

Dietary Exposure and Human Health Risk Assessment of Toxic Metals in Marketed Crayfish (*Procambarus clarkii*) from the Niger Delta Region of Nigeria

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Abstract

Crayfish is widely consumed in Nigeria and may accumulate toxic metals from polluted aquatic environments, particularly in oil-producing regions of the Niger Delta. This study evaluated the concentrations and potential human health risks of selected toxic metals in the edible tissues of *Procambarus clarkii* obtained from Ogbe-Ijoh Market, Delta State, Nigeria. Samples were collected from ten vendor-linked crayfish consignments representing source communities supplying Ogbe-Ijoh Market during the dry and wet seasons and analysed for cadmium (Cd), lead (Pb), nickel (Ni), and chromium (Cr) using atomic absorption spectroscopy (AAS) following standard acid digestion procedures. Pollution index (PI), target hazard quotient (THQ), hazard index (HI), and cancer risk (CR) were computed to assess potential health risks. In the dry season, metal concentrations ($\text{mg}\cdot\text{kg}^{-1}$) ranged from 4.3 - 39.5 for Pb, 1.4 - 14.2 for Ni, and 2.8 - 23.5 for Cr, whereas wet-season concentrations ranged from 3.7 - 55.4 for Pb, 0.5 - 5.9 for Ni, and 2.7 - 10.4 for Cr. Cadmium was below the detection limit in all samples. Lead exhibited the highest concentrations in both seasons. PI values exceeded unity ($\text{PI} > 1$) across sampling locations, indicating contamination. THQ and HI analyses identified Pb as the principal contributor to non-carcinogenic risk, particularly during the wet season, with higher exposure indices observed in children. Estimated cancer risk values for Pb exceeded acceptable limits at several locations. The ele-

vated Pb concentrations and associated health risk indices underscore the need for continuous environmental monitoring, stricter pollution control measures, and public awareness regarding crayfish consumption in oil-impacted communities. Regular surveillance of toxic metals in commonly consumed aquatic foods is essential to safeguard public health in the Niger Delta region.

Keywords

Toxic Metals, *Procambarus clarkii*, Seasonal Variation, Health Risk Assessment, Nigeria

1. Introduction

Crayfish is a widely consumed and nutritionally significant seafood resource that contributes substantially to dietary protein intake in Nigeria. Naturally enriched with high-quality proteins, vitamins, and essential minerals contribute significantly to dietary quality and food security, particularly in coastal and inland communities. *Procambarus clarkii* (red swamp crayfish) is particularly valued because of its affordability, palatability, and culinary versatility. Beyond its nutritional relevance, this species represents an important source of livelihood for artisanal fishers and small-scale traders (Waribo et al., 2019). While moderate consumption of crayfish provides substantial nutritional benefits, excessive or prolonged intake of contaminated crayfish may pose health risks owing to the potential accumulation of toxic substances, particularly heavy metals (Adebiyi et al., 2019). Environmental contamination due to anthropogenic activities, including crude oil exploration and spills, industrial discharges, mining operations, and agricultural runoff, has increasingly impacted aquatic ecosystems in Nigeria, particularly in the Niger Delta region (Numbere et al., 2023). Among the most concerning pollutants are heavy metals, such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni), which are characterised by persistence, toxicity, and the ability to bioaccumulate in aquatic biota. When present above permissible thresholds, these metals pose ecological threats and significant public health concerns (Ayanda et al., 2020). Owing to their benthic feeding habits and close interactions with sediments, crayfish readily absorb and accumulate metals in their tissues, making them effective bioindicators of aquatic pollution. Monitoring metal concentrations in crayfish provides valuable insights into environmental contamination levels and potential dietary exposure risks (Kazery et al., 2025; Nwineewii et al., 2019). Although *P. clarkii* exhibits relative tolerance to low environmental metal concentrations, previous studies have demonstrated that metal accumulation in crayfish tissues is dose- and time-dependent (Undie et al., 2019). Prolonged exposure to contaminated environments, such as parts of the Niger Delta, may result in substantial tissue burden, even in the absence of overt toxicity in the organism. However, for human consumers, chronic dietary exposure to elevated heavy metal concentrations may result in

adverse health outcomes including neurological impairment, renal dysfunction, reproductive disorders, and carcinogenesis (Waqas et al., 2024; Zhang et al., 2023; Lawal et al., 2021). Given the widespread consumption of *P. clarkii* in Nigeria and increasing reports of environmental contamination, continuous evaluation of toxic metal concentrations in this species is essential. Despite existing studies, data on seasonal variability and associated human health risk assessments remain limited in several Nigerian markets. Therefore, this study investigated the concentrations of selected toxic metals (Pb, Cd, Cr, and Ni) in *Procambarus clarkii* obtained from ten vendor-linked crayfish consignments sold at Ogbe-Ijoh Market in Delta State, Nigeria, representing source communities predominantly located within the Niger Delta region, a recognised hotspot of oil and industrial activities. In addition to quantifying metal levels, this study also evaluated the potential non-carcinogenic health risks associated with crayfish consumption using established human health risk assessment models. These findings aim to support evidence-based food safety regulations, environmental monitoring, and public health protection strategies.

2. Materials and Methods

2.1. Study Area and Sample Collection

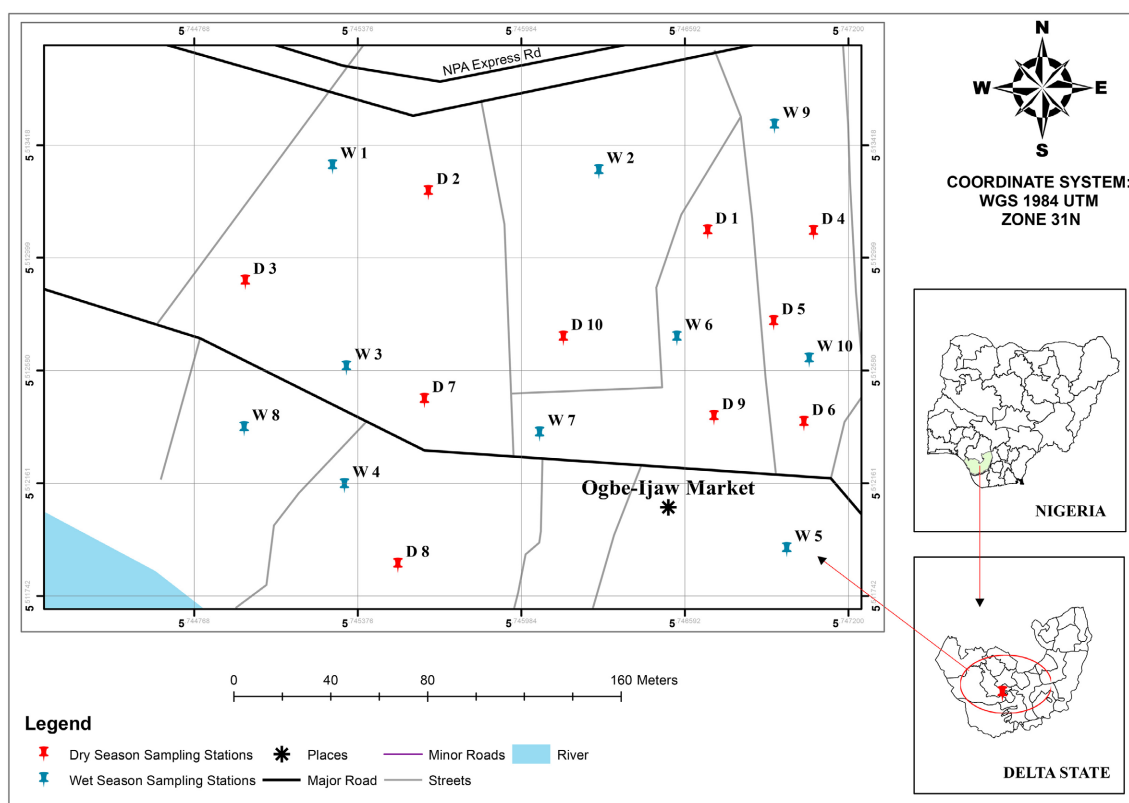


Figure 1. Map showing the location of Ogbe-Ijoh Market in Delta State, Nigeria.

Crayfish samples were obtained from Ogbe-Ijoh Market (5.5053°N, 5.9094°E), a major commercial hub for dried crayfish trade within the Niger Delta region of

Delta State, Nigeria. The market was selected because of its importance in regional seafood distribution and its relevance to consumer dietary exposure. The geographic location of the study area is shown in **Figure 1**. A total of twenty (20) dried crayfish samples were collected during the dry and wet seasons (10 samples per season). Each sample represented a vendor-linked crayfish consignment associated with a source community supplying the market. Thus, the ten “locations” referred to in this study represent distinct vendor sampling points linked to source communities, rather than arbitrary sampling points within the market. To support seasonal comparison, dry- and wet-season samples were obtained through repeated sampling of the same vendor locations during both periods. Samples were randomly purchased from the selected vendors, placed in clean polyethylene bags, and handled using disposable gloves to minimise contamination during collection and transportation. Upon arrival at the laboratory, samples were stored at 4 °C prior to processing.

2.2. Acid Digestion and Elemental Analysis

Approximately 1.00 g of the homogenised crayfish sample was digested using aqua regia (9 mL HNO₃; 3 mL HCl) in 250 mL glass beakers. The mixture was partially covered with watch glass and heated on an electric hotplate at 100 °C for 2 h in a fume hood. After digestion, the samples were allowed to cool to room temperature and filtered through Whatman No. 41 filter paper into 50 mL volumetric flasks. The filtrates were diluted to the mark with deionised water and stored at 4 °C before analysis. The concentrations of lead (Pb), nickel (Ni), cadmium (Cd), and chromium (Cr) were determined using flame atomic absorption spectrophotometry (FAAS) (Buck Scientific Model 210). The instrument demonstrated the capability to detect trace concentrations of the analysed metals in the digest solutions, with Pb, Ni, and Cr detectable at approximately 0.010 mg/L, 0.009 mg/L, and 0.044 mg/L, respectively, while Cd was not detected under the analytical conditions employed. Concentrations reported as below detection/non-detect were treated as zero in subsequent exposure and risk calculations. Calibration curves were prepared using standard solutions of each metal and analyses were performed according to the manufacturer’s operational guidelines. Metal concentrations were expressed in mg·kg⁻¹ dry weight following established analytical procedures (El Hosry et al., 2023). The use of dry-weight concentrations was considered appropriate because the crayfish samples were purchased in commercially dried form, which reflects the actual marketed and consumed state of the product.

2.3. Quality Control and Evaluation of Analytical Performance

The analytical accuracy and precision were evaluated using spiked recovery and replicate analyses. For the recovery assessment, two aliquots of each homogenised crayfish sample were prepared: one portion was spiked with a known concentration of mixed metal standard solution, while the second portion remained un-

spiked and served as a control. Both portions were digested and analysed under identical conditions. The percentage recovery (%) was calculated as follows:

$$\text{Recovery \%} = \frac{S - \mu}{T} * 100. \quad (1)$$

where:

S = heavy metal concentration in the spiked sample,

μ = heavy metal concentration in the unspiked sample, and

T = amount of metal added during spiking.

Reagent blanks were included in the analytical procedure to monitor for possible contamination. All samples were analysed in duplicate to evaluate precision, and mean concentrations were reported (Bankole et al., 2023).

2.4. Human Health Risk Assessment

Human health risks associated with crayfish consumption were evaluated using established non-carcinogenic risk assessment models recommended by the United States Environmental Protection Agency (USEPA).

Estimated Daily Intake (EDI)

The estimated daily intake (EDI) of heavy metals through crayfish consumption was calculated as

$$\text{EDI} = \frac{C \times \text{IR} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \quad (2)$$

where:

C = metal concentration in crayfish ($\text{mg} \cdot \text{kg}^{-1}$),

IR = ingestion rate ($0.02 \text{ kg} \cdot \text{person}^{-1} \cdot \text{day}^{-1}$) adopted from USEPA-based exposure assessment approaches and applied as a conservative screening-level estimate for both adults and children).

EF = exposure frequency ($365 \text{ days} \cdot \text{year}^{-1}$),

ED = exposure duration (70 years for adults),

BW = body weight (70 kg for adults; 16 kg for children),

AT = averaging time for non-carcinogens ($\text{ED} \times 365 \text{ days}$).

Although dried crayfish is typically consumed in relatively small quantities, the selected ingestion rate was retained as a protective assumption to avoid underestimation of dietary exposure.

Target Hazard Quotient (THQ)

Non-carcinogenic health risks were assessed using the Target Hazard Quotient (THQ).

$$\text{THQ} = \frac{\text{EDI}}{\text{RfD}} \quad (3)$$

where RfD is the oral reference dose ($\text{mg} \cdot \text{kg}^{-1} \cdot \text{day}^{-1}$). The RfD values adopted were:

Cd = 0.001; Pb = 0.004; Ni = 0.02; Cr = 0.003.

A THQ value < 1 indicates negligible risk, whereas a THQ value ≥ 1 suggests a

potential non-carcinogenic health risk (USEPA, 2000).

Hazard Index (HI)

The cumulative noncarcinogenic risk from multiple metals was estimated using the Hazard Index (HI):

$$HI = \sum THQ_i \quad (4)$$

where THQ_i represents the individual hazard quotient for each metal. An HI value < 1 indicates an acceptable risk, whereas an HI value ≥ 1 suggests potential health concerns.

Pollution Index (PI)

The pollution index (PI) for each metal was calculated as follows:

$$PI = \frac{C_{\text{sample}}}{C_{\text{permissible}}} \quad (5)$$

where C_{sample} is the measured metal concentration in the crayfish and $C_{\text{permissible}}$ is the corresponding benchmark concentration for each metal. A PI value > 1 indicates contamination (Dey et al., 2021). The PI approach adopted in this study was adapted from previous crayfish contamination assessments (Adebiyi et al., 2019). Metal-specific benchmark values for Pb, Ni, and Cr were selected from commonly cited guideline values for fish and seafood in the literature. Cadmium was below the detection limit and was therefore excluded from PI interpretation.

Cancer Risk (CR)

The lifetime carcinogenic risk (CR) associated with dietary exposure to lead (Pb) through crayfish consumption was estimated using the cancer slope factor (CSF) approach. The CR was calculated using the following equation:

$$CR = \frac{EF \times ED \times IR \times CF \times C \times CSF}{BW \times AT} \times 10^{-3} \quad (6)$$

where CSF is the cancer slope factor (mg/kg/day), and the other parameters have been defined previously. An acceptable lifetime carcinogenic risk level of 10^{-5} was adopted based on established risk assessment guidelines (Naseri et al., 2021; Shaheen et al., 2016). A CSF value of $0.0085 \text{ (mg/kg/day)}^{-1}$ was adopted for Pb for screening-level carcinogenic risk estimation, consistent with its application in previous food contamination and Pb exposure risk assessment studies (Nag & Cummins, 2022; Adebiyi et al., 2019). However, the use of an oral CSF for dietary Pb exposure is not uniformly harmonized across all regulatory frameworks and should therefore be interpreted with caution.

2.5. Statistical Data Analysis

Statistical analyses were performed using R statistical software package (R Core Team, 2023). Descriptive statistics, including the mean, range, and standard deviation, were computed to summarise the distribution of heavy metal concentrations in crayfish samples. The pollution index (PI) was calculated to evaluate the contamination status of individual metals. Cluster analysis was performed to examine potential grouping patterns and similarities among the analysed metals.

Pearson's correlation analysis was conducted to assess the relationships between the heavy metals across the sampled matrices. Statistical significance was evaluated at a 95% confidence level ($P < 0.05$).

3. Result and Discussion

3.1. Quality Assurance and Control

The accuracy of the analytical procedure was evaluated using spike recovery experiments. The percentage recoveries of Pb, Ni, Cr, and Cd ranged from 82.4% to 97.4%. These values fall within the generally accepted recovery range of 80% - 120% for elemental analysis in complex matrices, indicating satisfactory analytical accuracy and minimal matrix interference in the analysis. The recovery results are summarised in **Table 1**. This acceptance range is consistent with the method validation guidelines outlined in the U.S. Food and Drug Administration's Elemental Analysis Manual (FDA, 2018), as well as the established analytical chemistry principles and international validation guidelines (Skoog et al., 2014; Magnusson & Örnemark, 2014). Therefore, the analytical data generated in this study were considered reliable for subsequent risk assessments.

Table 1. Analytical results for percentage recovery (% R) of the analysed metals.

S/N	Metals	Amount spiked (mg/kg)	Amount recovered (mg/kg)	Percentage recovery (%)
1	Pb	5.0	4.12	82.4
2	Ni	5.0	4.60	92.0
3	Cr	5.0	4.87	97.4
4	Cd	5.0	4.72	94.4

3.2. Heavy Metals Concentration in Crayfish

The range and mean concentrations of the analysed metals (Pb, Ni, Cr, and Cd) in crayfish samples collected from oil-producing communities of the Niger Delta are presented in **Table 2** and **Table 3**. The results revealed noticeable variability in metal levels across sampling locations and seasons. During the dry season, the Pb concentrations ranged from 4.3 to 39.5 mg/kg, with a mean value of 18.2 ± 12.2 mg/kg. The Cr content ranged between 2.80 and 23.5 mg/kg (mean: 9.82 ± 7.47 mg/kg), whereas the Ni content varied from 1.4 to 14.2 mg/kg (mean: 3.46 ± 3.91 mg/kg). Cd levels were below the detection limit in all samples analysed. The coefficient of variation was the highest for Ni, indicating pronounced spatial heterogeneity across the sampling locations. Similarly, in the wet season, Pb remained the most abundant element, ranging from 3.7 to 55.4 mg/kg, with a mean value of 23.9 ± 16.3 . Chromium ranged between 2.7 and 10.4 mg/kg (mean: 6.32 ± 2.85 mg/kg), whereas Ni varied from 0.5 to 5.9 mg/kg (mean: 2.26 ± 1.51 mg/kg). The Cd levels remained below the detection limit across all sampling sites. Across both seasons, the order of decreasing mean concentrations followed the pattern $Pb > Cr > Ni > Cd$. The dominance of Pb in both seasons suggests persistent anthropo-

genic inputs, which may be linked to oil exploration activities, pipeline corrosion, gas flaring emissions, and artisanal refining operations in the Niger Delta region. The relatively wide concentration ranges and elevated standard deviations, particularly for Pb and Cr, indicated localised contamination hotspots rather than a uniform distribution within the aquatic environment. Cadmium (Cd) was below the detection limit in all *P. clarkii* samples analysed in both seasons. This finding contrasts with previous studies conducted in the Niger Delta region, where detectable Cd accumulation has been reported in crayfish and other seafood species. For instance, [Elekima et al. \(2020\)](#) and [Waribo et al. \(2019\)](#) documented measurable Cd concentrations in crayfish and related aquatic organisms at impacted sites. Reported Cd levels in regional seafood have ranged from trace values to as high as 3.62 mg/kg in contaminated environments. The absence of detectable Cd in the present study may reflect a relatively lower Cd input at the sampled locations, reduced environmental bioavailability, or possible species-specific differences in uptake and accumulation patterns. These results suggest that Cd contamination is not currently a dominant concern in oil-producing communities compared with Pb and Cr. The total Cr concentrations in the crayfish samples exhibited substantial spatial variability across the oil-producing communities of the Niger Delta. During the dry season, Cr concentrations ranged from 2.8 to 23.5 mg/kg (mean: 9.82 ± 7.47 mg/kg), whereas wet-season concentrations ranged from 2.7 to 10.4 mg/kg (mean: 6.32 ± 2.85 mg/kg). Although higher mean values were observed during the dry season, paired statistical analysis indicated that seasonal differences were not statistically significant ($p > 0.05$), suggesting that localised contamination sources, rather than seasonal hydrological changes, predominantly influenced Cr distribution. When compared with the maximum permissible limit of 0.5 mg/kg recommended for chromium in fish by the FAO/WHO guidelines, the concentrations observed in this study markedly exceeded the regulatory thresholds across all sampling locations. Even the lowest recorded value exceeded the recommended limit several-fold, indicating potential environmental and public health concerns. Similar elevated Cr concentrations in crayfish from Delta State were reported by [Igbuku \(2015\)](#), who documented levels exceeding the recommended limits in selected towns. Similarly, [Uhegbu et al. \(2012\)](#) reported measurable Cr concentrations in seafood from the Niger Delta region. The elevated Cr levels observed in this study may reflect persistent anthropogenic inputs associated with oil exploration activities, industrial discharges, corrosion of petroleum infrastructure, and artisanal refining operations prevalent in the region. It should be noted that total chromium was quantified in this study, and the speciation between Cr(III) and the more toxic Cr(VI) forms was not determined. Nonetheless, the high total Cr concentration warrants continued monitoring and a detailed risk evaluation. Lead (Pb) was the most dominant metal detected in crayfish samples across both seasons. Concentrations ranged from 4.3 to 39.5 mg/kg (mean: 18.2 ± 12.2 mg/kg) in the dry season and from 3.7 to 55.4 mg/kg (mean: 23.9 ± 16.3 mg/kg) in the wet

season. Although the seasonal differences were not statistically significant ($p > 0.05$), the magnitude of Pb accumulation was substantial. The concentrations recorded in this study were markedly higher than those reported in other Nigerian studies. Adebisi et al. (2019) reported Pb levels ranging from 0.40 - 1.40 mg/kg (mean: 0.91 mg/kg) in *Palaemon hastatus* from Ile-Ife, Nigeria, with values below the WHO/USEPA permissible limits and associated with target hazard quotients less than one. Similarly, dried crayfish samples from Calabar markets in the Niger Delta contained Pb concentrations between 0.02 and 0.24 mg/kg (dry weight), with average values below the Codex maximum level of 0.2 mg/kg. Earlier Nigerian reports have documented Pb levels ranging from 0.002 - 2.04 mg/kg, which is substantially lower than the concentrations observed in the present study. In contrast, all the Pb concentrations recorded in this study exceeded the international guideline limits for fish, including the Codex maximum level of 0.2 mg/kg and the FAO/WHO permissible range of 0.3 - 0.5 mg/kg. The markedly elevated Pb levels observed may reflect localised contamination associated with oil exploration activities, pipeline corrosion, gas flaring emissions, artisanal refining, and other anthropogenic inputs prevalent in the oil-producing communities in the Niger Delta. These findings suggest a significantly higher contamination burden in the present study area than in previously reported Nigerian sites. To contextualise these findings within the broader scientific literature, previously reported concentrations of Pb, Cr, and Ni in crayfish from different geographical regions were compiled and are presented in Table 4. This comparison clearly indicates that the metal concentrations observed in the present study were substantially higher than those reported in most Nigerian and international studies, particularly for Pb and Cr.

Table 2. Heavy metal concentrations in crayfish during the dry season (mg/kg).

LOCATION	Pb	Ni	Cr	Cd
DS 1	8.1 ± 0.04	3.6 ± 0.36	5.2 ± 0.04	BDL
DS 2	36.1 ± 0.11	14.2 ± 0.43	3.9 ± 0.04	BDL
DS 3	4.3 ± 0.01	1.6 ± 0.01	20.3 ± 0.02	BDL
DS 4	16.5 ± 0.04	1.9 ± 0.02	2.8 ± 0.07	BDL
DS 5	23.8 ± 0.04	1.6 ± 0.04	23.5 ± 0.91	BDL
DS 6	39.5 ± 0.4	4.5 ± 0.4	15.6 ± 0.11	BDL
DS 7	5.5 ± 0.25	1.8 ± 0.22	3.7 ± 0.35	BDL
DS 8	16.4 ± 1.45	1.5 ± 0.60	9.2 ± 0.67	BDL
DS 9	17.9 ± 0.81	1.4 ± 0.18	9.4 ± 0.11	BDL
DS 10	16.2 ± 0.01	2.6 ± 0.11	4.6 ± 0.08	BDL
Mean	18.2 ± 12.2	3.46 ± 3.91	9.82 ± 7.47	BDL
RANGE	4.3 - 39.5	1.4 - 14.2	2.8 - 23.5	

Table 3. Heavy metal concentrations in crayfish during the wet season (mg/kg).

LOCATION	Pb	Ni	Cr	Cd
WS 1	20.5 ± 0.04	5.9 ± 0.71	10.4 ± 0.14	BDL
WS 2	26.1 ± 0.04	1.7 ± 0.14	9.8 ± 0.11	BDL
WS 3	3.7 ± 0.04	1.3 ± 0.00	3.9 ± 0.00	BDL
WS 4	31.4 ± 1.24	1.0 ± 0.05	8.3 ± 0.95	BDL
WS 5	55.4 ± 0.04	0.9 ± 0.11	4.9 ± 0.07	BDL
WS 6	4.6 ± 0.07	2.5 ± 0.60	2.9 ± 0.18	BDL
WS 7	25.6 ± 0.17	2.6 ± 1.70	8.3 ± 3.39	BDL
WS 8	36.4 ± 0.18	2.8 ± 0.11	7.6 ± 0.35	BDL
WS 9	5.6 ± 0.07	0.5 ± 0.00	4.6 ± 0.49	BDL
WS 10	30.5 ± 0.14	2.3 ± 0.04	2.7 ± 0.04	BDL
Mean	23.9 ± 16.3	2.26 ± 1.51	6.32 ± 2.85	
RANGE	3.7 - 55.4	0.5 - 5.9	2.7 - 10.4	-

Table 4. Comparison of mean heavy metal concentrations (mg/kg, dry weight) in crayfish—present study vs credible literature.

Study	Location	Species	Pb (mg/kg)	Cr (mg/kg)	Ni (mg/kg)
Present study (range)	Niger Delta, Nigeria	Crayfish (whole)	4.3 - 55.4	2.8 - 23.5	1.4 - 14.2
Adebiyi et al., 2019	Nigeria	<i>Palaemon hastatus</i>	0.4 - 1.4	1.80 - 1.90	-
Umeoguaju et al., 2023	Niger Delta	Seafood pooled	4.35	2.26	5.26
Udiba et al., 2022	Calabar, Nigeria	Dried crayfish	0.02 - 0.24	-	-
Peng et al., 2022	Yangtze Basin, China	<i>P. clarkii</i>	0.05 - 0.56	0.49 - 7.48	0.27 - 1.60
Mistri et al., 2020	Italy	<i>P. clarkii</i>	0.51 - 2.43	-	-
Suárez-Serrano et al., 2010	Spain (Ebro River)	<i>P. clarkii</i>	0.05 - 0.41	1.72 - 2.65	-
Goretti et al., 2016	Italy (polluted)	<i>P. clarkii</i>	0.9 - 8.5	-	-
Anandkumar et al., 2020	China	<i>P. clarkii</i>	0.0041 - 2.3	0.64 - 3.3	Not reported
Ikem et al., 2021	USA (Missouri)	Crayfish species	0.71 - 0.80	0.23 - 0.26	0.70 - 0.79

3.3. Seasonal Variation of Heavy Metals in Crayfish (Dry Weight Basis)

The seasonal variations in heavy metal concentrations across the ten sampling locations are presented in **Table 5**. All concentrations were expressed on a dry weight basis. Lead (Pb) exhibited higher mean concentrations during the wet season (23.9 ± 16.3 mg/kg) than during the dry season (18.2 ± 12.2 mg/kg). In contrast, chromium (Cr) and nickel (Ni) recorded relatively higher mean values during the dry season (Cr: 9.82 ± 7.47 mg/kg; Ni: 3.46 ± 3.91 mg/kg) than in the wet season (Cr: 6.32 ± 2.85 mg/kg; Ni: 2.26 ± 1.51 mg/kg). Cadmium (Cd) remained below the detection limit in both seasons. Despite observable fluctuations between seasons, paired statistical analysis revealed no significant seasonal differences in Pb ($p = 0.400$), Ni ($p = 0.337$), or Cr ($p = 0.272$) (**Table 6**). Seasonal comparisons were based on repeated sampling of the same vendor locations during the dry and

wet seasons. These findings indicated that seasonal hydrological changes did not exert a statistically significant influence on heavy metal accumulation in crayfish across the sampled locations. Higher wet-season Pb concentrations may be associated with increased surface runoff and mobilisation of contaminants during rainfall events that are common in the Niger Delta region. Conversely, the relatively elevated dry-season Cr and Ni values may reflect reduced dilution effects during periods with lower water volumes. However, the lack of statistical significance suggests that spatial heterogeneity and localised contamination sources exert stronger control over heavy metal distribution than seasonal variation. As the concentrations were determined on a dry weight basis, caution should be exercised when comparing the values directly with international permissible limits, which are typically expressed on a wet weight basis. The relatively high standard deviations observed across locations further support the influence of spatial variability on metal distribution patterns.

Table 5. Seasonal variation of heavy metals in crayfish across sampling locations (mg/kg).

Location	Pb (Dry)	Pb (Wet)	Ni (Dry)	Ni (Wet)	Cr (Dry)	Cr (Wet)	Cd (Dry)	Cd (Wet)
1	8.1 ± 0.04	20.5 ± 0.04	3.6 ± 0.36	5.9 ± 0.71	5.2 ± 0.04	10.4 ± 0.14	BDL	BDL
2	36.1 ± 0.11	26.1 ± 0.04	14.2 ± 0.43	1.7 ± 0.14	3.9 ± 0.04	9.8 ± 0.11	BDL	BDL
3	4.3 ± 0.01	3.7 ± 0.04	1.6 ± 0.01	1.3 ± 0.00	20.3 ± 0.02	3.9 ± 0.00	BDL	BDL
4	16.5 ± 0.04	31.4 ± 1.24	1.9 ± 0.02	1.0 ± 0.05	2.8 ± 0.07	8.3 ± 0.95	BDL	BDL
5	23.8 ± 0.04	55.4 ± 0.04	1.6 ± 0.04	0.9 ± 0.11	23.5 ± 0.91	4.9 ± 0.07	BDL	BDL
6	39.5 ± 0.4	4.6 ± 0.07	4.5 ± 0.4	2.5 ± 0.60	15.6 ± 0.11	2.9 ± 0.18	BDL	BDL
7	5.5 ± 0.25	25.6 ± 0.17	1.8 ± 0.22	2.6 ± 1.70	3.7 ± 0.35	8.3 ± 3.39	BDL	BDL
8	16.4 ± 1.45	36.4 ± 0.18	1.5 ± 0.60	2.8 ± 0.11	9.2 ± 0.67	7.6 ± 0.35	BDL	BDL
9	17.9 ± 0.81	5.6 ± 0.07	1.4 ± 0.18	0.5 ± 0.00	9.4 ± 0.11	4.6 ± 0.49	BDL	BDL
10	16.2 ± 0.01	30.5 ± 0.14	2.6 ± 0.11	2.3 ± 0.04	4.6 ± 0.08	2.7 ± 0.04	BDL	BDL

Values are presented as the mean ± standard deviation of triplicate measurements. BDL = below the detection limit.

Table 6. Seasonal summary statistics.

Metal	Dry (Mean ± SD)	Wet (Mean ± SD)	<i>p</i> -value
Pb	18.2 ± 12.2	23.9 ± 16.3	0.40
Ni	3.46 ± 3.91	2.26 ± 1.51	0.337
Cr	9.82 ± 7.47	6.32 ± 2.85	0.272
Cd	BDL	BDL	–

BDL = Below detection limit. *p*-values obtained using paired t-test (or Wilcoxon signed-rank test).

3.4. Pollution Index (PI) Assessment of Heavy Metals in Crayfish Samples

The Pollution Index (PI) values for Pb, Ni, and Cr in crayfish samples across the dry and wet seasons are presented in **Table 7**. The PI was calculated using metal-

specific benchmark values, and a PI value > 1 was taken to indicate contamination. The results showed that PI values for all three metals exceeded unity at multiple sampling locations in both seasons, confirming contamination of the marketed crayfish samples. Lead (Pb) contamination was evident across most sampling locations, with dry-season PI values ranging from 2.15 to 19.8 and wet-season values ranging from 1.85 to 27.8. Although Pb contamination remained widespread, the magnitude of contamination was generally lower than that observed for Ni and Cr at several locations. Elevated Pb PI values during the wet season at some locations suggest possible seasonal redistribution of metal contaminants, potentially influenced by runoff and environmental mobilisation. Nickel (Ni) exhibited pronounced contamination at several sampling points, with PI values ranging from 2.80 to 28.4 in the dry season and 1.00 to 11.8 in the wet season. The highest Ni contamination was recorded at Location 2 during the dry season, indicating substantial accumulation at that point. The consistently elevated Ni PI values across many locations suggest that Ni represents an important contamination concern in the marketed crayfish samples. Chromium (Cr) also showed marked contamination, with dry-season PI values ranging from 2.80 to 23.5 and wet-season values ranging from 2.70 to 10.4. Particularly high Cr contamination was observed at Locations 3, 5, and 6 during the dry season, indicating notable spatial variability in Cr accumulation. Compared with the wet season, the higher dry-season Cr PI values at several locations may reflect localised concentration effects and reduced dilution. Across the dataset, the contamination pattern did not follow a single uniform order at all locations; however, Ni and Cr generally exhibited stronger contamination intensity than Pb at several sampling points. The widespread occurrence of PI values above unity indicates persistent metal contamination in the analysed crayfish and suggests potential public health concern, especially considering the frequent dietary use of crayfish as a food ingredient in the study area.

Table 7. Pollution Index (PI) of heavy metals in crayfish during dry and wet seasons.

Location	Pb (Dry)	Pb (Wet)	Ni (Dry)	Ni (Wet)	Cr (Dry)	Cr (Wet)
1	4.05	10.3	7.2	11.8	5.2	10.4
2	18.1	13.1	28.4	3.4	3.9	9.8
3	2.15	1.85	3.2	2.6	20.3	3.9
4	8.25	15.7	3.8	2	2.8	8.3
5	11.9	27.8	3.2	1.8	23.5	4.9
6	19.8	2.3	9	5	15.6	2.9
7	2.75	12.8	3.6	5.2	3.7	8.3
8	8.2	18.2	3	5.6	9.2	7.6
9	8.95	2.8	2.8	1	9.4	4.6
10	8.1	15.3	5.2	4.6	4.6	2.7

Note: $PI = C_{\text{sample}}/C_{\text{permissible}}$, where $C_{\text{permissible}}$ represents the benchmark value adopted for each metal from commonly cited fish/seafood guideline values in the literature. $PI > 1$ indicates contamination.

3.5. Human Health Risk Assessment

3.5.1. Estimated Daily Intake (EDI)

The estimated daily intake (EDI) values of Pb, Ni, and Cr for adults and children across the ten source locations are presented in Supplementary **Tables S1-S4**. For adults, during the dry season, the Pb EDI values ranged from 0.00123 to 0.01129 mg/kg/day, whereas those of Cr ranged from 0.0008 to 0.0067 mg/kg/day. Nickel showed comparatively lower exposure levels (0.0004 - 0.0041 mg/kg/day). Similar exposure patterns were observed during the wet season, with Pb exhibiting the highest intake value across most locations. In all cases, children recorded substantially higher EDI values than adults due to their lower body weight, reflecting greater susceptibility to dietary metal exposure.

3.5.2. Target Hazard Quotient (THQ) and Hazard Index (HI)

The calculated Target Hazard Quotient (THQ) and cumulative Hazard Index (HI) values are presented in **Tables 8-11**. A THQ value of less than 1 indicates negligible non-carcinogenic risk, whereas $\text{THQ} \geq 1$ suggests potential health concerns. For adults during the dry season, the Pb THQ values exceeded unity at seven of the ten sampling locations, with the highest value observed at Location 6 (THQ = 2.82). Chromium also exceeded the safety threshold at Locations 3, 5, and 6, with a maximum THQ of 2.24 at Location 5. In contrast, the Ni THQ values remained below 1 at all locations, indicating a relatively low noncarcinogenic risk of nickel exposure. The cumulative risk, expressed as HI, exceeded 1 at nine of the ten locations, with the highest value recorded at Location 6 (HI = 4.37). These results indicate the potential combined health risks associated with simultaneous exposure to multiple metals at several source locations. For children, THQ and HI values were markedly higher across all sampling locations. All sites recorded HI values substantially greater than unity, with the highest cumulative risk observed at location 6 (HI = 19.12). Elevated THQ values for both Pb and Cr were widespread, whereas Ni values remained below the risk threshold. The consistently higher indices in children reflect their increased vulnerability, resulting from their lower body weight and proportionally greater intake. Across all locations, the contribution to non-carcinogenic risk followed the order of $\text{Pb} > \text{Cr} > \text{Ni}$.

3.5.3. Cancer Risk (CR)

The lifetime carcinogenic risk (CR) associated with Pb exposure was estimated using the cancer slope factor approach. It should be noted that the carcinogenic risk estimates for Pb presented in this study are based on a screening-level application of a literature-derived cancer slope factor and should therefore be interpreted with caution. For adults, the CR values at several sampling locations exceeded the acceptable benchmark level of 10^{-5} , indicating potential carcinogenic concerns associated with long-term consumption. The highest CR values corresponded to locations with elevated Pb concentrations, particularly Locations 6 and 5. For children, the CR values were substantially higher across most sampling locations owing to elevated EDI levels, exceeding the acceptable risk level

at most sites. These findings suggest that prolonged consumption of crayfish sourced from certain communities may pose long-term carcinogenic risks, particularly for younger consumers. Although minor numerical differences were observed between the dry and wet seasons, statistical analysis indicated no significant seasonal variation ($p > 0.05$). Therefore, spatial variability among source locations appears to exert a stronger influence on health risk levels than seasonal variability. Generally, Pb was identified as the dominant contributor to both non-carcinogenic and carcinogenic risks, Cr contributed moderately at selected locations, and Ni posed a comparatively minimal risk. The markedly elevated HI and CR values observed in children underscore their heightened susceptibility to heavy metal exposure through dietary intake of crayfish from contaminated sources.

Table 8. Target Hazard Quotient (THQ) and Hazard Index (HI) of heavy metals in crayfish (Children-Dry Season).

Location	THQ-Pb	THQ-Ni	THQ-Cr	HI
1	2.53	0.23	2.17	4.93
2	11.28	0.89	1.63	13.80
3	1.34	0.10	8.46	9.90
4	5.16	0.12	1.17	6.45
5	7.44	0.10	9.79	17.33
6	12.34	0.28	6.50	19.12
7	1.72	0.11	1.54	3.37
8	5.13	0.09	3.83	9.05
9	5.59	0.09	3.92	9.60
10	5.06	0.16	1.92	7.14

Table 9. Target Hazard Quotient (THQ) and Hazard Index (HI) of heavy metals in crayfish (Adult-Dry Season).

Location	THQ-Pb	THQ-Ni	THQ-Cr	HI
1	0.58	0.05	0.50	1.13
2	2.58	0.20	0.37	3.15
3	0.31	0.02	1.93	2.26
4	1.18	0.03	0.27	1.48
5	1.70	0.02	2.24	3.96
6	2.82	0.06	1.49	4.37
7	0.39	0.03	0.35	0.77
8	1.17	0.02	0.88	2.07
9	1.28	0.02	0.90	2.20
10	1.16	0.04	0.44	1.64

Table 10. Target Hazard Quotient (THQ) and Hazard Index (HI) of heavy metals in crayfish (Adult-Wet Season).

Location	THQ-Pb	THQ-Ni	THQ-Cr	HI
1	1.47	0.08	0.99	2.54
2	1.87	0.02	0.93	2.82
3	0.27	0.02	0.37	0.66
4	2.24	0.01	0.79	3.04
5	3.96	0.01	0.47	4.44
6	0.33	0.04	0.28	0.65
7	1.83	0.04	0.79	2.66
8	2.60	0.04	0.72	3.36
9	0.40	0.01	0.44	0.85
10	2.18	0.03	0.26	2.47

Table 11. Target Hazard Quotient (THQ) and Hazard Index (HI) of heavy metals in crayfish (Children-Wet Season).

Location	THQ-Pb	THQ-Ni	THQ-Cr	HI
1	6.41	0.37	4.33	11.1
2	8.16	0.11	4.08	12.3
3	1.16	0.08	1.63	2.87
4	9.81	0.06	3.46	13.3
5	17.3	0.06	2.04	19.4
6	1.44	0.16	1.21	2.81
7	8.00	0.16	3.46	11.6
8	11.3	0.18	3.17	14.7
9	1.75	0.03	1.92	3.70
10	9.53	0.14	1.13	10.8

3.6. Pearson's Correlation Analysis

Pearson's correlation analysis was performed to evaluate the relationships among the concentrations of Pb, Ni, and Cr in crayfish samples across seasons (Table S5, Supplementary Material). In the wet season, Pb exhibited a weak negative correlation with Ni ($r = -0.26$) and a weak positive correlation with Cr ($r = 0.27$). Notably, Ni showed a moderate positive correlation with Cr ($r = 0.45$), suggesting potential co-mobilisation and similar geochemical behaviours. This association may be linked to rainfall-induced redox fluctuations that promote the dissolution of Fe-Mn oxyhydroxides in the sediments. As both Ni and Cr are known to be strongly associated with Fe-Mn oxide phases, their concurrent release into the water column during periods of increased runoff and sediment disturbance could enhance their bioavailability and subsequent accumulation in crayfish. During the

dry season, Pb showed weak negative correlations with Ni ($r = -0.20$) and Cr ($r = -0.15$) concentrations. A moderate positive correlation was observed between Pb and Ni ($r = 0.61$), possibly reflecting concentration effects under reduced dilution and more stable sediment conditions. Conversely, Cr demonstrated weak to moderate negative correlations with Pb ($r = -0.32$) and Ni ($r = -0.29$), indicating differences in seasonal mobility patterns or competitive uptake mechanisms. Seasonal variability in the correlation structure suggests that hydrological dynamics, redox-driven sediment processes, and changes in metal bioavailability play important roles in governing heavy metal accumulation in crayfish.

3.7. Hierarchical Cluster Analysis

Hierarchical cluster analysis (HCA) based on Euclidean distance was performed to examine the similarity patterns of heavy metals in crayfish samples. The Euclidean distance matrix is presented in **Table S6** (Supplementary Material), The clustering pattern is illustrated in **Figure 2**. The dendrogram revealed two distinct clusters. Ni and Cr were grouped closely together, exhibiting a very small Euclidean distance (7.55), indicating a strong similarity in their distribution patterns and possible shared geochemical controls or common environmental sources. In contrast, Pb formed a separate cluster, reflecting its distinct accumulation behaviour relative to that of Ni and Cr. This clustering pattern is consistent with the correlation analysis and further supports the likelihood of similar mobility pathways for Ni and Cr, which are potentially associated with Fe-Mn oxide dynamics and sediment interactions during seasonal hydrological fluctuations. The separation of Pb suggests differences in its source contributions, transport mechanisms, and bioavailability in aquatic environments.

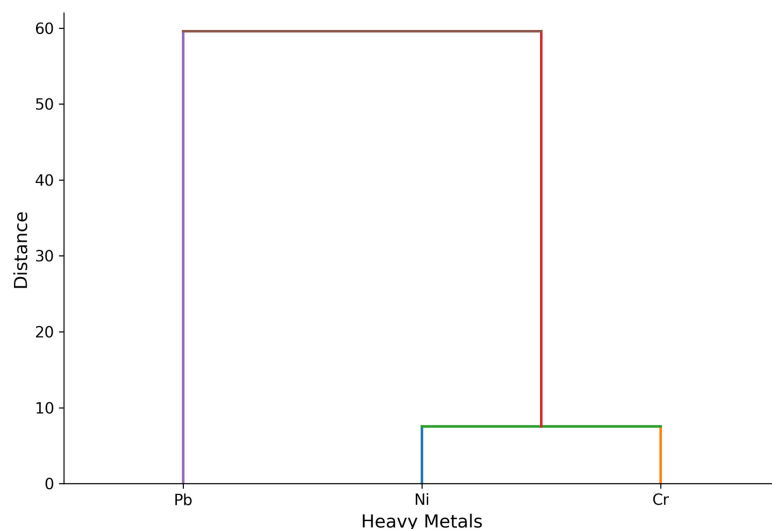


Figure 2. Hierarchical Cluster Analysis of Heavy metals concentration of cray fish.

4. Conclusion

This study demonstrated substantial contamination of *Procambarus clarkii* mar-

keted in the Niger Delta by toxic metals, particularly lead (Pb) and chromium (Cr), with concentrations consistently exceeding the international permissible limits on a dry weight basis. Pollution index values greater than unity across all sampling locations confirmed significant contamination pressure, whereas the risk assessment outcomes identified Pb as the dominant contributor to both non-carcinogenic and carcinogenic risks. Although seasonal differences were not statistically significant, spatial variability strongly influenced the metal accumulation patterns, indicating localised anthropogenic inputs. The target hazard quotient and hazard index values revealed potential health concerns, particularly for children who exhibited markedly higher exposure indices. Although Cd was not detected and Ni posed a comparatively lower risk, the elevated Pb levels highlighted the need for routine monitoring, stricter environmental regulations, and public awareness of consumption patterns in oil-impacted communities. These findings underscore the importance of the sustained surveillance of aquatic food products in the Niger Delta to mitigate long-term public health risks.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- Adebiyi, F. M., Ore, O. T., & Ogunjimi, I. O. (2019). Evaluation of Human Health Risk Assessment of Potential Toxic Metals in Commonly Consumed Crayfish (*Palaemon hastatus*) in Nigeria. *Heliyon*, *6*, e03092. <https://doi.org/10.1016/j.heliyon.2019.e03092>
- Anandkumar, A., Li, J., Prabakaran, K., Xi Jia, Z., Leng, Z., Nagarajan, R. et al. (2020). Accumulation of Toxic Elements in an Invasive Crayfish Species (*Procambarus clarkii*) and Its Health Risk Assessment to Humans. *Journal of Food Composition and Analysis*, *88*, 103449. <https://doi.org/10.1016/j.jfca.2020.103449>
- Ayanda, O. I., Bello, O. A., & Nwabuisi, O. I. (2020). Trace Metal Toxicity in Some Food Items in Three Major Markets in Ado-Odo/OTA LGA, Ogun State, Nigeria and Associated Health Implications. *African Health Sciences*, *20*, 2050-2061. <https://doi.org/10.4314/ahs.v20i4.63>
- Bankole, A. O., Ogunkeyede, A. O., Odionye, J. N., Giwa, B., Mbaoma, O. C., Akpeji, B. H. et al. (2023). Physicochemical Properties and Health Risks of Informal E-Waste Processing at Alaba International Market in Lagos, Nigeria. *Journal of Geoscience and Environment Protection*, *11*, 176-202. <https://doi.org/10.4236/gep.2023.119012>
- Dey, M., Akter, A., Islam, S., Chandra Dey, S., Choudhury, T. R., Fatema, K. J. et al. (2021). Assessment of Contamination Level, Pollution Risk and Source Apportionment of Heavy Metals in the Halda River Water, Bangladesh. *Heliyon*, *7*, e08625. <https://doi.org/10.1016/j.heliyon.2021.e08625>
- El Hosry, L., Sok, N., Richa, R., Al Mashtoub, L., Cayot, P., & Bou-Maroun, E. (2023). Sample Preparation and Analytical Techniques in the Determination of Trace Elements in Food: A Review. *Foods*, *12*, Article 895. <https://doi.org/10.3390/foods12040895>
- Elekima, I., Edookue, R. B., Pepple, N. F., Aworu, A. M., & Chioma, A. E. B. (2020). Evaluation of Some Heavy Metals in Selected Sea Foods Directly from the Creeks in Rivers State, Nigeria. *Journal of Advances in Medical and Pharmaceutical Sciences*, *22*, 29-39. <https://doi.org/10.9734/jamps/2020/v22i1030198>

- FDA (2018). *Elemental Analysis Manual (EAM), Version 5.4*. U.S. Department of Health and Human Services. <https://www.fda.gov/media/86499/download>
- Goretti, E., Pallottini, M., Ricciarini, M. I., Selvaggi, R., & Cappelletti, D. (2016). Heavy Metals Bioaccumulation in Selected Tissues of Red Swamp Crayfish: An Easy Tool for Monitoring Environmental Contamination Levels. *Science of The Total Environment*, 559, 339-346. <https://doi.org/10.1016/j.scitotenv.2016.03.169>
- Igbuku, A. U. (2015). Determination of Heavy Metals in Crayfish Sold in Selected Towns (Asaba, Ozoro, Patani, and Sapele), Delta State, Nigeria. *Journal of Sciences and Multi-disciplinary Research*, 7, 47-54.
- Ikem, A., Ayodeji, O. J., & Wetzel, J. (2021). Human Health Risk Assessment of Selected Metal(Loid)s via Crayfish (*Faxonius virilis*, *Procambarus Acutus acutus*) Consumption in Missouri. *Heliyon*, 7, e07194. <https://doi.org/10.1016/j.heliyon.2021.e07194>
- Kazery, J. A., Garteiser, J. W., Cockrell, C. M., Doubert, A. D., Ervin, J. E., Brown, M. S. et al. (2025). Internal and External Spatial Analysis of Trace Elements in Local Crayfish. *Environmental Technology*, 46, 1215-1228. <https://doi.org/10.1080/09593330.2024.2380396>
- Lawal, K. K., Ekeleme, I. K., Onuigbo, C. M., Ikpeazu, V. O., & Obiekezie, S. O. (2021). A Review on the Public Health Implications of Heavy Metals. *World Journal of Advanced Research and Reviews*, 10, 255-265. <https://doi.org/10.30574/wjarr.2021.10.3.0249>
- Magnusson, B., & Örnemark, U. (2014). *The Fitness for Purpose of Analytical Methods: A Laboratory Guide to Method Validation and Related Topics* (2nd ed.). EURACHEM. <https://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-731>
- Mistri, M., Munari, C., Pagnoni, A., Chenet, T., Pasti, L., & Cavazzini, A. (2020). Accumulation of Trace Metals in Crayfish Tissues: Is *Procambarus clarkii* a Vector of Pollutants in Po Delta Inland Waters? *The European Zoological Journal*, 87, 46-57. <https://doi.org/10.1080/24750263.2020.1717653>
- Nag, R., & Cummins, E. (2022). Human Health Risk Assessment of Lead (pb) through the Environmental-Food Pathway. *Science of The Total Environment*, 810, Article 151168. <https://doi.org/10.1016/j.scitotenv.2021.151168>
- Naseri, K., Salmani, F., Zeinali, M., & Zeinali, T. (2021). Health Risk Assessment of Cd, Cr, Cu, Ni and Pb in the Muscle, Liver and Gizzard of Hen's Marketed in East of Iran. *Toxicology Reports*, 8, 53-59. <https://doi.org/10.1016/j.toxrep.2020.12.012>
- Numbere, A. O., Gbarakoro, T. N., & Babatunde, B. B. (2023). Environmental Degradation in the Niger Delta Ecosystem: The Role of Anthropogenic Pollution. In S. C. Izah, & M. C. Ogwu (Eds.), *Sustainable Development and Biodiversity* (pp. 411-439). Springer. https://doi.org/10.1007/978-981-19-6974-4_15
- Nwineewii, J. D., Edori, O. S., & Marcus, A. C. (2019). Heavy Metal Content of Surface Water and Crab (*Potamon fluviatile*) from the New Calabar River, Rivers State, Nigeria. *Journal of Chemical Society of Nigeria*, 44, 1035-1043.
- Peng, F., Li, J., Gong, Z., Yue, B., Wang, X., Manyande, A. et al. (2022). Investigation of Bioaccumulation and Human Health Risk Assessment of Heavy Metals in Crayfish (*Procambarus clarkii*) Farming with a Rice-Crayfish-Based Coculture Breeding Modes. *Foods*, 11, Article 261. <https://doi.org/10.3390/foods11030261>
- R Core Team (2023). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. <https://cir.nii.ac.jp/crid/1370298755636824325>
- Shaheen, N., Irfan, N. M., Khan, I. N., Islam, S., Islam, M. S., & Ahmed, M. K. (2016). Presence of Heavy Metals in Fruits and Vegetables: Health Risk Implications in Bangladesh. *Chemosphere*, 152, 431-438. <https://doi.org/10.1016/j.chemosphere.2016.02.060>
- Skoog, D. A., Holler, F. J., & Crouch, S. R. (2014). *Principles of Instrumental Analysis* (6th

ed.). Cengage Learning.

Suárez-Serrano, A., Alcaraz, C., Ibáñez, C., Trobajo, R., & Barata, C. (2010). *Procambarus Clarkii* as a Bioindicator of Heavy Metal Pollution Sources in the Lower Ebro River and Delta. *Ecotoxicology and Environmental Safety*, 73, 280-286.

<https://doi.org/10.1016/j.ecoenv.2009.11.001>

Udiba, U. U., Odey, M. O., Udofia, U. U., Akpan, E. R., Ama, J., Antai, E. E. et al. (2022). Dietary Intake, Carcinogenic and Non-Carcinogenic Risk Potentials of Lead, Cadmium, Mercury and Arsenic Exposure via Consumption of Dried Crayfish in Calabar, Nigeria. *Journal of Geoscience and Environment Protection*, 10, 340-363.

<https://doi.org/10.4236/gep.2022.108021>

Uhegbu, F. O., Chinyere, G. C., Ugbogu, A. E., & Nwoku, K. C. (2012). Arsenic and Chromium in Sea Foods from Niger Delta of Nigeria: A Case Study of Warri, Delta State. *Bulletin of Environmental Contamination and Toxicology*, 89, 424-427.

<https://doi.org/10.1007/s00128-012-0667-y>

Umeogaju, F. U., Akaninwor, J. O., Essien, E. B., Amadi, B. A., Igboekwe, C. O., Ononamadu, C. J., & Ikimi, C. G. (2023). Heavy Metals Contamination of Seafood from the Crude Oil-Impacted Niger Delta Region of Nigeria: A Systematic Review and Meta Analysis. *Toxicology Reports*, 11, 58-82. <https://doi.org/10.1016/j.toxrep.2023.06.011>

Undie, U., Eneji, I., & Khan, M. (2019). Assessment of Heavy Metals in Water and Fishes of Oyo Field and Ilaje Coastal Waters, Ondo State, Nigeria. *Environmental and Earth Sciences Research Journal*, 6, 97-102. <https://doi.org/10.18280/eesrj.060301>

USEPA (2000). *U.S.E.P. Supplementary Guidance for Conducting Health Risk Assessment of Chemical Mixtures*. USEPA.

Waqas, W., Yuan, Y., Ali, S., Zhang, M., Shafiq, M., Ali, W. et al. (2024). Toxic Effects of Heavy Metals on Crustaceans and Associated Health Risks in Humans: A Review. *Environmental Chemistry Letters*, 22, 1391-1411.

<https://doi.org/10.1007/s10311-024-01717-3>

Waribo, H. A., Bartimaeus, E. S., & Onuoha, I. C. (2019). Assessment of Some Heavy Metal Content of Dried Crayfish Sold in Creek Road Market, Borokiri, Port Harcourt, Nigeria. *Asian Journal of Fisheries and Aquatic Research*, 5, 1-6.

<https://doi.org/10.9734/ajfar/2019/v5i130068>

Zhang, L., Song, Z., Zhou, Y., Zhong, S., Yu, Y., Liu, T. et al. (2023). The Accumulation of Toxic Elements (Pb, Hg, Cd, As, and Cu) in Red Swamp Crayfish (*Procambarus clarkii*) in Qianjiang and the Associated Risks to Human Health. *Toxics*, 11, Article 635.

<https://doi.org/10.3390/toxics11070635>

Supplementary Material

Table S1. Estimated Daily Intake (EDI) of heavy metals in crayfish (Adults-Dry Season) (EDI expressed in mg/kg/day).

Location	Pb	Ni	Cr	Cd
1	0.00231	0.00103	0.00149	BDL
2	0.01031	0.00406	0.00111	BDL
3	0.00123	0.00046	0.00580	BDL
4	0.00471	0.00054	0.00080	BDL
5	0.00680	0.00046	0.00671	BDL
6	0.01129	0.00129	0.00446	BDL
7	0.00157	0.00051	0.00106	BDL
8	0.00469	0.00043	0.00263	BDL
9	0.00511	0.00040	0.00269	BDL
10	0.00463	0.00074	0.00131	BDL

Table S2. Estimated Daily Intake (EDI) of heavy metals in crayfish (Children-Dry Season).

Location	Pb	Ni	Cr	Cd
1	0.01013	0.00450	0.00650	BDL
2	0.04513	0.01775	0.00488	BDL
3	0.00538	0.00200	0.02538	BDL
4	0.02063	0.00238	0.00350	BDL
5	0.02975	0.00200	0.02938	BDL
6	0.04938	0.00563	0.01950	BDL
7	0.00688	0.00225	0.00463	BDL
8	0.02050	0.00188	0.01150	BDL
9	0.02238	0.00175	0.01175	BDL
10	0.02025	0.00325	0.00575	BDL

Table S3. Estimated Daily Intake (EDI) of heavy metals in crayfish (Adults-Wet Season) (EDI expressed in mg/kg/day).

Location	Pb	Ni	Cr	Cd
1	0.00586	0.00169	0.00297	BDL
2	0.00746	0.00049	0.00280	BDL
3	0.00106	0.00037	0.00111	BDL
4	0.00897	0.00029	0.00237	BDL
5	0.01583	0.00026	0.00140	BDL
6	0.00131	0.00071	0.00083	BDL
7	0.00731	0.00074	0.00237	BDL

Continued

8	0.01040	0.00080	0.00217	BDL
9	0.00160	0.00014	0.00131	BDL
10	0.00871	0.00066	0.00077	BDL

Table S4. Estimated Daily Intake (EDI) of heavy metals in crayfish (Children-Wet Season) (EDI expressed in mg/kg/day).

Location	Pb	Ni	Cr	Cd
1	0.02563	0.00738	0.01300	BDL
2	0.03263	0.00213	0.01225	BDL
3	0.00463	0.00163	0.00488	BDL
4	0.03925	0.00125	0.01038	BDL
5	0.06925	0.00113	0.00613	BDL
6	0.00575	0.00313	0.00363	BDL
7	0.03200	0.00325	0.01038	BDL
8	0.04550	0.00350	0.00950	BDL
9	0.00700	0.00063	0.00575	BDL
10	0.03813	0.00288	0.00338	BDL

Table S5. Pearson's correlation matrix of heavy metals during wet and dry seasons.

		Wet Season			Dry Season		
		Pb	Ni	Cr	Pb	Ni	Cr
Wet Season	Pb	1					
	Ni	-0.26	1				
	Cr	0.27	0.45	1			
Dry Season	Pb	-0.04	-0.20	-0.15	1		
	Ni	-0.14	0.02	0.39	0.61	1	
	Cr	-0.32	-0.22	-0.58	0.09	-0.29	1

Table S6. Euclidean distance matrix of heavy metals in crayfish samples.

Euclidean Distance Matrix:			
Heavy Metals	Pb	Ni	Cr
Pb	1	59.577311	54.313494
Ni	59.577311	1	7.545409
Cr	54.313494	7.545409	1