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BIOACCUMULATION OF CARCINOGENIC AND NON-CARCINOGENIC METALS IN *TYMPANOTONUS FUSCATUS* FROM NIGERIAN MANGROVES: HEALTH RISK ASSESSMENT

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ABSTRACT: *Metal and metalloid contamination in aquatic environments poses significant ecological and human health risks, particularly in mangrove ecosystems exposed to industrial and domestic pollution. This study investigates the bioaccumulation of iron (Fe), zinc (Zn), lead (Pb), cadmium (Cd), copper (Cu), and arsenic (As) in Tympanotonus fuscatus var. fuscatus from the soft-bottom mangrove swamps of Lower Ibaka Creek, Rivers State, Nigeria. Samples were collected bimonthly from three sites between January and June 2023. A total of 270 shellfish samples were analyzed using Atomic Absorption Spectrophotometry (AAS) after nitric acid digestion following APHA methods. Quality control measures included reagent blanks, certified reference materials, and calibration standards. Results indicate Fe and Zn were the most abundant metals, while Pb, Cd, Cu, and As were detected at lower concentrations. Pb and Cd exceeded permissible limits in some locations. The estimated daily intake (EDI) and hazard quotient (HQ) values were below threshold limits, suggesting no immediate non-carcinogenic risks, although higher HQ values for children indicate increased susceptibility. Cancer risk (CR) values for Pb and As remained within acceptable limits. ANOVA and Duncan's Multiple Range Test ($p<0.05$) revealed significant spatial variations in metal accumulation. The findings highlight potential ecological threats and the need for pollution control strategies. Continuous environmental monitoring and further research on bioaccumulation pathways are recommended to safeguard aquatic resources and human health in the region.*

KEYWORDS: Metals and metalloids, Bioaccumulation, *Tympanotonus fuscatus*, Health risk, Mangrove pollution.

INTRODUCTION

Metals and metalloid pollution in global aquatic ecosystems represents a compelling and urgent environmental issue. The persistence of these contaminants, their inherent capacity for bioaccumulation in organisms, and the subsequent biomagnification through food chains pose profound risks to both ecological stability and human health (**Islam** et al., 2015). Mangrove swamps, recognized globally as among the most productive and biologically diverse ecosystems, are crucial for supporting complex aquatic life and providing vital resources for local coastal communities (**Alongi**, 2014). These environments also play a critical role as natural carbon sinks.

Despite their ecological importance, mangrove ecosystems are increasingly subjected to severe anthropogenic pressures. Activities such as unmitigated industrial discharge, indiscriminate domestic waste disposal, and extensive resource exploitation, particularly oil exploration activities, introduce vast quantities of toxic metals and metalloids into the environment (**Zhang** et al., 2014). Mangrove sediments act as natural sinks, accumulating heavy metals from diverse sources, including industrial effluents, agricultural runoff, and domestic waste streams. This vulnerability necessitates rigorous assessment to understand the extent of contamination.

The Ibaka mangrove swamp in Rivers State, Nigeria, epitomizes the global challenge of coastal ecosystem contamination. This region is exposed to multiple sources of pollution, including effluents from major oil and gas industries, extensive dredging operations, and domestic sewage derived from surrounding densely populated settlements (**Chris** et al., 2023). These sources contribute toxic metals such as Pb, Cd, Hg, and As into the environment, which are subsequently assimilated by aquatic organisms (**Saunders et al., 2022**).

Shellfish inhabiting these mangrove swamps, particularly the common periwinkle species *Tympanotonus fuscatus var fuscatus*, are ecologically significant. They function as benthic organisms critical to sediment processing and serve as important bioindicators of environmental pollution. Furthermore, *T. fuscatus* is a crucial dietary staple, widely consumed as a primary protein source by coastal populations in the region. Consequently, the bioaccumulation of toxic metals and metalloids in the tissues of this species presents a direct and measurable threat to human health via the food chain (**Zhang** et al., 2014). Clinical studies have established that consumption of contaminated shellfish can lead to severe adverse health outcomes, including neurological disorders, kidney dysfunction, and cardiovascular diseases (**Islam** et al., 2015).

Despite the acknowledged ecological and economic significance of *T. fuscatus* and the known pollution status of the Ibaka mangrove swamp, there exists a notable lack of comprehensive scientific data quantifying the levels of metal(loid) contamination in this specific species and the corresponding risks to human consumers.

This study was specifically designed to bridge this critical knowledge gap by investigating the bioaccumulation of key metals and metalloids (Fe, Zn, Pb, Cd, Cu, and As) in *T. fuscatus* muscle tissues, which represent the mostly consumed part of the organism. This was achieved by determining the concentrations of Fe, Zn, Pb, Cd, Cu, and As bioaccumulated in *T. fuscatus* muscle tissues across the Ibaka Creek sampling sites, analyzing the spatial variability in the metal(loid) concentrations among the three sampling locations, and by assessing the potential

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non-carcinogenic and carcinogenic health risks posed to local adult and child populations through the consumption of this periwinkle.

The anticipated findings of this research provide essential data for formulating public health policies and developing effective strategies for pollution mitigation in mangrove ecosystems, thereby promoting the sustainable use of marine resources in alignment with Sustainable Development Goal 14 (Life Below Water).

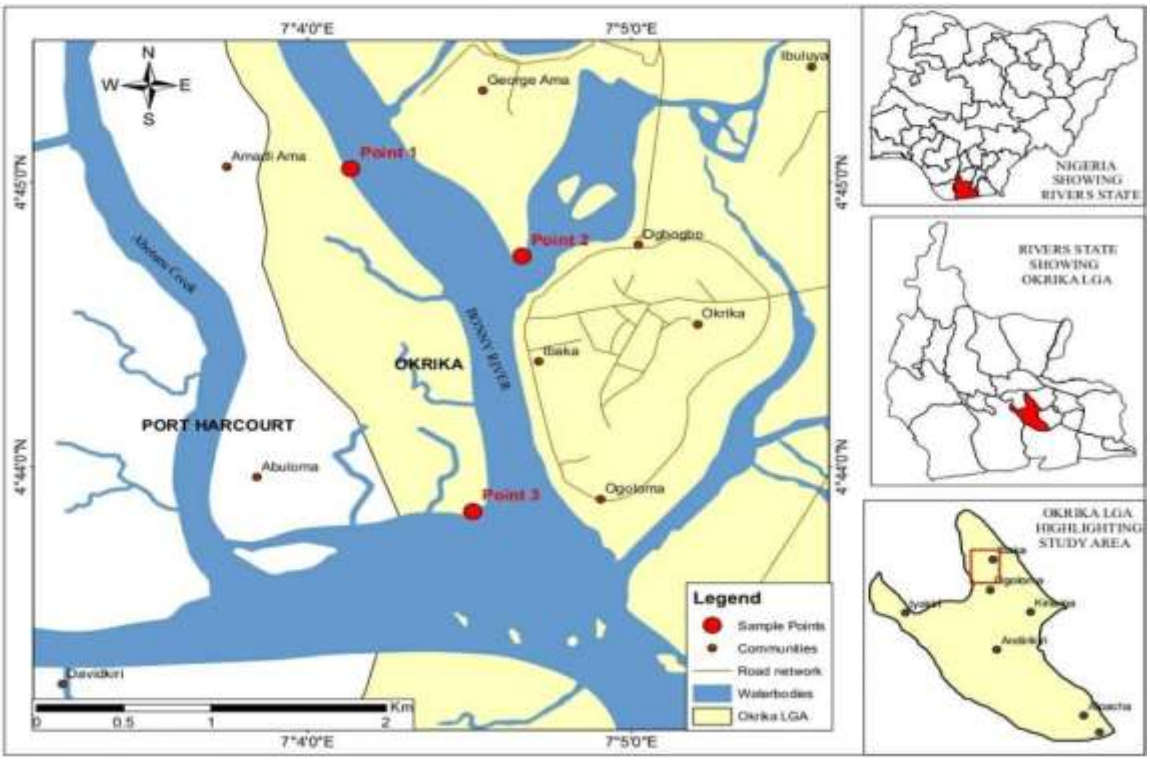
MATERIALS AND METHODS

Study Area and Site Selection

The study was executed within the Lower Ibaka Creek, which constitutes a soft-bottom mangrove ecosystem in Rivers State, Nigeria. This area is fundamentally impacted by diurnal tidal activity. Three distinct sampling sites were selected across the creek, representing major fishing zones exposed to varying degrees of anthropogenic pollution.

The precise geographical coordinates for the sampling locations are Site 1 (Amadi Ama) at 4∘45′02.5″N, 7∘04′07.4″E; Site 2 (Ogbogbo) at 4∘44′45.5″N, 7∘04′38.4″E; and Site 3 (Ogoloma) at 4∘43′55.7″N, 7∘04′30.6″E. The ambient environment is impacted by diverse sources, including industrial discharges from oil and gas companies, dredging operations, and domestic waste from adjacent coastal communities. Co-occurring macrobenthic species in the area include other periwinkles (*Pachymelania fusca*), gobies, crabs, and mudskippers.

Figure 1. Section of the Bonny River (Site 1 (Amadi Ama), Site 2 (Ogbogbo) and Site 3 (Ogoloma)).



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Sample Collection and Preparation

The target organism, the periwinkle *Tympanotonus fuscatus var fuscatus* (Linnaeus, 1758), was collected from the three designated sites in the Lower Ibaka Creek. Sampling was conducted bimonthly over a period of six months, from January 2023 to June 2023.

A total of fifteen *T. fuscatus* individuals were collected from each sample location during each sampling event, resulting in a total sample size of 270 representative shellfish samples analyzed over the study period. Samples were harvested during low tide by local fisherfolk using locally fabricated traps at 21-day intervals. The mean length and weight of the harvested *T. fuscatus* specimens were recorded as 11.02±0.06 cm and 12.21±0.31 g, respectively. Samples were immediately stored in pre-acid-cleaned, sealed, and labeled polythene bags within ice boxes and transported rapidly to the laboratory.

In the laboratory, muscle tissues, selected as the most frequently consumed portion of the shellfish, were carefully dissected from 8 to 10 individuals per sample, dried, and stored in clean, clearly labelled plastic containers pending analysis.

Sample Digestion and Chemical Analysis

Sample digestion was performed in triplicate following the American Public Health Association (APHA) standard methods. A precisely weighed sample of approximately 0.95±0.01 g of dried muscle tissue was placed in an acid-washed Teflon digestion container. Concentrated nitric acid (HNO_3) was added, and the mixture was heated to 100°C. Hydrogen peroxide (H_2O_2) was subsequently added until the cessation of brown fumes, indicating complete digestion.

The resulting digested solutions were filtered using Whatman 0.42 µm filter paper into 50 mL volumetric flasks and brought to volume using distilled-deionized water. The final filtrates were transferred to pre-cleaned plastic bottles for instrumental analysis. A separate description of a microwave digestion protocol involving HNO_3 and HNO_3:HF (1:1 v/v) at staged pressures (1.5 MPa, 1.0 MPa, 1.5 MPa) was also employed during preparation, reinforcing the rigor of the methods.

The concentrations of Fe, Zn, Pb, Cd, Cu, and As were quantified using an Atomic Absorption Spectrophotometer (AAS), Model 210 VGP, Buck Scientific. The instrument was calibrated using established atomic absorption standards. Specific wavelengths were utilized for each element: Pb (217.0 nm), Cd (228.8 nm), As (193.7 nm), Zn (213.9 nm), and Cu (324.8 nm). Metal concentration in the sample extracts was determined by comparing the measured absorbance values against the analytical calibration curve.

Quality Assurance and Quality Control (QA/QC)

To ensure the accuracy and reliability of the analytical data, rigorous QA/QC procedures were implemented. These included the concurrent analysis of reagent blanks, certified reference materials obtained from Sigma-Aldrich, and calibration standards in every batch. Equipment drift was inspected periodically, typically after every 10 samples.

The calculated percentage recovery (%R) rates for the measured metals confirmed the reliability of the digestion and analytical processes: Fe (89.0%), Pb (98%), Cd (100%), As

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(99.6%), Zn (84.4%), and Cu (97.6%). Furthermore, the linearity of the calibration curves, as indicated by the high R^2 variance, confirmed the precise instrumental response: As (0.9915), Cd (0.9670), Cu (0.9882), Fe (0.9915), Pb (0.9795), and Zn (0.9881).

Human Health Risk Assessment of *Tympanotonus fuscatus* (USEPA 1989; 2004, 2011 Model)

The potential human health risks associated with the consumption of *T. fuscatus* were evaluated using the standard health risk assessment framework established by the United States Environmental Protection Agency (USEPA). The evaluation targeted both non-carcinogenic and carcinogenic risks for two distinct populations: adults and children.

The exposure parameters used in the risk assessment model are detailed in Table 1. These values account for differences in body weight (BW), exposure duration (ED), and ingestion rate (IR) between adults and children.

Table 1: Exposure Parameters Used for Health Risk Assessment via Consumption Pathway

Parameter	Unit	Children	Adult
Exposure time (ET)	H/event	1	0.58
Average time (AT) (ED x 365)	Days	2190	10950
Body weight (BW)	Kg	15	70
Exposure frequency (EF)	Days/years	350	350
Exposure duration (ED)	Years	6	30
Ingestion rate (IR)	L/day	1.00	2.00

Chronic Daily Intake (CDI)

The Chronic Daily Intake (CDI) estimates the average daily exposure dose of a specific metal or metalloid contaminant consumed through the shellfish.

$$CDI = \frac{CHM \ x \ IR}{Bw} \qquad (1)$$

Where CHM represents the mean concentration of individual heavy metal in the studied *T. fuscatus* (mg/kg), IR is the standard ingestion rate of fish (0.036 kg/day based on Nigerian fish consumption) , and Bw represents the average body weight (70 kg for adults and 15 kg for children).

Non-Carcinogenic Risk Assessment

Non-carcinogenic risks were evaluated using the Hazard Quotient (HQ) and the cumulative Hazard Index (HI).

The **Hazard Quotient (HQ)** evaluates the potential for adverse health effects resulting from a specific metal exposure relative to the safe reference dose (RfD).

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$HQ = \frac{CDI}{RfD}$ (2)

The **Hazard Index (HI)** represents the total potential non-carcinogenic risk resulting from the cumulative exposure to all metals studied (Córdoba-Tovar et al., 2023**)**.

$HI = \sum HQ$ (3)

A calculated HI value less than 1 (<1) suggests the risk is acceptable, and adverse non-carcinogenic effects are unlikely **(**USEPA (2004). An HI>1 indicates potential negative effects warranting further chemical-specific evaluation, and an HI>4 is considered to represent a high negative effect (USEPA 2008).

Carcinogenic Risk Assessment

The carcinogenic risk was assessed using the **Individual Lifetime Cancer Risk (ILCR)**, commonly referred to as **Cancer Risk (CR)**. This metric estimates the probability of an individual developing cancer over a 70-year lifetime due to exposure to the toxicant **(**USEPA, **1999).**

$ILCR = CDI \times CSF$ (4)

Where CSF represents the Cancer Slope Factor, a toxicity value established by the USEPA (2008). The risk is considered negligible or safe when CR is below 1.0×10−6 (representing one cancer case per million of the exposed population). Risks between 1.0×10^{-6} and 1.0×10^{-4} indicate a potential but tolerable risk, while values exceeding 1.0×10^{-4} (CR > 1: 1,000 cancer cases in the studied population) suggest a significant risk (USEPA 2008; Sultana et al., 2017).

The Total Lifetime Cancer Risk (TLCR) is calculated as the sum of the CR values for all carcinogenic metals.

$TLCR = \sum ILCR = ILCR_1 + ILCR_2 + ILCR_3 + ...n$

It gives an estimate of the combined carcinogenic effect due to intake of all studied metals via a single matrix (*T. Fuscatus).*

Statistical Analyses

Descriptive statistics, including mean, standard deviation (SD), and standard error of the mean (SE), were calculated. Analysis of variance (ANOVA) was employed to test for significant differences in metal concentrations among the sampling sites. Normality and variance homogeneity assumptions were evaluated using the Kolmogorov-Smirnov/Shapiro-Wilk tests and the Levene test, respectively. Where significant differences were detected, the Duncan Multiple Range Test (DMRT) was applied to differentiate between specific means at a significance level of $p<0.05$.

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RESULTS AND DISCUSSIONS

Results

Metals Bioaccumulation and Spatial Distribution

The analysis of metal(loid) concentrations in the muscle tissue of *Tympanotonus fuscatus* revealed significant variations across the three sampling sites (Table 1).

Table 1: Concentration of Metals and Metalloids in *Tympanotonus fuscatus* Muscle Tissue (mg/kg dry weight)

Metals	Study Locations		
	Site 1	Site 2	Site 3
Fe	19.7 [ab]	22.1[a]	15.5[b]
Zn	91.33 [c]	111.2 [b]	137.23 [a]
Pb	0.004 [a]	0.005 [a]	0.004 [a]
Cd	0.016 [a]	0.013 [b]	0.015 [a]
Cu	0.98 [a]	0.89 [b]	0.92 [a]
As	0.002 [a]	0.002 [a]	0.002 [a]

Fe and Zn were identified as the most abundant metals detected in the shellfish, consistent with high background levels in estuarine environments. Fe concentrations ranged from 15.5 mg/kg (Site 3) to 22.1 mg/kg (Site 2), with statistical analysis indicating significant spatial variations ($P<0.05$) between Site 3 and the other locations. Zn concentrations were observed in the range of 91.33 mg/kg (Site 1) to 137.23 mg/kg (Site 3). However, spatial variations were not statistically significant ($P>0.05$) when comparing across the sites.

The remaining metals (Pb, Cd, Cu, and As) were detected at substantially lower concentrations. Pb concentrations were minimal, ranging only from 0.004 mg/kg (Sites 1 & 3) to less than 0.005 mg/kg (Site 2). Cd concentrations were also low, ranging from 0.013 mg/kg to 0.016 mg/kg. Neither Pb nor Cd showed statistically significant differences across the sites. Cu varied slightly from 0.89 mg/kg (Site 2) < 0.98 mg/kg (Site 1), also lacking significant spatial differentiation ($P > 0.05$). As concentrations were consistently low and uniform across all three sites at 0.002 mg/kg, this suggests uniform low-level contamination (Table 1). Despite the generally low levels, Pb and Cd concentrations were noted to exceed permissible limits in certain locations.

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Estimated Daily Intake (EDI)

The EDI values were calculated for both adult and child populations across the three sampling sites, reflecting the estimated dose of metal(loid) consumed daily per kilogram of body weight (Table 2).

Table 2: Estimated Daily Intake (EDI) (mg/kg/day) of *T. Fuscatus*

	Adults			**Children**			
Metal	**Site 1**	**Site 2**	**Site 3**	**Site 1**	**Site 2**	**Site 3**	RfD_o (mg/kg/day)
Pb	3.43E-7	3.00E-7	3.43E-7	8.00E-7	7.00E-7	8.00E-7	0.004
Fe	1.10E-3	1.24E-3	1.09E-3	2.57E-3	2.91E-3	2.56E-3	0.7
Cd	1.11E-6	1.03E-6	1.11E-6	2.60E-6	2.40E-6	2.60E-6	0.001
Cu	5.21E-5	5.47E-5	5.29E-5	1.22 -4	1.28E-4	1.24E-4	0.04
Zn	2.49E-3	2.7E-3	3.25E-3	5.81E-3	6.50E-3	7.58E-3	0.3
As	1.29E-7	1.29E-7	1.29E-7	3.00E-7	3.00E-7	3.00E-7	0.0003

Figure 2: Zinc (Zn) and Iron (Fe) Concentration in Periwinkles (*T. fuscatus*).

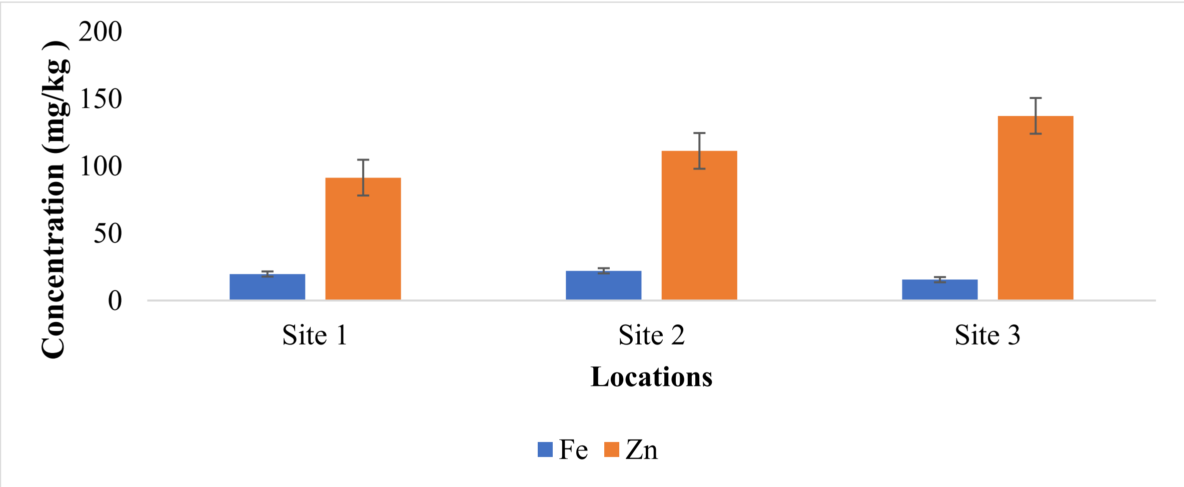

Figure 3: Lead (Pb) Cadmium (Cd), and Arsenic (As) Concentration in *T. fuscatus*.

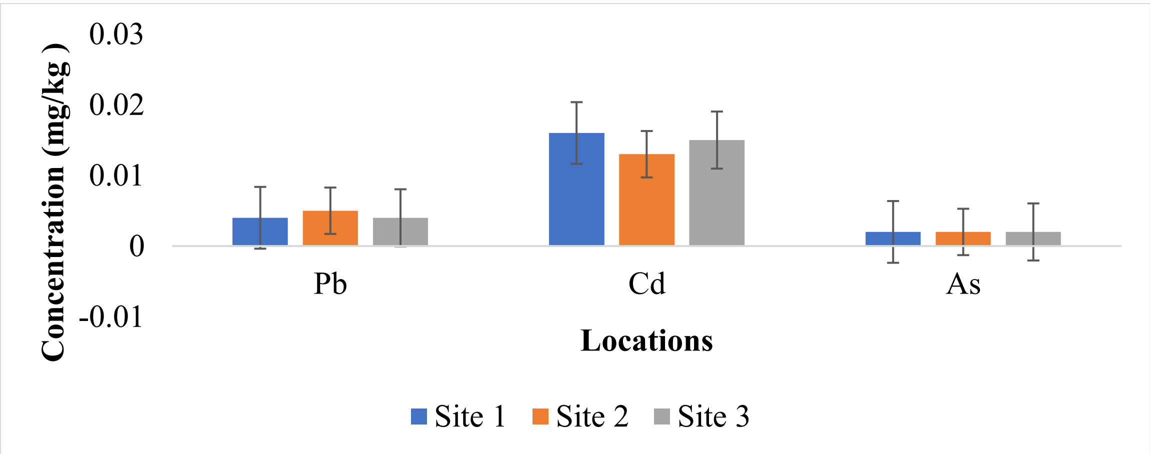

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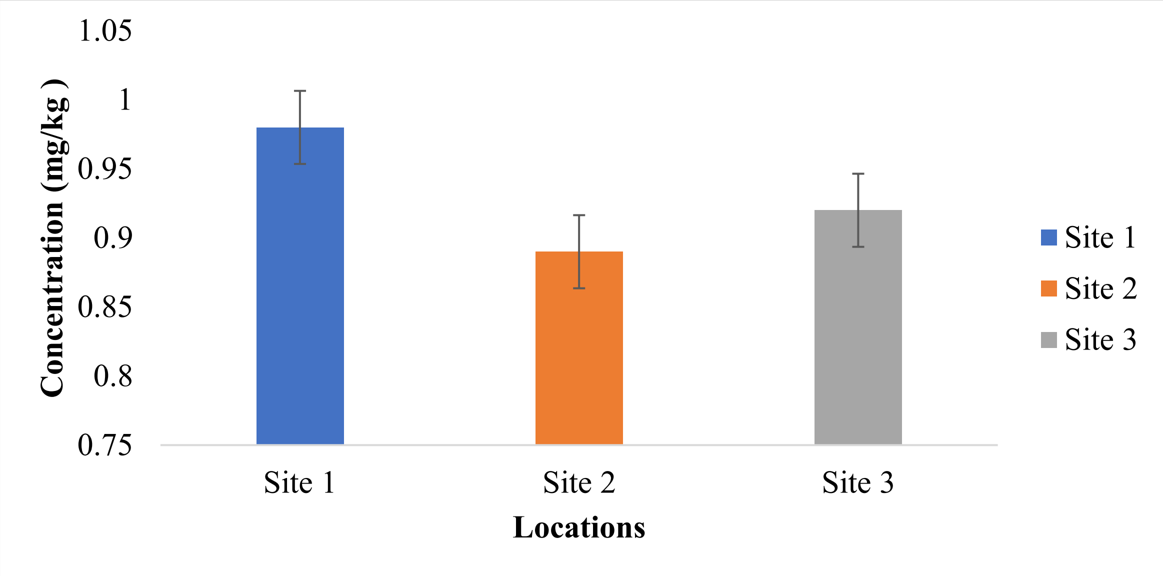
Figure 4: Copper (Cu) Concentration in *T. fuscatus*.



The observed results show that Zn and Fe were mostly consumed (with higher EDI values), which is in direct proportionality with their concentrations in the periwinkle tissue. A consistent pattern was observed wherein the EDI values for children were approximately 2.3 to 2.5 times greater than those calculated for adults across all metals and sites. The highest estimated exposure occurred for Zn, specifically for children consuming periwinkle from Site 3 ($7.58E^{-3}$ mg/kg/day), which corresponds directly to the highest measured Zn concentration at that site.

Non-Carcinogenic Risk Assessment (HQ and HI)

Hazard Quotient (HQ)

The HQ values, which assess non-carcinogenic risk from individual metal exposure, are presented in Table 3. All individual HQ values for Pb, Fe, Cd, Cu, Zn, and As were found to be substantially below the threshold of 0.1 and 1.0 (USEPA, 2011 & 2004).

Table 3: Hazard Quotients (HQ) of Metals and Metalloids from *T. Fuscatus Exposure*

	Adults			Children		
Metal	**Site 1**	**Site 2**	**Site 3**	**Site 1**	**Site 2**	**Site 3**
Pb	8.57E-4	7.5E-4	8.57E-4	2.00E-3	1.75E-3	2.00E-3
Fe	1.6E-3	1.8E-3	1.6E-3	3. E-3	4.2E-3	3.7E-3
Cd	1.11E-3	1.03E-3	1.11E-3	2.60E-3	2.40E-3	2.60E-3
Cu	1.3E-3	1.4E-3	1.3E-3	3.1E-3	3.2E-3	3.1E-3
Zn	8.3E-3	9.3E-3	1.08E-2	1.94E-2	2.17 E-2	2.53 E-
As	4.29E-4	4.29E-4	4.29E-4	1.00E-3	1.00E-3	1.00E-3

Zn contributed the highest HQ values among all elements, peaking at 1.08E−2 for adults and 2.53E−2 for children at Site 3. This finding establishes Zn as the primary contributor to non-carcinogenic risk, reflecting its high measured bioaccumulation concentration. Although there was generally a low probability of non-cancer effects, the HQ values for children were consistently higher than those for adults, highlighting the increased vulnerability of younger populations.

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Hazard Index (HI)

The cumulative non-carcinogenic risk, expressed as the HI, ranged from 1.30E-2 to 1.50E-2 for adults and 2.90E-2 to 3.50E-2 for children across the three sites. Site 3 recorded the highest HI value for both groups (Adults: 1.50E-2; Children: 3.50E-2). Since all HI values were far below the critical threshold of 1, the consumption of *T. fuscatus* currently poses negligible cumulative non-carcinogenic health risk for either adults or children.

Carcinogenic Risk Assessment (CR and TLCR)

Individual Cancer Risk (CR)

The CR values calculated for exposure to individual metals through *T. fuscatus* consumption are presented in Table 4.

Table 4: Carcinogenic Risk (CR) of Metals and Metalloids in *T. fuscatus* for both groups

	Adults			Children		
Metal	**Site 1**	**Site 2**	**Site 3**	**Site 1**	**Site 2**	**Site 3**
Pb	1.50E-9	1.32E-9	1.50E-9	3.52E-9	3.08E-9	3.52E-9
Cd	4.16E-7	3.86E-7	4.16E-7	9.80E-7	9.00E-7	9.80E-7
As	9.03E-7	9.03E-7	9.03E-7	2.10E-6	2.10E-6	2.10E-6

The CR values for metal carcinogens (Pb, Cd, and As) were studied for both populations groups and the evaluated results were found below the negligible risk threshold of 1.0×10−6. In contrast, As showed CR values of 9.03E−7 (As) for adults (negligible) and 2.10E−6 for children at all sites. These values for children were still within the threshold value of 10-6, expressing little carcinogenic concern from the population's exposure to periwinkle over both childhood and adult lifetimes.

Total Lifetime Cancer Risk (TLCR)

The TLCR values ranged from 2.02E−6 to 2.95E−6 for adults, indicating a very low potential risk that slightly exceeds the 1.0×10−6 negligible threshold. For children, the TLCR ranged from 4.65E−6 to 6.92E−6. These values fall within the low-to-moderate risk range (1.0×10^{-6} to 1.0×10^{-4}), underscoring the necessity for environmental control, especially for vulnerable populations.

DISCUSSION

Bioaccumulation Dynamics of Essential Metals (Fe and Zn) in *T. fuscatus*

The data clearly establish Fe and Zn as the most abundantly bioaccumulated metals in *T. fuscatus* muscle tissue, with concentrations significantly higher than the other four elements (Pb, Cd, Ni, and As) investigated. Fe levels are frequently high in estuarine mollusks due to the natural composition of mangrove sediments, where Fe cycles extensively in response to redox changes influenced by tidal activity and microbial processes (Tabassum et al., 2024).

However, the elevated Zn levels, particularly the peak concentration of 137.23 mg/kg recorded at Site 3, suggest a strong localized anthropogenic input augmenting the natural requirement of

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Zn as an essential trace element. The spatial maximum for Zn at Site 3 is particularly noteworthy because this location also corresponded to the highest calculated HI and TLCR values.

Iron concentrations varied across the study sites, with one location exhibiting higher levels than others. This observed trend of Fe is similar to that of Zn. This established correlation directly links a specific localized pollution source (likely domestic effluent or agricultural runoff, as noted in previous studies) to the highest calculated risk endpoints for the consuming population. Previous studies in mangrove ecosystems have reported comparable patterns, often linking fluctuations in Fe levels to differences in sediment composition, industrial discharges, and tidal influences (**Ekperusi** et al., 2024; **Ogbeide and Henry, 2024**).

Bioaccumulation Dynamics of Carcinogenic Metals (Pb and Cd) **in *T. Fuscatus***

The toxicologically crucial finding reveals that despite the extremely low concentration ranges for Pb (0.004−0.005 mg/kg) and Cd (0.013−0.016 mg/kg), these trace levels were sufficient to exceed established permissible regulatory limits in some locations. This outcome confirms the stringent control needed for highly toxic, non-essential metals in food matrices. For such persistent pollutants, even minimal bioaccumulation represents a regulatory compliance failure and signals a public health concern requiring intervention targeting diffuse sources. The low overall concentrations of Pb found contrast favorably with highly industrialized areas where vehicular emissions typically result in higher Pb burdens. However, bioavailability of metals could influence their uptake and retention in the tissues of organisms. Despite the anthropogenic release of metals into the ecosystem, their chemical form (speciation), size, pH, and presence of dissolved organic matter could influence the fraction of the metal that can be absorbed by living organisms (**Zhu et al., 2023**; **Ma** et al., 2023).

The findings of this study are consistent with recent research on carcinogenic risks in mangrove ecosystems. For instance, **Anyanwu and Chris (2023**) reported similarly low CR values for Pb, Cd, and Zn in mollusks from uncontaminated mangrove swamps, while **Uchenna et al. (2023**) highlighted the role of natural processes in mitigating metals and metalloids bioavailability.

Spatial Variation and Contamination Source Tracing

The statistically significant spatial variations observed, particularly for Fe and Zn, reinforce the understanding that metal distribution in the Ibaka mangrove is heterogeneous, dictated by site-specific environmental factors. The fluctuation in Fe concentration (Site 2 highest, Site 3 lowest) is likely related to physical disturbance, such as dredging activities or localized tidal scouring, which affects sediment composition and the bioavailability of iron through redox changes.

Conversely, the remarkably low and uniform concentrations observed for As and Cu across all sites suggest limited acute anthropogenic contributions of these specific elements. This uniformity implies that natural attenuation processes, such as strong metal adsorption to the soft-bottom sediments or specific geochemical characteristics of the creek, may be effectively reducing the presence while limiting the bioavailability of As and Cu in the water column and, consequently, their uptake by benthic organisms.

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Assessment of Non-Carcinogenic Risks (HQ and HI)

The health risk assessment indicates that the consumption of *T. fuscatus* currently poses no immediate non-carcinogenic risk. All individual HQ and cumulative HI values were calculated to be significantly below the critical threshold of 1. This finding provides reassurance regarding the current safety profile for non-carcinogenic endpoints, aligning with results reported from similar, relatively uncontaminated mangrove ecosystems.

Among the six elements studied, Zn emerged as the dominant non-carcinogenic risk contributor, characterized by the highest HQ values. This dominance is a direct consequence of Zn's high measured concentration in the shellfish tissue, which drives the calculated chronic daily intake. While the calculated risk remains minimal, Zn should be prioritized in future environmental monitoring programs, as any significant environmental increase would be the element most likely to push the cumulative HI closer to the threshold of concern.

Vulnerability of Child Populations

A crucial finding of the risk assessment is the consistent elevation of HQ and HI values for children, which were approximately 2.3 times higher than those for adults. This disparity is not due to greater absolute intake but results from the differential physiological modeling used in the CDI calculation. The lower average body weight (15 kg vs 70 kg) for children dictates a substantially higher dose per kilogram of body weight for the same level of contaminant exposure. This physiological difference translates into a heightened susceptibility for younger populations, emphasizing the necessity for targeted public health warnings and specific pollution control measures aimed at protecting vulnerable age groups.

Assessment of Carcinogenic Risks (CR and TLCR)

Analysis of carcinogenic risk revealed that Fe, Pb, Cd, Cu, and Zn presented negligible cancer risk ($CR<1.0\times10^{-6}$). However, despite having the lowest measured tissue concentration (0.002 mg/kg), arsenic (As) was identified as the overwhelming driver of carcinogenic risk. This phenomenon illustrates that for carcinogens, the intrinsic toxicity, quantified by the Cancer Slope Factor (CSF), is often more critical than the magnitude of exposure.

The CR for As in children (2.10E−6) slightly exceeds the 1.0×10^{-6} negligible risk level, placing it in the low end of the USEPA's "potential risk" zone.

The cumulative TLCR confirms that the total cancer risk is minimal but non-negligible. For adults, the TLCR slightly exceeded 1.0×10^{-6}. For children, the TLCR values (4.65E−6 to 6.92E−6) fall within the low-to-moderate risk range. The fact that the cumulative cancer risk is driven predominantly by a known, highly toxic metalloid like As is a significant finding.

While the current risks are low, the identification of As as the main risk factor implies that any future increase in environmental As loading, perhaps from new industrial discharges or changes in local geochemical conditions, could rapidly push the TLCR into unacceptable ranges. This potential for rapid risk escalation mandates stringent preventative environmental management rather than simply reactive monitoring.

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CONCLUSION

This study provides a comprehensive assessment of metal(loid) bioaccumulation and associated human health risks from the consumption of *Tympanotonus fuscatus var fuscatus* collected from the Lower Ibaka Creek, Rivers State, Nigeria. Fe and Zn were identified as the most abundant metal(loid) in the muscle tissues, confirming high background levels exacerbated by anthropogenic inputs, including domestic and industrial waste. Although concentrations of Pb and Cd were generally low, they were found to exceed permissible food safety limits in some locations, highlighting regulatory non-compliance.

The ability of the Ibaka mangrove system to maintain low concentrations of these highly hazardous metals suggests the possibility and significance of effective local attenuation processes or limited acute inputs for these specific heavy metals.

The health risk assessment indicated that the non-carcinogenic risk, quantified by the HI, is currently acceptable (HI<1) for both adults and children, with Zn being the primary risk contributor. However, the calculated HQ and TLCR values were substantially higher for children, underscoring their increased physiological vulnerability to contaminant exposure. Furthermore, the Total Lifetime Cancer Risk (TLCR) was driven slightly above the negligible threshold by Arsenic (As), placing children in the low-to-moderate cancer risk probability threshold.

The findings emphasize that while the acute consumption risk is low, the potential for long-term health concerns, driven primarily by As and exacerbated by high Zn levels, necessitates continuous and targeted environmental monitoring. Immediate pollution control strategies are required to mitigate Pb and Cd non-compliance and prevent future risk escalation, thereby safeguarding the crucial ecological health of the mangrove ecosystem and the public safety of the coastal population.

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