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Heavy Metals Contamination in Mmili Ocha River Sediments: Seasonal Variation, Ecological Risk, and Human Health Concerns

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ABSTRACT
This study assessed the concentration, contamination status, ecological risk, source relationships, and human health implications of heavy metals in the sediments of the Mmili Ocha River during the rainy and dry seasons. Sediment samples were collected from three sampling stations during the rainy and dry seasons and analyzed for cadmium (Cd), arsenic (As), iron (Fe), zinc (Zn), chromium (Cr), lead (Pb), and mercury (Hg) using atomic absorption spectroscopy (AAS). The mean concentrations of the metals were: Fe (2332.50 ± 333.18 mg/kg), Zn (59.83 ± 22.20 mg/kg), Pb (21.98 ± 5.57 mg/kg), Cr (2.24 ± 0.60 mg/kg), Cd (0.69 ± 0.21 mg/kg), As (0.43 ± 0.21 mg/kg), and Hg (0.15 ± 0.01 mg/kg). Pearson correlation analysis revealed strong positive associations among Cd, As, Fe, Zn, Cr, and Pb (r = 0.790–0.999) in the rainy season and among As, Fe, Zn, Cr, Pb, and Hg (r = 0.723–0.988) in the dry season, indicating common anthropogenic sources and similar geochemical behavior. Geo-accumulation Index (Igeo) classified most metals as unpolluted, while Enrichment Factor (EF) indicated significant to extremely high enrichment for Cd and Pb, suggesting anthropogenic influence. Contamination Factor (CF) and Degree of Contamination (Cd) indicated low to moderate contamination, whereas Pollution Load Index (PLI) values (<1) suggested no overall sediment pollution. The Potential Ecological Risk Index (PERI) ranged from 120.94 to 188.04, indicating low to moderate ecological risk, with Cd and Hg contributing most to the ecological risk. Human health risk assessment identified ingestion as the dominant exposure pathway, with Total Hazard Index (THI) values of 32.26 for children and 3.46 for adults, indicating potential non-carcinogenic risks, particularly among children. The findings indicate increasing anthropogenic pressure on the river sediments, emphasizing the need for continuous environmental monitoring and improved waste management practices to safeguard aquatic ecosystems and protect public health.

Keywords: Ecological risk, Heavy metals, Human health risk assessment, Sediment contamination, Seasonal variation

INTRODUCTION
Heavy metal pollution has become one of the growing environmental challenges affecting rivers and other aquatic ecosystems, particularly in developing countries where human activities continue to place pressure on natural water resources. In Nigeria, many rivers are increasingly exposed to contamination from industrial discharges, agricultural runoff, mining activities, dredging, sewage disposal, and poor waste management practices (Jolaosho *et al.,* 2023; Emenike *et al.,* 2020). These activities introduce toxic metals into the aquatic environment, reducing water quality and threatening both aquatic life and human health. Metals such as cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), mercury (Hg), zinc (Zn), and iron (Fe) are of major environmental concern because they are persistent, non-biodegradable, and capable of accumulating in sediments and living organisms over time (Ezechi and Diara, 2025; Uwaifo *et al.,* 2023; Awosusi *et al.,* 2020).

River sediments are often regarded as important indicators of environmental pollution because they serve as storage sites for heavy metals. Over time, these metals can accumulate in sediments and may later be released back into the water when environmental conditions change, thereby prolonging contamination within the ecosystem (Okafor *et al.,* 2024; Bawa-Allah, 2023). For this reason, sediment analysis is widely used to assess the long-term pollution status of rivers and to understand the extent of ecological disturbance in aquatic environments.

Several studies carried out in different parts of Nigeria have reported elevated levels of heavy metals in river sediments, with pollution indices indicating moderate to high ecological risks, particularly for cadmium and lead (Abdu-Raheem *et al.,* 2024; Ololade *et al.,* 2024). In many cases, some metal concentrations exceeded recommended safety limits, raising concerns about possible ecological damage and human health problems, especially among vulnerable groups such as children (Bawa-Allah, 2023; Okafor *et al.,* 2024). Seasonal changes also influence heavy metal contamination, as runoff during the rainy season often increases the movement of pollutants into rivers, while reduced water volume during the dry season may encourage metal accumulation (Ayodeji *et al.,* 2026; Adesiyan *et al.,* 2018).

Although several Nigerian rivers have been studied, smaller rivers that provide water for domestic activities, irrigation, and fishing in local communities still receive limited scientific attention (Adetunji *et al.,* 2025). The Mmili Ocha River is one of such rivers that may be affected by surrounding human activities, yet little information exists regarding its sediment quality and associated environmental risks. Therefore, this study investigated the concentration of selected heavy metals in the sediments of the Mmili Ocha River during the rainy and dry seasons. The study also evaluated the contamination status, ecological risks, and potential human health implications associated with exposure to the contaminated sediments.

MATERIALS AND METHODS

Study Area

Abakpa is situated in Enugu East Local Government Area of Enugu State, southeastern Nigeria (6.47° N, 7.53° E). Originally an agrarian community, it has transformed into a densely populated, low-income urban area due to the expansion of coal-related activities during the colonial period. Portions of the area are currently used as active dumpsites, highlighting ongoing challenges in solid waste management.

The Mmili Ocha River flows from the Abakpa Bridge area and is influenced by upstream inputs from the abandoned Onyeama coal mine, as well as leachates from nearby dumpsites, raising concerns about potential contamination.

To assess this, sediment samples were collected along the river to evaluate heavy metal concentrations and overall environmental quality. The study area map (Figure 1) highlights the river course, sampling locations, and major pollution sources.

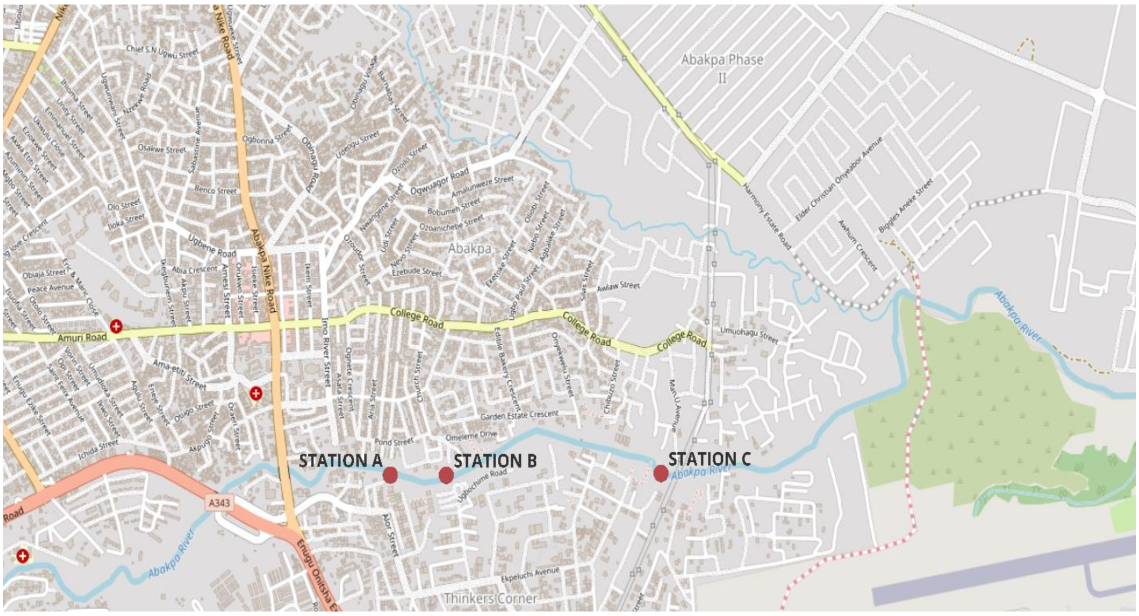

Figure 1: The Topographic map of Abakpa Area, Enugu, Enugu State Nigeria. Inset is the Study Area with Sample Locations.

Sample Collection and Preparation

Sediment samples were collected from the Mmili Ocha River, which extends from Abakpa Bridge through Ifo within Enugu metropolis, during both the rainy season (May–July) and the dry season (December–February). Three samples were obtained each month, resulting in a total of eighteen samples.

For sampling purposes, the river was stratified into three segments: upper, middle, and lower reaches. One sample was collected from each segment. Sediments were obtained at depths of 5–15 cm using appropriate tools and transferred into sterile, labeled, airtight polyethylene bags for preservation and transport to the laboratory.

In the laboratory, samples were air-dried at ambient temperature for seven days. The dried sediments were then pulverized into fine powder using a clean ceramic Teflon mortar and pestle, sieved to ensure uniform particle size, and subsequently stored in a desiccator prior to further analysis.

Digestion and Heavy Metal Analysis of the Sediment Sample

Exactly 2g of each air-dried sediment sample was accurately weighed and transferred into a clean digestion flask. A mixed acid solution (20 Cm^3) consisting of concentrated nitric acid (HNO_3), perchloric acid ($HClO_4$), and sulfuric acid (H_2SO_4) was carefully added in the proportions 650 Cm^3, 80 Cm^3, and 20 Cm^3, respectively. The mixture was then gently heated until a clear solution was obtained, indicating complete digestion of the samples. After cooling, the digest was diluted to 50 mL with distilled water and filtered to obtain a clear solution ready for heavy metal analysis.

Reagent blanks were prepared following the same procedure, excluding the sediment samples. The concentrations of heavy metals in the digested samples were determined using a Varian AA240 Atomic Absorption Spectrophotometer, in accordance with the standard methods prescribed by the American Public Health Association (APHA, 2015).

ASSESSMENT OF POLLUTION INDICES

Geo-Accumulation Index (Igeo)

The geo-accumulation index (Igeo) was calculated using the Müller (1969) model (Singh *et al.,* 2017; Jena *et al.,* 2019), according to equation (1):

$$I_{geo} = \text{Log}_2\left(\frac{Cn}{1.5 \times Bn}\right) \qquad (1)$$

where Cn is the measured metal concentration and Bn is the geochemical background value. In the absence of local background data, global crustal averages from Turekian and Wedepohl (1961) were used (Cd 0.30, Zn 95, Pb 20, Cr 90, Fe 47,200, As 13, Hg 0.4 mg/kg). The Igeo scale ranges from ≤0 (uncontaminated) to >5 (extremely polluted), with intermediate classes indicating increasing contamination.

Enrichment factor (EF)

The enrichment factor (EF) was used to evaluate whether sediment metal concentrations originate from natural or anthropogenic sources, with Fe as the normalizing element (El Zokm *et al.,* 2020). EF was calculated using equation 2:

$$EF = \frac{(\text{Metal}/\text{Fe})\text{Sediment}}{(\text{Metal}/\text{Fe})\text{Shale}} \qquad (2)$$

using an average shale Fe value of 47,200 mg/kg (Turekian and Wedepohl, 1961; Gehan *et al.,* 2020). EF values were classified as: <2 (no enrichment), 2–<5 (moderate), 5–<20 (significant), 20–<40 (very high), and >40 (extremely high enrichment) (Sutherland, 2000).

Contamination Factor (CF)

The contamination factor (CF) is a simple index for assessing heavy metal contamination (Hakanson, 1980), calculated as

$$CF = \frac{\text{C metal}}{\text{C background}} \qquad (3)$$

Where C_{metal} denotes the concentration of the target metal measured in the sediment, and $C_{background}$ represents the corresponding geochemical background concentration. The global average shale values reported by Turekian and Wedepohl (1961) were used as the reference background concentrations. CF is classified as: <1 (low), 1–<3 (moderate), 3–<6 (considerable), and ≥6 (very high contamination) (Hakanson, 1980).

Degree of Contamination (Cd)

To ascertain the level of contamination in the sediment, the degree of contamination (Cd) is often computed as the total of all contamination factors, which is expressed as equation 4:

$$Cd = \sum CF \qquad (4)$$

Cd is classified as: Cd<8 indicates low contamination, 8 ≤ Cd < 16 indicates moderate contamination, 16≤Cd<32 indicates considerable contamination, and 32≥Cd indicates very high contamination, in that order (Biose and Oyagha, 2024).

Pollution Load Index (PLI)

The pollution load index (PLI) evaluates overall sediment toxicity and contamination (Ihedioha *et al.,* 2017), calculated as equation 5;

$$PL1 = [\text{CF}_1 \times \text{CF}_2 \times \text{CF}_3 \times ---- \times CF_n]^{1/n} \qquad (5)$$

where n is the number of metals. Pollution levels are classified as low (CF<1), moderate (1–3), considerable (3–6), and high (CF>6). A PLI of 1 indicates baseline conditions, PLI > 1 reflects declining site quality and PLI<1 denotes an unpolluted state (Mohiuddin et al., 2010).

Potential Ecological Risk Index (PERI)

Heavy metal pollution in sediments was assessed using Hakanson's (1980) potential ecological risk index method.

$$Er^i = Tr.Cf \qquad (6)$$

Tr represents the toxic-response factor of each metal (Cr = 2, Cd = 30, Hg = 40, Pb = 5, Zn = 1, As = 10), while Cf is the contamination factor. The ecological risk factor (Er_i) is classified as: <40 (low), 40–<80 (moderate), 80–<160 (considerable), 160–<320 (high), and ≥320 (very high risk) (Hakanson, 1980).

The potential ecological risk index (RI) is the sum of all individual risk factors, similar to the degree of contamination, calculated using equation 7;

$$RI = \sum Er^i \quad (7)$$

Assuming i = 1, Er_i represents the ecological risk factor. The potential ecological risk index (RI) is classified as: <150 (low), 150–<300 (moderate), 300–<600 (considerable), and >600 (very high ecological risk) (Hakanson, 1980).

Human Health Risk Assessment

Human health risks from heavy metals were assessed following USEPA (1989, 1996) methods (Ihedioha *et al*., 2017), considering exposure through inhalation (ADD_{inh}), ingestion ($ADD_{in}g$), and dermal absorption (ADD_{erm}) using equations 8 to 10.

$$ADD_{inh} = \frac{C \times R_{inh} \times EF \times ED}{PEF \times BW \times AT} \quad (8)$$

$$ADD_{ing} = \frac{C \times R_{ing} \times EF \times ED \times 10^{-6}}{BE \times AT} \quad (9)$$

$$ADD_{derm} = \frac{C \times SL \times SA \times ABS \times EF \times ED \times 10^{-6}}{BW \times AT} \quad (10)$$

$ADD_{(inh)}$, $ADD_{(ing)}$, and $ADD_{(derm)}$ represent average daily doses (mg/kg/day) for non-carcinogenic exposure via inhalation, ingestion, and dermal contact, calculated using mean metal concentrations and standard exposure parameters (body weight, intake rates, exposure duration/frequency, skin area, adherence, absorption, and particle emission). Health risks were assessed using the Hazard Quotient (HQ), defined as the ratio of ADD to the reference dose (RfD), which represents a safe daily exposure level unlikely to cause adverse effects over a lifetime, calculated from equation 11.

$$HQ = \frac{ADD}{RfD} \quad (11)$$

ADD is the average daily dose (mg/kg/day) and RfD the reference dose, with $RfD_{(inh)}$ calculated from RfC adjusted for age-specific inhalation rates and body weight. Overall risk from multiple metals is expressed as the Total Hazard Index (THI), the sum of individual HQs.

$$\text{Total hazard index } (THI) = HQ_1 + HQ_2 + \cdots + HQ_n \quad (12)$$

If THI < 1.0, significant additive or toxic effects are unlikely; no further evaluation is needed.
If THI > 1.0, there may be concern for non-cancer health effects.

Data Analysis

All determinations were conducted in triplicate, and the data generated were analyzed statistically using the Statistical Package for the Social Sciences (SPSS) version 27 and Microsoft Excel 2016. Pearson's correlation analysis was performed to evaluate the relationships among the measured heavy metals in the sediment samples.

RESULT AND DISCUSSION

Heavy Metal Concentrations of the Sediment

The heavy metal concentrations in the sediments of Mmili Ocha River reflect a combined influence of natural geological inputs and human-driven activities such as urban runoff, agricultural practices, waste disposal, and possible minor industrial contributions. River sediments commonly function as both sinks and secondary sources of contaminants, where metals accumulate over time and may be remobilized under changing environmental conditions (Emenike *et al.,* 2020; Okafor *et al.,* 2024). The observed results reveal clear spatial and seasonal variability across sampling stations, indicating differing levels of metal enrichment among the studied elements.

Cadmium (Cd) concentrations ranged from 0.45 ± 0.06 to 0.78 ± 0.09 ppm in the rainy season and increased in the dry season to 0.64 ± 0.08–0.94 ± 0.10 ppm, with the highest value recorded at Station C (0.94 ± 0.10 ppm). This seasonal rise suggests localized anthropogenic influence and enhanced accumulation during low-flow conditions. Such dry-season enrichment aligns with reports that reduced river discharge limits dilution and promotes sediment-bound metal retention (Adesiyan *et al.,* 2018; Ayodeji *et al.,* 2026). Cadmium, being highly toxic and non-essential, is commonly linked to fertilizers, battery waste, sewage discharge, and industrial effluents (Tchounwou *et al.,* 2012). The values obtained indicate moderate contamination levels comparable to those reported in other Nigerian river systems (Abdu-Raheem *et al.,* 2024; Ololade *et al.,* 2024).

Arsenic (As) concentrations varied from (0.23 ± 0.02–0.29 ± 0.04 ppm) in the rainy season and increased notably in the dry season to (0.52 ± 0.07–0.72 ± 0.09 ppm), with the highest level at Station C. This pronounced seasonal increase suggests enhanced sediment adsorption and retention under reduced hydrodynamic conditions. Arsenic mobility is strongly controlled by redox conditions and fine sediment characteristics, which typically intensify during dry periods (Emenike *et al.,* 2020; Bawa-Allah, 2023). Although values remain relatively low, the dry-season elevation suggests gradual accumulation, likely influenced by agricultural runoff and domestic wastewater inputs (Awosusi and Adisa, 2020; Okafor *et al.,* 2024).

Iron (Fe) recorded the highest concentrations among all the analyzed metals, ranging from (1979 ± 89 to 2346 ± 96 ppm**)** during the rainy season and increasing to (2021 ± 91 to 2841 ± 121 ppm**)** in the dry season. The predominance of iron is primarily attributed to its natural abundance in crustal materials and the weathering of iron-bearing minerals. However, anthropogenic inputs from the nearby dumpsite may have further contributed to the elevated concentrations. The disposal of corroded iron and steel materials, scrap metals, discarded cans, and other metallic wastes can generate leachate, which is transported into the surrounding soils and the Mmili Ocha River through surface runoff and infiltration. Farming activities around the dumpsite may also facilitate the movement of these contaminants into the river sediments (Pasquier *et al.,* 2022; Ihedioha *et al.,* 2017). The relatively higher iron concentrations observed during the dry season are likely associated with reduced river flow, lower dilution, and increased sediment accumulation, a pattern consistent with previous studies on Nigerian river sediments (Jolaosho *et al.,* 2023).

Zinc (Zn) ranged from (34 ± 4.00–53 ± 5.00 ppm) during the rainy season and increased in the dry season to (51 ± 6.00–91 ± 9.00 ppm), with Stations B and C showing higher values. Although zinc is an essential trace element, elevated concentrations may become toxic. Its occurrence in sediments is commonly associated with domestic waste, agricultural inputs, galvanized materials, and urban runoff (Tchounwou *et al.,* 2012). The observed seasonal increase reflects reduced flow conditions that favor sediment retention and metal accumulation (Adesiyan *et al.,* 2018; Bawa-Allah, 2023), consistent with moderately impacted Nigerian rivers (Awosusi and Adisa, 2020).

Chromium (Cr) concentrations were relatively low, ranging from (1.37 ± 0.17–2.49 ± 0.20 ppm) in the rainy season and slightly increasing to (2.61 ± 0.21–2.70 ± 0.21 ppm) in the dry season. These low values suggest minimal industrial influence, as chromium is typically associated with industrial processes such as tanning, dyeing, and metal plating (Järup, 2003). The results indicate that chromium in the study area is likely derived mainly from natural geological sources with limited anthropogenic input, consistent with findings from less industrialized river systems in southeastern Nigeria (Abdu-Raheem *et al.,* 2024; Okafor *et al.,* 2024).

Lead (Pb) concentrations ranged from (14.70 ± 1.50–24.75 ± 2.65 ppm) in the rainy season and increased in the dry season to (21.46 ± 2.06–30.32 ± 3.02 ppm). The relatively elevated Pb levels highlight significant anthropogenic influence. Lead contamination is often associated with vehicular emissions, improper waste disposal, battery waste, and urban runoff (Uwaifo *et al.,* 2023). The consistent dry-season increase indicates accumulation due to reduced flushing capacity. Similar concentrations have been reported in urban and semi-urban Nigerian rivers influenced by human activities (Jolaosho *et al.,* 2023; Ololade *et al.,* 2024).

Mercury (Hg) levels remained relatively stable across seasons, ranging from (0.14 ± 0.02–0.15 ± 0.02 ppm) in the rainy season and (0.15 ± 0.02–0.17 ± 0.02 ppm) in the dry season. The minimal variation suggests limited localized mercury pollution. However, mercury remains highly toxic due to its tendency to bioaccumulate and biomagnify in aquatic food chains (USEPA, 2011; Tchounwou *et al.,* 2012). The observed levels likely represent background environmental concentrations, consistent with other Nigerian freshwater systems (El Zokm *et al.,* 2020).

The overall distribution of heavy metals in the sediments of Mmili Ocha River follows the order Fe >> Zn > Pb > Cr > Cd > As > Hg, indicating a clear dominance of iron over all other measured elements. This exceptionally high level of iron is largely attributed to its natural abundance in the Earth's crust, meaning its presence in the sediment is mainly controlled by geological weathering processes rather than pollution sources (Turekian and Wedepohl, 1961). In contrast, the relatively elevated levels of zinc, lead, and cadmium point more strongly toward human influence, most likely from activities such as waste disposal, agricultural runoff, and urban inputs entering the river system, which gradually enrich the sediments with these metals over time (Emenike *et al.,* 2020). Chromium, arsenic, and mercury occur at comparatively lower concentrations, suggesting limited industrial contribution in the study area, as these metals are often associated with more intense industrial or manufacturing activities (Abdu-Raheem *et al.,* 2024). Across all sampling locations, a consistent seasonal pattern is observed, with higher metal concentrations recorded during the dry season compared to the rainy season. This trend can be explained by reduced river flow during the dry period, which lowers dilution capacity and promotes the settling and accumulation of metals within the sediment matrix. In contrast, the rainy season introduces higher water volumes that help disperse and dilute contaminants, temporarily reducing their concentration in sediments. This seasonal behaviour is widely reported in tropical river systems where hydrological variation strongly influences sediment chemistry (Adesiyan *et al.,* 2018; Ayodeji *et al.,* 2026).

Overall, the findings suggest that the Mmili Ocha River is not heavily industrially polluted but is moderately impacted by ongoing human activities in its catchment area. While iron largely reflects natural geological background levels, the noticeable enrichment of cadmium, lead, and zinc signals emerging anthropogenic pressure that should not be ignored. If these inputs continue without proper management, there is a risk of gradual sediment contamination that could affect aquatic organisms and potentially pose long-term ecological and human health concerns, making continuous environmental monitoring necessary (Bawa-Allah, 2023; Okafor *et al.,* 2024).

Table 1: Results of the heavy metal concentrations of the evaluated water sediment from mmili ocha river

SEASON		RAINY			DRY		
Parameters	**Unit**	**Station A**	**Station B**	**Station C**	**Station A**	**Station B**	**Station C**
Cadmium	ppm	0.45 ± 0.06	0.46 ± 0.05	0.78 ± 0.09	0.86 ± 0.08	0.64 ± 0.08	0.94 ± 0.10
Arsenic	ppm	0.23 ± 0.03	0.23 ± 0.02	0.29 ± 0.04	0.52 ± 0.07	0.58 ± 0.08	0.72 ± 0.09
Iron	ppm	1979 ± 89	2225 ± 85	2346 ± 96	2021 ± 91	2583 ± 113	2841 ± 121
Zinc	ppm	34 ± 4.00	47 ± 5.00	53 ± 5.00	51 ± 6.00	83 ± 8.00	91 ± 9.00
Chromium	ppm	1.37 ± 0.17	1.57 ± 0.17	2.49 ± 0.20	2.61 ± 0.21	2.69 ± 0.24	2.70 ± 0.21
Lead	ppm	14.70 ± 1.50	17.22 ± 1.62	24.75 ± 2.65	21.46 ± 2.06	23.42 ± 2.32	30.32 ± 3.02
Mercury	ppm	0.15 ± 0.02	0.14 ± 0.02	0.15 ± 0.02	0.15 ± 0.02	0.16 ± 0.02	0.17 ± 0.02

Key: Station A = Water sample from upstream at coordinates latitude N 6°28'34.734'' and longitude E7°31'3.216''
Station B = Water sample from midstream at coordinates latitude N 6°28'34.752'' and longitude E7°31'2.50212''
Station C= Water sample from downstream at coordinates latitude N 6°28'34.41'' and longitude E 7°32' 8.90988''

Comparison of Measured Heavy Metal Concentrations with Sediment Quality Guidelines

Comparison of the heavy metal concentrations in Table 1 with the sediment quality guideline values in Table 2 shows that the sediments of Mmili Ocha River are generally within acceptable environmental limits, although some metals indicate moderate human influence and gradual accumulation.

Cadmium (Cd) concentrations ranged from (0.45 ± 0.06 to 0.94 ± 0.10 ppm). Most values were below the USEPA limit of 0.6 ppm and close to the TEC value of 0.99 ppm, particularly at Station C during the dry season. Although the concentrations remain far below the PEC value of 4.98 ppm and WHO limit of 6 ppm, the higher dry season values suggest increasing anthropogenic input, likely from agricultural runoff, domestic waste, and other human activities (Abdu-Raheem *et al.,* 2024; Ololade *et al.,* 2024).

Arsenic (As) concentrations ranged from (0.23 ± 0.02 to 0.72 ± 0.09 ppm), which are well below the TEC (9.79 ppm) and PEC (33.0 ppm) values. This indicates low arsenic contamination and minimal ecological risk. However, the increase observed during the dry season suggests gradual accumulation under low-flow conditions where sediment retention is enhanced (Emenike *et al.,* 2020).

Iron (Fe) showed the highest concentrations, ranging from (1979 ± 89 to 2841 ± 121 ppm). Although no specific sediment quality guideline is available for Fe, its predominance is expected because iron is one of the most abundant elements in the Earth's crust and is naturally derived from the weathering of iron-bearing rocks and minerals (Turekian & Wedepohl, 1961). However, the elevated Fe concentrations may also reflect anthropogenic inputs from the nearby dumpsite, where corroded iron and steel materials, scrap metals, discarded cans, and other metallic wastes generate leachate that can be transported into the river through runoff and infiltration. Consequently, the observed Fe levels likely result from the combined influence of natural geological processes and human activities in the study area (Pasquier *et al.,* 2022; Ihedioha *et al.,* 2017).

Zinc (Zn) concentrations ranged from (34 ± 4.00 to 91 ± 9.00 ppm) and remained below the USEPA limit of 110 ppm, WHO limit of 123 ppm, TEC value of 121 ppm, and PEC value of 459 ppm. This suggests that zinc levels are still within safe limits. However, the dry season increase, especially at Stations B and C, points to moderate enrichment from urban runoff, agricultural activities, and domestic waste sources (Awosusi and Adisa, 2020).

Chromium (Cr) concentrations ranged from (1.37 ± 0.17 to 2.70 ± 0.21 ppm), which are far below the USEPA and WHO limits of 25 ppm as well as the TEC and PEC values. These low levels indicate limited industrial contamination in the study area and suggest that chromium mainly originates from natural sources (Järup, 2003).

Lead (Pb) concentrations ranged from (14.70 ± 1.50 to 30.32 ± 3.02 ppm). Although all values were below the USEPA limit of 40 ppm and the TEC value of 35.8 ppm, Pb levels were relatively higher than most other toxic metals, especially during the dry season. This suggests moderate anthropogenic contamination from urban runoff, vehicular emissions, waste disposal, and battery-related activities (Uwaifo *et al.,* 2023).

Mercury (Hg) concentrations ranged from (0.14 ± 0.02 to 0.17 ± 0.02 ppm) and remained below the TEC value of 0.18 ppm and PEC value of 1.06 ppm. The low concentrations indicate minimal mercury contamination. However, because mercury can bioaccumulate in aquatic organisms, continuous monitoring remains important (USEPA, 2011; Tchounwou *et al.,* 2012).

Overall, the comparison with sediment quality guidelines suggests that Mmili Ocha River sediments are not heavily polluted, as most metals remain below recommended limits. However, the elevated dry season concentrations of cadmium, lead, and zinc indicate increasing human influence and gradual metal buildup in the river sediments. This highlights the need for regular environmental monitoring and proper waste management to prevent future ecological and health risks (Bawa-Allah, 2023; Okafor *et al.,* 2024).

Table 2: Sediment quality Guidelines (SQG) for metal elements in ppm

Metal Elements	USEPA Sediment Quality Guidelines (SQG) Limit	WHO Sediment Quality Guidelines (SQG) Limit	Threshold Effect Concentration (TEC)	Probable Effect Concentration (PEC)
Cadmium	0.6	6	0.99	4.98
Arsenic	-	-	9.79	330
Iron	-	-	-	-
Zinc	110	123	121	459
Chromium	25	25	43.4	111
Lead	40	-	35.8	128
Mercury	-	-	0.18	1.06

Pearson Correlation Analysis of Heavy Metals in Water Sediments

The Pearson correlation analysis (Tables 3 and 4) revealed predominantly positive relationships among the heavy metals, suggesting common anthropogenic sources and similar geochemical behavior in the sediments (Mohiuddin *et al.,* 2010; Ololade *et al.,* 2024). During the rainy season, cadmium exhibited strong positive correlations with arsenic (r = 0.934), chromium (r = 0.990), and lead (r = 0.980), while chromium and lead were also highly correlated (r = 0.993). Iron showed an almost perfect correlation with zinc (r = 0.999), indicating that iron-bearing minerals may facilitate the adsorption and retention of zinc and other trace metals in the sediments (Pasquier *et al.,* 2022). Mercury displayed comparatively weaker correlations (r = 0.499–0.781), suggesting that its distribution may be influenced by additional environmental processes such as atmospheric deposition and organic matter interactions (Tchounwou *et al.,* 2012).

In the dry season, strong positive correlations persisted among arsenic, iron, zinc, lead, chromium, and mercury, with particularly high associations between arsenic and lead (r = 0.987), iron and zinc (r = 0.988), and chromium and mercury (r = 0.919). These relationships indicate common contamination sources and enhanced metal accumulation under reduced river flow conditions (Ayodeji *et al.,* 2026; Bawa-Allah, 2023). Conversely, cadmium showed weak correlations with iron (r = 0.171), zinc (r = 0.112), and chromium (r = 0.431), suggesting relatively different mobility or localized inputs during the dry season (Awosusi and Adisa, 2020). Overall, the observed correlations indicate that municipal waste disposal, urban runoff, and leachate infiltration are the primary contributors to heavy metal contamination in the study area.

Table 3: Pearson correlation coefficient matrix for the water sediment in rainy season

	Cadmium	Arsenic	Iron	Zinc	Chromium	Lead	Mercury
Cadmium	1						
Arsenic	.934	1					
Iron	.799	.812	1				
Zinc	.790	.802	.999	1			
Chromium	.990	.909	.860	.852	1		
Lead	.980	.931	.900	.894	.993	1	
Mercury	.575	.781	.500	.499	.529	.555	1

Table 4: Pearson correlation coefficient matrix for the water sediment in dry season

	Cadmium	Arsenic	Iron	Zinc	Chromium	Lead	Mercury
Cadmium	1						
Arsenic	.624	1					
Iron	.171	.852	1				
Zinc	.112	.841	.988	1			
Chromium	.431	.723	.466	.550	1		
Lead	.651	.987	.858	.824	.608	1	
Mercury	.648	.890	.601	.641	.919	.821	1

Geo-accumulation Index (Igeo) of the Sediments

The geo-accumulation index (Igeo) results (Table 5) generally show that the sediments of Mmili Ocha River are not heavily polluted by heavy metals. Most of the metals recorded Igeo values less than zero, which according to the Müller classification indicates an "unpolluted" sediment condition. This suggests that the metal levels in the river are mainly controlled by natural geological processes, with only slight influence from human activities.

Among all the metals analyzed, cadmium showed the highest Igeo values, ranging from 0.00–0.79 during the rainy season and 0.51–1.06 in the dry season. The highest value was recorded at Station C in the dry season (1.06), indicating an "unpolluted to moderately polluted" condition. This suggests slight cadmium enrichment in the river sediment, likely linked to human activities such as waste disposal, agricultural runoff, and domestic discharges (Emenike *et al.,* 2020; Tchounwou *et al.,* 2012). The higher dry season values further show that reduced river flow and lower dilution during this period encourage metal accumulation in sediments (Adesiyan *et al.,* 2018; Ayodeji *et al.,* 2026).

Arsenic, iron, zinc, chromium, lead, and mercury all recorded negative Igeo values, indicating that the sediments remain unpolluted with respect to these metals. Although iron exhibited the highest concentration among the analyzed metals, its low Igeo values suggest that its presence is likely influenced by both natural geological processes and anthropogenic activities in the study area (Pasquier *et al*., 2022; Ihedioha *et al*., 2017).

Zinc and lead showed slight increases during the dry season, suggesting minor anthropogenic input from urban runoff, agricultural activities, and waste disposal, but their levels still remained within the unpolluted category (Awosusi and Adisa, 2020; Uwaifo *et al.,* 2023).

Overall, the Igeo assessment indicates that Mmili Ocha River sediments are generally safe from serious heavy metal contamination. However, the slight enrichment of cadmium and the seasonal increase of some metals during the dry season suggest emerging human influence on the river system. Continuous environmental monitoring is therefore important to prevent future metal buildup and possible ecological or health risks (Bawa-Allah, 2023; Okafor *et al.,* 2024).

Table 5: The Geo-accumulation Index (Igeo) of the sediments rainy and dry season

Season	**Rainy**			**Dry**			**Igeo Classification**	
Parameters	Station A	Station B	Station C	Station A	Station B	Station C	Igeo Value	Description
Cadmium	0.0	0.03	0.79	0.93	0.51	1.06	0 – 1	Unpolluted to moderately polluted
Arsenic	-6.41	-6.41	-6.07	-5.23	-5.07	-4.76	≤ 0	Unpolluted
Iron	-5.16	-4.99	-4.92	-5.13	-4.78	-4.64	≤ 0	Unpolluted
Zinc	-2.07	-1.6	-1.43	-1.48	-0.78	-0.65	≤ 0	Unpolluted
Chromium	-6.62	-6.43	-5.76	-5.69	-5.65	-5.64	≤ 0	Unpolluted
Lead	-1.03	-0.8	-0.28	-0.48	-0.36	0.02	≤ 0	Unpolluted
Mercury	-2.0	-2.1	-2.0	-2.0	-1.91	-1.82	≤ 0	Unpolluted

Enrichment Factor (EF) of the Sediments

The Enrichment Factor (EF) results (Table 6) indicate that the sediments of Mmili Ocha River are influenced by both natural geological processes and human activities. Among the analyzed metals, cadmium showed the highest enrichment, with EF values ranging from 32.53–52.31 during the rainy season and increasing to 38.98–66.95 in the dry season. The highest value was recorded at Station A during the dry season (66.95), indicating extremely high enrichment and suggesting strong anthropogenic input. This may be linked to activities such as waste disposal, agricultural runoff, and sewage discharge around the river environment (Tchounwou *et al.,* 2012). Similar cadmium enrichment patterns have been reported in contaminated river sediments across Nigeria (Abdu-Raheem *et al.,* 2024; Ololade *et al.,* 2024).

Lead also recorded relatively high EF values, ranging from 17.53–24.90 in the rainy season and 21.40–25.19 during the dry season. The highest enrichment was observed at Station C in the dry season (25.19), indicating significant to very high enrichment. This suggests that lead contamination in the river is strongly influenced by human activities such as urban runoff and indiscriminate waste disposal (Uwaifo *et al.,* 2023).

Zinc showed moderate to significant enrichment, with EF values ranging from 8.54–11.22 in the rainy season and 12.54–15.97 in the dry season. Mercury also showed noticeable enrichment, with values between 7.06 and 8.94 across both seasons. Although mercury concentrations were relatively low, the EF values suggest some level of anthropogenic contribution, possibly from domestic wastes and runoff entering the river system (Emenike *et al.,* 2020).

In contrast, arsenic and chromium recorded low EF values throughout the study. Arsenic ranged from 0.38–0.93, while chromium ranged from 0.36–0.68 across all stations and seasons. These values indicate minimal enrichment, suggesting that both metals are mainly derived from natural geological sources rather than human activities. The low chromium enrichment also points to limited industrial influence within the study area (Järup, 2003).

A clear seasonal pattern was observed, with most metals showing higher EF values during the dry season than in the rainy season. This trend suggests that reduced water flow and lower dilution during the dry period encourage the accumulation of metals in the sediments, whereas increased rainfall during the wet season helps disperse contaminants (Adesiyan *et al.,* 2018; Ayodeji *et al.,* 2026).

Overall, the EF results show that Mmili Ocha River is moderately affected by anthropogenic activities, particularly through the enrichment of cadmium and lead. While some metals still reflect natural background conditions, the increasing accumulation of toxic metals indicates growing environmental pressure on the river system, highlighting the need for regular monitoring and proper environmental management to reduce potential ecological and human health risks (Bawa-Allah, 2023; Okafor *et al.,* 2024).

Table 6: The Enrichment factor (EF) of the sediments for rainy and dry season

Season	**Rainy**			**Dry**			**EF Classification**	
Parameters	Station A	Station B	Station C	Station A	Station B	Station C	EF Range	Description
Cadmium	35.78	32.53	52.31	66.95	38.98	52.06	20 – 40	Very high to extremely high enrichment
Arsenic	0.42	0.38	0.45	0.93	0.82	0.92	< 2	Deficiency to minimal enrichment
Zinc	8.54	10.5	11.22	12.54	15.97	15.91	5 – 20	Significant enrichment
Chromium	0.36	0.37	0.56	0.68	0.55	0.5	< 2	Deficiency to minimal enrichment
Lead	17.53	18.26	24.9	25.06	21.4	25.19	5 – 20 → 20 – 40	Significant to very high enrichment
Mercury	8.94	7.42	7.54	8.76	7.31	7.06	5 – 20	Significant enrichment

Contamination Factor (CF) of the Sediments

The contamination factor (CF) results (Table 7) show that the sediments of Mmili Ocha River are generally experiencing low to moderate contamination, although some metals indicate noticeable human influence. Cadmium recorded CF values between 1.50 and 2.60 during the rainy season and increased further to 2.13–3.13 in the dry season. The highest value was observed at Station C during the dry season (3.13), indicating considerable cadmium contamination at that location. This pattern suggests increasing anthropogenic input, likely from agricultural runoff, waste disposal, and other human activities around the river catchment (Emenike *et al.,* 2020; Awosusi and Adisa, 2020). Similar observations have been reported in other Nigerian river sediments where cadmium contamination was linked to human activities and seasonal accumulation effects (Abdu-Raheem *et al.,* 2024; Ololade *et al.,* 2024).

Arsenic, iron, zinc, and chromium all recorded CF values below 1 across both seasons, indicating low contamination levels. Arsenic values ranged from 0.02–0.06, iron from 0.04–0.06, zinc from 0.36–0.96, and chromium from 0.02–0.03. These low values suggest that the concentrations of these metals are still close to natural background levels and may largely originate from natural geological processes rather than major pollution sources (Turekian and Wedepohl, 1961). The relatively low chromium contamination further indicates limited industrial influence within the study area, since chromium pollution is commonly associated with industrial discharge and metal-processing activities (Järup, 2003; Okafor *et al.,* 2024).

Lead showed moderate contamination, with CF values ranging from 0.73–1.24 during the rainy season and increasing to 1.07–1.52 during the dry season. The highest Pb contamination was recorded at Station C in the dry season (1.52), indicating stronger human influence at that station, possibly from urban runoff, refuse disposal, and vehicular-related inputs (Uwaifo *et al.,* 2023). Mercury also showed moderate contamination across all stations, with CF values ranging from 1.75–2.12. Although the Hg values were not extremely high, the consistent moderate contamination is environmentally important because mercury is highly toxic and can bioaccumulate in aquatic organisms over time, thereby posing potential ecological and human health risks (USEPA, 2011; Tchounwou *et al.,* 2012).

Generally, the dry season recorded higher CF values than the rainy season for most metals. This trend suggests that reduced river flow and lower dilution during the dry period promote the accumulation of metals in river sediments, whereas increased water volume during the rainy season helps disperse contaminants (Adesiyan *et al.,* 2018; Ayodeji *et al.,* 2026). Overall, the CF assessment indicates that Mmili Ocha River sediments are not severely polluted but are already showing signs of moderate contamination, particularly for cadmium, lead, and mercury. Continuous monitoring and proper environmental management are therefore necessary to prevent further buildup of these metals in the river ecosystem (Bawa-Allah, 2023; Okafor *et al.,* 2024).

Table 7: Contamination Factor (CF) of the sediments for rainy and dry season

Season	Rainy			Dry			CF Classification	
Parameters	Station A	Station B	Station C	Station A	Station B	Station C	**CF range**	Description
Cadmium	1.50	1.53	2.60	2.87	2.13	3.13	20 – 40	Moderate to considerable contamination
Arsenic	0.02	0.02	0.02	0.04	0.04	0.06	CF < 1	Low contamination
Iron	0.04	0.05	0.05	0.04	0.05	0.06	CF < 1	Low contamination
Zinc	0.36	0.49	0.56	0.54	0.87	0.96	CF < 1	Low contamination
Chromium	0.02	0.02	0.03	0.03	0.03	0.03	CF < 1	Low contamination
Lead	0.73	0.86	1.24	1.07	1.17	1.52	1 ≤ CF < 3	Moderate contamination
Mercury	1.88	1.75	1.88	1.88	2.00	2.12	1 ≤ CF < 3	Moderate contamination

Degree of Contamination (Cd) and Pollution Load Index (PLI) of the Sediments

The Degree of Contamination (Cd) and Pollution Load Index (PLI) results (Table 8) provide an overall assessment of the contamination status of the Mmili Ocha River sediments across the rainy and dry seasons. The Cd values ranged from 4.55 to 6.47, indicating generally low to moderate contamination within the study area. During the rainy season, Station A and Station B recorded Cd values of 4.55 and 4.72 respectively, which fall within the low contamination category, while Station C recorded a slightly higher value of 6.38, indicating moderate contamination. In the dry season, all stations showed increased Cd values, with Station A recording the highest value (6.47), followed by Station B (6.29). The seasonal increase suggests that metal accumulation becomes more pronounced during the dry period due to lower river flow and reduced dilution capacity, which enhances the retention of contaminants within sediments (Adesiyan *et al.,* 2018; Ayodeji *et al.,* 2026).

The relatively higher Cd values observed at Station C during the rainy season and across the dry season stations may reflect localized anthropogenic inputs such as runoff from nearby human activities, waste disposal, and agricultural practices. Similar observations have been reported in other Nigerian river systems where sediment contamination increased in areas exposed to urban and agricultural influence (Emenike *et al.,* 2020; Ololade *et al.,* 2024). However, despite these increases, the Cd values remained below critical contamination thresholds, indicating that the river sediments are not yet heavily degraded.

The Pollution Load Index (PLI) values ranged from 0.20 to 0.31 across all stations and seasons. Since all values were below 1, the sediments are classified as unpolluted. During the rainy season, PLI values increased slightly from Station A (0.20) to Station C (0.27), while the dry season recorded slightly higher values of 0.28 and 0.31 at Stations A and B respectively. Although these values remain within the "no pollution" category, the gradual increase during the dry season suggests ongoing accumulation of metals in the sediment environment. This pattern supports previous findings that tropical river sediments tend to retain more contaminants during periods of low water discharge (Bawa-Allah, 2023; Jolaosho *et al.,* 2023).

Overall, the Cd and PLI assessments indicate that the sediments of Mmili Ocha River are presently experiencing low to moderate contamination and are not heavily polluted. Nevertheless, the consistent increase in contamination indices during the dry season points to growing anthropogenic pressure on the river system. Continuous environmental monitoring and proper waste management practices are therefore important to prevent future deterioration of sediment quality and associated ecological risks (Okafor *et al.,* 2024; Uwaifo *et al.,* 2023).

Table 8: Degree of Contamination (Cd) and Pollution Load Index (PLI) of the sediments for rainy and dry season

Season	Locations	CD	CD Class	Contamination Category	PLI	PLI Class	Pollution Status
Rainy	Station A	4.55	Cd<8	Low contamination	0.20	PLI<1	No pollution
	Station B	4.72	Cd<8	Low contamination	0.22	PLI<1	No pollution
	Station C	6.38	Cd<8	Moderate contamination	0.27	PLI<1	No pollution
Dry	Station A	6.47	Cd<8	Moderate contamination	0.28	PLI<1	No pollution
	Station B	6.29	Cd<8	Moderate contamination	0.31	PLI<1	No pollution

Potential Ecological Risk Index (PERI) of the Sediments

The Potential Ecological Risk Index (PERI) results (Table 9) reveal varying degrees of ecological risk associated with heavy metals in the sediments of Mmili Ocha River across both rainy and dry seasons. The ecological risk assessment shows that cadmium (Cd) and mercury (Hg) contributed most significantly to the overall ecological risk of the sediments, while arsenic (As), zinc (Zn), chromium (Cr), and lead (Pb) posed relatively low ecological threats. This pattern reflects the high toxic response factors of Cd and Hg, which are known to have strong ecological impacts even at relatively low concentrations (Hakanson, 1980; Tchounwou *et al.,* 2012).

During the rainy season, the overall RI values ranged from 120.94 at Station B to 160.28 at Station C. Stations A and B were classified under low ecological risk, while Station C recorded a moderate ecological risk. The higher RI value at Station C was mainly influenced by elevated Cd (78.00) and Hg (75.20) risk factors, suggesting stronger anthropogenic influence at that location. Possible sources may include agricultural runoff, domestic waste discharge, and urban-related activities around the river environment (Emenike *et al.,* 2020; Uwaifo *et al.,* 2023).

In the dry season, ecological risk values increased across all stations, with RI values ranging from 151.28 to 188.04, placing all locations within the moderate ecological risk category. Station C recorded the highest RI value (188.04), followed by Station A (167.71), while Station B had the lowest value (151.28). The increase observed during the dry season suggests enhanced accumulation of metals in the sediments due to lower river flow, reduced dilution, and increased retention of contaminants within the sediment matrix (Adesiyan *et al.,* 2018; Ayodeji *et al.,* 2026).

Cadmium showed moderate to considerable ecological risk across most stations, with Eri values increasing from 45.00–78.00 during the rainy season to 64.00–94.00 in the dry season. This indicates that Cd is one of the major contributors to ecological stress in the river sediments. Mercury also recorded relatively high ecological risk values ranging from 70.00 to 84.80, despite its low concentration in the sediments. This is largely due to the extremely high toxicity and bioaccumulative nature of mercury in aquatic ecosystems (USEPA, 2011; Tchounwou *et al.,* 2012). In contrast, As, Zn, Cr, and Pb all recorded low ecological risk factors, indicating that their current concentrations are less likely to cause immediate ecological harm.

Overall, the PERI assessment suggests that the sediments of Mmili Ocha River are experiencing low to moderate ecological risk, with the dry season showing greater ecological pressure than the rainy season. The findings further indicate that cadmium and mercury are the primary metals driving ecological risk within the river system. Although the overall risk level is not yet severe, the gradual increase in ecological risk during the dry season highlights the need for continuous environmental monitoring and effective pollution control measures to prevent future deterioration of the aquatic ecosystem (Bawa-Allah, 2023; Okafor *et al.,* 2024).

Table 9: Potential Ecological Risk Index (PERI) of the sediments for rainy and dry season

Season	**Location**	**Potential Ecological risk factor (Er^i)**						**RI**	**Potential Ecological Risk Index**
		Cd	As	Zn	Cr	Pb	Hg		
Raining	Station A	45.00	0.20	0.36	0.04	3.65	75.20	124.45	Low ecological risk
	Station B	45.90	0.20	0.49	0.05	4.30	70.00	120.94	Low ecological risk
	Station C	78.00	0.24	0.56	0.08	6.20	75.20	160.28	Moderate ecological risk
Dry	Station A	86.10	0.44	0.54	0.08	5.35	75.20	167.71	Moderate ecological risk
	Station B	64.00	0.48	0.87	0.08	5.85	80.00	151.28	Moderate ecological risk
	Station C	94.00	0.60	0.96	0.08	7.60	84.80	188.04	Moderate ecological risk
Individual Ecological Risk Factor (Er)		moderate to considerable	Low	low	low	Low	moderate to considerable		

Human Health Risk Assessment of Heavy Metals in the water sediments

The human health risk assessment of heavy metals in the sediments of the Mmili Ocha River showed that the level of risk differed across the various metals and exposure pathways (Table 10). The study evaluated exposure through inhalation, ingestion, and dermal contact for both children and adults using Average Daily Dose (ADD), Reference Dose (RfD), Hazard Quotient

(HQ), and Total Hazard Index (THI). Among the three exposure routes, ingestion was clearly the most important pathway, while inhalation and dermal contact contributed very little to the overall risk. This pattern has also been reported in previous environmental studies, where accidental ingestion of contaminated sediments was identified as the major route of heavy metal exposure, especially among children (USEPA, 2011; Tchounwou *et al.,* 2012).

Iron (Fe) recorded the highest concentration in the sediment with a mean value of 2332.50 ± 333.18 mg/kg, followed by zinc (59.83 ± 22.20 mg/kg) and lead (21.98 ± 5.57 mg/kg). However, the potential health risk depended not only on the concentration of the metals but also on their toxicity and level of exposure. In children, iron produced the highest ingestion hazard quotient (HQ) of 15.57, followed by arsenic (6.70), chromium (3.50), cadmium (3.22), and mercury (2.34). These values were all above the recommended safety limit of 1, indicating possible non-carcinogenic health effects from long-term ingestion of contaminated sediments. In adults, the ingestion HQ values were generally lower, although iron still recorded a value of 1.67. The higher risks observed in children are expected because children are more vulnerable to environmental contaminants due to their lower body weight, higher exposure rate, and frequent hand-to-mouth activities (USEPA, 2011).

Cadmium, which had a mean concentration of 0.69 ± 0.21 mg/kg, recorded ingestion HQ values of 3.22 for children and 3.45×10^{-1} for adults. This suggests that children may be more susceptible to cadmium-related health effects such as kidney damage and developmental disorders after prolonged exposure (Tchounwou *et al.,* 2012). Arsenic also showed elevated ingestion risk, particularly in children, where the HQ value reached 6.70 compared to 7.17×10^{-1} in adults. This indicates that continuous exposure to arsenic-contaminated sediments may pose health concerns over time.

Lead recorded a relatively high concentration of 21.98 ± 5.57 mg/kg in the sediments. Although no reference dose was provided for lead in the assessment table, the ingestion ADD values of 1.03×10^{-1} for children and 1.10×10^{-2} for adults suggest considerable exposure potential. Lead is well known for its harmful effects on the nervous system, especially in children, where prolonged exposure may affect learning ability, behavior, and mental development (USEPA, 2011; Uwaifo *et al.,* 2023).

In comparison, zinc showed relatively low health risk despite its higher concentration in the sediments. The ingestion HQ values for zinc were below 1 for both children (9.30×10^{-1}) and adults (9.97×10^{-2}), indicating that zinc exposure is unlikely to cause immediate health effects at the current levels. Mercury and chromium also contributed to ingestion risk, particularly among children, although their values remained lower than those of iron and arsenic.

Unlike ingestion, inhalation exposure showed extremely low risk levels for all analyzed metals. The Total Hazard Index (THI) for inhalation was 1.81×10^{-4} for children and 2.22×10^{-4} for adults, both of which were far below the safety threshold of 1. Individual inhalation HQ values were similarly very low, indicating that breathing in sediment-associated particles is unlikely to pose serious health concerns in the study area.

Dermal exposure also contributed minimally to the overall health risk. The dermal THI value was 1.88×10^{-3} for both children and adults, which is well below the acceptable limit. The low dermal HQ values suggest that direct skin contact with the sediments is not a major pathway of exposure in the river environment.

Overall, the findings show that the sediments of the Mmili Ocha River are moderately affected by heavy metal contamination, with ingestion representing the main route of human exposure. Children appear to be more at risk than adults due to their greater sensitivity and exposure characteristics. Although inhalation and dermal risks were negligible, the elevated ingestion risks associated with iron, arsenic, cadmium, chromium, and mercury indicate growing human impact on the river system. These findings highlight the need for regular environmental monitoring, improved waste disposal practices, and better management of human activities around the river in order to reduce future ecological and public health risks (Emenike *et al.,* 2020; Okafor *et al.,* 2024).

Table 19: Human Health Risk Assessment

Metals	Metal Conc. (mg/kg)	Age group	Inhalation			Ingestion			Dermal		
			ADD	RfD	HQ	ADD	RfD	HQ	ADD	RfD	HQ
Cd	0.69 ± 0.21	Children	2.46×10^{-10}	6.67×10^{-6}	3.69×10^{-5}	3.22×10^{-3}	1.00×10^{-3}	3.22	1.26×10^{-8}	2.5×10^{-5}	5.04×10^{-4}
		Adult	1.39×10^{-10}	2.86×10^{-6}	4.86×10^{-5}	3.45×10^{-4}	1.00×10^{-3}	3.45×10^{-1}	1.08×10^{-9}	2.5×10^{-5}	4.32×10^{-5}
As	0.43 ± 0.21	Children	1.54×10^{-10}	2.00×10^{-5}	7.70×10^{-6}	2.01×10^{-3}	3.00×10^{-4}	6.70	7.88×10^{-9}	2.85×10^{-4}	2.77×10^{-5}
		Adult	8.66×10^{-11}	8.57×10^{-6}	1.01×10^{-5}	2.15×10^{-4}	3.00×10^{-4}	7.17×10^{-1}	6.75×10^{-10}	2.85×10^{-4}	2.37×10^{-6}
Fe	2332.50 ± 333.18	Children	8.33×10^{-7}	—	—	1.09×10^{1}	7.00×10^{-1}	15.57	4.28×10^{-5}	7.0×10^{-2}	6.11×10^{-4}
		Adult	4.70×10^{-7}	—	—	1.17	7.00×10^{-1}	1.67	3.66×10^{-6}	7.0×10^{-2}	5.23×10^{-5}
Zn	59.83 ± 22.20	Children	2.14×10^{-8}	2.00×10^{-4}	1.07×10^{-4}	2.79×10^{-1}	3.00×10^{-1}	9.30×10^{-1}	1.10×10^{-6}	9.0×10^{-2}	1.22×10^{-5}
		Adult	1.21×10^{-8}	8.57×10^{-5}	1.41×10^{-4}	2.99×10^{-2}	3.00×10^{-1}	9.97×10^{-2}	9.39×10^{-8}	9.0×10^{-2}	1.04×10^{-6}
Cr	2.24 ± 0.60	Children	8.00×10^{-10}	6.67×10^{-5}	1.20×10^{-5}	1.05×10^{-2}	3.00×10^{-3}	3.50	4.11×10^{-8}	7.5×10^{-5}	5.48×10^{-4}
		Adult	4.51×10^{-10}	2.86×10^{-5}	1.58×10^{-5}	1.12×10^{-3}	3.00×10^{-3}	3.73×10^{-1}	3.52×10^{-9}	7.5×10^{-5}	4.69×10^{-5}
Pb	21.98 ± 5.57	Children	7.85×10^{-9}	—	—	1.03×10^{-1}	—	—	4.03×10^{-7}	—	—
		Adult	4.43×10^{-9}	—	—	1.10×10^{-2}	—	—	3.45×10^{-8}	—	—
Hg	0.15 ± 0.01	Children	5.36×10^{-11}	2.00×10^{-4}	2.68×10^{-7}	7.01×10^{-4}	3.00×10^{-4}	2.34	2.75×10^{-9}	2.1×10^{-5}	1.31×10^{-4}
		Adult	3.02×10^{-11}	8.57×10^{-5}	3.52×10^{-7}	7.52×10^{-5}	3.00×10^{-4}	2.51×10^{-1}	2.36×10^{-10}	2.1×10^{-5}	1.12×10^{-5}
THI		Children			1.81×10^{-4}			32.26			1.88×10^{-3}
		Adult			2.22×10^{-4}			3.46			1.88×10^{-3}

CONCLUSION

The present study revealed that sediments from the Mmili Ocha River contain measurable concentrations of heavy metals, with iron, zinc, and lead occurring at relatively higher levels. Pearson correlation analysis showed strong positive associations among most metals, suggesting common anthropogenic sources, particularly municipal waste disposal, urban runoff, and leachate infiltration. Pollution indices (Igeo, EF, CF, Cd, PLI, and PERI) indicated generally low to moderate contamination and ecological risk, although cadmium and lead showed notable anthropogenic enrichment. Human health risk assessment identified ingestion as the primary exposure pathway, with children facing greater potential non-carcinogenic risks than adults. Overall, the findings highlight increasing anthropogenic pressure on the Mmili Ocha River and underscore the need for continuous environmental monitoring, improved waste management, and effective pollution control strategies to protect aquatic ecosystems and public health.

RECOMMENDATIONS

The study recommends continuous monitoring of Mmili Ocha River sediments to detect seasonal changes and prevent worsening pollution. It emphasizes improving waste management and enforcing environmental regulations to stop indiscriminate dumping and reduce human activities that introduce heavy metals like lead and cadmium.

Public awareness campaigns should be carried out to educate nearby communities on the health risks of contaminated sediments and promote better sanitation practices. Environmental authorities are urged to implement regular sediment quality monitoring, enforce existing laws, and conduct routine ecological and health risk assessments for early detection of pollution threats.

To reduce health risks—especially for children—direct contact with contaminated sediments should be minimized, particularly during recreational activities. Finally, further research is encouraged to examine heavy metal accumulation in aquatic organisms and to identify pollution sources using advanced analytical methods

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