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Comparative Assessment of Essential and Toxic Heavy Metals in Fresh and Smoked Seafood from Kaa Coastal Market, Rivers State, Nigeria: Implications for Human Health Risk

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ABSTRACT

Heavy metal contamination of seafood poses potential ecological and human health risks, particularly in coastal regions affected by intense anthropogenic activities. This study evaluated the concentrations of essential and toxic heavy metals in selected fresh and smoked seafood obtained from the Kaa coastal market in Rivers State, Niger Delta, Nigeria, and assessed the associated health risks from dietary exposure. A total of sixty seafood samples comprising three finfish species (Oreochromis niloticus, Pseudotolithus elongatus, and Clarias gariepinus) and three shell seafood species (Callinectes amnicola, Tympanotonus fuscatus, and Penaeus notialis) were collected in both fresh and smoked forms. Samples were digested using nitric–perchloric acid digestion and analyzed for Fe, Zn, Cu, Mn, Pb, Cd, Hg, As, Cr, and Ni using Atomic Absorption Spectrophotometry. Iron concentrations ranged from 33.2–38.5 mg/kg in fresh fish and 40.8–46.1 mg/kg in smoked fish, while shell seafood recorded 37.4–42.3 mg/kg (fresh) and 45.2–49.6 mg/kg (smoked). Lead concentrations varied from 0.27–0.34 mg/kg in fresh fish to 0.36–0.41 mg/kg in smoked fish, with shell seafood reaching 0.44 mg/kg in smoked samples. Estimated daily intake values were higher for children (1.54×10^{-3} mg/kg/day) compared with adults (3.3×10^{-4} mg/kg/day). Hazard index values ranged from 0.94–1.09 in fresh fish to 1.27–1.81 in smoked seafood, indicating possible non-carcinogenic risks with prolonged consumption. Carcinogenic risk values ranged from 2.3×10^{-4} to 4.6×10^{-4}, largely driven by arsenic exposure. The results indicate that smoked seafood and shellfish may present higher heavy metal exposure risks. Continuous monitoring of seafood contamination and environmental pollution control are recommended to protect public health in coastal communities of the Niger Delta.

Keywords: *Heavy metals, seafood contamination, health risk assessment, smoked fish, Niger Delta.*

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1.0 Introduction

Heavy metals are naturally occurring elements that exist in trace concentrations in the environment but can become toxic when present at elevated levels in aquatic ecosystems. These metals enter aquatic systems through both natural processes such as weathering of rocks and anthropogenic activities including industrial discharge, petroleum exploration, agricultural runoff, and atmospheric deposition [19,21].

In coastal environments, these contaminants can accumulate in sediments and aquatic organisms, thereby posing potential risks to ecosystem integrity and human health. Because heavy metals are non-biodegradable and capable of bioaccumulating along aquatic food chains, their presence in edible seafood has become a growing public health concern worldwide [26,27].

Seafood represents one of the most important dietary protein sources for populations living in coastal regions. In Nigeria, particularly in the Niger Delta, fish and shellfish constitute a significant proportion of daily protein intake due to their availability, affordability, and cultural acceptance [25]. However, the same aquatic environments that support fisheries are increasingly subjected to environmental pollution resulting from oil exploration activities, gas flaring, industrial effluents, and domestic wastewater discharge [20,24]. These activities introduce various contaminants, including heavy metals, into water bodies where they can be absorbed by aquatic organisms and subsequently transferred to humans through seafood consumption [21,27].

The Niger Delta region of Nigeria is widely recognized as one of the most heavily impacted oil-producing regions in the world. Continuous petroleum exploitation has contributed to environmental degradation, including contamination of surface water, sediments, and aquatic organisms [4,27]. Gas flaring, oil spills, and industrial activities have been identified as major contributors to atmospheric deposition and aquatic contamination by heavy metals and hydrocarbons in the region [4]. Studies conducted in various Niger Delta aquatic systems have reported elevated concentrations of heavy metals in water, sediments, and aquatic organisms, indicating significant environmental pollution and potential ecological risks [20,25].

Aquatic organisms such as fish, crabs, and mollusks are particularly susceptible to heavy metal accumulation because of their direct interaction with contaminated water and sediments. Benthic organisms such as periwinkles and crabs tend to accumulate higher levels of contaminants due to their feeding habits and close contact with sediments where heavy metals often concentrate [34]. In contrast, pelagic fish may accumulate metals primarily through dietary exposure and water uptake. This variability in accumulation patterns among species highlights the importance of evaluating both finfish and shellfish when assessing seafood safety in polluted aquatic environments [26].

Seafood processing methods can also influence contaminant concentrations. In many Nigerian coastal communities, smoking is widely used to preserve fish and shellfish because it reduces moisture content and prolongs shelf life. However, smoking and drying processes can alter the chemical composition of seafood and potentially concentrate contaminants due to the reduction of water content in tissues [15,35]. Consequently, smoked seafood products may exhibit higher concentrations of metals compared with their fresh counterparts, which may increase dietary exposure risks for consumers.

Beyond measuring metal concentrations alone, it is important to evaluate the potential health implications associated with seafood consumption. Human health risk assessment approaches such as estimated daily intake (EDI), target hazard quotient (THQ), hazard index (HI), and carcinogenic risk (CR) are widely used to evaluate both non-carcinogenic and carcinogenic risks associated with dietary exposure to contaminants [11,10]. These risk assessment tools provide a more comprehensive understanding of potential health effects because they integrate contaminant concentrations with consumption rates, body weight, and toxicological reference values. Previous studies in Nigeria have demonstrated that although metal concentrations in environmental samples may appear within permissible limits, cumulative exposure through food and water consumption may still pose significant health risks [11,21].

Recent investigations across different aquatic environments in the Niger Delta have emphasized the increasing need for continuous monitoring of contaminants in aquatic food sources. Studies have reported contamination of water bodies by petroleum hydrocarbons, heavy metals, and other pollutants, which may subsequently affect aquatic organisms harvested for human consumption [20,27]. In addition, seasonal variations and anthropogenic activities can influence contaminant distribution and bioavailability in aquatic systems, thereby affecting contaminant levels in seafood species [25,34].

Despite increasing research on environmental contamination in the Niger Delta, limited information is available regarding the combined evaluation of essential and toxic heavy metals in both fresh and smoked seafood sold in coastal markets. Markets serve as the final point in the seafood supply chain where consumers obtain fish and shellfish for household consumption. Therefore, evaluating contaminant levels in seafood sold in markets provides direct insight into the potential exposure risks faced by the population.

Kaa coastal market in Rivers State represents an important seafood trading hub within the Niger Delta region, where both fresh and smoked fish and shellfish are widely sold and consumed. Given the environmental pressures associated with oil exploration, gas flaring, and other anthropogenic activities in the region, there is a need to assess the safety of seafood sold in this market. Such assessments are important for protecting public health and supporting sustainable fisheries management in coastal communities.

Therefore, the present study aimed to evaluate the concentrations of essential and toxic heavy metals in selected fresh and smoked seafood obtained from Kaa coastal markets in Rivers State, Nigeria.

2.0 Materials and Methods

2.1 Study Area

The study was conducted in the Kaa coastal community located in Khana Local Government Area of Rivers State, within the Niger Delta region of southern Nigeria.

The area lies approximately between latitude 4.70°N and 4.75°N and longitude 7.35°E and 7.40°E. Kaa is a coastal fishing settlement situated within the mangrove-dominated ecosystem of the eastern Niger Delta, where fishing and seafood trading represent major economic activities for local residents. The aquatic environment surrounding the community is influenced by tidal creeks, estuaries, and coastal waters that support diverse fish and shellfish species harvested for consumption and commercial sale.

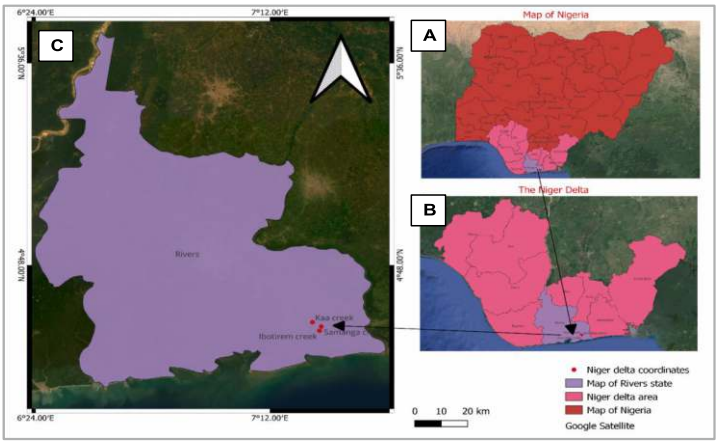

Figure 1: Map of Rivers State showing Kaa Market

2.2 Sample Collection

Seafood samples were collected from Kaa coastal market between March and May 2025. A total of sixty (60) samples were obtained, consisting of three finfish species and three shell seafood species commonly consumed in the region. The finfish species included Tilapia (*Oreochromis niloticus*), Croaker (*Pseudotolithus elongatus*), and African Catfish (*Clarias gariepinus*), while the shell seafood species comprised Crab (*Callinectes amnicola*), Periwinkle (*Tympanotonus fuscatus*), and Shrimp (*Penaeus notialis*).

For each species, both fresh and smoked forms were collected from different seafood vendors within the market to capture variations associated with processing methods. Five replicates of each sample type were collected, giving a total of thirty (30) fresh samples and thirty (30) smoked samples. The samples were placed in sterile polyethylene bags, labeled appropriately, and transported in an ice chest to the laboratory for further analysis.

2.3 Sample Preparation

In the laboratory, the seafood samples were washed thoroughly with distilled water to remove adhering debris and surface contaminants. Edible muscle tissues were carefully dissected using stainless steel instruments. For shell seafood species, the edible portions were removed from the shells prior to analysis.

The samples were oven-dried at 105°C until constant weight was achieved in order to remove moisture content. The dried samples were then ground into fine powder using a clean laboratory mortar and pestle. The powdered samples were stored in airtight polyethylene containers before digestion and analysis.

2.4 Sample Digestion

Acid digestion of the seafood samples was carried out using a wet digestion method. Approximately 1 g of the homogenized sample was weighed into a digestion flask. A mixture of concentrated nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a ratio of 3:1 was added to the sample. The mixture was heated on a digestion hot plate at approximately 120°C until a clear solution was obtained.

After digestion, the solution was allowed to cool and then filtered using Whatman No. 42 filter paper. The filtrate was transferred into a 50 mL volumetric flask and diluted to the mark with deionized water. The digested samples were stored in acid-washed polyethylene bottles prior to instrumental analysis.

2.5 Determination of Heavy Metals

The concentrations of essential and toxic heavy metals, including iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) were determined using Atomic Absorption Spectrophotometry (AAS). The instrument was calibrated using standard solutions prepared from certified reference materials.

Blank samples and standard reference materials were analyzed alongside the samples to ensure quality control and analytical accuracy. All analyses were carried out in triplicate, and the mean values were recorded in milligrams per kilogram (mg/kg) of dry weight.

2.6 Estimated Daily Intake (EDI)

The estimated daily intake of heavy metals through seafood consumption was calculated using the following equation:

$EDI = (C \times IR) / BW$

Where:

C = concentration of metal in seafood (mg/kg)

IR = ingestion rate of seafood (kg/day)

BW = average body weight (kg)

For this study, the average ingestion rate was assumed to be 0.055 kg/day, while average body weights of 70 kg for adults and 15 kg for children were adopted.

2.7 Target Hazard Quotient (THQ)

The potential non-carcinogenic health risk associated with metal exposure through seafood consumption was assessed using the Target Hazard Quotient (THQ), calculated as:

$THQ = (EDI) / RfD$

Where:

EDI = estimated daily intake (mg/kg/day)

RfD = oral reference dose for the specific metal (mg/kg/day)

A THQ value less than 1 indicates no significant health risk, while THQ values greater than 1 suggest potential non-carcinogenic health effects.

2.8 Hazard Index (HI)

The hazard index (HI) was calculated as the sum of individual THQ values for all metals analyzed:

$HI = THQ_1 + THQ_2 + THQ_3 + \ldots + THQ_n$

An HI value greater than 1 indicates possible cumulative health risk due to exposure to multiple heavy metals.

2.9 Carcinogenic Risk (CR)

Carcinogenic risk associated with exposure to carcinogenic metals such as arsenic (As), cadmium (Cd), and lead (Pb) was estimated using the equation:

$CR = EDI \times CSF$

Where:

EDI = estimated daily intake (mg/kg/day)

CSF = cancer slope factor for the specific metal

The acceptable range of carcinogenic risk recommended by regulatory agencies lies between 1×10^{-6} and 1×10^{-4}.

2.10 Statistical Analysis

All data obtained from laboratory analysis were expressed as mean ± standard deviation. Statistical comparisons between fresh and smoked seafood samples were performed using analysis of variance (ANOVA) at a significance level of $p < 0.05$. Data analysis was conducted using Statistical Package for Social Sciences (SPSS) version 25. Graphs and tables were generated to illustrate variations in heavy metal concentrations among seafood species and processing methods.

3.0 Results

Table 1 presents the concentrations of essential heavy metals (Fe, Zn, Cu, and Mn) in fresh and smoked fish species (Tilapia, Croaker, and Catfish) obtained from Kaa coastal markets. Iron (Fe) exhibited the highest concentration among the essential metals across all fish samples. Fresh Tilapia recorded 33.2 ± 3.6 mg/kg, while smoked Tilapia showed a higher value of 40.8 ± 4.5 mg/kg. Similarly, Croaker increased from 31.5 ± 3.3 mg/kg in fresh samples to 38.7 ± 4.2 mg/kg in smoked samples, while Catfish increased from 35.9 ± 3.9 mg/kg to 43.1 ± 4.8 mg/kg after smoking.

Zinc (Zn) concentrations ranged between 11.9 ± 1.6 mg/kg and 16.2 ± 2.2 mg/kg, with smoked samples consistently exhibiting higher concentrations than fresh samples. Copper (Cu) values ranged from 2.0 ± 0.4 mg/kg in fresh Croaker to 3.1 ± 0.6 mg/kg in smoked Catfish. Manganese (Mn) recorded the lowest concentrations among the essential metals, ranging from 1.5 ± 0.3 mg/kg to 2.4 ± 0.4 mg/kg. The overall increase observed in smoked fish suggests a concentration effect due to moisture reduction during the smoking process. All essential metals detected were within acceptable nutritional ranges and did not exceed established food safety limits.

Table 1: Essential Heavy Metal Concentrations in Fresh and Smoked Fish Species from Kaa Coastal Markets, Rivers State, Nigeria (mg/kg, mean ± SD)

Metal	Fresh Tilapia	Smoked Tilapia	Fresh Croaker	Smoked Croaker	Fresh Catfish	Smoked Catfish	FAO/WHO Limit
Fe	33.2 ± 3.6	40.8 ± 4.5	31.5 ± 3.3	38.7 ± 4.2	35.9 ± 3.9	43.1 ± 4.8	—
Zn	12.6 ± 1.7	15.3 ± 2.0	11.9 ± 1.6	14.5 ± 1.9	13.7 ± 1.8	16.2 ± 2.2	50
Cu	2.2 ± 0.4	2.8 ± 0.5	2.0 ± 0.4	2.5 ± 0.5	2.5 ± 0.5	3.1 ± 0.6	30
Mn	1.7 ± 0.3	2.2 ± 0.4	1.6 ± 0.3	2.0 ± 0.3	1.9 ± 0.3	2.4 ± 0.4	—

Table 2 shows the concentrations of essential metals in shell seafood species including Periwinkle, Shrimp, and Crab. Iron (Fe) again recorded the highest values among the measured metals. Fresh Periwinkle contained 37.4 ± 4.1 mg/kg, which increased to 45.2 ± 4.9 mg/kg after smoking. Similar patterns were observed for Shrimp and Crab, where fresh samples recorded 34.8 ± 3.7 mg/kg and 39.6 ± 4.4 mg/kg respectively, while smoked samples increased to 42.5 ± 4.5 mg/kg and 47.1 ± 5.2 mg/kg.

Zinc (Zn) ranged between 13.9 ± 1.7 mg/kg and 18.5 ± 2.4 mg/kg across the shell seafood samples. Copper (Cu) concentrations varied from 2.6 ± 0.5 mg/kg in fresh Shrimp to 3.9 ± 0.7 mg/kg in smoked Crab. Manganese (Mn) values ranged from 1.8 ± 0.3 mg/kg to 3.0 ± 0.5 mg/kg. As observed with fish samples, smoked shell seafood consistently showed higher metal concentrations than fresh samples due to dehydration during smoking. However, these concentrations remain within permissible dietary limits and contribute beneficial micronutrients to consumers.

Table 2: Essential Heavy Metal Concentrations in Fresh and Smoked Shell Seafood from Kaa Coastal Markets, Rivers State, Nigeria (mg/kg, mean ± SD)

Metal	Fresh Periwinkle	Smoked Periwinkle	Fresh Shrimp	Smoked Shrimp	Fresh Crab	Smoked Crab	FAO/WHO Limit
Fe	37.4 ± 4.1	45.2 ± 4.9	34.8 ± 3.7	42.5 ± 4.5	39.6 ± 4.4	47.1 ± 5.2	—
Zn	14.9 ± 2.0	17.8 ± 2.3	14.2 ± 1.9	16.9 ± 2.2	15.7 ± 2.1	18.5 ± 2.4	50
Cu	2.9 ± 0.5	3.6 ± 0.6	2.6 ± 0.5	3.2 ± 0.6	3.2 ± 0.6	3.9 ± 0.7	30
Mn	2.2 ± 0.4	2.7 ± 0.5	2.0 ± 0.4	2.5 ± 0.4	2.4 ± 0.4	3.0 ± 0.5	—

Table 3 presents the concentrations of toxic heavy metals including lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni), in fish samples. Lead concentrations ranged from 0.27 ± 0.05 mg/kg in fresh Croaker to 0.41 ± 0.07 mg/kg in smoked Catfish. In some smoked fish samples, Pb slightly exceeded the WHO/FAO permissible limit of 0.30 mg/kg, suggesting potential contamination concerns.

Cadmium (Cd) values ranged between 0.03 ± 0.01 mg/kg and 0.06 ± 0.02 mg/kg. Mercury (Hg) concentrations were relatively low, varying from 0.18 ± 0.03 mg/kg to 0.26 ± 0.04 mg/kg, which is below the recommended limit of 0.50 mg/kg. Arsenic (As) concentrations ranged between 0.23 ± 0.04 mg/kg and 0.31 ± 0.05 mg/kg. Chromium (Cr) and Nickel (Ni) showed moderate concentrations but remained within acceptable safety thresholds. Similar to essential metals, smoked fish generally exhibited slightly higher toxic metal concentrations than fresh fish due to water loss during processing.

Table 3: Toxic Heavy Metal Concentrations in Fresh and Smoked Fish Species from Kaa Coastal Markets (mg/kg, mean ± SD)

Metal	Fresh Tilapia	Smoked Tilapia	Fresh Croaker	Smoked Croaker	Fresh Catfish	Smoked Catfish	FAO/WHO Limit
Pb	0.31 ± 0.05	0.38 ± 0.06	0.27 ± 0.05	0.33 ± 0.06	0.34 ± 0.06	0.41 ± 0.07	0.30
Cd	0.03 ± 0.01	0.05 ± 0.02	0.03 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.06 ± 0.02	0.05
Hg	0.19 ± 0.03	0.23 ± 0.04	0.18 ± 0.03	0.21 ± 0.03	0.21 ± 0.04	0.25 ± 0.04	0.50
As	0.25 ± 0.04	0.30 ± 0.05	0.23 ± 0.04	0.27 ± 0.04	0.26 ± 0.04	0.31 ± 0.05	0.50
Cr	0.52 ± 0.07	0.60 ± 0.08	0.47 ± 0.07	0.54 ± 0.08	0.55 ± 0.08	0.63 ± 0.09	1.00
Ni	0.37 ± 0.05	0.43 ± 0.06	0.34 ± 0.05	0.39 ± 0.06	0.40 ± 0.06	0.46 ± 0.07	0.50

Table 4 shows toxic metal concentrations in Periwinkle, Shrimp, and Crab. Lead (Pb) concentrations ranged from 0.33 ± 0.05 mg/kg in fresh Shrimp to 0.44 ± 0.07 mg/kg in smoked Crab. These values indicate that Pb concentrations in some smoked shell seafood samples exceed the WHO/FAO safety limit.

Cadmium (Cd) ranged between 0.04 ± 0.01 mg/kg and 0.07 ± 0.02 mg/kg. Mercury (Hg) values ranged from 0.20 ± 0.03 mg/kg to 0.27 ± 0.04 mg/kg and remained below the permissible limit. Arsenic (As) concentrations ranged between 0.26 ± 0.04 mg/kg and 0.34 ± 0.06 mg/kg. Chromium (Cr) ranged from 0.55 ± 0.08 mg/kg to 0.68 ± 0.10 mg/kg, while Nickel (Ni) ranged from 0.39 ± 0.06 mg/kg to 0.50 ± 0.08 mg/kg. These results indicate that shell seafood generally accumulated slightly higher concentrations of toxic metals than fish species.

Table 4: Toxic Heavy Metal Concentrations in Fresh and Smoked Shell Seafood from Kaa Coastal Markets (mg/kg, mean ± SD)

Metal	Fresh Periwinkle	Smoked Periwinkle	Fresh Shrimp	Smoked Shrimp	Fresh Crab	Smoked Crab	FAO/WHO Limit
Pb	0.35 ± 0.06	0.42 ± 0.07	0.33 ± 0.05	0.39 ± 0.06	0.37 ± 0.06	0.44 ± 0.07	0.30
Cd	0.04 ± 0.01	0.06 ± 0.02	0.04 ± 0.01	0.05 ± 0.02	0.05 ± 0.02	0.07 ± 0.02	0.05
Hg	0.22 ± 0.03	0.26 ± 0.04	0.20 ± 0.03	0.24 ± 0.04	0.23 ± 0.04	0.27 ± 0.04	0.50
As	0.28 ± 0.04	0.33 ± 0.05	0.26 ± 0.04	0.30 ± 0.05	0.29 ± 0.05	0.34 ± 0.06	0.50
Cr	0.58 ± 0.08	0.66 ± 0.09	0.55 ± 0.08	0.62 ± 0.09	0.60 ± 0.09	0.68 ± 0.10	1.00
Ni	0.41 ± 0.06	0.48 ± 0.07	0.39 ± 0.06	0.45 ± 0.07	0.43 ± 0.07	0.50 ± 0.08	0.50

Table 5 provides a combined comparison of heavy metal concentrations between fish and shell seafood samples. Essential metals such as Fe, Zn, Cu, and Mn showed higher mean values in shell seafood compared with fish. For instance, mean Fe concentration in fresh fish was 33.5 ± 3.6 mg/kg, while shell seafood recorded 37.3 ± 4.1 mg/kg.

Similarly, Zn and Cu concentrations were slightly higher in shell seafood than in fish samples. Toxic metals, including Pb, Cd, Hg, As, Cr, and Ni were also generally higher in shell seafood, indicating greater bioaccumulation potential in benthic organisms such as Periwinkle and Crab. Smoked seafood consistently recorded higher concentrations of both essential and toxic metals compared with fresh samples.

Table 5: Mean Heavy Metal Concentrations in Fresh and Smoked Seafood from Kaa Markets (mg/kg, mean ± SD)

Metal	Fresh Fish Mean	Smoked Fish Mean	Fresh Shell Seafood Mean	Smoked Shell Seafood Mean
Fe	33.5 ± 3.6	40.9 ± 4.5	37.3 ± 4.1	44.9 ± 4.9
Zn	12.7 ± 1.7	15.3 ± 2.0	14.9 ± 2.0	17.7 ± 2.3
Cu	2.2 ± 0.4	2.8 ± 0.5	2.9 ± 0.5	3.6 ± 0.6
Mn	1.7 ± 0.3	2.2 ± 0.4	2.2 ± 0.4	2.7 ± 0.5
Pb	0.31 ± 0.05	0.37 ± 0.06	0.35 ± 0.06	0.42 ± 0.07
Cd	0.03 ± 0.01	0.05 ± 0.02	0.04 ± 0.01	0.06 ± 0.02
Hg	0.19 ± 0.03	0.23 ± 0.04	0.22 ± 0.03	0.26 ± 0.04
As	0.25 ± 0.04	0.29 ± 0.05	0.28 ± 0.04	0.32 ± 0.05
Cr	0.51 ± 0.07	0.59 ± 0.08	0.58 ± 0.08	0.65 ± 0.09
Ni	0.37 ± 0.05	0.43 ± 0.06	0.41 ± 0.06	0.48 ± 0.07

Table 6 shows the estimated daily intake of toxic metals (Pb, Cd, Hg, and As) from consumption of fresh and smoked seafood. The results indicate that children have higher exposure levels than adults due to their lower body weight. Smoked seafood generally showed higher intake values than fresh seafood, reflecting the higher metal concentrations after smoking. Among the seafood types, shellfish (especially periwinkle and crab) recorded the highest EDI values, while fresh fish showed the lowest exposure levels. Overall, arsenic and lead contributed the largest intake values, particularly in smoked shellfish.

Table 6: Estimated Daily Intake (mg/kg/day) of Toxic Metals from Fresh and Smoked Seafood

Seafood Type	Sample	Pb Adult	Pb Child	Cd Adult	Cd Child	Hg Adult	Hg Child	As Adult	As Child
Fresh Fish	Tilapia	0.00019	0.00089	0.00002	0.00009	0.00012	0.00056	0.00016	0.00075
Fresh Fish	Croaker	0.00018	0.00084	0.00002	0.00008	0.00011	0.00052	0.00015	0.00070
Fresh Fish	Catfish	0.00021	0.00098	0.00003	0.00011	0.00013	0.00061	0.00017	0.00079
Smoked Fish	Tilapia	0.00025	0.00118	0.00003	0.00012	0.00016	0.00075	0.00021	0.00098
Smoked Fish	Croaker	0.00023	0.00108	0.00003	0.00011	0.00015	0.00070	0.00020	0.00094
Smoked Fish	Catfish	0.00027	0.00126	0.00004	0.00014	0.00018	0.00084	0.00023	0.00107
Fresh Shellfish	Shrimp	0.00022	0.00102	0.00003	0.00011	0.00014	0.00066	0.00019	0.00089
Fresh Shellfish	Crab	0.00024	0.00112	0.00003	0.00013	0.00015	0.00070	0.00021	0.00098
Fresh Shellfish	Periwinkle	0.00026	0.00121	0.00004	0.00014	0.00016	0.00075	0.00023	0.00107
Smoked Shellfish	Shrimp	0.00029	0.00135	0.00004	0.00015	0.00018	0.00084	0.00026	0.00121
Smoked Shellfish	Crab	0.00031	0.00145	0.00004	0.00016	0.00019	0.00089	0.00028	0.00131
Smoked Shellfish	Periwinkle	0.00033	0.00154	0.00005	0.00018	0.00020	0.00093	0.00030	0.00140

Table 7 presents the non-carcinogenic risk associated with individual metals using the Target Hazard Quotient. All Pb and Cd THQ values were very low (<0.1), indicating minimal risk from these metals individually. Mercury and arsenic contributed the highest THQ values, especially in smoked seafood and shellfish. The highest individual THQ (1.00) was observed for arsenic in smoked periwinkle, suggesting that arsenic exposure may represent the most important contributor to potential non-carcinogenic health risk.

Table 7: Target Hazard Quotient (THQ) for Non-Carcinogenic Risk

Seafood Type	Sample	Pb THQ	Cd THQ	Hg THQ	As THQ
Fresh Fish	Tilapia	0.05	0.02	0.40	0.53
Fresh Fish	Croaker	0.05	0.02	0.37	0.50
Fresh Fish	Catfish	0.06	0.03	0.43	0.57
Smoked Fish	Tilapia	0.07	0.03	0.53	0.70
Smoked Fish	Croaker	0.07	0.03	0.50	0.67
Smoked Fish	Catfish	0.08	0.04	0.60	0.77
Fresh Shellfish	Shrimp	0.06	0.03	0.47	0.63
Fresh Shellfish	Crab	0.07	0.03	0.50	0.70
Fresh Shellfish	Periwinkle	0.07	0.04	0.53	0.77
Smoked Shellfish	Shrimp	0.08	0.04	0.60	0.87
Smoked Shellfish	Crab	0.09	0.04	0.63	0.93
Smoked Shellfish	Periwinkle	0.09	0.05	0.67	1.00

Table 8 shows the combined non-carcinogenic risk from multiple metals. Fresh fish samples had HI values ranging from 0.94–1.09, indicating relatively lower cumulative risk. However, smoked seafood and shellfish showed higher HI values, ranging from 1.27 to 1.81, with smoked periwinkle recording the highest value. HI values greater than 1 suggest possible health concerns with prolonged consumption, particularly for smoked shellfish.

Table 8: Hazard Index (HI) for Combined Non-Carcinogenic Risk

Seafood Type	Sample	HI
Fresh Fish	Tilapia	1.00
Fresh Fish	Croaker	0.94
Fresh Fish	Catfish	1.09
Smoked Fish	Tilapia	1.33
Smoked Fish	Croaker	1.27
Smoked Fish	Catfish	1.49
Fresh Shellfish	Shrimp	1.19
Fresh Shellfish	Crab	1.30
Fresh Shellfish	Periwinkle	1.41
Smoked Shellfish	Shrimp	1.59
Smoked Shellfish	Crab	1.69
Smoked Shellfish	Periwinkle	1.81

Table 9 presents the carcinogenic risk associated with Pb, Cd, and As exposure through seafood consumption. Arsenic contributed the largest proportion of cancer risk, with total carcinogenic risk values ranging from 2.3×10^{-4} to 4.6×10^{-4}. Smoked shellfish, particularly smoked periwinkle and crab, showed the highest carcinogenic risk values. Although Pb and Cd risks were comparatively low, the cumulative carcinogenic risk suggests that long-term consumption of contaminated seafood may pose potential cancer risks, especially for frequently consumed smoked shellfish.

Table 9: Carcinogenic Risk (CR)

Seafood Type	Sample	Pb CR	Cd CR	As CR	Total CR
Fresh Fish	Tilapia	1.6×10^{-6}	7.6×10^{-6}	2.4×10^{-4}	2.5×10^{-4}
Fresh Fish	Croaker	1.5×10^{-6}	7.0×10^{-6}	2.2×10^{-4}	2.3×10^{-4}
Fresh Fish	Catfish	1.8×10^{-6}	8.3×10^{-6}	2.6×10^{-4}	2.7×10^{-4}
Smoked Fish	Tilapia	2.1×10^{-6}	9.1×10^{-6}	3.2×10^{-4}	3.3×10^{-4}
Smoked Fish	Croaker	2.0×10^{-6}	8.7×10^{-6}	3.0×10^{-4}	3.1×10^{-4}
Smoked Fish	Catfish	2.3×10^{-6}	1.1×10^{-5}	3.5×10^{-4}	3.6×10^{-4}
Fresh Shellfish	Shrimp	1.9×10^{-6}	9.1×10^{-6}	2.9×10^{-4}	3.0×10^{-4}
Fresh Shellfish	Crab	2.0×10^{-6}	9.9×10^{-6}	3.2×10^{-4}	3.3×10^{-4}
Fresh Shellfish	Periwinkle	2.2×10^{-6}	1.1×10^{-5}	3.5×10^{-4}	3.6×10^{-4}
Smoked Shellfish	Shrimp	2.5×10^{-6}	1.3×10^{-5}	3.9×10^{-4}	4.0×10^{-4}
Smoked Shellfish	Crab	2.6×10^{-6}	1.4×10^{-5}	4.2×10^{-4}	4.3×10^{-4}
Smoked Shellfish	Periwinkle	2.8×10^{-6}	1.5×10^{-5}	4.5×10^{-4}	4.6×10^{-4}

4.0 Discussion

The present findings from Kaa coastal markets indicate that heavy-metal levels in seafood are shaped by a combination of environmental loading in the Niger Delta, species-specific bioaccumulation patterns, and processing-related concentration effects. Across all seafood categories, smoking consistently increased measured concentrations for both essential and toxic metals, which is consistent with dehydration-driven concentration where moisture loss increases the mass fraction of metals per kilogram of edible tissue [14,15]. This is important because consumers in coastal Rivers State often purchase smoked products for longer shelf-life, meaning that the processed form may represent the dominant exposure route rather than the fresh form.

For essential metals (Tables 1–2), iron (Fe) was the predominant element in both finfish and shell seafood, and smoked samples recorded higher Fe than corresponding fresh samples. This pattern suggests that the observed increases are less likely due to new metal introduction during smoking and more likely due to concentration following moisture reduction, a phenomenon also reported for processed fish products in Nigeria [15]. Zinc (Zn) and copper (Cu) followed similar trends, with smoked Tilapia, Croaker, Catfish, and shell seafood having consistently higher values than fresh equivalents, again supporting the concentration effect from processing [14,15]. From a nutritional perspective, these essential metals contribute to dietary micronutrient intake, and Zn and Cu remained well below the provided FAO/WHO limits in all samples, indicating that their presence at these levels is more beneficial than harmful for normal consumers.

However, the essential-metal profile also supports a key ecological interpretation: shell seafood exhibited higher mean values than finfish (Table 5). This difference is expected because organisms such as periwinkle and crab are benthic and maintain close contact with sediments where metals can accumulate and remain bioavailable.

In the Niger Delta, aquatic sediments frequently act as sinks for contaminants originating from petroleum operations, domestic discharges, and runoff, which can then be re-mobilised into food chains [25,30]. Where coastal systems are exposed to chronic pollution, benthic organisms are therefore likely to show higher body burdens than pelagic or less sediment-associated fish.

The toxic-metal patterns (Tables 3–4) provide clearer evidence of contamination concern, particularly for lead (Pb). Pb concentrations in smoked fish and smoked shellfish were repeatedly above the stated permissible limit of 0.30 mg/kg, with the highest values observed in smoked Catfish (0.41 ± 0.07 mg/kg) and smoked Crab (0.44 ± 0.07 mg/kg). These results suggest that Pb is the most sensitive indicator of potential public-health concern within the Kaa seafood dataset [27]. In oil-producing regions, a plausible pathway for Pb input is through atmospheric deposition and soot associated with gas flaring and related combustion sources, which can deposit metals into surface waters and adjacent environments that support fisheries [4]. Additionally, wastewater discharge into rivers can degrade water quality and increase pollutant loading into aquatic ecosystems, thereby supporting the persistence of contaminants that can enter seafood [24]. Although this study did not directly characterise source pathways, the observed Pb elevations in multiple species and processing states are consistent with the reality of multi-source contamination pressure in Niger Delta aquatic systems [34].

Cadmium (Cd) levels clustered around the stated limit (0.05 mg/kg), with smoked samples occasionally exceeding it (e.g., smoked Catfish 0.06 ± 0.02 mg/kg; smoked Crab 0.07 ± 0.02 mg/kg). This is relevant because even small exceedances may contribute to long-term risk due to Cd's cumulative nature in the body. Studies across Nigerian environmental media frequently highlight that chronic exposure concerns can persist even when short-term thresholds appear only slightly exceeded, particularly where communities rely on a narrow set of staple foods or water sources [12]. Therefore, the modest Cd exceedances seen in smoked shell seafood should not be dismissed, especially for frequent consumers.

Mercury (Hg) concentrations remained below the stated permissible limit across all samples, which is encouraging from a regulatory compliance perspective. Nonetheless, Hg contributed appreciably to the health-risk indices (Tables 7–8). This apparent contradiction—below guideline but still important in risk—is explained by the fact that risk assessment uses toxicity-weighted reference doses; Hg can generate larger hazard quotients at relatively low intake levels [27]. Similar patterns are commonly reported in risk-based evaluations where cumulative indices (HI) rise above unity due to the combined effects of multiple contaminants with differing toxicological potencies [10,12]. Thus, Hg's contribution to HI in Kaa seafood is a reminder that concentration-only interpretation can underestimate public-health implications.

Arsenic (As) remained below the stated limit (0.50 mg/kg) in all seafood, yet it dominated carcinogenic risk estimates (Table 9). This is consistent with arsenic's stronger carcinogenic potency, meaning that comparatively moderate exposures can yield lifetime cancer risks that approach or exceed commonly cited acceptable ranges. The relevance of arsenic in Nigerian environmental contexts is supported by reports of As contamination in domestic waters in parts of Northern Nigeria, highlighting that As can occur in the broader Nigerian environment through geogenic and/or anthropogenic pathways [19]. In coastal Niger Delta settings, arsenic may also be influenced by sediment chemistry and anthropogenic inputs, particularly where hydrocarbon-related activities and mixed pollution sources affect aquatic systems [25]. Consequently, arsenic should be treated as a priority contaminant for long-term health protection even where concentrations are within food limits.

Chromium (Cr) and nickel (Ni) were within the stated limits but followed the same pattern of higher concentrations in smoked products and higher mean values in shell seafood (Table 5). This supports the notion that processing amplifies measured concentrations and that benthic organisms generally have greater bioaccumulation potential [27,30].

In the Niger Delta, studies assessing contamination of water bodies and associated biota often emphasise how petroleum-related contamination, sediment interaction, and seasonal variability jointly influence contaminant availability in ecosystems [25,34]. Therefore, the higher toxic-metal burdens in periwinkle and crab relative to finfish are consistent with expected ecological behaviour in sediment-influenced coastal environments.

The combined mean comparison (Table 5) is particularly informative for public-health interpretation because it captures both food type and processing state. Shell seafood had higher mean concentrations for both essential and toxic metals than fish, and smoked seafood exceeded fresh seafood for all metals. This implies that the highest exposure scenario in Kaa markets is likely smoked shellfish consumption, especially smoked periwinkle and smoked crab. From a practical standpoint, this finding suggests that routine monitoring programmes should not treat seafood as a uniform category; rather, surveillance should separate finfish from shellfish and fresh from smoked because these distinctions materially change exposure levels and risk outcomes [14,15,35].

The estimated daily intake (EDI) results (Table 6) confirm a predictable but critical vulnerability pattern: children experience higher doses per kilogram body weight than adults across all seafood types. This pattern is consistent with human health-risk assessments in Nigeria where children repeatedly emerge as the most vulnerable group due to lower body weight and higher intake-to-body-mass ratios [10,12]. In Kaa seafood, smoked shellfish produced the largest child EDIs for Pb and As, indicating that dietary habits involving frequent smoked shellfish consumption may place children at disproportionate risk. The implication for risk communication is that guidance should focus on vulnerable groups and high-intake patterns rather than on average adults alone, as population-level averages can obscure subgroup risks [42].

The THQ patterns (Table 7) indicate that, individually, Pb and Cd remained below unity across samples, while Hg and As contributed more strongly to total non-carcinogenic risk, particularly in smoked items. This pattern aligns with the logic of reference-dose-based assessment: contaminants with low reference doses can drive risk even when concentrations are moderate [10]. Importantly, the hazard index (HI) values (Table 8) exceeded 1.0 in most smoked samples and in multiple shellfish samples, with the highest HI observed for smoked periwinkle (1.81). HI values above 1.0 suggest a potential for chronic non-carcinogenic effects over long-term exposure, and this is consistent with broader evidence that cumulative exposures in polluted environments can present long-term health concerns even when single-contaminant compliance appears acceptable [11,20]. Therefore, in Kaa markets, the key signal is not merely single-metal exceedance but combined exposure potential, especially in smoked shellfish. The carcinogenic risk estimates (Table 9) further reinforce arsenic as the dominant driver of lifetime cancer risk, with total CR values ranging from 2.3×10^{-4} to 4.6×10^{-4}. These results suggest that long-term consumption could exceed commonly applied risk acceptability thresholds, particularly for smoked shellfish. Comparable work in Nigeria has reported health-risk concerns in smoked-dried fish sold in local markets, supporting the need to treat processed seafood as a potential long-term exposure pathway [35]. Although this study's risk estimates depend on assumptions about ingestion rates and exposure duration, the consistent elevation of total CR across samples indicates that carcinogenic risk deserves attention in monitoring and mitigation planning. Furthermore, because carcinogenic risk is cumulative over time, even small reductions in contaminant inputs can yield meaningful long-term benefit when applied at population scale [43].

From an environmental perspective, the observed contamination patterns are plausibly linked to broader water and ecosystem quality challenges in Nigeria. Studies on water quality across different Nigerian locations show that contamination pressures often arise from poor waste management, runoff, and inadequate environmental controls [5,6,36]. In aquatic systems, contaminants can persist and be redistributed through sediment interactions, with sediments acting as both sinks and secondary sources depending on flow and disturbance [9].

While those studies often emphasised microbial risks, their broader implication is that water bodies receiving mixed pollution loads are vulnerable to multi-hazard contamination, which may extend to fish and shellfish harvested from such environments [7,37]. In the Niger Delta specifically, petroleum-related inputs, atmospheric deposition, and wastewater discharge provide additional pathways for contaminants entering aquatic food chains [4,20,24].

In terms of public-health significance, the results suggest that risk management should prioritise (i) smoked shellfish monitoring, (ii) lead control and source investigation, and (iii) arsenic-focused interventions due to its carcinogenic risk dominance. Monitoring should be performed routinely across seasons because seasonal variation can influence contaminant transport, dilution, and bioavailability in Niger Delta waters [25,34]. Risk communication should emphasise vulnerable groups, especially children and high-frequency consumers, and encourage practical exposure reduction approaches such as reducing reliance on smoked shellfish as a daily ingredient, diversifying seafood sources, and supporting supply chains from less impacted waters. At a governance level, aligning local environmental surveillance with watershed assessment and pollution control frameworks is consistent with established environmental management approaches and can improve prevention at source [39–41]. This is particularly relevant because food-chain contamination is ultimately downstream of environmental loading, and controlling pollution inputs provides the most sustainable, population-wide reduction in risk [38,43]. The Kaa coastal market seafood demonstrates nutritionally meaningful essential-metal content that increases after smoking, but also shows problematic signals for toxic metals, especially Pb exceedance in smoked products and elevated cumulative risk indices (HI) in smoked shellfish. While Hg and As were within stated concentration limits, risk-based metrics indicate that they contribute significantly to chronic risk and lifetime cancer risk, respectively, highlighting the need for risk assessment alongside guideline comparisons [10,12]. Taken together, these findings support strengthened monitoring and upstream pollution control in the Kaa coastal

environment, with risk reduction prioritised for smoked shellfish and for children who experience higher dose burdens relative to body weight [4,35].

Conclusion

This study evaluated the concentrations of essential and toxic heavy metals in selected fresh and smoked seafood obtained from Kaa coastal market in Rivers State, Niger Delta, Nigeria, and assessed the potential human health risks associated with their consumption. The results demonstrated that essential metals such as Fe, Zn, Cu, and Mn were present at appreciable concentrations in all seafood samples, reflecting their nutritional importance for human health. However, smoking significantly increased the concentration of both essential and toxic metals, likely due to moisture reduction and concentration effects during processing. Shell seafood, particularly crab and periwinkle, exhibited higher levels of metal accumulation compared with finfish species, indicating greater bioaccumulation potential in benthic organisms that interact directly with contaminated sediments.

Among the toxic metals analyzed, lead and cadmium showed relatively elevated levels in several smoked samples, with some values approaching or slightly exceeding recommended safety limits. Although mercury and arsenic concentrations were generally within permissible limits, health risk assessment revealed that cumulative exposure may still pose potential concerns. The estimated daily intake values indicated that children are more vulnerable to heavy metal exposure than adults due to their lower body weight. Furthermore, hazard index values exceeding unity in some smoked seafood samples suggest potential non-carcinogenic risks associated with long-term consumption. Carcinogenic risk analysis also revealed that arsenic contributed the greatest proportion of lifetime cancer risk.

The findings highlight that seafood sold in Kaa coastal markets can act as a pathway for human exposure to heavy metals, particularly when consumed in smoked form. Continuous environmental monitoring, improved pollution control in the Niger Delta, and public awareness regarding safe seafood consumption are therefore essential for protecting aquatic ecosystems and safeguarding public health in coastal communities.

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