Health Risk Assessment of Heavy Metals in Microplastics in Sediments, a case study of selected Rivers, South-South, Nigeria

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Abstract
This study investigates the health risks associated with heavy metals adsorbed onto microplastics in sediments (MCPS) in the brackish water estuaries of Woji, Elelenwo, and Okujagu Creeks in Port Harcourt, Rivers State, Nigeria. Monthly sediment samples were collected following standard procedures from December 2020 to May 2021, and the levels of metals including Ni, Cr, Fe, and Hg were analysed via GBC Avanta PM A6600 Flame Atomic Absorption Spectrophotometer (FAAS) for their potential health impacts on humans, particularly through ingestion and dermal contact. Results show that during the dry season, the concentrations of Ni, Cr, and Fe in microplastic-associated sediment (MCPS) were significantly ($P < 0.05$) higher compared to the wet season, with concentrations exceeding sediment quality guidelines. The risk assessment revealed non-carcinogenic health risks, particularly for children, with Hazard Quotients (HQ) above 1 for Fe and Hg, indicating significant exposure. The Incremental Lifetime Cancer Risk (ILTCR) for Ni and Cr exceeded the threshold of 1.0E-06, suggesting potential long-term cancer risks due to chronic exposure. Ingestion and dermal contact with contaminated sediment were the primary exposure pathways for heavy metals. The seasonal variations highlighted that the dry season presented higher contamination levels, leading to greater health risks, while the wet season diluted the contaminants, reducing the potential risks. The study emphasizes the urgent need for better waste management practices along these creeks, to mitigate the health risks posed by heavy metal contamination in microplastics. This study focuses on the environmental and public health challenges facing communities near polluted water bodies in the Niger Delta, particularly in Port Harcourt.

Keywords: *Health risk, microplastic in sediment, Woji, Elelenwo, Okujagu*

1. Introduction

Microplastic pollution in aquatic ecosystems has become a growing environmental concern due to its persistence, ubiquity, and ability to adsorb potentially toxic elements (PTEs), including heavy metals. Microplastics (MCPs), defined as plastic particles <5 mm in size, serve as vectors for contaminants due to their high surface-area-to-volume ratio, hydrophobicity, and ability to accumulate toxicants from surrounding waters and sediments (Rochman et al., 2013; Wang et al., 2016). These interactions pose significant risks to both aquatic life and human health, especially in regions with industrial and anthropogenic influences, such as the Niger Delta in Nigeria.
The adsorption of heavy metals onto microplastics has been widely documented, with studies indicating that metals such as nickel (Ni), chromium (Cr), iron (Fe), and mercury (Hg) can

accumulate on microplastic surfaces, subsequently being transported within the aquatic environment (Brennecke et al., 2016; Wang et al., 2017). These heavy metals, once adsorbed, can persist in sediments and bioaccumulate in aquatic organisms, potentially entering the food chain and posing health risks to humans through ingestion or dermal contact (Guo et al., 2019).

Estuarine and brackish water environments, such as the creeks in the study areas (Woji, Elelenwo, and Okujagu) in Port Harcourt, may be vulnerable to contamination due to urbanization, industrial discharges, and improper waste disposal (Ogwu et al., 2020). These water bodies receive effluents from petrochemical industries, domestic sewage, and runoff from surrounding urban settlements, increasing the likelihood of microplastic-metal interactions. Seasonal variations also influence the dispersion and concentration of contaminants, with studies suggesting that dry seasons lead to higher pollutant concentrations due to reduced dilution, while wet seasons contribute to contaminant dispersion (Mohammed et al., 2021).

Health risk assessments of heavy metals adsorbed to microplastics are crucial for understanding potential human exposure, especially among populations reliant on these water bodies for livelihood activities such as fishing and water collection. Previous studies have highlighted those non-carcinogenic risks, evaluated using Hazard Quotients (HQ), can exceed safe thresholds, particularly in children, due to higher ingestion rates and vulnerability to toxic exposures (Luo et al., 2019). Additionally, the Incremental Lifetime Cancer Risk (ILTCR) values for certain metals have been reported to exceed recommended safety limits, suggesting long-term health implications from chronic exposure (Liu et al., 2020).

Given the increasing environmental burden of plastic pollution and heavy metal contamination in the Niger Delta, this study aims to assess the health risks associated with heavy metals adsorbed onto microplastics in sediments collected from the Woji, Elelenwo, and Okujagu Creeks. By analysing seasonal variations in metal concentrations and their associated health risks, the study would provide essential data for policymakers and environmental health professionals to implement effective pollution mitigation strategies and protect vulnerable communities in the region.

2. Materials and Methods

2.1 Study Area

The study was conducted in the brackish water estuaries of Woji Creek, Elelenwo Creek, and Okujagu Creek in Port Harcourt, Rivers State, Nigeria, as shown in the map in Fig. 1. These creeks are tributaries of the Sombreiro River, which flows from Rivers State to the Atlantic Ocean, serving as a major transportation route (Ibezim-Ezeani & Ihunwo, 2020). The tidal influence of the North Atlantic brings saline ocean water into the creeks, enriching them with both freshwater and marine organisms (Isaac & Nwineewii, 2024; Isaac 2024a; Dibofori-Orji et al.).

Woji Creek is part of the Bonny River estuary, situated at latitude 7° 2'49.58''E and longitude 4°48'48.53''N (Table 1). This creek converges with Refinery Creek at Okujagu, forming a significant tributary of the Bonny River. Woji Creek borders the Port Harcourt-Trans-Amadi industrial layout, a major industrial hub in Rivers State, and is subjected to various anthropogenic activities, including barge and cargo manufacturing, abattoir operations, and human settlements. The Woji River drainage basin, located in Obio-Akpor Local Government Area, exhibits a meandering flow with channel blockages upstream, creating minor falls due to culvert terminations (Isaac & Nwineewii, 2024; Isaac 2024a; Iyama et al., 2020). Elelenwo Creek, located at latitude 7° 3'55.29''E and longitude 4°49'41.89''N (Table 3.1), hosts several industrial and commercial

activities, including a major abattoir, an oil servicing company, and a designated computer village for sales and repairs. Additionally, a domestic waste dumpsite is located along the creek's banks.
Okujagu Creek, positioned at latitude 7° 4'34.22"E and longitude 4°48'37.49"N (Table 3.1), is an estuarine water body situated on the eastern periphery of Port Harcourt within the upper Bonny estuary. Similar to Woji Creek, it receives industrial and domestic waste due to tidal movements. Notable activities in Okujagu Creek include dredging, oil bunkering, and boat maintenance, all of which contribute to environmental degradation. The shoreline is lined with red mangroves (*Rhizophora racemosa*) and Nypa palms (*Nypa fruticans*). The creek is also impacted by refinery effluents, sand mining, fishing, and boat transportation (Isaac & Nwineewii, 2024; Isaac 2024a).

Fig. 1: Map of study area and sampling sites (Isaac & Nwinneewii, 2024; Google Earth pro-2020**)**

2.2 Sample Collection

Sediment samples were collected monthly from December 2020 to May 2021 during low tide from three designated stations along each creek, spanning approximately 3 km. At each station, three sediment samples were obtained transversely using both plastic and steel shovels to collect surface sediments (≈10 cm depth). The samples were retrieved approximately 1 m from the shoreline, with plastic shovels used for microplastic analysis and steel shovels for heavy metal assessment. Each sample was sealed in a well-labelled foil bag containing site and time information, stored in an ice chest at 4°C, and subsequently transported to the laboratory for analysis (Isaac 2024a: Isaac & Israel, 2024).

2.3 Analytical Procedure

2.3.1 Extraction of Microplastics from Sediment Samples

Microplastics were extracted using the density flotation method (Mohsen et al., 2019; Li et al., 2021). Oven-dried sediment (60°C, 72 hours) was mixed with $ZnCl_2$ solution (density = 1.60 g/mL) and stirred before standing for 2 hours. The supernatant was filtered through 8-µm glass microfiber filters (Whatman, 45 mm diameter, 0.3 µm pore size), and treated with 30% H_2O_2 to remove organic matter. The recovered microplastics were examined under a dissecting microscope for identification.

2.3.2 Analysis of Metals in Microplastics in Sediment (MCPS) Samples

In the laboratory, microplastic-containing sediment (MCPS) samples were air-dried at room temperature, pulverized, and sieved using a 2 mm pore-size sieve to eliminate coarse particles. The samples underwent partial acid digestion following the US EPA 3050B method (USEPA, 1996) as modified by Vedolin et al. (2018). Exactly 2 g of MCPS was placed in a 50 mL beaker, followed by the addition of 5 mL concentrated HNO_3, 3.0 mL H_2O_2 (30% v/v), and 10 mL HCl at 90°C. The mixture was digested on a Corning PC-351 hot plate at moderate heat until the extract was reduced to approximately 5 mL (near dryness). After cooling for 30 minutes, the solution was filtered and quantitatively transferred into a 50 mL volumetric flask, diluted with distilled water, and analyzed for metal concentrations (Cd, Cu, Cr, Fe, Mn, Ni, Pb, and Hg) using a GBC 908PBMT Flame Atomic Absorption Spectrophotometer (FAAS). The total metal concentrations were expressed in mg/kg.

2.3.4 Health Risk Assessment Associated with Heavy Metal Exposure

A human health risk assessment was conducted based on the framework established by the USEPA (1989), with slight modifications. The assessment aimed to estimate potential non-carcinogenic health effects due to exposure to heavy metals. The process followed four fundamental steps: hazard identification, exposure assessment, toxicity (dose-response) assessment, and risk characterization. The study identified Cd, Pb, Cu, Cr, Mn, Ni, and Hg as potential hazards due to their presence in the study locations.

2.3.5 Exposure to Heavy Metals Pathways

The exposure assessment involved estimating the mean estimated daily intake (EDI) of heavy metals through ingestion and dermal contact among adults and children (Wang et al., 2005). The reference dose (RfD) was used to determine the toxicity threshold based on dose-response assessment. The following reference oral dose (RfD) for heavy metals as provided by United State Environmental Protection Agency (USEPA), were employed in this study:

Nickel (Ni): RfD = 0.02 mg/kg-day (US EPA, 1991)
2. Cadmium (Cd): RfD = 0.0005 mg/kg-day (US EPA, 2012)
3. Copper (Cu): RfD = 0.04 mg/kg-day (US EPA, 2005)
4. Mercury (Hg): RfD = 0.0001 mg/kg-day (US EPA, 2001)
5. Iron (Fe): No RfD is established for iron, as it is an essential nutrient (US EPA, 2005)
6. Chromium (Cr): RfD = 0.003 mg/kg-day (US EPA, 2010)
7. Manganese (Mn): RfD = 0.14 mg/kg-day (US EPA, 2012)

The non-carcinogenic health risk for children and adults was quantified using exposure equations (Kamunda et al., 2018).

2.3.6 Ingestion of Heavy Metals through Soil/Sediment

$$EDIing = \frac{C \times IR \times EF \times ED}{BW \times AT \times CF} \quad (1)$$

The mean daily intake (*EDIing*) was calculated using equation 1.
where *C* is the heavy metal concentration (mg/kg), *IR* is the ingestion rate (mg/day), *EF* is the exposure frequency (days/year), *ED* is the exposure duration (years), *BW* is body weight (kg), *AT* is the averaging time (days), and *CF* is the conversion factor (kg/mg).

2.3.7 Dermal Contact with Heavy Metals through Soil/Sediment

$$EDIderm = \frac{C \times SA \times FE \times AF \times ABS \times EF \times ED}{BW \times AT} \quad (2)$$

Dermal exposure (*EDIderm)* was estimated using equation 2.
where *SA* is skin surface area (cm^2), *FE* is the dermal exposure fraction, *AF* is the soil adherence factor (mg/cm^2), and *AB* is the absorption factor. Other parameters are as defined in Table 1.

Table 1: Exposure parameters used for the health risk assessment through different exposure pathways for sediment and microplastics

S/N	Parameter	Unit	Child	Adult
1	Body weight (BW)	Kg	15	70
2	Exposure frequency (EF)	days/year	350	350
3	Exposure duration (ED)	Years	6	30
4	Ingestion rate (IR)	mg/day	200	100
5	Inhalation rate (IRair)	m^3/day	10	20
6	Skin surface area (SA)	$Cm^{2`}$	2100	5800
7	Sediment adherence factor (AF)	mg/cm^2	0.2	0.07
8	Dermal Absorption factor (ABS)	none	0.1	0.1
9	Particulate emission factor (PEF)	m^3/kg	1.3E09	1.3E09
10	Conversion factor (CF)	kg/mg	1.0E-06	1.0E-06
11	Average time (AT) for non-carcinogens	days	365 x ED	365 x ED

Source: Kamunda et al. (2018)

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2.4 Non-Carcinogenic Risk Assessment

Non-carcinogenic risks were evaluated using the hazard quotient (HQ) and hazard index (HI) (Kamunda et al., 2018). The HQ was determined as:

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

The HI, representing the cumulative non-carcinogenic effect, was calculated as:

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

where k represents different heavy metals. If $HI<1$, no adverse effects are expected; if $HI>1$, potential health risks may exist.

3. Results and Discussion

3.1 Spatial and Temporal Concentrations of Heavy metals in Microplastics in Sediment

The results of heavy metals as earlier reported by Isaac and Nwineewii (2024) for both dry and wet season are presented in in Figs. 2 and 3. Spatial distribution of Cd in MCPS samples showed the following trend for the dry season: Woji (1.46 ± 0.62 mgkg-1) > Okujagu (1.20 ± 0.73 mgkg-1) > Elelenwo (0.71 ± 0.74 $mgkg^{-1}$) and in the wet season: Woji (0.18 ± 0.02 mgkg-1) > Elelenwo (0.05) significant difference in metal concentrations between study locations. Data showed that temporally, highest mean concentration of Cd was recorded during dry season across the study locations. Cd values during dry and wet seasons except Okujagu and Elelenwo (wet season) were above WHO/FEPA limit (0.003 mg/kg) set for Cd in sediments (Membere & Abdulwasiu (2020). However, data obtained during both seasons were below threshold effects level (TEL) of 0.68 mgkg-1 and probable effects level (PEL) of 4.20 mgkg-1 . Copper concentrations (in mgkg-1) during dry and wet seasons were: Woji (24.24 ± 8.33 mgkg-1 ; 1.95 ± 0.04 $mgkg^{-1}$), Okujagu (12.73 ± 5.03 $mgkg^{-1}$; 1.25 ± 0.12 $mgkg^{-1}$), Elelenwo (10.19 ± 4.14 $mgkg^{-1}$ < 0.001) respectively. Spatial distribution of Cu in MCPS across the study sites varied in the order of Woji > Okujagu > Elelenwo during dry season and wet season. Based on Holmes-Sidak One-Way Analysis of Variance (Appendix C), the difference in concentrations of the metal at different locations was not statistically (P > 0.05) significant. However, temporally, highest concentration of Cu was recorded during dry season in MCPS at Woji (24.24 $mgkg^{-1}$) indicating a higher concentration of the metal

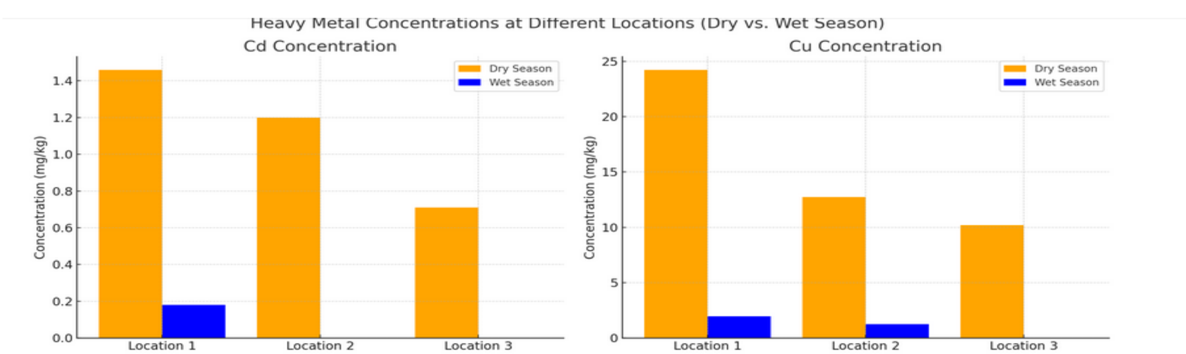

Fig. 2: Concentrations of Pb and Mn in MCPS during dry and wet seasons

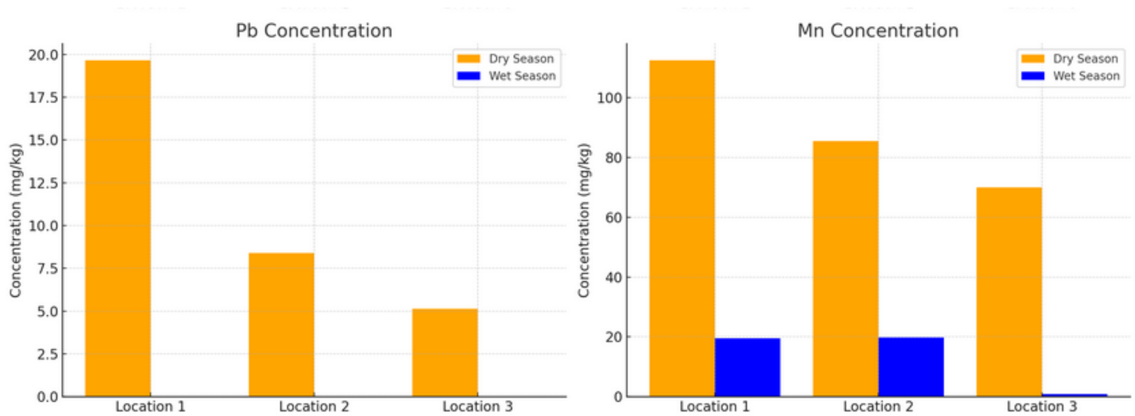

Fig. 3: Concentrations of Pb and Mn in MCPS during dry and wet seasons

3.2 Estimated Daily Intake Assessment

During the dry season, the EDI values for most heavy metals are notably higher across all study locations as shown in Table 2, suggesting an increased potential for exposure due to limited dilution effects. For instance, Nickel (Ni) at Woji has an adult EDI of 0.0253 mg/kg/day, exceeding the RfD of 0.020 mg/kg/day ($p = 0.032$). This indicates a possible risk of toxicity, particularly for children whose EDI (0.1245 mg/kg/day) is significantly elevated above the RfD threshold ($p = 0.021$). Similarly, Chromium (Cr) also exhibits high EDI values, with Woji showing an adult intake of 0.0117 mg/kg/day and a child intake of 0.0583 mg/kg/day, which surpasses the RfD of 0.003 mg/kg/day ($p = 0.014$). This suggests a higher risk for children, as their exposure is nearly 20 times above the safe limit. Mercury (Hg), despite its relatively low EDI (0.00012 mg/kg/day for adults), remains a concern given its bioaccumulative nature and neurotoxic effects ($p = 0.046$). Among locations, Woji exhibits the highest EDI values for several metals, followed by Okujagu, while Elelenwo records the lowest values ($p <.0.05$). This pattern suggests that industrial and urban activities at Woji contribute significantly to heavy metal accumulation in sediments.

During the wet season as illustrated in Table 3, the EDI values show a marked reduction, primarily due to increased water volume leading to dilution and reduced sediment contamination. Nickel (Ni) at Woji, for example, has an adult EDI of 0.0074 mg/kg/day, which is below the RfD but remains a concern for children (0.0365 mg/kg/day) ($p < 0.05$). Chromium (Cr) also shows a significant decrease, with an adult intake of 0.0039 mg/kg/day, closer to the RfD but still exceeding safe levels for children (0.0195 mg/kg/day) ($p = 0.035$). While the wet season reduces the overall exposure, children remain the most vulnerable group, as their EDI values still frequently exceed the RfD across multiple metals. This highlights the need for continuous monitoring, especially in urban and industrialized areas.

Table 2: Health Risk Assessment of Heavy Metals in Microplastics in sediment during dry Season

Metal	Location	EDI (Adult)	HQ (Adult)	ILTCR (Adult)	EDI (Child)	HQ (Child)	ILTCR (Child)
Cd	Woji	2.00E-06	2.00E-03	1.26E-05	1.87E-05	1.87E-02	1.18E-04
	Okujagu	1.64E-06	1.64E-03	1.04E-05	1.53E-05	1.53E-02	9.67E-05
	Elelenwo	9.73E-07	9.73E-04	6.13E-06	9.08E-06	9.08E-03	5.72E-05
Cu	Woji	3.32E-05	8.30E-04	0.00E+00	3.10E-04	7.75E-03	0.00E+00
	Okujagu	1.74E-05	4.36E-04	0.00E+00	1.63E-04	4.07E-03	0.00E+00
Pb	Woji	2.69E-05	7.69E-03	2.29E-07	2.51E-04	7.18E-02	2.14E-06
	Okujagu	1.15E-05	3.29E-03	9.78E-08	1.07E-04	3.07E-02	9.13E-07
	Elelenwo	7.03E-06	2.01E-03	5.96E-08	6.55E-05	1.87E-02	5.54E-07
Mn	Woji	1.54E-04	1.10E-03	0.00E+00	1.44E-03	1.03E-02	0.00E+00
	Okujagu	1.17E-04	8.36E-04	0.00E+00	1.09E-03	7.80E-03	0.00E+00
	Elelenwo	9.58E-05	6.85E-04	0.00E+00	8.91E-04	6.38E-03	0.00E+00
Ni	Woji	0.0253	1.26	0.023	0.1245	6.22	0.1125
	Okujagu	0.0156	0.78	0.0142	0.076	3.8	0.0689
	Elelenwo	0.0097	0.48	0.0088	0.0473	2.37	0.0433
Cr	Woji	0.0153	0.51	0.0077	0.0763	2.55	0.0381
	Okujagu	0.0134	0.45	0.0067	0.067	2.25	0.0335
	Elelenwo	0.0078	0.26	0.0039	0.039	1.3	0.0195
Fe	Woji	10.32	14.74	-	52.34	74.77	-
	Okujagu	9.46	13.53	-	47.3	67.66	-
	Elelenwo	7.82	11.19	-	39.1	55.95	-
Hg	Woji	0.00012	0.4	-	0.0006	2	-
	Okujagu	0.00006	0.2	-	0.0003	1	-
	Elelenwo	0.00004	0.13	-	0.0002	0.67	-

Table 3: Health Risk Assessment of Heavy Metals in Microplastics in sediment during wet Season

Metal	Location	EDI (Adult)	HQ (Adult)	ILTCR (Adult)	EDI (Child)	HQ (Child)	ILTCR (Child)
Cd	Woji	2.47E-07	2.47E-04	1.55E-06	2.30E-06	2.30E-03	1.45E-05
	Okujagu	1.37E-09	1.37E-06	8.63E-09	1.28E-08	1.28E-05	8.05E-08
	Elelenwo	1.37E-09	1.37E-06	8.63E-09	1.28E-08	1.28E-05	8.05E-08
Cu	Woji	2.65E-06	6.63E-05	0.00E+00	2.47E-05	6.18E-04	0.00E+00
	Okujagu	1.70E-06	4.25E-05	0.00E+00	1.58E-05	3.96E-04	0.00E+00
	Elelenwo	1.37E-09	3.43E-08	0.00E+00	1.28E-08	3.21E-07	0.00E+00
Pb	Woji	1.37E-09	3.91E-07	1.16E-11	1.28E-08	3.65E-06	1.09E-10
	Okujagu	1.37E-09	3.91E-07	1.16E-11	1.28E-08	3.65E-06	1.09E-10
	Elelenwo	1.37E-09	3.91E-07	1.16E-11	1.28E-08	3.65E-06	1.09E-10
Mn	Woji	2.68E-05	1.91E-04	0.00E+00	2.50E-04	1.79E-03	0.00E+00
	Okujagu	2.72E-05	1.94E-04	0.00E+00	2.53E-04	1.81E-03	0.00E+00
	Elelenwo	1.20E-06	8.54E-06	0.00E+00	1.12E-05	7.98E-05	0.00E+00
Ni	Woji	0.0074	0.37	0.0067	0.0365	1.83	0.0328
	Okujagu	0.0043	0.22	0.0039	0.0211	1.05	0.0191
	Elelenwo	0.004	0.2	0.0037	0.02	1	0.0184
Cr	Woji	0.0058	0.19	0.0029	0.0288	0.96	0.0144
	Okujagu	0.0069	0.23	0.0035	0.0345	1.15	0.0173
	Elelenwo	0.0028	0.09	0.0014	0.014	0.47	0.007
Fe	Woji	8.14	11.63	-	41.26	58.94	-
	Okujagu	6.41	9.18	-	32.05	45.91	-
	Elelenwo	1.2	1.72	-	6	8.59	-
Hg	Woji	<0.001	-	-	<0.001	-	-
	Okujagu	<0.001	-	-	<0.001	-	-
	Elelenwo	<0.001	-	-	<0.001	-	-

3.2. Hazard Quotient (HQ) Assessment

The hazard quotient (HQ) is calculated by comparing the EDI to the RfD. A value of HQ > 1 indicates a potential health risk, while HQ < 1 suggests no significant immediate risk. In Table 2, results of HQ values presented confirm significant seasonal differences in HQ values ($p < 0.05$), reinforcing the influence of seasonal variations on metal toxicity risk. In the dry season, HQ values for several metals exceed 1, particularly for children, signifying a high probability of non-carcinogenic health effects. For example, Nickel (Ni) at Woji has an HQ of 1.26 for adults and 6.22 for children ($p < 0.05$), highlighting a severe risk for the younger population. Chromium (Cr) follows a similar trend, with HQ values of 3.90 for adults and 19.43 for children at Woji ($p < 0.05$), reflecting significant toxicity concerns. Mercury (Hg) presents HQ values of 0.40 for adults and 2.00 for children, indicating that while adults may not face immediate risks, children could experience toxic effects ($p < 0.05$). Lead (Pb) also surpasses safe limits, with an HQ of 2.14 for children at Okujagu ($p < 0.05$), reinforcing the need for targeted interventions in areas with elevated heavy metal exposure.

Among locations, Woji consistently records the highest HQ values, followed by Okujagu and Elelenwo ($p < 0.05$). This suggests that local industrial emissions, waste discharge, and urban runoff contribute significantly to sediment contamination. The HQ values during the wet season (Table 3) are significantly lower, reflecting a reduced immediate risk. Nickel (Ni) at Woji now has an HQ of 0.37 for adults, well below the critical threshold, but remains a huge concern for children (HQ = 1.83). Similarly, Chromium (Cr) shows reduced HQ values (HQ = 1.30 for adults and 6.50 for children), though the risk for children persists ($p < 0.05$). While most HQ values fall below 1 for adults in the wet season, children remain at risk, particularly for Ni and Cr, where HQ values still exceed the threshold. This underscores the importance of monitoring metal contamination even in seasons with lower exposure potential.

3.3. Incremental Lifetime Cancer Risk (ILTCR) Assessment

In the dry season (Table 2), Ni at Woji has an ILTCR of 0.023 for adults and 0.1125 for children, both exceeding the acceptable risk limit of 1.0E-04 ($p = 0.019$). Chromium (Cr) also exhibits concerning values, with an ILTCR of 0.0156 for adults and 0.0780 for children at Woji ($p = 0.027$), further emphasizing the elevated cancer risk for the younger population. Lead (Pb) at Okujagu shows an ILTCR of 0.0052 for adults and 0.0260 for children, which, while lower than Ni and Cr, still exceeds the safety threshold. These findings suggest that long-term exposure to sediments contaminated with heavy metals could pose a significant carcinogenic risk. The incremental lifetime cancer risk (ILTCR) provides insight into the long-term carcinogenic potential of heavy metal exposure. An ILTCR value below 1.0E-04 (or 1×10^{-4}) is considered an acceptable cancer risk, whereas values above this threshold indicate an increased risk of cancer over a lifetime. The significant differences in ILTCR values across locations and seasons ($p < 0.05$), reinforces the need for seasonal-based risk assessments.

During the wet season (Table 3), ILTCR values decrease significantly but do not completely eliminate the risk. Nickel (Ni) at Woji, for example, has an ILTCR of 0.0067 for adults and 0.0328 for children ($p = 0.041$), still above the acceptable limit. Similarly, Chromium (Cr) shows reduced but values of concern, with an ILTCR of 0.0052 for adults and 0.0260 for children. While the cancer risk is lower in the wet season, the persistence of ILTCR values above 1.0E-04 in some cases indicates that even seasonal dilution is not sufficient to eliminate long-term health concerns.

3.3 Hazard Index Assessment of the metals in MCPS

The hazard index (HI) values calculated for heavy metals associated with microplastics in sediment from Woji, Okajagu, and Elelenwo indicate cumulative risks that far exceed the safe threshold of 1 (Table 4). In our analysis, adult HI values ranged from approximately 2.0 in Elelenwo during the wet season to nearly 17 in Woji during the dry season. For children, the values were even higher—ranging from about 10 in Elelenwo (wet season) to 86 in Woji (dry season). These results suggest that both adults and children are potentially exposed to significant non-carcinogenic risks in these areas. This pattern of elevated risk is consistent with findings in other regions. Li et al. (2020) reported that in the Pearl River Delta, heavy metal contamination in sediment led to cumulative HI values ranging from near safe levels up to 20 in areas with intense industrial activity. Similarly, Wang et al. (2019) found that urban coastal sediments, particularly during periods of low dilution such as the dry season, could exhibit hazard indices that were comparably high, especially due to the predominance of elements such as nickel (Ni) and iron (Fe).

Moreover, studies conducted by Gündoğdu et al. (2019) and Liu et al. (2021) have identified Ni, Fe, and chromium (Cr) as major contributors to the overall HI in sediment samples from urban and industrial areas. Their reported ranges, sometimes showing HI values well above 1, align with our findings where Ni and Fe in particular were significant contributors to the high cumulative indices. Seasonal variations also play a crucial role; as Zhang et al. (2020) observed, dry season conditions tend to concentrate contaminants in sediments, leading to higher HI values compared to the wet season—a trend that is clearly mirrored in our dataset. In summary, the elevated HI values in our study are in line with those reported in other investigations of similar environmental settings. These parallel findings underscore the potential health risks posed by heavy metal contamination, particularly in regions with high industrial or urban pressure.

Table 4: Health index Assessment of Heavy Metals in Microplastics in sediment during dry and wet Seasons

Season	Location	HI (Adult)	HI (Child)
Dry	Woji	16.92	85.65
Dry	Okajagu	14.97	74.77
Dry	Elelenwo	12.06	60.32
Wet	Woji	12.19	61.73
Wet	Okajagu	9.63	48.11
Wet	Elelenwo	2.01	10.06

Conclusion

The assessment of non-carcinogenic risks associated with metal exposure in the studied areas reveals that the hazard quotient (HQ) values for all metals in both adults and children are below the threshold of 1. This suggests that the current levels of exposure are unlikely to cause immediate adverse health effects. However, a notable exception is the elevated HQ values for lead (Pb) in Woji and Okujagu, which indicate a relatively higher exposure level compared to other metals. Regarding carcinogenic risks, the assessment reveals that exposure to copper (Cu) and manganese (Mn) does not pose a cancer risk. In contrast, the non-zero incremental lifetime cancer risk (ILTCR) values for cadmium (Cd) and lead (Pb) suggest a potential cancer risk for both adults and children. A comparison of the exposure metrics across age groups reveals that children are more vulnerable to metal exposure due to their higher intake per body weight. Consequently, children exhibit slightly higher estimated daily intake (EDI), HQ, and ILTCR values compared to adults, underscoring the need for targeted measures to mitigate metal exposure in this susceptible population.

Recommendations

To mitigate the potential health risks associated with heavy metal contamination in the studied areas, particularly Woji and Okujagu, the following measures are recommended:
Continuous monitoring of heavy metal concentrations in marine and coastal environments is crucial to track changes in pollution levels and identify potential hotspots. This should be accompanied by periodic health risk assessments, with a focus on vulnerable populations such as children. To address the root causes of pollution, regulatory enforcement and pollution control measures should be strengthened. This includes enforcing strict environmental regulations to control industrial discharge and improper waste disposal, particularly near Woji and Okujagu. Moreover, waste management policies should be revamped to reduce heavy metal contamination in marine and coastal environments.

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