Heavy Metals Distribution in Mangrove Leaves in Various Sudanese Coastal Zones at The Red Sea

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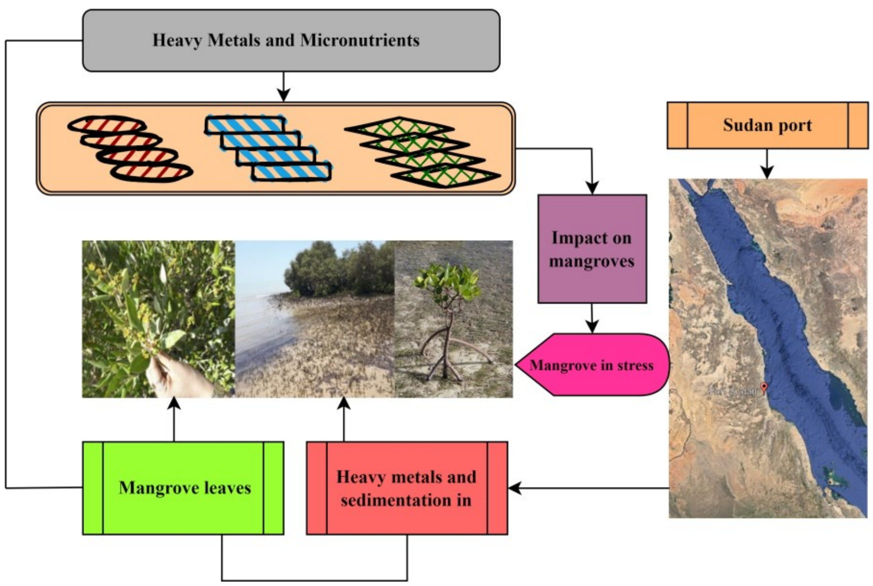

Graphical Abstract

ABSTRACT

Mangrove ecosystem contamination, especially in the Red Sea region, has caused major concerns on a worldwide scale. The heavy metal accumulation typical of a mangrove species, *Avicenna marina* L.,(*A. marina*) leaves and soluble salts in sediments have not been studied on the Red Sea coast of Sudan. The present study investigates the two nutrients calcium (Ca) and iron (Fe) and heavy metals such as barium (Ba), titanium (Ti), and strontium (Sr) in the mangrove species *A. marina* in the leaves of six different locations in the Red Sea coastal area, as follows: (Hamasyat (HM) Keligo (KG), and Enkfel (EK) of the Gulf of Dunnabeb, and three sites were selected in the south of the Sudanese coast as follows: (Amarat Island (AM), Ibn Abbas Island (BN), and Ras Kassar (RK). The results demonstrate that the maximum calcium (Ca)and iron (Fe) concentrations in mangrove leaves were 35.9 mg/kg and 4.10 mg/kg recorded at RK and AM, respectively, in the south region of the Red Sea. The heavy metal concentrations (mg/kg) vary between different locations. The higher concentration of heavy metals in mangrove leaves increased as Ba was 1.1 mg/kg in the EG north region. While Ti (0.5 mg/kg) and Sr (2.80 mg/kg) higher concentrations were recorded in AM and EK, respectively, in the south area than in the other experimental sites. Heavy metals and soluble salts in sediments are continuously monitored in mangrove habitats to ensure they keep within allowed limits. These results could be useful as a database for prospective ecological research, preservation efforts, and long-term sustainable management of the Sudanese mangrove ecosystems throughout the Red Sea coastal.

Keywords: heavy metal contamination, *Avicennia marina*, soluble salts, Red Sea

1. Introduction

Mangrove plant species play a crucial role in maintaining the health and stability of coastal ecosystems (Saoum and Sarkar, 2024). These plants are mostly found between the land and sea areas flooded with tidal waters, mainly at upper water levels and subject to storms in tropical and semi-tropical regions (Aljahdali and Alhassan, 2020). The fast growth of the marine sector and a major change in the world climate are attracting the ecological significance of mangroves to the attention of many people, making their protection a global concern (Ali Solangi et al., 2022). However, mangrove plays a major role in the fight against global warming, coastal erosion, and the storage of enormous quantities of carbon in sediments as a natural barrier (Anu et al., 2024). Heavy metal pollution is a key environmental dilemma as the metals in contaminated sediments may gather in the various organisms of the estuarine ecosystem and ultimately enter the food chain, thereby affecting the human (Afzaal et al., 2022). There are several studies that cultivated mangrove species as dependable bio-indicators for heavy metal contamination (Ashournejad et al., 2019; Jimenez et al., 2021). Due to the metal toxicity and bioaccumulation potential determination, the cycling of heavy metals is a serious concern in mangrove environments (Wang et al., 2024). Heavy metals, which cannot degrade, would accumulate in plant tissues after being transported from soils, where they would cause adverse effects on plants. Mangrove trees can store metals, transferring these elements from the sediment and concentrating them in their tissues (Nguyen et al., 2020). Mangroves remove heavy metals through chemical processes: absorption, cation exchange, and filtration, through their various mechanisms (Dubey et al., 2018). Aresearch study mainfocused on a higher range of heavy metals in leaf matter for several mangrove species, such as true mangrove and white mangrove (Badarudeen et al., 2014). This attribute makes *Avicennia marina* L (*A. marina*) a valuable species, allowing scientists to use experimental testing and monitoring to gather quantitative data regarding the environmental health of its habitat (Einollahipeer et al., 2013). The ability of mangrove species to resist removal, control heavy metal uptake at the roots, and limit their movement to the shoots (Arumugam et al., 2018). Mangrove performs an important role in coastal areas; they provide shelter; they grow in abundance in saline soil and salty water, frequently inundated with fresh and saltwater (Kamaruzzaman et al., 2009). Previously, some studies focus on mangrove mapping through different satellite images and state

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that 75% using NDVI (Normalized Difference Vegetation Index) (Aslam et al., 2023), machine learning method (Aslam et al., 2024a) and land use land cover technique (Aslam et al., 2024b). A research study reported that mangrove biomass also determine with remote sensing technique but also need some validation points with field data (K. A. Solangi et al., 2019). Therefore, field data very important a research revealed that many mangrove species in the field accumulate metals, including copper (Cu), zinc (Zn), lead (Pb), iron (Fe), manganese (Mn), and cadmium (Cd), mostly in their roots and leaves (Khan and Aljahdali, 2022).

Some studies suggested that mangroves may accumulate and translocate some metals with leaf Bioconcentration Factors (BCFs) greater than one, e.g. 1.5–2.4 for *A. marina* 1.7 for *Aegiceras corniculatum* and 1.2 for *Kandelia candel* (Chen et al., 2013). In this context, mangrove *Avicennia marina* grows in the intertidal zones along the eastern coastlines of the Arabian Peninsula, forming discrete communities in several locations (Abou Seedo et al., 2017). These complex root systems, like those of other coastal species, can help slow the erosion rate by promoting sediment development within their complex structures. Various species of mangroves have a unique capacity to develop and adapt to their surroundings, enhancing coastlines with their intricate root systems and promoting plant growth (Solangi et al., 2021). The mangrove ecosystem in Bahrain becomes polluted in many ways, most notably by wastewater discharge from the Tubli sewage treatment plant and, to some extent, by urban and industrial runoff. This study investigates the heavy metals distribution in the mangrove leaves as affected by the urban community wastewater release in three mangrove places in the Tubli Bay area (Bartolini et al., 2011). Nazli and Hashim (2010) reported Cu and Pb concentrations in the roots and leaves of crabapple mangroves. They concluded that the roots of this species had a high capacity to take up heavy metals and could be a viable phytoremediation species for heavy metal treatment in Malaysian mangrove ecosystems. A previous study examined the effects of heavy metals inflowing into the estuaries and the overall health of the mangrove ecosystem in a coastal area of south Gujarat, India (Dudani et al., 2017). An earlier research was carried out in the region (Rabigh lagoon) in Saudi Arabia; the primary purpose of this research was to examine the physiological response to heavy metals in *A. marina* leaves and to assess ecological risk by determining the concentrations of these metals in coastal sediment (Aljahdali and Alhassan, 2020). One of the world's most at-risk areas for rising sea levels, both in terms of the area of low-lying land inundated and the percentage of populations influenced, is the Mekong River Delta (MRD) in Vietnam, which is inhabited by enormous and

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ever-changing mangrove forests (Dasgupta, 2007). Using a dataset of published research from the literature, metal concentrations were measured in mangrove sediments and mangrove root and leaf tissue in different countries. Keeping this view, present study focuses on heavy metals contamination in the mangrove environments in Sudan. Mangrove forests most of the vegetation on the Red Sea coast of Sudan and are subject by *A. marina*. Particular, the mangrove ecosystems have not received enough attention in relation to this research. The main objective of the present to find out the status of three heavy metals such as barium (Ba), titanium (Ti), and strontium (Sr) and two nutrients calcium (Ca) and iron (Fe) in the leaves of mangrove species (*Avicennia marina.*L.) at the six different locations of Red Sea coastal. The distribution pattern of certain heavy metals in mangrove leaves is investigated in order to understand the essential role of mangrove plants in the cycling of these metals.

2. Material and method

2.1 Study Area

The study was conducted in six regions, three areas selected in north of the Sudanese coast as follows: (Hamasyat (HM), Keligo (KG)- Enkfel (EK) of the Gulf of Dungonab and three sites were selected in south of the Sudanese coast as follows: (Amarat Island (AM), Ibn Abbas Island (BN) and Ras Kassar (RK)) of the Aqib region with the coordinates of 20° 16' 48.835" N and 38° 30' 45.263 E (figure. 1) to investigate the mangrove species *A. marina*. The area is characterized by a semi-arid climate with a mean daily temperature of 29 °C in winter and 42°C in summer. Annual rainfall averaged 164 mm, tides are unusual, with a mean spring tide of 0.1 m.

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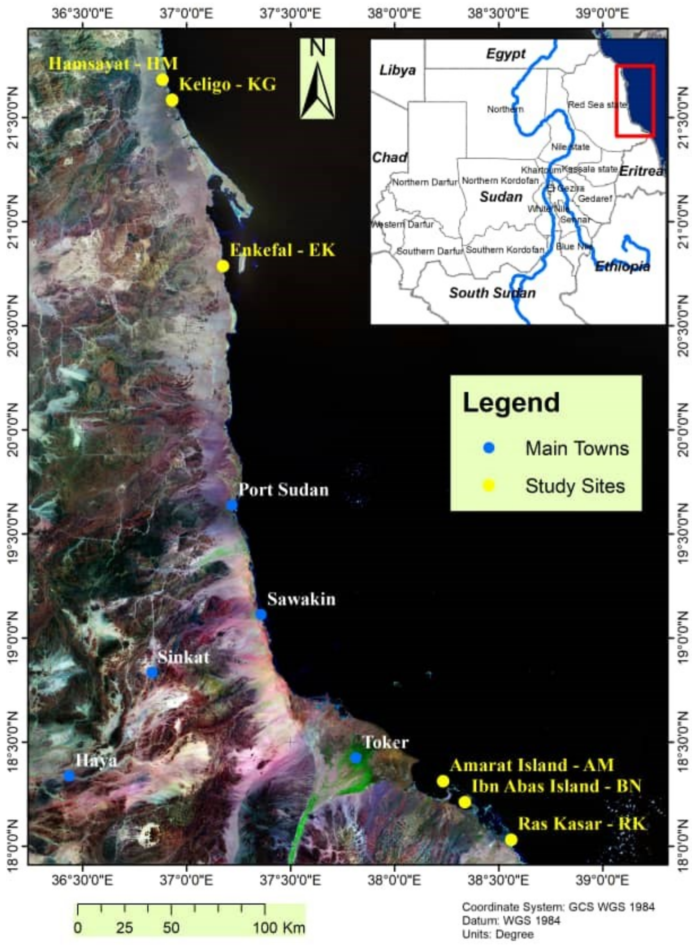

Figure 1. Location map of six different sites of study area.

2.2 Soil sampling

Soil samples were randomly collected from six different locations in the Red Sea coastal area of Sudan in the winter season from December 2022 to February 2023. The coordinates were recorded using a hand-held Garmin GPS-62s device. Prior to the field survey, sampling points were inputted into the GPS-62s to facilitate route tracking and identify convenient sampling locations. Soil samples were collected with a soil auger, packed into plastic bags, labelled with the sampling location, and carried to the Sudan University of Science and Technology, Soil Department laboratory for the physio-chemical analysis. The samples were air-dried at room temperature and sifted through 2-mm and < 2-mm sieves. For the electrical conductivity (EC) analysis, the < 2-mm fraction was utilized. Subsample portions were set aside for soil pH and nutrient analysis. Total 55 soil samples were collected from various locations within the selected areas. A subsample portion of a 2-mm mesh after oven drying (40 °C) for 48 h was also used for soil textural class measurements. Soil textural classes, sediments particles size distribution and its percentages were estimated by the field texture determination method (FAO, 2006).

2.3 Plant sample preparation

Mangrove leaves were plucked in different locations to analyse nutrients and heavy metals. Samples were analysed using an XRF device in atomic energy, Khartoum. First, samples were washed with distilled water to remove any sand and debris, then air-dried for seven days. The dried sample was crushed and kept in airtight cellophane until it was time to utilize it. To obtain a noticeable and comprehensive extraction of the active components in the plant samples, about 10 g of the mangroves**.** 1.0 g of the powdered sample was pressed by (15 tons per cm. For quality control, four standard reference materials were used and treated in the same manner.

2.4 XRF measurement

Dispersive energy XRF spectroscopy with a resolution of 109 keV using an ORTKC Si (Li) detector. The major source employed to measure Ca, Cr, Cu, Fe, K, Mn, Ni, Sr, and Zn in some wild edible plants from Sudan was radioisotope Cd, which has an energy of 22.1 KeV. The XRF spectrometer was used to measure plant pellets, and each measurement took three thousand seconds. A Cd-109 x-ray source was used to excite x-rays, and the resulting spectra were then uploaded to a computer. After that, the spectra were examined, and the computer's AXIL-XRF program was used to determine the elements' concentration in the samples. For quality control, hay powder was used as a standard reference and handled identically. A standard reference of hay powder was used for quality control (Ebrahim et al., 2012).

For RBS studies, backscattered particles of a 3 MeV proton beam at a scattering angle 0 of 165° were found using a silicon PIPS detector from Canberra with 14 keV of energy resolution and 25mm of active area. The experimental setup has been described in detail elsewhere. (Roumié et al., 2004). Analyses have become powerful analytical methods for multi-element analysis (Ahmed, 2014). The characteristic X-rays that are emitted are measured by a high-resolution X-ray detector (liquid nitrogen-cooled Si or Li). Twenty to twenty-five elements can be found at the same time using the XRF multi-element analysis technology (Markowitz *et al*., 2002). Benefits include little sample preparation, non-destructiveness, use across a broad range of concentrations, good precision and accuracy, and the ability to assess solid, powder, and liquid samples. It is also almost independent of the chemical state of the fee-based analyte. Certain drawbacks, like x-rays. The fee

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sample has limited penetration (I mm layer), and light elements (below Na) have extremely low sensitivity. However, although is feasible on a novel instrument, limits of detection are only moderate, inter-element (MATRIX) effects could be significant and necessitate computer correction, and instrumentation is relatively expensive (Clapera, 2006).

2.5 Organic matter

Removal of small amounts of organic matter (organic carbon less than 05%) is unnecessary. When HCL is used, subsequent treatments will remove soluble salts and iron oxides and aluminum. Salt washing will reduce gypsum, if present to an amount that will not interfere with the proper dispersion of soil particles. FAO Soil Bulletin 10 (1984) J. Dewis and F. Feitas Harmful effect of $CaCO_3$. (1) Fixation of phosphate (po4) 3 (2) unavailability of iron; oxides ferrous into ferrous (3) loss of ammonia: $CaCO_3$ increases pH and produces OH while reacting with NH4.

2.5 Data analysis

One-way ANOVA was used to determine significant changes in heavy metal concentrations in *A. marina* leaves and soluble salts in sediment. Where there significant difference, Duncan's Multiple Range tests at a significant level of $P < 0.05$ was used to separate the mean values. IBM SPSS Statistics version 20.0 (Corp., Armonk, NY, USA) was used for the analysis. Origin Pro 9.0 (Northampton, Massachusetts, USA) was used to create the Calcium (Ca), Magnesium (Mg) and Nitrogen (N), frequency (%) and soil sediments frequency (%) graphs.

3. Results

3.1 Potassium and iron concentration in mangrove leaves

The amounts of calcium (Ca) and iron (Fe) in mangrove species (*A. marina* leaves were different in various regions of the Red Sea coast in Sudan, in the north (HM, KG, and EK) and the south (AM, BN, and RK) figure 2. The maximum Ca concentration in mangrove leaves was observed at two south locations of the red sea coast, by RK and BN, at 35.9 mg/kg and 31.6 mg/kg. However, a minimum Ca concentration in mangrove leaves was noted in the north area of Red Sea KG by 3.4 mg/kg. The greater Fe concentration in mangrove leaves was recorded in the south region of the Red Sea AM by 4.10 mg/kg compared to the entire experimental location. While the lowest Fe (0.80 mg/kg) concentration was also noted in the south region compared to the north regions of the Red Sea, these findings suggest that soil type and mangrove development affect the concentration of Ca and Fe across sites.

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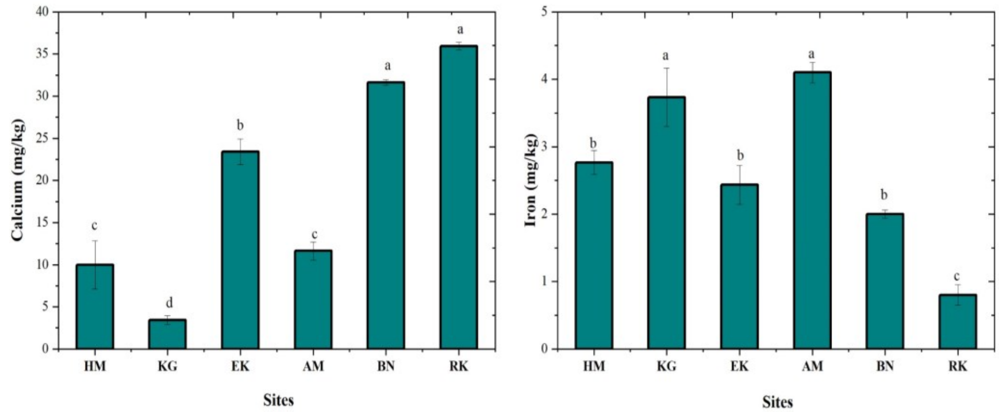

Figure 2. Determination of calcium (Ca) and iron (Fe) absorption concentrations in mangrove species at six various north and south Red Sea coastal regions. Based on Duncan's multiple tests, The letters specify significant influences at p < 0.05, replicates n = 3.

Note: North regions: Hamasyat (HM), Kelijo (KG), Enkfel (EK), and South regions: Amarat Island (AM), Ibn Abbas Island (BN), and Ras Kassar (RK) of Red Sea coast in Sudan.

3.2 Examination of heavy metals in mangrove leaves

The heavy metal concentrations such as barium (Ba), titanium (Ti), and strontium (Sr) in the mangrove species (*A.marina.* presented a huge amount of difference in the mean concentrations collected from the Red Sea coast in Sudan. The heavy metal range in the mangrove leaves at each site is shown in table 1. The results for Ba indicate non-significant differences across six different areas, while Ba was found to have a higher value, i.e., 1.1 mg/kg, in EG on the north side of the Red Sea coast. In contrast, significant ($p < 0.05$) differences were observed for the Ti and Sr mg/kg heavy metal concentrations. Specifically, higher concentrations of Ti by 0.5 mg/kg were observed in the AM south region. Whereas maximum concentrations of Sr by 2.80 mg/kg were observed at the south location of the EK site compared to other areas.

Table 1. Heavy metals Barium (Ba), Titanium (Ti) and Strontium (Sr) mg/kg concentrations in mangrove species (*A.marina*at six various north and south red sea coastal regions. The different letters specify significant influences at $p < 0.05$, replicates $n = 3$, based on Duncan's

Sites	**Ba** (mg/kg)	**Ti** (mg/kg)	**Sr** (mg/kg)
HM	0.3 ± 0.06^{a}	0.2 ± 0.05^{bc}	0.16 ± 0.03^{b}

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KG	0.2±0.03[a]	0.4±0.05[ab]	0.13±0.03[b]
EK	1.1±0.09[a]	0.1±0.01[c]	2.80±1.20[a]
AM	0.2±0.02[a]	0.5±0.12[a]	0.13±0.02[b]
BN	0.2±0.05[a]	0.1±0.03[c]	0.36±0.03[b]
RK	0.2±0.03[a]	0.2±0.05[bc]	0.50±0.02[b]

multiple tests.

Note: North regions: Hamasyat (HM), Kelijo (KG), Enkfel (EK), and South regions: Amarat Island (AM), Ibn Abbas Island (BN), and Ras Kassar (RK) of Red Sea coast in Sudan.

3.3 Electrical conductivity (EC) and soil pH (pH)

The presented data on electrical conductivity (EC) and soil pH showed variance for different locations of Red Sea coastal areas shown figure 3. However, soil EC showed changes across the entire experimental location. At the same time, the highest EC value was noted at 6.5 dS/m in KG on the north side of the study area, while the lowest EC level was recorded at 2.2 dS/m in HM in the north area of the Red Sea. The greater soil pH was observed in the BN south region, and the lowest soil pH was recorded at 7.1 on the KG north side of the experimental sites.

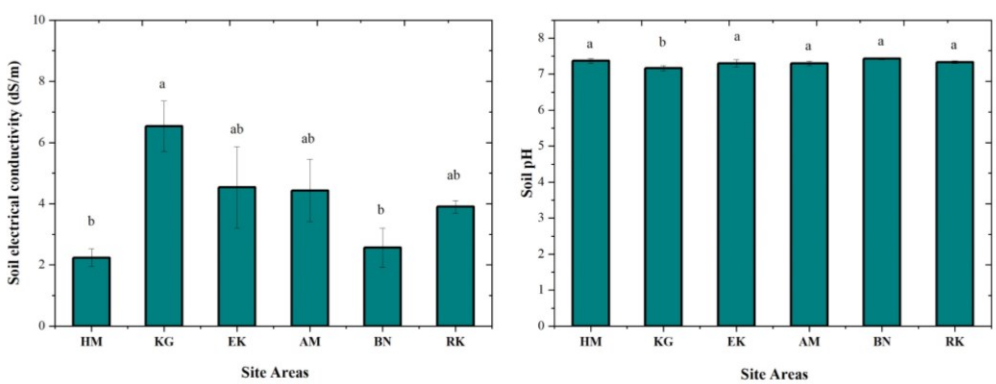

Figure 3. The figure shows ranges of EC and pH under cultivation mangrove (*A. marina.* at six various north and south Red Sea coastal regions. Based on Duncan's multiple tests, The letters specify significant influences at $p < 0.05$, replicates $n = 3$.

Note: North regions: Hamasyat (HM), Kelijo (KG), Enkfel (EK), and South regions: Amarat Island (AM), Ibn Abbas Island (BN), and Ras Kassar (RK) of Red Sea coast in Sudan.

3.4 Soluble salt concentration in sediments

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The concentrations of soluble saltssodium (Na), chloride (Cl), bicarbonate (HCO_3), and carbon trioxide (CO_3), for the different experimental areas are described in table 2. Different salt ranges vary in different regions of the Red Sea area. The higher Na and Cl concentration ranges were 56.3 meq/L^{-1} and 49.1 meq/L^{-1} , respectively, presented in KG, the north area of the Red Sea. Similarly, lower salt concentrations were recorded in the HM north side of the coastal area. Therefore, the maximum concentration of HCO_3 salt was 14.5 meq/L on the EK north side of the study area. While the lowest concentration of HCO_3 was found in the BN region, which was 6.8 meq/L^{-1} across all locations. The greater range of CO_3 was 3.62 meq/L^{-1}, recorded in the north area of the study, and the lowest value was also recorded in the north side of the study location. Most of the soluble salt concentrations were recorded in the northern region of the Red Sea coastal area.

Table 2. Chlorine (CL), Hydrogen carbonate (HCO_3), Carbon trioxide (CO_3) and sodium (Na) of six different locations.

Study Site	**Na (meq/L^{-1})**	**CL (meq/L^{-1})**	**HCO_3 (meq/L^{-1})**	**CO_3 (meq/L^{-1})**
HM	9.3 ± 1.45^{c}	14.3 ± 2.3^{c}	8.8 ± 0.6^{c}	1.33 ± 0.31^{c}
KG	56.3 ± 4.25^{a}	49.1 ± 7.4^{a}	16.3 ± 1.0^{a}	3.62 ± 0.32^{a}
EK	34.8 ± 8.91^{b}	31.1 ± 9.9^{abc}	14.5 ± 0.2^{ab}	3.33 ± 0.33^{a}
AM	37.6 ± 8.8^{ab}	36.1 ± 7.1^{bc}	10.8 ± 2.9^{a}	2.66 ± 0.28^{ab}
BN	20.1 ± 5.50^{bc}	18.0 ± 4.5^{bc}	6.8 ± 2.1^{c}	1.66 ± 0.26^{bc}
RK	31.6 ± 2.60^{b}	27.1 ± 2.1^{bc}	9.6 ± 0.33^{c}	2.66 ± 0.22^{ab}

3.5 Soil sediment frequency percentages

The frequency percentages of the size of sediment particles (e.g., clay, silt, carafe sand, medium sand, fine sand, and very fine sand) showed changes across the various experimental sites (figure 4). However, figure 3 showed that fine and very fine sand particles were dominant mostly in the south area of the study region. The highest frequency percentages were found in the BN site, at 34.7%, for fine and very fine sand particles. The highest clay frequency was 27.7% recorded in AM in the south region. Among all sediment particles, carafe sand showed lower frequency percentages in AM, KG, BN, and EK: 8.6%, 8.0%, 10.0%, and 15.6%, respectively.

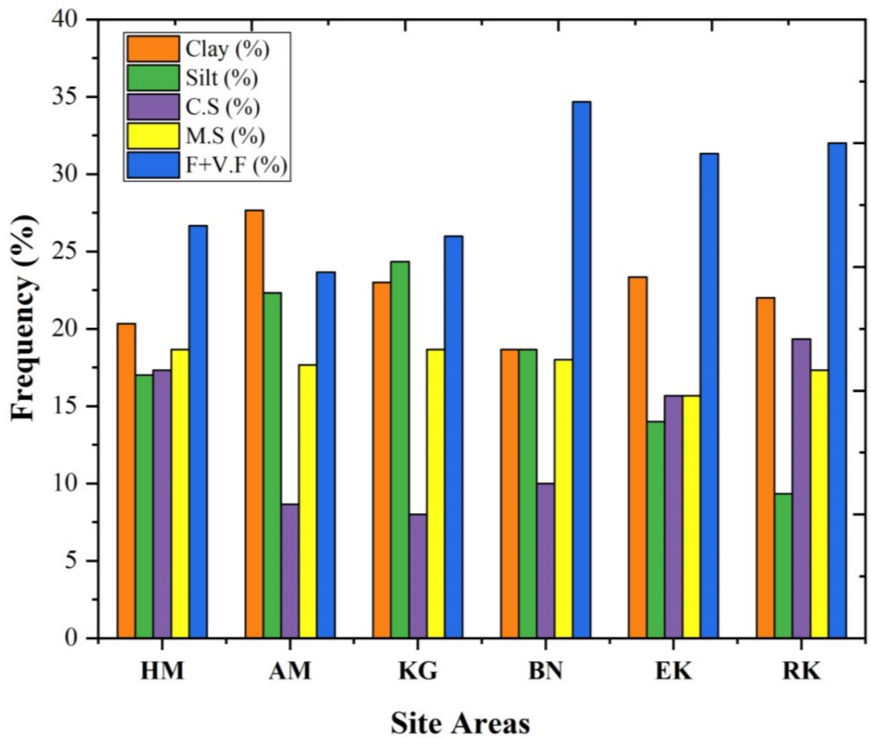

Figure 4. This figure shows soil textural classes of six different coastal areas' north and south locations. North regions: Hamasyat (HM), Kelijo (KG), Enkfel (EK), and South regions: Amarat Island (AM), Ibn Abbas Island (BN), and Ras Kassar (RK) of the Red Sea coast in Sudan

Note: CS: (Carafe sand), MS: (medium sand), and F+VF: (fine sand and very fine sand)

3.6 Nutrient percentages in sediments

Sediment nutrient percentages, organic carbon (OC), calcium (Ca), magnesium (Mg), and nitrogen (N), presented the modification among all study locations figure 5. The highest OC was 19.4% found in AM in the north area. The lowest OC was 10.7% in EK in the south region,and higher Ca percentages in sediments were observed in the following directions: 9.4%, 9.3%, and 8.7%, i.e., HM, AM, and KG, respectively, in the north region. Meanwhile, Mg percentages also increased on the north side of the Red Sea coastal area. The highest N in sediment was 7% observed in RK in the southern regions. The lowest N in sediments was 5%, which was noted in BN in the north region and RK in the south region of the Red Sea coast in Sudan.

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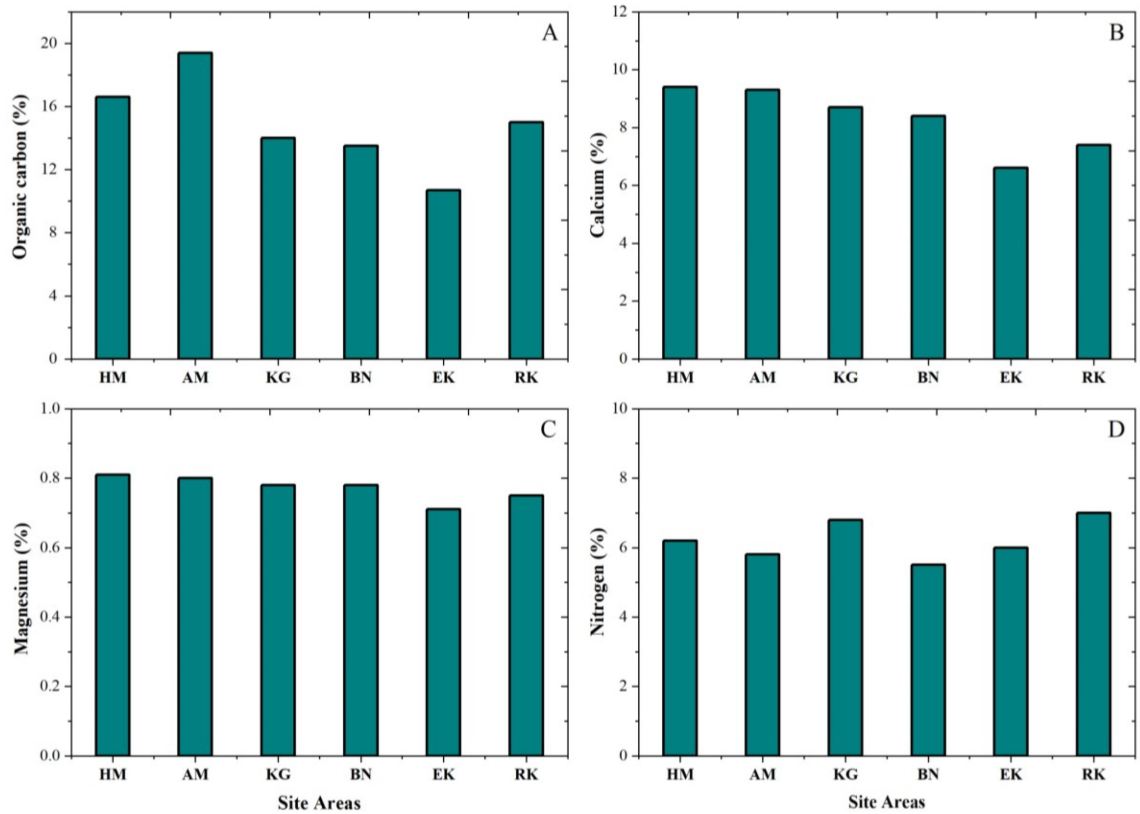

Figure 5. This figure shows the nutrient percentages of organic carbon (OC), n calcium (Ca), magnesium (Mg), and nitrogen (N) in the sediments of six different north and south locations of coastal areas. North regions: Hamasyat (HM), Kelijo (KG), Enkfel (EK), and South regions: Amarat Island (AM), Ibn Abbas Island (BN), and Ras Kassar (RK) of the Red Sea coast in Sudan

3.7 Influence of Sediment Grain Sizes on Heavy Metals and Nutrients

The cluster heat map revealed the relationship between the sites and other dependent variables such as the heavy metals, nutrients and soil grain sizes (figure 5). The cluster for the six sites, at the highest similarity level, revealed a close relationship between the sites except for site KG. Additionally, Na and Cl showed more association with site KG. Two groups were formed for the independent variables at the highest similarity level. Na, Cl, F+V.F, clay, silt, OC and M.S form a single group, revealing that Na, Cl, OC and M.S. were more associated with clay and silt grain types. However, the second group was formed containing Sr, Mg, Ti, EC, Fe, CO3, K, C.S. HCO_3, Ca, pH and N (figure 6).

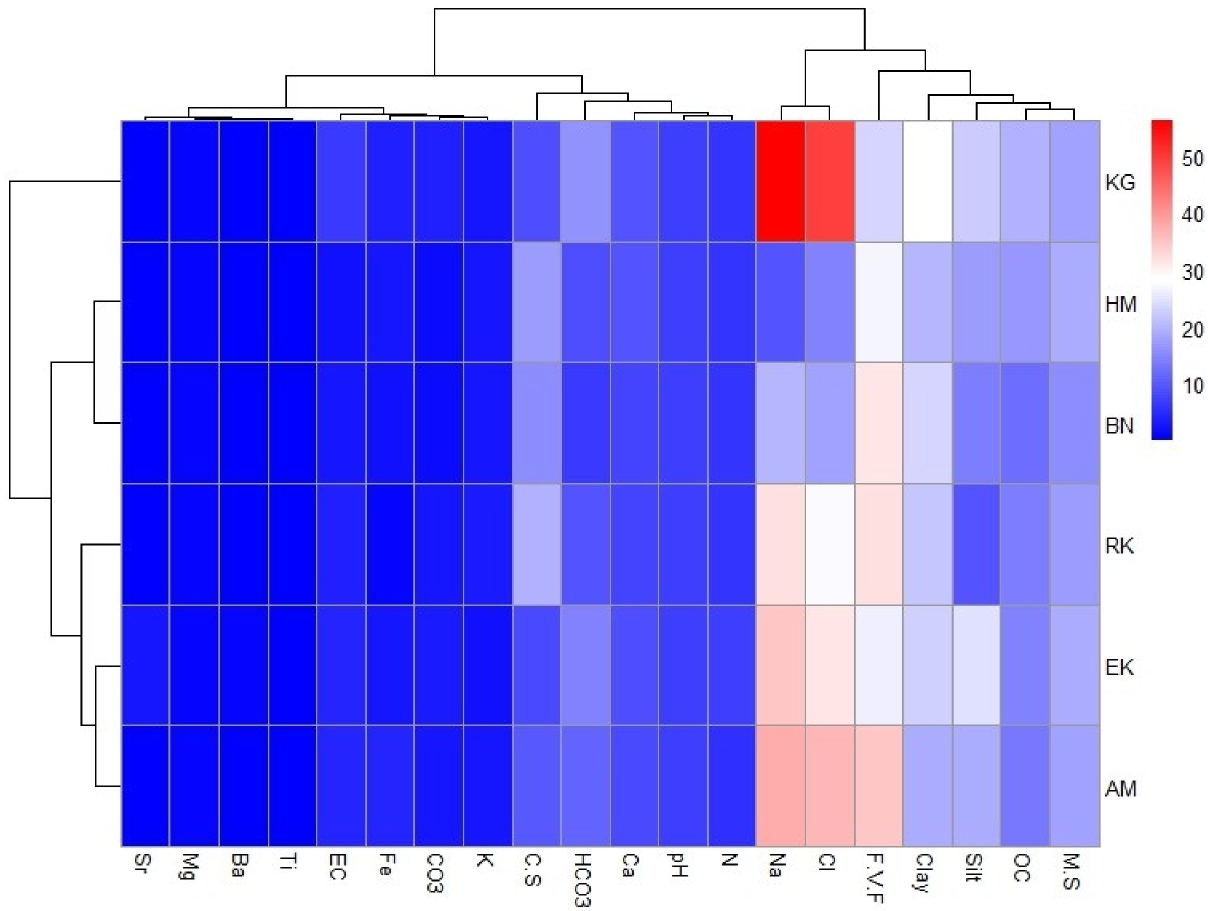

Figure 6. Cluster Heat Map for the relationship between the sites, heavy metals, nutrients and sediment grain sizes.

3.8 Principal Component Analysis

The principal component analysis (PCA) biplot and contribution plot (figure 7) for the influence of sediment grain sizes on heavy metals, nutrients and soil properties in the different sites revealed a total variation of 72.7 % contributed by PC1 48.9% and PC2 by 23.8% respectively. Based on the aforementioned total variation by the PCs, a positive correlation exists between clay grain types and Fe, Na, Ti, Cl, OC, EC and CO3, influenced by site AM and KG (figure 6). Additionally, the silt grain type was positively correlated with Mg, HCO_3, Ca, M.S, Ba, Sr, and N, and was influenced by site EK. It is important to note that overall in terms of contribution to relationships revealed by the PCA, Clay and Mg had the lowest contribution (figure 8).

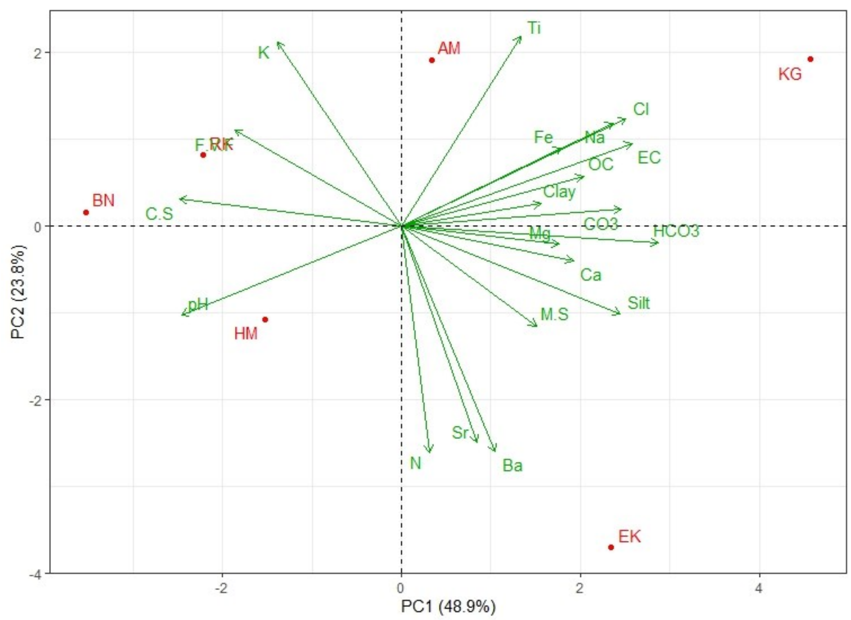

Figure 7. Principal Component Analysis (PCA) biplot for the influence of sediment grain sizes on heavy metals, nutrients and sediment properties .

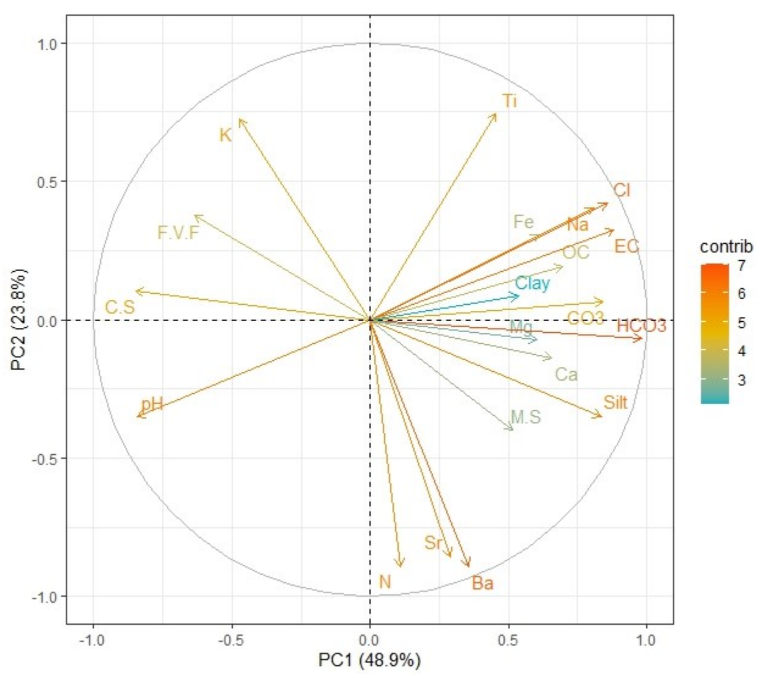

Figure 8. Principal Component Analysis contribution plot for the influence of sediment grain sizes on heavy metals, nutrients and sediment properties.

4. Discussion

The current data investigates the accumulation of trace elements Ca and Fe and heavy metals in mangrove species *A. marina* leaves and examines the OC, N, Mg, and Ca contents of sediment particles at six red sea coastal areas. To survive in their extreme environment, mangrove plants have developed a number of specific adaptations, such as diverse root systems and altered bark and leaf structures. The present research showed higher Ca and Fe were noted in the southern locations of the Red Sea coast, by 35.9 mg/kg and 31.6 mg/kg in the RK and BN, respectively. Mangrove positions in the north and south Red Sea are considered to have low leaf nutrient concentrations, mostly Ca and Fe, indicating the possibility of nutrient limitation in north and south Red Sea mangroves throughout the stands. The mangrove species *Avicennia* species are considered to have better resistance tolerance and acquire several compared to other mangrove species (Parida and Jha, 2010; Wang et al., 2022). Therefore, Ca and Fe are important nutrients for limiting plant growth, where nitrogen increases the number of leaves in plants. Fe mostly to enhanced root development. This crucial micronutrient, Fe, and its uptake and distribution to plant parts are necessary for the photosynthetic process and leaf tissue (Solangi et al., 2023). A previous study found that five mangrove species living in north Queensland, Australia, had significant iron requirements from the seedling to tree stage of development (Almahasheer H, 2006).

Furthermore, the high concentration of these nutrients in mangrove leaves may be that these metals are micronutrients that are essential metals for mangrove growth and metabolism and thus are absorbed and used by mangrove plants. Fe is toxic when high levels accumulate; it could act with catalytic by Fenton reaction to generate hydroxyl radicals, which could damage lipids, proteins, and DNA. However, the current study showed that Sr concentration is higher in mangrove leaves than Ba and Ti in the EK north region of the Red Sea (table 1).

The previous study demonstrated similar results: strontium was easily transferred to the aboveground part of soybean (Dresler et al., 2018). In its stable forms, strontium is not particularly toxic to plants. However, it frequently has a negative impact on the uptake of specific nutrients, mostly calcium, due to its negative impact on plant development and growth (Burger and Lichtscheidl, 2019). It is noted that strontium was quickly transferred to the leaves, and in general, its accumulation in plant parts was reduced as follows: leaves > stems > roots > seeds. Different types of mangrove species and the various ranges of heavy metal concentrations would affect the

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bioavailability of the heavy metal potential of mangroves and their environment (Dubey et al., 2018).

The current study results showed the soil EC range fluctuates between the highest 6.5 EC (dS/m) and the lowest 2.2, while soil pH was slightly alkaline throughout the north and south regions of the study area. This may impact the mangrove species found in the different types of mangrove ecosystems due to the salinity levels that fluctuate due to high temperatures and oceanic fluctuations (Barik et al., 2018). The salinity could have been described by different particle sizes and mineral compositions in soil sediment (Fernandes et al., 2019). However, the carbonate-bearing (calcite and aragonite) and evaporated (halite) minerals are widely famous for salinity control (F. Solangi et al., 2019). It is noted by previous studies(Alsamadany et al., 2020; Usman et al., 2013), that most of the pH levels, which were shown by some researchers in sediment samples of coastal areas, were alkaline and fluctuated between 7.49 and 8.51 in their study at sites 6 and 13, respectively. The distribution of particle sizes in sediments is often considered an effective tool for investigating the lactogenic pathways andtheir parent material origin. The percentages of the size of sediment particles and their distribution present results were found the fine sand and very fine sand particles (range between 26% to 34%) were dominant across the various location and highest percentages of fine sand particles was found in south regions (Fig 4). Similar results were observed in an earlier study: sediment particles formed of sand varied between 64.10 and 94.60%, while the fine mud fraction was 5.40%. The presence of fine sediment particles in mostly all the sediment samples is possibly due to many reasons, including the parent material, urban intrusion, and degradation of coastlines along the experimental area. Changes in sediment deposition patterns, particularly for fine particles, and chemical processes can be attributed for the different distributions of heavy metals in sediments across large regional scales (Naz et al., 2023).

The difference in sediment grain size in the oceans can be influenced by a variety of factors, including sedimentary behavior and sediment transportation. Multiple studies have demonstrated that mangrove ecosystems can enhance the amount of suspended solids formed by decreasing water dynamics and allowing fine-grained sediments, which are a primary source of minor element absorbance, to have more time to deposit (Talukdar et al., 2023; Xiong et al., 2018). The present study showed salt such as Na+, Cl^-, HCO_3 and CO_3 were significantly affected by the coastline Red Sea area. Na and Cl are important micronutrients in plants and participate in various physicochemical processes (Colmenero-Flores et al., 2019; Raven, 2017). The Seawater alkaline

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nature is simplified as the charge balance of conservative ions (Na+, Ca^2+, K+, Cl−) and some minor elements' redox state (Krumins et al. 2013). The primary sources of the HCO_3 concentration were organic and terrigenous elements obtained from the soil . It has been shown to be crucial in regulating the potentially hazardous elements (Mosa et al., 2016). However, the mean value percentages of soil OC, soil N, Mg, and Ca (soluble salts) varies between locations in the north and south of the Red Sea coastline. Worldwide red sea area covered with mangrove ecosystems have been reported lowest OC ranges by 15 g m^{-2} yr^{-1} which is many times lower than the average global estimate of 163 g m^{-2} yr^{-1} of OC. The nutrient cycling nitrogen and phosphorus is a key factor influencing the seawater inorganic carbon system and the global carbon cycle (Dai et al., 2018). Nitrogen is a major element for plant growth, and Mg is an alkaline micronutrient in ionic form by plants (Solangi et al., 2023). The Mg ions are involved in chlorophyll-related processess within the plant and are moderately more present in seawater than the other major elements (Saderne et al., 2018). A wide range of interacting influences between several critical nutrients and the calcium-rich soils on Aldabra is likely to occur (Solangi et al., 2024). It promotes the application of a composite variable to describe the complete effect of nutrient content on mangroves.

The association revealed by the cluster heat map with the independent variables forming two groups, comprising a group with Na, Cl, F+V.F, clay, silt, OC, and M.S, indicates that Na, Cl, OC, and M.S are more related to finer grain types like clay and silt. However, the grouping of Sr, Mg, Ti, EC, Fe, CO_3, K, C.S, HCO_3, Ca, pH, and N in the second group suggests a distinct cluster and implies a specific geochemical and granulometric association, helping to understand nutrient and contaminant distribution (Unda-Calvo et al., 2019). Our findings align with the previous study (Toller et al., 2021) except for KG's unique Na and Cl association, indicating localized influences. The positive correlation between clay grain types and Fe, Na, Ti, Cl, OC, EC, and CO_3, with sites AM and KG influencing these variables, and the positive correlation between silt grain type with Mg, HCO_3, Ca, M.S, Ba, Sr, and N, influenced by site EK, with low contributions of clay and Mg suggests that while they are present, their impact is minimal compared to other factors (Sing, 2022). These results align with a previous study (Moquet et al., 2021), except for the unique correlations between AM and KG sites, indicating site-specific influences.

5. Conclusion

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This study investigates the *A. marina* mangrove species, leaves sequester a substantial amount of Ca and Fe in the Red Sea. The Ca higher range in mangrove leaves was observed at two south locations of the Red Sea coast, by RK and BN, at 35.9 mg/kg and 31.6 mg/kg. In this research, heavy metal concentration in mangrove leaves does not reflect the comprehensive picture of heavy metal status in mangroves and its temporal appropriation of these metals. Meanwhile, the Na^+, Cl^-, HCO_3, and CO_3 were recorded in the northern region of the Red Sea coastline. Fine and very fine sand particles were dominant, mostly in the BN sites, with 34.7% in the south area of the study region. However, the percentages of organic carbon (OC), calcium (Ca), magnesium (Mg), and nitrogen (N) were found in the north region of the studied side. Further study need to clarify the heavy metal concentration of mangroves roots and plant total biomass nutrient content. Other toxic heavy metal concentrations further investigate the soil sediments in the Red Sea area in Sudan.

CRediT authorship contribution statement

Rabha K M Khalil: Investigation, Formal analysis, Data curation. **Kashif A Solangi:** review & editing, Writing – original draft, Formal analysis. **Abdullahi B Alhassan:** Formal analysis, Writing – review & editing. **Waseem R Khan:** review & editing and **Mohammed O Aljahdali** Supervision, Project administration, Funding acquisition, Conceptualization

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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