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Evaluation of Heavy Metals/Metalloids of High Toxic Response Factors in Sediments of Lekki Lagoon (Southwest Nigeria) and its Implication for Public Health

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Abstract
The unassailable increase in industrial growth and the concomitant urbanization in and around Lekki Free Trade Zone (LFTZ) informed the evaluation of toxic metal by-products in the nearby Lekki Lagoon in southwest Nigeria. The specific objectives were to determine the extent of sediments' degradation using various indices of contamination; unveil potential heavy metals of high toxic coefficients in sediments; and assess the associated human health risks. Horiba U-53 Multiparameter Meter (10-M) Cable was employed to determine water characteristics such as salinity, pH, redox potential and depth.Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) was employed for identification and measurement of the constituents of heavy metals in sediments. The measured concentrations of the various metals were used to compute non-carcinogenic and carcinogenic indices using the United States Environmental Protection Agency risk assessment model. Heavy metals such as Cu, Cd, Hg and As were below threshold effect concentration (TEC) in sediments suggesting there was no probability of negative biological effects. The mean probable effect quotients (*mPECQs*) varied from 10 % to 17 % possibility of sediments producing toxic effects. Considering indices of contamination such as the contamination factors (CF), enrichment factors, (EF), geo-accumulation index (I_{geo}), potential contamination index (C_p), toxic risk index (TRI) and integrated ecological risk index (RI), Pb, Cd and Cu posed no threat to the aquatic ecosystem. Meanwhile, Co, Zn, Ni, As and Hg in sediments showed severe to very severe contamination through C_p. Contamination of As was the most widespread, followed by Zn contamination which covered approximately half of the study area, exhibiting moderate to high and moderate to very high contamination respectively. The EF, Pearson correlation, Principal Component (PCA) and Cluster analyses uncloaked both anthropogenic and geogenic pathways of As, Hg, Zn, Ni and Co into the lagoon. The non carcinogenic risks (*HI*) associated with toxic metals in sediments were within the safe level. However, children's population was more prone to cancer risks than adults through accidental ingestion given the average concentrations of Ni and As in the sediments.

Keywords: *Toxic metals, Lekki Lagoon, indices of contamination, non-carcinogenic risk, cancer risks*

Introduction

Lekki Lagoon, located in Lagos and Ogun States, southwest Nigeria, is a large expanse of shallow freshwater body, being fed by Oni River from northeast and, Osun and Saga rivers from northwest (Adesalu and Nwankwo, 2009). Its southern coastline falls within Ibeju-Lekki Local Government Area which hosts the Lekki Free Trade Zone (LFTZ) sited 50 km away from the city center. This LFTZ is the biggest in West Africa, and one of the fastest growing Free Trade Zones in the world (Zeng, 2012). The zone hosts local and foreign investments running into billions of dollars, among which are petrochemical plants, a subsea gas pipeline project and the largest deep-sea port in West Africa. Also, Africa's largest Granulated Urea Fertilizer Plant (GUFP) and one of the biggest oil refineries in the world were commissioned in March, 2022 and May, 2023 respectively. It is widely admitted that such massive industrial activities will contaminate the air, soil and the nearby aquatic environmentwith heavy metal by-products (e.g., Ikem *et al*., 2003; Khan *et al*., 2004; Ali *et al*., 2019; Kulbatand Sokolowska,2019). Premised on this, most of the heavy metals (HMs) produced in this area will undoubtedly find their way into Lekki Lagoon where they accumulate in the bottom sediments which are natural geo-sorbent (Kulbat and Sokolowska, 2019, Zhou *et al.*, 2020; Koniarz*et al.*, 2023). The local and commercial agricultural activities in addition to indiscriminate waste disposal may also increase the accumulation of heavy metals (HMs) in the lagoon. The close proximity of Lekki Lagoon to the pollutant sources presents pertinent questions about the impact of the HMs on the aquatic ecosystem as evidences abound in other places with similar situation (Zakaly*et al.*, 2019; Liu *et al.*, 2021; Nour *et al.*, 2022). Aside from anthropogenic sources, natural phenomena such as volcanic eruptions and weathering of rocks exposed on the earth's surface significantly contribute to heavy metal pollution (Shallari*et al.*, 1998; He *et al.*, 2005; Arruti*et al.*, 2010). Relative to geogenic processes, it is believed that anthropogenic activities introduce larger quantities of these metals in different environments (Pacyna, 1996; Manev *et al.*, 2020).

The non-biodegradability, bio-accumulative nature and persistency enhance the accumulation of these HMs in sediments, and at certain levels of concentrations, may portend danger to the ecosystem. Some HMs and metalloids have high toxic response coefficients, implying that at relatively low to very low concentrations, ecological and human health risk indices will be high. Such HMs and metalloids with high toxic response factors considered in this study are As, Sb, Cd, Hg, Ni, Pb, Cu and Zn. Bioaccumulation at relatively low concentrations of these metals may produce toxic effects on aquatic organisms, and a higher health risk to humans as they can be enriched in human body through the food chain (Ali *et al.*, 2019; Özkoç and Ariman, 2023). Lekki Lagoon is well-known for its major biodiversity reserves which have been providing an important source of livelihood for the people of Lagos and Ogun States in Nigeria (Emmanuel*et al*., 2010). Upon the fast-growing population and increasing industrial growth, the study area is becoming more vulnerable to toxic metal by-products as the day passes. It is pertinent to note that these heavy metals entering the food chain through consumption of fish and other aquatic organisms can ruin the ecosystem. Most of the HMs under consideration for this study have been ranked among the ten most toxic substances by the Agency for Toxic Substances and Disease Registry, Atlanta, Georgia, USA *(*ATSDR, 2022*)*. Therefore, the continuous monitoring of pollution status of this lagoon deserves the effort, as it will unveil the environmental conditions and trends, and support policy development and its implementation.

The health hazards produced through the food chain has become a global issue. Grandjean*et al.* (1997) and Myers *et al.* (2003), presented that inorganic mercury (IHg) in an aquatic environment can be biologically transformed into toxic methyl-mercury (MeHg) which can increase risk of neurodevelopmental disorder. Literature had it that exposure to lead (Pb) beyond the permissible concentration in humans can cause spontaneous abortions (Guan *et al.*, 2010), or results into reduced birth weight and gestational hypertension (Bellinger, 2005). Tucker (2008) submitted that consumption of aquatic organisms contaminated in cadmium may not be harmful as small amount will stay in the body. Tucker (*Op. Cit.*), however, emphasized that, if such contaminated food is consumed over a long period of time, Cd can damage the kidney, liver and heart. Antimony (Sb) could be released to the air, soil or aquatic environment through smelting of lead and other metals, and coal-fired power plants (Xi *et al.*, 2022). Diquattro *et al.* (2020) and Diquattro *et al.* (2021) reported that Sb is introduced into aquatic environments from sources such as weathering of sulphide ores (geogenic), leaching of mining wastes and industrial activities (anthropogenic). These authors pointed out that high Sb as low as above 1 ppm is toxic to ecosystems and potential public health hazard through the accumulation in food chain. Also, that Sb is poisonous and carcinogenic to humans, though the mechanism causing toxicity is nebulous. Arsenic is a pervasive element released into aquatic environment through activities like metal smelting, chemical manufacturing, and agro-allied production (Singh and Banerjee, 2008; Pedlar*et al.* 2002). Bears *et al.* (2006) and Han *et al.* (2019) attested to the fact that aquatic environment contaminated with arsenic (As) may give rise to bioaccumulation in resident organisms and can lead to biochemical and physiological disorders. Also, toxic dosage of As in human body may result into cardiovascular effects, lung disorders and developmental delay in children (Pecina *et al.*, 2021). Nickel is a ferromagnetic element with source of pollution from industrial activities, municipal and industrial wastes, and natural activities through wind-blown dust of weathered rocks/soils, forest fire and volcanoes (Genchi *et al.*, 2020). At certain level of concentration, Ni becomes an immunotoxin and carcinogen agent which can cause human health effects such as contact dermatitis, cardiovascular disease, asthma, and respiratory cancer (Chen *et al.*, 2017). A major pathway to nickel-induced toxicity in the respiratory tract, lung and immune system is through inhalation based on duration of exposure. Also, individuals with high prevalence of allergic contact dermatitis handling stainless steel and nickel-plated materials may be affected (Sinicropi *et al.*, 2010). Zinc is commonly found in nutritional supplements being a highly essential element needed by the body. However, accumulation of Zn in excess of what the body should bear is detrimental to human health. ATSDR (2005) documented that Zn usually enters the environment as particulate by-product of mining, purification of lead, zinc and cadmium ores, steel production, coal burning and burning of wastes. It was presented that consumption of aquatic organisms contaminated with zinc for a long period of time may overshoot the nutritional budget required by human body and cause anemia, damage the pancreas, and decrease levels of high-density lipoprotein (HDL) cholesterol. Also added, is the fact that, direct contact with Zn polluted water can result to skin irritation in humans. The use of copper in anti-fouling paint for boat hulls clearly indicates that it is toxic to aquatic organisms. Solomon (2009) emphasized that copper is one of the most toxic metals to aquatic organisms, and being an algaecide, its inadvertent discharge into water body will decrease algal growth and decimate the population. He complemented Heydarnejad*et al.* (2013) by his emphasis on the fact that high concentration of copper harm vital organs in fish such as the gills, liver, kidney and brain.

Several publications exist on heavy metal pollution in the Southwest Nigeria's coastal environments (Olatunji and Abimbola, 2010; Adebowale *et al.*, 2011; Amaeze*et al.*, 2012; Bamanga*et al.*, 2019; Bassey *et al.*, 2019; Phillips *et al.*, 2020a; 2020b among others). However,toxic response factors of HMs in relation to ecotoxicology, and the consequences of various HM concentrations on human health were not among the objectives of their researches, hence were not discussed.

The understanding of the ecotoxicological risks that may be inherent in sediments enriched with HMs of high toxic response coefficients are of great importance for protecting coastal ecosystems. Also, assessment of sediments' quality based on the international sediment quality guidelines (ISQGs) as presented by Buchman (2008) will help the understanding of probability of adverse biological effects within certain spectrum of concentrations. The consumption of some of these aquatic resources by human and the related biochemical processes pose a serious threat to public health (Ali *et al.*, 2019; Al-Kahtany*et al.*, 2023). Also, it is pertinent to note that direct exposure to heavy metals (Cd, Hg, Cu, Ni, Pb, Zn etc.) and metalloids (As and Sb) of high toxic response factors through dermal contact at relatively low concentrations can adversely affect human health. The objectives set out for this study are to (1) determine the concentrations of heavy metals/metalloids with high toxic response coefficients (toxic factor ≥ 5 except Zn = 1), and assess the sediments quality on the basis of ISQGs (Buchnan, 2008), (2) calculate the various indices of contamination in order to establish the extent of environmental degradation, (3) infer anthropogenic or geogenic contribution to the heavy metal load based on Pearson Correlation Analysis (PSA), (4) evaluate the potential ecological risk based on calculated Risk Index (RI) or Toxicity Risk Index (TRI), and suggest human health risks associated with the selected metals.

Materials and Methods

Study Area

Lekki Lagoon is a transitional lagoon which connects Ondo, Ogun and Lagos States in southwest Nigeria, where it lies approximately within latitudes 6° 34' N and 6° 38' N and longitudes 3° 26' E and 3° 29' E (Fig. 1). It is one of the ten lagoons in Lagos State covering a surface area of about 247 square kilometres at the southwest sector of the Gulf of Guinea coast. Lekki Lagoon is fed by network of rivers and creeks imposing the freshwater/non-saline nature, with water column of less than 3.0 m in most places, to a maximum of 6.4 m (Kusemiju, 1981). The coastal area is a major part of Lagos Island which has grown to be a brimful focus of commercial activities in Lagos. The intertropical convergence zone (ITCZ) is an equatorial zone where trade winds converge, though, largely valid over the equatorial oceans, the region of maximum rainfall can be decoupled over the continents. The rainfall seasonality is traditionally attributed to the north-south migration of the ITCZ which follows the sun, hence, shifts seasonally with pressure belts and isotherms (Dezfuli, 2017; Nicholson, 2018). The study area falls within a region governed by well-defined rainy season from March/April to October/November, and dry season which is influenced by Harmattan wind from the Sahara which begins from October/November to March/April. The annual mean temperature is 26 °C in the south and 28 °C in the north with annual range of ± 4 °C (Adeaga*et al.*, 2019; Phillips *et al.*, 2020a). Lekki Lagoon opens into the Atlantic Ocean through Epe and Lagos lagoons, and Lagos Harbour.

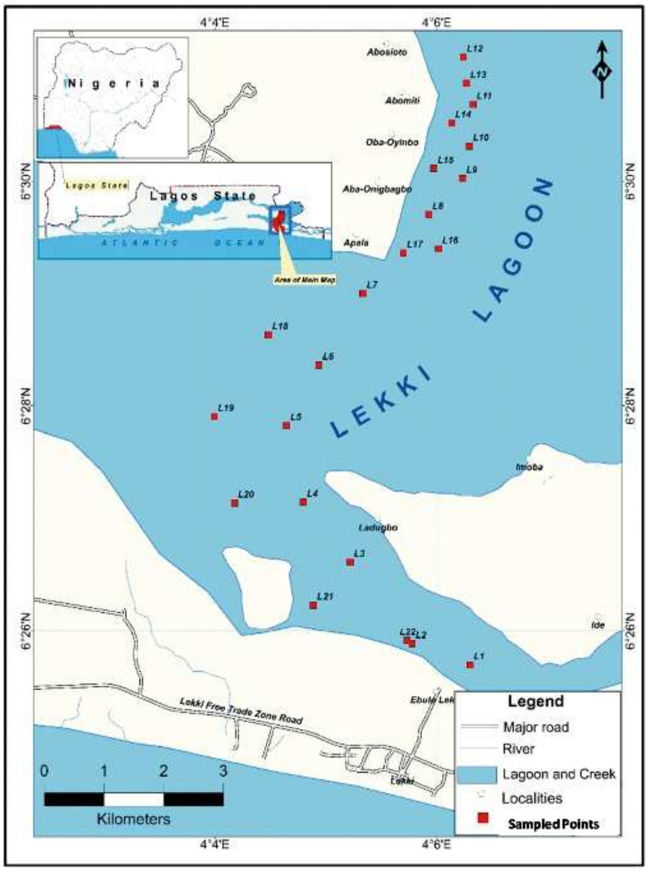

Fig. 1: The map showing stations sampled in Lekki Lagoon, Southwest Nigeria

Sample Collection and Measurements

Field studies were carried out in Lekki Lagoon, starting from the chosen station at its southeastern end, to the northern part, and towards the west, back to the southern end (Fig. 1). The stations investigated are in close proximity to the Lekki Free Trade Zone in Ibeju-Lekki area of Lagos State. Sampling was done in March, 2022, just one week before the commissioning of the Africa's biggest Granulated Urea Fertilizer Plant (GUFP) in the area. A total of 22 surface samples of sediment were collected from twenty-one stations using a Van Veen grab surface sampler. Samples were kept in air-tight polythene bags and labelled according to the sampled stations. Also, on the spot measurements of salinity, pH, oxidation-reduction potential and depth were done using Horiba U-53 Multiparameter Meter (10-M) Cable. Sampled stations were positioned using Garmin Gpsmap 86sci floating handheld GPS.

Grain Size Analysis

The particle size analysis was performed in the laboratory using the mechanical sieving method. Sediment samples were pre-treated with H_2O_2 solution to remove organic matter, and subsequently, measured dry weight of each sample was wet-sieved in a mechanical sieve shaker using 63 micron-sized mesh until mud particles are completely removed. The residues are fractions > 63 µm which were dried and weighed to get the mud fractions (silt and clay). The fractions > 63 µm for each sample was separated into various fractions using a set of test sieves (ASTM E11) mechanically vibrated for about 15 minutes using a Ro-tap shaker. The results were used to calculate the statistical mean, and the average grain sizes were defined.

Analytical Methods

The samples for chemical analysis were oven-dried at 35°C for 72 hours. An agate mortar and pestle were used to grind the dried samples and filtered through a 63 µm aperture sieve. Precisely 30 g each of the pulverized samples (<63 µm) were kept in variously labelled dispensary cellophane bags. Heat pre-treatment at ignition temperature of 500°C was done and samples cooled. Subsequently, 0.2 g of each pre-heated samples was digested in a Teflon vessel placed in a microwave digester by employing aqua regia technique which involved the mixture of concentrated HNO_3 and HCl at a 1:3 ratio. This digestion was carried out at relatively low temperature which allowed volatile Hg to be analysed with other metals of interest. After the digestion was complete, identification and measurement of the heavy metal contents in solution was done by using Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) at the mineral laboratory of the Bureau Veritas Commodities, Canada. The method detection limits for the chosen package are As = Zn = 1 ppm, Cd = Ni = Pb = Sb = Cu = 0.1 ppm, Co = 0.2 ppm, Hg = 0.01 pm, Al = 0.01 %, and Fe = 0.04 %.

Sediment Contamination and Health Indices

The multi-index assessment of contamination in sediments of Lekki Lagoon involved the frequently used contamination factor (CF), sediment enrichment factor (EF), geoaccumulation index (I_{geo}) and potential contamination index (C_p). The impact of the heavy metal concentrations in sediments was assessed on the basis of the International Sediment Quality Guidelines (ISQGs) presented by Buchman (2008) which gave consideration to the Consensus-based sediment quality parameters such as the threshold effects concentration (TEC), probable effects concentration (PEC), and the mean probable effect concentration quotient (*mPECQ*). Also, considered are ecotoxicological risk indices such as the potential ecological risk index (PERI), risk index (RI) and toxic risk index (TRI), to measure the impact of the heavy metal contamination and more importantly the influence of HMs with high toxic response coefficients in sediments. The non-carcinogenic and carcinogenic risk indices were considered in child and adult for the assessment of impact on human health.

Sediment Quality Assessment

The International sediment quality guidelines (ISQGs) present a simple and comparative mean for evaluation of potential hazard connected with the content of metals in the sediments to aquatic organisms (Baran *et al.*, 2016; Ke *et al.*, 2017; Özkoç and Ariman, 2023). Four types of limit values based on threshold effect level (TEL), probable effect level (PEL), threshold effect concentration (TEC) and probable effect concentration (PEC) were employed to assess the ecosystem's potential risk. The TEL and PEL values are the empirical values from Consensus based sediment quality guidelines (SQGs) which were used to calculate toxic risk index (TRI) in order to evaluate the ecotoxicity of the aquatic system (Zhang *et al.*, 2019).

The mean probable effect concentration quotients (*mPECQ*) were calculated following the method suggested by Ingersoll *et al.* (2001) as indicated:

$$mPECQ = \sum_{i=1}^{n}(C_i/PEC_i)/n \quad \text{.................................(1)}$$

Where C_i is the measured concentration of heavy metal in consideration, PEC_i is its PEC value, n is the number of heavy metals considered in the sediment. Toxicity ranking is based on percentage possibility as *mPECQ*< 0.1 = 10 % possibility, *mPECQ*= 0.1 - < 0.5 indicates 17 % possibility, *mPECQ*= 0.5 - < 1.0 implies 56 % possibility, *mPECQ*> 1.0 indicates 97 % possibility, and *mPECQ*> 5.0 implies 100 % possibility.

Contamination Factor (CF) and Potential Contamination Index (C_p)

Contamination factor (CF) was calculated as a ratio between measured concentration (C_s) of heavy metal in sediment and the background values (C_{ref}) presented by the international sediment quality guidelines (Buchman, 2008). The ISQGs background and reference values were used because of the need for consistency arising from data comparison, and more importantly, acceptable sediment quality guidelines are yet to be developed for the region being investigated.

$$CF = C_s / C_{ref} \quad \text{..(2)}$$

The levels of heavy metal contamination resulting from equation 1 were defined as CF < 1 low contamination; 1 ≤ CF < 3 moderate contamination; 3 ≤ CF < 6 high contamination; CF ≥ 6 very high contamination (Hakanson, 1980; Tytia and Kostecki, 2019).

Degree of Contamination

The contamination degree (C_d) of HMs in sediments as proposed by Hakanson (1980), is the sum of all the calculated CF for each sample as expressed in equation 2. Considering n as the n^{th} heavy metal (pollutant), the C_d is depicted as follows: C_d< 6 is low; 6 <C_d< 12 = moderate; 12 <C_d< 24 = considerably high; and C_d> 24 = high.

$$Cd = \sum_{i=1}^{n} CF \quad \text{...(3)}$$

Modified Contamination Degree (mCd)

In order to cater for cases of many heavy metals, the modified contamination degree (mC*d*) which averages the contamination degree (C_d) based on number of metals (n) was proposed by Abrahim and Parker (2008) as presented in equation 4.

$$mCd = \frac{\sum_{i=1}^{n} CF}{n} \quad \text{...(4)}$$

Based on quantitative values, the mC*d* classifies level of contamination as mC*d*< 1.5 nil to very low, 1.5 ≤ mC*d*< 2 = low; 2 ≤ mC*d*< 4 = moderate, 4 ≤ mC*d*< 8 = high, 8 ≤ mC*d*< 16 = very high, 16 ≤ mC*d*< 32 extremely high, and mC*d*> 32 = ultra-high.

Potential Contamination Index (C_p)

The C_p is the ratio of the maximum concentration (C_{max}) of a specific heavy metal to its background value (C_b) in a sample of sediment (Davaulter and Rognerud, 2001; Chandramohan *et al.*, 2016; Perumal *et al.*, 2021). The classes of contamination according to C_p values are C_p< 1 = low contamination; 1 < C_p< 3 = moderate contamination; and C_p> 3 = severe or very severe contamination. It is expressed in equation 5 as

$$C_p = C_{max} / C_b \quad \text{..(5)}$$

Geoaccumulation Index (I_{geo})

The geoaccumulation index as first developed by Muller (1979) was employed to evaluate the degree of heavy metal pollution in sediment. It is a quantitative indicator for assessment of degree of heavy metal pollution in sediments (Karbassi*et al.*, 2008). This indicator is defined as below.

$$I_{geo} = \log_2[C_n/(1.5b_n)] \quad \text{.......................................(6)}$$

C_n is the concentration of individual heavy metal n, b_n is its background value, and 1.5 is used because of likely variation in the reference values for a given heavy metal in the environment, as well as slight anthropogenic influences. The background values used for this work were from Buchman (2008).The geoaccumulation index has been classified into seven by Muller (1969) as follows: Class 0 (practically uncontaminated): I_{geo} ≤ 0; Class 1 (uncontaminated to moderately uncontaminated): 0<I_{geo}< 1; Class 2 (moderately contaminated): 1 <I_{geo}< 2; Class 3 (moderately to heavily contaminated): 2 <I_{geo}< 3; Class 4 (heavily contaminated): 3 <I_{geo}< 4; Class 5 (heavily to extremely contaminated): 4 <I_{geo}< 5; Class 6 (extremely contaminated): 5 >I_{geo}< 6.

Enrichment Factor (EF)

The appraisal of enrichment factor (EF) is based on the evaluation of the heavy metal enrichment in the sediment. Usually, a geochemically distinguishing element with a high concentration in the environment is used as reference metal for normalization (Pandey *et al.*, 2016). The present study employed Fe as the normalizing metal to calculate for the sediment enrichment factor used in the determination of pollutant source. This method has been widely used to evaluate the extent of heavy metal contamination driven by geological and anthropogenic activities in coastal environments (Fry *et al.*, 2021). The value of EF > 2 implies anthropogenic source of enrichment (Hu *et al.*, 2013; Nour *et al.*, 2019). The EF values were obtained from the formula (Eq. 7), while classification of values is based on Faiz *et al.* (2009).

$$EF = \frac{\frac{C_{M(s)}}{C_{N\ (s)}}}{\frac{B_{(R)}}{B_{N\ (R)}}} \quad \text{...(7)}$$

C_M is the measured concentration of heavy metal (HM) in the sample (s) and C_N is concentration of the normalizing metal in the sample (s), while, $B_{(R)}$ is the reference/background value of the concerned HM and $B_{N(R)}$ is the reference value of the normalizing element. Sakan*et al.* (2009) suggested the interpretation of EF as (i) EF < 1 = background concentration or no enrichment; (ii) EF of 1-3 = minor; (iii) EF from 3-5 = moderate; (iv) EF of 5-10 = moderately severe; (v) EF of 10-25 = severe; EF from 25-50 = very severe; and EF >50 = extremely severe.

Ecotoxicological Indicators

The toxic risk index (TRI) and risk index (RI) arising from potential ecological risk index (PERI) were considered for assessment of potential hazard that connects with content of heavy metals in sediments to organisms (Baran *et al.*, 2016).

The toxic risk index (TRI) was recently approved for use as a measure of ecotoxicity on the basis of TEL and PEL (Ustaoglu and Islam, 2020). The TRI of HMs is calculated as below:

$$TRI_i = \sqrt{[(Ci/TEL)2 + (Ci/PEL)2]/2} \quad \text{.......................(8)}$$

$$TRI = \sum_{i=1}^{n} TRI_i \quad \text{...(9)}$$

TRI_i is the toxic risk index of single heavy metal i, Ci is the measured concentration of the heavy metal, n refers to the number of the various heavy metals, and TRI is the integrated toxic risk index of the sample of sediment under consideration. The present study adopted the classification of Zhang *et al.* (2019) to describe the extent of ecotoxicity threat based on the calculated values of TRI. The categories of risk are TRI < 5 implies no toxic risk, TRI of 5-10 translates to low risk, TRI of 10-15 indicates moderate toxic risk, TRI of 15-20 is of considerable toxic risk and TRI > 20 refers to a very high toxic risk.

The risk index (RI) is the summation of all the monomial ecological risk factors (PERI) for the detection of heavy metal contaminants in sediment (Perumal *et al.*, 2021). The potential ecological risk index was originally proposed by Hakanson (1980) who suggested the quantitative method used in equations 10-12 as follows:

$$RI = \sum_{i=1}^{n} E_i \quad \text{...(10)}$$

$$E_i = T_i f_i \quad \text{...(11)}$$

$$F_i = \frac{C_t}{C_b} \quad \text{...(12)}$$

Ei is the potential ecological risk factor for single heavy metal; T_i refers to the toxic response factor for potentially toxic element (PTE); *Fi* refers to the metal contamination factor, C_i is the measured concentration of heavy metal in the sediment sample, and Cb is the background value of the reference metal. Heavy metals with high toxic response factor of ≥ 5 were considered except Zn that is, though, with low T_i,but a prolific contaminant. According to Pecina *et al.* (2021), such metals with their T_i values are Hg = 40, Cd = 30, As = 10, Ni = 6, Co = Cu = Pb = 5, and Zn = 1. The RI values were classified into 9 categories of ecological risk as follows: (i) *Ei*< 40 = low; (ii) 40 <*Ei*< 80 = moderate; (iii) 80 <*Ei*< 160 = considerably high; (iv) 160 <*Ei* <320 = high; (v) *Ei*> 320 = very high; (vi) RI < 150 = low risk; (vii) 150 = RI < 300 implies moderate risk, (viii) 300 = RI < 600 indicates considerable risk, and (ix) RI > 600 indicates very high ecological risk for the sediment (Hakanson, 1980).

Human Health Risk Assessment

Owing to their toxicity and accumulation properties, heavy metals in sediment through the food chain (ingestion) can impose negative health impacts on human depending on the period of exposure (Jafarabadi*et al.*, 2017). Also, humans can uptake these metals through inhalation and dermal contact. The health risk associated with Lekki Lagoon sediments was performed by utilizing non-carcinogenic risks and carcinogenic risks with the United States Environmental Protection Agency (USEPA) 1989-2004 models. The standard/reference values of factors and parameters for computation of human risk indices due to exposure to heavy metals in sediments were sourced from relevant literature (USEPA, 2002; 2004a; 2004b; 2020; Ferreira-Baptista and De Miguel, 2005; De Miguel *et al.*, 2007; Li *et al.*, 2014; Wang and Lu, 2017; Chen *et al.*, 2017; Rehman *et al.*, 2018; Zhang *et al.*, 2018; 2019; and Pecina *et al.*, 2021). The present study considered two common pathways, that is, ingestion and dermal contacts of sediment particles.

In order to assess the potential health risk that could be posed by heavy metal contaminants, the non-carcinogenic risk (HI) and carcinogenic risk (LCR) were employed. The quantity of exposure was calculated by utilizing the exposure risk assessment documented by USEPA (1989, 2004a, b). The risk guidelines of USEPA (1989-2004) for calculation of exposure dose through direct ingestion and dermal absorption presented are as follows:

Direct Ingestion:

$$Exp_{ing} = (Csed \times IngR \times CF \times EF \times ED) / (BW \times AT) \quad ...(13)$$

Where Exp_{ing} is the ingestion exposure risk from HMs in sediment; *Csed* indicates the measured concentration of HMs in sediment; *IngR* is the extent of ingestion per day; *CF* is the conversion factor for the measurement unit; *EF* is the exposure frequency; *ED* denotes exposure duration time; *BW* is the weight for an adult or child; and *AT* is the number of days in 30 and 6 (Iqbal *et al.*, 2013; Tokath, 2021).

Direct Ingestion:

$$Exp_{derm} = (Csed \times CF \times SA \times AF \times ABS \times EF \times ED) / (BW \times AT) \quad ......(14)$$

Exp_{derm} is the risk from HMs in sediment through dermal contact; SA is the exposure area of the skin; AF denotes the adhesion index of the HM on unit area of the skin; and ABS is the dermal adsorption rate from the sediment (Pecina *et al.*, 2021). To compute the non-carcinogenic hazard quotient (HQ) for every HM, the exposure risk (Exp_{ing} or Exp_{derm}) is divided by the reference dose (RfD) also referred to as the toxicity threshold value.

$$HQ = Exp_{ing} / RfD \text{ or } Exp_{derm} / RfD \quad ......(15)$$

The comprehensive non-carcinogenic risk of several HMs on human can be inferred from the total potential non-carcinogenic (HI) calculated using the formula in equation 16.

$$HI = \sum HQ_i = Exp_i / RfD_i \quad ......(16)$$

Based on USEPA standard (2000), six classes of HI exists as follows: HI < 1 = no health risk; 1 < HI < 1.5 = low risk; 1.5 < HI < 2 = low-medium health risk; 2 < HI < 2.5 = medium risk; 2.5 < HI < 3 = next high risk; HI > 3 = high risk.

However, for carcinogenic risk (CR), the exposure is multiplied by the corresponding slope factor (SF) to yield a cancer risk level as in equation 17.

$$CR = Exp_{ing} \times SF \text{ or } Exp_{derm} \times SF \quad ......(17)$$

The total lifetime cancer risk (LCR) is computed by utilizing equation 18, and defined as summation of the individual cancer risk along all exposure pathways (Pan *et al.*, 2018).

$$LCR = \sum CR \quad ......(18)$$

The carcinogenic risk (CR) and the lifetime cancer risk (LCR) have been classified as follows:
Class I = CR ≤ 1×10^{-6} very low, Class II = 1×10^{-6} < CR ≤ 1×10^{-4} low, Class III = 1×10^{-4} < CR ≤ 1×10^{-3} moderate, Class IV = 1×10^{-3} ≤ CR ≤ 0.1 high, and Class V = CR > 0.1 very high.

Results and Discussion

Water and Sediment Characteristics

The results of the physicochemical parameters of water and particle size distribution determined are shown in Table 1. Shallow water depth (0.4 m – 2.8 m), slightly acidicwater (pH = 6.41-6.78), freshwater with trace amount of salt (0.2-0.3 ppt) and a slightly low to moderate oxidation-reduction potential (ORP) of +160 mV to +211 mV characterized the Lekki Lagoon. Approximately 71.43 % of the stations investigated have sand grade surface-sediment dominated by fine sand class (Ø ≤ 3) and very few medium-sand (Ø ≤ 2), while mud fractions were prevalent in the remaining stations (Ø > 4). This implies that the sediments were emplaced under very low hydrodynamic energy, consequent upon long distance of sediment-load transport by the network of rivers that connect the lagoon. The trace amount of salt in this water may indicate that suspended particles were also contributed from the distant sea through Lagos Harbour into the lagoon.

Table 1: Water Characteristics and Grain Size Distribution in Sediments

Sample number	Water depth (m)	pH	Salinity, ppt	ORP mV	Grain Size Distribution: Diameter (Ø) and wt. % retained						Sand sizes %	Mud sizes %
					Ø ≤ 0	Ø ≤ 1	Ø ≤ 2	Ø ≤ 3	Ø ≤ 4	Ø > 4		
L1	1.00	6.78	0.3	170	0.60	2.01	2.82	3.82	1.61	89.13	10.86	89.13
L2	1.30	6.65	0.3	177	0.61	8.10	24.29	38.46	11.74	16.80	83.19	16.80
L3	2.00	6.63	0.3	184	0.40	2.41	17.27	54.42	17.67	7.83	92.17	7.83
L4	1.80	6.60	0.3	185	0.22	0.86	9.48	51.72	30.60	7.11	92.88	7.11
L5	1.85	6.61	0.3	188	0.19	2.21	54.02	37.94	3.09	2.56	97.44	2.56
L6	2.60	6.72	0.3	195	0.20	4.91	21.88	61.55	10.02	1.43	98.56	1.43
L7	2.20	6.52	0.3	183	0.00	0.20	0.40	0.40	0.40	98.60	1.40	98.60
L8	2.15	6.51	0.2	201	0.00	0.32	0.18	0.26	4.80	94.44	5.56	94.44
L9	2.70	6.61	0.2	205	0.18	0.28	0.22	0.24	10.61	88.41	11.53	88.41
L10	2.50	6.59	0.2	205	0.21	5.89	33.36	49.69	5.82	5.13	94.97	5.13
L11	0.90	6.59	0.2	205	0.16	9.61	38.84	45.85	3.40	2.06	97.86	2.06
L12	0.90	6.41	0.2	204	2.08	28.90	34.10	26.82	6.03	2.08	97.92	2.08
L13	0.40	6.39	0.2	211	1.25	15.45	39.46	37.16	3.97	2.72	97.28	2.72
L14	0.50	6.44	0.2	207	0.18	1.61	9.68	66.93	19.76	1.83	98.16	1.83
L15	0.50	6.55	0.2	205	0.18	2.22	48.89	42.22	4.85	1.64	98.36	1.64
L16	0.95	6.57	0.2	202	0.60	6.90	25.08	52.21	11.29	3.23	96.77	3.23
L17	0.40	6.58	0.2	202	0.00	6.02	23.69	53.81	15.26	1.20	98.79	1.20
L18	1.20	6.54	0.3	202	3.43	16.52	32.83	41.84	2.79	2.57	97.42	2.57
L19	2.80	6.61	0.3	201	0.20	0.40	0.60	2.60	14.80	81.40	18.60	81.40
L20	1.10	6.58	0.3	203	0.20	8.20	36.89	46.51	4.92	3.28	96.71	3.28
L21	1.50	6.54	0.3	205	0.00	0.00	0.00	0.00	1.60	98.40	1.60	98.40

ORP- Oxidation-reduction potential

Heavy Metal Concentrations and Sediment Quality Assessment

The concentrations of metals in various samples of sediments were in the decreasing order of Fe > Al > Zn > Co > Ni > Pb > Cu > As > Hg (Table 2). Among the metals with high toxic response coefficients ($T_i \geq 5$), in ppm, Coranged from 3.3-32.4, Ni from 1.0-42.0, As (metalloid)from 0.25-5.80 and Hgfrom 0.005-0.120, withmean concentrations in sediments above their background values (Table 2). In contrast, Sb (metalloid) was below the detection limit of 0.1 ppm in all sediments, which implied lower concentration than its background value. The maximum concentration of Co was recorded for station L9 and lowest at station 17. The concentrations of Pb in stations L1, L2, L7, L8, L9, and L21; and Cu in stations L2 and L7 were above their reference values. The ecological effects at various concentrations of heavy metals were evaluated using the ISQGs (Buchman, 2008). In order to evaluate the impact of contaminants on the resident organisms in this lagoon, the TEL, TEC, PEL and PEC were compared to the measured concentrations of HMs. Figures 2a-h compare the concentrations of heavy metals to the set limits of the consensus-based sediment quality guidelines. The stations enriched in cobalt are at the upper reach around Apala - Aba Onigbagbo – Oba Oyingbo (L7, L8 and L9), southern portion (L19, L20 and L21) and southeastern portion (L1, L2 and L3) in decreasing order of heavy metal concentration (Fig. 2a). The values for TEL, PEL, TEC and PEC are not available for cobalt; hence comparison could not be made. It is pertinent to note that all samples highly enriched in mud fractions are the only ones enriched in cobalt at the upper reach of the lagoon. The highest concentration of Cu recorded at Apala area (L7) was below all threshold values (TEL and TEC), hence no probability of negative biological effect (Fig 2b). The variation in concentrations of Pb was not influenced by particle size distribution, and all concentrations are below threshold to pose hazardous threat (Fig. 2c). Figure 2d presents the concentrations of Zn in stations L1, L8, L9, L19 and L21 above the threshold effect level (TEL) and threshold effect concentration (TEC). These concentrations are significant, though may not produce adverse effects on sediment dwelling fauna being below PEC and PEL.It was observed that the sediments from these stations are overwhelmed by mud-size fractions above 81 % (Table 2). Approximately 33.3 % of the stations sampled (L1, L2, L7, L8, L9, L19 and L21) contain Ni concentrations above TEL and TEC (Fig. 2e).

The concentrations of Ni in stations L2 and L7 are not acceptable as values are above PEL, implying adverse effects may be produced on benthic organisms (MacDonald *et al.*, 2011; Thompson and Wasserman, 2015). Cadmium, Hg and As have contents below TEL and TEC in all stations, except As with value slightly above TEL in station L21, hence the stations concerned are highly habitable for aquatic organisms (Figs. 2f-h).

The mean probable effect concentration quotients (*m-PECQs*) have been used to predict the potential toxicity of the sediment samples (Long *et al.*, 2006; Koniarz*et al.*, 2023). The m-PECQs give a combined assessment of heavy metal contamination and help to elucidate the overall effects of contaminants in sediments (Phillips *et al.*, 2020b). The values of *m-PECQs* were below 0.1 for 61.9 % of sediment samples, whereas, the remaining samples were ≥ 0.1 < 0.5, implying 10 % and 17 % possibility of sediments producing toxic effects on the dwelling organisms respectively (Table 3). According to Perumal *et al.* (2021), the potential contamination index obtained for all heavy metals of concern, inferred severe to very severe contamination (C_p> 3), except Cd, Pb and Cu (C_p = 1 < 3) that indicated moderate contamination (Table 2). Such metals with severe to very severe contamination based on index of potential contamination (C_p) are Zn > Hg > Ni > Co in dwindling order of strength.

Table 2: Metal Concentrations in part per million (ppt), Sediment Quality Parameters and Potential Contamination Index

Sample No	Fe %	Al %	Co Ppm	Cu Ppm	Pb Ppm	Zn ppm	Ni Ppm	Cd ppm	As Ppm	Sb Ppm	Hg Ppm
L1	8.89	6.38	16.4	11.1	14.7	138.0	34.0	0.10	5.80	<0.1	0.100
L2	8.32	9.52	29.6	22.5	16.5	104.0	38.0	0.20	1.60	<0.1	0.100
L3	4.24	3.50	16.8	4.9	7.4	73.0	9.7	0.05	3.10	<0.1	0.040
L4	0.98	1.38	8.0	3.4	5.1	58.0	8.2	0.05	1.70	<0.1	0.110
L5	0.53	0.92	8.1	1.8	1.7	12.0	2.3	0.05	0.25	<0.1	0.005
L6	1.98	2.46	6.7	11.0	5.8	28.0	5.9	0.05	1.50	<0.1	0.030
L7	7.52	10.52	26.1	26.5	18.2	96.0	42.0	0.10	1.00	<0.1	0.100
L8	8.92	4.00	32.4	11.7	14.0	137.0	29.0	0.20	3.90	<0.1	0.110
L9	8.99	7.99	34.9	13.5	15.0	136.0	30.0	0.20	3.60	<0.1	0.110
L10	1.47	1.63	4.9	1.0	2.7	18.0	2.2	0.05	1.30	<0.1	0.005
L11	1.36	0.70	7.7	1.0	2.2	19.0	2.2	0.05	1.30	<0.1	0.005
L12	0.41	0.68	8.1	1.1	1.4	11.0	2.1	0.05	0.25	<0.1	0.005
L13	0.47	0.86	5.1	1.0	1.7	11.0	1.7	0.05	0.25	<0.1	0.005
L14	0.61	0.75	3.4	0.6	1.3	8.0	1.1	0.05	0.70	<0.1	0.005
L15	0.45	0.72	8.2	1.1	1.4	9.0	2.1	0.05	0.25	<0.1	0.005
L16	1.34	0.68	7.4	1.0	2.4	21.0	2.0	0.05	1.50	<0.1	0.005
L17	0.50	0.83	3.3	0.5	1.2	8.0	1.0	0.05	0.60	<0.1	0.005
L18	0.55	0.93	8.2	1.5	1.8	14.0	2.2	0.05	0.25	<0.1	0.005
L19	8.60	7.05	30.0	9.9	13.9	135.0	28.0	0.20	4.20	<0.1	0.100
L20	4.21	3.07	17.2	5.0	7.7	80.0	9.5	0.05	2.90	<0.1	0.020
L21	8.97	6.85	17.4	12.1	14.5	141.0	35.0	0.05	6.20	<0.1	0.120
Mean ± SD	3.78 ± 0.81	3.40 ± 0.73	14.28 ± 2.32	6.77 ± 1.68	7.17 ± 1.39	59.86 ± 11.94	10.8 7± 3.41	0.08 ± 0.09	2.01 ± 0.41	-	0.04 ± 0.01
Minimum	0.41	0.68	3.3	0.5	1.2	8.0	1.0	0.05	0.25	-	0.005
Maximum	8.99	10.52	32.4	26.5	18.2	138.0	42.0	0.20	5.80	-	0.120
Background Value (Buchman, 2008)	1.39	0.26	10.0	17.5	10.5	22.5	9.9	0.20	1.10	-	0.028
C_p	6.47	40.46	3.24	1.51	1.73	6.13	4.24	1.00	5.27	-	4.290
TEL	-	-	-	35.7	35.0	123.0	18.0	0.59	5.90	-	0.170
PEL	-	-	-	197.0	91.3	315.0	36.0	3.53	17.00	-	0.480
TEC	-	-	-	31.6	35.8	121.0	22.7	0.99	9.79	-	0.180
PEC	-	-	-	149.0	128.0	459.0	48.6	4.98	33.00	-	1.060

Assessment of Heavy Metal Contamination

Quantitative indices such as *CF*, *Cd*, *mCd*, *PLI*, I_{geo} and *EF* were used to assess the extent of heavy metal contamination in the sediments, and the calculated values of these variables are shown in Tables 4, 5 and 6.

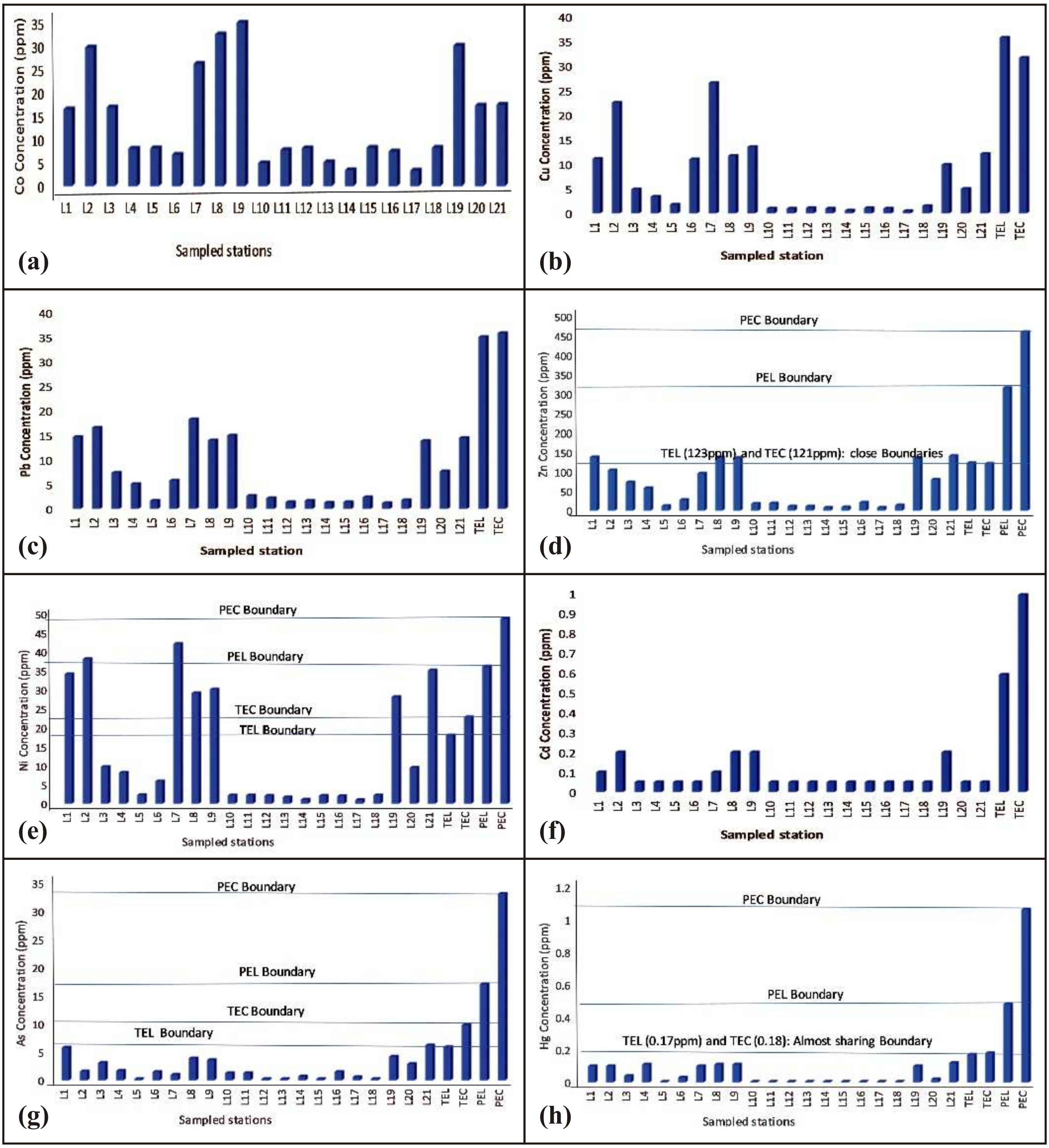

Fig. 2(a-h): Spatial distribution of heavy metals in sediments and assessment of sediment quality, Lekki Lagoon, Southwest Nigeria.

The calculated value of CF < 1 was obtained for Cu, Cd, Pb, Ni, Co, Hg, Zn and As, in approximately 90.5 %, 81.0 %, 66.7 %, 66.7 %, 57.1 %, 52.4 %, 47.6 % and 38.1 % of all stations respectively, implying low contamination (Hakanson, 1980). This alludes to the fact that As contamination is the most widespread in Lekki Lagoon, and Zn followed as it covered 52.4 % of sampled stations. Arsenic contamination ranged from moderate contamination (1 ≤ CF < 3) to high contamination (3 ≤ CF < 6), as Zn was the most spurious heavy metals in this lagoon with moderate contamination (1 ≤ CF < 3) to very high contamination,

Table 3: The Probable Effect Concentration Quotients (PECQ) for Heavy Metals and The Mean PECQ

Sample No	Cu	Pb	Zn	Ni	Cd	As	Hg	*mPECQ*
L1	0.07	0.11	0.30	0.70	0.02	0.18	0.09	0.21
L2	0.15	0.13	0.23	0.78	0.04	0.05	0.09	0.21
L3	0.03	0.06	0.16	0.20	0.01	0.09	0.04	0.08
L4	0.02	0.04	0.13	0.17	0.01	0.05	0.10	0.07
L5	0.01	0.01	0.03	0.05	0.01	0.01	0.01	0.02
L6	0.07	0.05	0.06	0.12	0.01	0.05	0.03	0.06
L7	0.18	0.14	0.21	0.86	0.02	0.03	0.09	0.22
L8	0.08	0.11	0.30	0.60	0.04	0.12	0.10	0.19
L9	0.09	0.12	0.30	0.62	0.04	0.11	0.10	0.20
L10	0.01	0.02	0.04	0.05	0.01	0.04	0.01	0.03
L11	0.01	0.02	0.04	0.05	0.01	0.04	0.01	0.03
L12	0.01	0.02	0.02	0.04	0.01	0.01	0.01	0.02
L13	0.01	0.01	0.02	0.03	0.01	0.01	0.01	0.01
L14	0.004	0.01	0.02	0.02	0.01	0.02	0.01	0.01
L15	0.01	0.01	0.02	0.04	0.01	0.01	0.01	0.02
L16	0.01	0.02	0.05	0.04	0.01	0.05	0.01	0.03
L17	0.003	0.01	0.02	0.02	0.01	0.02	0.01	0.01
L18	0.01	0.01	0.03	0.05	0.01	0.01	0.01	0.02
L19	0.07	0.11	0.30	0.58	0.04	0.13	0.09	0.19
L20	0.03	0.06	0.17	0.20	0.01	0.88	0.02	0.20
L21	0.08	0.11	0.31	0.72	0.01	0.19	0.12	0.22

i.e., $CF \geq 6$ (Table 4). The contamination degree was very high in most cases because it considered the sum of all *CF*s of all metals. Approximately 43 % of the stations investigated were not polluted or had very low contamination ($mCd < 1.5$). These stations (L5, L11-L18) had no significant contamination by any of the heavy metals with high toxic response factors (Table 4). High degree of contamination in decreasing order of impact was recorded for stations L7, L2, L9, L21, L9, L1 and L8 with $4 \leq mCd < 8$. The consideration of I_{geo} further complement that the lagoon is practically not contaminated with Cd, Cu, and Pb as the maximum values calculated for this index are -0.59, 0.01 and 0.2 respectively (Table 5). However, moderate contamination ($1 < I_{geo} < 2$) of Hg, Ni, As, Zn, and Co within the coverage of 38.1 %, 23.8 %, 23.8 %, 19.0 %, and 9.5 % of the stations investigated in relative order, was inferred. Also, in 23.8 % of the stations covered, Zn moderately to heavily contaminated ($2 < I_{geo} < 3$) the geo-sorbent (Table 5). There is no enrichment of heavy metals of concern in most part of the lagoon ($EF < 1$). Of 21 stations, L5, L12, L15 and L18 are with minor enrichment (EF = 1-3) of Co. Remarkably, station L4 showed moderate enrichment of Zn (EF = 3.67) and minor enrichment of As (EF = 2.19). There was no enrichment for Cd, Cu and Pb in all stations, while Ni (EF = 1.17) and Hg showed minor and moderately severe enrichment (EF = 5.61) respectively in only station L4. It is pertinent to note that metals with enrichment $EF < 2$ were sourced geogenically, while contamination of those with $EF > 2$ were driven by anthropogenic activities (Fry *et al.*, 2021). This suggested that contamination of Cu, Pb, Cd, Ni, Zn, As and Hg were due to natural activities, except station L4 where moderate to moderately severe enrichment of As< Zn < Hg due to anthropogenic activities were uncloaked.

Ecotoxicological Risk Assessment

Toxic risk index (*TRI*) was used to evaluate the ecotoxicity employing the method of Ustaoglu and Islam (2020), and values calculated for each metal are presented in table 7. The results showed that the integrated toxic risk index was at its maximum in sediment from station L21 (TRI = 4.34) while, sample L13 presented the lowest value of TRI = 1.40 (Table 7). The *TRI* demonstrated that there was no toxic risk in the lagoon since values were < 5 (Zhang *et al.*, 2019).

The evaluation of potential ecological risk index (PERI) may serve as a tool to understand the possible ecological threats that may arise through the discharge of heavy metals into aquatic habitats (Hossain *et al.*, 2021). The monomial potential ecological risk factors (*Ei*) of Co, Cu, Pb, Ni, Cd and As in all stations indicate low ecological risk ($Ei < 40$) except where As showed moderate risk in stations L1 (Ei = 52.7) and L21 (Ei = 56.4). High ecological risk (Ei = 171.6) was displayed by Hg in station L21 (Table 8). Also, stations L1, L2, L4, L7, L8, L9 and L19 were impacted by Hg contamination (Ei = 142.8 to 157.2), exposing the stations to considerably high potential ecological risk (Perumal *et*

Table 4: Contamination Factors (CF) of heavy metals in Sediments

Sample No	Fe	Al	Co	Cu	Pb	Zn	Ni	Cd	As	Hg	*Cd*	*mCd*
L1	6.39	24.54	1.64	0.63	1.40	6.13	3.43	0.50	5.27	3.57	53.5	5.35
L2	5.99	36.62	2.96	1.29	1.57	4.62	3.84	1.00	1.45	3.57	62.91	6.29
L3	3.05	13.46	1.68	0.28	0.70	3.24	0.98	0.25	2.82	1.42	27.88	2.53
L4	0.71	5.31	0.80	0.19	0.49	2.58	0.83	0.25	1.55	3.93	16.64	1.66
L5	0.38	3.54	0.81	0.10	0.61	0.53	0.23	0.25	0.23	0.18	6.86	0.69
L6	1.42	9.46	0.67	0.63	0.55	1.24	0.59	0.25	1.36	1.07	17.24	1.72
L7	5.41	40.46	2.61	1.51	1.73	4.27	4.24	0.50	0.90	3.57	65.2	6.52
L8	6.42	15.38	3.24	0.67	1.33	6.08	2.93	1.00	3.55	3.93	44.53	4.45
L9	6.47	30.73	3.49	0.77	1.43	6.04	3.03	1.00	3.27	3.93	60.16	6.02
L10	1.06	6.27	0.49	0.06	0.26	0.80	0.22	0.25	1.18	0.18	10.77	1.08
L11	0.98	2.69	0.77	0.06	0.21	0.84	0.22	0.25	1.18	0.18	5.33	0.53
L12	0.29	2.64	0.81	0.06	0.13	0.49	0.21	0.25	0.23	0.18	5.29	0.53
L13	0.34	3.31	0.51	0.06	0.16	0.49	0.70	0.25	0.23	0.18	6.23	0.62
L14	0.44	2.88	0.34	0.03	0.12	0.36	0.11	0.25	0.64	0.18	5.35	0.54
L15	0.32	2.77	0.82	0.06	0.13	0.40	0.21	0.25	0.23	0.18	5.37	0.54
L16	0.96	2.62	0.74	0.06	0.23	0.93	0.20	0.25	1.36	0.18	7.53	0.75
L17	0.36	3.19	0.33	0.03	0.11	0.36	0.10	0.25	0.55	0.18	4.97	0.49
L18	0.39	3.58	0.82	0.09	0.17	0.62	0.22	0.25	0.23	0.18	6.55	0.66
L19	6.19	27.12	3.00	0.57	1.32	6.00	2.83	1.00	3.82	3.57	55.42	5.54
L20	3.03	11.81	1.72	0.29	0.73	3.56	0.96	0.25	2.64	0.71	25.7	2.57
L21	6.45	26.35	1.74	0.69	1.38	6.27	3.54	0.25	5.64	4.29	56.6	5.66

Table 5: Geoaccumulation Index (Igeo) of selected heavy Metals in Sediments

Sample No	Fe	Al	Co	Cu	Pb	Zn	Ni	Cd	As	Hg
L1	2.09	4.03	0.13	-1.24	-0.10	2.03	1.19	-1.59	1.81	1.25
L2	1.99	4.61	0.98	-0.22	0.07	1.62	1.36	-0.59	-0.05	1.25
L3	1.02	3.17	0.16	-2.43	-1.09	1.11	-0.61	-2.59	0.91	0.070
L4	-1.09	1.82	-0.91	-2.95	-1.63	0.78	-0.86	-2.59	0.04	1.39
L5	-1.98	1.24	-0.89	-3.88	-3.22	-1.49	-2.69	-2.59	-2.73	-3.07
L6	-0.08	2.66	-1.16	-1.25	-1.44	-0.27	-1.33	-2.59	-0.14	-0.49
L7	1.85	4.75	0.79	0.01	0.21	1.51	1.49	-1.59	-0.72	1.25
L8	2.09	3.36	1.11	-1.17	-0.17	2.02	0.96	-0.59	1.24	1.39
L9	2.11	4.36	1.22	-0.96	-0.07	2.01	1.01	-0.59	1.12	1.39
L10	-0.50	2.06	-1.62	-4.72	-2.49	0.91	-2.76	-2.59	-0.35	-3.07
L11	-0.62	0.84	-0.96	-4.72	-2.85	-0.83	-2.76	-2.59	-0.35	-3.07
L12	-2.35	0.80	-0.89	-4.61	-3.51	-1.62	-2.83	-2.59	-2.73	-3.07
L13	-2.15	1.14	-1.56	-4.72	-3.22	-1.62	-3.13	-2.59	-2.73	-3.07
L14	-1.78	0.94	-2.15	-5.51	-3.61	-2.08	-3.76	-2.59	-1.24	-3.07
L15	-2.22	0.88	-0.87	-4.61	-3.51	-0.91	-2.83	-2.59	-2.73	-3.07
L16	-0.64	0.80	-1.02	-4.72	-2.72	-0.69	-2.89	-2.59	-0.137	-3.07
L17	-2.06	1.09	-2.18	-5.72	-3.72	-2.08	-3.89	-2.59	-1.461	-3.07
L18	-1.93	1.25	-0.87	-4.13	-3.13	-1.27	-2.76	-2.59	-2.73	-3.07
L19	2.04	4.18	1.00	-1.41	-0.18	2.00	0.91	-0.59	1.347	1.25
L20	1.01	2.98	0.19	-2.39	-1.04	1.24	-0.65	-2.59	0.81	-1.07
L21	2.11	4.13	0.21	-1.21	-0.12	2.06	1.24	-2.59	1.91	1.51

al., 2021). The high values obtained for mercury was as a result of its very high toxic response factor such that at very low but enriched concentrations, may negatively impact the ecosystem. The risk index (RI) represents the sum of all the monomial ecological risk index of heavy metals in sediment. Almost 71.4 % of samples from all stations indicated low risk as the RI was below 150, hinting low ecological risk (Table 8). The RI values for the relatively more contaminated stations varied from 194.3-278.5, suggesting moderate risk to the ecological community.

Table 6: Enrichment Factors (EF) for heavy Metals in Sediments

Sample No	Al	Co	Cu	Pb	Zn	Ni	Cd	As	Hg
L1	3.83	0.25	0.09	0.21	0.96	0.53	0.08	0.82	0.59
L2	6.11	0.49	0.21	0.26	0.77	0.64	0.17	0.24	0.60
L3	4.41	0.55	0.09	0.23	1.06	0.32	0.08	0.92	0.47
L4	7.53	1.13	0.27	0.68	3.67	1.17	0.36	2.19	5.61
L5	9.23	2.12	0.27	0.42	1.40	0.61	0.67	0.59	0.47
L6	6.64	0.47	0.44	0.38	0.87	0.41	0.18	0.95	0.75
L7	7.48	0.48	0.28	0.32	0.79	0.78	0.09	0.16	0.66
L8	2.39	0.50	0.10	0.20	0.95	0.45	0.16	0.55	0.61
L9	4.75	0.53	0.12	0.22	0.93	0.47	0.15	0.50	0.61
L10	5.92	0.46	0.05	0.24	0.76	0.21	0.24	1.11	0.17
L11	2.75	0.78	0.05	0.21	0.86	0.22	0.26	1.20	0.18
L12	8.86	2.74	0.21	0.45	1.66	0.72	0.87	0.77	0.60
L13	9.78	1.50	0.17	0.47	1.45	0.50	0.75	0.67	0.53
L14	6.57	0.77	0.07	0.28	0.81	0.25	0.58	1.45	0.40
L15	8.55	2.53	0.19	0.41	1.24	0.65	0.79	0.70	0.55
L16	2.71	0.76	0.05	0.23	0.97	0.21	0.26	1.41	0.18
L17	8.87	0.91	0.08	0.31	0.99	0.28	0.71	1.51	0.50
L18	9.04	2.07	0.21	0.43	1.58	0.56	0.64	0.57	0.45
L19	4.38	0.48	0.09	0.21	0.97	0.45	0.16	0.61	0.58
L20	3.89	0.56	0.09	0.24	1.18	0.31	0.08	0.87	0.23
L21	4.08	0.26	0.10	0.21	0.97	0.54	0.03	0.87	0.66

Table 7: Toxic risk index (TRI) of Heavy Metals and the Integrated Toxic Risk Index (TRI) in Sediments

Sample Number	Cu	Pb	Zn	Ni	Cd	As	Hg	*TRI*
L1	0.22	0.32	0.85	1.49	0.12	0.74	0.44	4.18
L2	0.45	0.36	0.64	1.67	0.24	0.20	0.44	4.00
L3	0.10	0.16	0.45	0.43	0.06	0.39	0.18	1.77
L4	0.07	0.11	0.36	0.36	0.06	0.22	0.49	1.67
L5	2.89	0.04	0.07	0.10	0.06	0.03	0.02	3.21
L6	0.22	0.13	0.17	0.26	0.06	0.19	0.13	1.16
L7	0.53	0.39	0.59	1.84	0.17	0.13	0.44	4.09
L8	0.24	0.3	0.85	1.27	0.24	0.49	0.49	3.88
L9	0.27	0.32	0.84	1.32	0.24	0.46	0.49	3.94
L10	1.14	0.06	0.11	0.1	0.06	0.16	0.02	1.65
L11	1.14	0.05	0.01	0.1	0.06	0.16	0.02	1.54
L12	1.25	0.03	0.07	0.09	0.06	0.03	0.02	1.68
L13	1.14	0.04	0.07	0.04	0.06	0.03	0.02	1.40
L14	2.15	0.03	0.05	0.05	0.06	0.09	0.02	2.45
L15	1.25	0.03	0.06	0.09	0.06	0.03	0.02	1.54
L16	1.14	0.05	0.13	0.09	0.06	0.19	0.02	1.68
L17	1.79	0.03	0.05	0.03	0.06	0.08	0.02	2.06
L18	1.7	0.04	0.09	0.1	0.06	0.03	0.02	2.04
L19	0.2	0.3	0.83	1.23	0.24	0.53	0.44	3.77
L20	0.1	0.26	0.43	0.41	0.06	0.37	0.09	1.72
L21	0.24	0.31	0.87	1.54	0.06	0.79	0.53	4.34
Mean	0.87	0.16	0.36	0.6	0.1	0.25	0.21	2.56
Minimum	0.1	0.03	0.01	0.03	0.06	0.03	0.02	1.40
Maximum	2.8	0.39	0.87	1.84	0.24	0.79	0.53	4.34

Table 8: Monomial Potential Ecological Risk Index (PERI) for heavy Metals and Risk Index in Sediments

Sample No	Co	Cu	Pb	Zn	Ni	Cd	As	Hg	RI
L1	8.20	3.51	7.00	6.13	17.10	15.0	52.7	142.8	252.0
L2	14.80	6.45	7.85	4.62	19.20	30.0	14.5	142.8	240.2
L3	8.40	1.40	3.50	3.24	4.90	7.5	28.2	56.8	113.9
L4	4.00	0.95	2.45	2.58	4.15	7.5	15.5	157.2	194.3
L5	4.05	0.50	3.05	0.53	1.15	7.5	2.3	7.2	26.2
L6	3.35	3.15	2.75	1.24	2.95	7.5	13.6	42.8	77.3
L7	13.00	7.55	8.65	4.27	21.20	15.0	9.0	142.8	221.4
L8	16.20	3.35	6.65	6.08	14.60	30.0	35.5	157.2	269.5
L9	17.40	3.85	7.15	6.04	15.10	30.0	32.7	157.2	269.4
L10	2.45	0.30	1.30	0.80	1.10	7.5	11.8	7.2	32.4
L11	3.85	0.30	1.05	0.84	1.10	7.5	11.8	7.2	33.6
L12	4.05	0.30	0.65	0.49	1.05	7.5	2.3	7.2	23.5
L13	2.55	0.30	0.80	0.49	3.50	7.5	2.3	7.2	24.6
L14	1.70	0.15	0.60	0.36	0.55	7.5	6.4	7.2	24.4
L15	4.10	0.30	0.65	0.40	1.05	7.5	2.3	7.2	23.5
L16	3.70	0.30	1.15	0.93	1.00	7.5	13.6	7.2	35.3
L17	1.65	0.15	0.55	0.36	0.50	7.5	5.5	7.2	23.4
L18	4.10	0.45	0.85	0.62	1.10	7.5	2.3	7.2	24.1
L19	15.00	2.85	6.60	6.00	14.10	30.0	38.2	142.8	255.5
L20	8.60	1.45	3.65	3.56	4.80	7.5	26.4	28.4	84.3
L21	8.70	3.45	6.90	6.27	17.70	7.5	56.4	171.6	278.5
Mean	7.13	2.45	3.51	2.65	7.04	12.5	18.2	66.9	120.3
Minimum	1.65	0.15	0.55	0.36	0.50	7.5	2.3	7.2	23.4
Maximum	17.40	7.55	8.65	6.27	21.20	30.0	56.4	171.6	278.5

Interrelationship among Heavy Metals and Source Identification

The source(s) of heavy metals and their interrelationship in this lagoon were determined using Pearson Correlation analysis (Karthikeyan *et al.*, 2018). The correlation coefficients for these metals are displayed in Table 9. Strong statistical relationship was identified between Fe and Al ($r = 0.903$) which implies they were contributed from geogenic activities (natural source). It is widely believed that a strong positive correlation between Al or Fe and heavy metals infer natural source, specifically from weathering of rocks/soils around the region of deposition (Magesh *et al.*, 2017; Tytia and Kostecki, 2019; Zhou *et al.*, 2020; Baran *et al.*, 2023). Accordingly, Al showed very strong positive relationship with most of the metals of high toxic response coefficients, specifically, Ni, Pb, Cu, Co, Hg and Cd in decreasing order of strength (Table 9). Also, strong interrelationship was observed between Al and Zn, though Zn has low toxicity but was in highly significant quantity in most of the samples. However, a moderate statistical correlation was identified between As (metalloid) and Al ($r = 0.566$). In contrast, strong relationship exists between Fe and As ($r = 0.814$), which probably, may account for differences in stability of Al in comparison to Fe under certain redox conditions. While Fe is a siderophile, it is equally a chalcophile, implying, it can be precipitated along with As under anoxic conditions. In addition, As exhibited weak though positive statistical relationship with Cu and Cd. It is suggested that the behaviour that characterized As in Lekki Lagoon is implicit in contributions driven by both lithogenic and anthropogenic activities.

Multivariate Statistics and Cluster Analysis

Principal Component Analysis (PCA)

PCA was employed to ascertain possible relationships among metals, understand the magnitude of contamination by the various metals and infer the sources of these pollutants (Perumal *et al.*, 2021). Considering the difference in background/reference values of metals, their concentrations were normalized to avoid exaggerated and misconceived relationship among metals, and also, log-transformed where required before multivariate method was applied. Two principal components which explained 92.78 % of the system variance was unveiled based on the Eigen values greater than 0.5 (Table 10). The variance of the first principal component (PC1) was 84.36 % with Eigen value of 7.379, and uncloaked weak positive loading in all metals. While Fe (0.36) and Zn (0.35) presented the highest loading, Cd (0.21), Co (0.26), As (0.27) and Cu (0.27) displayed the least loading (Fig. 3a). Consequent upon the relative immobility of Al, and that it is not easily influenced by anthropogenic activities, the positive loading of all contaminants alongside Al and Fe suggested input of natural activities (Baltas *et al.*, 2020). The PC2 with percentage variance of 8.42 % and Eigen value at 0.736 displayed strong negative loading (-0.743) for As, and weak negative loading for Fe (-0.110), Hg (-0.102) and Zn (-0.273), attesting to their contribution from anthropogenic activities (Fig 3b).

Cluster Analysis

In order to generate clusters for the metals as variables (R-mode), and same for the sediment samples (Q-mode), the paired group method was the algorithm used and Euclidean similarity measure was considered. The dendrogram that arose from R-mode cluster analysis showed 3 main classes where Al served as the outlier, being with the highest normalized concentration (Fig. 4a). The Class-1 was represented by Fe and Zn nearest in normalized concentration-ranking to Al, and based on similarity index, shared same input source implicit in lithogenic activities (Fig. 4a). The Class-1 metals are equally connected to Class-2 and Class-3 hence, natural sources have also been suggested for these classes. This is not surprising, especially for Cd, as it is usually found in association with zinc ore, and are commonly produced from zinc byproducts. In ores such as chalcopyrite and bornite, Cu occurs in nature, though, also, commonly obtained from anthropogenic activities such as smelting, leaching and electrolysis involving its ores and minerals. The Class-2 was constituted by Pb, Cd and Cu which have been identified not to have shown enrichment and contamination in almost all the stations in the lagoon. Lead (Pb) is usually strongly bound by organic compounds, shares chemical affinity with Cu and may be in chemical bond with Cd. The hierarchical cluster that made up Class-3 is composed of Co, Ni, Hg and As. These metals showed more toxicity than the variables that constituted the other cluster classes. Premised on their similarity with Fe, different from that with Al, both anthropogenic and geogenic activities have been inferred as their paths into this lagoon. The Q-mode cluster analysis unveiled two main groups of samples according to the extent of sediment-contamination/degradation by the heavy metal-contaminants (Fig. 4b). The Group-2, constituted by L9, L19, L21, L1, L2 and L7, represents the class of sediments in stations where relatively more contamination has been imposed by both geogenic and anthropogenic activities. The sediment samples from these stations are predominantly constituted by mud fractions, except L2 with prevalence of fine sand fractions and small but significant quantity of mud particles (Table 1). Apart from the local human activities around these stations, the grain size characteristics may have provided enough surface area for adsorption, hence, the attendant heavy metal accumulation.

Table 9: Pearson's correlation coefficient matrix for the heavy metals in sediments of Lekki Lagoon, southwest Nigeria

	Fe	Al	Co	Cu	Pb	Zn	Ni	Cd	As	Hg
Fe	1									
Al	0.905	1								
Co	0.904	0.846	1							
Cu	0.805	0.940	0.778	1						
Pb	0.955	0.952	0.889	0.906	1					
Zn	0.975	0.839	0.877	0.723	0.923	1				
Ni	0.948	0.957	0.850	0.908	0.970	0.905	1			
Cd	0.776	0.703	0.899	0.645	0.738	0.729	0.721	1		
As	0.814	0.566	0.578	0.402	0.684	0.875	0.667	0.424	1	
Hg	0.871	0.816	0.792	0.763	0.886	0.914	0.893	0.688	0.728	1

Appraisal of Human Health Risk

Lekki Lagoon accommodates different species of fish and aquatic plants which made it a major biodiversity reserve, and, serves as a source of livelihood for the residents in the immediate community. The direct dermal contact and consumption of the aquatic organisms by human made it consequential to evaluate the public health risk that may arise due to contamination by heavy metals in sediments of this

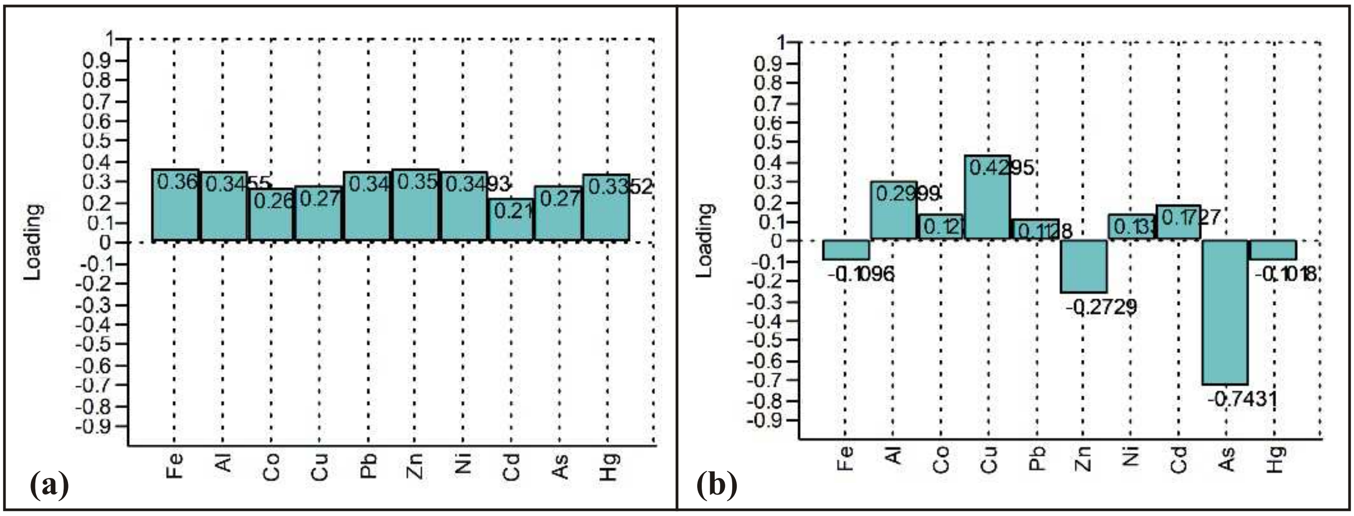

Fig. 3: (a) The plot of PCA Loading for Component 1. **(b)** The plot of PCA Loading for Component 2.

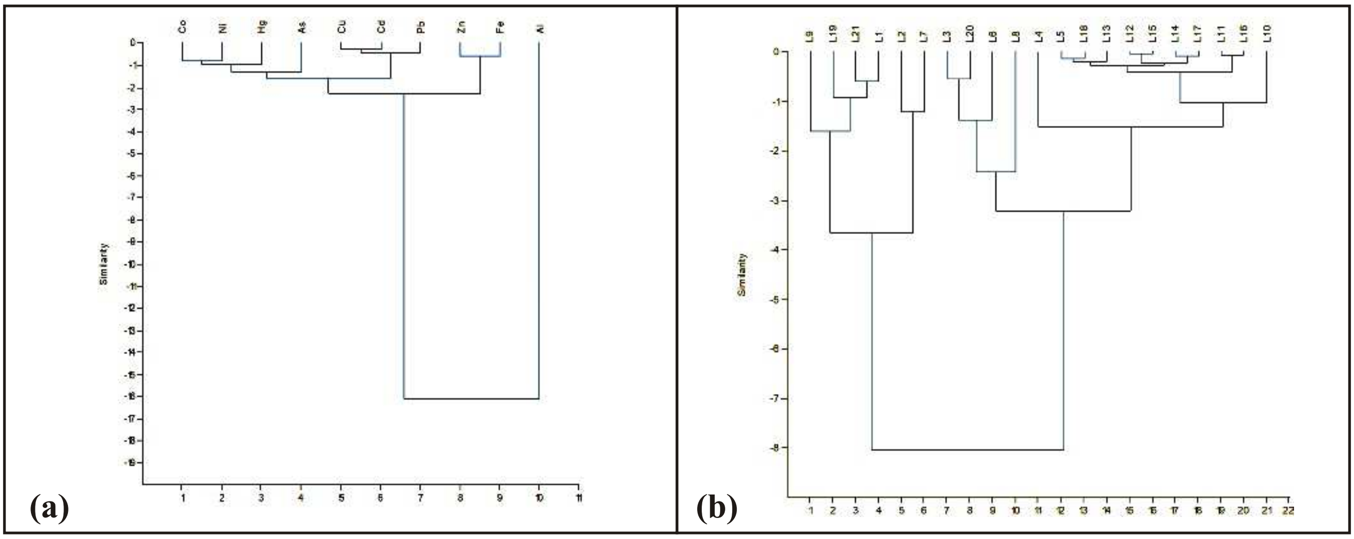

Fig. 4: (a) The dendrogram hierarchical cluster of inter-relationship of heavy metals in sediments. **(b)** The dendrogram showing hierarchical cluster of sediment-samples based on their heavy metal components.

lagoon. The present research considered exposure through dermal contact and ingestion pathways, as there are adequate standard factors/parameters developed for computation of risk index for most of the toxic metals in sediments (Iqbal *et al.*, 2013; Nour *et al.*, 2022). In order to understand the deleterious impacts inherent in these sediments enriched in toxic heavy metals on human health, evaluation of non-carcinogenic and carcinogenic risk was done. This human health risk assessment was conducted for 8 widely known carcinogenic heavy metals (Co, Cu, Pb, Zn, Ni, Cd, As and Hg) in sediments due to their comparative potential toxicity, and availability of literature on detailed dose-response relations (USEPA, 2016).

Evaluation of Non-Carcinogenic risk

The computed exposure doses for heavy metals in sediments of Lekki Lagoon, for direct ingestion (Exp_{ing}) and dermal absorption (Exp_{derm}) pathways are presented in Table 11. The values of the exposure doses were used to calculate non carcinogenic hazard quotients (*HQ*) and comprehensive non-carcinogenic risk (*HI*), and the resulting values presented in Table 12. The *HQ* represents the monomial or single metal impact for *HI*. Considering the mean hazard quotients for exposure by ingestion (Exp_{ing}), the decreasing order of contribution by metals to adults and children health risks are HQ_{ing}: Co > As > Pb > Ni > Zn > Cu > Hg > Fe (Table 12). Contrarily, the decreasing order of health risk posed by these toxic metals on adults and children through dermal absorption (mean HQ_{derm}) As > Pb > Cd > Ni > Hg > Co > Zn > Cu > Fe. The non-carcinogenic quotients of heavy metals in sediments from all the stations indicated no health risk (HQ< 1.0) except where exposure through ingestion of Co at its maximum value (1.4) implied low health risk to children (Table 12). The comprehensive non-carcinogenic hazard risk on child at the maximum dose of exposure through ingestion for all metals in sediments (HI = 1.8) has unveiled medium to low health risk (Yuan *et al.*, 2020). It is appropriate to consider all metals and not a single metal since human population will be exposed to their collective contents in sediments (HI), hence, becomes more practical to identify the accurate impacts (Wahab, 2020). Therefore, the all-inclusive results of HI were within the safe level (HI< 1), except Co and As for non-carcinogenic health risks to children through ingestion (HI_{max} = 1.8) and dermal exposures (HI_{max} = 1.62) respectively. The children experienced higher non-cancer effects than adults as they were involved in hand-to-mouth activities that may incur chronic diseases such as nausea, skin toxicity and cardiovascular toxicity (USEPA, 2011; Magni *et al.*, 2021). However, the HI_{mean} in all, suggested that there was no unusual non-carcinogenic risk upshot through ingestion and dermal routes for adults and children due to these heavy metals in the sediments of the investigated lagoon.

Evaluation of Carcinogenic risk

The carcinogenic risks were only calculated for toxic metals whose slope factors were available in literature for ingestion and dermal exposure routes. While slope factor for As, Cd, Pb and Ni were at hand to evaluate cancer risks through ingestion route, only As was available for the determination of hazard risks through dermal exposure. The calculated carcinogenic and lifetime cancer risk for adults and children, through ingestion and dermal exposures are displayed in Table 13. The values of ΣCR_{ing} obtained for adults revealed low cancer risk (Class II) being above 1.0 x 10^{-6} and below CR ≤ 1.0 x 10^{-4} where mean, minimum and maximum concentrations of heavy metals in sediments were separately considered. Meanwhile, a higher cancer risk of Class III (1.0 x 10^{-4}< CR ≤ 1.0 x 10^{-3}) was inferred for children i.e., moderate carcinogenic effects may be imposed at the mean and maximum metal concentrations. The CR_{ing} arising from Pb contamination in sediments posed no health risk (Class I) to the adults and children's population except at maximum concentration where it showed low cancer effects on children. Nickel and Cd in sediment samples produced low cancer effects (Class II) through the ingestion route on adult residents. Sediments containing the mean and maximum concentrations of Ni and maximum concentration of As produced moderate cancerous effects on children (Tables 13). Based on the mean concentration of As, there is no threat of cancer effect for all categories of the population through dermal contact (CR_{derm}). Nevertheless, sediment sample with the highest concentration of As, unveiled moderate cancer threat (Class III) to children through dermal contact. Conspicuously, through accidental ingestion, the children were in the higher carcinogenic risk group than the adults, specifically from the average concentrations of Ni and As in sediments.

Table 11: The Exposure dosage for direct ingestion and dermal absorption of toxic metals in sediments for the study area (adult and child)

HMs	Exp_{ing}						Exp_{derm}					
	Adult			*Child*			*Adult*			*Child*		
	Mean	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*
Fe	5.4E-06	5.9E-07	1.3E-05	5.0E-05	5.5E-06	1.2E-04	2.2E-08	2.3E-09	5.1E-08	1.4E-07	9.2E-05	3.4E-04
Al	4.9E-06	9.7E-07	1.5E-05	4.5E-05	9.1E-06	1.4E-04	1.9E-08	3.9E-09	6.0E-08	1.3E-07	1.5E-04	3.9E-04
Co	2.0E-05	4.7E-06	4.6E-05	1.9E-04	4.4E-05	4.3E-04	8.1E-08	1.9E-08	1.9E-07	5.3E-07	7.4E-04	1.2E-03
Cu	9.7E-06	7.1E-07	3.8E-05	9.0E-05	6.7E-06	3.5E-04	3.9E-08	2.9E-09	1.5E-07	2.5E-07	1.1E-04	9.9E-04
Pb	1.0E-05	1.7E-06	2.6E-05	9.6E-05	1.6E-05	2.4E-04	4.1E-08	6.8E-09	1.0E-07	2.7E-07	2.7E-04	6.8E-04
Zn	8.6E-05	1.1E-05	2.0E-04	8.0E-04	1.1E-04	1.8E-03	3.4E-07	4.6E-08	7.9E-07	2.2E-06	1.8E-03	5.2E-03
Ni	1.6E-05	1.4E-06	6.0E-05	1.5E-04	1.3E-05	5.6E-04	6.2E-08	5.7E-09	2.4E-07	4.1E-07	2.2E-04	1.6E-03
Cd	1.2E-07	7.1E-08	2.9E-07	1.1E-06	6.7E-07	2.7E-06	4.7E-10	2.9E-10	1.1E-09	3.1E-09	1.1E-05	7.5E-06
As	2.9E-06	3.6E-07	8.3E-06	2.7E-05	3.3E-06	7.7E-05	3.4E-07	4.3E-08	9.9E-07	2.3E-06	5.6E-05	2.2E-04
Hg	5.7E-08	7.1E-09	1.7E-07	5.3E-07	6.7E-08	1.6E-06	2.3E-10	2.9E-11	6.8E-10	1.5E-09	1.1E-06	4.5E-06

Conclusions

Lekki Lagoon is characterized by freshwater with trace amount of salt, shallow water column, and a slightly acidic to almost neutral water. Metals such as Fe, Al, Zn, Co, Ni, As and Hg in the sediments showed average concentrations above their reference values. Sediments from 23.81 % of the stations contained significant

Table 12: The Hazard Quotients (HQs) and Non-Carcinogenic risk index (HI) of heavy metals in sediments for direct ingestion and dermal contact (adult and child)

HMs	HQ_{ing}						HQ_{derm}					
	Adult			*Child*			*Adult*			*Child*		
	Mean	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*
Fe	7.7E-06	8.4E-07	1.8E-05	7.2E-05	7.8E-06	1.7E-04	3.9E-05	4.2E-06	9.2E-05	3.6E-04	3.9E-05	8.6E-04
Co	6.8E-02	1.6E-02	1.5E-01	6.3E-01	1.5E-01	1.4E-00	1.3E03	2.9E-04	2.9E-03	1.2E-02	2.8E-03	2.8-02
Cu	2.4E-04	1.8E-05	9.5E-04	2.3E-3	1.7E-04	8.8E-03	8.1E-04	6.0E-05	3.2E-03	7.5E-03	5.6E-04	2.9E-02
Pb	2.9E-03	4.9E-04	7.4E-03	2.7E-02	4.6E-03	6.9E-02	2.0E-02	3.3E-03	5.0E-02	1.8E-01	3.1E-02	4.6E-01
Zn	2.9E-04	3.8E-05	6.6E-04	2.7E-03	3.6E-04	6.1E-03	1.1E-03	1.5E-04	2.6E-03	1.1E-02	1.4E-03	2.5E-02
Ni	7.8E-04	7.1E-05	3.0E-03	7.3E-03	6.7E-04	2.8E-02	2.9E-03	2.7E-04	1.1E-02	2.7E-02	2.5E-03	1.0E-01
Cd	1.2E-04	7.1E-05	2.9E-04	1.1E-03	6.7E-04	2.7E-03	1.2E-02	7.1E-03	2.9E-02	1.1E-01	6.7E-02	2.67E-01
As	9.6E-03	1.2E-03	2.8E-02	9.0E-02	1.1E-02	2.6E-01	2.3E-02	2.9E-03	6.7E-02	2.2E-01	2.7E-02	6.3E-01
Hg	1.9E-04	2.4E-05	5.7E-04	1.8E-03	2.2E-04	5.3E-03	2.7E-03	3.4E-04	8.2E-03	2.5E-02	3.2E-03	7.6E-02
HI	0.08	0.02	0.19	0.77	0.16	1.82	0.06	0.01	0.17	0.59	0.13	1.62

Table 13: The Cancer Risk (CRingandCRderm) computed for carcinogenic heavy metals based on available reference values and total Lifetime Cancer Risk (LCR) for Adult and Child.

HMs	CR_{ing}						CR_{derm}					
	Adult			*Child*			*Adult*			*Child*		
	Mean	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*	*Mean*	*Min*	*Max*
Fe	-	-	-	-	-	-	-	-	-	-	-	-
Al	-	-	-	-	-	-	-	-	-	-	-	-
Co	-	-	-	-	-	-	-	-	-	-	-	-
Cu	-	-	-	-	-	-	-	-	-	-	-	-
Pb	8.7E-08	1.5E-08	2.2E-07	8.1E-07	1.4E-07	2.1E-06	-	-	-	-	-	-
Zn	-	-	-	-	-	-	-	-	-	-	-	-
Ni	1.4E-05	1.3E-06	5.5E-05	1.3E-04	1.2E-05	5.1E-04	-	-	-	-	-	-
Cd	1.8E-06	1.1E-06	4.3E-06	1.7E-05	1.0E-05	4.0E-05	-	-	-	-	-	-
As	4.3E-06	5.4E-07	1.2E-05	4.0E-05	5.0E-06	1.2E-04	1.05E-05	1.31E-06	3.03E-05	9.81E-05	1.22E-05	2.83E-04
Hg	-	-	-	-	-	-	-	-	-	-	-	-
ΣCR	2.03×10^{-5}	2.92×10^{-6}	7.15×10^{-5}	1.89×10^{-4}	2.73×10^{-5}	6.68×10^{-4}	1.05×10^{-5}	1.31×10^{-6}	3.03×10^{-5}	9.81×10^{-5}	1.22×10^{-5}	2.83×10^{-4}

quantity of Zn above the ISQGs TEL and TEC but below the PEL and PEC values, hence, may not produce adverse effects on the ecosystem. Arising from the concentrations of heavy metals of high toxic response coefficients such as Cu, Cd, Hg and As below TEL and TEC in sediments, there was no probability of negative biological effects. Also, the mean probable effect quotients (*mPECQs*) obtained from 61.9 % and 28.1 % of all stations, inferred only 10 % and 17 % possibility of sediments producing toxic effects respectively. In contrast, potential contamination index (C_p) discerned severe to very severe contamination of Co, Zn, Ni, As and Hg, and also, Pb, Cd and Cu indicated moderate contamination in sediments. Contamination of As was the most widespread, followed by Zn contamination which covered approximately half of the study area, exhibiting moderate to high and moderate to very high contamination respectively. The *TRI* demonstrated that there was no toxic risk in the lagoon, I_{geo} equally indicated no contamination of Cd, Cu and Pb, but moderate contamination of Hg, Ni, As, Zn and Co was revealed in few portions of the lagoon. The enrichment of Cu, Pb, Cd, Ni, Zn, As and Hg in most samples was suggested to have been driven by geogenic activities. This assertion was complemented by strong positive Pearson's correlations between Al or Fe and these metals. The fact that, As, showed strong correlation with Fe but moderate to weak positive correlations with Al, Co, Pb, Ni, Cd and Cu, and moderate to severe enrichment (*EF*> 2) of Zn, Hg and As were indicated in few places, attested to anthropogenic origin.

The integrated potential ecological risk index (RI) presented low ecological risk for majority of the samples, while few samples, mostly from southeast portion of the lagoon unveiled moderate risk to the ecological community. Principal component and cluster analyses discerned both anthropogenic and geogenic pathways of As, Hg, Zn, Ni and Co into the lagoon.

The non carcinogenic risks (*HI*) associated with toxic metals in sediments were within the safe level, except sediments with the highest concentrations of Co and As that posed threat to the children's population through direct ingestion and dermal contacts. Specifically, from the average concentrations of Ni and As in the sediments, children were more prone to cancer risks than adults through accidental ingestion.

Recommendations

Due to the current build-up of heavy metal pollutants in this lagoon, and the unassailable increase in industrial growth in this area, the need for adequate policy formulation is pertinent. Therefore, continuous monitoring of this lagoon through diligent studies is required. In order to provide more accurate assessments of the risks associated with heavy metal contamination to the ecosystem, chemical fractionation of the sediments should be included in further studies.

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