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Elemental pollution status of different components of Ologe Lagoon, Lagos, Nigeria

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ABSTRACT

This study evaluated the concentrations and distributions of nutrient and non-nutrient elements in water, sediment, mud, and vegetation of Ologe Lagoon, Lagos, Nigeria. Nutrient elements including Na, Ca, K, and Mg were found in high concentration values in the different components of the freshwater ecosystem. While the water had the least concentration of the elements, *Trapa natans* had the highest. Aluminium showed similar distribution patterns in the different components, except for *T. natans*. All the samples correlated significantly with water ($p < 0.05$). Both the sediment and mud showed low potential ecological risk indexes of 5.3 and 5.92, respectively. Copper had the highest ecological risk with respect to single regulator indexes in the mud and sediment, notwithstanding its low concentration in the two components. Pollution indices suggested the low severity of non-nutrient elemental contamination of water, sediment, mud, and vegetation of Ologe Lagoon, and therefore, it is safe for human consumption, but not for agricultural irrigation. *Pistia stratiotes* and *T. natans* showed potentiality for use as photo-stabilisers and phytoremediators for some of the elements. The presence of radionuclides and rare earth elements in the components of Ologe Lagoon are instructive for specific policy initiatives to mitigate their effects on the population.

Key words: freshwater salinisation, multivariate analysis, nutrient and non-nutrient metals, Ologe Lagoon, radionuclides, rare earth elements

HIGHLIGHTS

- Radionuclides were reported in the components of Ologe Lagoon, a freshwater ecosystem.
- High nutrient-element concentration associated with increased salinisation were found in the different components of Ologe Lagoon.
- There is a low contamination of the components of the Lagoon with respect to non-nutrient elements.
- Water from Ologe is unsuitable for agricultural irrigation owing to high concentration of nutrient metal elements.
- Pistia stratiotes and T. natans showed potential for the remediation of Zn, Cr, Cu, Th, and U.

1. INTRODUCTION

A sanitation policy for the protection of water resources is critical to attaining Sustainable Development Goals (SDGs) in urban areas characterised by unplanned habitat growth and an uncoordinated water supply system (Mugagga & Nabaasa 2016). Rapid population growth and industrial discharges threaten aquatic life, the economy, and the clean water supply in riverine communities. The discharge of salty wastewater from the processing of food and allied products degrades water quality and thus renders the water unsuitable for domestic and industrial applications without prior treatments via desalination (Panagopoulos 2021, 2022; Panagopoulos & Giannika 2022). Particularly that there is connectivity in the underground and surface water systems, thus making it possible for high volumes of contaminated water to affect the water supply (Kabuba & Maliehe 2021).

The lethal effects of nutrient and non-nutrient mineral elements constituting aquatic micro-pollutants on aquatic biota, terrestrial organisms, and humans have been extensively investigated. Their toxicity to animals and man is still relevant and will continue to increase owing to natural and anthropogenic processes that generate and release wastes containing different mineral elements into the environment (Bassey *et al.* 2019). Investigation of the elements in aquatic systems is very essential, as a slight alteration in their concentration above the threshold levels could lead to serious environmental hazards, and health challenges for consumers, and may threaten food security, particularly with recent reports of increased salinisation of freshwater from metal chlorides and salts (Ojekunle *et al.* 2016). Their presence in water is of high environmental significance because they are not removed by self-purification (Benhaddya *et al.* 2019). The elements also alter the biogeochemical cycles within freshwater habitats that affect the contiguous human population (Rizk *et al.* 2022). Non-nutrient mineral elements, in particular, exert significant negative impacts on the environment because of their abundance, toxicity, and persistence, which lead to their bioaccumulation in aquatic organisms and ubiquity in marine environments (Liu *et al.* 2016; Ali *et al.* 2019). Hence, Huang *et al.* (2020) listed them as priority pollutants. Their presence in the sediment–water–plant ecosystem is significant because of their possible influence on the food chain and their toxicity to human survival and well-being. Vari *et al.* (2022) suggested that assessing levels of non-nutrient elements in a body of water is a vital indicator of the river's health, its biota, and the quality of fish reared in it. Nutrient elements, on the other hand, are responsible for the widespread salinisation of freshwater ecosystems driven by human activities, sea-level rise, and climate change. This is receiving global attention because of its threat to biodiversity, functioning, and services produced by freshwater. A saltier freshwater changes the structure, functioning, communities, and benefits obtainable from aquatic ecosystems by altering their physical environments (Cunillera-Montcusí *et al.* 2022).

Previous studies on Ologe Lagoon focused mainly on trace non-nutrient elements; meanwhile, nutrient elements of water bodies are currently receiving attention because of increased salinisation and its attendant consequences. This study assessed the nutrient and non-nutrient element pollution status of the different components of Ologe Lagoon. The results would have practical application in the formulation of the sanitation policy guiding the health of Ologe Lagoon and would contribute to achieving the SDGs and to the discussion on salinisation as an emerging global problem impacting safe drinking water.

2. MATERIALS AND METHODS

2.1. Study site and sample collection

Ologe Lagoon, as shown in Figure 1, is located between latitudes 6°26N and 6°30N and longitudes 3°01E and 3°07E. It has a surface area of 64.5 km^2 and 5 m deep with jetties at Ibiye, Otto, Era, Agbara, Obele, and Gbenko. The lagoon is highly productive with a predicted fishing yield of 73.8 kg ha^{-1} yr^{-1} (Akin-Oriola & Awokoya 1998). The sampling points in this study are detailed in Figure 2 as L1–L4 (Lat. 6°26′56.71″N, Long. 3° 2′43.18″E; Lat. 6°27′51.18″N, Long. 3° 4′20.75″E; Lat. 6°28′7.80″N, Long. 3° 5′25.10″E and Lat. 6°28′54.79″N, Long. 3° 6′21.05″E). It is a hyposaline, freshwater system connected to the Atlantic Ocean by a series of channels leading to the Lagos waterfront and Badagry Creek. Its main sources of water are the Owo,

Figure 1 | Google map showing the location of Ologe Lagoon.

Figure 2 | Google map showing the location of Ologe Lagoon and the sampling points.

Toluwu, Ore, Ilo, Oponu, and Imede rivers in neighbouring Ogun State, Nigeria. The lagoon experiences one dry season and one wet season annually, which is typical of the climate of southern Nigeria. Effluents from the Agbara industrial area are emptied into the lagoon through the Agbara stream. The lagoon serves several socio-economic needs in its proximate towns and villages in the Badagry area (Bassey *et al.* 2019).

2.2. Sample preparation

Between January and June of 2021, 24 water samples were collected at different points and depths (0–5 m) from the lagoon benthic zone with an open water grab sampler equipped with a simple pull-ring. Samples, upon collection, were transferred into polyethylene containers with screw caps. The containers had been previously soaked in 1:1 nitric acid for 24 h before the final rinse with Milli-Q water. Samples were kept in chilled boxes and transported to the laboratory. One litre of the water sample, upon arrival in the laboratory, was transferred into a beaker containing 10 mL of concentrated HNO_3. The water sample was filtered and boiled slowly on a hot plate to less than 150 mL. The beakers were allowed to cool, and another 10 mL of concentrated HNO_3 was added. The heating continued with the addition of concentrated HNO_3 as necessary until digestion was complete. The samples were evaporated again to dryness and the beakers were cooled, followed by the addition of 10 mL of HCl solution (1:1 v/v), and then filtered using a pre-pleated Whatman filter (Merck, Grade 595: 4–7 μm). The filtrates were transferred to a volumetric flask and diluted to the mark with Milli-Q water to a final volume of 50 mL (U.S. EPA 1996). Milli-Q water was used for the dilution of standards and quality control (QC) solutions. These were also stabilised in high-purity, 2% (v/v) concentrated nitric acid (HNO_3). Calibration and QC solutions were prepared from the Accustandard QCSTD-27 multi-element solution.

Sediment and mud samples (20 cm depth) were collected at different points from the lagoon benthic zone in a pre-cleaned Ekman dredge (6″ × 6″ × 6″) (Wildco Instruments, Sargeant, USA) and instantly placed in iced flexible bags. Vegetation samples, including water lettuce (*Pistia stratiotes*) and water chestnut (*Trapa natans*), were uprooted from the lagoon coastline. A total of 24 samples of sediments, mud, and vegetation were collected from

January to June 2021, covering the onset and peak of rains in the region. All samples were air-dried in the laboratory drying cabinet at ambient temperature. Meanwhile, air-drying of vegetation samples was done after rinsing free of mud and sediment particles. The samples were digested with 5 mL mixtures of nitric and perchloric acids (HNO_3:$HClO_4$, 3:1 v/v) and heated separately on a digestion block at 180 °C for 3 h.

2.3. Sample analysis on inductively coupled plasma optical emission spectroscopy (ICP-OES)

Sample analysis was performed on an Agilent 720-ES ICP-OES instrument with a hermetically sealed megapixel CCD detector, next-generation VistaChip II detection technology, a robust 40 MHz plasma system, and Agilent Expert II software. Upon optimisation of the instrument for analysis, plasma and auxiliary gas flows were 1.5 L/min, each. The spray chamber was glass cyclonic with a standard axial torch, and a sea spray nebuliser operating at 220 kPa was employed. As a measure of quality control, the machine was recalibrated after every 15 determinations to check for instrumental drift.

2.4. Calibration equations and regression coefficient values for mineral elements

The regression coefficient (R) values were $1 \leq R \geq 0.999$ in respect of all the mineral elements except for Be, Ca, Cd, Th, and Zn, which were between 0.978 and 0.998. The excellent R values suggest the suitability of the instrument for the mineral elements' determination.

2.5. Determination of water pollution indices

The sodium absorption ratio (SAR), percent sodium (%Na), and Kelly's index (KI) of water samples drawn from Ologe Lagoon were estimated to determine their agricultural suitability as described by Sheng *et al.* (2022) using the following expressions:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}} \qquad (Exp.1)$$

$$\%\mathrm{Na} = \frac{\mathrm{Na}^{+} + \mathrm{K}^{+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{K}^{+} + \mathrm{Na}^{+}} \times 100 \qquad (Exp.2)$$

$$\mathrm{KI} = \frac{\mathrm{Na}^{+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}} \qquad (Exp.3)$$

Mineral elements commonly encountered in polluted water for which background values are available were used to compute the single-factor pollution index, the water quality index (WQI), and the potential ecological risk index (PERI). The indexes are calculated as follows:

$$\text{Single factor pollution index } \left(P_i = \frac{C_i}{Q_i}\right), \qquad (Exp.4)$$

where C_i is the measured elemental concentration; Q_i the reference value of the element.

$$\text{Water quality index (WQI)} \left(\frac{1}{n}\sum_{i}^{n} P_i\right) \qquad (Exp.5)$$

where P_i is the single elemental pollution index; n means the types of elements determined in the water samples (Zhuang & Lu 2020).

The Nemerow comprehensive pollution index was calculated as follows (Zhuang & Lu 2020):

$$P_n = \sqrt{\frac{\max{(P_i)}^2 + \mathrm{mean}(P_i)^2}{2}} \qquad (Exp.6)$$

This reflects current elemental pollution in water and the different contributions of various elements.

2.6. Determination of potential ecological index for elements in sediment and mud

The PERI was estimated by the following expression:

$$\text{PERI} = \sum_{f}^{i} E = \sum_{f}^{i} T_f^i C_f^i = \sum_{f}^{i} T_f^i \frac{C^i_{\text{surface}}}{C^i_{\text{reference}}} \qquad (Exp.7)$$

where C^i_{surface} is the concentration (mg kg^{-1}) of non-nutrient metals in sediment and mud samples; $C^i_{\text{reference}}$ is the reference value for each of the metals; C_f^i is the pollution index of the non-nutrient metal; T_f^i is the response coefficient for the toxicity of the single non-nutrient metal (As = 10, Co = Cu = Ni = Pb = 5, Mn = Zn = 1, Cr = V = 2); and E_f^i is the potential ecological risk factor of the non-nutrient metal i (Weber *et al.* 2013; Zhuang & Lu 2020).

2.7. Determination of enrichment factor for elements in the sediment and mud

The non-dimensional enrichment factor (EF) was calculated to estimate the non-nutrient metal contamination status and peculiarity of the potential sources (anthropogenic vs. natural). The EF was calculated using the expression:

$$\text{EF} = \frac{(\text{Me/Al})_{\text{sample}}}{(\text{Me/Al})_{\text{baseline}}} \qquad (Exp.8)$$

where $(\text{Me/Al})_{\text{sample}}$ is the metal-to-Al ratio in the sample measured, and $(\text{Me/Al})_{\text{baseline}}$ is the natural background value of the metal-to-Al ratio (Liu *et al.* 2016).

2.8. Determination of the geological accumulation index

The geological accumulation index (I_{geo}) was calculated using the expression:

$$I_{\text{geo}} = \log_2 \frac{C_i}{(K * B_i)} \qquad (Exp.9)$$

where C_i is the heavy metal measured concentration, B_i is the geochemical background value of the heavy metal, and K is the diagenetic coefficient which is taken to be 1.5 (Liu *et al.* 2016).

2.9. Determination of bioconcentration factor

Bioconcentration factor (BCF) was calculated using the following expression:

$$\text{BCF} = \frac{C_B}{C_W} = \frac{\text{Metals (part of aquatic plant)}}{\text{Metals (water)}} \qquad (Exp.10)$$

where C_B represents the average concentration of the element in the biota, i.e., a certain tissue (μg/g of moist mass), and C_W represents the concentration of the element in water (μg/mL) (Wang 2016).

2.10. Biota sediment accumulation factor

Biota sediment accumulation factor (BSAF) was calculated using the following expression:

$$\text{BSAF} = \frac{C_B}{C_S} \qquad (Exp.11)$$

where C_B represents the average concentration of the element in the biota, i.e., a certain tissue (μg/g of moist mass), and C_S refers to the concentration of the element in the sediment (μg/g) (Ziyaadini *et al.* 2017).

2.11. Statistical analysis

Nutrient and non-nutrient data were subjected to ANOVA and the significantly different treatment means were separated using Duncan multiple range test (DMRT). Also, experimental data were summarised using descriptive statistics including mean, minimum and maximum values, and standard error of means. The Pearson moment correlation was used to test the degree of relationship among the samples, while multivariate analysis was performed using R software version 3.6 to understand the relationship among the metals.

3. RESULTS AND DISCUSSION

As observed in Table 1, in all the samples (water, sediments, mud, and vegetation), the nutrient mineral elements except Cu and Se were remarkably higher than the non-nutrient mineral elements and the reverse was the case for Al. The metal is present in the samples in similar concentrations as nutrient elements. Water samples consistently contained the least nutrient mineral elements, while the vegetation samples contained the highest. However, *T. natans* contained significantly higher contents than *P. stratiotes.* Mud samples contained more nutrient mineral elements than sediments. The macronutrient mineral elements (i.e. Na, Mg, K, and Ca) were remarkably higher in all the samples (water, sediments, mud, and vegetation) than the micromineral elements (i.e. Cu, Fe, Mn, Se, and Zn).

The high concentrations of nutrient elements observed in this study are associated with anthropogenic salinisation. This could be related to the increased pumping of saline groundwater by adjacent industries due to the lack of a provincial water system, increased industrial activities, and unrestricted deposition of industrial wastes into the lagoon and its adjoining rivers (Fajemila *et al.* 2020). High concentrations of nutrient elements, particularly in their chloride forms, can free up other freshwater pollutants, contribute to higher levels of corrosive chlorides in the water supply, and have adverse effects on water quality and the ecosystem, resulting in ecological shifts and degradation. In particular, Ca^{2+} and Mg^{2+} can shift the balance of positive and negative charges between the contiguous soil and freshwater, forcing metals and substances that emit radiation out of the soil and into the water. This probably accounts for the levels of U in the components of the Ologe Lagoon. The metals may become magnified down the food chain, leading to food composition changes as more salt-tolerant creatures take over, with greater implications for human consumers (Shechet 2021). Beyond concentration values, the ratios of these metals to one another (Na/K and Mg/Ca) have been shown to affect aquatic life. Some of these elements, particularly K, have been found to modulate the toxicity of other toxic elements, including Tl, because of their similar biogeochemical characteristics and behaviours at the cellular level (Tatsi *et al.* 2015). Different previous studies have substantiated increased salinisation of freshwater bodies resulting from metal chlorides and salts, and such reports are, however, non-existent on the present study site.

The high concentration values of Al and Fe in the samples correspond to a classical weathering product in tropical areas where the sediments are mainly composed of Al and Fe (Weber *et al.* 2013). Except for a few elements, sediment, mud, and the two vegetation types showed higher concentrations of the elements. It follows that sediment and mud adsorb pollutants from water, thereby lowering their concentration in the water. In the same vein, the metals are translocated into the plants, thus showing similar results. The presence of Al indicates the potential hazard that the consumption of Ologe Lagoon can cause, as Al is known to disrupt normal metabolism. Depending on water quality parameters, the tolerable concentration of Al for aquatic life ranges between 87 and 1,400 $\mu g\ L^{-1}$ (U.S. EPA 2022a, 2022b). Several species of aquatic biota have shown sensitivity to Al toxicity that resulted in mortality in extreme cases (U.S. EPA 2022a, 2022b). Iron affects aquatic organisms by disturbing normal metabolism and osmoregulation and by changing the structure and quality of benthic habitats and food resources. Iron contamination may impact the biodiversity and abundance of periphyton, benthic invertebrates, and fishes (Heikkinen *et al.* 2022). In moderate doses, it is considered an essential nutrient for human health (Demiral *et al.* 2021). Recent reports have indicated increased Fe concentrations in freshwaters, thus raising concerns because of its vital role in biogeochemical processes (Bjorneras *et al.* 2017). Iron contributes to large-scale browning of freshwaters, resulting in staining, offensive appearances and tastes, and aesthetic and operational concerns. Iron in this study is more than the previous average reported for the same lagoon. Except for the nutrient and radionuclide elements not previously reported, the results in this study are consistent with the previous works (Adeboyejo *et al.* 2009; Bassey *et al.* 2019).

Uranium was available in all samples. The presence of U in the different components of Ologe Lagoon presents a disturbing scenario, with the average concentration increasing from the water to the sediment, mud, and the two types of vegetation. Uranium has significant chemical and radiological toxicity, with the potential for bioaccumulation and dispersion by aquatic biota (Bergmann & Graça 2020). Other radionuclides found in the various components of Ologe include Th and Tl, and the concentration of the elements increased from water to the other components, suggesting a bioaccumulation tendency. The presence of Th and Tl indicates the use of phosphate fertiliser, rare earth mining, and run-off from fertiliser-producing or milling plants at the Agbara Industrial Estate. Similar studies reported these concentrations from mining rivers in Portugal; 0.003–700 μg/L of Th had been

Table 1 | Concentration of mineral elements in water, sediment, mud, and vegetation samples from Ologe lagoon ($n = 24$)

Element type	Water (mg/L)			Sediments (mg kg^{-1}, dry weight)			Mud (mg kg^{-1}, dry weight)			Vegetation (mgkg^{-1}, dry weight)						
										P. stratiotes			*T. natans*			
	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	± SEM**
Nutrient																
Ca	376.65 ± 259.46d*	68.35	596.04	2,471.95 ± 2,621.09b	627.83	6,870.23	1,464.91 ± 545.02c	841.14	2,092.52	2,500.78 ± 1,535.19b	728.38	3,414.39	3,382.20 ± 380.69a	3,113.01	3,651.39	± 514.678
K	248.34 ± 172.93d	95.43	465.63	1,665.96 ± 3,647.20c	10.81	8,190.13	388.21 ± 178.11d	155.73	589.82	3,879.98 ± 3,495.18b	31.97	6,857.99	8,440.99 ± 5,629.17a	4,460.57	12,421.41	± 1,525.174
Mg	258.32 ± 186.40b	51.87	439.65	478.16 ± 622.33b	174.01	1,590.39	1,179.97 ± 480.68a	572.31	1,726.01	1,059.03 ± 736.73a	208.75	1,507.25	1,263.19 ± 225.93a	1,103.43	1,422.94	± 201.448
Na	2,059.23 ± 1,466.73b	547.41	3,885.36	938.81 ± 1,190.06cd	314.40	3,061.84	665.08 ± 132.10d	474.26	767.90	2,739.09 ± 2,122.89ab	387.54	4,514.30	3,249.46 ± 959.75a	2,570.82	3,928.11	± 499.739
Cu	1.17 ± 0.65b	0.44	1.73	8.06 ± 2.61a	5.43	11.38	9.78 ± 2.94a	7.24	13.20	8.60 ± 2.59a	7.04	11.59	7.34 ± 2.29a	5.72	8.95	± 1.509
Fe	684.10 ± 636.00c	55.92	1,429.52	566.26 ± 166.62c	328.93	777.10	6,624.99 ± 2,749.66a	2,611.91	8,802.53	3,235.77 ± 2,599.05b	328.77	5,335.05	2,457.45 ± 1,191.60b	1,614.86	3,300.03	± 1,103.793
Mn	41.79 ± 48.04b	9.29	112.92	43.91 ± 78.67b	0.26	184.13	55.34 ± 33.85b	13.63	96.23	88.96 ± 75.31b	2.68	141.53	101.39 ± 33.13a	77.96	124.82	± 12.180
Se	8.3E-3	0.00	0.02	0.08	0.00	2.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	± 0.016
Zn	1.07 ± 0.79d	0.00	1.91	27.45 ± 9.27c	18.21	42.65	38.75 ± 9.67b	27.47	51.11	47.12 ± 9.17b	37.86	56.21	97.80 ± 74.59a	45.06	150.55	± 15.869
Non-nutrient																
Ag	0.00b	0.00	0.00	0.20 ± 0/00b	0.00	4.91	1,304.23 ± 655.58a	0.00	2,611.91	0.00b	0.00	0.00	0.00b	0.00	0.00	± 260.836
Al	695.12 ± 514.52d	64.24	1,152.65	1,193.14 ± 267.10c	982.77	1,628.37	8,894.02 ± 2,712.53a	5,024.76	11,198.01	1,561.03 ± 1,264.87b	251.47	2,775.90	1,618.64 ± 753.82b	1,085.60	2,151.67	± 1,534.275
As	0.01	0.00	0.13	0.03	0.00	0.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	± 0.006
Ba	3.71 ± 3.57c	0.99	8.59	6.31 ± 13.42c	0.00	30.31	14.21 ± 7.86b	3.47	22.34	16.46 ± 14.26b	0.00	25.22	24.06 ± 4.05a	21.20	26.93	± 3.652
Cr	2.13 ± 2.06b	0.51	4.85	0.04c	0.00	0.89	16.48 ± 9.52a	3.40	24.03	4.56 ± 3.96b	0.00	7.05	4.34 ± 6.13b	0.00	8.67	± 2.863
Ni	0.18 ± 0.19	0.00	0.44	0.00	0.00	0.00	0.17 ± 0.18	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.00	± 0.0429
Pb	0.12 ± 0.08	0.00	0.18	0.00	0.00	0.00	0.03 ± 0.07	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	± 0.023
Th	1.91 ± 1.76c	0.13	3.92	10.84 ± 9.87b	4.25	27.68	22.44 ± 8.78a	10.61	30.77	11.92 ± 3.84b	7.50	14.42	9.44 ± 3.85b	6.72	12.16	± 3.289
Tl	0.02 ± 0.03**	0.00	0.05	0.31 ± 0.36	0.00	0.84	0.10 ± 0.18	0.00	0.37	0.09 ± 0.15	0.00	0.26	0.06 ± 0.09	0.00	0.12	± 0.052
U	0.43 ± 0.45c	0.03	0.96	2.88 ± 2.79a	0.69	6.61	3.69 ± 3.48a	0.03	6.70	1.36 ± 1.12b	0.43	2.60	2.41 ± 1.24b	1.54	3.29	± 0.572
V	0.72 ± 0.78b	0.00	1.58	0.00c	0.00	0.00	3.85 ± 3.17a	0.00	7.07	0.00c	0.00	0.00	0.00c	0.00	0.00	± 0.747

*Mean values denoted by different letters in a row significantly at $p < 0.05$.

**SEM, standard error of the means.

measured in lakes close to mines, drainage water of U and Fe mines in southern Brazil, and coastal waters of Lagos, Nigeria (Carvalho *et al.* 2007; Omale *et al.* 2014; Doose *et al.* 2021). The release of Th into the environment is of concern, though the environmental risks associated with Th are still not well understood, particularly in aquatic ecosystems. The element has, however, been reported to decrease the abundance of bacteria and increase diatom, ciliate, and rotifer populations in a freshwater ecosystem, thereby increasing the plankton population for fishes. The concentration of Tl obtained in the water, sediment, mud, and vegetation of Ologe Lagoon is greater than 0.002 mg L^{-1}, 1 mg kg^{-1}, and 0.03–1 mg kg^{-1} allowed for drinking water, soil, and plants, respectively (Cvjetko *et al.* 2010); this may affect the lagoon ecosystem, threaten the fish catch, and disrupt other socio-economic activities around the lagoon. As shown in Table 2, the Tl concentration increased from water through the sediment to the two vegetation types. This observation is consistent with the report of Wallwork-Barber *et al.* (1985) that showed an increase in Tl concentration between water and the other ecosystem components, thus confirming its tendency to bioaccumulate. Thallium is recognised as a priority pollutant in freshwater ecosystems and more acutely toxic to mammals than As, Cu, Hg, Cd, Pb, and Zn but is still not regulated as part of the Water Framework Directive (Tatsi *et al.* 2015). Thallium concentrations as low as 10 μL^{-1} have been demonstrated to be toxic to different freshwater biota, including microalgae, macroalgae, amphipods, fish larvae, and other invertebrates at the bottom of the food web (Tatsi *et al.* 2015). However, K^+ modulates Tl toxicity (Tatsi *et al.* 2015). The concentrations of non-nutrient elements (Pb, Cr, and Ag) in this study are lower than U.S. Environmental Protection Agency's (U.S. EPA) water and sediment quality guidelines for freshwater aquatic life (U.S. EPA 2022a, 2022b).

As indicated in Table 2, Na, Mg, and K correlated very strongly with Zn; Mg, Cr, and Al correlated very strongly with Fe; Cr and Al also correlated very strongly. A strong correlation was observed between Al and Mg, Cr and Mg, and Na and Mg, while Ba correlated moderately with K and Mg, Cr and Ba, Cu and Na also correlated moderately. These correlations suggested common behaviours and that the elements accumulated from similar sources of pollution. The finding in this study is in agreement with previous reports from other water bodies in different countries that a significant correlation between metals indicates redistribution in the sediments by similar physicochemical processes or that they originate from a common source.

The correlation matrix in Table 3 depicts the degree of relationship existing between water, sediment, mud, and vegetation of Ologe Lagoon. Results show very strong to strong relationships between water and the other components ($p < 0.05$) concerning their elemental contents, except for *T. napans*. The poor elemental content (Table 2) and the correlation of *T. napans* with the other components of Ologe Lagoon suggest its suitability as a plant food source for herbivorous vertebrates and invertebrates of the freshwater ecosystem.

Three principal components with Eigen values greater than unity were extracted, with a cumulative contribution of 82.27%, as shown in Table 4. Potassium, Mg, Na, and Zn contributed 40.847% of the variation observed in the water, sediments, mud, and vegetation examined in Ologe Lagoon, while Mg, Al, Cr, and Fe contributed 27% of the variation observed, and Ba contributed 13.688% of the variation observed in the lagoon.

3.1. Pollution indices

3.1.1. Suitability evaluation of the lagoon water for irrigation

The SAR, %Na, and KI of Ologe Lagoon were 81.72, 78.4%, and 3.24, respectively, as shown in Table 5. These values indicate that the lagoon water is unsuitable for irrigation purposes because it leads to the breakdown of soil aggregates. The soil becomes hard and compact when dry, which reduces the infiltration rates of water and air into the soil, and affects its structure. High saline water causes plant roots to undergo a reverse osmotic process, resulting in stunted growth, wilting, and eventual death. Other implications of these indices include waterlogging issues, groundwater contamination, losses in soil fertility, and other associated secondary impacts on the dependent ecosystem that may affect food security (Mohanavelu *et al.* 2021).

3.1.2. WQI and Nemerow index

The WQI of 6.47 for the water of Ologe Lagoon, as indicated in Table 5, is within the 0–25 (excellent) WQI, suggesting the suitability of the water for drinking. The calculated Nemerow comprehensive pollution index (5.87), however, suggested heavy pollution of the sediment (Kowalska *et al.* 2018).

The increased salinity of Ologe Lagoon water as shown by the pollution status (Table 5) may lead to a decrease in leaf water potential, relative water content, and gas exchange parameters and result in increased sodium and chloride uptake (Rawat *et al.* 2018). Plants accumulate sodium in their roots and restrict its translocation to the

Table 2 | Correlation coefficients of relationships between various mineral elements

	Ca	K	Mg	Na	Ag	Al	As	Ba	Cr	Cu	Fe	Mn	Ni	Pb	Se	Th	Tl	U	V	Zn
Ca	1																			
K	0.841	1																		
Mg	0.620	0.601	1																	
Na	0.433	0.798	0.293	1																
Ag	−0.278	−0.417	0.411	−0.635	1															
Al	−0.181	−0.331	0.503	−0.584	0.994	1														
As	0.066	−0.294	−0.609	−0.499	−0.301	−0.332	1													
Ba	0.753	0.848	0.929	0.583	0.085	0.181	−0.586	1												
Cr	−0.164	−0.239	0.593	−0.433	0.968	0.982	−0.502	0.292	1											
Cu	0.628	0.231	0.732	−0.237	0.463	0.543	0.003	0.542	0.516	1										
Fe	0.008	−0.080	0.741	−0.272	0.885	0.922	−0.587	0.458	0.967	0.636	1									
Mn	0.757	0.907	0.783	0.801	−0.226	−0.130	−0.566	0.934	0.005	0.372	0.215	1								
Ni	−0.899	−0.698	−0.287	−0.448	0.582	0.501	−0.301	−0.462	0.501	−0.443	0.316	−0.560	1							
Pb	−0.906	−0.560	−0.649	−0.097	−0.001	−0.096	−0.152	−0.631	−0.079	−0.877	−0.246	−0.577	0.813	1						
Se	0.203	−0.211	−0.467	−0.497	−0.250	−0.265	0.985	−0.462	−0.434	0.168	−0.492	−0.465	−0.403	−0.314	1					
Th	0.201	−0.122	0.661	−0.511	0.847	0.890	−0.170	0.3551	0.860	0.863	0.887	0.084	0.071	−0.520	−0.043	1				
Tl	0.319	−0.182	−0.242	−0.554	−0.076	−0.070	0.902	−0.308	−0.234	0.434	−0.255	−0.355	−0.462	−0.512	0.959	0.218	1			
U	0.386	0.0262	0.519	−0.558	0.673	0.712	0.187	0.313	0.620	0.805	0.591	0.001	−0.100	−0.604	0.310	0.850	0.499	1		
V	−0.443	−0.513	0.284	−0.640	0.982	0.959	−0.327	−0.033	0.937	0.291	0.824	−0.328	0.724	0.187	−0.307	0.734	−0.173	0.5461	1	
Zn	0.863	0.927	0.824	0.574	−0.059	0.036	−0.364	0.956	0.112	0.504	0.257	0.890	−0.593	−0.688	−0.243	0.244	−0.131	0.3596	−0.185	1

Table 3 | Correlation coefficient of the relationships between various samples

	Water	Sediment	Mud	*P. stratiotes*	*T. natans*
Water	1				
Sediments	0.47080846	1			
Mud	0.38694793	0.39107713	1		
P. stratiotes	0.65662427	0.82184275	0.4805169	1	
T. natans	0.45099146	0.79990692	0.22563984	0.9116358	1

Table 4 | Principal component analysis (PCA) of elements in water, sediments, mud, *P. stratiotes*, and *T. natans* of Ologe Lagoon

	Component 1	Component 2	Component 3
Ca	0.403	0.054	−0.109
K	0.925	−0.080	0.185
Mg	0.644	0.734	0.104
Na	0.863	−0.069	−0.115
Al	−0.100	0.977	0.024
Ba	0.389	0.256	0.811
Cr	−0.104	0.905	0.344
Cu	0.453	0.055	−0.784
Fe	0.208	0.962	−0.121
Zn	0.890	0.188	0.067
Initial eigenvalue	4.085	2.774	1.369
% Variance	40.847	27.736	13.688

Table 5 | Pollution status of water of Ologe Lagoon

Pollution characteristic	Water
WPI	
SAR	81.72
% Sodium	78.4
KI	5.24
WQI	6.47
Nemerow comprehensive pollution index (P_n)	5.87

aerial part when irrigated with high-salinity water. High salt levels in the water produce oxidative stress in plants, resulting in an increase in electrolyte leakage and lipid peroxidation (Oyedeji *et al.* 2022).

3.1.3. The potential ecological risk index

The PERI values for the sediment and mud of the Ologe Lagoon were 5.3 and 5.92, respectively, suggesting a low ecological risk for the elements. Copper presented the highest ecological risk concerning single regulator indexes in both the sediment and mud, notwithstanding its low concentration. Copper was followed by Zn and Cr in the sediment and mud samples, respectively. Though both had low toxicity coefficients, they had a higher ecological risk compared to other non-nutrient elements.

3.1.4. Enrichment factor

The EF for the various elements in the sediment and mud is shown in Table 6. Except for Cr, Cu, and Tl, all of the elements studied were significantly more abundant in the sediments than those in the mud. The average

Table 6 | EF for elements in the sediment and mud of Ologe Lagoon

	Sediment	Mud
Element		
Ca	7.45 (15.26)	0.6 (0.68)
K	4.20 (15.13)	0.13 (0.7)
Mg	2.14 (5.21)	0.71 (0.82)
Na	6.56 (15.67)	0.62 (0.57)
Ba	0.73 (2.55)	0.22 (0.27)
Cr	0.66	1.64 (1.9)
Cu	12.06 (12.14)	1.96 (1.96)
Mn	3.47 (10.65)	0.59 (0.81)
Ni	0.05 (0.05)	
Th	60.57 (113.35)	16.82 (18.32)
Tl	14.85 (29.48)	0.64 (1.89)
U	52.25 (87.86)	8.92 (12.95)
V		0.26 (3.87)
Zn	19.36 (22.05)	3.67 (3.84)

Note: The values obtained from the mean concentration of each metal are indicated followed by those from the maximum concentrations in brackets.

concentration value of the elements yielded lower EF values compared to the maximum elemental concentration in the brackets. Except for Ba and Ni, which could be regarded as products of weathering, the other elements in the sediment of Ologe Lagoon are attributable to pollution from biota or drainage sources. The nutrient elements, such as Ba, Mn, and Tl, in the mud are products of weathering. While Mg and Na had minor enrichment in the sediment, K had moderate enrichment. The sediment had severe enrichment with Ca and Na, very severe enrichment with Cu, Tl, and Zn, and extremely severe enrichment with Th and U. The mud had had minor enrichment with Cr, Cu, and Zn; moderate enrichment with U; and very severe enrichment with Th. The difference in the EF values between the sediment and mud is related to their grain size, which determines metal adsorption and removal.

3.1.5. The geo-accumulation index (I_{geo})

The geo-accumulation index (I_{geo}) values as shown in Table 7 were used to assess metal pollution in the sediments of Ologe Lagoon. The results of the I_{geo} value for all elements fall in class 0, indicating no pollution across the seasons. The I_{geo} is associated with a qualitative scale of pollution intensity with seven classes. The two extremes of the classification are $I_{geo} \leq 0$ and $I_{geo} \geq 5$, which indicate unpolluted and extremely polluted sediments, respectively.

Table 7 | Geological accumulation index

Element	C_i	K	B_i	I_{geo}
Cr	2.1	1.5	67.30	−5.644
Cu	1.2	1.5	22.50	−4.796
Pb	0.1	1.5	21.00	−8.301
Ni	0.2	1.5	31.00	−7.861
Zn	1.1	1.5	65.40	−6.48

3.1.6. BCF of elements in *P. stratiotes* and *T. natans*

The BCF of elements in *P. stratiotes* and *T. natans* is shown in Table 8. The ability of *T. natans* to bio-concentrate Zn makes it a potential candidate for the phytostabilisation and phytoremediation of Zn compared to

Table 8 | Bioconcentration factor of elements in *P. stratiotes* and *T. natans*

Elements	Al	Ca	K	Mg	Na	Ba	Cr	Cu	Fe	Mn	Zn	Th	U	Tl
P. stratiotes	0.2	0.6	0.04	0.3	0.1	4.5	2.2	7.2	0.3	0.3	42.8	6.3	3.5	0
T. natans	0	0	0	0	0	6.5	2	6.1	0	0.4	88.9	4.9	6	0.3

P. stratiotes. Barium, Cr, Cu, Th, and U can be phytoremediated alongside Zn in any Zn-impacted soil by the two vegetation types because plant species with BCF values >1 have demonstrated potential success for phytoremediation for those elements.

3.1.7. Biota sediment accumulation factor

P. stratiotes and *T. natans*, as shown in Table 9, have BSAF values greater than 2 for Ba, Cr, and Mn and can therefore be regarded as macro-concentrators and bio-indicators for those elements. This assertion agrees with the BCF values for the different elements except for Mn. *P. stratiotes* can be regarded as a micro-concentrator for Cu and Th; and a de-concentrator for the nutrient elements Al, Zn, and U, thus releasing them into the sediment. *T. natans* may also be the source of Th, Tl, and U in the sediment of Ologe Lagoon according to this classification.

Table 9 | Biota sediment accumulation factor for *P. stratiotes* and *T. natans*

Elements	Al	Ca	K	Mg	Na	Ba	Cr	Cu	Fe	Mn	Zn	Th	U	Tl
P. stratiotes	0.2	0.9	0.4	0.4	0.4	2.6	23	1.1	0.2	2	0.5	1.1	0.5	0
T. natans	0	0	0	0	0	3.8	21.5	0.9	0	2.3	1.04	0.9	0.8	0.3

4. CONCLUSIONS

The results from this study showed high concentrations of nutrient elements in the different components of the Ologe Lagoon ecosystem. A higher concentration of the various nutrient elements (Ca, Mg, K, and Na) was detected. Arsenic, Cr, Ag, and Se were detected once at different times in water and the sediment at concentrations below permissible levels. Higher nutrient element concentrations in the study are attributable to anthropogenic salinisation activities in the adjoining industries whose wastewater feeds the lagoon. Aluminium and Fe resulting from classical weathering were the elements with the highest concentration. The non-nutrient elements showed lower concentration values and were lower than the permissible quality guidelines for freshwater aquatic life. Uranium, Th, and Tl were detected in increasing concentrations in water compared to the other media, suggesting bioaccumulation. There was a strong correlation between the elemental content of water and the other components of Ologe Lagoon, except for *T. napans*. The WQI for the water of Ologe Lagoon indicated its suitability for drinking, while the Nemerow comprehensive pollution index suggested heavy pollution of the sediment. However, the results of the I_{geo} values for all elements fall in class 0, indicating no pollution across the seasons. The high salinity of Ologe water as shown by the SAR, %Na, and KI values indicated its unsuitability for irrigation purposes or the need for advanced technology for salt reduction before use. *T. natans and P. stratiotes* showed a potent accumulation of Zn; however, they can be recommended as emergent hydrophytes for the phytoremediation of Ba, Cr, Cu, Zn, Th, and U because of their BCF and BSAF values for the elements. While the results from this study are necessary for efficient and strategic water management and drainage practices that avoid the accumulation of salts in water, the effects of water from the lagoon on the metabolism and physiology of plants and human metabolism via animal studies should be investigated to assure water security.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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