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Trace Metal Dynamics in Niger Delta Mangrove: A Comprehensive Contamination, Pollution, and Bioaccumulation Modeling

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Abstract: This study aimed to investigate the spatial contamination, pollution load, and bioaccumulation of trace metals in the mangrove swamp of the Niger Delta Estuary, focusing on water, sediment, Periwinkles (*P. fusca*), and Whelks (*T. fuscatus*). Samples were collected from May and August 2023 and analyzed for heavy metals (Fe, Zn, Pb, Cd, Cu, and As) across three stations in the Ibaka mangrove swamp, Upper Bonny River Creek, using standard methods. There were station-specific variations for Fe and Zn, while there were no such variations for Pb, Cd, Cu, and As. In surface water, significant differences were observed in Fe, Zn, and Pb concentrations between stations, while Cd, As, and Cu showed minor variations. Sediment analysis revealed varying concentrations of Fe, Zn, Pb, Cd, Cu, and As across stations. The Pollution Load Index (PLI) for water indicated low pollution levels, while the sediment PLI showed elevated pollution in Station 3. Enrichment Factor (EF) values demonstrated significant contamination, especially for Cd. Bioaccumulation Factor (BAF) values in *T. fuscatus* and *P. fusca* were generally below 1, suggesting a low risk of metal contamination to humans. The study underscores the significance of ongoing monitoring and mitigation measures for long-term ecosystem and community health, particularly in addressing heavy metal contamination in sediment.

Keywords; Mangrove, Contamination, Heavy Metal, Bioaccumulation, Pollution

INTRODUCTION

The Ibaka mangrove swamp in the Niger Delta region is an important ecological and socio-economic centre (Udofia *et al*., 2021). However, several environmental degradation issues brought about by oil and gas exploration activities are posing serious problems in this area. Acts of sabotage, crude oil theft, and operational spills have affected both the terrestrial and aquatic ecosystems in the region (Isiaq and Lawal, 2023). The Ibaka mangrove swamp plays a crucial role in maintaining the balance of nature and supporting local communities. But oil and gas exploration activities are all around us and they are causing problems for the environment (Okotie *et al*., 2018). These problems include operational spills and acts of vandalism that hurt both land-based and aquatic ecosystems.

The Ibaka mangrove swamp is vital for the local community's sustenance and economic activities. Fishing and seafood consumption are the cornerstones of their way of life. However, crude oil pollution is posing a significant threat to this way of life through the release of hazardous metals (Sankhla *et al*., 2016; Hojjati-Najafabadi *et al*., 2022). As the region undergoes industrial expansion, commercial activities, and population growth, waste generation is on the rise (Onyena and Sam, 2020). This has led to improper disposal practices, resulting in the pollution of land, air, and water resources.

The untreated or inadequately treated effluents discharged into water bodies are a particular cause for concern, as they introduce heavy metal contamination into the ecosystem (Edokpayi *et al*., 2017; Ilyas *et al*., 2019). These heavy metals, notorious for their persistence and deleterious effects on aquatic life and the ecological balance, pose a formidable risk to the Ibaka mangrove swamp community, primarily through the consumption of river-caught fish and tainted water sources.

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This study aims to bridge the existing gap in knowledge concerning heavy metal contamination in the Ibaka mangrove swamp in the upper reaches of the Bonny River Creek. The study will mostly look at water, sediment, and, more importantly, the health risks of eating *Pachymelania fusca* and *Tympanotonus fuscatus*. Researchers have already looked into the presence of toxic metals in different areas of the Niger Delta. However, the specific risks that come with heavy metal contamination in the Ibaka mangrove swamp are still being looked into. The goal of this study is to find out what effects these toxic metals might have on health and the environment, especially in the tissues of fish species that are known to store these contaminants, which could be harmful to humans. An understanding of these risks is indispensable in crafting strategies to mitigate potential adverse effects on both human well-being and the fragile ecological equilibrium of the region.

MATERIAL AND METHODS

Study Area

Tidal activity has an impact on the Ibaka mangrove swamp, a soft-bottom mangrove ecosystem. It covers an area between the longitudes and latitudes of Station 1 (4°45'02.5"N 7°04'07.4" E), Station 2 (4°44'45.5"N 7°04'38.4" E), and Station 3 (4°43'55.7"N 7°04'30.6"E). The swamp is exposed to pollution from various sources, including domestic and industrial waste from companies like oil and gas and dredging companies, as well as densely populated coastal settlements. The main fish families found in the swamp are Lutjanidae, Clupeidae, Cichlidae, and Claroteidae, with Claroteidae being less common. Other tidal mudflat species include periwinkles (*Pachymelania fusca*) and (*Tympanotonus fuscatus*), gobies, crabs, and mudskippers.

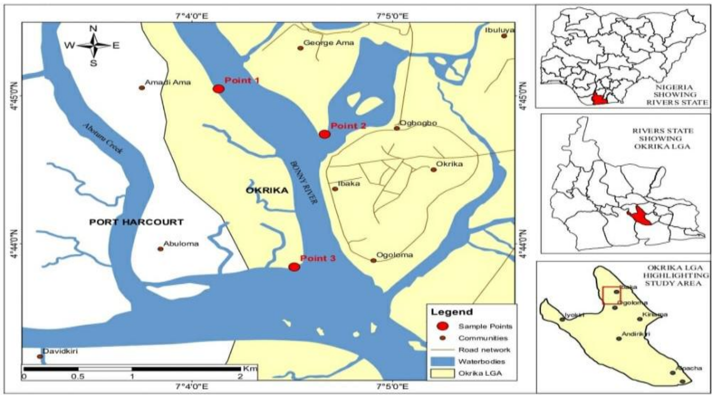

Figure 1. Section of the Bonny River sampled stations studied (Station 1 (Amadi ama), Station 2 (Ogboggo) and Station 3 (Ogoloma).

Sampling and Digestion of Water

Water sampling was done according to Ndimele and Kumolu-Johnson (2012). The sampling process involved the collection of water samples from the creek, below the water's surface. samples were homogenised from three locations. Each homogenized sample was divided into three 500 ml plastic bottles. Plastic bottles were cleaned and rinsed with distilled water before sampling. They were immersed in a creek to ensure accuracy. After collection, 2 mL of nitric acid was added to each sample to minimize metal adsorption. The bottles were labelled with the sampling date and location. The samples were then transported to the laboratory and stored at 4˚C until further analysis. Water samples were digested in triplicate using concentrated nitric acid (Analytical Grade), following the method described by Zhang (2009

Sampling and Digestion of Sediment Samples

Sediment samples were collected from the bottom surface of Okrika from May and August 2023. Three grabs were randomly taken from the banks and mid-creek, homogenized, and placed in clean polyethene bags. The surface layer of sediment is crucial for the exchange of metals between sediments and water and serves as a reserve for benthic organisms. The samples were stored in an icebox and transported to the laboratory. They were thawed at room temperature, transferred to pre-acid cleaned evaporating beakers, dried in an oven, ground, and sieved. Digestion of the sediment samples was carried out using a mixture of concentrated nitric acid and hydrochloric acid in a 1:3 ratio. Approximately 2 g of dry sediment was weighed and placed into a 50 mL acid-cleaning beaker. A freshly prepared mixture of HNO_3 and HCl was added to the sediment, and the mixture was gently boiled over a water bath. The digested sample was filtered using Whatman 0.42 µm filter paper into a 50 mL volumetric flask and analyzed for heavy metals using AAS. A blank solution was prepared as a control.

Sampling and Digestion of the Sampled Shellfishes

Periwinkle *T. fuscatus* and *P. fusca* samples were collected from Lower Buguma Creek using cast fishing nets. The samples were collected from three main fishing zones twice, from January 2023 to June 2023. The samples were stored in pre-acid cleaned polythene bags, sealed, labelled, and stored in ice boxes. The samples were transported to a laboratory for analysis, where they were analyzed for muscle tissues, which are the most consumed part of the fish. The study found that significant levels of toxic metals in muscle tissues could pose greater human health risks. The two fish species analyzed are the most consumed from the dam all year round. The shellfish muscles were weighed and digested in triplicate using APHA (2005) methods. Concentrated nitric acid was added to each weighed fish muscle, heated at 100˚C, and hydrogen peroxide was added until no brown fumes were observed. The digested fish sample solutions were filtered using Whatman 0.42 µm filter paper into 50 mL volumetric flasks filled with distilled-deionized water. The resulting filtrate was then transferred to pre-cleaned plastic bottles. The process ensured accurate and reliable results.

Analysis of Heavy Metals

Atomic Absorption Spectrophotometers (AAS) were utilized for determining metal concentrations for iron, zinc, lead, cadmium, copper, and arsenic, adhering strictly to APHA (1998) procedures.

Statistical analysis

One-way analysis of variance (ANOVA) was used to determine the differences in heavy metal concentrations in sediment and benthic fauna between wet and dry seasons at a significance level of 0.05. The standard errors were also calculated. IBM SPSS Statistics 20 and Microsoft Excel 2010 were used for all statistical analysis.

The metals pollution load index (MPLI)

Pollution load index (MPLI) measures the amount of metal in sediment that is above background concentration. According to Yang *et al*. (2016), it provides comprehensive information about the metal toxicity in a particular sample. MPLI is calculated by multiplying the concentrations by nth root. A MPLI value > 1 indicates pollution, whereas a value of < 1 indicates no pollution (Barakat *et al*. 2020). The MPLI was calculated using the formula proposed by Tomilson *et al*. (1980).

$$MPLI = (CF1 \times CF2 \times CF3 \cdots \times CFn)1⁄n \quad (1)$$

CF is the contamination factor and n is the number of metals studied in the present study.

Degree of Contamination (DC)

Several trace metals are present in sediment, which can pose environmental risks. Essien *et al*. (2019) used it in a study developed by Hakanson (1980). The equation is given by:

$$DC = \sum_{i=1}^{n} Cf_1 \quad (2)$$

The contamination factor of metal is Cf1. A DC greater than 24 is considered to have a very high degree of contamination, whereas a DC greater than 6 is considered to have a low degree of contamination.

Enrichment Factor (EF)

An Enrichment Factor (EF) analysis of the measured heavy metals was conducted (Buat-Menard and Chesselet, 1979)

$$\mathrm{EF} = \frac{\mathrm{Cn/Cref\ sample}}{\mathrm{Bn/Bref}} \quad (3)$$

The concentration of the examined metal in the sample is Cn, the concentration of the reference metal (Fe) is Cref, and the background concentration of the examined metal is Bn. A classification of Enrichment Factors was made based on the following categories: EF = 2 absence to negligible enrichment, EF = 2-5 reasonable enrichment, EF = 5-20 severe enrichment, EF = 20-40 excess enrichment, and EF > 40 exceptional enrichments.

Bio-water Accumulation Factor

By dividing the heavy metal concentration in fish tissue by the concentration in the water, the tissue concentration of heavy metals through the water was calculated using simple form BAF;

BAF = Concentration of metals in fishes (mg/kg) /Concentration of metals in water (mg/kg). (4)

The concentration of heavy metals in fish tissue is divided by the sediment heavy metal concentration to form BSAF.

Bio-sediment accumulation

BAF = Concentration of metals in fishes (mg/kg) /Concentration of metals in sediment (mg/kg). (5)

A ratio between the metal concentrations in fish tissues and the metal concentrations in the water or sediment was calculated using Microsoft Excel 2010.

RESULTS

Iron (Fe), zinc (Zn), lead (Pb), cadmium (Cd), copper (Cu), and arsenic (As) were found in high amounts in the Periwinkles (*P. fusca*) and (*T. fuscatus*). The results are shown in Table 1. The measurements were taken in mg/Kg, and the samples were collected from the Ibaka mangrove swamp in the Upper reaches of Bonny River Creek. For *T. fuscatus*, Fe concentrations varied between 15.54 mg/Kg and 22.12 mg/Kg across the three stations. Station 2 had the highest concentration of 22.12±3.41 mg/kg, while Station 3 had the lowest concentration, recording 15.54±3.71 mg/kg. There was a significant difference ($P > 0.05$) between station 3 and the other two stations.

On the other hand, *P. fuscar* showed iron concentrations ranging from 17.56 mg/kg to 20.17 mg/kg. Station 2 had the highest iron concentration of 20.17±3.24 mg/kg, while Station 3 had the lowest iron concentration of 17.747±0.37 mg/kg. There was a significant difference ($P > 0.05$) between station 2 and the other two stations. The concentration of zinc in *T. fuscatus* ranged from 91.33 to 137.23 mg/kg, with Station 3 showing the highest concentration (137.23±9.09 mg/kg) and Station 1 showing the lowest concentration (91.33±3.22 mg/kg). There were only minor differences in zinc concentration among the three stations. Meanwhile, the concentration of zinc in the P. audit ranged from 101.34 to 132.33 mg/kg, with Station 3 having the highest concentration (132.33±11.91 mg/kg) and Station 1 having the lowest concentration (101.34±4.29 mg/kg). A slight variation was observed in the concentrations of *T. fuscatus* at the three stations.

The lead (Pb) concentration in *T. fuscatus* ranged from 0.004 to 0.005 mg/kg. Station 2 had the highest Pb concentration (0.005±0.00 mg/kg), while Stations 1 and 2 had the lowest concentration (0.004±0.00 mg/kg). There were no significant differences ($P < 0.05$) among the three sample stations. Meanwhile, the lead (Pb) concentration in *P. fusca* ranged from 0.007 to 0.008 mg/kg. The highest concentration of Pb (0.008±0.04 mg/kg) was noted in Stations 1 and 3, while the lowest concentration was 0.007±0.03 mg/kg in Station 2. There were no significant differences ($P < 0.05$) among the three sampling stations for this metal as well.

Cadmium (Cd) concentrations were measured in *T. fuscatus* and *P. fusca* at three sampled stations. The concentration in *T. fuscatus* ranged from 0.013 to 0.016 mg/kg, with the highest concentration

(0.016±0.00 mg/kg) observed in station 1 and the lowest concentration (0.013±0.00 mg/kg) in station 2. No significant differences ($P < 0.05$) were observed among the three stations. On the other hand, the concentration of Cd in *P. fusca* varied between 0.012 to 0.013 mg/kg, with the highest concentration (0.013±0.01 mg/kg) recorded in stations 1 and 2 and the lowest concentration (0.012±0.00 mg/kg) in station 2. No significant variations ($P < 0.05$) were observed in the three stations.

Similarly, Copper (Cu) concentrations were measured in *T. fuscatus* and *P. fusca* at the three sampled stations. The concentration of Cu in *T. fuscatus* varied between 0.89 and 0.98 mg/kg, with the highest concentration (0.98±0.02 mg/kg) recorded in Station 1 and the lowest concentration (0.89±0.05 mg/kg) in Station 2. No significant variations ($P < 0.05$) were observed among the three stations. The concentration of Cu in *P. fusca* ranged from 0.81 to 0.85 mg/kg, with the highest concentration (0.85±0.04 mg/kg) recorded in station 2 and the lowest concentration (0.81±0.03 mg/kg) in station 1. No significant variations ($P < 0.05$) were observed in the three stations.

However, the concentration of arsenic (As) in both fish species at all sampled stations was 0.002 mg/kg. No significant variations ($P < 0.05$) were observed in the three stations. The consistent As concentration recorded in all sample stations indicates a relatively low level of contamination with no variation among the sampled stations.

Table 1. Metals Concentration in Periwinkles (*T. fuscatus and P. fusca*).

(Concentration mg/Kg)						
T. fuscatus						
Locations	**Fe**	**Zn**	**Pb**	**Cd**	**Cu**	**As**
Station 1	19.7±0.70^{a}	91.33±3.22^{b}	0.004±0.00^{a}	0.016±0.00^{a}	0.98±0.02^{a}	0.002±0.00^{a}
Station 2	22.1±3.40^{a}	111.2±4.91^{ab}	0.005±0.00^{a}	0.013±0.00^{a}	0.89±0.05^{a}	0.002±0.00^{a}
Station 3	15.5±3.70^{b}	137.23±9.09^{a}	0.004±0.00^{a}	0.015±0.00^{a}	0.92±0.05^{a}	0.002±0.00^{a}
P. fusca						
Locations	**Fe**	**Zn**	**Pb**	**Cd**	**Cu**	**As**
Station 1	17.8±0.37^{b}	101.34±4.29^{b}	0.008±0.004^{a}	0.013±0.01^{a}	0.81±0.03^{a}	0.002±0.00^{a}
Station 2	20.20±3.2^{a}	113.26±5.99^{ab}	0.007±0.003^{a}	0.012±0.00^{a}	0.85±0.04^{a}	0.002±0.00^{a}
Station 3	17.56±3.2^{b}	132.33±11.91^{a}	0.008±0.004^{a}	0.013±0.01^{a}	0.82±0.04^{a}	0.002±0.00^{a}

Table 2 displays the spatial distribution of heavy metals in surface water across three distinct sampling stations in Rivers State, Nigeria. The results reveal that Station 2 exhibits the highest concentration of Fe (51.72±2.84 ml/L), while Station 1 records the lowest concentration at 31.01±1.11 ml/L. Significant differences ($P > 0.05$) exist between the stations. In the case of Zn, Station 3 registers the highest concentration (17.08±2.09 mg/L), while Station 1 reports the lowest value (11.05±2.15 mg/L). There are significant variations ($P > 0.05$) between Station 3 and the other two stations, while no significant difference ($P > 0.05$) is observed between Stations 1 and 2.

In terms of Pb levels, Station 3 has the highest concentration (0.090.01), followed by Station 2 (0.080.01), and Station 1 has the lowest value (0.070.01). There are no significant differences ($P > 0.05$) in the values among the stations. In the case of Cd, Stations 1 and 2 display the lowest concentrations (0.06±0.01), while Station 1 records slightly higher concentrations (0.07±0.01) of the metal. No significant variations ($P > 0.05$) are observed in the values across the stations.

As concentration is highest in Station 1 (0.005±0.00), while Stations 2 and 3 report the lowest values (0.004±0.00). There are no significant variations ($P > 0.05$) in the values across the stations. Cu concentration is highest in Station 3 (165.27±13.04) and lowest in Station 1 (146.83±16.04). Slight variations ($P > 0.05$) in Cu concentrations exist between the three stations.

Table 2. Spatial Variation of Metals in Water

Locations	**Fe (ml/L)**	**Zn (mg/L)**	**Pb (mg/L)**	**Cd (mg/L)**	**Cu (mg/L)**	**As (mg/L)**
Station 1	31.01±1.11^{c}	11.05±2.15^{b}	0.07±0.01^{a}	0.06±0.01^{a}	146.83±16.04^{b}	0.005±0.00^{a}

Station 2	51.72±2.84^{a}	12.59±3.04^{b}	0.08±0.01^{a}	0.06±0.01^{a}	151.99±18.35^{ab}	0.004±0.00^{a}
Station 3	44.94±0.94^{b}	17.08±2.09^{a}	0.09±0.01^{a}	0.07±0.01^{a}	165.27±13.04^{a}	0.004±0.00^{a}

Table 3 illustrates the spatial distribution of metals in sediment collected from three distinct stations in Rivers State, Nigeria. The examined metals include Fe, Zn, Pb, Cd, Cu, and As. Station 3 records the highest Fe concentrations (1760.96±128.3 mg/Kg), followed by Station 2 (1643.49±77.58 mg/Kg), with Station 1 reporting the lowest Fe concentrations (1628.32±12.64 mg/Kg). The highest Zn concentration is observed in Station 3 (248.66±3.66 mg/Kg), while the lowest Zn concentration is in Station 1 (218.19±4.35 mg/Kg). No significant differences ($P < 0.05$) are found between Zn concentrations in Stations 1 and 2, but both Stations 1 and 2 significantly differ from Station 3.

Regarding Pb content, Station 3 exhibits the highest concentration (14.27±0.03 mg/Kg), whereas Station 1 has the lowest Pb concentration (7.86±1.38 mg/Kg). No significant differences ($P < 0.05$) are observed between Pb content in Stations 2 and 3, and Stations 1 and 2 are also not significantly different ($P < 0.05$) from each other, although Stations 1 and 3 do differ significantly ($P > 0.05$).

Cu content is highest in Station 3 (689.23±86.78 mg/Kg) and lowest in Station 1 (490.71±23.47 mg/Kg). Significant variations ($P > 0.05$) exist among the three sampling stations for Cu. Station 2 records the highest Cd concentration (4.33±0.31 mg/Kg), while Station 1 reports the lowest Cd concentration (2.85±0.56 mg/Kg). Station 3 registers the highest As concentration (0.019±0.00 mg/Kg), and Station 1 displays the lowest As concentration (0.016±0.00 mg/Kg). As reveals no significant differences ($P < 0.05$) between Stations 2 and 3, while Station 1 differs significantly ($P > 0.05$) from the other two Stations.

Table 3. Spatial variation of metals in sediment

Locations	Fe (mg/Kg)	Zn (mg/Kg)	Pb (mg/Kg)	Cd (mg/Kg)	Cu (mg/Kg)	As (mg/Kg)
Station 1	1628.32±12.64^{b}	218.19±4.35^{b}	7.86±1.38^{b}	2.85±0.56^{b}	490.71±23.47^{c}	0.016±0.00^{b}
Station 2	1643.49±77.58^{b}	212.77±0.84^{b}	10.78±0.01^{ab}	4.33±0.31^{a}	566.53±29.26^{b}	0.018±0.00^{a}
Station 3	1760.96±128.3^{a}	248.66±3.66^{a}	14.27±0.03^{a}	3.25±0.24^{ab}	689.23±86.78^{a}	0.019±0.00^{a}

Figures 2 and 3 display the pollution load index (PLI) values for water and sediment samples obtained from three stations. The PLI values for water samples demonstrate no significant differences, as all three stations show remarkably low PLI values ranging from 0.002 to 0.03, signifying a low level of pollution. However, in the sediment samples, there is a notable disparity in PLI values between Station 1 (0.837) and Station 3 (0.837), with Station 3 exhibiting a higher PLI value, indicating elevated pollution levels.

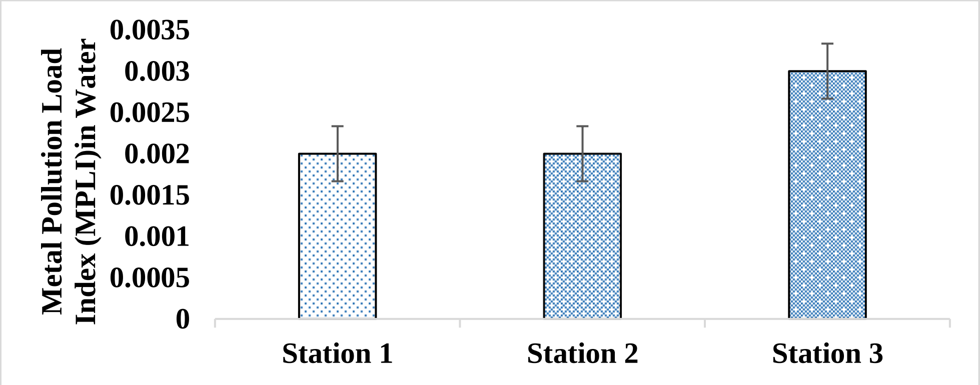

Figure 2. Metal Pollution Load Index (MPLI)in Water

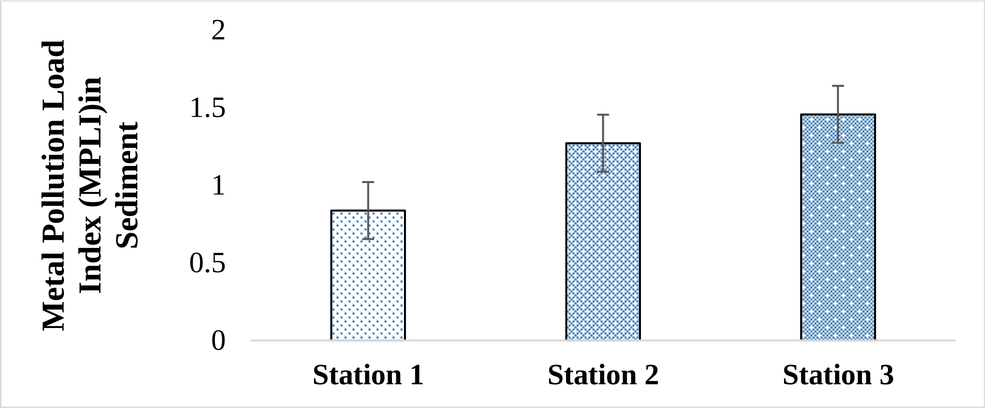

Figure 3. Metal Pollution Load Index (MPLI) in Sediment

Table 4 presents the Enrichment Factor (EF) for heavy metals in water and sediment samples collected from three different stations. The water samples showed the following variation in values: Cd (625.85 to 730.15), Pb (0.02 to 0.02), Zn (0.27 to 0.42), As (0.00 to 0.00), and Cu (3.13 to 3.52), while the sediment samples showed the following variation: Cd (646.96 to 982.93), Pb (0.04 to 0.08), Zn (0.11 to 0.13), As (0.00 to 0.00), and Cu (0.23 to 0.32).

The Enrichment Factor (Er) of heavy metals in sediment and water follows a descending order across the three stations: Cd > Cu > Zn > Pb > As in Station 1, Station 2, and Station 3. However, there is a significant variation in the sediment samples between Station 1 (646.96), Station 2 (982.93), and Station 3 (737.77), with Station 2 showing a higher EF value for Cd. The Pb values exhibited variability, ranging from 0.04 in station 1 to 0.08 in station 3. Notably, there is a noteworthy divergence in sediment samples across all three stations, with each station displaying ascending EF values. For Zinc (Zn), the values in the sediment range between 0.11 in Station 2 and 0.13 in Station 3. No significant variation was observed in the sediment samples between all three stations, with all three stations having increasing EF values. On the contrary, the concentration of As shows no substantial variations, as the ecological risk factor values remain steady at 0.00 across all three stations. However, the concentrations of Cu showed a slight variation, ranging from 0.23 in Station 3 to 0.32 in Station 3.

When considering Cd, there is a notable disparity among sediment samples taken from Station 1 (625.85), Station 2 (625.85), and Station 3 (730.15), with Station 3 displaying a higher EF value. In contrast, Pb values demonstrate little variation in the water collected from Station 1, Station 2 (0.02), and Station 3. Regarding Zn, the water's content ranges from 0.27 at Station 1 to 0.42 at Station 3. A slight fluctuation is observable across all three stations in the water samples, with EF values increasing consistently. The concentration of As exhibits negligible differences, maintaining a steady ecological risk factor value of 0.00 for all three stations. However, the concentrations of Cu show a minor shift, ranging from 3.13 at Station 1 to 3.52 at Station 3. The degree of contamination (DC) values is consistently high for both water and sediment across all stations, indicating significant contamination levels in the samples.

Table 4. Heavy Metals Enrichment Factor and Degree of Contamination (DC)

	Water			**Sediment**		
Metals	**Station 1**	**Station 2**	**Station 3**	**Station 1**	**Station 2**	**Station 3**
Cd	625.85	625.85	730.15	646.96	982.93	737.77
Pb	0.02	0.02	0.02	0.04	0.06	0.08
Zn	0.27	0.31	0.42	0.12	0.11	0.13
As	0.00	0.00	0.00	0.00	0.00	0.00
Cu	3.13	3.24	3.52	0.23	0.26	0.32
DC	**189.025**	**216.444**	**227.454**	**2347.946**	**2437.918**	**2716.389**

Table 5 displays the bioaccumulation (BAF) of metal concentrations in *T. fuscatus* and *P. fusca*, comparing heavy metal concentrations in sediments. The metals BAF are arranged in descending order for each station and fish species: *T. fuscatus*: Station 1: Zn (0.419) > Fe (0.012) > Cd (0.006) > As (0.125) > Cu (0.002) > Pb (0.0005), Station 2: Zn (0.523) > Fe (0.014) > Cd (0.003) > As (0.111) > Cu (0.002) > Pb (0.0004) and Station 3: Zn (0.552) > Fe (0.009) > Cd (0.005) > As (0.105) > Cu (0.001) >Pb (0.0003). while *P. fusca*: Station 1: Zn (0.464) >2. Fe (0.011) > Cd (0.005) > As (0.125) > Cu (0.0016) > Pb (0.0010), Station 2: Zn (0.532) > 2. Fe (0.012) > Cd (0.003) > As (0.111) > Cu (0.0015) > Pb (0.0006), and Station 3: Zn (0.532) > Fe (0.010) > Cd (0.004) > As (0.105) > Cu (0.0012) > Pb (0.0006). BAF factors reveal the ability of the fish to captivate and accumulate heavy metals from aquatic media. The ability of fish communities to uptake and detoxify a variety of trace elements determines how they respond to metal-contaminated sediments. However, bioaccumulation factors (BAF) for *T. fuscatus* and *P. fusca* were generally lower than 1.

Table 5. Bio-sediment accumulation of metals Concentration in *T. fuscatus and P. fusca*.

Fish samples	Locations	Fe	Zn	Pb	Cd	Cu	As
T. fuscatus	Station 1	0.012	0.419	0.0005	0.006	0.002	0.125
	Station 2	0.014	0.523	0.0004	0.003	0.002	0.111
	Station 3	0.009	0.552	0.0003	0.005	0.001	0.105
P. fusca	Station 1	0.011	0.464	0.0010	0.005	0.0016	0.125
	Station 2	0.012	0.532	0.0006	0.003	0.0015	0.111
	Station 3	0.010	0.532	0.0006	0.004	0.0012	0.105

The bioaccumulation factor (BAF) of metal levels in *T. fuscatus* and *P. fusca* is shown in Table 6. This table mainly shows the levels of heavy metals in water. The BAF metals are grouped according to fish species, and each station is listed in decreasing order: For *T. fuscatus*: Station 1: Zn (8.265) > Fe (0.635) > Pb (0.057) > Cd (0.267) > As (0.4) > Cu (0.007); Station 2: Zn (8.832) > Fe (0.427) > Pb (0.063) > Cd (0.217) > As (0.5) > Cu (0.006); and Station 3: Zn (8.035) > Fe (0.345) > Pb (0.044) > Cd (0.214) > As (0.5) > Cu (0.006). For *P. fusca*: Station 1: Zn (9.171) > Fe (0.575) > Pb (0.114) > Cd (0.216) > As (0.4) > Cu (0.005); Station 2: Zn (8.996) > Fe (0.392) > Pb (0.088) > Cd (0.200) > As (0.5) > Cu (0.005); and Station 3: Zn (7.748) > Fe (0.391) > Pb (0.089) > Cd (0.186) > As (0.5) > Cu (0.004). Nevertheless, the bioaccumulation factors (BAF) for *T. fuscatus* and *P. fusca* tended to be consistently below 1.

Table 6. Bio-water accumulation of metals concentration in *T. fuscatus and P. fusca*.

Locations	Fe	Zn	Pb	Cd	Cu	As
			T. fuscatus			
Station 1	0.635	8.265	0.057	0.267	0.007	0.4
Station 2	0.427	8.832	0.063	0.217	0.006	0.5
Station 3	0.345	8.035	0.044	0.214	0.006	0.5
			P. fusca			
Station 1	0.575	9.171	0.114	0.216	0.005	0.4
Station 2	0.392	8.996	0.088	0.200	0.005	0.5
Station 3	0.391	7.748	0.089	0.186	0.004	0.5

DISCUSSION

Metals Concentration in Periwinkles *Tympanotonus fuscatus* and *Pachymelania fusca*

This study examines the concentrations of heavy metals in edible mollusk species *P. fusca* and *T. fuscatus* from three sampling stations in the Ibaka mangrove swamp. The results show lower iron concentrations in stations 2 and 3, suggesting local sources or environmental conditions influencing metal accumulation. Zn levels were relatively consistent across all stations, suggesting no significant variation in pollution. Pb levels in *T. fuscatus* were consistently low, indicating a low risk of lead exposure through consumption. According to Ogbuefi *et al*., (2023), the findings suggest potential local sources or environmental conditions influencing metal accumulation.

The observed concentrations of heavy metals in edible mollusk species (*P. fusca* and *T. fuscatus*) from the Ibaka mangrove swamp can be attributed to various factors, indicating both localized influences and potential environmental conditions that impact metal accumulation (Davies and Anyanwu, 2023). The lower iron concentrations in stations 2 and 3 suggest the presence of local sources or specific environmental conditions that influence the accumulation of this metal. According to Khan *et al*. (2021) and Rodgers *et al*. (2020), local anthropogenic activities, industrial discharges, or natural variations in sediment composition could contribute to these differences.

The relatively consistent levels of zinc across all stations indicate a uniform distribution and suggest no significant variation in pollution for this metal. Birch (2017) suggested that this consistency may reflect a balance between natural background levels and potential anthropogenic inputs. The consistently low levels of lead in *T. fuscatus* indicate a low risk of lead exposure through consumption of this mollusk species. Howver, Cd concentrations were also low and similar among the three stations, suggesting that Cd contamination is uniform within the sampling area. Minor differences were observed in Cu concentrations. The values are within a narrow range, indicating that Cu contamination is relatively uniform across the study area. As concentrations were consistent across all stations, suggesting that As contamination is low and does not significantly vary within the sampling area.

Uniform Cd contamination may pose risks to aquatic organisms and the broader ecosystem. Cd is known for its toxicity to aquatic life, and consistently low levels can still have adverse effects on sensitive species, disrupting the ecological balance (Rehman *et al*., 2018). Okereafor *et al*. (2020) suggest that Cd can accumulate in aquatic organisms and, when consumed by humans, pose health risks. Uniform contamination suggests a consistent exposure risk for communities relying on mollusks for sustenance. Continuous exposure, even to low levels, may have cumulative health effects over time (Sonone *et al*., 2020). While copper is an essential element, high concentrations can be detrimental to human health (Jomova *et al*., 2022).

The narrow range of Cu contamination suggests a uniform presence, which may affect aquatic organisms (Rehman *et al*., 2018). While copper is an essential trace element, elevated concentrations can be harmful, particularly to invertebrates (Jomova *et al*., 2022). The consistency indicates a potential consistent stressor on the aquatic ecosystem. The relatively even Cu contamination implies a consistent exposure risk for communities relying on mollusks. Monitoring and managing Cu levels in seafood are crucial for preventing adverse health effects (Stankovic *et al*., 2012).

The low and consistent levels of arsenic are reassuring from an ecological standpoint. As contamination, even at low levels, can impact aquatic organisms (Alidadi *et al*., 2019). The homogeneity implies a stable condition with minimal variation, which is beneficial for the overall health of the ecosystem. The low and consistent levels of arsenic provide reassurance for human health. According to Lin *et al*. (2020), Arsenic, even at low levels, can be harmful, and the uniformity suggests a stable exposure scenario. Regular monitoring remains essential to ensure sustained low levels.

Station 2 had the highest Fe concentration, while Station 3 had the lowest. These differences may be attributed to local variations in sources or environmental conditions influencing Fe accumulation in the study areas. Zn levels showed slight variations, but overall, the concentrations were similar, indicating relatively consistent Zn pollution across the sampling stations. Pb concentrations in *P. fusca* were consistently low across all stations, similar to the findings for *T. fuscatus*, suggesting minimal lead exposure risks. Cd concentrations were low and showed little variation, indicating a relatively uniform Cd contamination level within the study area. Similar to other metals, Cu concentrations displayed minor variations, but the values were generally consistent across the three stations. As concentrations were consistent and low across all stations, suggesting minimal contamination.

The low variability in heavy metal concentrations in both mollusk species across the sampling stations may indicate that these metals are widely distributed in the environment (Palpandi and Kesavan, 2012). The slight differences observed may be attributed to local factors influencing metal accumulation. The findings do not point to extreme contamination levels, which is positive for the ecological health of the area and the organisms inhabiting it. The relatively low concentrations of heavy metals in both mollusk species are encouraging from a human health perspective. Consuming mollusks with such low metal levels poses minimal risks of heavy metal exposure to local communities.

Spatial variation of metals in sediment

The study reveals spatial variability in Fe concentrations, which indicate potential variations in sediment quality across the study area. Higher Fe concentrations, particularly in Station 3, may affect benthic communities and overall sediment health (Lourino-Cabana *et al*., 2012). However, Enuneku *et al*. (2019) suggested that understanding these variations is crucial for assessing the impact on benthic communities and overall sediment health. According to Kavehei *et al*. (2021), significant differences in Zn concentrations among stations may suggest varying sources of contamination, impacting aquatic ecosystems differently and affecting the composition and health of benthic communities. Elevated Fe concentrations can have adverse effects on aquatic life, and continuous monitoring is essential to understand and manage health risks associated with Fe contamination (Chu *et al*., 2019). Variations in Zn concentrations suggest different contamination sources, and human populations relying on the river for water and food may face variable exposure risks (Kavehei *et al*., 2021).

The spatial distribution of Fe, Zn, and Pb concentrations in sediment samples has both ecological and health implications (Arfaeinia *et al*., 2019). Elevated Fe levels, particularly in Station 3, may impact sediment quality and benthic communities, affecting the composition and health of benthic ecosystems (Rehman *et al*., 2018). According to Belabed *et al*. (2017), different Zn concentrations indicate varying contamination sources, impacting aquatic ecosystems differently. Considering these sources is crucial for implementing targeted measures to mitigate potential ecological consequences. Pb concentrations in Station 3 pose risks due to their toxicity, emphasizing the need for monitoring and management to protect benthic communities and overall aquatic health (Akindele *et al*., 2020).

As a result of elevated Fe levels, aquatic life is potentially adversely affected, as are communities that depend upon the river's water supply for their livelihood. Consistent Pb levels across stations raise concerns for human health risks, and comprehensive monitoring and management strategies are essential to address potential health implications. Cd concentrations suggest varying exposure risks for human populations, as Cd is a known human carcinogen (Rehman *et al*., 2018).

The variation in Cu concentrations across stations indicates diverse sources of contamination, potentially impacting local ecosystems and benthic communities (Izegaegbe *et al*., 2020). Understanding these sources is crucial for assessing and mitigating ecological risks. Human health implications are significant, as variations in Cu levels highlight potential exposure risks for populations relying on the river (Chris *et al*., 2023).

Spatial Variation of Metals in Water

The spatial distribution of heavy metals, including Fe, Zn, and Pb, in surface water has both ecological and health implications. The highest Fe concentration in Station 2 suggests potential ecological impacts on surface water, potentially affecting aquatic ecosystems and affecting aquatic organisms' health (Ezemonye *et al*., 2019). Significant variations in Zn concentrations between Station 3 and other stations indicate differences in contamination sources, impacting aquatic ecosystems differently. According to Naja and Volesky (2017), consistent levels of Pb across all sampling stations suggest a relatively uniform source of contamination, raising concerns for aquatic ecosystems.

Water with elevated Fe concentrations could pose health risks, especially for drinking or domestic use (Bodrud-Doza *et al*., 2020). However, Zn concentrations differ at these stations, suggesting different contamination sources, which could pose health risks to humans (Dong *et al*., 2020). Pb contamination must be identified and addressed to minimize health risks. As a result, implementing effective monitoring and management strategies to protect aquatic ecosystems and human populations requires a thorough understanding of the sources and variations in metal concentrations.

According to Redwan and Elhaddad (2022), aquatic ecosystems are largely contaminated by a uniform source, possibly industrial discharges and agricultural runoff. There were no significant differences in Cd concentration between the stations, which could be because of industrial discharges and agricultural runoff. As contamination is consistent across all stations, with Station 1 having the highest concentration. Cu concentrations between stations suggest a possible uniformity in contamination sources, which could negatively affect aquatic ecosystems. Zeng *et al*. (2020) suggest that concentrations of heavy metals are likely to vary because of anthropogenic factors, such as local industrial activities and urbanization. In addition, significant variations in Fe and Zn levels suggest a need for targeted efforts to address contamination. As, Cd and Pb levels appear to be relatively consistent, which suggests a uniform source of contamination.

Metal Pollution Load Index (MPLI)

The study found that the water quality in the studied area is generally safe for diverse aquatic life, supporting biodiversity and reducing the risk of waterborne diseases (Hossain and Patra, 2020). The low PLI values across all three stations indicate minimal pollution impact on water quality, indicating a relatively clean water environment. This is crucial for supporting aquatic ecosystem health, as clean water is essential for supporting various organisms and contributing to the overall health of the aquatic ecosystem (Keeler *et al*., 2012). However, Hyde (2022) suggested that low PLI values also provide reassurance for public health, as water with minimal pollution levels is safer for human consumption and reduces the risk of waterborne diseases. This positive outlook for the aquatic ecosystem and local communities is emphasized, emphasizing the importance of maintaining clean water sources.

The low Pollution Load Index (PLI) values in the water samples indicate minimal ecological risk, supporting biodiversity and overall ecosystem health. Cantonati *et al*. (2020) confirmed that clean water provides a favourable habitat for various aquatic species, supporting biodiversity in the studied area. The low PLI values also indicate that the aquatic ecosystem is relatively undisturbed by pollution, contributing to overall water quality, habitats, and the well-being of aquatic organisms (Nsenga *et al*., 2020). This creates conditions conducive to the thriving of aquatic life, promoting a balanced and resilient aquatic community. The minimal ecological risk implies that the aquatic ecosystem is resilient to the impact of pollutants, ensuring long-term stability and sustainability (Sang *et al*., 2014). The study's findings provide a positive ecological outlook for the area, fostering a harmonious balance between different species and ecological processes.

Sediment pollution poses significant ecological implications, including vulnerability to the benthic ecosystem, potential bioaccumulation risk, and cascading effects on ecosystem health (Ma *et al*., 2020; Castro-Castellon *et al*., 2022). According to Li *et al*. (2020), Polluted sediments can disrupt the local food web, affecting organisms at different trophic levels, leading to imbalances in predator-prey relationships and potential declines in key species. Community health risks are also heightened, as the potential bioaccumulation of contaminants in fish and seafood poses health risks to those consuming these products (Hoque *et al*., 2022). The presence of pollution in sediment challenges the benthic ecosystem's resilience, making it more susceptible to long-term impacts (Enuneku *et al*., 2019). Environmental monitoring is crucial for identifying elevated PLI values in sediment, allowing for timely interventions and management strategies to mitigate potential ecological harm. Understanding the ecological implications offers opportunities for implementing sustainable management practices, such as reducing sediment pollution, which can contribute to the restoration of benthic habitats, promoting ecosystem health, and supporting sustainable fisheries.

Heavy Metals Enrichment Factor and Degree of Contamination (DC)

Heavy metal contamination in aquatic ecosystems can have significant ecological implications (Chris *et al*., 2023). Disparate enrichment in Cd, consistent Pb contamination in water, and fluctuating Zn levels in water suggest specific sources or varying contamination levels, leading to localized ecological disturbances (Nasiruddin *et al*., 2023). Steady As concentrations indicate low ecological risk, but even low concentrations can have sublethal effects on certain species (Wang *et al*., 2023). A minor shift in Cu concentrations indicates a slight variation in contamination sources or transport mechanisms, impacting sensitive aquatic organisms and the overall health of the ecosystem.

Consistently high Degree of Contamination (DC) values for both water and sediment indicate substantial contamination levels, posing a severe threat to the ecological integrity of the aquatic ecosystem (Ali *et al*., 2020). Jin *et al*. (2022) suggests that heavy metal accumulation in living organisms can disrupt growth and reproduction, affecting various trophic levels in the food web, and leading to imbalances, reduced biodiversity, and potential declines in key species. High contamination levels in both water and sediment pose ecological and health risks, emphasizing the interconnectedness of ecosystem health and human well-being (Delany-Crowe et 2019). Implementing measures to mitigate contamination sources is essential for safeguarding the ecosystem's health and ensuring the well-being of human communities dependent on it.

Bio-sediment accumulation of metals concentration in *T. fuscatus and P. fusca*.

The study reveals the bioaccumulation of heavy metals in fish, specifically Zn, Fe, and Cd, which can pose significant health risks to humans. Consumption of fish with high Cd levels can lead to kidney damage and other adverse effects, particularly for local communities that rely on these fish as a dietary staple (Ahmed *et al*., 2015). Chronic exposure to Cd through contaminated seafood can lead to long-term health issues (Zafarzadeh *et al*., 2018). The bioaccumulation factors (BAF) below 1 suggest that fish are not highly efficient accumulators of these metals, but continuous monitoring and assessment are essential to track changes over time. The study emphasizes the importance of comprehensive risk assessment considering multiple factors. Regular health monitoring is crucial to identify emerging health issues related to heavy metal exposure and guide public health interventions. Sustainable fishing practices and raising community awareness about potential risks are also essential. In conclusion, the study underscores the complex relationship between bioaccumulation in fish, human health risks, and ecological well-being.

The study explores the ecological implications of different metal accumulation patterns in fish species, *T. fuscatus* and *P. fusca*. According to Richir and Gobert (2016), the species-specific responses of fish species to metal-contaminated sediments, suggest that their unique abilities to uptake and detoxify trace elements can influence their interaction with the environment. The variability in metal uptake and detoxification abilities can have cascading ecological consequences, affecting the survival, reproduction, and population dynamics of fish species (Coffin *et al*., 2022). Ustaoğlu and Islam (2020) reported that high metal concentrations in sediments pose a potential threat to the overall health and balance of the aquatic ecosystem. This agrees with Sivalingam *et al*. (2021), who stated that high metal concentrations can disrupt the food web, impacting not only the studied fish species but also other organisms in the ecosystem, leading to imbalances in population dynamics and community structure.

Chris *et al*. (2023) emphasizes the need for ongoing monitoring of metal concentrations in both sediments and fish, as well as the importance of conservation efforts to protect aquatic ecosystems. According to Davies and Anyanwu (2023), For aquatic ecosystems to remain resilient and functional in the face of anthropogenic impacts, a holistic approach is essential. Additionally, human and wildlife protection must be balanced.

Bio-water accumulation of metals concentration in *T. fuscatus and P. fusca*.

The bioaccumulation factors (BAF) for *T. fuscatus* and *P. fusca* are consistently below 1, which is crucial for human health and ecological balance in the studied area. These fish species do not significantly accumulate heavy metals from the surrounding water, reducing the risk of exposure to high levels of these metals. Lower BAF values also indicate that the transfer of heavy metals from water to fish tissue is limited, reducing the risk of exposure to potentially harmful levels of heavy metals (Khallaf *et al*., 2018). Moreover, these fish species do not significantly impact the overall metal cycling and distribution in the aquatic ecosystem, which can pose risks to aquatic ecosystems by affecting fish health, disrupting food chains, and potentially causing long-term ecological imbalances. Thus, these fish species are not significant sinks of heavy metals from the water. Similar results have been reported by Akankali *et al*., (2019) and Davies and Ekperusi (2021) in the Niger Delta region of Nigeria. However, Cui *et al*., 2015 and Ahmed *et al*. (2019) reported higher Concentrations, bioaccumulation, and heavy metals in edible fish from Wuhan in China and in tissues of some commercial fishes from the Meghna River Estuary in Bangladesh.

CONCLUSION

The study findings indicate that low concentrations of heavy metals in mollusk species like *T. fuscatus* and *P. fusca* do not pose significant health risks. Nevertheless, continuous monitoring and mitigation efforts are imperative to ensure the long-term well-being of the ecosystem and the local communities dependent on these aquatic resources. The spatial distribution of metals in sediment underscores the necessity for comprehensive monitoring and management of heavy metal contamination within the research area. Identifying and addressing the sources of contamination is of paramount importance in managing and reducing ecological and health risks associated with these sediment-bound metals. Despite the relatively good quality of water in the region, concerns regarding sediment pollution raise potential ecological and health consequences. Effectively addressing sediment pollution is crucial for preserving the health of the benthic ecosystem and safeguarding the welfare of local communities reliant on aquatic resources. The study underscores the significance of comprehending the intricate interplay between heavy metal contamination, fish bioaccumulation, and potential risks to human health and the environment. Further research and conservation measures are essential to mitigate these risks and protect the health of both ecosystems and local communities.

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