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Toxicity of Trace Metals in Mangrove Oysters (Crassostrea Gasar) and the Associated Health Risk from Bundu-Ama Community in Rivers State

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ABSTRACT

Mangrove oysters (Crassostrea gasar) serve as important food sources in coastal communities but are at risk of accumulating toxic metals from polluted waters. This study quantified cadmium (Cd), chromium (Cr), zinc (Zn), and nickel (Ni) in oysters collected from three anthropogenically impacted stations within the Isaka-Bundu mangrove swamp (Bundu-Ama community, Rivers State, Nigeria). Oyster samples were analyzed using Atomic Absorption Spectrophotometry (AAS), and health risk parameters such as Chronic Daily Intake (CDI), Hazard Index (HI), and Carcinogenic Risk (CR) were computed using standard USEPA models. Findings showed that metal concentrations varied spatially across the stations: Ni concentrations were highest (8.142 mg/kg at Station 1) and greatly exceeded the FAO/WHO limit of 0.05 mg/kg. Zinc reached 9.965 mg/kg (Station 1) but remained below the 30 mg/kg limit. Cadmium levels (0.007–0.012 mg/kg) slightly exceeded the 0.005 mg/kg threshold, while Cr (0.015–0.032 mg/kg) was within safe limits. The combined non-carcinogenic Hazard Index (HI) was below 1 for adults (0.583–0.900), indicating tolerable risk, but exceeded 1 for children (2.721–4.202), suggesting potential non-carcinogenic health effects. Carcinogenic Risk (CR) values for Ni and Cr were above the acceptable USEPA range of $10E^{-6}$– $E10^{-4}$, implying potential lifetime cancer risks for frequent consumers particularly children. It was concluded that oysters from the Isaka-Bundu mangrove swamp are contaminated with trace metals, especially nickel, posing possible health hazards to the local population. The study recommends regular monitoring of seafood, enforcement of effluent discharge control, and community sensitization on safe seafood consumption.

INTRODUCTION

Human reliance on surface freshwater and coastal ecosystems for essential goods and services, including drinking water, fisheries, and recreation, places these environments at the intersection of ecological, economic, and political interests (Inya *et al.*, 2022). Mangrove ecosystems, in particular, are among the most productive coastal habitats, functioning as nurseries for fish and shellfish while providing natural protection against erosion and climate-related impacts. However, increasing anthropogenic pressures have subjected these systems to intense pollution stress, especially through the introduction of mineral and organic contaminants such as heavy metals (Chris and Anyanwu, 2022; Umeoguaju *et al.*, 2023). Mangrove oysters (Crassostrea gasar), as filter feeders, continuously process large volumes of water for nutrients, and consequently they can bioaccumulate trace metals such as cadmium (Cd), chromium (Cr), zinc (Zn), and nickel (Ni) in their tissues (Mititelu *et al.*, 2025; Davies *et al.*, 2023).

Over time, these metals bioaccumulate and may reach levels that pose serious risks to both the oysters and the humans who consume them (Davies *et al.*, 2023). Seasonal fluctuations further complicate this issue. During the rainy season, runoff and sediment resuspension increase pollutant inflow, whereas in the dry season, reduced water levels and slower circulation enhance the concentration of existing contaminants (Yunus *et al.*, 2020; El-Sharkawy, 2025; Ogunjimi and Akinola, 2024). Such changes directly influence the bioavailability and uptake of metals by oysters, leading to temporal variations in contamination levels.

The health implications of consuming contaminated seafood are profound. Chronic exposure to toxic trace metals, even at low concentrations, has been linked to severe health outcomes including kidney and liver dysfunction, neurological impairment, reproductive disorders, and carcinogenic effects (Mititelu, 2025; Davies *et al.*, 2023). This is particularly worrisome in coastal communities where seafood is a dietary staple and a major source of livelihood (Chris and Anyanwu, 2022). It is within this environmental and socio-economic context that the Isaka-Bundu mangrove swamp, located in the Bundu-Ama community of Rivers State, Nigeria, becomes a focal point of concern.

This area lies within the industrial hub of the Niger Delta, surrounded by oil-related activities, boat repair workshops, and densely populated settlements (Umeoguaju, 2023). Over the years, effluents from nearby industries, petroleum residues from artisanal refining, and domestic waste from adjoining communities have continuously found their way into the mangrove channels (Chris and Anyanwu, 2022). The result is a fragile ecosystem struggling to cope with persistent pollution pressures. Despite these visible signs

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of degradation, including discolored water, declining fish populations, and oily residues along the banks, the local population continues to depend heavily on mangrove oysters for food and income (Davies *et al.*, 2023).

Many residents remain unaware of the potential health dangers posed by metal accumulation in these shellfish (Mititelu, 2025). Given the ecological significance of mangrove oysters and their importance to the livelihood and food security of the Bundu-Ama community, it has become necessary to scientifically assess the extent of contamination within this environment. This study therefore investigates the concentration and spatial distribution of selected trace metals, cadmium (Cd), chromium (Cr), zinc (Zn), and nickel (Ni), in Crassostrea gasar collected from various locations within the Isaka-Bundu mangrove swamp.

In addition, it evaluates the potential human health risks associated with oyster consumption through the estimation of Chronic Daily Intake (CDI), Hazard Quotient (HQ), and Hazard Index (HI) for non-carcinogenic risks, as well as Cancer Risk (CR) for carcinogenic threats (Mititelu, 2025; Davies *et al.*, 2023). Through this integrative assessment, the study aims to provide empirical evidence that links environmental contamination to public health exposure, thereby informing both environmental management policies and community awareness initiatives in the Bundu-Ama region (Chris and Anyanwu, 2022; Umeoguaju, 2023).

MATERIALS AND METHODS

Study Area

The study was carried out in the Isaka-Bundu mangrove swamp, located in the upper reaches of the Bonny Estuary in Rivers State, Nigeria. This mangrove ecosystem is currently under considerable environmental pressure due to the continuous discharge of domestic and industrial wastes from nearby companies, creeks, and densely populated coastal settlements. Three sampling stations were strategically selected based on the level and nature of human activities observed across the swamp. Station 1 was located close to an abandoned crude oil bunkering site characterized by visible oil sheen, debris, and sediment heaps, all of which indicated petroleum-based contamination. Station 2 was situated near a densely populated settlement where human, animal, and domestic wastes were visible along the shorelines, reflecting significant urban pollution and surface runoff. Station 3 was positioned close to the Creek Road Market and Dockyard area, where maintenance fluids, solid and liquid wastes, and various effluents from commercial activities were discharged into the swamp environment (Davies *et al.*, 2021). Collectively, these three sampling points represented the varying degrees of anthropogenic impact and provided a comprehensive picture of pollution intensity across the Isaka-Bundu mangrove swamp.

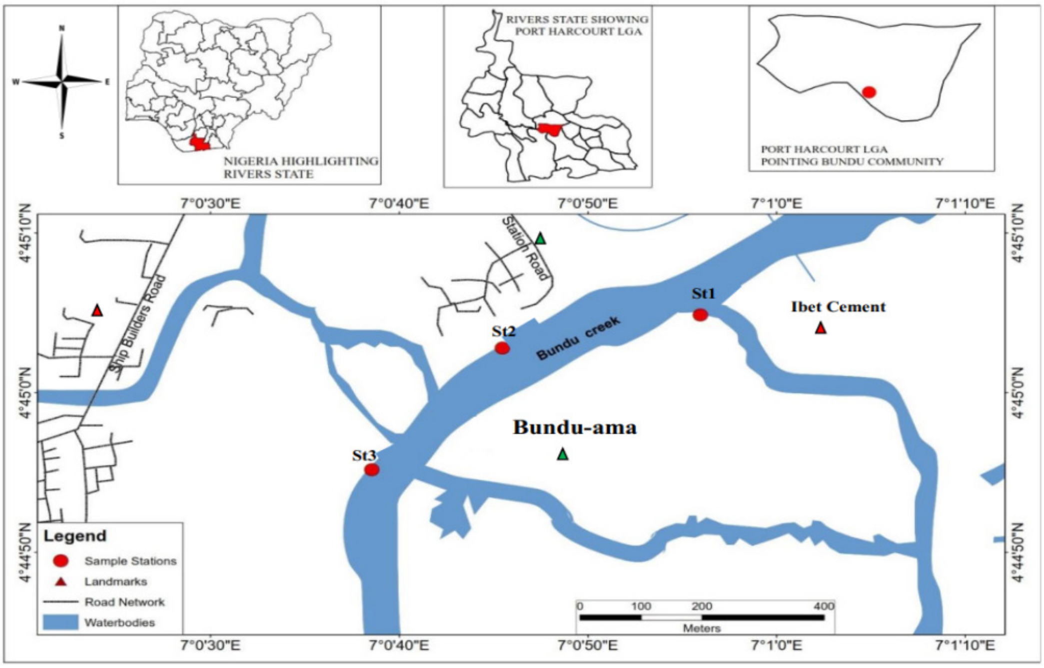

Figure 1: Map of Port Harcourt, Rivers State, Nigeria showing the study area

Sample Collection and Preparation

In the laboratory, oyster tissues were carefully excised, rinsed thoroughly with deionized water to remove adhering particles, and oven-dried to achieve a constant weight. The dried tissues were then subjected to acid digestion following the protocol described by Hossain (2022).

Live mangrove oysters (Crassostrea gasar) were obtained from local fishermen at the three selected stations. A total of sixty representative oyster samples, with an average length of 6.03 ± 0.62 cm and mean weight of 8.22 ± 0.18 g, were used for the study. The collected samples were transported to the laboratory in clean, ice-packed containers to prevent degradation. In the laboratory, oyster tissues were removed, rinsed thoroughly with deionized water to eliminate any adhering particles, and oven-dried to constant weight.

The dried tissues were then subjected to acid digestion following the method described by Hossain (2022). In this procedure, each sample was treated with concentrated nitric acid and heated at 40°C for one hour, then gradually increased to 140°C for three hours to ensure complete digestion. After digestion, the samples were allowed to cool, diluted with double-distilled water, and filtered into pre-cleaned, acid-washed plastic containers to remove any undigested residues.

Chemical Analysis and Quality Control

The concentrations of selected heavy metals Cd, Cr, Ni, and Zn were determined using a UNICAM Solaar 969 Atomic Absorption Spectrophotometer (AAS) equipped with an acetylene-air flame. Rigorous quality control measures, including the use of pre-cleaned glassware and blanks, were implemented to prevent analytical contamination. Metal concentrations were recorded and expressed in milligrams per kilogram (mg/kg) of dry weight.

All glassware and containers used during the analysis were thoroughly washed with 10% nitric acid and rinsed with deionized water to prevent contamination. Human health risk assessment followed USEPA guidelines (USEPA, 2004). Chronic Daily Intake (CDI) was estimated to quantify the average daily dose of each metal through oyster consumption (USEPA, 2001). CDI (mg/kg-day) was calculated using standard exposure parameters (body weight, ingestion rate, exposure frequency/duration) for adults (70 kg) and children (15 kg) (USEPA, 2001; Sharif *et al.*, 2016).

Non-carcinogenic risk for each metal was expressed by the Target Hazard Quotient (THQ), defined as the ratio of CDI to the oral Reference Dose (RfD) for that metal (Sharif *et al.*, 2016). The Hazard Index (HI) was computed as the sum of THQs across all metals to assess cumulative risk (USEPA, 2004). An HI or THQ above 1 indicates potential non-carcinogenic health concerns. For carcinogenic metals (Cd, Ni, Pb), Cancer Risk (CR) was estimated using published cancer slope factors (USEPA, 2004). CR represents the probability of an individual developing cancer over a lifetime of exposure; the USEPA considers risks between 10^{-6} and 10^{-4} as acceptable (USEPA, 2004; Rahman *et al.*, 2018). All calculations were performed using parameters and equations recommended by USEPA (2004, 2001).

Health Risk Assessment Methodology

Human Health Risk Assessment (HRA) of the exposed population and her environs was conducted to evaluate the potential health effects arising from the chronic consumption of contaminated oysters, adhering to the guidelines set forth by the USEPA (2004, 2011).

Chronic Daily Intake (CDI)

The CDI estimates the daily ingested dose of heavy metals over an extended period. The model below (Egn.1) provides the CDI calculated using ratio of the product of tissue concentration and consumption rate to the body weight of the consumer. The CDI represents the amount of a specific heavy metal absorbed into the body each day and is expressed in mg/kg/day.

CDI =CM x IR x ED x EF

BW x AT (1)

Where, CDI is the daily dose of heavy metals in mg/Kg, which the users are susceptible to through dermal exposure; Cw is the heavy metal concentration (mg/kg); EF is the exposure frequency (350 days/year), ED is the exposure duration (carcinogenic exposure) is 70 years (adult) and 6 years (children) and AT is the period over which exposure is averaged (days); for carcinogens, the average time is 24,500 days (Adult: lifetime exposure of 70 years by 350 days/yr), and 10,500 days (Adult: 30 years by 350 days/yr) for non-cancer risks while child risk is 2100 days (non-cancer risks: 6 years by 350 days/yr) and 24,500 days (cancer risk over an entire lifetime of exposure). BW is the average body weight of the consumers - 70kg (adult) and 15kg (children). (USEPA, 2001; USEPA, 2004).

All health risk indices were computed based on the standard methodology recommended by USEPA (2004).

Non-Carcinogenic Risk Assessment (HQ and HI)

The non-carcinogenic risk associated with individual metals was quantified using the Hazard Quotient (HQ) (Sharif *et al.*, 2016). The HQ is the ratio between the CDI and the reference dose (RfD) for a given metal (Sharif *et al.*, 2016). It is calculated using the equation:

HQ = CDI/RfD ...(2)

Where CDI is the chronic daily intake (mg/kg/day) and RfDo is the chronic oral Reference Dose (mg/kg/day), representing the dose an individual can sustain over a lifetime without adverse effects. An HQ value less than indicates an acceptable level of risk, whereas HQ > 1 suggests potential adverse non-carcinogenic health effects.

To assess the cumulative non-carcinogenic risk from simultaneous exposure to multiple metals via ingestion of mudskippers by the Bille population, the Hazard Index (HI) was determined as the sum of all HQ values for the metals analyzed:

Hazard Index(HI)=$\sum HQ_1 + HQ_2 + HQ_3 + HQ_4$ (3)

According to the USEPA (2004), an HI value below 1 suggests that there is no significant health concern, while values greater than 1 indicate potential non-carcinogenic health effects. An HI exceeding 4 reflects a high level of health risk that warrants urgent attention and further evaluation (USEPA, 2004).

Carcinogenic Risk Assessment (CR)

The Cancer Risk (CR) was estimated for carcinogenic metals (Cd, Cr, and Ni) . The CR was derived using the equation:

CR=CDE×CSF (4)

where CSF represents the cancer slope factor for each carcinogenic metal. The USEPA (2001) considers a CR range between 10^{-6} and 10^{-4} to be acceptable or tolerable, indicating a negligible to low risk of cancer development. However, a CR value greater than 10^{-4} is considered hazardous and indicative of a significant public health concern (Rahman *et al.*, 2019).

RESULTS AND DISCUSSION

Results

Distribution of Toxic Elements in Mangrove Oysters (Crassostrea gasar)

Table 1 presents the spatial variation of heavy metal concentrations in mangrove oysters (Crassostrea gasar) from the Isaka-Bundu mangrove swamp. The results revealed that nickel (Ni) recorded the highest concentrations among all metals, in the order of 8.142 mg/kg at Station 1 >4.023 mg/kg at Station 3 > 3.702 mg/kg at Station 2. Zinc (Zn) concentrations ranged from 6.545 mg/kg (Station 2) to 9.965 mg/kg (Station 1), making Zn the most abundant metal among all the metals studied, but still well below the 30 mg/kg FAO/WHO limit.

Cadmium (Cd) was found in the range of 0.007 mg/kg (Station 2) to 0.012 mg/kg (Station 3), slightly above the FAO/WHO limit of 0.005 mg/kg. Chromium (Cr) concentration was the lowest among the studied metals, ranging from 0.015 mg/kg to 0.032 mg/kg, remaining under the 0.05 mg/kg limit (Figure 1). The data indicate that Ni and Cd are elevated relative to safe levels, highlighting potential ecological and health risks for consumers.

Table 1: Spatial Distribution of Toxic Elements Levels (mg/kg) in Oysters (C. gasar)

Heavy metals (mg/kg)	Station 1	Station 2	Station 3	FAO/WHO 2009
Cadmium (Cd)	0.009	0.007	0.012	0.005
Chromium (Cr)	0.015	0.017	0.032	0.05
Zinc (Zn)	9.965	6.545	8.42	30
Nickel (Ni)	8.142	3.702	4.023	0.05

Human Health Risk Assessment of Exposure to C. Gasar

Estimated Chronic Daily Ingestion Rate (CDI)

Table 2 presents the Chronic Daily Intake (CDI) of heavy metals in Crassostrea gasar for both adults and children across the three sampling stations in the Isaka-Bundu mangrove swamp. The results revealed that zinc (Zn) recorded the highest CDI values, ranging from 1.864877 to 2.839342 mg/kg/day in adults and 8.702758 to 13.25026 mg/kg/day in children.

Nickel (Ni) followed closely, with adult CDI values between 1.054816 and 2.319912 mg/kg/day, and children exhibiting much higher levels ranging from 4.922477 to 10.82626 mg/kg/day. Chromium (Cr) showed lower but significant values, varying from 0.004274 to 0.009118 mg/kg/day in adults and 0.019945 to 0.04255 mg/kg/day in children.

Cadmium (Cd) had the lowest CDI values across all stations, ranging from 0.001995 to 0.003419 mg/kg/day in adults and 0.009308 to 0.015956 mg/kg/day in children. Table 2 showed that, children exhibited considerably higher CDI values than adults across all metals due to their lower body weight and higher intake rate per kilogram, indicating that they are more vulnerable to metal-related health risks in the study area.

Table 2: Chronic Daily Intake (CDI) (mg/kg/day) in C. gasar of adults and children

Heavy metals	Adults			Children			RfD_o (USEPA, 2005; 2016abc)
(mg/kg)	Section 1	Section 2	Section 3	Section 1	Section 2	Section 3	(mg/kg/day)
Cadmium (Cd)	0.002564	0.001995	0.003419	0.011967	0.009308	0.015956	0.001
Chromium (Cr)	0.004274	0.004844	0.009118	0.019945	0.022605	0.04255	0.003
Zinc (Zn)	2.839342	1.864877	2.399123	13.25026	8.702758	11.19591	0.3
Nickel (Ni)	2.319912	1.054816	1.146279	10.82626	4.922477	5.349304	0.02

Non-cancer Risk (HQ and HI) Evaluation of Mangrove Oysters (Crassostrea gasar)

Table 3 and figure 2 presents the Hazard Quotient (HQ) and Hazard Index (HI) values for Crassostrea gasar across the three sampling stations for both adults and children in the Isaka-Bundu mangrove swamp. Among the metals analyzed, zinc (Zn) exhibited the highest HQ values, ranging from 0.559 at Station 2 to 0.852 at Station 1 in adults, and from 2.611 to 3.975 in children, indicating that Zn was the primary contributor to non-carcinogenic risks. Nickel (Ni) followed, with adult HQ values between 0.021 and 0.046 and children between 0.098 and 0.217.

Chromium (Cr) showed moderate HQ values from 0.0021 to 0.0046 in adults and 0.0099 to 0.0213 in children, while cadmium (Cd) recorded the lowest HQs (10^{-6} range), suggesting minimal contribution to overall health risk. The calculated Hazard Index (HI), representing the combined non-carcinogenic effect of all metals, ranged from 0.583 to 0.900 for adults, values below 1, indicating no significant health concern.

However, for children, HI values ranged from 2.721 to 4.202, exceeding the safe threshold (HI > 1), signifying potential non-carcinogenic health risks, especially at Station 1 where contamination was most pronounced.

Table 3: Hazard quotient (HQ) in Crassostrea gasar across the stations

Heavy metals	**Adults**			**Children**		
(mg/kg)	**Section 1**	**Section 2**	**Section 3**	**Section 1**	**Section 2**	**Section 3**
Cd	2.56438E-06	1.99452E-06	3.41918E-06	1.19671E-05	9.30776E-06	1.59562E-05
Cr	0.002136986	0.002421918	0.004558904	0.009972603	0.011302283	0.021274886
Zn	0.85180274	0.559463014	0.719736986	3.975079452	2.610827397	3.358772603
Ni	0.046398247	0.021096329	0.022925589	0.216525151	0.098449534	0.106986082
HI	0.900337973	0.58298126	0.747221479	4.201577205	2.720579215	3.487033571

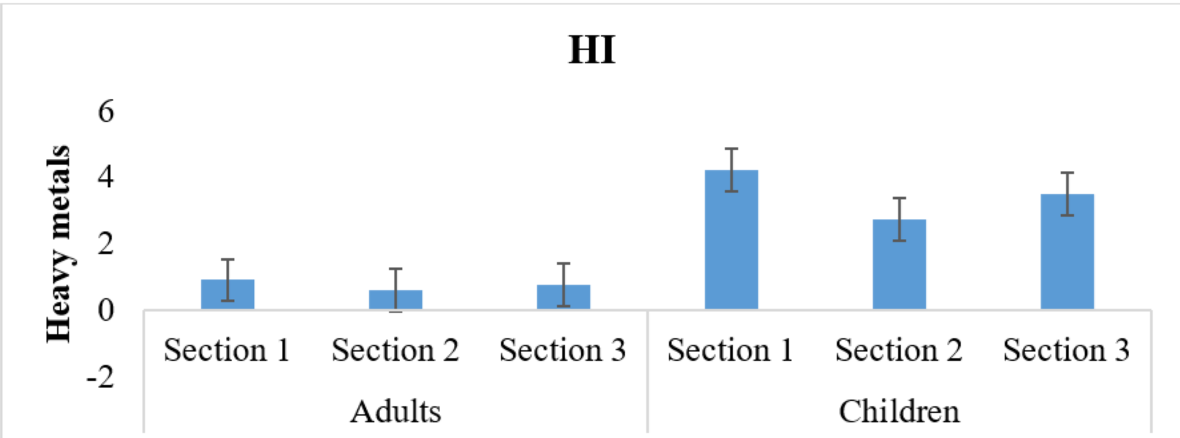

Figure 2: Hazard index (HI) in Crassostrea gasar across the stations

Cancer Risk from Heavy Metal Exposure via C.gasar Consumption

Table 4 presents the estimated cancer risk (CR) values for adults and children exposed to carcinogenic heavy metals through the consumption of Crassostrea gasar from the Isaka-Bundu mangrove swamp. Nickel (Ni) exhibited the highest carcinogenic risk, with CR values ranging from 0.0359 to 0.3681 for adults and from 0.1674 to 0.3681 for children. These values are far above the USEPA acceptable cancer risk threshold of 10-6 to 10-4, indicating a serious potential health concern for frequent oyster consumers.

Chromium (Cr) also showed notable carcinogenic potential, with values ranging from 0.0018 to 0.0084 in adults and 0.0084 to 0.0179 in children, which exceed the recommended limit and suggest long-term cancer risk from continuous exposure. Cadmium (Cd) recorded lower CR values, ranging from to 10^{-7} in adults and to 10^{-6} in children, though some still surpass the safe threshold. Children consistently exhibited higher CR values than adults, emphasizing their greater vulnerability due to lower body weight and higher metal intake rates.

Discussion

The concentrations of cadmium (Cd), chromium (Cr), zinc (Zn), and nickel (Ni) in Crassostrea gasar from the Isaka-Bundu mangrove swamp revealed pronounced spatial variations, reflecting the gradient of human activities and pollution intensity across the sampling stations. As shown in Table 1, nickel (Ni) exhibited the highest concentrations, with values ranging from 3.702 mg/kg at Station 2 to 8.142 mg/kg at Station 1, substantially exceeding the FAO/WHO (2009) permissible limit of 0.05 mg/kg. The elevated Ni levels highlight the influence of petroleum-related and industrial activities prevalent in the study area.

Station 1, located near the oil bunkering zone and dockyard, likely receives continuous inputs of petroleum residues, lubricating oils, and metallic leachates from ship maintenance and engine wash-offs. This trend is consistent with observations by Davies *et al.* (2023) and Umeoguaju (2023), who reported similarly high Ni concentrations in

Table 4: Potential Risk of Some Carcinogenic Heavy Metals via C. gasar Consumption

Adults				**Children**		
Heavy metals	**Section 1**	**Section 2**	**Section 3**	**Section 1**	**Section 2**	**Section 3**
Cd	9.7446E-07	7.579E-07	4.5475E-06	4.5475E-06	3.53695E-06	6.06336E-06
Cr	1.795E-03	2.0344E-03	8.3769E-03	8.3769E-03	9.4939E-03	1.787E-02
Ni	7.8877E-02	3.5863E-02	3.6809E-01	3.6809E-01	1.6736E-01	1.8187E-01

fish species collected from the New Calabar River and other Niger Delta waterways, attributing the enrichment to oil discharge, corrosion of metallic structures, and leaching of antifouling paints used in marine operations.

Nickel contamination poses both ecological and human health concerns due to its non-essential nature and high bioaccumulation potential. Long-term Ni exposure has been linked to dermatitis, respiratory complications, and carcinogenicity in humans (USEPA, 2012). The dominance of Ni in the oysters, therefore, underscores a significant anthropogenic footprint, aligning with the findings of Amadi *et al.* (2018), who associated Ni enrichment in Niger Delta waters with the release of lubricating and mechanical oils from marine and industrial activities.

Cadmium (Cd) concentrations in the oysters ranged from 0.007 mg/kg to 0.012 mg/kg, marginally exceeding the FAO/WHO (2009) limit of 0.005 mg/kg. Although these values are relatively low, they signify chronic input from agricultural fertilizers, domestic waste, and oil residues. Cadmium is a non-essential metal that poses toxicity even at trace concentrations, with prolonged exposure capable of causing renal dysfunction, bone demineralization, and carcinogenic effects (Davies *et al.*, 2023; Mititelu, 2025). Similar Cd levels have been reported in oysters and fish from other Niger Delta estuaries by Oyedeji (2023) and Chris and Anyanwu (2022), who also attributed Cd presence to fertilizer wash-offs and oil-related emissions. The consistent detection of Cd, albeit in low concentrations, indicates persistent background contamination likely linked to diffuse sources such as sewage inflow and agricultural runoff.

Chromium (Cr) concentrations, on the other hand, ranged from 0.015 to 0.032 mg/kg, remaining below the FAO/WHO (2009) permissible limit of 0.05 mg/kg. This suggests limited bioavailability of Cr in the Isaka-Bundu swamp, likely due to its strong affinity for sediment particles that reduces its mobility in aquatic environments. The low Cr levels observed in this study are consistent with findings by Yunus *et al.* (2020) and Ogunjimi and Akinola (2024), who also noted that sediment binding plays a critical role in regulating Cr uptake by filter-feeding organisms.

Despite its relatively low concentration, Cr potential to exist in the hexavalent form (Cr^{6+}), which is highly toxic and carcinogenic, warrants continued monitoring, particularly in areas of active industrial discharge.

Zinc (Zn), though an essential trace element, recorded moderately elevated concentrations ranging from 6.545 to 9.965 mg/kg. These values were below the 30 mg/kg threshold stipulated by FAO/WHO (2009), suggesting that while Zn accumulation is evident, it is not yet at toxic levels. However, the observed Zn enrichment may indicate continuous metal loading from galvanic materials, household wastes, and runoff from metallic roofs and industrial structures.

The concentration order at Station 1, Zn > Ni > Cr > Cd, mirrors trends observed in other polluted Niger Delta creeks (Chris and Anyanwu, 2022) and in estuaries of South and Southeast Asia (Yunus *et al.*, 2020), reflecting the dual influence of natural weathering and anthropogenic inputs on metal distribution.

As shown in table 2, the estimated daily intake (EDI) results demonstrated marked differences between adults and children. Children exhibited significantly higher EDI values across all metals due to their lower body weight and higher food intake relative to body mass. Zinc recorded the highest EDI values, ranging from 1.864877 to 2.839342 mg/kg/day for adults and 8.702758 to 13.25026 mg/kg/day for children, while Cd showed the lowest EDI (0.001995–0.003419 mg/kg/day in adults; 0.009308–0.015956 mg/kg/day in children).

This pattern agrees with the findings of Rahman *et al.* (2018) from the Noakhali Fish Market, Bangladesh, where children's EDI values for all metals were several times higher than those of adults, highlighting ingestion as the dominant exposure pathway. When compared with the Joint FAO/WHO Expert Committee on Food Additives (JECFA) guidelines (2009), adult EDI values for Cd (0.005 μg/kg/day) and Cr (0.05 μg/kg/day) remained below the Provisional Tolerable Daily Intake (PTDI), indicating minimal immediate risk for adults.

However, children's Ni and Zn EDI values exceeded the Tolerable Daily Intake (TDI) established by FAO/WHO (2011) and USEPA (2012), indicating possible chronic exposure risks. Similar conclusions were drawn by Adeola *et al.* (2022) and Okwunwa *et al.* (2024), who observed that children in coastal Nigerian communities were more vulnerable to heavy metal exposure due to higher per kilogram consumption rates and developing metabolic systems that limit detoxification efficiency.

The non-carcinogenic health risk indices in Table 3 further confirm these disparities. For adults, all Hazard Quotient (HQ) values were below 1, with Zn (0.559–0.852) and Ni (0.021–0.046) contributing the most. This implies that adult consumers face no immediate non-cancer health risk, consistent with the USEPA (2011) guideline that HQ or Hazard Index (HI) values below 1 indicate tolerable exposure. Conversely, in children, HQ values for Zn (2.611–3.975) and Ni (0.098–0.217) exceeded the benchmark, producing a total HI range of 2.721–4.202. This suggests potential health effects associated with chronic exposure through long-term oyster consumption. These findings differ from those of Hossain *et al.* (2022) and Ihedioha *et al.* (2016), who reported HI values below 1 for children consuming seafood from Bangladesh and southeastern Nigerian estuaries. Nonetheless, Hossain *et al.* (2022) and Ahmed *et al.* (2015) emphasized that HQ or HI values exceeding 1 denote possible long-term health implications, a conclusion also supported by Rahman *et al.* (2018), who found children's HQs to be consistently higher than adults in polluted aquatic environments.

The carcinogenic risk (CR) values presented in Table 4 reveal Ni and Cr as the dominant carcinogenic contributors. Ni exhibited CR values between 0.0359 and 0.3681 in adults, and 0.1674 to 0.3681 in children, while Cr showed CR values between 0.0084 and 0.0179. Both exceeded the USEPA acceptable range of 1×10^{-6} to 1×10^{-4}, indicating a considerable lifetime cancer risk. According to USEPA (2004) risk interpretation, a CR value of 1×10^{-3} suggests that one individual out of every 1,000 exposed may develop cancer during their lifetime, while 1×10^{-6} corresponds to a risk of one in one million. Hence, the Ni and Cr CR values observed here imply an approximate cancer probability of 1 in 100 to 1 in 10,000 among frequent consumers. These findings corroborate those of Hossain *et al.* (2022) and Rahman *et al.* (2018), who recorded similar Ni-driven carcinogenic risks in seafood from contaminated estuaries. Cd posed relatively low CR values (7.6×10^{-7}–6.1×10^{-6}), which fall within the acceptable limits proposed by USEPA (2011).

The overall trend in metal exposure and associated risk follows the sequence Zn > Ni > Cr > Cd, corresponding to their environmental abundance and biological roles. Zn and Cr, being essential elements, are generally regulated by physiological mechanisms, while Ni and Cd, which are non-essential, tend to bioaccumulate and exert toxicological effects even at low concentrations. The elevated Ni concentrations and its major contribution to carcinogenic risk further reinforce the role of petroleum-based contamination, particularly from bunkering, refining, and dockyard activities within the Bundu-Ama region. This agrees with Amadi *et al.* (2018), who linked Ni enrichment in Niger Delta aquatic systems to lubricating oil discharge and metal scrap leachates.

Furthermore, the pronounced health indices in children, despite relatively moderate environmental concentrations, highlight the importance of physiological and dietary factors in risk assessment. Children's higher intake rate per kilogram body weight, combined with immature detoxification and excretion mechanisms, increases their vulnerability to trace metal toxicity (Katarzyna *et al.*, 2022). Thus, while adults may not face immediate non-carcinogenic or carcinogenic risks (HI < 1 and most CR < 1×10^{-4}), children's exposure levels warrant significant concern and immediate mitigation.

CONCLUSION

This study revealed that mangrove Oysters (Crassostrea gasar) from the Isaka-Bundu swamp are contaminated by multiple trace metals, with marked spatial variation linked to local human activities. Zinc had the highest absolute tissue value (9.965 mg/kg at Station 1) but stayed below the 30 mg/kg FAO/WHO limit. Nickel measured 8.142 mg/kg at Station 1, 3.702 mg/kg at Station 2 and 4.023 mg/kg at Station 3, exceeding the 0.05 mg/kg limit by large margins. Cadmium ranged 0.007–0.012 mg/kg and chromium 0.015–0.032 mg/kg. Chronic daily intake (CDI) for adults ranged: Cd 0.001995–0.003419 mg/kg/day; Cr 0.004274–0.009118 mg/kg/day; Zn 1.864877–2.839342 mg/kg/day; Ni 1.054816–2.319912 mg/kg/day. For children CDI ranged: Cd 0.009308–0.015956 mg/kg/day; Cr 0.019945–0.04255 mg/kg/day; Zn 8.702758–13.25026 mg/kg/day; Ni 4.922477–10.82626 mg/kg/day.

Adult Hazard Index (HI) values (0.58298126–0.900337973) remained below 1, indicating no immediate non-carcinogenic concern for adults; children's HI (2.720579215–4.201577205) exceeded 1, indicating probable non-carcinogenic risk. Cancer risk (CR) for nickel (adults 0.035863759–0.368092757; children 0.167364208–0.368092757) and chromium (adults 0.001795068–0.008376987; children 0.008376987–0.017870904) were above the USEPA acceptable range (10^{-6}–10^{-4}), indicating potential lifetime cancer risk particularly for children and frequent oyster consumers in the Bundu-Ama community. indicating potential lifetime cancer risk for children and frequent oyster consumers in the Bundu-Ama community.

Therefore, immediate public advisories, strict pollution controls, and continuous monitoring are recommended to protect vulnerable groups, especially children, and to restore the ecological and public health integrity of the Isaka-Bundu mangrove environment.

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