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ASSESSING VARIATIONS IN METAL BIOACCUMULATION IN BLUE CRAB (*CALLINECTES AMNICOLA*) TISSUE FROM SEDIMENT IN ELECHI CREEK, RIVERS STATE, NIGERIA

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Abstract

This paper assessed the hazardous metal concentrations and bioconcentration in blue crab (*Callinectes Amnicola*) from sediment in Elechi Creek, Niger Delta. Sampling occurred at three distinct stations: Station 1 (ST1), a sand-fill area with limited tidal influence; Station 2 (ST2), near a sawmill; and Station 3 (ST3), downstream with stormwater inflows. Monthly collections of sediment, water, and crab tissue were conducted over six months, with metals analyzed via Atomic Absorption Spectrophotometry. Results showed notable spatial variations in metal levels. ST3 recorded the highest concentrations, with Fe at 35.8 ± 8.9 mg/L, Zn at 11.9 ± 3.1 mg/L, Cd at 0.06 ± 0.03 mg/L, and Cu at 114.1 ± 65.0 mg/L in surface water, while sediment levels included Fe at 161.1 ± 27.3 mg/kg and Cu at 425.1 ± 22.4 mg/kg. Bioaccumulation factors (BAF) and bioconcentration factors (BCF) indicated high metal uptake in crabs, especially for Zn and Fe; the BAF values were found to be 13.8571 mg/kg for Zn and 1.1955 mg/kg for Fe at ST3, hence showing higher bioavailability at this location. These results confirmed high levels of metals and accumulating trends in ST3, which might reflect some of the environmental impacts due to localized activities. Overall, this study is an indication of the fact that regular monitoring in the Niger Delta is unavoidable to reduce metal accumulation hazards both to aquatic ecosystems and public health.

Keywords:

Metal bioaccumulation, Callinectes amnicola, Niger Delta, Contamination.

1. INTRODUCTION

The Niger Delta region is one of the largest contributors to Nigeria's production of oil, housing extensive oil fields, refineries, and pipelines (Onyena and Sam, 2020). The economy of this region strongly relies on crude oil extraction, contributing not only to Nigeria's GDP but also to its foreign exchange earnings and federal revenue (Oluniyi, 2017). While the economic gains in oil production are incontestable, the environmental impacts, particularly on aquatic ecosystems of the Niger Delta, being felt, are most alarming (Sam and Zabbey, 2018; Okoyen et al., 2020).

Heavy metal contamination of aquatic ecosystems has become a concern worldwide, especially in regions with oil riches like the Niger Delta, where spills, leakages, and industrial discharges

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are frequent occurrences (Bashir et al., 2020; Davies and Odekina et al., 2022). The introduction of toxic heavy metals, such as cadmium, lead, and mercury, into water bodies disturbs the ecological balances and impacts marine life. Besides, it poses health risks to the surrounding human populations that depend on the functioning of these ecosystems for sustenance (Kuppusamy et al., 2020; Sayed et al., 2021). Among those key organisms, able to provide insights into this contamination, are the blue crabs (*Callinectes amnicola*), which are much consumed in the region and come into direct contact with sediment pollutants.

Monitoring metal concentrations in aquatic organisms such as blue crabs is essential for assessing ecological and health risks (Akankali and Davies, 2021). Bioindicators like *Callinectes amnicola* accumulate metals in their bodies, reflecting the contamination level of their habitats. The Bioconcentration Factor (BAF) of metals in blue crabs gives the useful metric to understand how these pollutants move from sediments into the biological system of the crabs, hence unraveling the potential exposure risks to humans who consume these crabs (Kennish 2019, Gu et al. 2022). Bioaccumulation and bioconcentration factors are very important tools useful in environmental monitoring; they help researchers appraise the level of concentration of metals in organisms relative to their environment (Chapman and Wang, 2001). In particular, BAF is extensively used to assess metal bioavailability and ecosystem health in contaminated environments. In the case of blue crabs from Elechi Creek, estimating BAF values for a suite of metals can provide information about the risks of heavy metal contamination to the aquatic food web and communities depending on them (Ungureanu and Mustatea, 2022).

Heavy metals are well known for their non-biodegradable nature and toxicity; hence, even at low concentrations, they pose long-term environmental and health risks (Mohammadi et al., 2019). Metals such as lead and mercury are neurotoxic, while cadmium can cause damage to the renal system. The presence of these metals in blue crabs calls for serious public health concern since contaminants can be transferred to humans through the consumption of seafood, affecting the different organ systems (Ali et al., 2019). Given this, research on BAF of heavy metals in *Callinectes amnicola* serves as an alert system for potential health impacts on local populations.

Water bodies of the Niger Delta face direct contamination from industrial discharges, while other secondary processes contribute to heavy metal levels, such as atmospheric deposition, agricultural runoff, and urban waste (Sankhla et al., 2016). This complex source of pollution makes management of pollution quite a feat, calling for broad-based monitoring. The blue crab and other aquatic organisms become very important bioindicators that postulate the accumulated effect of these sources of pollution on the environment (Crispin et al., 2024). Previous studies of heavy metal contamination have emphasized the critical need for regular monitoring in highly active industrial areas, especially where local communities depend on possibly polluted aquatic organisms for their nutrition (Masindi and Muedi, 2018; Anyanwu et al., 2018). Focusing on *Callinectes amnicola*, this study will attempt to fill the knowledge gap that exists in the area of bioavailability of metals in sediment and its potential risks to humans and marine life within Elechi Creek. Hence, this study attempts to establish the variability of metal levels in blue crabs and their BAF values in sediment, using the Elechi Creek as a case study. It will also provide important insights into the dynamics of metal bioconcentration and supply data that are useful in risk assessment, regulatory interventions, and community health protection in contaminated coastal environments. The findings could contribute to a better understanding of the complex interplay between industrial contamination and ecological health, offering a foundation for policy change and environmental remediation efforts in the region.

2. MATERIALS AND METHODS

2.1 Study Area

This study was conducted in Elechi Creek. Station 1 shows the Sand Fill area (Eagle Island) at N04°47.149' and E006°58.958' which is split by sand deposition, creating a partially enclosed section without tidal flux, while the other half remains free flowing. It features sharp sand, a hanging latrine, and vegetation dominated by Nipa palm (*Nypa fruticans*), with sparse white mangrove (*Avicennia germinans*), red mangrove (*Rhizophora racemosa*), and elephant grass (*Pennisetum purpureum*). Downstream, the Sawmill area at N04°47.28' and E006°59.255' also has Nipa palm dominance, with sparse white and red mangrove, and elephant grass surrounding the mangroves. Further downstream, the Appa area at N04°47.047' and E006°59.362' is similarly dominated by Nipa palm, sparse mangroves, and elephant grass, with notable features like Nipa palm felling, hanging latrines, and a large stormwater canal (Figure 1).

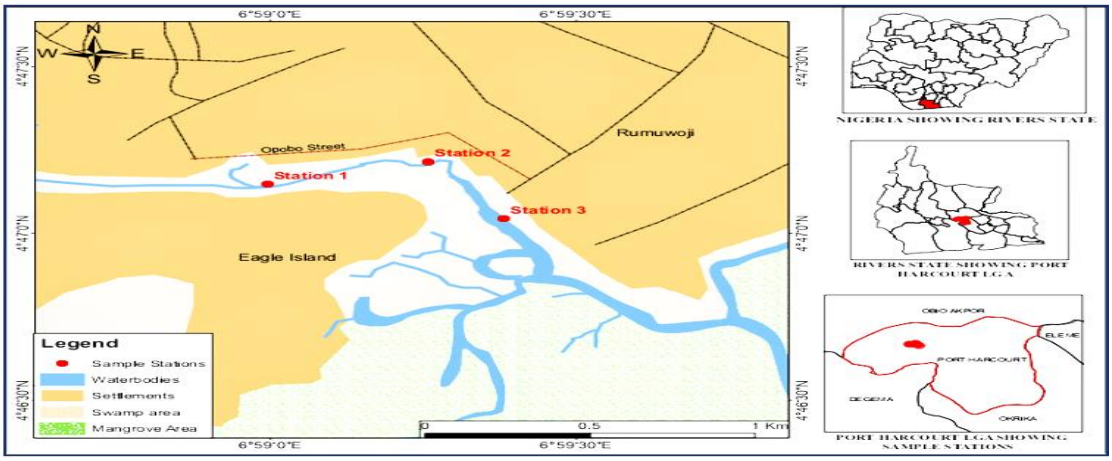


Figure 1: Map of Elechi Creek showing sampled stations

2.2 Sampling Techniques and Sampling procedure

The sampling sites from the study area were denoted with GPS coordinates. Triplicate samples of fish, sediment and water were collected once every month from three (3) selected sites. The timeline for sample collection in this study was 6 calendar months (wet season and dry season).

2.3 Sampling Procedure

A total of three stations was chosen and was at least 1000 meters apart along the river. Based on the peculiarities and features observed around the study area, three sampling stations were selected within the river to reflect different activities in the areas: Station 1, Station 2 and Station 3. Samples collected for analysis included sediment, water and shellfish. All sites were geo-referenced using a handheld global positioning system (GPS) receiver unit (Magellan GPS 315) to generate geographic coordinates (longitudes and latitudes) of the sampling area. Sampling was carried out once a month between January to June 2024. This was carried out during the first week of each sampling month.

2.3.1 Collection of Blue Crab (*Callinectes amnicola*) Samples

The shellfish samples were collected from the local fishermen at each sample station and stored in a cooler packed with ice block to maintain freshness and later transported to the laboratory.

2.3.2 Water Sample Collection

Surface water samples were collected in pre-cleaned high-density Schott glass bottles. The sampling bottles were cleaned using detergent then rinsed with tap water and soaked in 50% hydrochloric acid (HCl) for 24 hours before sampling. The bottles were then washed with tap water and rinsed with triple distilled water before sampling. The bottles were cleaned to ensure that they were not contaminated with metal residue before sampling and to prevent adhering metals to a glass surface since the acidification of the glass enhances metal dissolution. Samples

after collection were properly sealed and transported in an ice pack to the laboratory for analysis.

2.3.3 Sediment Collection

A total of nine sediment samples were taken at monthly intervals for six months, from January to June 2024, from three sampling stations. The sediments were collected once a month for six months in the form of composite from three different stations using an 'Ekman grab' sampler and kept in a plastic container which has been previously treated with 10 % nitric acid for 24 hours and rinsed with de-ionized water. Muddy sediment was collected and not sandy sediment because of the low porosity of the former. Sediment samples was air dried; the shellfish samples were granulated using a blender and the water was digested using 20 ml conc. H_2SO_4.

All samples were taken to Giolee Global Resources Limited, 18 Uyo Street, Rumuomasi, Port Harcourt. In the laboratory, samples were stored at 20°C until further treatment and analysis using the Atomic Absorption Spectrophotometric Machine (API-RP 45). The reason for sampling from the bank was to ensure that the water and sediment samples represented the actual and pronounced pollution pockets in the study area.

2.4 Heavy metal analysis

The heavy metal analysis was done using APHA 3111 (Eze and Chigbu, 2015). The heavy metals analyzed were Chromium (Cr), Lead (Pb), Copper (Cu), Cadmium (Cd), and Iron (Fe), using the Atomic Absorption Spectrophotometric (AAS) method. The instrument setting and operational conditions were done according to the manufacturers' specifications.

2.4.1 Total Digestion for Heavy Metals

The samples were heated in the fume hood with an electrical mantle at 250 ^{o}C until the granule changed from dark to grey colouration (this ensured complete digestion). The digested solution was removed from the fume hood, placed on the workbench and allowed to cool after heating. 20 ml of distilled water was added and allowed to cool further. The digested solution was sieved using a Whatman 42 filter ashless filter paper into a 100 ml glass volumetric flask. The digested filtrate in the volumetric flash was made up to the 100 ml mark on the flask. This was later transferred to a clean 100 ml plastic bottle and labelled. Sample extracts were ready for AAS analysis for Pb, Cr, Cu, Cd and Fe.

2.4.2 Evaluation of Tissue Concentration of Heavy Metals

The bioaccumulation through water and sediments in tissues was calculated by simple form of bioaccumulation factor, BAF, and Bioconcentration Factor, BCF, by the division of heavy metal concentration in shellfish tissue to that in water and simple form BSAF by the division of heavy metal concentration in shellfish tissue to that in sediment. It was calculated using concentrations at dry weight. It is the relation of the concentration of heavy metal in a fish species to the levels of such heavy metal in water and sediment which is described as (USEPA, 2005).

$$BAF/BCF = \frac{\text{Concentration in fish}}{\text{Concentration in Water}} \quad (1)$$

$$BAF/BCF = \frac{\text{Concentration in fish}}{\text{Concentration in Sediment}} \quad (2)$$

BAF/BCF value greater than 1 indicates high accumulation potential

2.5 Quality Assurance/Quality Control

Quantitative analysis, using an internal standard, was performed under optimum experimental conditions based on the method reported by Shi et al. (2018). All proper Quality Assurance measures were addressed throughout the field and laboratory methodology adjusted wherever necessary to maximize data quality. The cleaning of sample bottles was done in the laboratory for this purpose by using mild hydrochloric acid and then rinsed with de-ionized water. All the reagents used were of analytical grade, and the glass was cleaned very carefully. Standard

methods for the investigation of heavy metals and mineral elements were conducted to determine the quality of shellfish, water, and sediments. For this purpose, an atomic absorption spectrophotometer and Flame Photometer (FP Model 140)-Perkin-Elmer were employed. Deionized water was consistently used throughout the study. Samples for the heavy metals under consideration were collected within Port Harcourt and analyzed independently. The shellfish, water, and sediment samples were appropriately labelled, while the shellfish was stored in an ice-chest container to maintain reliability and then transported to the laboratory for further analysis.

3. RESULTS

3.1 Mean Variations of the Metals Levels in Blue Crab, (*Callinectes amnicola*)

Table 1 presents the mean variations in metal levels in blue crab (*C. ammicola*) at three different stations, encompassing Cd, Pb, Fe, As, Zn, and Cu concentrations. Cd and Pb levels remained consistently low across all stations, recorded at 0.003±0.001 mg/kg and 0.004±0.000 mg/kg, respectively. Significant variations were observed in Fe concentrations among stations, with values of 30.9±5.5 mg/kg, 26.15±4.8 mg/kg, and 42.8±4.8 mg/kg at stations 1, 2, and 3, respectively. As levels were uniformly low, with values of 0.003±0.002 mg/kg at all stations. Furthermore, variations were noted in Zn and Cu concentrations, with higher levels observed at station 3. Zn values ranged from 144.8±6.7 mg/kg to 164.9±12.4 mg/kg across the three stations, while Cu values ranged from 4.72±5.8 mg/kg to 5.51±4.4 mg/kg at stations 1, 2, and 3, respectively. Overall, the data reveals spatial discrepancies in metal concentrations in blue crab specimens, emphasizing the importance of comprehensive monitoring and management strategies in aquatic ecosystems.

Table 1: Variations of the metal levels in blue crab (*Callinectes amnicola*)

Heavy metals (mg/kg)	Station 1	Station 2	Station 3
Cd	0.003±0.001 [a]	0.003±0.002 [a]	0.003±0.002 [a]
Pb	0.004±0.00 [a]	0.004±0.00 [a]	0.004±0.00 [a]
Fe	30.9±5.51 [ab]	26.15±4.85 [b]	42.8±4.85 [a]
As	0.003±0.002 [a]	0.004±0.002 [a]	0.003±0.002 [a]
Zn	144.8±6.78 [b]	110.2±12.4 [c]	164.9±12.4 [a]
Cu	4.72±5.84 [ab]	3.83±4.48 [b]	5.51±4.48 [a]

3.2 Mean Variations of the Hazardous Metals Concentrations in Sediment

The results in Table 2 shows the spatial variation in hazardous metal concentrations across sediment samples from three sampling stations (ST1, ST2, and ST3), with notable differences observed for certain metals. However, iron (Fe) concentrations are relatively stable across all stations, ranging from 154.1 ± 20.3 mg/kg at ST1 and ST2 to a slightly higher concentration of 161.1 ± 27.3 mg/kg at ST3, marking ST3 as the station with the highest Fe level. Zinc (Zn) concentrations show minimal variability, with mean values nearly identical across the three stations: 211.9 ± 22.3 mg/kg at ST1 and ST2, and a slightly reduced concentration of 210.9 ± 20.7 mg/kg at ST3. This slight difference suggests Zn distribution is relatively uniform among the sites. Meanwhile, lead (Pb) displays a modest increase at ST3, with a concentration of 10.20 ± 2.17 mg/kg, compared to 9.60 ± 5.23 mg/kg at ST1 and ST2. Although the variation in Pb levels is limited, ST3 records the highest concentration. Cadmium (Cd) levels show mild spatial variation, with ST3 at 3.43 ± 1.68 mg/kg, slightly higher than the consistent concentration of 3.02 ± 1.14 mg/kg observed at ST1 and ST2, indicating ST3 has the highest Cd concentration. Although Copper (Cu) concentration is significantly elevated at ST3, reaching 425.1 ± 22.4 mg/kg, compared to 382.9 ± 22.5 mg/kg at both ST1 and ST2, marking ST3 as the station with the highest Cu concentration by a substantial margin. Arsenic (As) also records a small increase at ST3, with a concentration of 0.017 ± 0.003 mg/kg, slightly higher than the levels at ST1 and ST2, which are 0.014 ± 0.003 mg/kg and 0.015 ± 0.003 mg/kg, respectively. Although the concentration is minimal, the highest value is at ST3.

Table 2: Variations of the hazardous metals' concentrations in sediment

	(mg/kg)					
Stations	**Fe**	**Zn**	**Pb**	**Cd**	**Cu**	**As**
ST1	154.0±20.3[a]	212.0±22.3[a]	9.60±5.23[a]	3.02±1.14[a]	383.0±22.5[a]	0.014±0.003[a]
ST2	154.1±20.27[a]	211.9±22.3[a]	9.6±5.23[a]	3.02±1.14[a]	382.9±22.5[a]	0.015±0.003[a]
ST3	161.1±27.3[a]	210.9±20.7[a]	10.20±2.17[a]	3.43±1.68[a]	425.1±22.4[a]	0.017±0.003[a]

3.3 Concentrations of Hazardous Metals in Surface Water

The analysis of hazardous metal concentrations in surface water, as presented in Table 3, reveals notable variations across the three sampling stations (ST1, ST2, and ST3). Station ST1 consistently demonstrates the lowest concentrations among the three stations, with iron (Fe) at 33.2 ± 10.5 mg/L, zinc (Zn) at 10.6 ± 3.70 mg/L, lead (Pb) at 0.07 ± 0.03 mg/L, cadmium (Cd) at 0.04 ± 0.02 mg/L, copper (Cu) at 111.4 ± 65.8 mg/L, and arsenic (As) at 0.004 ± 0.003 mg/L. These levels serve as the baseline for comparison. However, station ST3 shows slightly elevated concentrations for several metals compared to ST1. Fe is observed at 35.8 ± 8.9 mg/L, and Zn at 11.9 ± 3.1 mg/L. Cd also has a minor increase, recorded at 0.06 ± 0.03 mg/L. The Cu concentration is similarly elevated at 114.1 ± 65.0 mg/L. However, Pb and As levels remain comparable to those at ST1, with Pb at 0.07 ± 0.02 mg/L and As at 0.004 ± 0.003 mg/L. Station ST2 generally exhibits intermediate concentrations between ST1 and ST3. Fe remains consistent with ST1 at 33.2 ± 9.19 mg/L, while Zn is moderately higher at 11.4 ± 5.0 mg/L. Pb shows a slight increase to 0.11 ± 0.06 mg/L, as does Cd at 0.05 ± 0.02 mg/L. Cu is the highest among the three stations at 115.27 ± 67.3 mg/L, and As is slightly elevated at 0.005 ± 0.003 mg/L. Generally, ST1 registers the lowest concentration across all metals, establishing it as the least contaminated site. ST3 records the highest levels for Fe, Zn, Cd, and Cu, while ST2 generally falls between ST1 and ST3, though it has the highest Cu concentration among the stations

Table 3: Concentrations of hazardous metals in surface water

	(mg/L)					
Stations	**Fe**	**Zn**	**Pb**	**Cd**	**Cu**	**As**
ST1	33.2±10.5[b]	10.6±3.7[a]	0.07±0.03[b]	0.04±0.02[a]	111.4±65.8[b]	0.004±0.003[a]
ST2	33.2±9.19[b]	11.4±5.0[a]	0.11±0.06[a]	0.05±0.02[a]	115.3±67.3[a]	0.005±0.003[a]
ST3	35.8±8.9 [a]	11.9±3.1[a]	0.07±0.02[b]	0.06±0.03[a]	114.1±65.0[a]	0.004±0.003[a]

3.4 Bioaccumulation Factor (BAF) of Metals in *Callinectes amnicola*

In Table 4, examining the Bioaccumulation Factor (BAF) values for metals in *Callinectes amnicola* across different sampling stations reveals notable variations. For iron (Fe), the highest BAF value is observed at Station 3 (ST3) with 1.1955 mg/kg, while the lowest value is at Station 2 (ST2) with 0.7877 mg/kg. Regarding zinc (Zn), the highest BAF value occurs at ST3 with 13.8571 mg/kg, whereas the lowest is at ST2 with 9.6667 mg/kg. For lead (Pb), the BAF values remain consistent across all stations, with the same highest and lowest values observed at ST1, ST2, and ST3 (0.0571 mg/kg). However, Cadmium (Cd) exhibits minor fluctuations, with the highest BAF value observed at ST1 (0.075 mg/kg) and the lowest at ST3 (0.05 mg/kg). In addition, it can be noticed that the BAF values of Cu have small ranges: the highest value in ST3 was 0.0483 mg/kg, while the lowest was in ST2, at 0.0332 mg/kg. Lastly, for As, regular values of BAF were found among all stations having the same maximum and minimum values in ST1, ST2, and ST3, with 0.75 mg/kg. These results reflect the different trends of metallic accumulations in *Callinectes amnicola* from one sampling station to another. In light of metal exposure risks, they are very important within any given aquatic environment.

Table 4: Bioaccumulation factor (BAF) of metals in *Callinectes Amnicola*

	(mg/kg)					
Stations	**Fe**	**Zn**	**Pb**	**Cd**	**Cu**	**As**
ST1	0.930723	13.66038	0.057143	0.075	0.04237	0.75
ST2	0.787651	9.666667	0.036364	0.06	0.033226	0.8
ST3	1.195531	13.85714	0.057143	0.05	0.048291	0.75

3.5 Bioconcentration Factor BCF and Bioaccumulation Factor of Metals in *Callinectes amnicola*

Table 5 presents the bioconcentration factors of different metals in *Callinectes amnicola* tested at different sites. For ST1, BCF values were observed as follows: Fe (0.2005), Zn (0.6833), Pb (0.0004), Cd (0.0009), Cu (0.0123), and As (0.2143). The following metals presented values of BCF in ST2 similar to ST1: Fe (0.1697), Zn (0.5201), Pb (0.0004), Cd (0.0009), Cu (0.0100), and As (0.2667). The BCF values, for example, recorded at ST3 were as follows: Fe (0.2657), Zn (0.7819), Pb (0.0004), Cd (0.0009), Cu (0.0130), and As (0.1765). *Callinectes amnicola* had been observed to be more efficient at bioaccumulating the metals of zinc and iron in preference to the other metals, while there was little concentration observed in the case of lead and cadmium. All these BCFs are continued to assess any risk that may arise in aquatic ecosystems. Table 6 presents the metals' BAFs in *Callinectes amnicola* at each sampling site for the different metals. The range of BCFs at ST1 was as follows: Fe (0.2005), Zn (0.6833), Pb (0.0004), Cd (0.0009), Cu (0.0123), and As (0.2143). Similarly, ST2 revealed BCF values for Fe as 0.1697, Zn as 0.5201, Pb as 0.0004, Cd as 0.0009, Cu as 0.0100, and As as 0.2667. For ST3, the respective calculated BCF values were Fe (0.2657), Zn (0.7819), Pb (0.0004), Cd (0.0009), Cu (0.0130), and As (0.1765). These results show the various patterns of metal accumulation within the *Callinectes amnicola*, whereby zinc and iron will have remarkable bioconcentration, while lead and cadmium have barely accumulated. Systematic measurement of BAF values is so important for the assessment of potential ecological risks within aquatic ecosystems.

Table 5: Bioconcentrations factor (BCF) of Metals in *Callinectes Amnicola*

	(mg/kg)					
Stations	**Fe**	**Zn**	**Pb**	**Cd**	**Cu**	**As**
ST1	0.200519	0.683341	0.000417	0.000993	0.012327	0.214286
ST2	0.169695	0.520057	0.000417	0.000993	0.010003	0.266667
ST3	0.265673	0.781887	0.000392	0.000875	0.012962	0.176471

Table 6: Bioconcentrations Factor (BAF) of Metals in *Callinectes amnicola*

	(mg/kg)					
Stations	**Fe**	**Zn**	**Pb**	**Cd**	**Cu**	**As**
ST1	0.200519	0.683341	0.000417	0.000993	0.012327	0.214286
ST2	0.169695	0.520057	0.000417	0.000993	0.010003	0.266667
ST3	0.265673	0.781887	0.000392	0.000875	0.012962	0.176471

4. DISCUSSION

4.1 Spatial distribution of heavy metal contamination in aquatic ecosystems

The study focused on the spatial distribution of heavy metal contamination in aquatic ecosystems at three stations and blue crab *C. ammicola* at Elechi Creek. Cd and Pb values were, however, consistently low between all the stations, which indicated minimal anthropogenic inputs or low bioavailability of those metals in the study area. However, there was a high difference of significance regarding the levels of Fe, Zn, and Cu among the stations, thus suggesting possible sources of contamination and a spatial variation in metal accumulation.

Several reasons that may be responsible for the differences in the level of metals observed among the blue crab specimens in various stations of the study area are remarkably vast in the Niger Delta region, especially Rivers State. Cd and Pb usually originate from industrial activities, urban runoff, and mining operations, which could contaminate water bodies through several discharging routes or atmospheric deposition (Hanfi et al., 2020). However, the uniformity in the concentration levels of Cd and Pb throughout all stations may portray a minimal anthropogenic input, and there might be some effective natural attenuation processes that so far could be limiting their bioaccumulation in aquatic organisms (Zhou et al., 2023; Ekoa, 2023).

Large variation in the Fe concentrations within the studied stations may indicate a possible source of contamination or natural geochemical gradient within the study area (Cyriac et al., 2021). The high levels of Fe at Station 2 might originate from inputs by natural weathering of soil erosion or resuspension of sediments (Wen et al., 2020), which may be indicative of crude oil contamination in the creeks of the Niger Delta (Masindi and Muedi, 2018; Mansor et al., 2024). Relatively low concentrations of Fe in Stations 1 and 3 may be due to dilution effects or lower sedimentation rates with a change in the chemistry of waters (Giles et al., 2016; Liu and Algeo, 2020).

The differences in Zn and Cu values between the different stations expose their spatial distribution in terms of metal accumulation and perhaps different sources of contamination, especially at Station 3. These values denote inputs from industrial discharges, urban runoff, or farm activities next to the analyzed stations (Marrugo-Negrete et al., 2017). On the contrary, Aigberua and Inengite (2019) noted that Zn and Cu are constituent elements of crude oil and therefore releases that are associated with oil exploration activities coupled with production and transportation lead to widespread environmental contamination. Oil discharges coupled with spills and leakages introduce Zn and Cu into aquatic environments where they accumulate in the sediments and biotas inclusive of the blue crab, according to Wang et al. (2022).

It should be noted that considering these findings, the spatial anomalies of trace metal concentrations in blue crab specimens have profound implications for ecosystem health and human wellbeing. High loads of heavy metals like Fe, Zn, and Cu can then accumulate in aquatic organisms and biomagnify through food webs, posing a serious risk to both the predators and human consumers. Contaminated seafood consumption results in chronic exposure to heavy metals, which causes several health defects such as neurological disorders, cardiovascular diseases, and developmental abnormalities. Several studies reported that neurologic disorders to cardiovascular disease, developmental abnormalities, etc., are caused by consuming contaminated seafood with chronic exposure to heavy metals (Rehman et al., 2018; Yang et al., 2020; Munir et al., 2021). Heavy metal contamination in aquatic ecosystems disturbs ecosystem functioning, impairs nutrient cycling, and reduces biodiversity.

4.2 Variations of The Hazardous Metals Concentrations in Sediment

The concentration analysis of hazardous metals in sediment samples collected from Elechi Creek at ST1, ST2, and ST3 represents valuable information with respect to the spatial distribution and variability of metal contamination within an aquatic environment. This

knowledge is paramount for the proper assessment of potential environmental risks and their implications within the scope of ecosystem health and human well-being. Data from both ST1 and ST2 showed consistent hazardous metals in sediments, while little higher concentrations were recorded at ST3, especially for Fe, Pb, Cu, and As. It is important to note that the mean concentration of Fe and Zn was constant throughout all the stations, pointing to a similar characteristic of the sediments or identical sources of pollution governing the metal deposition. However, ST3 presents an average concentration of Pb, Cu, and As slightly higher than the one recorded for ST1 and ST2, indicating a localized contamination or specific sources of anthropogenic activities in proximity to ST3.

Further, several factors might be accountable for the spatial differences in hazardous metals concentrations in sediment samples. The stations near an industrial facility, urban district, or agricultural activities would probably show higher concentrations of metals from direct discharges, runoff, or atmospheric deposition of pollutants (Wang et al., 2020). The slower the water flows or stagnant conditions around a station, the higher the accumulation of metals due to sedimentation and deposition of particulate matter carrying metals (Xue et al., 2022). Sediments with a higher organic content or those that are composed of fine grain particles may have higher metal adsorption capacity, hence the higher metal concentrations in some sediment samples (Zhang et al., 2014). Anthropogenic activities like industrial discharge, urban runoff, mining, and agricultural practices around the creeks could contribute massively to metal contamination in aquatic environments (Pandey and Kumari, 2023). Higher levels of metals in sediments may be harmful to benthic organisms such as macroinvertebrates, bivalves, and microorganisms that live in sediment; these are important components of nutrient cycling, sediment bioturbation, and ecosystem functions (Urban-Malinga et al., 2023). Accordingly, the toxicity of metals can disrupt physiological processes, decrease reproductive success, and cause population declines within benthic communities through alterations in the natural function of habitats (Shen et al., 2022).

Building up a high concentration of metals in sediment can alter the quality and physical properties of the sediment, such as habitat quality for benthic organisms. The change in structure and stability of sediments can affect sediment-water interactions, nutrient dynamics, and oxygen availability and, in turn, will affect ecosystem processes and the biota of sediment-dwellers. For instance, Anyanwu et al. (2018) pointed out that chronic long-term exposure to hazardous metals in sediment could have a long-lasting effect on ecosystem structure, function, and resilience. Community dynamics will be altered along with the trophic interaction, leading to a shift in the timing of ecosystem productivity due to the long-term legacy effect of metal contamination, as mentioned by Zorzal-Almeida et al. (2021) and Siddique et al. (2024).

4.3 Bioaccumulation Factor (BAF) of Metals in *Callinectes amnicola*

Bioaccumulation is based on the increase in metals within tissues over time, while biomagnification refers to an increase in concentrations of metals as it moves up the trophic ladder. According to Nnaji et al. (2023), the BAFs of metals in *Callinectes amnicola* will elucidate accumulation patterns of metals in the species across various sampling stations in Eagle Island Creek. Understanding these ranges of values on BAF is important in the prediction of health hazards both to crabs and human consumers and for evaluating the condition of health in the aquatic ecosystem.

Callinectes ammicola exhibits an effective bioaccumulation of zinc and iron from all stations, with their BAF values higher when compared to other metals. This indicates that these metals are being easily absorbed and bio-accumulated within the tissues of the crab and reflect possibly high levels of zinc and iron in the environment where they are dwelling (Somerset et al., 2015). Saher and Siddiqui (2019) say that the bioavailability and uptake depend on sediment composition, water chemistry, and dietary preference of the crab. However, lead and cadmium present minimum bioaccumulation in *Callinectes amnicola* because of their relatively low BAF values observed at all stations. Here, the low bioavailability or the slower kinetics of uptake of

both lead and cadmium by the crab are considered a consequence of either its physicochemical properties or metabolic processes (Truchet et al., 2023; de Almeida et al., 2022). However, despite the low metal bioaccumulation in crab tissues, infestation from lead and cadmium presence in the tissues still presumes potential health risks both to the crab population and human consumers, according to Lordan and Zabetakis (2022).

There are several reasons contributing to variations observed in the BAF values between different sampling stations within Elechi Creek. Different water quality parameters, sediment composition, and physicochemical characteristics of the creek might alter the bioavailability and uptake of metals by *C. ammicola* (Taylor et al., 2019). Such factors as pH, dissolved oxygen levels, and organic matter content are likely to affect the speciation and, thus, bioavailability of metals in the aquatic environment, yielding different BAF values of metals in crab tissues (Bakker et al., 2017). As Dalu et al. (2018) pointed out, metals in the creek may not be homogeneously distributed owing to the difference in the sources of metal contamination, including industrial discharges, urban runoff, and agriculture activities, besides natural weathering processes. Higher BAF values for *Callinectes amnicola* regarding metals from specific sources or via pathways may indicate localized hotspots of metal accumulation in the creek. Biological parameters, such as feeding habits, metabolic rates, and physiological characteristics of *C. ammicola*, may also have their impact on this process of metal bioaccumulation and -concentration in crab tissues.

Freeman and Ovie (2017) present several concerns with regard to human consumers who use crabs as part of their diet due to the presence of metals in *C. ammicola* tissues. Accidents in the form of consumption of crab meat contaminated with a higher number of metals, including zinc and iron from crabs, may be beyond permissible limits by different regulatory authorities. These metals can cause health risks through prolonged consumption of crabs, which can further result in heavy metal toxicity, gastrointestinal disturbance, neurological disorders, renal dysfunction, and cardiovascular complications (Rehman et al., 2018; Isangedighi and David, 2019).

Bioaccumulation and biomagnification of the metals which may have accumulated in *C. ammicola* tissues along the food chain may also pose increased health risks to humans upon consumption of organisms at higher trophic levels. Biomagnification of the metallic content in the human consumers who may consume the contaminated crab can thus be achieved, posing increased health risks to them. Some of the gastrointestinal disorders associated with the consumption of crab contaminated with metals may include nausea, vomiting, abdominal pain, and diarrhea (Ahmed et al., 2023).

Both lead and cadmium are considered neurotoxicants that pose detriments to neurological development and functions in humans (Zhou et al., 2020). Chronic exposure to lead and cadmium through seafood contamination might also contribute to the incidence of cognitive impairment, learning disabilities, behavioral problems, and neurodegenerative maladies in human populations, especially in susceptible groups like children and pregnant women (Lucchini et al., 2015; Garza-Lombó et al., 2018; Sharma et al., 2020). The increased levels of metals in *C. ammicola* reflect important food safety concerns for consumers who depend on seafood as a staple of their diet. Adequate measures should be taken to reduce exposure to metals to avoid adverse health effects due to the consumption of polluted seafood.

4.4 Bioconcentration Factor (BCF) of Metals in *Callinectes amnicola*

While biomagnification refers to an increase in concentrations up the food chain, bioconcentration can be defined as the gradual accumulation of metals in tissues over time (Nnaji et al., 2023). The BCFs of metals in *Callinectes amnicola* will provide information on accumulation patterns of metals within these species across different sampling stations at Elechi Creek. Understanding these differences in BCF values is quite important so that the health risks associated both with crabs and consumers along with the general health of the aquatic ecosystem can be considered.

C. ammicola shows efficient bioconcentration of zinc and iron at all the stations; BCF values are always higher than that of other metals. These metals seem to have been highly absorbed and retained within the crab's tissues, thus probably indicating high concentrations of zinc and iron in the ambient environment (Somerset et al., 2015). Some factors may include sediment composition, water chemistry, and dietary preferences of the crab influencing bioavailability and uptake of the metals (Saher and Siddiqui, 2019).

Low values of BCF recorded at all the stations for lead and cadmium suggest that there was a minimum bioconcentration of both metals in *Callinectes amnicola*. This might be attributed to the lower bioavailability or slower uptake kinetics of lead and cadmium by the crab, probably due to their physicochemical properties or metabolic processes (Truchet et al., 2023; de Almeida et al., 2022). However, even though in crab their metal accumulations are minimal, according to Lordan and Zabetakis, 2022, the presence in tissues of lead and cadmium can be dangerous for both the population of crabs and the people consuming them health wise.

The differences in the BCF values obtained from the various sampling stations could have been based on water quality parameters, sediment composition, and physicochemical characteristics of Elechi Creek. These include pH, levels of dissolved oxygen, and content of organic matter, all of which can influence metal speciation and bioavailability in the aquatic environment and, correspondingly, can have effects on the BAF values of metals in crab tissues (Taylor et al., 2019).

Spatially, there may be variations in the sources of metal contamination, including industrial discharges, urban runoff, agricultural activities, and natural weathering processes that could show variation in metal concentration across the creek. Higher BAF values for metals emanating from specific sources or pathways of contamination may reflect localized hotspots of accumulation of these metals within the creek in *C. ammicola* (Dalu et al., 2018). Some of the biological factors that can influence bioaccumulation and bioconcentration of metals in crab tissues are feeding habits, metabolic rates, and physiological characteristics of *C. ammicola* (Freeman and Ovie, 2017).

The assertion is supported by Freeman and Ovie, who examined feedings habit, metabolic rates, and physiological characteristics of *C. ammicola*. Health implications have been raised by the presence of metals in *C. ammicola* tissues for human consumers of crab. The ingestion of crab meat contaminated with a higher amount of these metals, such as zinc and iron, can result in intake beyond the permissible limits prescribed by regulatory authorities. Chronic exposure to these metals through crab consumption may lead to several adverse effects on human health, including heavy metal toxicity, gastrointestinal problems, neurological disorders, renal impairment, and cardiovascular diseases, among Zhang et al. (2021) and Ali and Khan (2018).

Bioaccumulation and biomagnification of metals building up in the tissues of *C. ammicola* across the food chain pose more health risks to human consumers of organisms at higher trophic levels. Biomagnification of contaminated crabs may occur in human consumers since it involves consumption. Consumption of contaminated crabs through ingestion of metals will lead to gastrointestinal illnesses, which are manifested by nausea, vomiting, abdominal pain, and diarrhea (Ahmed et al., 2023).

Among such neurotoxicants, certain metals include lead and cadmium, which have developmental and functional neurological adverse impacts in humans (Zhou et al., 2020). Long-term contact with such sea foods contaminated with lead and cadmium might increase the risk of cognitive impairments, learning disabilities, behavioral disorders, and neurodegenerative diseases not only in the general population but most importantly in sensitive groups like children and pregnant women (Lucchini et al., 2015; Garza-Lombó et al., 2018; Sharma et al., 2020).

Because such low levels of metals in tissues can still pose threats to human consumers of crab food, due diligence in the monitoring of BCF values of metals in crab tissues becomes quintessential in assessing seafood safety for public health protection.

5. CONCLUSION

This study examined how hazardous metals are distributed in space within Elechi Creek of the Niger Delta and the resultant bioaccumulation of the metals in the blue crab species (*Callinectes amnicola*). Station 3 consistently showed elevated concentrations of key metals, such as Fe, Zn, Cd, and Cu, in sediment and water samples. These levels suggest that localized activities, possibly from stormwater inflows and Nipa palm disturbances, contribute significantly to metal accumulation in the downstream areas of the creek. The bioaccumulation factors (BAF) and bioconcentration factors (BCF) calculated for crab tissue provide valuable information on the species' capacity to accumulate these metals from their environment. The highest BAF values were observed for Zn and Fe, highlighting the potential of *Callinectes amnicola* as an indicator species for metal contamination in this aquatic ecosystem. The study emphasizes the need for continuous monitoring programs to assess seasonal variations and track changes in metal concentrations over time. Additionally, regulatory bodies should consider implementing pollution control measures to minimize the input of hazardous metals into aquatic systems, especially in areas of high human activity.

REFERENCE

Abbas, H. H., Aly-Eldeen, M. A., and Abdel-Gawad, H. A. (2020). Evaluation of heavy metal contamination in water and their effects on Blue Crab (*Portunus pelagicus*) and shrimp (*Penaeus semisulcatus*) in the Suez Canal. *Environmental Monitoring and Assessment*, 192, 468.

Ahmed, S., Uddin, M. F., Hossain, M. S., Jubair, A., Islam, M. N., and Rahman, M. (2023). Heavy metals contamination in shrimp and crab from southwest regions in Bangladesh: Possible health risk assessment. *Toxicology Reports*, *10*, 580-588.

Aigberua, A. O., and Inengite, A. K. (2019). Chemical speciation and mobility of heavy metal (Pb, Cd, Zn, Mn) pollutants in crude oil contaminated soils of Niger Delta, Nigeria. *Elixir Appl Chem*, *126*, 52543-52548.

Akankali, J. A., and Davies, I. C. (2021). Heavy metals and physicochemical parameters evaluation in the upper reaches of Bonny River, Niger Delta, Nigeria. *Journal of Applied Sciences and Environmental Management*, *25*(8), 1341-1348.

Ali, H., Khan, E., and Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. *Journal of chemistry*, *2019*(1), 6730305.

Anyanwu, B. O., Ezejiofor, A. N., Igweze, Z. N., and Orisakwe, O. E. (2018). Heavy metal mixture exposure and effects in developing nations: an update. *Toxics*, *6*(4), 65.

Bakker, A. K., Dutton, J., Sclafani, M., and Santangelo, N. (2017). Accumulation of nonessential trace elements (Ag, As, Cd, Cr, Hg, and Pb) in Atlantic horseshoe crab (Limulus polyphemus) early life stages. *Science of the Total Environment, 596*, 69-78.

Bashir, I., Lone, F. A., Bhat, R. A., Mir, S. A., Dar, Z. A., and Dar, S. A. (2020). Concerns and threats of contamination on aquatic ecosystems. In *Bioremediation and Biotechnology: Sustainable Approaches to Pollution Degradation* (pp. 1-26).

Chapman, P. M., and Wang, F. (2001). Assessing sediment contamination in estuaries. *Environmental Toxicology and Chemistry: An International Journal, 20*(1), 3-22.

Crispin, A., and Parthasarathy, P. (2024). Heavy Metal Accumulation in Sediments of a Non-Perennial River in South India: Implications for Ecology and Human Health–A Multi-Index and Statistical Assessment. *Soil and Sediment Contamination: An International Journal*, 1-21.

Cyriac, M., Gireeshkumar, T. R., Furtado, C. M., Fathin, K. F., Shameem, K., Shaik, A., ... and Balachandran, K. K. (2021). Distribution, contamination status, and bioavailability of trace metals in surface sediments along the southwest coast of India. *Marine Pollution Bulletin, 164*, 112042.

Dalu, T., Wasserman, R. J., Wu, Q., Froneman, W. P., and Weyl, O. L. (2018). River sediment metal and nutrient variations along an urban–agriculture gradient in an arid austral landscape: implications for environmental health. *Environmental Science and Pollution Research*, *25*(3), 2842-2852.

Davies, I. C., Odekina, U. M., and Akoko, S. (2022). Distribution of Toxic Metals in Biota, Sediments and Water from a Polluted Mangrove Swamp in Rivers State. *Journal of Geography, Environment and Earth Science International*, *26*(4), 1-14.

Davies, I. C., Wokeh, K. O., Mohamad, N. A., and Fathurrahman, L. (2023). Assessment of temporal variation of water quality parameters and ecotoxic trace metals in Southern Nigeria coastal water. *Polish Journal of Environmental Studies, 32*(5), 1-10.

de Almeida Rodrigues, P., Ferrari, R. G., Kato, L. S., Hauser-Davis, R. A., and Conte-Junior, C. A. (2022). A systematic review on metal dynamics and marine toxicity risk assessment using crustaceans as bioindicators. *Biological Trace Element Research*, 1-23.

Eze, S. O., and Chigbu, G. C. (2015). Physical, chemical and microbiological parameters of Iyi Okai Stream in Abiriba, Ohafia local government area, Abia State, Nigeria. *European Journal of Pure and Applied Chemistry Vol*, *2*(1).

Freeman, O., and Ovie, O. (2017). Heavy metal bioaccumulation in periwinkle (*Tympanostomus Spp*) and blue crab (*Callinectes amnicola*) harvested from a perturbed tropical mangrove forest in the Niger Delta, Nigeria. *Journal of Agriculture and Ecology Research International*, *11*(1), 1-12.

Garza-Lombó, C., Posadas, Y., Quintanar, L., Gonsebatt, M. E., and Franco, R. (2018). Neurotoxicity linked to dysfunctional metal ion homeostasis and xenobiotic metal exposure: redox signaling and oxidative stress. *Antioxidants and redox signaling*, *28*(18), 1669-1703.

Giles, C. D., Isles, P. D., Manley, T., Xu, Y., Druschel, G. K., and Schroth, A. W. (2016). The mobility of phosphorus, iron, and manganese through the sediment–water continuum of a shallow eutrophic freshwater lake under stratified and mixed water-column conditions. *Biogeochemistry*, *127*, 15-34.

Gu, X., Wang, Z., Wang, J., Ouyang, W., Wang, B., Xin, M., ... and Liu, X. (2022). Sources, trophodynamics, contamination, and risk assessment of toxic metals in a coastal ecosystem

by using a receptor model and Monte Carlo simulation. *Journal of Hazardous Materials, 424*, 127482.

Hanfi, M. Y., Mostafa, M. Y., and Zhukovsky, M. V. (2020). Heavy metal contamination in urban surface sediments: sources, distribution, contamination control, and remediation. *Environmental monitoring and assessment*, *192*, 1-21.

Isangedighi, I. A., and David, G. S. (2019). Heavy metals contamination in fish: effects on human health. *Journal of Aquatic Science and Marine Biology*, *2*(4), 7-12.

Kennish, M. J. (2019). *Practical Handbook of Estuarine and Marine Pollution*. CRC Press.

Kuppusamy, S., Thavamani, P., Venkateswarlu, K., Lee, Y. B., Naidu, R., and Megharaj, M. (2020). Remediation approaches for heavy metal contamination in aquatic environments. *Environmental Chemistry Letters, 18*(6), 1999-2027.

Liu, X., and Algeo, T. J. (2020). Integrated analysis of lake sedimentary records of trace metal pollution over the past 200 years. *Science of the Total Environment, 712*, 136396.

Lordan, R., and Zabetakis, I. (2022). Cadmium: A focus on the Brown crab (*Cancer pagurus*) industry and potential human health risks. *Toxics*, *10*(10), 591.

Lucchini, R. G., Aschner, M., Bellinger, D. C., and Caito, S. W. (2015). Neurotoxicology of metals. In *Handbook on the Toxicology of Metals* (pp. 299-311). Academic Press.

Mansor, M. I., Fatehah, M. O., Aziz, H. A., and Wang, L. K. (2024). Occurrence, Behaviour and Transport of Heavy Metals from Industries in River Catchments. In *Industrial Waste Engineering* (pp. 205-277). Cham: Springer International Publishing.

Marrugo-Negrete, J. L., Marrugo-Negrete, J., and Díez, S. (2017). Human health impacts of exposure to metals through extreme consumption of fish from the Colombian Caribbean Sea. *Environmental Geochemistry and Health, 40*, 229-242.

Masindi, V., and Muedi, K. L. (2018). Environmental contamination by heavy metals. In M. S. Naushad (Ed.), *Heavy Metals: Sources, Toxicity, and Remediation Techniques* (pp. 1-24). Elsevier.

Mohammadi, S., Jafarizadeh, M., Shafiei, A., and Peydayesh, M. (2019). Lead and cadmium levels in edible tissues of fish from Maharlu Lake, Iran: Risk-based consumption advisories. *Human and Ecological Risk Assessment: An International Journal, 25*(3), 1-10.

Nnaji, N. D., Onyeaka, H., Miri, T., and Ugwa, C. (2023). Bioaccumulation for heavy metal removal: a review. *SN Applied Sciences*, *5*(5), 125.

Okoyen, E., Raimi, M. O., Oluwatoyin, O. A., and Williams, E. A. (2020). Governing the environmental impact of dredging: Consequences for marine biodiversity in the niger delta region of Nigeria. *Okoyen E, Raimi MO, Omidiji AO, Ebuete A W. Governing the Environmental Impact of Dredging: Consequences for Marine Biodiversity in the Niger Delta Region of Nigeria. Insights Mining Science and Technology*, *2*(3), 555586.

Oluniyi, A. E. (2017). Nigeria's oil and gas production and Niger Delta militant: The need of oil resources to stop oil reliance for sustainable development. *Global Journal of Human Social Science*, *17*(5), 22-34.

Onyena, A. P., and Sam, K. (2020). A review of the threat of oil exploitation to mangrove ecosystem: Insights from Niger Delta, Nigeria. *Global ecology and conservation*, *22*, e00961.

Pandey, S., and Kumari, N. (2023). Impact assessment of heavy metal pollution in surface water bodies. *Metals in Water*, 129-154.

Rehman, K., Fatima, F., Waheed, I., and Akash, M. S. H. (2018). Prevalence of exposure of heavy metals and their impact on health consequences. *Journal of cellular biochemistry*, *119*(1), 157-184.

Saher, N. U., and Siddiqui, A. S. (2019). Occurrence of heavy metals in sediment and their bioaccumulation in sentinel crab (*Macrophthalmus depressus*) from highly impacted coastal zone. *Chemosphere*, *221*, 89-98.

Sam, K., and Zabbey, N. (2018). Contaminated land and wetland remediation in Nigeria: opportunities for sustainable livelihood creation. *Science of the Total Environment*, *639*, 1560-1573.

Sankhla, M. S., Kumari, M., Nandan, M., Kumar, R., and Agrawal, P. (2016). Heavy metals contamination in water and their hazardous effect on human health. *International Journal of Current Microbiology and Applied Sciences, 5*(10), 759-766.

Sayed, A. E., Abdel-Gawad, F. K., and Mekkawy, I. A. (2021). Environmental and public health impacts of heavy metal contamination. *Toxicology Reports, 8*, 1385-1395.

Sharma, S., Wakode, S., Sharma, A., Nair, N., Dhobi, M., Wani, M. A., and Pottoo, F. H. (2020). Effect of environmental toxicants on neuronal functions. *Environmental Science and Pollution Research*, *27*, 44906-44921.

Shen, M., Zhang, Q., Li, R., Zeng, G., and Cheng, H. (2022). Bioaccumulation and health risk assessment of heavy metals in aquatic food webs from the Liaohe River basin, China. *Environmental Science and Pollution Research*, *29*(15), 22445-22458.

Shi, G., Han, X., Zhang, Z., and Zhang, F. (2020). Pollution characteristics and risk assessment of heavy metals in aquatic products from the Bohai Sea, China. *Marine Pollution Bulletin*, *150*, 110751

Siddique, A., Al Disi, Z., AlGhouti, M., and Zouari, N. (2024). Diversity of hydrocarbon-degrading bacteria in mangroves rhizosphere as an indicator of oil-pollution bioremediation in mangrove forests. *Marine Pollution Bulletin*, *205*, 116620.

Somerset, V., Van der Horst, C., Silwana, B., Walters, C., and Iwuoha, E. (2015). Biomonitoring and evaluation of metal concentrations in sediment and crab samples from the North-West Province of South Africa. *Water, Air, and Soil Pollution*, *226*, 1-25.

Taylor, A. A., Tsuji, J. S., Garry, M. R., McArdle, M. E., Goodfellow, W. L., Adams, W. J., and Menzie, C. A. (2020). Critical review of exposure and effects: implications for setting regulatory health criteria for ingested copper. *Environmental management*, *65*, 131-159.

Truchet, D. M., Negro, C. L., Buzzi, N. S., Mora, M. C., and Marcovecchio, J. E. (2023). Assessment of metal contamination in an urbanized estuary (Atlantic Ocean) using crabs as biomonitors: A multiple biomarker approach. *Chemosphere*, *312*, 137317.

Ungureanu, G., and Mustatea, G. (2022). Analysis of heavy metal bioaccumulation in fish tissues from polluted ecosystems. *Ecological Indicators, 144*, 109396.

Urban-Malinga, B., Jakubowska, M., and Białowąs, M. (2021). Response of sediment-dwelling bivalves to microplastics and its potential implications for benthic processes. *Science of the Total Environment*, *769*, 144302.

Wang, J., Shan, Q., Liang, X., Guan, F., Zhang, Z., Huang, H., and Fang, H. (2020). Levels and human health risk assessments of heavy metals in fish tissue obtained from the agricultural heritage rice-fish-farming system in China. *Journal of hazardous materials*, *386*, 121627.

Wen, Y., Li, W., Yang, Z., Zhang, Q., and Ji, J. (2020). Enrichment and source identification of Cd and other heavy metals in soils with high geochemical background in the karst region, Southwestern China. *Chemosphere*, *245*, 125620.

Xue, P., Ding, J., Wang, P., and Lu, R. (2016). Recent progress in the mechanochromism of phosphorescent organic molecules and metal complexes. *Journal of Materials Chemistry C*, *4*(28), 6688-6706.

Yang, X., Wang, X., Yang, Y., Zhang, J., and Xie, J. (2020). Exposure to heavy metals in crabs and associated human health risks. *Ecotoxicology and Environmental Safety, 208*, 111461.

Zhang, C., Yu, Z. G., Zeng, G. M., Jiang, M., Yang, Z. Z., Cui, F., ... and Hu, L. (2014). Effects of sediment geochemical properties on heavy metal bioavailability. *Environment international*, *73*, 270-281.

Zhang, H., Zhao, Y., Wang, Z., and Liu, Y. (2021). Distribution characteristics, bioaccumulation and trophic transfer of heavy metals in the food web of grassland ecosystems. *Chemosphere*, *278*, 130407.

Zhou, L., Wu, F., Meng, Y., Byrne, P., Ghomshei, M., and Abbaspour, K. C. (2023). Modeling transport and fate of heavy metals at the watershed scale: State-of-the-art and future directions. *Science of The Total Environment*, *878*, 163087.

Zhou, R., Zhao, J., Li, D., Chen, Y., Xiao, Y., Fan, A., ... and Wang, H. L. (2020). Combined exposure of lead and cadmium leads to the aggravated neurotoxicity through regulating the expression of histone deacetylase 2. *Chemosphere*, *252*, 126589.

Zorzal-Almeida, S., and de Oliveira Fernandes, V. (2021). Ecological thresholds of periphytic communities and ecosystems integrity in lower Doce River basin. *Science of the Total Environment*, *796*, 148965.