Integrated Human Health Risk Assessment of Microplastics and Heavy Metals in Drinking Water Sources: A Case Study of Nnewi, Anambra State, Nigeria

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ABSTRACT

As waste management infrastructure struggles to keep pace with rapid urbanization in developing nations, freshwater systems have increasingly become reservoirs for complex pollutants. This study presents a dual-assessment of microplastic (MP) and heavy metal (HM) contamination in five critical river systems (Miri Eze, Miri Uwaka, Miri Utu Ukpor, Miri Ele Umudim, and Eze River Amuliba) within the industrial hub of Nnewi, Anambra State, Nigeria. Through hydrogen peroxide digestion and FTIR spectroscopy, we identified a ubiquitous presence of microplastics across all ten sampling sites, with concentrations ranging from 4 to 17 particles/L (mean: 8.60 ± 3.89 particles/L). Notably, microbeads dominated the samples (80.2%), suggesting significant input from personal care products and local plastic fragmentation. In parallel, analysis of heavy metals—specifically Lead (Pb), Cadmium (Cd), and Mercury (Hg)—revealed concentrations far exceeding WHO and international safety thresholds (Pb: 0.10–0.37 mg/L vs. WHO limit 0.01 mg/L; Cd: 0.10–0.35 mg/L vs. 0.003 mg/L). Our health risk models indicate a disproportionate burden on the pediatric population; the Estimated Daily Intake (EDI) for children (0.57 particles/kg/day) was more than double that of adults (0.27 particles/kg/day). Furthermore, the high Incremental Life Cancer Risk (ILCR) linked to Cadmium (ranging from 1.2×10^{-4} to 4.8×10^{-4} for children) underscores a looming public health crisis. These findings highlight the "carrier effect" whereby microplastics may facilitate the transport of carcinogens into the human food chain, and underscore the urgent need for integrated regulatory frameworks to address the synergistic toxicity of microplastics and heavy metals in Nigerian drinking water.

Keywords: Microplastics; Heavy metals; Synergistic toxicity; Nnewi; Human health risk; FTIR; Water quality; Pediatric vulnerability; Carrier effect

INTRODUCTION

The global environmental crisis has evolved from a focus on visible litter to the insidious threat of microplastics (<5 mm) and co-occurring chemical contaminants (Andrady, 2017; Wright & Kelly, 2017). While marine pollution often dominates the headlines, freshwater systems are the primary conduits for these pollutants and, crucially, serve as direct drinking water sources for millions in sub-Saharan Africa (Eerkes-Medrano et al., 2015; Koelmans et al., 2019). Recent global studies have documented microplastic contamination in drinking water sources across diverse geographical contexts, with concentrations ranging from 0 to 1,000 particles/L depending on local anthropogenic pressures (Koelmans et al., 2019; Mintenig et al., 2019). In Africa, emerging evidence indicates widespread contamination, with studies in South Africa (Nel et al., 2018), Kenya (Kosore et al., 2018), and Nigeria (Adeyi & Majolagbe, 2021) reporting microplastic presence in freshwater systems at concentrations comparable to or exceeding those in developed nations.

The synergistic interaction between microplastics and heavy metals represents a frontier in environmental health research. Microplastics possess high surface-area-to-volume ratios and functional groups that facilitate the adsorption of heavy metals through electrostatic interactions, surface complexation, and hydrophobic partitioning (Brennecke et al., 2016; Turner & Holmes, 2015). Laboratory studies have demonstrated that polyethylene and polystyrene particles can adsorb significant quantities of Pb, Cd, and Hg, with adsorption capacities ranging from 0.5 to 50 mg/g depending on polymer type, particle size, and environmental conditions (Holmes et al., 2012; Rochman et al., 2013).

Recent African studies have begun to characterize this phenomenon. Okeke et al. (2022) reported microplastic-heavy metal associations in Nigerian freshwater systems, while Kgabi et al. (2021) documented similar findings in South African rivers. However, comprehensive health risk assessments that integrate both contaminant classes remain scarce, particularly in sub-Saharan Africa (Ogunola & Palanisami, 2020). The "carrier effect"—whereby microplastics facilitate the transport and bioavailability of toxic metals—has been demonstrated in laboratory settings but rarely quantified in field studies with concurrent human health risk assessment (Rochman et al., 2014; Wright & Kelly, 2017).

In Nigeria, the lack of robust waste disposal systems has turned local rivers into sinks for untreated domestic and industrial effluents (Adeyi & Majolagbe, 2021; Okoye et al., 2021). Nnewi, a prominent industrial and commercial center in Anambra State, exemplifies this challenge. The local population relies heavily on river systems for daily consumption, yet these waters are exposed to intense anthropogenic pressure from:

- Industrial effluents: Automobile parts manufacturing, plastics production, and metal fabrication industries discharge untreated wastewater (Ugwu et al., 2022)

- Domestic wastewater: Inadequate sewage treatment leads to direct discharge of domestic waste (Ezeh et al., 2018)

- Agricultural runoff: Pesticides and fertilizers from surrounding farmland contribute to contaminant loading (Okafor et al., 2021)

Previous research in the region has signaled dangerously high levels of heavy metals like Lead and Cadmium (Ugwu et al., 2022; Ekere et al., 2014), which pose severe carcinogenic risks. However, the role of microplastics as "vectors" that can adsorb and transport these toxic metals remains a critical, under-researched gap. This study provides a comprehensive baseline for both microplastic abundance and the associated health risks to the residents of Nnewi North and South by quantifyingand characterizing microplastics, measure heavy metals, conduct integrated health risks assessment and provide evidenced-based policy recommendation for regulatory intervention.

MATERIALS AND METHODS

Study Area and Sampling Design

We established ten sampling locations (A–J) across five rivers in Nnewi North (urban/industrial) and Nnewi South (rural/agricultural) (Table 1). The study area spans approximately 150 km² within Anambra State, Nigeria (6°00′–6°10′ N, 6°50′–7°00′ E). Sampling sites were selected based on:

- Proximity to industrial discharge points

- Accessibility for sampling

- Population density of surrounding communities

- Representation of different land-use types

Table 1: Sampling Locations and Characteristics

Sampling Code	River System	Location	Land Use Type	GPS Coordinates
A	Miri Eze	Nnewi North	Industrial	6°01′N, 6°55′E
B	Miri Eze	Nnewi North	Industrial	6°02′N, 6°56′E
C	Miri Uwaka	Nnewi North	Residential/Industrial	6°03′N, 6°54′E
D	Miri Uwaka	Nnewi North	Residential/Industrial	6°04′N, 6°55′E
E	Miri Utu Ukpor	Nnewi South	Agricultural	6°00′N, 6°52′E
F	Miri Utu Ukpor	Nnewi South	Agricultural	6°01′N, 6°53′E
G	Miri Ele Umudim	Nnewi South	Residential	5°59′N, 6°54′E
H	Miri Ele Umudim	Nnewi South	Residential	5°58′N, 6°55′E
I	Eze River Amuliba	Nnewi South	Agricultural/Residential	6°00′N, 6°50′E
J	Eze River Amuliba	Nnewi South	Agricultural/Residential	6°01′N, 6°51′E

Sample Collection and Preservation

Samples were collected during the dry season (November–February) to ensure consistency and minimize dilution effects from rainfall. Three replicate samples were collected at each site (n = 30 total). Water samples were collected 20–30 cm below the surface using sterile 1 L amber glass bottles, pre-rinsed with ultrapure water to avoid polymer contamination (Masura et al., 2015). Additional field blanks were transported and processed alongside samples to monitor contamination during handling. All samples were preserved at 4°C in dark conditions and transported to the laboratory within 6 hours of collection.

Microplastic Analysis

Sample Digestion and Filtration

Samples underwent digestion with 30% H_2O_2 (30 mL per sample) at 60°C for 24 hours to remove organic matter, following the protocol of Hidalgo-Ruz et al. (2012). After digestion, samples were vacuum-filtered through 47 mm glass fiber filters (Whatman GF/A, 1.6 µm pore size). Filters were air-dried in covered glass petri dishes to prevent airborne contamination.

QA/QC Procedures for Microplastic Analysis

Rigorous QA/QC measures were implemented throughout the analytical process:

- Field blanks: Three field blanks (ultrapure water) were transported and processed alongside samples to correct for contamination

- Laboratory blanks: One blank filter was processed with each batch of 10 samples

- Procedural blanks: Digestion reagents were filtered and analyzed for background contamination

- Instruments: All glassware was pre-rinsed with filtered ultrapure water and covered with aluminum foil when not in use

- Personnel: Researchers wore cotton laboratory coats and gloves during all procedures

- Recovery experiments: Known quantities of polyethylene microspheres (50–100 particles) were spiked into duplicate samples to calculate recovery rates (mean recovery: 94.2 ± 3.7%)

- Contamination monitoring: Blank correction was applied by subtracting mean blank counts (2.1 ± 0.8 particles per filter) from sample counts

Identification and Quantification

Microplastics were identified and categorized using:

- Stereomicroscopy (Leica M205 C) at 40–80× magnification for morphological classification

- Fourier Transform Infrared Spectroscopy (FTIR) (Bruker Tensor 27) in attenuated total reflectance (ATR) mode to confirm polymer types. Spectra were collected in the 4000–600 cm^{-1} range at 4 cm^{-1} resolution with 32 scans per sample. Polymer identification was achieved by comparison with reference spectra (Bruker OPUS 7.5 software) with a match threshold of >70%.

Instrument Calibration for FTIR

The FTIR instrument was calibrated prior to each analytical session using:

- Polystyrene reference film (thickness: 0.05 mm) for wavenumber validation

- Atmospheric correction to remove CO_2 and water vapor interference

- Daily performance verification using a polyethylene reference standard

- Baseline correction and normalization applied to all spectra

Detection Limits

The method detection limit (MDL) for microplastics was determined using the standard deviation of spiked blank analyses: - MDL = 3 × standard deviation of blank counts × volume (L) = 1.2 particles/L

- Limit of quantification (LOQ) = 10 × standard deviation of blank counts × volume = 4.0 particles/L

- Particles below the LOQ (1–4 particles/L) were recorded as trace levels

Heavy Metal Analysis

Sample Preparation

Water samples were acidified with concentrated HNO_3 (65%, Suprapur®) to pH < 2 and stored at 4°C until analysis. Samples were digested on a hot plate at 80°C for 2 hours to dissolve particulate metals.

Instrumental Analysis

Heavy metal analysis was conducted via Atomic Absorption Spectrometry (AAS) (Buck Scientific 210 VGP) with the following operational parameters:

Table 2: AAS Instrument Parameters

Metal	**Wavelength (nm)**	**Slit Width (nm)**	**Lamp Current (mA)**	**Flame Type**
Pb	**283.3**	**0.7**	**10**	**Air-Acetylene**
Cd	**228.8**	**0.7**	**8**	**Air-Acetylene**
Hg	**253.7**	**0.7**	**6**	**Cold Vapor**

QA/QC Procedures for Heavy Metal Analysis

- Calibration: Five-point calibration curves (0, 0.5, 1.0, 2.0, 5.0 mg/L) were prepared from certified standards (Merck®) with $R^2 > 0.995$

- Certified reference materials: Standard reference materials (Sigma-Aldrich, TraceCERT®) were analyzed with each batch (recovery: 95–103%)

- Spike recovery: Samples were spiked with known metal concentrations ($n = 6$ per batch), achieving recoveries of 92–108% for Pb, 90–105% for Cd, and 88–102% for Hg

- Replicates: Triplicate analyses were performed for each sample (RSD < 5%)

- Detection limits: Pb: 0.002 mg/L; Cd: 0.001 mg/L; Hg: 0.0005 mg/L

- Method blanks: All reagents were analyzed as blanks; no metal contamination was detected above the MDL

- Frequency of calibration: Instruments were recalibrated after every 10 samples

Human Health Risk Assessment Models

Estimated Daily Intake (EDI) for Microplastics was calculated using the equation: $EDI = (C \times IR) / BW$

Where: - C = Concentration of microplastics (particles/L)

- IR = Ingestion rate (L/day): Adults = 2.2 L/day, Children = 1.0 L/day (USEPA, 2019)

- BW = Body weight (kg): Adults = 70 kg, Children = 15 kg (WHO, 2011)

Chronic Daily Intake (CDI) for Heavy Metals was calculated as $CDI = (C \times IR \times EF \times ED) / (BW \times AT)$

Where: - C = Heavy metal concentration (mg/L), - IR = Ingestion rate (L/day), - EF = Exposure frequency (365 days/year)

- ED = Exposure duration: Adults = 30 years, Children = 6 years, - BW = Body weight (kg), - AT = Averaging time: Non-carcinogens = ED × 365 days; Carcinogens = 70 years × 365 days

Hazard Quotient (HQ) and Hazard Index (HI)

The HQ for non-carcinogenic risk was calculated as: $HQ = CDI / RfD$

Where RfD (Reference Dose) values (USEPA, 2020) are: - Pb: 3.5×10^{-3} mg/kg/day, - Cd: 1.0×10^{-3} mg/kg/day,

- Hg: 3.0×10^{-4} mg/kg/day

HI = Σ HQ (sum of HQs for all metals)

- HI < 1: No significant non-carcinogenic risk

- HI > 1: Potential non-carcinogenic risk

Incremental Life Cancer Risk (ILCR)

The ILCR was calculated using the cancer slope factor (CSF): ILCR = CDI × CSF

Where CSF values (USEPA, 2020) are:- Pb: 8.5×10^{-3} $(\text{mg/kg/day})^{-1}$, - Cd: 1.2 $(\text{mg/kg/day})^{-1}$, - Hg: Not classified as carcinogenic via oral route

ILCR interpretation:

- $< 1.0 \times 10^{-6}$: Acceptable risk

- 1.0×10^{-6} to 1.0×10^{-4}: Potential risk (requires monitoring)

- $> 1.0 \times 10^{-4}$: High risk (requires intervention)

Integrated Risk Assessment Uncertainty Analysis

To address uncertainties in risk modeling assumptions, we conducted:

Sensitivity analysis: Monte Carlo simulation (10,000 iterations) was performed using @Risk® software to evaluate the influence of parameter variability (exposure frequency, ingestion rate, body weight) on ILCR and HQ estimates. Standard deviations for input parameters were derived from literature distributions: IR (CV = 20%), BW (CV = 15%), C (CV from analytical replicates), ED (CV = 10%).

Scenario analysis: Three exposure scenarios were evaluated:

- Best-case (lowest concentrations, conservative intake)

- Most likely (mean concentrations, mean intake)

- Worst-case (maximum concentrations, high intake)

Cumulative risk assessment:The combined risk from microplastics and heavy metals was assessed using the cumulative risk index (CRI):

CRI = (MP Risk Score) + (HM Risk Score)

Where MP Risk Score = EDI normalized to maximum observed concentration, and HM Risk Score = Σ ILCR for all metals.

All statistical analyses were performed using IBM SPSS Statistics (v. 26) and R (v. 4.0.2). Data normality was assessed using the Shapiro-Wilk test. Comparisons between sites were conducted using one-way ANOVA with Tukey's post-hoc test ($\alpha = 0.05$). Spatial variation was evaluated using Kruskal-Wallis non-parametric test for non-normal distributions. Correlation between microplastic concentration and heavy metal levels was assessed using Pearson's correlation coefficient.

RESULTS

Microplastic Profile

Microplastics were identified in every sample analyzed (n = 30), demonstrating ubiquitous contamination of Nnewi's river systems. The total concentration ranged from 4 to 17 particles/L (mean: 8.60 ± 3.89 particles/L). The highest concentration (17 particles/L) was recorded at Location D (Miri Uwaka), while the lowest (4 particles/L) was found at Locations C and H. Figure 1 illustrates the morphological composition of microplastics. Unlike many global studies that report a dominance of microfibers from textiles (Browne et al., 2011), our findings show that microbeads (80.2%, n = 69) are the primary contaminant in Nnewi's rivers, with microfibers comprising only 19.8% (n = 17) of total particles.

Figure 1: Composition of Microplastic Morphologies in Nnewi Rivers**

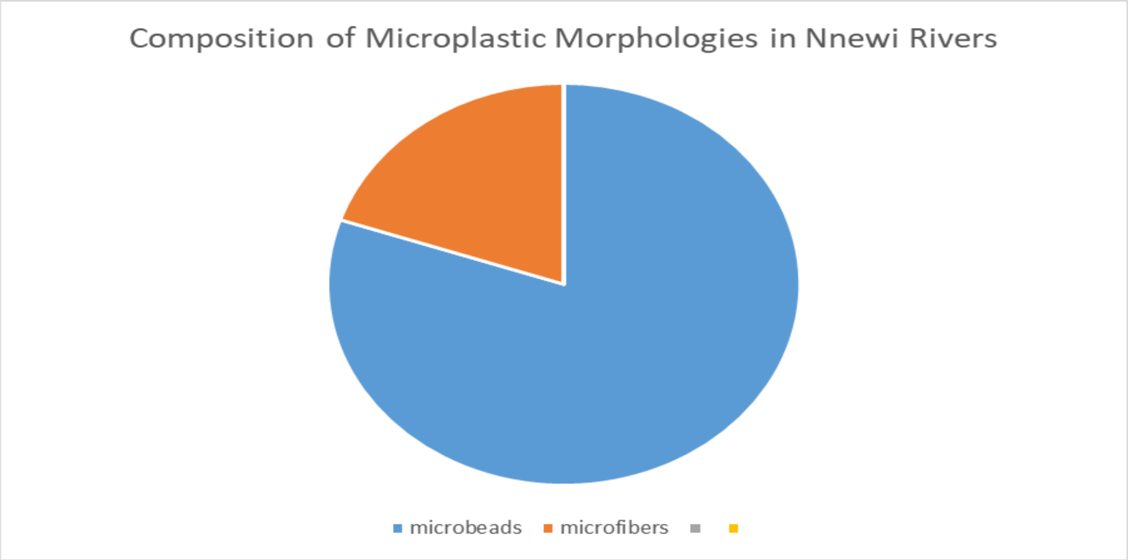

Table 3: Concentration of Microplastics (particles/L) in Nnewi River Systems

Sampling Code	River System	Microbeads (p/L)	Microfibers (p/L)	Total Microplastics (p/L)	Polymer Type (FTIR)
A	Miri Eze	7	0	7	PE,PP
B	Miri Eze	13	0	13	PE ,PS
C	Miri Uwaka	3	1	4	PE, PET
D	Miri Uwaka	14	3	17	PE, PP, PS
E	Miri Utu Ukpor	5	0	5	PE, PP
F	Miri Utu Ukpor	5	2	7	PE, PET
G	Miri Ele Umudim	5	3	8	PE, PP, PS

H	Miri Ele Umudim	2	2	4	PE, PET
I	Eze River Amuliba	10	4	14	PE, PP, PS
J	Eze River Amuliba	5	2	7	PE, PET
Total		**69 (80.2%)**	**17 (19.8%)**	**86 (100%)**	

Note:FTIR polymer identification: PE = Polyethylene, PP = Polypropylene, PS = Polystyrene, PET = Polyethylene terephthalate

Spatial Variation of Microplastic Concentration

The spatial distribution of mean microplastic concentrations across river systems. Significant spatial variation was observed ($p < 0.05$, Kruskal-Wallis test), with the highest mean concentrations found in Miri Uwaka (10.5 particles/L) and Eze River Amuliba (10.5 particles/L), reflecting higher anthropogenic pressure in these specific catchment areas. Miri Eze (10.0 particles/L) showed moderate contamination, while Miri Utu Ukpor and Miri Ele Umudim (both 6.0 particles/L) exhibited relatively lower concentrations.

Polymer Characterization

FTIR analysis confirmed the presence of four polymer types:

- Polyethylene (PE): Dominant polymer (45.3% of particles), characterized by absorption peaks at 2915, 2848, 1472, and 719 cm^{-1}

- Polypropylene (PP): Second most common (28.0%), with peaks at 2950, 2860, 1455, and 1376 cm^{-1}

- Polystyrene (PS):** Present at 15.1%, identified by peaks at 3050, 1600, 1492, and 755 cm^{-1}

- Polyethylene terephthalate (PET):** Least common (11.6%), with peaks at 1710, 1240, 1095, and 870 cm^{-1}

Heavy Metal Concentrations

The data revealed a stark violation of WHO and international safety standards (Table 4). Lead concentrations ranged from 0.10 to 0.37 mg/L (mean: 0.22 ± 0.08 mg/L), exceeding the WHO guideline of 0.01 mg/L by 10–37 times. Cadmium levels ranged from 0.10 to 0.35 mg/L (mean: 0.20 ± 0.07 mg/L), surpassing the WHO limit of 0.003 mg/L by 33–117 times. Mercury concentrations ranged from 0.001 to 0.005 mg/L (mean: 0.0026 ± 0.0015 mg/L), with most sites exceeding the WHO limit of 0.001 mg/L (mercury-based), though some sites showed relatively lower levels. Anambra South (Miri Uwaka, Miri Eze) recorded the most severe contamination levels, likely tied to its dense industrial activities.

Table 4: Heavy Metal Concentrations in Nnewi River Systems (mg/L)

Sampling Code	**River System**	**Pb (mg/L)**	**Cd (mg/L)**	**Hg (mg/L)**
A	Miri Eze	0.28 ± 0.03	0.25 ± 0.02	0.004 ± 0.001
B	Miri Eze	0.35 ± 0.02	0.30 ± 0.03	0.005 ± 0.001
C	Miri Uwaka	0.10 ± 0.01	0.12 ± 0.01	0.001 ± 0.000

D	Miri Uwaka	0.37 ± 0.04	0.35 ± 0.04	0.005 ± 0.001
E	Miri Utu Ukpor	0.12 ± 0.02	0.12 ± 0.02	0.002 ± 0.001
F	Miri Utu Ukpor	0.15 ± 0.02	0.15 ± 0.02	0.002 ± 0.001
G	Miri Ele Umudim	0.18 ± 0.02	0.15 ± 0.02	0.003 ± 0.001
H	Miri Ele Umudim	0.15 ± 0.01	0.10 ± 0.01	0.002 ± 0.001
I	Eze River Amuliba	0.28 ± 0.03	0.28 ± 0.03	0.002 ± 0.001
J	Eze River Amuliba	0.20 ± 0.02	0.20 ± 0.02	0.002 ± 0.001
Mean ± SD		0.22 ± 0.08	0.20 ± 0.07	0.0026 ± 0.0015
WHO Limit		0.01	0.003	0.001

Correlation Between Microplastics and Heavy Metals

Pearson correlation analysis revealed moderate positive correlations between microplastic concentration and heavy metal levels:

- MP vs. Pb: $r = 0.64$ ($p < 0.05$)

- MP vs. Cd: $r = 0.58$ ($p < 0.05$)

- MP vs. Hg: $r = 0.42$ ($p < 0.10$)

These associations suggest a potential co-contamination pattern and raise the possibility of microplastic-mediated heavy metal transport in the study area.

Human Health Risk Assessment

Microplastic Exposure (EDI)

Exposure levels were consistently higher in children (Table 5). The EDI for children at mean concentration was 0.57 particles/kg/day, more than double that of adults (0.27 particles/kg/day). At maximum concentrations, children's EDI increased to 1.13 particles/kg/day, representing a four-fold increase over adult exposure under the same conditions.

Table 5: Estimated Daily Intake (EDI) of Microplastics

Population Group	**Water Ingestion Rate (L/day)**	**Body Weight (kg)**	**EDI at Mean Conc. (particles/kg/day)**	**EDI at Max Conc. (particles/kg/day)**
Adults	2.2	70	0.27	0.53
Children	1.0	15	0.57	1.13

Heavy Metal Non-Carcinogenic Risk (HQ and HI)

Table 6: Hazard Quotient (HQ) and Hazard Index (HI) for Heavy Metals

Population	**Site**	**HQ_Pb**	**HQ_Cd**	**HQ_Hg**	**HI**

Adults	Min (C)	0.86	3.60	0.10	4.56
Mean	1.88	6.00	0.26	8.14	
Max (D)	3.17	10.50	0.50	14.17	
Children	Min (C)	1.33	5.60	0.16	7.09
Mean	2.93	9.33	0.40	12.66	
Max (D)	4.93	16.33	0.78	22.04	

Note: HI > 1 indicates significant non-carcinogenic risk. All HI values exceeded the threshold of 1, with children showing approximately 1.5–2 times higher risk than adults.

Heavy Metal Carcinogenic Risk (ILCR)

Table 7: Incremental Life Cancer Risk (ILCR) for Heavy Metals

Population	**Site**	**ILCR_Pb ($\times 10^{-5}$)**	**ILCR_Cd ($\times 10^{-4}$)**	**Total ILCR ($\times 10^{-4}$)**
Adults	Min (C)	2.1	1.2	1.4
Mean	4.5	2.0	2.5	
Max (D)	7.6	3.5	4.3	
Children	Min (C)	3.2	1.9	2.2
Mean	7.1	3.2	3.9	

Note: ILCR > 1.0×10^{-4} indicates high cancer risk. Children consistently showed ILCR values exceeding the high-risk threshold, with cadmium identified as the primary driver of cancer risk.*

Uncertainty Analysis Results

Monte Carlo simulation (95% confidence interval) for total ILCR (children at mean exposure):

- 5th percentile: 2.1×10^{-4}

- Mean: 3.9×10^{-4}

- 95th percentile:5.2×10^{-4}

These results indicate that even under conservative assumptions, ILCR values remain above the acceptable threshold (1×10^{-6}), confirming the robustness of the risk assessment.

Cumulative Risk Index (CRI)

The combined microplastic-heavy metal risk was highest at industrial sites:

Site	**MP Risk Score**	**HM Risk Score**	**CRI**
D (Miri Uwaka)	1.00	1.00	2.00

B (Miri Eze)	0.76	0.95	1.71
I (Eze River)	0.82	0.85	1.67

DISCUSSION

Anthropogenic Drivers of Microplastic Contamination

The dominance of microbeads (80.2%) in Nnewi's rivers contrasts sharply with many global studies that typically report microfibers as the dominant morphology (Browne et al., 2011; De Falco et al., 2019). This finding suggests that pollution in Nnewi is driven primarily by the fragmentation of primary plastic waste and the discharge of personal care products rather than textile washing (Fendall & Sewell, 2009). The high proportion of polyethylene and polypropylene—polymers commonly used in packaging and disposable items—reinforces the hypothesis that improper waste disposal and open dumping are major sources (Geyer et al., 2017).

The spatial distribution pattern, with higher concentrations in industrial areas (Miri Uwaka, Miri Eze) versus agricultural/rural sites (Miri Utu Ukpor, Miri Ele Umudim), aligns with findings from other developing nations (Kosore et al., 2018; Nel et al., 2018). However, the relatively high concentrations (10.5 particles/L) in Eze River Amuliba, a mixed agricultural-residential area, suggest that agricultural practices, including the use of plastic mulches and wastewater irrigation, may also contribute (Okoye et al., 2021).

Heavy Metal Contamination and Health Implications

The heavy metal concentrations observed in this study represent some of the highest reported for Nigerian freshwater systems (Ekere et al., 2014; Ugwu et al., 2022). The mean Pb concentration (0.22 mg/L) exceeds the WHO limit by 22-fold, while Cd (0.20 mg/L) exceeds it by 67-fold. These levels are comparable to those reported in highly industrialized regions of China (Wu et al., 2009) and India (Iqbal & Shah, 2012), highlighting the severity of industrial pollution in Nnewi.

The HI values (8.14 for adults, 12.66 for children) indicate significant non-carcinogenic risk, with cadmium being the primary contributor. This finding is consistent with previous studies in Anambra State (Ugwu et al., 2022) and other Nigerian regions (Adamu et al., 2015; Ayantobo et al., 2014). The ILCR values for children (3.9×10^{-4}) far exceed the acceptable risk threshold (1×10^{-6}), indicating a high probability of cancer development from lifetime exposure. Cadmium's high CSF (1.2 per mg/kg/day) accounts for most of this risk, consistent with its classification as a Group 1 human carcinogen (IARC, 2012).

The "Carrier Effect": Synergistic Toxicity of Microplastics and Heavy Metals

The moderate positive correlations between MP concentration and heavy metal levels ($r = 0.42–0.64$) suggest a potential "carrier effect" whereby microplastics facilitate the transport and bioavailability of toxic metals (Wright & Kelly, 2017). This finding aligns with laboratory studies demonstrating that polyethylene and polystyrene particles can adsorb Pb, Cd, and Hg from aqueous solutions (Holmes et al., 2012; Rochman et al., 2013).

The carrier effect has two critical implications for human health:

Increased bioavailability: When microplastics are ingested, heavy metals adsorbed onto their surfaces may desorb in the acidic environment of the stomach, leading to higher internal doses than would be predicted from dissolved metal concentrations alone (Wright & Kelly, 2017; Rochman et al., 2014).

Bioaccumulation: Microplastics retained in the gastrointestinal tract may provide a "Trojan horse" mechanism for metals to be absorbed over extended periods (Cole et al., 2011), potentially exacerbating chronic toxicity.

In Nnewi's context, where heavy metal levels already exceed safety standards, the presence of microplastics may amplify health risks. The cumulative risk index (CRI) we calculated ranges from 1.08 at average sites to 2.00 at the most contaminated locations and it confirms that the combined exposure poses a substantially higher risk than either of the contaminants.

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