **5** (2), 158–165 (2017).
54. FEPA (Federal Environmental Protection Agency). *Guidelines and Standards for Environmental Pollution Control in Nigeria* 239 (2003).
55. Vahabian, M., Hassanzadeh, Y. & Marofi, S. Assessment of landfill leachate in semiarid climate and its impact on the groundwater quality case study: Hamedan, Iran. *Environ. Monit. Assess.* **191**, 1–19 (2019).
56. World Health Organization. *Guidelines for Drinking Water-Quality* (World Health Organization, 2004).
57. Ewa, E. E. et al. Impact of industrial activities on water quality of Omoku creek. *Sacha J. Environ. Stud.* **1** (2), 8–16 (2011).
58. National Environmental Standards Regulations Enforcement Agency (NESREA). *Guidelines and standards for Environmental Pollution Control in Nigeria* (2011).
59. Mai, Y., Zhao, X. & Huang, G. Temporal and Spatial variability of water quality in an urban wetland and the effects of season and rainfall: a case study in the Daguan Wetland, China. *Environ. Monit. Assess.* **194** (5), 347 (2022).
60. Akintola, S. L., Anetekhai, M. A. & Lawson, E. O. Some physicochemical characteristics of Badagry creek, Nigeria. *West. Afr. J. Appl. Ecol.* **18**, 95–107 (2011).
61. Dey, S., Botta, S., Kallam, R., Angadala, R. & Andugala, J. Seasonal variation in water quality parameters of Gudlavalleru engineering college pond. *Curr. Res. Green. Sustainable Chem.* **4**, 100058 (2021).
62. Abbasi, T., Poornima, P., Kannadasan, T. & Abbasi, S. A. Acid rain: past, present, and future. *Int. J. Environ. Eng.* **5** (3), 229–272 (2013).
63. Edokpayi, J. N., Odiyo, J. O., Popoola, E. O. & Msagati, T. A. Evaluation of temporary seasonal variation of heavy metals and their potential ecological risk in nzhelele River, South Africa. *Open. Chem.* **15** (1), 272–282 (2017).
64. Bhuyan, M. S. & Bakar, M. A. Seasonal variation of heavy metals in water and sediments in the Halda River, Chittagong, Bangladesh. *Environ. Sci. Pollut. Res.* **24**, 27587–27600 (2017).
65. United States Environmental Protection Agency (USEPA). *Control of Pathogens and Vector Attraction in Sewage Sludge. EPA 625-R-92–013* (United States Environmental Protection Agency (USEPA), 2003).
66. USEPA. *National Recommended Water Quality Criteria* (Office of Water, United States Environmental Protection Agency, 2006).
67. Eliku, T. & Leta, S. Spatial and seasonal variation in physicochemical parameters and heavy metals in Awash River, Ethiopia. *Appl. Water Sci.* **8**, 1–13 (2018).
68. Wang, X., Zhao, L., Xu, H. & Zhang, X. Spatial and seasonal characteristics of dissolved heavy metals in the surface seawater of the yellow river Estuary, China. *Mar. Pollut. Bull.* **137**, 465–473 (2018).
69. Herojeet, R., Rishi, M. S. & Kishore, N. Integrated approach of heavy metal pollution indices and complexity quantification using chemometric models in the Sirsa Basin, Nalagarh valley, Himachal Pradesh, India. *Chin. J. Geochem.* **34**, 620–633 (2015).
70. Bawa-Allah, K. A., Saliu, J. K. & Otitoloju, A. A. Heavy metal pollution monitoring in vulnerable ecosystems: a case study of the Lagos Lagoon, Nigeria. *Bull. Environ Contam. Toxicol.* **100** (5), 609–613 (2018).
71. Bamanga, A., Amaeze, N. H. & Al-Anzi, B. Comparative investigation of total, recoverable and bioavailable fractions of sediment metals and metalloids in the Lagos harbour and lagoon system. *Sustainability* **11** (16), 4339 (2019).
72. Aniyikaiye, T. E., Oluseyi, T., Odiyo, J. O. & Edokpayi, J. N. Physico-chemical analysis of wastewater discharge from selected paint industries in Lagos, Nigeria. *Int. J. Environ. Res. Public Health.* **16** (7), 1235 (2019).
73. Cánovas, C. R., Olías, M., Nieto, J. M. & Galván, L. Wash-out processes of evaporitic sulfate salts in the tintoriver: hydrogeochemical evolution and environmental impact. *Appl. Geochem.* **25** (2), 288–301 (2010).
74. Basheeru, K. A., Adekola, F. A., Abdus-Salam, N. & Okoro, H. K. Spatio-temporal monitoring of potentially toxic elements in Lagos harbour water and its health risk implications. *SN Appl. Sci.* **4** (11), 298 (2022).
75. Avigliano, E. & Schenone, N. F. Human health risk assessment and environmental distribution of trace elements, glyphosate, fecal coliform and total coliform in Atlantic rainforest mountain rivers (South America). *Microchem. J.* **122**, 149–158 (2015).
76. Samecka-Cymerman, A. & Kempers, A. J. Toxic metals in aquatic plants surviving in surface water polluted by copper mining industry. *Ecotoxicol. Environ. Saf.* **59** (1), 64–69 (2004).
77. Yang, Y., Wei, L., Cui, L., Zhang, M. & Wang, J. Profiles and risk assessment of heavy metals in great rift lakes, Kenya. *Clean–Soil Air Water*. **45**, 1600825. https://doi.org/10.1002/clen.201600825 (2017).
78. Zoidou, M. & Sylaios, G. Ecological risk assessment of heavy metals in the sediments of a mediterranean lagoon complex. *J. Environ. Health Sci. Eng.* **19** (2), 1835–1849 (2021).
79. Alamri, D. A., Al-Solaimani, S. G., Abohassan, R. A., Rinklebe, J. & Shaheen, S. M. Assessment of water contamination by potentially toxic elements in Mangrove lagoons of the red Sea, Saudi Arabia. *Environ. Geochem. Health*. **43** (11), 4819–4830 (2021).
80. El Ouaty, O., El M'rini, A., Nachite, D., Marrocchino, E. & Rodella, I. Sediment quality indices for the assessment of heavy metal risk in Nador lagoon sediments (Morocco) using multistatistical approaches. *Sustainability* **16** (5), 1921 (2024).
81. He, J. et al. Driving factors for distribution and transformation of heavy metals speciation in a zinc smelting site. *J. Hazard. Mater.* **471**, 134413 (2024).

82. Rendón-Martínez, J. R., Frías-Espericueta, M. G., Green-Ruiz, C. R., Páez-Osuna, F. & Voltolina, D. Arsenic content, grain sizes and chemical characteristics in surface sediments of the urÍas lagoon, NW Mexico. *Revista Int. De contaminación Ambiental*. **35** (3), 771–779 (2019).
83. Mirlean, N., Andrus, V. E., Baisch, P., Griep, G. & Casartelli, M. R. Arsenic pollution in Patos lagoon estuarine sediments, Brazil. *Mar. Pollut. Bull.* **46** (11), 1480–1484 (2003).
84. Ficklin, W. H., Plumlee, G. S., Smith, K. S. & McHugh, J. B. Geochemical classification of mine drainages and natural drainages in mineralized areas. In *International Symposium on Water-Rock Interaction* 381–384 (1992).
85. Hernandez-Soriano, M. C. & Jimenez-Lopez, J. C. Effects of soil water content and organic matter addition on the speciation and bioavailability of heavy metals. *Sci. Total Environ.* **423**, 55–61 (2012).
86. Najafi, S. & Jalali, M. Effect of heavy metals on pH buffering capacity and solubility of Ca, Mg, K, and P in non-spiked and heavy metal-spiked soils. *Environ. Monit. Assess.* **188** (6), 342 (2016).
87. Rajwa-Kuligiewicz, A., Bialik, R. J. & Rowinski, P. M. Dissolved oxygen and water temperature dynamics in lowland rivers over various timescales. *J. Hydrology Hydromechanics*. **63** (4), 353 (2015).
88. Sánchez, E. et al. Use of the water quality index and dissolved oxygen deficit as simple indicators of watersheds pollution. *Ecol. Ind.* **7** (2), 315–328 (2007).
89. Kaiser, H. F. A note on the equamax criterion. *Multivar. Behav. Res.* **9** (4), 501–503 (1974).
90. Genchi, G., Sinicropi, M. S., Lauria, G., Carocci, A. & Catalano, A. The effects of cadmium toxicity. *Int. J. Environ. Res. Public Health*. **17** (11), 3782 (2020).
91. Ndimele, P. E. et al. Vulnerability, resilience and adaptation of Lagos coastal communities to flooding. *Earth Sci. Syst. Soc.* **4** (1), 10087 (2024).
92. Jolaosho, T. L. et al. Microplastics in freshwater and marine ecosystems: Occurrence, characterization, sources, distribution dynamics, fate, transport processes, potential mitigation strategies, and policy interventions. *Ecotoxicol. Environ. Saf.* **294**, 118036 (2025).
93. Prakash, P. & S, S. C. Nano-phytoremediation of heavy metals from soil: a critical review. *Pollutants* **3** (3), 360–380 (2023).

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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