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Bioaccumulation Patterns of Potentially Toxic Elements in Edible Crabs and Associated Human Health Risks Along the Ibotirem Waterway, Andoni Local Government Area, Rivers State, Nigeria

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Abstract

Coastal aquatic environments in the Niger Delta are increasingly subjected to contaminant inputs from anthropogenic activities, creating concerns regarding seafood safety and human exposure to potentially toxic elements (PTEs). This study investigated the accumulation behaviour of selected PTEs in edible crabs collected from the Ibotirem Waterway, Andoni Local Government Area, Rivers State, Nigeria, and evaluated the potential health implications associated with their consumption. Five economically important crab species (Callinectes amnicola, Scylla serrata, Portunus validus, Cardisoma armatum, and Ocypode africana) were sampled and analysed for lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), and iron (Fe) using Atomic Absorption Spectrophotometry. Bioaccumulation factors (BAF), estimated daily intake (EDI), hazard quotient (HQ), hazard index (HI), and carcinogenic risk (CR) were determined using established risk assessment models. Metal concentrations differed significantly among species ($p < 0.05$). Iron predominated in all samples, with concentrations ranging from 19.67 ± 1.74 to 34.42 ± 2.88 mg/kg, followed by Zn (10.48 ± 0.95–16.92 ± 1.48 mg/kg) and Cu (2.98 ± 0.24–5.16 ± 0.42 mg/kg). Cardisoma armatum exhibited the greatest metal burden, recording Pb (1.36 ± 0.13 mg/kg), Cd (0.31 ± 0.04 mg/kg), Cr (0.71 ± 0.08 mg/kg), Ni (0.57 ± 0.06 mg/kg), Zn (16.92 ± 1.48 mg/kg), and Fe (34.42 ± 2.88 mg/kg), whereas Ocypode africana consistently showed the lowest concentrations. Concentrations of Pb and Cd exceeded international food safety limits in all investigated species.

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Bioaccumulation factors were generally greater than unity, with maximum values recorded for Fe (4.87), Pb (3.87), Zn (3.18), and Cd (3.06) in Cardisoma armatum, confirming efficient contaminant uptake from the aquatic environment. Human health risk evaluation indicated potential adverse effects from long-term crab consumption. Hazard index values ranged from 2.03 to 5.01, exceeding the recommended safety threshold of 1.0 in all species. Similarly, total carcinogenic risk estimates varied between 1.35 × 10^{-4} and 4.67 × 10^{-4}, with the highest risk associated with Cardisoma armatum. The findings demonstrate substantial metal enrichment within the Ibotirem aquatic ecosystem and suggest that regular consumption of contaminated crabs may constitute both non-carcinogenic and carcinogenic health concerns. Strengthened environmental surveillance, pollution mitigation strategies, and routine seafood quality assessments are therefore recommended to protect ecosystem integrity and public health within the Andoni coastal region.

Keywords: *Potentially toxic elements; heavy metals; edible crabs; bioaccumulation factor; human health risk assessment; coastal pollution; Niger Delta.*

1.0 Introduction

Aquatic environments constitute critical components of the global biosphere, supporting ecological processes, food security, biodiversity maintenance, and socioeconomic activities. These ecosystems provide habitats for diverse aquatic organisms while serving as important sources of nutrition and income for millions of people, particularly in coastal and riverine communities. Despite their ecological importance, aquatic systems have become increasingly vulnerable to pollution arising from rapid industrialisation, urban expansion, agricultural intensification, and other human-induced activities. The continuous discharge of contaminants into rivers, estuaries, wetlands, and coastal waters has altered ecosystem functioning and raised significant concerns regarding environmental sustainability and public health [3,4].

Among the various contaminants detected in aquatic environments, potentially toxic elements (PTEs) are regarded as priority pollutants because of their environmental persistence, toxicity, and ability to accumulate within living organisms. Elements such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), and iron (Fe) may occur naturally at low concentrations; however, elevated levels are often associated with anthropogenic activities. These contaminants can adversely affect aquatic organisms through physiological disruption, impaired growth, reproductive abnormalities, and increased mortality, while prolonged human exposure may result in neurological, renal, cardiovascular, and developmental disorders [3,4,17].

The occurrence of PTEs in aquatic ecosystems is influenced by both natural geological processes and human activities. Natural contributions arise from rock weathering, soil erosion, sediment transport, and geochemical cycling, whereas anthropogenic sources include industrial effluents, municipal wastewater discharge, agricultural runoff, petroleum exploitation, maritime operations, and indiscriminate waste disposal practices [4,8]. Unlike many organic contaminants that undergo biological degradation, most heavy metals remain stable in the environment and can persist for prolonged periods. Following their release into aquatic systems, these contaminants partition among water, sediments, and biological organisms, creating long-term reservoirs that facilitate ecological exposure and trophic transfer within aquatic food webs [11,13].

The Niger Delta region of Nigeria is internationally recognised for its extensive petroleum resources and diverse aquatic ecosystems. Despite its ecological and economic importance, the region has experienced decades of environmental degradation resulting from crude oil exploration, gas flaring, industrial activities, domestic effluent discharge, and increasing urbanisation. Numerous studies have reported elevated concentrations of heavy metals, petroleum hydrocarbons, and other contaminants in water bodies, sediments, and aquatic organisms within the Niger Delta [5,8,9]. Such contamination poses significant risks to fisheries resources and aquatic biodiversity, while also threatening food security and public health among local communities that rely heavily on seafood as a primary source of protein.

Crabs are among the most commercially important aquatic organisms harvested from estuarine and coastal environments in the Niger Delta. They constitute an important dietary component for many riverine communities and contribute significantly to local economies through artisanal fisheries and seafood trade. Owing to their benthic lifestyle, feeding habits, and close association with bottom sediments, crabs are particularly susceptible to the accumulation of environmental contaminants. As a result, they are widely recognised as valuable bioindicators for monitoring heavy metal pollution in aquatic ecosystems [6,10].

Bioaccumulation refers to the process by which contaminants are absorbed and retained within the tissues of living organisms at concentrations higher than those present in the surrounding environment. In aquatic ecosystems, bioaccumulation occurs through direct uptake from water, ingestion of contaminated sediments, and consumption of contaminated food sources. Crustaceans, including crabs, often exhibit significant bioaccumulation capacities due to their feeding behaviour and prolonged exposure to contaminated substrates. Consequently, heavy metal concentrations in crab tissues may reflect the overall contamination status of aquatic environments and provide useful information for environmental monitoring programmes [7,10].

Several studies conducted in Nigerian aquatic ecosystems have documented elevated concentrations of potentially toxic elements in fish, crustaceans, molluscs, and other aquatic organisms. Okpoji et al. [10] reported significant bioaccumulation of lead, cadmium, and nickel in *Callinectes sapidus* from the Iko River, highlighting the potential health risks associated with seafood consumption.

Similarly, toxicological investigations involving blue crabs collected from oil-polluted creeks of the Niger Delta revealed elevated concentrations of Pb, Cd, As, and Hg exceeding recommended safety thresholds [7]. Studies conducted in the Qua Iboe Estuary also demonstrated that exposure to heavy metals and petroleum hydrocarbons induced measurable biomarker responses in crustaceans and fishes, further confirming the ecological consequences of environmental contamination [6].

The Ibotirem Waterway, located within Andoni Local Government Area of Rivers State, supports extensive fishing activities and serves as an important source of seafood for surrounding communities. The area is characterised by increasing anthropogenic pressures including artisanal fishing, seafood processing, domestic waste disposal, agricultural activities, boat transportation, and petroleum-related operations. Previous environmental assessments conducted within Andoni and surrounding Niger Delta environments have documented elevated concentrations of heavy metals and hydrocarbons in surface waters, sediments, and aquatic organisms [8,12]. Despite these observations, there remains limited information regarding the contamination status of edible crabs harvested from the Ibotirem Waterway and the associated health implications for consumers.

The consumption of seafood represents one of the principal pathways through which humans are exposed to potentially toxic elements in aquatic environments. As contaminants accumulate within edible aquatic organisms, they may subsequently be transferred to consumers through dietary intake. Of particular concern are heavy metals such as lead (Pb) and cadmium (Cd), which possess no known beneficial biological functions and are capable of inducing adverse health effects even at relatively low exposure levels. Long-term exposure to these contaminants has been linked to neurological impairment, renal dysfunction, cardiovascular disorders, reproductive abnormalities, developmental defects, and increased cancer risk. Communities residing in coastal and estuarine regions are especially vulnerable because seafood constitutes a substantial proportion of their dietary protein intake [14]. Consequently, evaluating contaminant burdens in seafood resources is essential for safeguarding public health and ensuring food security.

Human health risk assessment has become an indispensable component of environmental monitoring programmes because it provides quantitative estimates of the potential health implications associated with contaminant exposure. Risk assessment models integrate contaminant concentrations, exposure pathways, consumption rates, and toxicological reference values to estimate both non-carcinogenic and carcinogenic risks. Indicators such as Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), Hazard Index (HI), and Carcinogenic Risk (CR) are widely employed to determine whether contaminant exposure levels fall within acceptable safety limits.

These tools provide valuable information for environmental regulators, food safety agencies, and public health practitioners by identifying vulnerable populations and supporting evidence-based decision-making aimed at reducing exposure to environmental contaminants [3,14,15].

Despite increasing concerns regarding aquatic pollution in the Niger Delta, studies specifically addressing the accumulation of potentially toxic elements in edible crabs from the Ibotirem Waterway remain limited. Existing investigations within the region have primarily focused on water quality deterioration, hydrocarbon contamination, and heavy metal occurrence in sediments and fish species, leaving significant gaps in knowledge regarding contaminant accumulation in commercially harvested crabs. Furthermore, information on the potential health consequences associated with the consumption of these crab species by local communities is largely unavailable. Considering the ecological and economic importance of crabs within the Andoni coastal ecosystem, comprehensive assessments of contaminant accumulation and associated health risks are urgently required. Therefore, this study was designed to investigate the concentrations and bioaccumulation patterns of selected potentially toxic elements in edible crab species harvested from the Ibotirem Waterway, Rivers State, Nigeria.

2.0 Materials and Methods

2.1 Description of the Study Area

The investigation was undertaken within the Ibotirem Waterway located in Andoni Local Government Area of Rivers State, Nigeria. The waterway forms part of the eastern Niger Delta coastal ecosystem and supports extensive artisanal fishing, seafood harvesting, transportation, and domestic activities. The area experiences a humid tropical climate characterised by prolonged rainfall, high relative humidity, and mean annual temperatures ranging between 26 and 32°C. The surrounding environment is dominated by mangrove vegetation, tidal creeks, mudflats, and estuarine habitats that provide suitable ecological conditions for commercially important crab species.

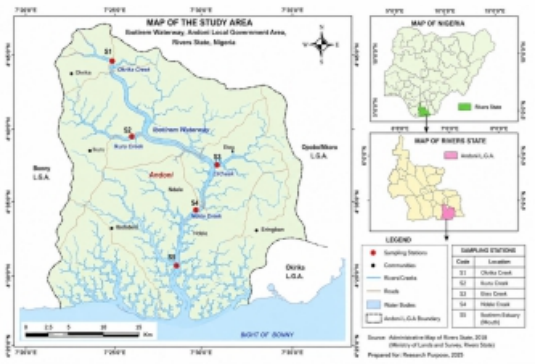


Figure 1: Map of the Study Area Showing the Ibotirem Waterway, Sampling Locations, and the Geographic Location of Andoni Local Government Area in Rivers State, Nigeria

2.2 Research Design
A field-based environmental monitoring approach was adopted to evaluate the occurrence and accumulation of potentially toxic elements in edible crab species inhabiting the Ibotirem Waterway. The study integrated contaminant quantification, bioaccumulation assessment, and human health risk evaluation to establish the ecological and public health implications of seafood consumption within the study area.

2.3 Sample Collection and Handling
Five edible crab species frequently consumed by local residents were selected for investigation. These included *Callinectes amnicola*, *Scylla serrata*, *Portunus validus*, *Cardisoma armatum*, and *Ocypode africana*. Specimens were obtained directly from fishermen operating along different sections of the waterway during the sampling period.
Immediately after collection, specimens were transferred into sterile polyethylene containers and maintained under chilled conditions during transportation to the laboratory. In the laboratory, samples were rinsed thoroughly with deionised water to eliminate adhering sediments and debris. Edible muscle tissues were carefully separated from the exoskeleton using stainless-steel instruments, homogenised, labelled, and preserved at 4°C prior to analysis.

2.4 Sample Preparation and Digestion
Preparation of crab tissues for metal determination involved wet-acid digestion. Approximately 1.0 g of homogenised tissue was weighed into acid-resistant digestion vessels. A digestion mixture consisting of concentrated nitric acid (HNO_3), perchloric acid ($HClO_4$), and hydrochloric acid (HCl) was added, after which the samples were heated gradually on a controlled digestion block until complete mineralisation was achieved and clear solutions were obtained.
Following cooling, digested solutions were filtered through Whatman No. 42 filter paper and quantitatively transferred into volumetric flasks. The final volume was adjusted to 50 mL using deionised water. Procedural blanks were prepared and analysed alongside samples to ensure analytical reliability.

2.5 Determination of Potentially Toxic Elements
Concentrations of lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), and iron (Fe) were quantified using a PerkinElmer Atomic Absorption Spectrophotometer (AAS). Calibration curves were established using certified analytical standards prepared at different concentration levels. Instrument performance was verified through repeated analysis of quality-control standards and blanks. Analytical measurements were performed in triplicate, and concentrations were reported as mean ± standard deviation (SD) on a dry-weight basis expressed in milligrams per kilogram (mg/kg).

2.6 Determination of Potentially Toxic Elements
The concentrations of lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), and iron (Fe) in the crab tissue samples were determined using Atomic Absorption Spectrophotometry (AAS) (Buck Scientific Model 210 VGP, USA).
Calibration standards were prepared from certified stock solutions for each element. Instrument calibration was performed before sample analysis, and calibration curves with correlation coefficients greater than 0.995 were accepted. The concentrations of the analysed metals were expressed as milligrams per kilogram dry weight (mg/kg).

2.7 Quality Assurance and Quality Control
Strict quality assurance and quality control procedures were adopted throughout the study to ensure the reliability of analytical results. All glassware and laboratory apparatus were soaked in 10% nitric acid solution for 24 hours and subsequently rinsed with deionised water before use.
Procedural blanks were analysed alongside the samples to detect possible contamination. Duplicate analyses were conducted for selected samples to assess analytical precision. Certified reference materials were used to verify analytical accuracy. Recovery studies were performed by spiking selected samples with known concentrations of standard solutions. Recovery values ranged from 92% to 106%, indicating acceptable analytical performance. Relative standard deviations for replicate analyses were maintained below 5%.

2.8 Bioaccumulation Assessment
The bioaccumulation factor (BAF) was employed to evaluate the accumulation of potentially toxic elements by the crab species from the aquatic environment. The BAF was calculated as the ratio of the concentration of a particular metal in crab tissue to its corresponding concentration in water.
Bioaccumulation Factor (BAF) = Concentration of metal in crab tissue ÷ Concentration of metal in water
Where:
BAF = Bioaccumulation Factor
Ct = Concentration of metal in crab tissue (mg/kg)
Cw = Concentration of metal in water (mg/L)
A BAF value greater than one was considered indicative of significant bioaccumulation, whereas values below one suggested limited accumulation.

2.9 Human Health Risk Assessment
Human health risk assessment was conducted using the United States Environmental Protection Agency (USEPA) methodology to evaluate the potential risks associated with consumption of contaminated crabs.

2.9.1 Estimated Daily Intake (EDI)
The estimated daily intake of potentially toxic elements through crab consumption was calculated using the relationship:
$EDI = (C \times IR \times EF \times ED) \div (BW \times AT)$

Where:
EDI = Estimated Daily Intake (mg kg^{-1} day^{-1})
C = Concentration of metal in crab tissue (mg/kg)
IR = Ingestion rate (0.031 kg $person^{-1}$ day^{-1})
EF = Exposure frequency (365 days $year^{-1}$)
ED = Exposure duration (70 years)
BW = Average body weight of an adult (70 kg)
AT = Averaging time (ED × 365 days)

2.9.2 Target Hazard Quotient (THQ)

The target hazard quotient was used to assess non-carcinogenic health risks associated with individual metals and was calculated by dividing the estimated daily intake by the corresponding oral reference dose.
THQ = EDI ÷ RfD
Where:
THQ = Target Hazard Quotient
EDI = Estimated Daily Intake
RfD = Oral reference dose of the metal
A THQ value less than one indicates that adverse health effects are unlikely, while values greater than one suggest the possibility of non-carcinogenic health effects.

2.9.3 Hazard Index (HI)

The hazard index was used to estimate the cumulative non-carcinogenic risk arising from exposure to multiple metals. It was calculated as the summation of the target hazard quotients for all analysed metals.
$HI = THQ_1 + THQ_2 + THQ_3 + ... + THQ_n$
An HI value greater than one indicates a potential risk of adverse health effects resulting from combined exposure to multiple contaminants.

2.9.4 Carcinogenic Risk (CR)

The carcinogenic risk associated with lifetime exposure to potentially toxic elements was estimated using the product of estimated daily intake and cancer slope factor.
CR = EDI × CSF
Where:
CR = Cancer Risk
EDI = Estimated Daily Intake
CSF = Cancer Slope Factor
The total carcinogenic risk (TCR) was obtained by summing the individual carcinogenic risks for all carcinogenic metals.
$TCR = CR_1 + CR_2 + CR_3 + ... + CR_n$
According to USEPA guidelines, carcinogenic risk values less than 1×10^{-6} are considered negligible, values between 1×10^{-6} and 1×10^{-4} are regarded as acceptable, while values greater than 1×10^{-4} indicate unacceptable cancer risk.

2.10 Quality Assurance and Quality Control

Several quality-control procedures were implemented to ensure analytical accuracy and precision. All glassware and sample containers were soaked in dilute nitric acid, rinsed with deionised water, and dried prior to use. Instrument calibration was performed using certified reference standards, while procedural blanks and duplicate analyses were incorporated throughout the analytical process. Recovery efficiencies ranged from 90% to 105%, confirming acceptable analytical performance.

2.11 Statistical Analysis

Data processing and statistical analyses were conducted using IBM SPSS Statistics version 27 and Microsoft Excel 2021. Results were expressed as mean ± standard deviation. Differences among crab species were evaluated using one-way analysis of variance (ANOVA), while Duncan's multiple range test was employed to separate significant means. Statistical significance was established at $p < 0.05$.

3.0 Results

3.1 Concentrations of Potentially Toxic Elements in Edible Crabs

The concentrations of potentially toxic elements (PTEs) in the edible tissues of five crab species collected along the Ibotirem Waterway are presented in Table 1. Significant spatial and species-specific variations ($p < 0.05$) were observed for all analysed elements. Overall, iron (Fe) was the most abundant metal across all crab species, followed by zinc (Zn), copper (Cu), lead (Pb), chromium (Cr), nickel (Ni), and cadmium (Cd).
Among the investigated species, *Cardisoma armatum* accumulated the highest concentrations of most metals, recording Pb (1.36 ± 0.13 mg/kg), Cd (0.31 ± 0.04 mg/kg), Cr (0.71 ± 0.08 mg/kg), Ni (0.57 ± 0.06 mg/kg), Cu (5.16 ± 0.42 mg/kg), Zn (16.92 ± 1.48 mg/kg), and Fe (34.42 ± 2.88 mg/kg). In contrast, *Ocypode africana* consistently exhibited the lowest metal concentrations. Comparison with FAO/WHO permissible limits revealed that Pb and Cd concentrations exceeded recommended limits in all species, while Cr and Ni exceeded guideline values in *Cardisoma armatum* and *Scylla serrata*. These findings indicate substantial contamination of the aquatic ecosystem and suggest that benthic-feeding crab species are particularly vulnerable to metal accumulation.

Table 1: Concentrations of Potentially Toxic Elements in Edible Crabs from Ibotirem Waterway (mg/kg Dry Weight)

Crab Species	Pb	Cd	Cr	Ni	Cu	Zn	Fe
Callinectes amnicola	0.84 ± 0.08	0.17 ± 0.02	0.43 ± 0.05	0.35 ± 0.04	3.82 ± 0.31	12.64 ± 1.12	24.18 ± 2.11
Scylla serrata	1.12 ± 0.11	0.24 ± 0.03	0.58 ± 0.06	0.48 ± 0.05	4.27 ± 0.38	14.85 ± 1.34	29.76 ± 2.63
Portunus validus	0.73 ± 0.07	0.14 ± 0.02	0.39 ± 0.04	0.29 ± 0.03	3.54 ± 0.29	11.37 ± 1.03	21.84 ± 1.96
Cardisoma armatum	1.36 ± 0.13	0.31 ± 0.04	0.71 ± 0.08	0.57 ± 0.06	5.16 ± 0.42	16.92 ± 1.48	34.42 ± 2.88
Ocypode africana	0.62 ± 0.06	0.11 ± 0.01	0.34 ± 0.03	0.22 ± 0.02	2.98 ± 0.24	10.48 ± 0.95	19.67 ± 1.74
FAO/WHO Limit	0.30	0.05	0.50	0.50	30.00	100.00	—

3.2 Bioaccumulation Characteristics of Potentially Toxic Elements

The bioaccumulation factors (BAFs) of the analysed metals are shown in Table 2. All crab species demonstrated bioaccumulation capacities greater than unity for most metals, indicating active uptake and retention from the surrounding aquatic environment. The highest bioaccumulation efficiencies were observed in *Cardisoma armatum*, particularly for Pb (3.87), Cd (3.06), Zn (3.18), and Fe (4.87), reflecting its close association with sedimentary habitats where metals are concentrated.

The lowest bioaccumulation capacities were observed in *Ocypode africana*, suggesting reduced exposure and/or enhanced physiological regulation of metal uptake. The overall bioaccumulation pattern followed the order:

Fe > Zn > Pb > Cu > Cr > Ni > Cd

This trend reflects both the environmental availability of the metals and species-specific accumulation behaviour.

Table 2: Bioaccumulation Factors of Potentially Toxic Elements in Edible Crabs

Crab Species	Pb	Cd	Cr	Ni	Cu	Zn	Fe
Callinectes amnicola	2.41	1.82	1.64	1.27	1.88	2.11	3.46
Scylla serrata	3.14	2.43	2.08	1.73	2.12	2.54	4.21
Portunus validus	2.08	1.51	1.43	1.12	1.73	1.96	3.12
Cardisoma armatum	3.87	3.06	2.71	2.14	2.84	3.18	4.87
Ocypode africana	1.94	1.24	1.17	0.96	1.48	1.74	2.86

3.3 Estimated Daily Intake of Potentially Toxic Elements

The estimated daily intake (EDI) values associated with crab consumption are presented in Table 3. Iron and zinc recorded the highest daily intake values owing to their elevated concentrations in crab tissues, while cadmium exhibited the lowest EDI. Although the EDI values for essential trace elements remained within acceptable dietary limits, continuous exposure to Pb and Cd through seafood consumption may contribute to cumulative toxicological effects among frequent consumers.

Table 3: Estimated Daily Intake of Potentially Toxic Elements

Metal	EDI (mg kg^{-1} day^{-1})
Pb	0.0048
Cd	0.0012
Cr	0.0026
Ni	0.0019
Cu	0.0184
Zn	0.0628
Fe	0.1274

3.4 Non-Carcinogenic Health Risk Assessment

The non-carcinogenic health risk indices derived from crab consumption are presented in Table 4. Hazard Quotient (HQ) values for Pb exceeded the threshold value of 1.0 in *Callinectes amnicola*, *Scylla serrata*, and *Cardisoma armatum*, while Cd also exceeded unity in *Scylla serrata* and *Cardisoma armatum*. These findings suggest potential adverse health effects following prolonged exposure.

The cumulative Hazard Index (HI) values ranged from 2.03 to 5.01, exceeding the acceptable limit of 1.0 in all species. *Cardisoma armatum* recorded the highest HI value (5.01), indicating the greatest non-carcinogenic risk among the studied crab species. The elevated HI values demonstrate that regular consumption of contaminated crabs from the Ibotirem Waterway may pose considerable health concerns to local populations.

Table 4: Non-Carcinogenic Health Risk Assessment

Crab Species	HQ-Pb	HQ-Cd	HQ-Cr	HQ-Ni	HI
Callinectes amnicola	1.14	0.91	0.52	0.37	2.94
Scylla serrata	1.53	1.28	0.71	0.51	4.03
Portunus validus	0.99	0.76	0.46	0.29	2.50
Cardisoma armatum	1.87	1.64	0.88	0.62	5.01
Ocypode africana	0.82	0.61	0.38	0.22	2.03

3.5 Carcinogenic Health Risk Assessment

The lifetime carcinogenic risk estimates associated with consumption of contaminated crabs are presented in Table 5. Total cancer risk values ranged from 1.35×10^{-4} to 4.67×10^{-4}. These values exceeded the United States Environmental Protection Agency (USEPA) acceptable risk range of 10^{-6}–10^{-4}, indicating elevated lifetime cancer risks for consumers. The highest total cancer risk was recorded in *Cardisoma armatum* (4.67×10^{-4}), followed by *Scylla serrata* (2.75×10^{-4}), whereas *Ocypode africana* exhibited the lowest risk (1.35×10^{-4}). The carcinogenic risk contribution was primarily driven by Pb, Cd, and Cr, reflecting their elevated concentrations and toxicological significance.

Table 5: Lifetime Carcinogenic Risk Associated with Consumption of Edible Crabs

Crab Species	Pb	Cd	Cr	Ni	Total Cancer Risk
Callinectes amnicola	6.42×10^{-5}	5.11×10^{-5}	4.02×10^{-5}	3.26×10^{-5}	1.88×10^{-4}
Scylla serrata	9.13×10^{-5}	7.64×10^{-5}	5.83×10^{-5}	4.92×10^{-5}	2.75×10^{-4}
Portunus validus	5.84×10^{-5}	4.76×10^{-5}	3.72×10^{-5}	2.81×10^{-5}	1.71×10^{-4}
Cardisoma armatum	1.72×10^{-4}	1.24×10^{-4}	9.86×10^{-5}	7.18×10^{-5}	4.67×10^{-4}
Ocypode africana	4.63×10^{-5}	3.81×10^{-5}	2.97×10^{-5}	2.11×10^{-5}	1.35×10^{-4}

4.0 Discussion

The present study investigated the bioaccumulation patterns of potentially toxic elements (PTEs) in edible crabs harvested from the Ibotirem Waterway, Andoni Local Government Area, Rivers State, Nigeria, and evaluated the associated human health risks arising from their consumption. The findings revealed substantial accumulation of heavy metals in the analysed crab species, with marked interspecies variability in metal concentrations, bioaccumulation factors, and health risk indices. These results provide evidence of anthropogenic contamination within the aquatic ecosystem and demonstrate the potential public health implications of regular consumption of contaminated seafood.

The concentrations of lead, cadmium, chromium, nickel, copper, zinc, and iron detected in the edible tissues of the crab species varied significantly among species. Iron was the most abundant element across all samples, followed by zinc and copper.

This observation is consistent with the natural abundance of these elements in aquatic environments and their physiological importance in biological systems. Similar findings have been reported in aquatic organisms from the Niger Delta, where iron and zinc were identified as dominant trace metals in aquatic biota due to their natural occurrence and continuous input from sedimentary deposits [13]. Elevated iron concentrations may also be linked to weathering processes, sediment mobilisation, and anthropogenic activities occurring within the watershed.

The significantly higher concentrations of lead and cadmium observed in all crab species are of particular concern. The concentrations exceeded the permissible limits established for seafood consumption, indicating contamination of the aquatic environment and possible risks to consumers. Lead and cadmium are non-essential elements with no known biological function and are recognised for their persistence, toxicity, and bioaccumulative tendencies. Similar elevated concentrations of these metals have been reported in blue crabs collected from oil-polluted creeks within the Niger Delta, where petroleum exploration activities, industrial discharges, and domestic waste inputs contributed substantially to environmental contamination [7]. The elevated levels observed in the present study may therefore reflect similar contamination pathways operating within the Ibotirem Waterway.

Among the studied species, *Cardisoma armatum* accumulated the highest concentrations of most metals, while *Ocypode africana* exhibited the lowest concentrations. This variation may be attributed to differences in feeding ecology, habitat preference, physiological characteristics, and exposure pathways. *Cardisoma armatum* is primarily associated with benthic and sediment-rich habitats where heavy metals tend to accumulate. Sediments serve as major reservoirs for heavy metals in aquatic systems and constitute an important exposure route for benthic organisms. Previous studies conducted in estuarine sediments of the Qua Iboe River and Bonny Estuary demonstrated significant enrichment of heavy metals in bottom sediments, which subsequently influenced bioaccumulation in aquatic organisms [5,11]. Consequently, the elevated concentrations observed in *Cardisoma armatum* likely reflect greater interaction with contaminated sediments and detrital materials.

The bioaccumulation factor analysis further demonstrated the capacity of the crab species to concentrate metals from the aquatic environment. Bioaccumulation factors greater than unity were recorded for most metals, indicating active uptake and retention within biological tissues. The highest bioaccumulation factors were observed in *Cardisoma armatum*, particularly for lead, cadmium, zinc, and iron. These findings suggest that the species possesses a high capacity for metal accumulation and may serve as a valuable bioindicator of environmental contamination within the study area. Similar observations were reported by Okpoji et al. [10], who documented significant bioaccumulation of nickel, lead, and cadmium in *Callinectes sapidus* collected from the Iko River. Their findings demonstrated that crustaceans readily accumulate toxic metals and can be used as sentinel organisms for monitoring environmental quality.

The observed bioaccumulation pattern, characterised by the dominance of iron and zinc over other metals, reflects both environmental availability and biological regulation. Essential trace elements such as iron, zinc, and copper are required for physiological processes and are therefore actively absorbed by aquatic organisms. However, when environmental concentrations become elevated, these essential elements may accumulate beyond physiological requirements and contribute to toxicological effects. Studies involving crustaceans exposed to petroleum hydrocarbons and heavy metals in the Qua Iboe Estuary similarly demonstrated enhanced accumulation of both essential and non-essential elements in exposed organisms [6].

The estimated daily intake values indicated that consumers of crabs harvested from the Ibotirem Waterway are exposed to measurable quantities of potentially toxic elements. Although the estimated daily intake values for individual metals appeared relatively low, continuous exposure through regular seafood consumption may result in cumulative toxicological effects over time. The importance of chronic dietary exposure to contaminants has been emphasised in previous studies involving fish and shellfish from contaminated aquatic ecosystems [1,14]. Continuous ingestion of contaminated seafood may lead to gradual accumulation of toxic metals within human tissues, increasing the likelihood of adverse health outcomes.

The non-carcinogenic health risk assessment revealed hazard quotient values exceeding unity for lead and cadmium in several crab species. Hazard quotient values greater than one indicate the possibility of adverse health effects resulting from long-term exposure. Lead exposure has been associated with neurological disorders, developmental abnormalities, cardiovascular diseases, and renal dysfunction, while cadmium exposure has been linked to kidney damage, skeletal disorders, and carcinogenic outcomes [7,14]. The elevated hazard quotient values recorded for these metals therefore suggest that regular consumption of contaminated crabs may present substantial health concerns for local populations dependent on seafood as a primary protein source.

The cumulative hazard index values exceeded the acceptable threshold of one in all analysed species, demonstrating significant combined non-carcinogenic risks. This finding highlights the importance of evaluating cumulative exposure rather than focusing solely on individual contaminants. Humans are simultaneously exposed to multiple contaminants through dietary pathways, and synergistic interactions among metals may enhance toxicological responses. Similar observations have been reported in studies involving smoked fish products and aquatic organisms from polluted environments in Nigeria, where cumulative risk indices exceeded acceptable safety limits [14].

The elevated hazard index values observed in the present study underscore the need for comprehensive risk management strategies within the study area.

The carcinogenic risk assessment revealed total cancer risk values exceeding the acceptable range recommended by international regulatory agencies. The highest carcinogenic risk was associated with *Cardisoma armatum*, whereas *Ocypode africana* exhibited comparatively lower risk levels. These findings indicate that lifetime consumption of contaminated crabs may increase the probability of cancer development among exposed populations. The elevated carcinogenic risks are primarily attributable to the presence of lead, cadmium, chromium, and nickel, all of which possess established carcinogenic properties. Similar concerns have been raised in previous environmental health studies conducted in oil-bearing communities within the Niger Delta, where chronic exposure to environmental contaminants was linked to increased health risks [8,12].

The contamination observed in the present study may be attributed to multiple anthropogenic activities occurring within the Andoni coastal environment. Domestic wastewater discharges, agricultural runoff, boat traffic, artisanal fishing activities, seafood processing, and petroleum-related operations constitute important sources of heavy metals within aquatic ecosystems [4,8]. Studies conducted in Andoni surface waters and surrounding Niger Delta environments have consistently documented elevated concentrations of heavy metals and hydrocarbons associated with these activities [8,12]. The persistence of such contaminants in aquatic systems facilitates their transfer into sediments and subsequent uptake by aquatic organisms.

Conclusion

This investigation examined the occurrence and accumulation of potentially toxic elements in edible crab species obtained from the Ibotirem Waterway, Andoni Local Government Area, Rivers State, Nigeria, and evaluated the potential health implications associated with their consumption. The results demonstrated widespread contamination of the aquatic ecosystem, as evidenced by the elevated concentrations of Pb, Cd, Cr, Ni, Cu, Zn, and Fe detected in all analysed crab species. Iron and zinc constituted the dominant metals across the sampled organisms, whereas lead and cadmium occurred at concentrations exceeding internationally recommended food safety limits. Among the investigated species, *Cardisoma armatum* consistently recorded the highest contaminant burden and bioaccumulation capacity, suggesting greater exposure to sediment-associated pollutants and enhanced retention of metals within its tissues. Conversely, *Ocypode africana* exhibited comparatively lower metal concentrations and accumulation efficiencies. These variations emphasise the importance of ecological behaviour, habitat utilisation, and feeding strategies in determining contaminant uptake by aquatic organisms.

The bioaccumulation assessment revealed efficient transfer of metals from the aquatic environment into crab tissues, confirming the suitability of these organisms as indicators of environmental quality within coastal ecosystems. Elevated bioaccumulation factors observed for several metals indicate sustained contaminant availability in the surrounding water and sediment matrix. From a public health perspective, the risk assessment results demonstrated that routine consumption of the investigated crab species may expose consumers to unacceptable levels of toxic metals. Hazard quotient and hazard index values exceeded recommended safety thresholds in several cases, while carcinogenic risk estimates surpassed acceptable regulatory limits, indicating the possibility of adverse long-term health outcomes among frequent consumers.

The findings further suggest that contaminant inputs into the Ibotirem Waterway are likely associated with a combination of domestic, agricultural, transportation, and petroleum-related activities that characterise much of the Niger Delta environment. Continued release of these contaminants may not only compromise ecological integrity but also threaten food security and community health through the contamination of aquatic resources. Consequently, sustained environmental surveillance, routine seafood quality monitoring, and stricter enforcement of pollution control regulations are necessary to minimise contaminant loading into the aquatic ecosystem. In addition, public health awareness campaigns and evidence-based environmental management strategies should be prioritised to reduce exposure risks and promote the sustainable utilisation of fisheries within the Andoni coastal region.

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