



Evaluation of heavy metals and their potential risk to human health from seafood in Escravos Estuary, Southern Nigeria

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ABSTRACT

In this study, we investigated the levels of heavy metals in sediment, shrimps, silver catfish and their potential bioaccumulation, trophic transfer and the associated risk to human health from the Escravos estuary in southern Nigeria. The values of heavy metals in shrimps and silver catfish were disproportionately higher than the allowable limits for seafood, with values in the gills and the rest of the fish higher than those of the muscle, liver and gonads. Furthermore, the increased BSAF for Cd, Cr and Cu in the study, underscore the uptake of metals from sediments into shellfish. High EDI and HR values from silver catfish for adults and children indicate immediate health risks, with the values for children considerably high, emphasizing the urgent need for regulatory measures and continuous monitoring of seafood from the estuary to protect the health of coastal population within the subregion.

1. Introduction

Heavy metals are naturally occurring elements that have a relatively high atomic weight and a density at least five times greater than that of water (Chinedu and Chukwuemeka, 2018). In Nigeria, oil and gas production, mining of ore deposits, use of agrochemicals, and the manufacture of fast consumer goods are among the several industrial activities capable of influencing the dispersion and distribution of heavy metals and metalloids into the environment (Ihedioha et al., 2017). Once in the environment, metals are partitioned among the various compartments in soil, water, and biota in relation to their state or reactive potentials (Yahya et al., 2016). Heavy metals that enter the aquatic environment may accumulate in the sediments, resulting in the concentrations of these elements in sediments several times higher than those in the water column (Zhao et al., 2018; Liu et al., 2021). Thus, sediments are generally considered as sinks for heavy metals in aquatic ecosystems (Qiu et al., 2011; Ekperusi and Asiwa, 2024). On the other hand, trace elements found in sediments may enter the food chain through uptake and trophic transfer, posing health risks to aquatic organisms and humans (Gao et al., 2015; Yang et al., 2021). The pink shrimp, *Penaeus notialis* (Pérez Farfante, 1967) is a benthic decapod characterized by a

soft body, long antennae and legs, with thin and semi-transparent exoskeleton. Shrimp belong to the largest class of crustaceans, Malacostraca, which includes crabs, lobsters, krill and woodlice. *P. notialis* is native to the West African region and constitutes a major fishery product for artisanal and trawl fishing. While the cultivation technology for pink shrimp is not yet fully developed, juvenile and adult pink shrimps are commonly found in estuaries across the Niger Delta region (Ebonwu et al., 2007). Shrimp is a crucial seafood commodity, traded globally with an annual market value exceeding US \$20 billion, accounting for 19 % of international trade (Islam et al., 2003). The silver catfish, *Chrysichthys nigrodigitatus* (Lacepède, 1803) is an important demersal fish species in tropical ecosystems (Ikongbeh et al., 2015). It is abundant and a regular fish found in catches of artisanal and commercial fishers across coastal communities. Silver catfish feed on shrimps and other crustaceans as a source of food.

Many coastal and marine organisms, shrimps, and fish accumulate elevated levels of metals from the surrounding water and sediment (Arulkumar et al., 2017; Adimalla and Wang, 2018).

They act as bioindicators for monitoring aquatic pollution, due to their relatively large size, lifespan, trophic level and use for human consumption (Zhou et al., 2008). Trace metals taken up by sediment-

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dwelling or benthic organisms can be transferred across the food chain, ultimately impacting human health (Yousif et al., 2021; Abarshi et al., 2017). Furthermore, tissue concentrations of trace metals in seafood can be employed as bioindicators for contaminants monitoring in aquatic ecosystems (Baki et al., 2018). Oil spills and the discharge of effluents from the petrochemical industry have been described as the primary source of hazardous heavy metal pollution in the Niger Delta region of Nigeria (Sankhla et al., 2020; Chinedu and Chukwuemeka, 2018; Wel-deslassie et al., 2018). Heavy metals and metalloids, such as arsenic, cadmium, chromium, copper, lead and mercury are toxic to both aquatic and terrestrial ecosystems, as well as to human health when they enter the food chain. Understanding how these metals move through the food chain can help assess the potential risks to the environment and ultimately to human health. Despite the growing literature on heavy metals prevalence from coastal ecosystems in the Niger Delta region, there is a dearth of knowledge on the ecological and human health risk assessment of trace metals from commonly consumed seafood in the region. In this study, we evaluated the heavy metal concentration in a coastal food chain from the Escravos Estuary and the potential risk to human health. The specific objectives are to; 1) investigate the concentration of heavy metals in sediments, shrimps and silver catfish, 2) assess the uptake of heavy metals from sediments to shrimps, 3) understand the transport of heavy metals from shrimps to silver catfish and 4) evaluate the potential human health risks associated with heavy metal exposure through the consumption of contaminated seafood.

2. Materials and methods

2.1. Description of the study area

The study was carried out in two island communities along the Escravos estuary (Fig. 1). Both communities are part of several clusters of islands making up the Gbaramatu Kingdom, an area dominated by the Ijaw ethnic group in Warri Southwest Local Government Area, Delta State, Nigeria. The estuary is a major route for commercial shipping and local transportation from coastal islands to several cities across the Niger Delta region. Several smaller rivers and tributaries of the Niger River drain into the estuary before emptying into the Gulf of Guinea section of the Atlantic Ocean. The main activities in the area include petroleum and gas production, petrochemical plant operation, barge operations for transporting industrial goods for oil and petrochemical servicing

operations, and subsistent and artisanal fishing using wooden canoes and speedboats with small and medium-size onboard engines. These economic activities release wastes into the estuary. Along the estuary, creeks and coastal islands, the vegetative cover is mainly mangrove. Mangroves serve as a protection from coastal flooding, and also a breeding ground for coastal organisms and migratory birds. They also provide vital ecosystem services like the provision of seafood and regulation of carbon in coastal ecosystems (Membere and Abdulwasiiu, 2020).

2.2. Samples collection

Sediment samples for the study were collected from Kurutie (5°34'43.497" N, 5°20'29.263" E) and Okerenkoko (5°37'10.452" N, 5°24'20.592" E) sections of the estuary in September 2023. Both locations were selected due to the increased human population compared to other islands along the estuary. At the sample site, triplicate sediment samples were collected from the shoreline during low tide using a sediment grab. The samples were collected into a clean bucket and mixed thoroughly to form a composite before they were wrapped in a sterile polyethene bag (zip locks). Samples of adult pink shrimp (*P. notialis*) and silver catfish (*C. nigrodigitatus*) with an average total length measuring 11–13 cm and 29–33 cm and weight of 127–129 g and 946–987 g respectively were purchased from the catches of artisanal fishers at the jetties of both island communities between 06:00 and 09:00 h on each visit. Pink shrimp and silver catfish were selected due to their relative abundance as some of the commonly consumed shell and finfish in the region. Samples of sediments and fishery products were labelled using permanent ink and kept in an ice box (Igloo cooler) before they were transported via speedboats to the laboratory for analysis. A total of 54 samples which consist of 18 sediment, 18 pink shrimp and 18 silver catfish (9 samples each from both location) were collected for the study.

2.3. Sample preparation and laboratory analysis

Sediment samples were air-dried for 2 days and were sieved using a 2 mm mesh sieve. For digestion, 0.2 g of sediment was weighed into a digestion tube and 5 ml of nitric acid (HNO₃) was added together with 2 ml of perchloric acid (HClO₄) and 5 ml of hydrochloric acid (HCl). The sample was heated in an oven for 1 h at 160 °C. After proper digestion,



Fig. 1. Map of study area showing sampling sites in red dots along the Escravos estuary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the sample was allowed to cool down and was filtered using a Whatman filter paper. The filtrate was transferred into a 50 ml flask and was reconstituted to a 25 ml mark with distilled water. Shrimp samples were defrosted, measured and weighed before cutting into bits. The cut samples were put into a beaker and were oven-dried to a constant weight at 160 °C for 24 h before grounded to powder. About 0.2 g of the sample was placed in a 50 ml digestion tube and 2.5 ml of H₂SO₄/selenium mixture was added and heated at 150 °C for 1 h. After cooling, 3 ml of H₂O₂ was added and heated at 130 °C for 2 h. The solution was filtered and reconstituted to 25 ml before analysis. Fish samples were defrosted, measured and weighed before dissection. Target tissues such as muscle, gills, gonads, liver and the rest of the fish were collected and dried in an oven at 160 °C for 24 h. The dried samples were ground into powder using an octagonal agnate mortar and pestle. Dried samples (0.2 g) of the fish were digested with concentrated sulphuric (H₂SO₄) and nitric acid (HNO₃) in a ratio of 3:1 and heated in a water bath at 160 °C and allowed to cool down. The samples were filtered and reconstituted into 25 ml before analysis. Sediments, shrimps and fish samples were analysed using an atomic absorption spectrophotometer (Perkin Elmer Corporation, United States).

2.4. Quality assurance and quality control

All reagents used for the extraction and analysis were analytical grades. Glassware and utensils were sterilised in the oven overnight after washing with distilled water and rinsed with 10 % HNO₃ before use. Certified reference materials for coastal sediments and biota samples were applied for the analysis as described in Ekperusi and Asiwa (2024). Analytical blanks and quality control samples were treated the same way as the samples, and concentrations were determined using standard solutions. Limit of detection (LOD) and quantitation (LOQ) were calculated using three and ten times the standard deviation of the blanks. The recovery rate for surrogates was in the range of 89–100 % for the analysed metals.

2.5. Data analysis

The data were analysed using Statistical Package for Social Science version 23 and Microsoft Excel 2016. Descriptive statistics such as mean and standard deviation were applied to summarise the data and mean comparison for both stations was done using one-way analysis of variance (ANOVA) at a 95 % confidence level. All the concentrations of heavy metals in sediments, shrimps and fish were reported in mg kg⁻¹.

2.6. Biota-sediment accumulation factor

The biota-sediment accumulation factor (BSAF) was determined by the ratio of metal concentration in biota (shrimp) over the concentration in the sediment.

$$BSAF = \frac{C_{biota}}{C_{sediment}}$$

where C_{biota} = concentration of heavy metals in shrimps and $C_{sediment}$ = concentration of metals in sediments from the estuary.

2.7. Trophic transfer factor

Trophic transfer factor (TTF) is a ratio that indicates how much a contaminant is transferred from one trophic level to the next. In this case, the movement of metals through the food chain from a lower trophic level to a higher one. Calculating trophic transfer involves understanding the concentration of the heavy metal at each trophic level and how it increases as it moves up the food chain. It is calculated as follows:

$$TTF = \frac{C_{HTL}}{C_{LTL}}$$

where C_{HTL} represents the concentration of metals at the higher trophic level, and C_{LTL} indicate the concentration of metals at the lower trophic level.

2.8. Health risk assessment

The potential health risk to human population through the consumption of contaminated shells and finfishes (pink shrimp and silver catfish) with heavy metals was assessed using the estimated daily intake (EDI) and hazard ratio (HR). EDI was calculated as follows;

$$EDI = CIR/BW$$

where EDI is the estimated daily ingestion rate in mg kg⁻¹ day⁻¹ of body weight, C is the amount of the contaminants in the seafood in mg kg⁻¹, IR is the seafood ingestion rate, which is equivalent to 0.00068 and 0.00762 (kg⁻¹ capital⁻¹ day⁻¹) for crustaceans and demersal fish from the Food Balance Sheet for Nigeria published by the Food and Agricultural Organisation (FAO, 2024) and BW is the average body weight for adult (60.7 kg) and children (30 kg) in West Africa (Goon et al., 2011; Walpole et al., 2012; Table S1). The HR estimates the risk level of exposure to pollutants from dietary intake and calculated thus:

$$HR = EDI/RfD$$

where HR is the hazard ratio, EDI is the estimated daily ingestion rate and RfD is the reference dose factors computed according to the USEPA (2019) values of 0.001, 0.003, 0.04 and 0.0035 for Cd, Cr, Cu and Pb respectively (See Table S2).

3. Results and discussion

3.1. Heavy metals concentration in sediment

The heavy metals (Cd, Cr, Cu and Pb) concentration in the sediment of both sites revealed differences in mean values with the levels of metals in Kurutie lower than the corresponding values in Okerenkoko (Table 1). However, the application of a one-way analysis of variance indicates no significant differences ($p > 0.05$) in the mean values of metals between both sites, except for Cd. The lack of a significant difference in the levels of heavy metals from both sites reflects similar activities peculiar to the study area and not the respective islands could be impacting the estuary. The values reported for metals in sediments were similar to those reported recently from the estuary (Ekperusi and Asiwa, 2024). Similar values were also reported for Cd, Cu and Pb from the Nun Estuary, Bayelsa State (Gijo and Alagoa, 2022), Buguma Creek, Rivers State (Ikeogu et al., 2023) and from Ologe Lagoon, Lagos State (Ndimele et al., 2011). Although lower (Kanu and Idowu, 2017; Ekelumu et al., 2019) and higher values (Ikeogu et al., 2023) have also been reported in the region as well. The values of heavy metals in sediments reported in our study (except for Cd) were lower than the target values for heavy metals in contaminated sediments for the petroleum industry in Nigeria (EGASPIN, 2018) and the sediment pollution regulations for coastal ecosystems in the United States (USEPA, 2007). Given the level of metals reported in sediments below permissible limits (aside from Cd), no immediate risk is warranted for organisms living at the bottom substrate or interacting with surface sediments in the estuary. However, there is a need for regular monitoring of contaminated sediments in the estuary as increase industrial activities could results in elevated levels of contaminants including metals entering the estuary in the long-term.

Table 1Heavy metals concentration (mean $\pm$ SE, range in bracket) in sediments collected from the Escravos estuary in September 2023 and permissible limits.

Metals	Present study		EGASPIN ^a	USEPA ^b		
	Kurutie	Okerenkoko	Target value	Not polluted	Moderately polluted	Heavily polluted
Cd	0.00	2.33	0.8	–	<6	>6
Cu	0.43	0.78	36	<25	25–50	>50
Cr	0.11	0.39	100	<25	25–75	>75
Pb	1.39	2.82	85	<40	40–60	>60

^a EGASPIN, 2018.^b USEPA, 2007

3.2. Heavy metals concentration in pink shrimp (*P. notialis*)

The variation in the heavy metal concentration in pink shrimp from the two sites is shown in Table 2. The mean values of heavy metals (0.17 ± 0.02 , 0.79 ± 0.0 , 11.24 ± 0.0 and 0.33 ± 0.0 mg kg⁻¹) reported in pink shrimp from Okerenkoko were higher than the values (0.12 ± 0.0 , 0.28 ± 0.0 , 5.16 ± 1.3 and 0.18 ± 0.0 mg kg⁻¹) in Kurutie for Cd, Cr, Cu and Pb respectively with significant differences reported for Cr ($P < 0.05$, F-value 186.28), Cu ($P < 0.05$, F-value 11.14) and Pb ($P < 0.05$, 24.68) between the two sites. The variability in heavy metals in shrimps from both sites is not unusual. Pink shrimps collected from both sites may have originated elsewhere within the estuary, thereby increasing their exposure to heavy metals. The concentration of heavy metals found in our study is similar to the values reported in *P. notialis* from Buguma Creek, Rivers State (Ikeogu et al., 2023), Itu Market, Akwa Ibom State (Oranusi et al., 2018) and in *P. semisulcatus* from the Persian Gulf (Pourang et al., 2005). In contrast, Ugegeh et al. (2022) reported higher values for Pb and Cd (3.08 and 0.26 mg kg⁻¹), but lower values for Cu and Cr (0.13 and 0.11 mg kg⁻¹) than our study for *P. monodon*, a close relative to *P. notialis* from the Lagos lagoon. Nkpaa et al. (2013) reported higher values for Cd (0.86 – 1.38 mg kg⁻¹), Cr (2.92 – 6.52 mg kg⁻¹) and Pb (6.91 – 30.6 mg kg⁻¹) in *P. notialis* from Ogoniland, Rivers State. The high values from Ogoniland are expected, considering the high level of crude oil pollution in the area from previous report (UNEP, 2011). Higher values were also reported for *P. monodon* in the Bay of Bengal, Bangladesh (Hossain and Khan, 2001), coastal areas in Ghana for *P. notialis* (Nyarko et al., 2023) and from the Gulf of Mexico for brown shrimp, *P. aztecus* (Castañeda-Chávez et al., 2022). In places with less oil operations, lower values have been reported compared to our study. The values reported in our study were higher than the values reported for the same species in Badagry Creek, Ologe and Lagos lagoons (Akintade et al., 2023) and from Eyo Beach, Cross River State (Ekpechi and Okori, 2022). Although a higher population in Lagos means increased anthropic inputs into the creeks and lagoons within the Lagos metropolis compared to Delta State, the increased petrochemical operations exposed to the Escravos estuary could be responsible for the elevated concentration of heavy metals in the tissues of pink shrimp compared to seafood from Lagos State.

As reported in our study, studies in Lagos lagoon also revealed significant differences in the mean concentrations of heavy metals across all stations (Akintade et al., 2023). The concentration of heavy metals present in seafood can vary based on size and the type of sediment they inhabit. The elevated level of Cu observed in shrimp in this study may be

Table 2Heavy metals concentration (mean $\pm$ SE in mg kg⁻¹ and range in brackets) in pink shrimp collected from the Escravos estuary in September 2023.

Metals	Kurutie	Okerenkoko	FMEnv	FAO/WHO
Cd	0.12	0.17	2	0.025 ^a
Cu	5.16	11.24	1–3	0.5 ^a
Cr	0.28	0.79	0.15	0.05
Pb	0.18	0.33	2	0.3 ^b

^a Cd and Cu - FAO/WHO, 2020.^b Pb - FAO/WHO, 2023(Codex).

connected to its role as an essential metal and could be more available for uptake compared to non-essential metals like Cd, Cr and Pb. The metal distribution in this study for pink shrimp was in the decreasing order of Cu > Cr > Pb > Cd. A similar order (Zn > Cu > Mn > Pb > Cr > Co > As > Ni > Cd) was reported for shrimps from Lagos lagoon (Akintade et al., 2023), Korle lagoon (Zn > Fe > Cu > Pb > Hg > Cd) in Ghana (Biney and Ameyibor, 1992), whereas, the reverse was the case for studies with *P. monodon* (Fe > Zn > Pb > Mn > Cd > Cu > Cr) from Lagos lagoon (Ugegeh et al., 2022) and for *P. monodon* and *P. notialis* (Zn > Cu > Cd > Pb > Cr), from the same region (Bello et al., 2017). The concentration of heavy metals observed in our study for pink shrimp were lower than the national allowable limits for Cd and Pb, but higher than the limits for Cu and Cr in seafood (FMEnv, 2003). Apart from Pb, the values of Cd, Cu and Cr were higher than the permissible limits for heavy metals in seafood by the Joint FAO/WHO Expert Committee on Food Additives (FAO/WHO, 2020) and the International Food Standards - Codex Alimentarius (FAO/WHO, 2023). The level of heavy metals above regulatory limits warrants caution given the likely increase in oil and gas operations and shipping activities within the Escravos oil processing zone and the potential impact on seafood from the estuary. Pink shrimp is consumed as a vital supplement in soup among coastal communities and in major cities across West Africa. Studies have shown variations in the maximum permissible limits for heavy metals in shrimps. Values below the limits were reported in shrimps from the Lagos lagoon (Akintade et al., 2023) and from lagoon and coastal areas in Ghana (Biney and Ameyibor, 1992; Nyarko et al., 2023), whereas others reported values above the permissible limits from Lagos Lagoon (Bello et al., 2017; Ugegeh et al., 2022) and in brown shrimp from the Gulf of Mexico (Castañeda-Chávez et al., 2022). The detection of concentrations within or above the permissible limits for metals like Cu, Cr and Cd, which do not have a biological function, represents a stress factor for shrimps (Castañeda-Chávez et al., 2022) and a potential human health risk for the consumption of shrimp from the estuary. There is a need for strict enforcement of laws and compliance with the release of effluents and wastewater into the estuary.

3.3. Heavy metals concentration in silver catfish (*C. nigrodigitatus*)

The variation in heavy metals concentration in the five tissues (muscle, gill, gonad, liver and rest of the fish) of silver catfish from the two study sites are shown in Fig. 2. Generally, the values for heavy metals reported in Okerenkoko were higher than those of Kurutie. In Kurutie, the concentration of heavy metals in the various tissues of silver catfish includes muscle (Cd 3.21 ± 2.5 , Cr 0.28 ± 0.2 , Cu 0.33 ± 0.1 and Pb 2.47 ± 0.7 mg kg⁻¹), gills (Cd 2.6 ± 0.6 , Cr 0.61 ± 0.1 , Cu 0.47 ± 0.2 and Pb 0.16 ± 0.1 mg kg⁻¹), gonads (Cd 2.39 ± 2.3 , Cr 0.41 ± 0.2 , Cu 0.29 ± 0.1 and Pb 0.67 ± 0.5 mg kg⁻¹), rest of the fish (Cd 3.78 ± 2.7 , Cr 0.52 ± 0.2 , Cu 0.45 ± 0.1 and Pb 2.61 ± 1.2 mg kg⁻¹), and liver (Cd 1.58 ± 0.8 , Cr 0.36 ± 0.2 , Cu 0.58 ± 0.2 and Pb 0.09 ± 0.0 mg kg⁻¹), whereas, in Okerenkoko it was muscle (Cd 3.25 ± 3.2 , Cr 7.30 ± 0.8 , Cu 0.25 ± 0.0 and Pb 0.42 ± 0.3 mg kg⁻¹), gills (Cd 3.30 ± 2.4 , Cr 6.1 ± 2.0 , Cu 0.17 ± 0.0 and Pb 5.53 ± 1.0 mg kg⁻¹), gonads (Cd 2.40 ± 2.3 , Cr 4.71 ± 4.4 , Pb 2.30 ± 2.2 and Cu 0.24 ± 0.0 mg kg⁻¹), rest of the fish (Cd 6.53 ± 2.4 , Cr 3.33 ± 1.7 , Cu 0.25 ± 0.0 and Pb 3.14 ± 3.1 mg kg⁻¹)

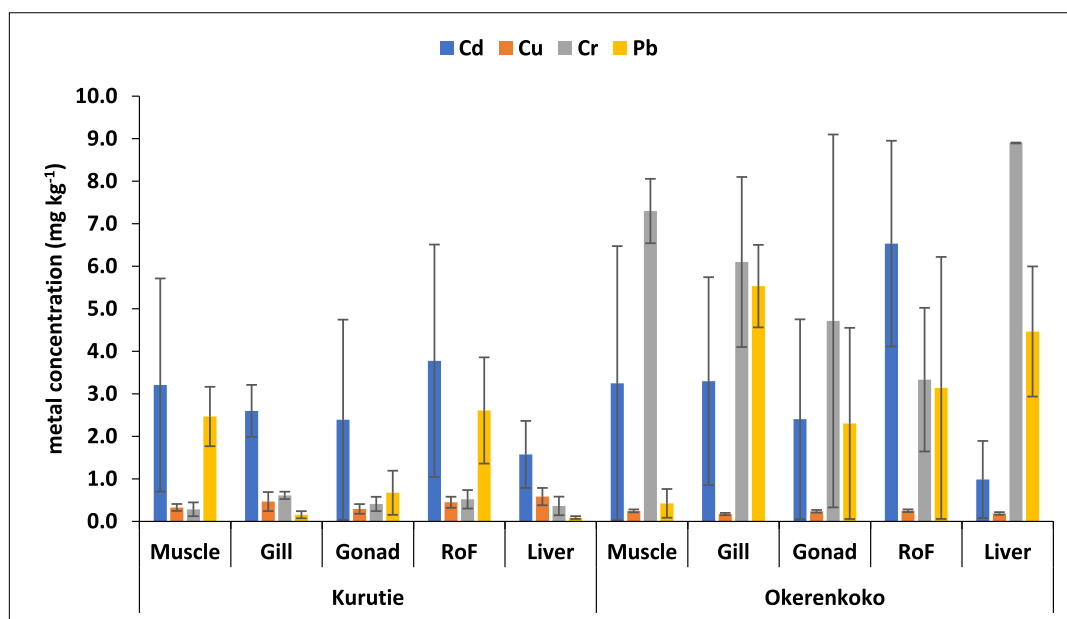


Fig. 2. Summary of heavy metals concentration (mean + SD) in tissues of silver catfish collected from the Escravos estuary in September 2023.

and liver (Cd 0.98 ± 0.9 , Cr 8.90 ± 0.0 , Cu 0.19 ± 0.0 and Pb $4.47 \pm 1.5 \text{ mg kg}^{-1}$) respectively (Table S4). Similar values comparable to our study were reported for heavy metals in the gills, muscles and liver of silver catfish from Epe, Lagos and Ologe lagoons (Kanu and Idowu, 2017; Abidemi-Iromini et al., 2022). Lower values were reported for heavy metals in the gills, muscle and liver of silver catfish from coastal areas in Lagos (Olubunmi et al., 2019; Aderinola et al., 2012; Bassey and Chukwu, 2019; Adetutu et al., 2023) and Brass estuary in Bayelsa State (Onu, 2024). Higher values were reported from Badagry Creek and Ologe Lagoon (Ndimele et al., 2011; Ajani and Balogun, 2015). The silver catfish has a geographical range within the Gulf of Guinea, spanning the coastline of the western and central regions of Africa. This range and feeding habit could influence the contrasting reports of heavy metals in the tissues of the silver catfish reported from various studies.

The metal distribution in the various tissues follows the decreasing order of RoF > gills > muscle > liver > gonads. The tissues in silver catfish accumulate metals with respect to metal interaction and bioavailability. The rest of the fish consists of the blood, head, bones and the visceral parts of the fish. Metals affinity and accumulation in these various tissues may be responsible for the cumulatively higher levels of metals in the rest of the fish compared to the other tissues in silver catfish. Olubunmi et al. (2019) reported that metals accumulated differently in the head, gill, intestine, trunk and tail of silver catfish from Badagry Creek, Lagos. Ajani and Balogun (2015) and Aderinola et al. (2012) also reported the highest concentrations of metals in the gills of silver catfish compared to other tissues from the same creek. In fish, the gill is one of the most vulnerable organs for metal accumulation due to its anatomical and physiological function (Ajani and Balogun, 2015). In contrast, Kanu and Idowu (2017) reported metal order for liver > gill > muscle in silver catfish samples from Epe and Ologe lagoons. For the respective metals in our study, the distribution in silver catfish was in the decreasing order of Cr > Cd > Pb > Cu. A similar pattern of heavy metals distribution was reported for the muscle (Cr > Cd > Pb > Cu), gills (Cr > Cd > Pb > Cu), gonad (Cr > Cd > Pb > Cu), liver (Cr > Cd > Pb > Cu) except for the RoF (Cd > Pb > Cr > Cu). Cr and Cd were relatively higher than Pb and Cu in the whole fish and the respective tissues except for the rest of the fish. The differences in the pattern of heavy metals distribution in the rest of the fish may be attributed to the various tissues making the rest of the fish, which does not provide a uniform tissue for analysis compared to the rest of the tissues assessed

for the study. Metal accumulation in fish tissues may depend on the fish species, habitat, feeding habit, organ, metabolic function and the reaction potentials of the metal concern (Griboff et al., 2017; Adetutu et al., 2023). Non-essential metals entering silver catfish via the gills, skin or ingestion can reach important organs in fish tissues (Akintade et al., 2023) predisposing fishes to stress and metal-induced impairment. The values for heavy metals in silver catfish from our study (Table S3) were higher than the national (FMEnv, 2003) and international recommended limits, except for Cu (FAO/WHO, 2020; FAO/WHO, 2023). The elevated levels of Cd, Cr and Pb in silver catfish could pose harm to humans since silver catfish is a common catch among artisanal fishers in the region. Therefore, state and federal regulators should ensure improve enforcement of regulations and strict compliance from industrial operations releasing effluents into the estuary. Also, there is a need for vigilance to ensure non-point sources of contaminants entering the estuary are identified and mitigated. Higher values above the recommended limits were also reported for Pb, Cd and Ni in silver catfish from Epe, Lagos and Ologe lagoons (Kanu and Idowu, 2017), whereas other studies of silver catfish collected from estuaries and creeks reported metal concentrations below or within the recommended limits (Ajani and Balogun, 2015; Olubunmi et al., 2019; Adetutu et al., 2023; Onu, 2024). A significant difference was reported with Cr ($p < 0.005$, F-value 5.525) in the tissues of silver catfish from both study sites, whereas, no significant difference was reported in the mean values of Pb and Cd in the liver, gills and muscle of silver catfish from Lagos and Ologe lagoon (Kanu and Idowu, 2017).

3.4. Biota-sediment accumulation factor for heavy metals

The BSAF is a critical parameter for assessing the uptake of contaminants from sediments to biota. A BSAF value <1 implies low or no accumulation of metals in biota from sediment, whereas a value >1 implies the accumulation of metals in the tissues of biota (Salam et al., 2020). In Kurutie, apart from Pb (0.1), the other metals had higher BSAF values above 1, which indicates an increase in bioaccumulation of metals, particularly for Cd (61.0), Cu (12.1) and Cr (2.4) from sediments to shrimps. In Okerenkoko, Cd (0.1) and Pb (0.1) had lower BSAF, while Cr (2.0) and Cu (14.3) had higher BSAFs (Table 3). The increased BSAF for Cd, Cr and Cu in the study, underscore the uptake and bioaccumulation of metals from sediments into shrimps and the potential

Table 3

Biota-sediment accumulation factor for heavy metals reported from the Escravos Estuary.

	Cd	Cr	Pb	Cu
Kurutie				
Shrimps	0.12	0.28	0.18	5.16
Sediments	0.00	0.11	1.39	0.43
BSAF	61.0	2.4	0.1	12.1
Okerenkoko				
Shrimps	0.17	0.79	0.33	11.24
Sediments	2.33	0.39	2.82	0.78
BSAF	0.1	2.0	0.1	14.3

transfer into higher trophic level. Cu and Cr had higher BSAF values in both sites compared to Cd which was only high in Kurutie. The increased BSAF for Cu compared to Cd for both sites could be due to its role as an essential metal needed for biological function compared to Cr and Cd which are non-essential metals with potential for stress in shrimps.

3.5. Trophic transfer factor of heavy metals in coastal food chain

The trophic transfer factor or biomagnification factor provides valuable insights into the possible transfer of heavy metals from a prey to a predator in aquatic ecosystems, shedding light on the potential transfer of metals from lower to higher trophic levels. A TTF value <1 indicates no trophic transfer which is usually desirable in ecological risk assessment, whereas a TTF value >1 indicates the increased transfer of metals from one trophic level to another along the food chain. In general, only Cr (2.65) in Kurutie, showed evidence of biomagnification and trophic transfer. All the other studied metals showed evidence of low or limited transfer from shrimp to silver catfish in both study sites (Table 4). The result suggests that the trophic transfer of heavy metals from shrimp to fish is influenced by the specific characteristics of each metal and the ecological dynamics prevailing between the prey and predator. The elevated metal levels reported in catfish may have come from their complex feeding habits (<https://www.fishbase.se/summary/2440>), geographical range or from the surrounding water as possible routes of entry into silver catfish. The findings underscore the complex dynamics of trophic transfer of heavy metals within aquatic ecosystems.

3.6. Risk assessment of heavy metals to human health from seafood

The potential risk of consuming contaminated seafood from the estuary to human health was evaluated relying on the EDI and the HR values for the studied metals. Calculated EDI values for seafood are usually compared against the tolerable or reference dose (RfD) for the metals concerned. The RfD represents an estimate of the daily exposure to which the human population may be continually exposed over a lifetime without considerable risk of effects. The risk becomes minimal if the ratio of EDI obtained is equal to or less than the RfD (USEPA, 2019). The HR value is an important indicator of potential health risks. An HR

Table 4

Trophic transfer factor of heavy metals from pink shrimp (*P. notialis*) to silver catfish (*C. nigrodigitatus*) from the Escravos Estuary.

	Cd	Cr	Pb	Cu
Kurutie				
Silver catfish	0.28	2.19	0.45	2.12
Shrimp	0.37	0.83	0.53	15.47
TTF	0.77	2.65	0.85	0.14
Okerenkoko				
Silver catfish	0.30	0.43	0.27	1.10
Shrimp	0.51	2.36	0.98	33.72
TTF	0.59	0.18	0.28	0.03

value of <1 indicates a low risk, while a value equal to or >1 means a high risk of contaminants to public health. The assessment considers adults and children comparing the calculated values with the RfD values for the studied metals.

For shrimps, the calculated EDI values for adults and children in both sites were below the RfD values for Cd, Cr, Pb and Cu. The HR values for both groups were <1 for both sites. The low EDI and HR values indicate no immediate health risk for adults and children consuming shrimp from the estuary. The values were in the order of Cr > Pb > Cu > Cd for Kurutie, while it was Pb > Cd > Cu > Cr for Okerenkoko (Table 5). Risk assessment was also evaluated for the muscle and whole fish from both sites. The EDI values for the muscle of silver catfish in Kurutie were within or lower than the RfD values for adults and children except for Cd in children, which was higher than the RfD values. In the whole fish from Kurutie, EDI values were within or below the RfD values. In the muscle and whole fish, the HR values were <1 for the heavy metals except for Cd in adults and children which was above 1. Bassey and Chukwu (2019) indicated that the hazard quotient for heavy metals was <1 for Ologe and Badagry lagoon for silver catfish. Adetutu et al. (2023) reported that the EDI of heavy metals in the tissues of silver catfish was low and the hazard values in the muscle of the fish was <1. In our study, the pattern for heavy metals was Cd > Pb > Cu > Cr for muscles of silver catfish and Cd > Pb > Cr > Cu for whole fish. A similar pattern of metal order was reported by Bassey and Chukwu (2019) for silver catfish from the Ologe and Badagry lagoons. However, in Okerenkoko, the EDI values for the muscles and the whole fish were higher than the RfD values, except for Cu in fish muscles for adults. The same trend was also seen in the HR values except for Cu in adults which was lower than 1. The heavy metals distribution follows the same trend for the muscle and the whole fish Cr > Cd > Pb > Cu. The result indicates that there is no immediate risk for islanders consuming silver catfish from the Kurutie section of the estuary. The reverse is the case for Okerenkoko where the consumption

Table 5

Result of the risk assessment for pink shrimp, muscle and whole fish for silver catfish collected from the Escravos estuary in September 2023.

Risk indicator	Categories	Cd	Cr	Pb	Cu
Pink shrimp	Kurutie				
	Adult	1.19E-06	2.69E-06	1.73E-06	1.56E-06
	Children	2.77E-06	6.26E-06	4.01E-06	3.63E-06
	HR	Adult 0.003978	0.002693	0.000575	3.9E-05
Pink shrimp	Okerenkoko				
	Adult	0.009243	0.006256	0.001337	9.07E-05
	Children				
	HR	Adult 0.000000	0.010000	0.000000	0.010000
Muscles	Kurutie				
	Adult	3.85E-06	1.78E-05	7.43E-06	2.81E-05
	Children	0.005527	0.007672	0.001067	0.000302
	HR	Adult 0.012842	0.017824	0.002478	0.000703
Muscles	Okerenkoko				
	Adult	0.000351	3.12E-05	0.00027	3.59E-05
	Children	0.000814^a	7.24E-05	0.000627	8.35E-05
	HR	Adult 1.168558	0.031158	0.089889	0.000898
Whole fish	Kurutie				
	Adult	2.71495	0.07239	0.208842	0.002087
	Children				
	HR	Adult 0.001481	0.000239	0.000656	0.000232
Muscles	Okerenkoko				
	Adult	0.003442	0.000556	0.001524	0.000538
	Children	4.937877	0.239423	0.218651	0.005794
	HR	Adult 11.47233	0.55626	0.508	0.013462
Muscles	Okerenkoko				
	Adult	0.355163	0.797968	0.046423	0.027109
	Children	0.825161	1.853946	0.107857	0.062984
	HR	Adult 1183.876	797.9681	15.47444	0.677728
Whole fish	Okerenkoko				
	Adult	2750.538	1853.946	35.95229	1.574588
	Children				
	HR	Adult 1.800594	3.318034	1.734999	0.120258
RfD values	Okerenkoko				
	Adult	4.18338	7.7089	4.03098	0.2794
	Children	6001.98	3318.034	578.3329	3.006456
	HR	Adult 13,944.6	7708.9	1343.66	6.985
RfD values	Okerenkoko				
	Adult	0.0003	0.001	0.003	0.04
	Children				
	HR				

^a The values in bold are higher than the RfD and HR values of 1.

of silver catfish poses an immediate health risk to consumers. The HR values for adults and children indicate substantial health risks, with the values for children considerably high, emphasizing the urgent need for regulatory measures and continuous monitoring to protect the health of the human population consuming seafood from the Okerenkoko section of the estuary. These contrasting results from both sites highlight the importance of considering the specific demographics and local conditions when assessing the potential health risks of consuming seafood from different sites within a study location. The implication for public health is that both locations may face some level of risk due to heavy metal exposure from increasing oil and gas operations. However, Okerenkoko has higher potential risks, particularly for Cd, Cr, and Pb. Cd has been linked to increased blood pressure and cardiac illness in fish (Singh et al., 2022). The accumulation of heavy metals in excessive amounts causes physiological effects including fin loss, gill underdevelopment, liver dysfunction, and fin malfunction in fingerlings (Nwabunike, 2016). Excess Cd can cause bone mineralization through bone damage or renal dysfunction (Chakraborty et al., 2013). The maturity of a fish from fry is restrained by the elevated presence of Pb (Johnson et al., 2007). The increasing levels of metals in the tissues of seafood may also be a contributing factor to fish stock decline in the estuary. In humans, acute exposure to Pb can cause loss of appetite, headache, hypertension, abdominal pain, renal dysfunction, fatigue, sleeplessness, arthritis, hallucinations and vertigo (Jaishankar et al., 2014). Chronic exposure to Pb can result in mental retardation, birth defects, psychosis, autism, allergies, dyslexia, weight loss, hyperactivity, paralysis and muscular weakness (Martin and Griswold, 2009). Cr exposure can result in oxidation-reduction derangement and abnormal enzymatic activity (Yüksel et al., 2021). Aside from inducing stress for biota, non-essential metals like Cd, Cr and Pb impair endocrine function and the blood circulatory system. They can also harm the liver, kidney and brain in humans (Griboff et al., 2017; Adetutu et al., 2023).

3.7. Comparison of heavy metals in sediments, shrimps and silver catfish from previous studies

Varying concentrations of heavy metals have been reported in sediments and seafood across coastal areas in Nigeria and elsewhere. Similar values comparable to our study were reported in sediments from estuaries and creeks in the Niger Delta region (Ndimele et al., 2011; Ngwoke et al., 2019; Okorondu et al., 2021; Gijo and Alagoa, 2022; Ikegu and Olumukoro, 2022; Ikeogu et al., 2023; Ekperusi and Asiwa, 2024) and in Thailand (Kobkeatthawin et al., 2021). Similar anthropic activities like petrochemical operations, shipping, speed boat transport and domestic activities prevalent across the region could be responsible for the similarities in metal distribution observed in sediments from creeks and estuaries in the region. Interestingly, lower values have also been reported in sediments from Nigeria (Kanu and Idowu, 2017; Ekelumu et al., 2019; Etuk et al., 2020; Membere and Abdulwasiiu, 2020; Numbere, 2020; Ewutanure et al., 2022; Chris and Anyanwu, 2023) and Peru (Custodio et al., 2022). The concentration of heavy metals found in our study is similar to the values reported for *P. notialis* and *P. monodon* from coastal areas in Nigeria (Bello et al., 2017; Oranusi et al., 2018; Ikeogu et al., 2023) and in *P. semisulcatus* from the Persian Gulf (Pourang et al., 2005). In contrast, higher values were reported for Penaeid shrimps in Nigeria (Nkpaa et al., 2013; Ugegeh et al., 2022; Chris and Anyanwu, 2023), Ghana (Nyarko et al., 2023), Bangladesh (Hossain and Khan, 2001), Gulf of Mexico (Castañeda-Chávez et al., 2022), Persian Gulf (Baboli and Velayatzadeh, 2013), and the Gulf of Mersin, Turkey (Ayas et al., 2016). The concentration of heavy metals in silver catfish reported in our study was similar to the values reported from lagoons in Lagos (Saliu et al., 2016; Kanu and Idowu, 2017; Abidemi-Iromini et al., 2022). However, lower (Aderinola et al., 2012; Akpanyung et al., 2014; Bassey and Chukwu, 2019; Olubunmi et al., 2019; Adetutu et al., 2023; Onu, 2024) and higher values (Ndimele et al., 2011; Ajani and Balogun, 2015) have been reported within the region as well. Although, surface water

sampling is essential for seafood assessment, which could be viewed as a limitation in this study, however, surface sediment is critical in understanding metal contaminants in coastal ecosystems and estuaries for benthic species like pink shrimp and silver catfish. Sediments serve as reservoirs for metal contamination and as a means of recontamination into the water column (Yüksel et al., 2024) so, benthic species foraging near surface sediment will have more interaction with sediment contaminants inputs compared to the water column. The contrasting reports from the levels of heavy metals in sediments and seafood in the region reinforces the need for vigilance and regular monitoring of coastal activities and seafood by state and federal regulators as increasing human population and industrial activities in coastal areas could pose more localised effects on the environment and human health.

4. Conclusion

This study investigated the levels of heavy metals in sediment, shrimps, silver catfish and their potential bioaccumulation, trophic transfer and the associated risk to human health. No significant difference was observed in the mean values of heavy metals in sediments, and the values of metals in sediments were below the regulatory limit, except for Cd. However, values in pink shrimp and silver catfish were above the allowable limits, except for Cu in seafood, with various tissues having disproportionately higher values, especially the rest of the fish, gills and muscle compared to the liver and gonads. The increased BSAF for Cd, Cr and Cu in the study, underscore the uptake of metals from sediments into shellfish, but limited evidence was observed for trophic transfer of metals between shrimps and catfish, except in Cr. Low EDI and HR values were reported for shrimps in adults and children from both study sites. In the muscle and whole fish from Kurutie, EDI and HR values were low and <1 for the heavy metals in adult and children except for Cd. The reverse is the case for Okerenkoko where the consumption of silver catfish poses an immediate and substantial health risks, with the values for children considerably high, emphasizing the urgent need for regulatory measures and continuous monitoring to protect the health of the coastal population within the subregion. Therefore, state and federal regulators should ensure improve enforcement of regulations and strict compliance from industrial operations releasing wastewater into the estuary. Also, there is a need for vigilance to ensure non-point sources of contaminants entering the estuary are identified and mitigated.

CRedit authorship contribution statement

Abraham O. Ekperusi: Writing – review & editing, Supervision, Software, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Amaka Michael:** Writing – review & editing, Project administration, Funding acquisition, Formal analysis. **Chidiogo H. Chukwurah:** Writing – review & editing, Writing – original draft, Methodology. **Naomi M. Sunday:** Writing – original draft, Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary data

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