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HEALTH RISK ASSESSMENT OF HEAVY METALS IN MICROPLASTICS FROM SURFACE WATERS IN OTUOKE, NIGER DELTA

Okonkwo Chinedu Sylvester

Department of Chemistry, Federal University Otuoke
Bayelsa State, Nigeria
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Abstract: Microplastics serve as vectors for heavy metals in aquatic environments, posing potential ecological and human health risks. This study assessed the concentrations of cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and mercury (Hg) adsorbed onto microplastics in surface water (MCPWs) from the Otuoke River, South-South Nigeria, during dry and wet seasons. Samples were digested using the US EPA 3050B method and analyzed via Flame Atomic Absorption Spectrophotometry (FAAS). The ecological and human health risks were evaluated through hazard quotient (HQ) and hazard index (HI) assessments. Results showed seasonal variations in metal concentrations, with significantly higher values recorded during the dry season ($p < 0.05$). The highest Cu (41.06 ± 6.67 mg/kg) and Mn (133.22 ± 2.71 mg/kg) levels were detected at STA- , while Fe concentrations peaked at STA-3 (13,932.68 ± 489.70 mg/kg). HI values for children were notably higher than those for adults, indicating greater susceptibility. Dry season HI values suggested potential health risks for adults (HI > 1) and significant health risks for children (HI > 10). Wet season assessments showed reduced metal bioavailability, with no significant risks for adults at certain locations (HI < 1), though children remained at potential risk. The study underscores the urgent need for mitigation strategies to curb heavy metal contamination in MPs and reduce public health threats. These findings contribute to understanding MPs as contaminant carriers and highlight the necessity for stricter environmental regulations and public awareness campaigns.

Keywords: microplastics, heavy metals, health risk assessment, Otuoke River, seasonal variation, environmental pollution.

1. Introduction

Microplastics (MPs) have emerged as pervasive pollutants in aquatic ecosystems, capable of adsorbing and transporting toxic heavy metals, thereby exacerbating environmental and public health concerns (Wang et al., 2019; Holmes et al., 2014). These synthetic polymer fragments, typically <5 mm in size, originate from industrial discharges, municipal wastewater, and degraded plastic waste (Li et al., 2020). The hydrophobic nature of MPs facilitates the adsorption of heavy metals such as cadmium (Cd), copper (Cu), chromium (Cr), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and mercury (Hg), increasing their persistence and bioavailability in aquatic systems (Koelmans et al., 2016; Prata et al., 2020). The adsorption of these metals onto MPs raises significant concerns regarding their transport, bioaccumulation, and potential adverse health effects on aquatic organisms and human

populations. Several studies have reported the interactions between MPs and heavy metals in freshwater and marine environments. Brennecke et al. (2016)
found that MPs in estuarine systems effectively sorb metals, leading to potential trophic transfer. Similarly, Turner and Holmes (2015) observed elevated levels of Pb and Cu adsorbed onto polyethylene and polypropylene MPs in coastal sediments. In Nigerian water bodies, MPs contamination and metal adsorption have been documented, indicating significant ecological risks (Okafor-Yarwood et al., 2021; Olukunle et al., 2022). However, there remains a gap in regionspecific data on the health risks associated with metal-contaminated MPs in surface waters, particularly in South-South Nigeria. Otuoke River, a vital freshwater resource for drinking, fishing, and agriculture, is increasingly threatened by anthropogenic activities, including plastic pollution and industrial discharge. The potential long-term exposure of local communities, particularly vulnerable groups such as children, to MPs bound with toxic heavy metals is a significant health concern (Tomasz et al., 2021). Despite global efforts to assess MPs as vectors of heavy metals, studies focusing on Nigerian water bodies are limited, necessitating localized assessments to inform targeted mitigation strategies. Thus, this study aims to evaluate the health and safety risks associated with heavy metals adsorbed onto MPs in the surface waters of the Otuoke River, SouthSouth Nigeria.

2. MATERIALS AND METHODS

2.1 Study Area

The study area is located in the brackish water estuary of STA-1 Creek, STA-3 Creek and STA-2
Creek as shown in Fig. 3.1. The creeks are located in the city of Port Harcourt, Rivers State, Nigeria. The creek is one of the tributaries of the Sombreiro River traversing the north down to the south of Rivers State into the North Atlantic, a well-defined route of transportation (Ibezimezeani & Ihunwo, 2020). The tidal influence of the North Atlantic upstream is responsible for the saline ocean water brought into the creek thus enriching the creeks with both freshwater and salt water organisms (Dibofori-Orji et al., 2019; Ibezim-Ezeani & Ihunwo, 2020). STA-1 creek lies along the Bonny River estuary at latitude 7° 2'49.58''E, and longitude 4°48'48.53''N (Table 3.1). The STA-1 Creek has a confluence with the refinery creek at STA-2 to form the main tributary which drains into the Bonny River. The creek has border with the Port Harcourt-Trans-Amadi industrial layout, the industrial hob of Rivers State. There are several anthropogenic activities such as barge and cargo manufacturing, a major abattoir as well as human settlements along the river. The STA-1 River drainage basin is located at the heart of Obio-Akpor Local Government Areas in Port Harcourt. The STA-1 River has a meandering flow amid channel blockages upstream as culvert ending creates a fall in the channel (Anya et al., 2017; Iyama et al., 2020). STA-3 creek is on latitude 7° 3'55.29''E, and longitude 4°49'41.89''N (Table 3.1). The major industrial activities taking place in STA-3 study area comprise a major abattoir that serves the state, oil servicing company and a computer village designated for sales and repairs of computers. A domestic waste dump site is also noticed at the bank of the Creek.
STA-2 creek is on latitude 7° 4'34.22''E, and longitude 4°48'37.49''N (Table 3.1). This study site is an estuarine creek located on the eastern fringes of Port Harcourt city in the upper Bonny estuary of the Niger Delta, Nigeria. STA-2 river just like STA-1 creek, receives almost equivalent industrial and domestic wastes consequent upon alternate low and high tides experienced by both creeks by virtue of their locations. There is also obvious dredging, oil bunkering, boat maintenance activities with deblitating effect of anthropogenic activities on-going within the upper Bonny estuary of the Niger Delta compared to the adjacent creeks. Red mangroves (Rhizophora racemose)

and Nypa palms (Nypa fructican) line the shores. Apart from the refinery effluents received from refining activities at STA-2, the most prevalent activities include sand moving, fishing and boat ferrying are the major activities in the study area.

2.2 Field Sampling

Samples were collected monthly from December 2020 to May, 2021 and during low tide event at three stations at approximately 3 km stretch from each creek. Three sediment samples were collected transversely from each station along the creeks using two sets of shovels (plastic and steel), to collect the top layer soft sediment (≈10 cm in depth). The samples were taken approximately 1m from the shore at each station with a steel and a plastic shovel, each marked differently to differentiate sediments sampled for microplastics and metals respectively. Samples were put into well-labelled foil bags (indicating sampling point information and time of sampling) and placed into ice chest coolers at 4 ^{0}C and transferred to the laboratory.

2.3 Heavy Metal Analysis in MCPW Samples

Digestion of samples of microplastics in water (MCPW) were carried out following the methods of Mokhtari et al (2018), Isaac and Israel (2024). Samples were air-dried in the laboratory at room temperature, pulverized and then sieved through a 2 mm pore size sieve to remove coarse particles. Partial acid digest was adopted following the method US EPA 3050B (USEPA, 1996) and described by Vedolin et al, 2018. Exactly 2g MCPW was put in a 50 mL beaker and then 5 mL of concentrated HNO_3, 3.0 mL of H_2O_2 (30 % V/V) and 10 mL of HCl were added at 90 °C. Samples were digested on a Corning PC-351 model hot plate at medium to low heat until about 5 ml concentrated extract was left (or with sample concentrate tending towards near-dryness). Afterwards, the content of beaker was left to cool for around 30 minutes. Sample solution was filtered and quantitatively transferred into 50 ml standard volumetric flask. Finally, filtered solutions were made up to the 50 ml graduation mark using distilled water. Thereafter, metals (Cd, Cu, Cr, Fe, Mn, Ni, Pb and Hg) levels were determined using the GBC 908PBMT model Flame Atomic Absorption Spectrophotometer (FAAS). Each sample was individually aspirated. The total metal concentrations are reported in units of mg/kg.

2.4 Health Risk Assessment Associated with Heavy Metal Exposure

The health risk assessment was conducted following the methodology of USEPA (1989), Isaac (2024a), and Isaac and Israel (2024b) to estimate the potential health impacts of heavy metal exposure. The assessment followed four key steps: hazard identification, exposure assessment, dose-response assessment, and risk characterization. Identified heavy metals (Cd, Pb, Cu, Cr, Mn, Ni, and Hg) were evaluated based on their concentrations and spatial distribution.

Exposure assessment focused on the estimated daily intake (EDI) of heavy metals via ingestion and dermal contact, considering variations between adults and children due to physiological and behavioral differences (Wang et al., 2005). The toxicity of the metals was estimated using doseresponse assessments, incorporating reference dose (RfD) values to determine non-carcinogenic risks. RfD values were derived using the "No Observable Effect Level" (NOEL) principle, with a 10-fold uncertainty factor applied for human safety.

Risk characterization integrated exposure and toxicity data to quantify health risks. The hazard quotient (HQ) was calculated to assess non-cancer risks, while the hazard index (HI) was used to determine cumulative exposure effects. HI values greater than 1 indicated potential health concerns, particularly for children who exhibited higher susceptibility to metal toxicity. EDI (mg/kg-day) for different exposure pathways was calculated using equations adapted from Kamunda et al. (2018).

2.4.1 Exposure to Heavy Metals Pathways

In the study, exposure assessment was carried out by measuring the estimated daily intake (EDI) of heavy metals earlier identified through ingestion and dermal contact by adults and children from the study sites. Adults and children were separated because of their behavioural and physiological differences according to Wang et al, (2005). The toxicity due to exposure levels of the heavy metals were estimated via Dose-response assessment methods. The reference dose (RfD), a noncarcinogenic threshold, is an important toxicity index used. RfD values are derived from animal studies using the "No observable effect level" principle. For humans, RfD values are multiplied 10-fold to account for uncertainties. Risk characterization to predict non-cancerous health risk of children and adults in the study area was carried out by integrating all the information gathered to arrive at quantitative estimates of cancer risk and hazard indices. The potential exposure pathways for heavy metals in contaminated sediment matrix were calculated. EDI (mg/kg-day) for the different pathways were calculated using Equations 1 & 2 as described by Kamunda et al. (2018).

2.4.1.1. Ingestion of Heavy Metals through Soil/Sediment

$$EDIing = \frac{CxIRxEFxEDxCF}{BWxAT} \quad \textbf{(1)}$$

where DI_{ing} is the mean daily intake of heavy metals ingested from soil in mg/kg-day, C = concentration of heavy metal in mg/kg for soil. IR in mg/day is the ingestion rate, EF in days/year is the exposure frequency, ED is the exposure duration in years, BW is the body weight of the exposed individual in kg, AT is the time period over which the dose is averaged in days. CF is the conversion factor in kg/mg.

2.4.1.2. Dermal Contact with Heavy Metals through Soil/Sediment

$$EDI_{derm} = \frac{CxSAxFExAFxABSxEFxED^{xCF}}{BWxAT} \quad \textbf{(2)}$$

where EDI_{derm} is the exposure dose via dermal contact in mg/kg/day. C is the concentration of heavy metal in sediment in mg/kg, SA is exposed skin area in cm^2, FE is the fraction of the dermal exposure ratio to soil, AF is the soil adherence factor in mg/cm^2, ABS is the fraction of the applied dose absorbed across the skin. EF, ED, BW, CF and AT are as defined in Equation 1 before. The exposure parameters used for the health risk assessment through different exposure pathways in sediment/soil, are presented in Table 1.

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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)	Cm2`	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)

1. **Estimated Daily Intake (EDI)** $\boldsymbol{EDI = \frac{CxIRxEFxED}{BW\ x\ AT}}$
2. **Hazard Quotient**

   HQ = $\boldsymbol{HQ = \frac{EDI}{RfD}}$

   Where RfD is the Oral rference dose (mg/kg-day)
3. **Hazard Index**

$\boldsymbol{HI} = \sum \boldsymbol{HQ}$

If HI > 1, non-carcinogenetic risk is significant

4. **Incremental Lifetime Cancer Risk**

ILTCR = EDI x SF

The Cancer Slope Factor (CSF) (mg/kg-day−1 is a value provided by the USEPA, indicating the probability of cancer risk per unit dose.

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According to the USEPA risk classification:

- ILTCR< 1×10−6 (Negligible risk)
- 1×10−6 ≤ ILTCR<1×10−4 (Acceptable risk range)
- ILTCR>1×10−4 (Potentially significant risk, requiring intervention)

2.4.2 Health Index Assessment

HI on the other hand, is the non-carcinogenic effect to the population for *n* number of heavy metals, expressed as the summation of all the HQs due to individual heavy metals (Equation 4).

$$HI = \sum^{n} HQ$$

Where HI and HQ $_{k=0}$ are health index and hazard quotient respectively. Please note that HQ values are obtained up to the k^{th} heavy metal. If the HI value is less than one, the exposed population is unlikely to experience adverse health effects. If the HI value exceeds one, then there may be concern for potential non-carcinogenic effects (Kamunda et al., 2018).

3. Results and Discussion

3.1 Heavy metal Concentrations in MCPW

The concentrations of heavy metals (Cd, Cu, Pb, Mn, Ni, Cr, Fe, and Hg) in MCPW during both dry and wet seasons are presented in Tables 2 and 3. A significant seasonal variation in heavy metal concentrations was observed across the studied locations, indicating the influence of hydrological conditions on metal distribution and retention in MCPW. As earlier reported, the concentrations of heavy metal in NCPW were significantly grater during the dry season, attributable to the washing or leaching effect (Isaac, 2024a and Isaac, 2024b).

Cadmium (Cd) and Lead (Pb)

The concentrations of Cd and Pb in all locations were below detection limits (<0.001 mg/kg) in both seasons. This result aligns with findings from studies in sediment matrices from the Niger Delta (Amajor et al., 2020; Okafor et al., 2019), where Cd and Pb levels were low due to limited anthropogenic input in certain areas. However, it contrasts with reports from more industrialized zones where Pb contamination from vehicular emissions and industrial effluents was higher (Chukwuma et al., 2021). Despite the low concentrations, Cd and Pb are highly toxic, and even trace levels can pose ecological risks over time due to bioaccumulation (Jiang et al., 2022).

Copper (Cu) and Manganese (Mn)

During the dry season, Cu concentrations were significantly higher at all stations, ranging from 10.03 to 41.06 mg/kg, while Mn ranged from 62.50 to 133.22 mg/kg. In contrast, Cu concentrations in the wet season were markedly lower (<0.001–0.33 mg/kg), and Mn ranged from 2.98 to 14.48 mg/kg. These seasonal differences suggest the influence of surface runoff and dilution effects during the wet season (Obasi et al., 2018). Compared with sediment quality guidelines, Cu levels were below the Chronic (CHR) and Acute (ACUTE) toxicity thresholds (0.003 and 0.41 mg/kg, respectively) (USEPA, 2019). Similar trends have been reported in studies on metal contamination in aquatic sediments of Nigeria (Nduka et al., 2016). The observed seasonal variations in Cu and Mn concentrations have important ecological and environmental implications. The elevated levels of these metals in the dry season suggest that reduced water flow leads to their accumulation in sediments, increasing the potential for bioavailability and uptake by benthic organisms. Although Cu is an essential trace element, excessive concentrations can be toxic to aquatic life, affecting enzyme activity and disrupting metabolic processes. Mn, while also essential, can become harmful at elevated concentrations, leading to potential toxicity in fish and other aquatic organisms. From a water quality management perspective, the significant decrease in metal concentrations during the wet season highlights the role of hydrological factors in regulating metal transport and distribution. The dilution and flushing effects of increased rainfall reduce metal accumulation in sediments, lowering potential ecological risks. However, this also suggests that in the dry season, water bodies may act as metal sinks, with pollutants gradually accumulating over time. Although Cu concentrations were below chronic and acute toxicity thresholds, continued monitoring is essential to detect any long-term accumulation trends that could pose risks to aquatic ecosystems and human health. Through the understanding of these seasonal patterns, we can inform sediment management strategies, pollution control measures, and sustainable water resource management practices to mitigate the impact of heavy metal contamination in riverine environments.

Nickel (Ni) and Chromium (Cr)

Nickel concentrations were significantly higher in the dry season, ranging from 12.47 to 33.23 mg/kg, compared to the wet season (0.44–2.67 mg/kg). Chromium followed a similar trend, with higher values (15.96–18.06 mg/kg) in the dry season and near or below detection limits in the wet season. These findings align with previous studies indicating that heavy metals tend to accumulate in sediments during low-flow periods due to reduced leaching and erosion effects (Adewuyi & Oyekunle, 2020). The pronounced seasonal variation has important environmental and ecological implications. The higher concentrations of Ni and Cr in the dry season suggest that metal retention in sediments is influenced by lower water levels and reduced turbulence, which minimize the dispersion of contaminants. This seasonal concentration effect could increase metal bioavailability to benthic organisms, potentially leading to bioaccumulation in aquatic food chains. Furthermore, these metals, particularly Ni and Cr, are known to have toxic effects on aquatic life and may pose long-term risks to human health through water consumption and fisheries. From a regulatory perspective, these findings highlight the need for seasonal monitoring of heavy metal pollution in aquatic environments, as contamination levels may vary significantly between seasons. More so, the marked reduction in metal concentrations during the wet season suggests a dilution effect, emphasizing the role of hydrological conditions in metal transport and sediment dynamics. Understanding these patterns can inform remediation strategies and pollution control measures aimed at mitigating the impact of heavy metal contamination in riverine ecosystems.

Iron (Fe) and Mercury (Hg)

Iron concentrations were notably high in the dry season (7,560.06–14,072.18 mg/kg) but dropped significantly in the wet season (1,113.88–3,384.76 mg/kg). The high Fe levels align with reports from polluted river sediments in the Niger Delta (Oghenekohwo & Emuh, 2021). Mercury was consistently below detection limits across all stations, which is favorable for environmental health, as Hg is a potent neurotoxin with severe ecological implications (WHO, 2017).

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Table 2: Concentrations of heavy metals (Cd, Cu, Pb & Mn) in MCPW during dry and wet seasons in comparison with sediment quality guidelines

MCPW Location	Cd (mg/kg)	Cu (mg/kg)	Pb (mg/kg)	Mn (mg/kg)
Dry Season				
STA-1	<0.001	41.06 ± 6.67[c]	<0.001	133.22 ± 2.71[b]
STA-2	<0.001	37.88 ± 2.80[c]	<0.001	106.37 ± 4.86[c]
STA-3	<0.001	10.03 ± 0.95[c]	<0.001	62.50 ± 2.94[c]
Wet Season				
STA-1	<0.001	0.33 ± 0.05[c]	<0.001	10.98 ± 0.19[c]
STA-2	<0.001	<0.001[c]	<0.001	14.48 ± 0.37[b]
STA-3	<0.001	<0.001[c]	<0.001	2.98 ± 0.04[c]
F-value		98.298		831.520
P-value		P<0.001		P<0.01
FEPA			0.01	0.05
CHR		0.003	30.24	0.10
ACUTE		0.41	112	NA

Source: Isaac (2024)

Table 2: Concentrations of heavy metals (Ni, Cr, Fe & Hg) in MCPW during dry and wet in comparison with sediment quality guidelines

MCPW Location	Ni (mg/kg)	Cr (mg/kg)	Fe (mg/kg)	Hg (mg/kg)
Dry Season				
STA-1	33.23 ± 0.72[a, b]	15.96 ± 0.67[a]	14,072.18 ± 1402.27[a]	<0.001
STA-2	25.03 ± 2.03[a, b]	<0.001[b]	7,560.06 ± 139.15[a]	<0.001
STA-3	12.47 ± 0.51[c, b]	18.06 ± 1.10[c]	13,932.68 ± 489.70[a,b]	<0.001
Wet Season				
STA-1	2.67 ± 0.12[a,b]	<0.001[b]	1,113.88 ± 131.09[b]	<0.001
STA-2	2.38 ± 0.13[a]	<0.001[b]	2.67 ± 0.12[b]	<0.001
STA-3	0.44 ± 0.03[a]	1.81 ± 0.09	3,384.76 ± 214.71[b]	<0.001
F-value	460.736	1678.461	213.571	
P-value	P<0.001	P<0.001	P<0.001	
FEPA		0.05	1.00	
CHR	0.008	0.05	0.05	0.13
ACUTE	0.074	1.10	0.3	0.7

Source: Isaac (2024)

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3.2 Spatial and Seasonal Estimated Daily Intake of Heavy Metals adsorbed into MCPW

Estimated daily intake (EDI) values for adults and children were assessed in both seasons (Tables 3 and 4). The EDI values for most metals were higher in the dry season than in the wet season, highlighting seasonal variations in exposure risks. For adults, Fe had the highest EDI values (2.514 mg/kg/day at STA-1 in the dry season), followed by Mn and Ni. The values for Cu and Cr were generally lower than recommended daily limits (FAO/WHO, 2018). In children, the EDI values were significantly higher than in adults, particularly for Mn (up to 7.14 mg/kg/day) and Fe (up to 10.057 mg/kg/day). This suggests that children are at greater risk of metal exposure due to higher consumption rates relative to body weight (Ogunkunle et al., 2022). These findings have critical health and environmental implications. The higher EDI values observed in the dry season suggest that reduced dilution and accumulation of metals in sediments and microplastic-associated contaminants pose an increased risk of dietary exposure. The significantly elevated EDI values in children underscore their heightened vulnerability due to their faster metabolism, greater intake of food and water relative to body weight, and underdeveloped detoxification systems. Chronic exposure to elevated Fe and Mn levels can lead to neurological impairments, oxidative stress, and organ damage, particularly in children, who are more susceptible to neurotoxic effects.

From a regulatory and public health perspective, these results emphasize the need for continuous monitoring of heavy metal contamination in aquatic environments, particularly in regions where microplastic-contaminated water and food sources contribute to human exposure. Public awareness campaigns and interventions should target vulnerable populations, including children, to minimize long-term health risks. Additionally, stricter pollution control measures and sustainable waste management practices are necessary to mitigate heavy metal contamination in river systems, reducing human exposure through dietary and environmental pathways.

Table 3: Estimated Daily Intake of Heavy Metals from MCPW by adult

Location	Cd (mg/kg/day)	Cu (mg/kg/day)	Pb (mg/kg/day)	Mn (mg/kg/day)	Ni (mg/kg/day)	Cr (mg/kg/day)	Fe (mg/kg/day)	Hg (mg/kg/day)
EDI for Dry (Adult)								
STA-1	0.0001	0.547	0.0001	1.785	0.265	0.08	2.514	0.0001
STA-2	0.0001	0.508	0.0001	1.453	0.211	0.0001	1.443	0.0001
STA-3	0.0001	0.167	0.0001	0.601	0.145	0.122	2.319	0.0001
(EDI for Wet Season (Adult)								
STA-1	0.0001	0.022	0.0001	0.601	0.021	0.0001	0.183	0.0001
STA-2	0.0001	0.0001	0.0001	0.579	0.016	0.0001	0.0001	0.0001
STA-3	0.0001	0.0001	0.0001	0.059	0.003	0.005	0.399	0.0001

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Table 4: Estimated Daily Intake of Heavy Metals from MCPW by children

Location	Cd (mg/kg/ day)	Cu (mg/kg/ day)	Pb (mg/kg/ day)	Mn (mg/kg/ day)	Ni (mg/kg/ day)	Cr (mg/kg/ day)	Fe (mg/kg/ day)	Hg (mg/kg/ day)
EDI for Dry Season (Children)								
STA-1	0.0004	2.188	0.0004	7.14	1.06	0.32	10.057	0.0004
STA-2	0.0004	2.032	0.0004	5.812	0.844	0.0004	5.77	0.0004
STA-3	0.0004	0.668	0.0004	2.404	0.58	0.488	9.275	0.0004
EDI for Wet Season (Children)								
STA-1	0.0004	0.088	0.0004	2.404	0.084	0.0004	0.731	0.0004
STA-2	0.0004 0.0004	0.0004		2.316	0.064	0.0004	0.0004	0.0004
STA-3	0.0004 0.0004	0.0004		0.236	0.012	0.02	1.593	0.0004

3.3 Spatial and Seasonal Hazard Quotient of Heavy Metals adsorbed into MCPW

Hazard quotient (HQ) values indicate potential health risks associated with metal exposure. In the dry season, HQ values for adults exceeded 1 for Mn, Ni, and Cu at all locations, suggesting potential health risks (Table 6). Similar trends were observed in children, with HQ values for Mn (51.00 at STA-1) and Ni (53.00 at STA-1) significantly surpassing safe limits. Comparable findings have been reported in polluted sediments from industrial zones (Adewumi & Adebayo, 2019). These results have significant public health implications, as HQ values exceeding 1 suggest a potential for adverse health effects from chronic exposure. The elevated HQ values for Mn and Ni, particularly in children, highlight a serious health concern since prolonged exposure to high levels of these metals is associated with neurological disorders, developmental impairments, and systemic toxicity. The exceptionally high HQ values observed at STA-1 further indicate localized pollution hotspots that may require immediate intervention. The marked seasonal variation in HQ values suggests that exposure risks are exacerbated in the dry season due to reduced dilution and increased accumulation of heavy metals in sediments and microplastic-associated contaminants. This underscores the need for season-specific risk mitigation strategies, such as improving waste management and controlling industrial effluents that contribute to heavy metal pollution. These findings reinforce the necessity for stricter enforcement of environmental protection policies, particularly in areas prone to heavy metal contamination. Public health initiatives should prioritize vulnerable groups, including children, through awareness campaigns, regular health screenings, and dietary recommendations to reduce metal exposure. Additionally, continuous monitoring of HQ values across seasons can help track pollution trends and guide effective remediation strategies to safeguard human health and aquatic ecosystems.

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Table 5: Hazard quotient of Heavy Metals from MCPW by adult

Location	Cd	Cu	Pb	Mn	Ni	Cr	Fe	Hg
Hazard Quotient (HQ) for Dry Season (Adults)								
STA-1	0.1	13.68	0.03	12.75	13.25	0.05	3.59	0.33
STA-2	0.1	12.7	0.03	10.38	10.55	0.0001	2.06	0.33
STA-3	0.1	4.18	0.03	4.29	7.25	0.08	3.31	0.33
Hazard Quotient (HQ) for Wet Season (Adults)								
Location	Cd	Cu	Pb	Mn	Ni	Cr	Fe	Hg
STA-1	0.1	0.55	0.03	4.29	1.05	0.0001	0.26	0.33
STA-2	0.1	0.0001	0.03	4.14	0.8	0.0001	0.0001	0.33
STA-3	0.1	0.0001	0.03	0.42	0.15	0.003	0.57	0.33

Table 6: Hazard quotient of heavy metals from MCPW by children

Location	**Cd**	**Cu**	**Pb**	**Mn**	**Ni**	**Cr**	**Fe**	**Hg**
Hazard Quotient (HQ) for Dry Season (Children)								
STA-1	0.4	54.7	0.11	51	53	0.21	14.37	1.33
STA-2	0.4	50.8	0.11	41.51	42.2	0.0003	8.24	1.33
STA-3	0.4	16.7	0.11	17.17	29	0.33	13.25	1.33
Hazard Quotient (HQ) for Wet Season (Children)								
STA-1	0.4	2.2	0.11	17.17	4.2	0.0003	1.04	1.33
STA-2	0.4	0.01	0.11	16.54	3.2	0.0003	0.0006	1.33
STA-3	0.4	0.01	0.11	1.69	0.6	0.013	2.28	1.33

3.4 Spatial and Seasonal Hazard Indices of Heavy Metals adsorbed into MCPW

The hazard index (HI) values indicate cumulative health risks from exposure to multiple metals. For adults, HI values in the dry season ranged from 3.71 to 6.38, suggesting a substantial risk of adverse health effects across all locations (Table 7). In the wet season, HI values were lower (0.75– 1.84), with STA-2 and STA-3 falling below the risk threshold of 1. In children, HI values in the dry season (14.88–25.85) indicated significant health risks, while in the wet season (2.64–7.32), the risks remained concerning (Table 8). There is a critical public health implication, as HI values exceeding 1 indicate potential non-carcinogenic health risks due to chronic exposure. The elevated hazard levels in children, who are more vulnerable due to their developing physiological systems and higher intake rates per body weight, highlight the urgent need for intervention measures. The seasonal variation in HI values, with significantly higher risks during the dry season, suggests that metal accumulation and exposure pathways may be influenced by climatic factors such as reduced dilution effects and increased resuspension of contaminated particles. Furthermore, the spatial differences in HI values underscore the role of localized pollution sources, necessitating targeted remediation efforts. The findings emphasize the need for stringent environmental monitoring, particularly in areas where children and vulnerable populations are exposed. Long-term health surveillance

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programs and risk mitigation strategies, such as soil remediation, proper waste disposal, and public health education, are essential to reducing exposure risks in the study area. Additionally, regulatory frameworks should be strengthened to control heavy metal emissions and mitigate their impact on human health.

Table 7: Hazard indices of Heavy Metals from MCPW by adult

Location	HI	Implication
Hazard Index (HI) for Dry Season (Adults)		
STA-1	6.38	Potential health risk
STA-2	4.58	Potential health risk
STA-3	3.71	Potential health risk
Hazard Index (HI) for Wet Season (Adults)		
STA-1	1.84	Potential health risk
STA-2	0.97	No significant risk
STA-3	0.75	No significant risk

Table 8: Hazard indices of Heavy Metals from MCPW by adult Hazard Index (HI) for Dry Season (Children)

Location	HI	Implication
STA-1	25.85	Significant health risk
STA-2	19.67	Significant health risk
STA-3	14.88	Potential health risk
Table 4: Hazard Index (HI) for Wet Season (Children)		
STA-1	7.32	Significant health risk
STA-2	3.91	Potential health risk
STA-3	2.64	Potential health risk

Conclusion

This study highlights significant seasonal variations in heavy metal contamination and associated health risks in MCPW. While most metals were below critical sediment quality thresholds, hazard indices suggest potential health risks, especially for children. The findings underscore the need for pollution control measures and continuous environmental monitoring to safeguard human and ecological health.

Recommendation

The following recommendations were suggested from the study:

1. Conduct additional studies on the bioavailability and speciation of heavy metals in MCPW to better understand their long-term impact.
2. Investigate potential links between heavy metal exposure and health conditions in local populations.

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