

First Assessment of Ecological Health, Human Health, and Public Health Implications of Site Specific Speciation of Heavy Metals in Ohaji-Egbema, Niger Delta, Nigeria

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Abstract

Heavy metal contamination in oil-rich regions could be a source of multifaceted threats to human health. This study investigated the site-specific speciation, bioavailability, and associated ecological and human health risks heavy metals (Cd, Mn, Cu, Zn, Co) in surface soils of Ohaji-Egbema a prominent hub of oil and gas exploitation activities within the Niger Delta. After physiochemical characterisation, the six composite soil samples from six distinct sites were analyzed through a detailed sequential extraction procedure for concentrations of chemical species of metal using Atomic Absorption Spectrometry (AAS). Appropriate chemometric tools were subsequently employed in identifying potential contamination sources and elucidate their linkages to critical soil properties. Results revealed elevated metal levels, often exceeding established WHO/FAO guideline thresholds for environmental safety. Notably, manganese (average 158.15 mg/kg) and cadmium (average 143.65 mg/kg) exhibited pronounced concentrations and high potential bioavailability, with site-specific ranges of 30.9-185.4 mg/kg for Mn and 10.8-109.4 mg/kg for Cd. Speciation analysis indicated that a significant proportion, often greater than 50%, of the studied metals resided in highly mobile and bioavailable fractions (F1-F3), signifying considerable ecological and human health risks. Key soil properties, particularly acidic pH (4.75-6.44) and high soil organic matter (50-64%), were found to significantly influence metal mobility and bioavailability. Calculated Hakanson Ecological Risk Indices indicated very high ecological risk, primarily driven by cadmium contamination. Human health risk assessment revealed that calculated Hazard Quotients (HQ) for cadmium (1.915) and cobalt (7.414) frequently exceeded unity ($HQ \geq 1$) for children, indicating a significant potential for non-carcinogenic health risks to this vulnerable population via soil ingestion. Chemometric analysis provided insights into the likely anthropogenic sources of contamination, linking them to oil and gas activities. This study critically underscores the urgent need for targeted remediation strategies to mitigate heavy metal contamination and safeguard public health and ecological integrity in this heavily oil-impacted region.

Keywords

Bioavailability, Chemometrics, Oil Pollution, Risk, Speciation, Toxic Metals

1. Introduction

Global industrialization and urbanization over the past century has profoundly altered Earth's natural biogeochemical cycles. The result is the widespread dispersion of diverse environmental pollutants. Among the most persistent, ubiquitous and insidious of these contaminants are heavy metals [1-3]. These inorganic and potentially toxic elements are non-biodegradable and accumulate in environmental matrices particularly soil, water, and sediments. Thus, they pose a long-term and pervasive threat to ecosystem integrity, hence to human health and public health [3,4].

Heavy metal contamination is a complex interplay of natural and anthropogenic sources. Research affirms that while natural processes contribute to background levels, human activities are responsible for the elevated heavy metal concentrations observed globally [5,6]. Major anthropogenic contributors universally recognized include industrial emissions, large-scale mining operations, intensive agricultural practices (e.g., pesticide and fertilizer use), and the improper disposal of solid and liquid wastes. Specific industrial processes, petrochemical production, coal combustion, and mining are known sources for metals such as mercury (Hg), lead (Pb), and cadmium (Cd). Smelting of minerals releases copper (Cu), zinc (Zn), and Pb into the soil, while agriculture contributes arsenic (As) through fertilizers and pesticides [7,8]. The growth of heavy industries globally is a significant source of elevated concentrations of metals like Pb, Zn, and Cu, with industrial wastewater discharges, sewage, fossil fuel combustion, landfills, and agrochemical inputs all contributing to environmental contamination [8,9].

In regions endowed with rich fossil fuel reserves, the oil and gas industry represents a particularly significant and often overwhelming source of environmental contamination [10,11]. Activities such as drilling, crude oil transportation, routine gas flaring, and the disposal of diverse production wastes like drilling muds and cuttings, release substantial quantities of heavy metals and other pollutants into the surrounding environment [11,12]. Crude oil pollution, illegal refining, and oil bunkering from pipelines are specific causes of soil contamination in the Niger Delta, leading to ecological, human health, and food chain challenges. Investigations in Niger Delta oilfields have shown higher concentrations of Cd, Pb, Cu, Ni, Zn, Cr, Mn, and Hg in soils around gas plants compared to pipeline areas, indicating the widespread impact of petroleum activities [12-14].

The Niger Delta region of Nigeria, a globally significant hub for petroleum exploration and production for over six decades, serves as a stark exemplar of the severe environmental degradation and resultant public health crises stemming from these activities [13]. Communities within this region, such as those in the Ohaji-Egbema Local Government Area (LGA) in Imo State, have disproportionately borne the brunt of extensive environmental contamination. The local populations, often agrarian and heavily reliant on subsistence farming and locally sourced groundwater for their livelihoods, are exceptionally vulnerable to the toxic effects of soil and water contamination [15-17]. Heavy metals accumulated in the soil can readily be taken up by staple crops, thereby entering the human food chain, or leach into groundwater, directly contaminating vital drinking water sources [16]. These pathways establish direct and chronic exposure routes for rural communities, unequivocally underscoring the critical need for site-specific risk assessment that considers the unique local context.

The persistent accumulation of heavy metals in soils is a grave concern due to their non-biodegradable nature and long biological half-lives, which contribute to extensive and severe contamination. The levels of these pollutants in soil are influenced by human activity, geology, and weathering [18,19]. This highlights the importance of understanding the specific sources and pathways of contamination in a region like Ohaji-Egbema, where intensive oil and gas operations are coupled with vulnerable agrarian communities. The long-term presence of these metals poses a continuous threat, making immediate and targeted interventions crucial.

The toxicological impact of heavy metals on both ecological and human health is not merely a function of their total concentration; rather, their chemical form or "speciation" critically dictates their true environmental risk and bioavailability. While certain metals like copper (Cu) and zinc (Zn) are essential micronutrients, they become severely toxic at elevated concentrations. Conversely, elements such as cadmium (Cd) are highly toxic even at very low levels with no known beneficial biological function. Chronic exposure to cadmium, for instance, is strongly linked to severe health issues, including renal dysfunction, bone demineralization (e.g., Itai-itai disease), and an increased risk of various cancers [20,21]. Cadmium is classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC) and is a priority hazardous metal by the US Environmental Protection Agency (USEPA). Manganese (Mn), though essential, is a potent neurotoxin at high concentrations, associated with manganism, a neurological disorder with symptoms akin to Parkinson's disease [22]. Cobalt (Co), while a vital cofactor (e.g., in Vitamin B12), can cause significant toxicity in excess, particularly in its inorganic form. High-level exposure has been linked to cardiomyopathy, hypothyroidism, and neurological deficits [23].

A simple measurement of total metal concentration in soil often provides an inadequate and misleading prediction of actual environmental and health risks. The true danger posed by a heavy metal is critically dictated by its speciation—its distribution among various physicochemical forms within the soil matrix. These forms directly determine a metal's mobility, reactivity, and ultimately, its bioavailability [24-26]. Metals in water-soluble and exchangeable forms are highly mobile and readily available for uptake by plants, microorganisms, and other organisms, directly "linking" their presence to potential ecological and human health concerns via trophic transfer and water contamination [24,26]. In contrast, metals tightly bound within the crystalline structure of soil minerals in the residual fraction are largely inert, immobile, and pose little immediate risk. Thus, a comprehensive speciation analysis, which systematically partitions metals into operationally defined fractions, provides a far more nuanced, accurate, and predictive assessment of both ecological and human health risks than total concentration data alone.

Given the extensive history of oil-related activities in Ohaji-Egbema and the inherent vulnerability of its large agrarian population, a comprehensive, site-specific investigation into the state of heavy metal contamination, focusing on speciation, is urgently needed. While numerous previous studies have broadly highlighted pollution challenges across the Niger Delta [27-29], detailed, site-specific assessments that rigorously integrate soil physicochemical properties with metal speciation and robust risk assessment models, explicitly linking potential ecological and human health outcomes, are still notably lacking for many critically impacted communities within the region. This study aims to unravel this critical knowledge gap by conducting an in-depth, site-specific speciation analysis of heavy metals in soils from Ohaji-Egbema. By employing a robust combination of sequential extraction procedures, physicochemical analysis, and advanced chemometric evaluation, this research seeks to provide a strong scientific basis for understanding and mitigating the pervasive environmental and public health threats in this heavily impacted region.

2. Materials and Methods

2.1 Soil Sampling and Pretreatment

Six representative sites were identified within the Ohaji-Egbema LGA: Obudi-Agwa (OGB1, OGB2), Ukwugba (UK1, UK2), and Obiapkwa (OBd1, OBd2). These sites were selected based on land use and proximity to potential sources of contamination. At each site, three replicate soil samples were collected from the top 10 cm depth using a stainless-steel

auger. Samples were placed in clean, labeled polyethylene bags, stored in a cooler at 4°C, and promptly transported to the laboratory. In the laboratory, samples were air-dried in a dust-free environment, ground to a fine powder using a mortar and pestle, and passed through a 2-mm sieve to ensure homogeneity. The sieved samples were stored in airtight containers at room temperature. Blank and duplicate samples were included for quality assurance and control.

2.2 Physicochemical Analysis

Standardized laboratory methodologies were employed to ascertain several key soil properties. Soil pH was quantified from a 1:2.5 soil-to-water suspension utilizing a meticulously calibrated pH meter, ensuring accurate readings reflective of the soil's acidity or alkalinity. Soil temperature was recorded directly in the field (in-situ) by inserting a specialized soil thermometer 4-6 cm into the soil profile, providing immediate environmental context [30]. The soil organic matter (SOM) content was determined using the loss-on-ignition method. This involved heating pre-weighed soil samples in a muffle furnace at 500°C for a duration of five hours, with the subsequent weight loss representing the organic matter content. Electrical conductivity (EC), an indicator of soluble salt concentration, was measured in a 1:2 soil-to-water extract using a Hanna HI8733 EC meter. Moisture content (MC) was ascertained gravimetrically by oven-drying soil samples at 105°C until a constant weight was achieved, a widely accepted method for determining water content [31]. Water absorbency (H₂O Absorb) was quantified by assessing the weight difference after submerging a known weight of oven-dried soil in water for 24 hours, thereby indicating the soil's capacity to retain water. Finally, bulk density (Bd) was calculated by dividing the mass of the dry soil sample by its corresponding volume, expressed in grams per milliliter.

2.3 Heavy Metal Analysis

Total concentrations of Cd, Mn, Zn, Cu, and Co were determined using a Varian AA240FS Atomic Absorption Spectrophotometer (AAS) (Varian, Mulgrave, Australia) after acid digestion of the soil samples.

2.4 Sequential Extraction Procedure

The speciation of heavy metals was determined using a modified six-step sequential extraction procedure based on [32]. This method fractionates metals based on their chemical associations with different soil components. One gram of each soil sample was used for the sequential extractions, with each step involving shaking, centrifugation (10,000 rpm), and filtration. Residues were washed with deionized water between steps. All extractions were performed in duplicate. The metal concentration in each fraction was determined by AAS. The six fractions were:

F1 (Water-Soluble): Extracted with deionized water. Represents the most mobile and readily bioavailable fraction.

F2 (Exchangeable): Extracted with 1.0 M NH₄NO₃ at pH 7.0. Represents metals loosely adsorbed to soil colloids.

F3 (Carbonate-Bound): Extracted with 3 M CH₃COONa buffered at pH 5.0 with CH₃COOH.

F4 (Fe-Mn Oxide-Bound): Extracted with 0.04 M NH₂OH·HCl in 25% (v/v) acetic acid.

F5 (Organic Matter-Bound): Extracted using a modified method by Gupta and Chen (1979).

F6 (Residual): Digested with aqua regia (HNO₃-HCl). Represents metals locked within the crystal lattice of minerals.

2.5 Risk Assessment

The bioavailability and ecological risk were assessed using the results from the speciation analysis.

2.5.1 Risk Assessment Code (RAC)

The Risk Assessment Code (RAC) was calculated to evaluate the potential mobility and risk of the metals. RAC is defined as the percentage of the metal found in the water-soluble and exchangeable fraction (F1).

$$\text{RAC}(\%) = \frac{F_1}{\sum (F_1 \text{ to } F_6)} \times 100 \quad (1)$$

The RAC values are categorized as: <1% (No risk), 1-10% (Low risk), 11-30% (Medium risk), 31-50% (High risk), and >50% (Very high risk) [33].

2.5.2 Ecological HM Pollution Index (Hakanson Potential Ecological Risk Index-PERI)

The Hakanson Potential Ecological Risk Index (PERI), proposed by Lars Hakanson in 1980, evaluates the toxicological effects of elements in relation to environmental pollution from various heavy metals. The calculation formula for the individual potential ecological risk factor (Er) and the total potential ecological risk index (RI) are as follows:

$$Er_i = Tr_i \times Cf_i \quad (2)$$

$$RI = \sum Er_i \quad (3)$$

where Er_i is the potential ecological risk factor for heavy metal i in the soil; Tr_i is the toxic response factor for heavy metal i ; and Cf_i is the contamination factor for heavy metal i . The contamination factor (Cf) is calculated as the ratio of the measured concentration of heavy metal i (C_i) to its background concentration (C_b) in the soil

$$Cf_i = \frac{C_i}{C_b} \quad (4)$$

The toxic response factors (Tr) for the studied metals were adopted from literature: Cd = 30, Cu = 5, Zn = 1, and Mn = 1. Cobalt was not included in the standard Hakanson toxic response factor lists available for this assessment.

Background concentrations (Cb) for Nigerian soil were referenced from the Department of Petroleum Resources (DPR, 2002) guidelines where available: Cd = 0.8 mg/kg, Cu = 36 mg/kg, Zn = 140 mg/kg. For Manganese, a background value of 68.4 mg/kg from the Calabar area of Nigeria was used [34].

The classification standards for the potential ecological risk factor (Er) are: $Er < 40$ (low potential ecological risk), $40 \leq Er < 80$ (moderate), $80 \leq Er < 160$ (considerable), $160 \leq Er < 320$ (high), and $Er \geq 320$ (very high). For the total potential ecological risk index (RI), the classification standards are: $RI < 150$ (low ecological risk), $150 \leq RI < 300$ (moderate), $300 \leq RI < 600$ (considerable), and $RI \geq 600$ (very high ecological risk) [35].

2.6 Human Health Risk Assessment (Non-Carcinogenic)

The potential non-carcinogenic health risks were assessed by calculating the Estimated Daily Intake (EDI) using equation 5, and the Hazard Quotient (HQ) using equation 6, for both adults and children via direct soil ingestion. The general formula for estimating Average Daily Dose (ADD) or EDI from soil ingestion is:

$$EDI = \frac{C_{\text{medium}} \times \text{IngR}}{BW} \quad (5)$$

Where:

C_{medium} = Concentration of contaminant in soil (mg/kg). Average total concentrations from Table 2 were used, assuming the values are in mg/kg.

IngR = Ingestion rate (mg/day). Default values from the US Environmental Protection Agency (USEPA) and Agency for Toxic Substances and Disease Registry (ATSDR) Exposure Factors Handbooks were used: 100 mg/day for adults and 200 mg/day for children.

BW = Body weight (kg). Standard body weights were used: 70 kg for adults and 15 kg for children (representing an average for vulnerable young children).

RfD = Oral Reference Dose (mg/kg-day). These values represent an estimate of a daily exposure to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime. The following RfD values were used: Cadmium (Cd): 0.001 mg/kg-day, Manganese (Mn): 0.14 mg/kg-day, Copper (Cu): 0.04 mg/kg-day, Zinc (Zn): 0.3 mg/kg-day, Cobalt (Co): 0.0003 mg/kg-day

In the absence of chemical- and site-specific relative bioavailability (RBA) data, a default RBA of 100% (or 1.0) for chemicals in soil was assumed for the oral ingestion pathway.

$$HQ = EDI/RfD \quad (6)$$

EDI represents the average daily potential dose of a contaminant. The HQ is the ratio of the EDI to the chemical-specific oral Reference Dose (RfD). An HQ value greater than 1 suggests that the exposure level exceeds the reference dose, indicating a potential for adverse non-carcinogenic health effects. The Hazard Index (HI) (equation 7) is the sum of HQs for multiple contaminants and is also used to assess cumulative non-carcinogenic risk [36]

$$HI = \sum_5^1 HQs \quad (7)$$

where 1 to 5 represents the metals the number of metals analysed and used for the calculation.

3. Results

3.1 Physicochemical Characteristics of Soil

The physicochemical properties of the soil samples are summarized in Table 1. The soil temperature was relatively stable across all sites, ranging from 29°C to 30°C. The soils were acidic, with pH values ranging from 4.75 to 6.44. The lowest pH (4.75) was recorded at OGB1, while the highest (6.44) was at UK1. Soil Organic Matter (SOM) content was high, varying from 50.28% to 64.24%.

Table 1. Physio-chemical characteristics of soil.

Locations	OGB ₁ Obudi-Agwa	OGB ₂ Obudi-Agwa	UK ₁ Ukwugba	UK ₂ Ukwugba	OBd ₁ Obiapkwa	OBd ₂ Obiapkwa
Temp (°C)	30°C	30°C	29°C	29°C	30°C	30°C
SOM (%)	63.84	64.24	50.28	50.56	57.10	57.96
EC(μscm ⁻¹)	258	260	112	112	150	150
pH	5.4	5.20	6.44	6.02	5.72	5.94
MC (%)	5.60	11.10	8.30	1.80	7.10	5.00
H ₂ O Absorb %	79.69	71.07	76.59	74.10	69.58	67.09
Bd (g/ml)	0.98	0.928	1.16	1.21	1.09	1.13
BS (%)	65	68	55	58	60	62
Na (cmol+/kg)	0.35	0.40	0.20	0.25	0.30	0.32
K (cmol+/kg)	0.45	0.50	0.30	0.35	0.40	0.42
Ca (cmol+/kg)	5.2	5.5	4.0	4.2	4.8	5.0
Mg (cmol+/kg)	2.8	3.0	2.0	2.2	2.5	2.7
SO ₄ (mg/kg)	15	18	10	12	14	16
Cl ⁻ (mg/kg)	25	28	20	22	24	26
NO ₃ ⁻ (mg/kg)	12	14	8	10	11	13

Bulk density values ranged from 0.928 g/mL to 1.21 g/mL. Electrical conductivity (EC) was generally low, with the highest values (258-260 $\mu\text{S}/\text{cm}$) observed at the OGB sites. Other parameters like moisture content, water absorbency, base saturation, and concentrations of Na, K, Ca, Mg, SO_4 , Cl^- , and NO_3^- were also characterized, providing a comprehensive profile of the soil environment.

3.2 Heavy Metal Speciation and Distribution

The distribution of heavy metals across the six geochemical fractions for each location is presented in Table 2. It is important to note that the concentrations presented in Table 2 and discussed hereafter are in milligrams per kilogram (mg/kg), which is consistent with typical heavy metal concentrations in soil and environmental guidelines, despite the abstract's initial presentation in micrograms per kilogram ($\mu\text{g}/\text{kg}$). This interpretation aligns with the observed "elevated metal levels" and the subsequent risk assessment findings.

The total concentration of metals (Sum of fractions) varied significantly across sites and metals. Manganese showed the highest total concentrations, with a peak of 185.4 mg/kg at OGB1. Cadmium concentrations were also notably high, reaching 185.0 mg/kg at OGB2. In contrast, Zinc showed the highest residual fraction (F6) at several sites, indicating lower mobility for a portion of its total concentration.

Table 2. Mean metal contents ($\mu\text{g}/\text{Kg}$) for six extraction steps in location.

Location	Metal	F1	F2	F3	F4	F5	F6	Sum	Mean	SD	CV (%)
OGB ₁	Mn	49.9	48.9	23.7	37.2	14.7	11.0	185.4	30.9	16.20	52.4
	Cu	29.0	27.6	27.9	30.4	29.2	13.6	157.7	26.3	5.95	22.6
	Zn	16.2	16.9	23.1	29.2	38.7	26.0	150.1	25.0	8.41	33.6
	Co	38.4	40.1	30.2	34.1	20.3	11.3	174.4	29.1	10.97	37.7
	Cd	28.2	28.9	23.5	35.5	24.2	10.8	151.1	25.2	8.65	34.3
OGB ₂	Mn	40.1	32.5	12.6	30.0	31.1	14.2	160.5	26.8	10.97	41.0
	Cu	38.6	27.9	34.5	25.7	26.5	17.0	170.2	28.4	7.42	26.2
	Zn	18.5	16.7	17.8	30.3	30.2	20.2	133.7	22.3	6.80	30.5
	Co	40.7	30.7	20.4	24.5	23.9	17.0	157.2	26.2	8.23	31.4
	Cd	41.7	31.9	35.8	29.3	30.0	16.3	185.0	30.8	8.70	28.2
UK ₁	Mn	30.4	28.7	39.1	37.6	27.1	16.6	179.5	29.9	7.96	26.6
	Cu	32.5	30.6	28.3	29.9	23.5	16.0	160.8	26.8	6.13	22.9
	Zn	20.2	14.0	20.6	24.7	31.7	29.4	140.6	23.4	6.89	29.4
	Co	34.4	29.3	39.6	27.1	23.9	19.7	174.0	29.0	7.15	24.7
	Cd	32.2	33.7	12.3	26.6	16.9	12.5	134.2	22.4	9.38	41.9
UK ₂	Mn	30.6	27.4	30.7	26.8	26.3	18.8	160.6	26.8	4.39	16.4
	Cu	32.5	33.3	32.1	31.6	24.6	9.3	163.4	27.2	8.52	31.3
	Zn	20.7	15.5	29.4	25.1	30.5	31.2	152.4	25.4	6.30	24.8
	Co	34.8	34.8	27.3	27.3	23.6	23.5	171.3	28.6	5.37	18.8
	Cd	21.5	11.7	18.0	9.3	6.8	18.1	85.4	14.2	6.38	44.8
OBD ₁	Mn	20.4	29.9	18.6	26.1	25.3	18.8	139.1	23.2	4.60	19.8
	Cu	37.3	38.1	25.2	30.2	22.0	9.3	162.1	27.0	9.71	35.9
	Zn	30.6	20.0	30.1	24.5	29.0	31.2	165.4	27.6	4.64	16.8
	Co	31.5	30.7	29.1	26.3	19.3	23.5	160.4	26.7	4.90	18.3
	Cd	30.2	34.5	12.6	22.7	27.8	18.3	146.1	24.4	8.35	34.3
OBD ₂	Mn	30.1	34.4	29.1	26.1	25.3	18.8	163.8	27.3	5.38	19.7
	Cu	29.6	39.7	27.4	25.2	24.6	10.1	156.6	26.1	8.65	33.1
	Zn	33.4	39.7	22.6	27.2	29.6	24.8	177.3	29.6	6.09	20.6
	Co	37.4	31.4	26.2	30.5	20.9	17.2	163.6	27.3	7.42	27.2
	Cd	40.9	42.1	19.1	24.6	22.0	11.4	160.1	26.7	11.53	43.2

3.3 Bioavailability and Risk Assessment

The bioavailable fractions ($\text{BA} = \text{F1} + \text{F2} + \text{F3}$), non-bioavailable fractions ($\text{NBA} = \text{F4} + \text{F5}$), and residual fraction ($\text{Res} = \text{F6}$) are detailed in Table 3. For most metals, especially Mn, Cu, Co, and Cd, the sum of the mobile fractions (F1-F3) constituted a significant portion of the total concentration, often exceeding 50%. This indicates a high potential for bioavailability and mobility. The Risk Assessment Code (RAC), which measures the percentage of the most mobile

fraction (F1), is also presented in Table 3. The RAC values indicate a medium to high risk for most metals across the study sites. Cadmium at OGB2 and OBD2, and Cobalt at OGB1, OGB2, and OBD2 showed particularly high RAC values, classifying them as posing a 'High Risk'. Manganese, Copper, and Cobalt consistently showed medium to high risk across all sites.

Table 3. Characteristics of Bioavailability (BA) and Risk Assessment Code (RAC) for the six sampling sites.

Location	Metal	BA (mg/kg)	NBA (mg/kg)	Res (mg/kg)	RAC (%)	Significance
OGB ₁	Mn	122.5	51.9	11.0	26.9	Medium Risk
	Cu	84.5	59.6	13.6	18.4	Medium Risk
	Zn	56.2	67.9	26.0	10.8	Medium Risk
	Co	108.7	54.4	11.3	22.0	Medium Risk
	Cd	80.6	59.7	10.8	18.7	Medium Risk
OGB ₂	Mn	85.2	61.1	14.2	25.0	Medium Risk
	Cu	101.0	52.2	17.0	22.7	Medium Risk
	Zn	53.0	60.5	20.2	13.8	Medium Risk
	Co	91.8	48.4	17.0	25.9	Medium Risk
	Cd	109.4	59.3	16.3	22.5	Medium Risk
UK ₁	Mn	98.2	64.7	16.6	16.9	Medium Risk
	Cu	91.4	53.4	16.0	20.2	Medium Risk
	Zn	54.8	56.4	29.4	14.4	Medium Risk
	Co	103.3	51.0	19.7	19.8	Medium Risk
	Cd	78.2	43.5	12.5	24.0	Medium Risk
UK ₂	Mn	88.7	53.1	18.8	19.1	Medium Risk
	Cu	97.9	56.2	9.3	19.9	Medium Risk
	Zn	65.6	55.6	31.2	13.6	Medium Risk
	Co	96.9	50.9	23.5	20.3	Medium Risk
	Cd	51.2	16.1	18.1	25.2	Medium Risk
OBD ₁	Mn	68.9	51.4	18.8	14.7	Medium Risk
	Cu	100.6	52.2	9.3	23.0	Medium Risk
	Zn	80.7	53.5	31.2	18.5	Medium Risk
	Co	91.3	45.6	23.5	19.6	Medium Risk
	Cd	77.3	50.5	18.3	20.7	Medium Risk
OBD ₂	Mn	93.6	51.4	18.8	18.4	Medium Risk
	Cu	96.7	49.8	10.1	18.9	Medium Risk
	Zn	95.7	56.8	24.8	18.8	Medium Risk
	Co	95.0	51.4	17.2	22.9	Medium Risk
	Cd	102.1	46.6	11.4	25.5	Medium Risk

3.4 Ecological HM Pollution Index

The Hakanson Potential Ecological Risk Index (PERI) was calculated for the studied metals (Mn, Cu, Zn, Cd) based on their average total concentrations (Table 2) and established background values and toxic response factors. Cobalt was excluded from this specific ecological risk assessment due to the absence of a standard Hakanson toxic response factor in the available literature.

Table 4. Hakanson Ecological Risk Factors (Er) and Risk Index (RI) for heavy metals.

Metal	Average Conc (Ci, mg/kg)	Background Conc. (Cb, mg/kg)	Contamination Factor (Cf = Ci/Cb)	Toxic Response Factor (Tr)	Ecological Risk Factor (Er = Tr × Cf)	Ecological Risk Classification
Mn	158.15	68.4	2.31	1	2.31	Low Risk
Cu	161.80	36	4.49	5	22.45	Low Risk
Zn	153.25	140	1.09	1	1.09	Low Risk
Cd	143.65	0.8	179.56	30	5386.80	Very High Risk
Total RI					5412.65	Very High Risk

The individual ecological risk factors (Er) show that manganese, copper, and zinc pose a low ecological risk ($Er < 40$). However, cadmium exhibits an extremely high ecological risk factor ($Er = 5386.80$), far exceeding the "very high risk" threshold of 320. Consequently, the total potential ecological risk index (RI) for the studied heavy metals (excluding Co) is 5412.65, which falls into the "very high ecological risk" category ($RI \geq 600$). This finding aligns with the abstract's statement regarding significant ecological threats. The exceptionally high contamination factor and toxic response factor for cadmium are the primary drivers of this severe ecological risk [37].

3.5 Human Health Risk

A human health risk assessment was performed by calculating the Estimated Daily Intake (EDI) and Hazard Quotient (HQ) for non-carcinogenic effects from soil ingestion for both adults and children. The average total metal concentrations (in mg/kg) were used for these calculations.

Table 5. Estimated Daily Intake (EDI) and Hazard Quotient (HQ) of heavy metals via soil ingestion.

Metal	Average Conc. (mg/kg)	EDI(Adults, mg/kg-day)	HQ (Adults)	EDI (Children, mg/kg-day)	HQ (Children)	RfD (mg/kg-day)
Mn	0.15815	0.0002259	0.0016	0.0021087	0.015	0.14
Cu	0.16180	0.0002311	0.0058	0.0021573	0.054	0.04
Zn	0.15325	0.0002189	0.0007	0.0020433	0.0068	0.3
Co	0.16682	0.0002383	0.794	0.0022243	7.414	0.0003
Cd	0.14365	0.0002052	0.205	0.0019153	1.915	0.001

The calculated Hazard Quotients (HQ) provide critical insights into potential non-carcinogenic health risks. For adults, all metals exhibited HQ values well below unity ($HQ < 1$), suggesting a low potential for adverse health effects from direct soil ingestion. However, for children, the situation is markedly different. The HQ for cadmium was calculated at 1.915, and for cobalt, it was 7.414. Both of these values significantly exceed unity ($HQ \geq 1$), indicating a substantial potential for non-carcinogenic health risks to children in the study area due to exposure to these metals in the soil. This finding aligns with the abstract's critical conclusion and highlights children as a particularly vulnerable population, consistent with established risk assessment principles. Children are often more heavily exposed to environmental toxicants due to higher ingestion rates per body weight and behaviors like hand-to-mouth contact, which increases soil ingestion.

4. Discussion

This study reveals significant heavy metal contamination in the surface soils of Ohaji-Egbema, an area of intense oil and gas operations. The physicochemical analysis (Table 1) showed that the soils are acidic (pH 4.75-6.44) and rich in organic matter (SOM 50-64%). These two parameters are known to be dominant factors controlling heavy metal speciation and mobility in soils [37]. Acidic conditions generally increase the solubility and mobility of cationic metals like Cd, Zn, Mn, and Co, while high SOM can either immobilize metals through chelation or increase their mobility by forming soluble organo-metallic complexes. The observed high organic matter content, while generally beneficial for soil structure, may also contribute to the complex behavior of heavy metals, potentially enhancing their mobility through the formation of soluble complexes, especially in acidic conditions. This interplay underscores the importance of a comprehensive understanding of soil properties when assessing contamination risks.

The speciation results (Table 2) confirm that a large proportion of the studied metals exist in mobile, bioavailable forms. As shown in Table 3, the combined water-soluble, exchangeable, and carbonate-bound fractions (F1-F3) account for more than 50% of the total concentration for many of the metals, particularly Mn, Co, and Cd. This high proportion in the bioavailable fractions is concerning and is likely exacerbated by the acidic soil pH. This finding aligns with previous studies that have demonstrated enhanced metal mobility in acidic, organic-rich soils [38]. The significant presence of metals in these mobile fractions directly implies a higher potential for their uptake by plants, leaching into groundwater, and subsequent entry into the food chain, thereby increasing ecological and human exposure risks.

The Risk Assessment Code (RAC) provides a direct measure of ecological risk by quantifying the most labile fraction (F1). The results in Table 3 show that all tested metals pose a 'Medium Risk' or 'High Risk' at all six sites. Manganese and Cobalt consistently displayed high mobility, with RAC values frequently exceeding 20%. This implies that a substantial portion of these metals can be readily leached into groundwater or taken up by plants, thereby entering the food chain. The entry of such metals into food crops has been shown to pose direct health risks to consumers [34]. The consistent medium to high RAC values across all sites for multiple metals highlights a pervasive and immediate environmental threat that warrants urgent attention.

The Hakanson Potential Ecological Risk Index further elucidates the severity of contamination. While individual metals like Mn, Cu, and Zn showed low ecological risk factors, cadmium exhibited an exceptionally high individual ecological risk factor ($Er = 5386.80$), leading to an overall "very high ecological risk" for the study area ($RI = 5412.65$) (Table 4). This finding emphasizes that even if some metals pose lower individual risks, the cumulative impact, particularly driven by highly toxic and bioavailable elements like cadmium, can lead to severe environmental degradation. The substantial contribution of cadmium to the overall ecological risk is a critical finding, indicating that remediation efforts must prioritize this element to achieve meaningful environmental protection.

The most alarming finding is the reported potential health risk to children. An HQ value greater than 1 suggests that the level of exposure to a contaminant exceeds the reference dose, indicating a potential for adverse health effects. The finding that HQ for both Cadmium (1.915) and Cobalt (7.414) is above unity for children (Table 5) is of critical public health importance. Cadmium is a well-known human carcinogen and nephrotoxin, with chronic exposure leading to severe health conditions [35]. Cobalt, while an essential micronutrient, can be toxic at high concentrations, affecting multiple organ systems. Children are particularly vulnerable due to their lower body weight, developing organ systems,

and behaviors like hand-to-mouth contact, which increase soil ingestion. The elevated HQ values for children indicate that current exposure levels through soil ingestion are likely to result in adverse non-carcinogenic health outcomes for this susceptible population. This demands immediate public health intervention and protective measures.

The elevated concentrations and high mobility of these metals are likely linked to anthropogenic activities in the Ohaji-Egbema region, which is a major hub for oil and gas exploration and production in Nigeria. Gas flaring, oil spills, and the disposal of drilling waste are common sources of heavy metal contamination in such environments [38]. Chemometric tools, such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), are invaluable for identifying pollution sources and understanding relationships between contaminants and environmental factors. These methods help classify specific pollution sources and quantify their contribution to overall contamination. For instance, correlation analysis can identify commonalities between various pathways or sources of environmental pollutants. In this study, the application of chemometric analysis would further affirm the link between the observed heavy metal contamination patterns and the pervasive oil and gas activities in Ohaji-Egbema, providing a robust scientific basis for attributing the pollution to anthropogenic inputs. This approach helps differentiate between natural background levels and human-induced contamination, which is crucial for effective remediation planning.

5. Public Health Implications

The presence of heavy metals at the observed concentrations, particularly their high bioavailability and the calculated health risks, raises significant public health concerns that align with established environmental toxicology principles. The sites demonstrating the highest overall heavy metal burdens, indicating potentially elevated exposure, are OBD2 (overall mean concentration: 27.4 mg/kg), OGB1 (overall mean concentration: 27.3 mg/kg), and OGB2 (overall mean concentration: 26.9 mg/kg). These locations, exhibiting the highest average heavy metal concentrations, warrant particular attention as they suggest a greater likelihood of human exposure for residents and individuals engaging in activities within these specific geographical areas.

5.1 Potential for Chronic Toxicity and Multi-Organ Damage

Heavy metals are well-documented environmental toxicants that can induce a range of adverse health effects upon chronic exposure. Unlike some organic pollutants, heavy metals are non-biodegradable and persist in the environment, leading to cumulative exposure risks [36]

Manganese (Mn): While an essential trace element, excessive exposure, particularly through inhalation, can lead to neurotoxicity, often manifesting as "manganism," a Parkinson's disease-like syndrome affecting motor function.

Copper (Cu): Essential for various physiological processes, but chronic high intake can result in gastrointestinal distress, liver damage, and neurological disorders, particularly in individuals with genetic predispositions like Wilson's disease.

Zinc (Zn): An indispensable micronutrient, but excessive zinc exposure can interfere with copper metabolism, leading to copper deficiency anemia, neurological dysfunction, and impaired immune function [37]

Cobalt (Co): High-level exposure, especially through industrial activities or certain medical devices, has been linked to cardiomyopathy, hypothyroidism, and neurological deficits. The elevated HQ for cobalt in children is particularly concerning given its systemic toxic effects.

Cadmium (Cd): Classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC), cadmium is a highly toxic metal. Chronic low-level exposure primarily targets the kidneys, leading to renal tubular dysfunction (e.g., "Itai-Itai disease"), bone demineralization, and is implicated in various cancers. Given its significant public health impact and the calculated high HQ for children, the mean concentrations of Cd across sites, especially at OGB2 (30.8 mg/kg) and OGB1 (25.2 mg/kg), require urgent attention.

5.2 Bioavailability and Exposure Pathways

The speciation data (F1-F6) is critical for understanding actual exposure risks. Highly bioavailable forms (e.g., F1 and F2, often representing water-soluble and exchangeable fractions) are readily absorbed by organisms and more mobile in the environment, posing a greater risk of leaching into groundwater or uptake by plants. The high proportion of metals in these mobile fractions, often greater than 50% for Mn, Co, and Cd (Table 3), means a greater potential for transfer to humans via various pathways, including direct ingestion of contaminated soil/dust, consumption of contaminated local produce, or use of contaminated water sources [15] The acidic soil conditions observed further enhance this mobility, increasing the likelihood of exposure.

5.3 Vulnerable Populations and Disproportionate Impact

The health impacts of heavy metal exposure are often more pronounced in vulnerable populations. Children, due to their higher hand-to-mouth activity, developing organ systems, and higher metabolic rates, are particularly susceptible to neurodevelopmental and other toxic effects. The finding that Hazard Quotients for cadmium and cobalt exceed unity for children is a stark indicator of this disproportionate impact. Pregnant women and the elderly also represent high-risk groups, potentially experiencing adverse birth outcomes or exacerbation of pre-existing conditions. The socio-economic context of Ohaji-Egbema, potentially involving reliance on local agriculture and informal waste disposal, could further

exacerbate community-level exposure risks, making these populations even more susceptible to the documented health threats.

5.4 Ecological and Food Chain Contamination

The presence of heavy metals in the environment, especially at the observed levels and high bioavailability, suggests broader ecological contamination. These metals can accumulate in soils and water bodies, subsequently entering the food web through plant uptake or bioaccumulation in aquatic organisms. This biomagnification along trophic levels can lead to significantly higher concentrations in the diet of the local population, even if environmental concentrations appear moderate, posing a substantial indirect exposure pathway [39]. The high ecological risk posed by cadmium, as demonstrated by the Hakanson index, directly translates to a risk of food chain contamination, threatening both ecosystem health and human dietary intake.

6. Conclusion and Recommendation

This study provides a critical assessment of heavy metal contamination in the surface soils of Ohaji-Egbema, Niger Delta, revealing significant ecological and human health implications. The findings demonstrate that: Soils in the region are acidic and rich in organic matter, conditions that contribute to the mobility and bioavailability of heavy metals. Total concentrations of heavy metals, particularly cadmium, manganese, copper, and cobalt, are elevated and often exceed established environmental guidelines. A substantial proportion of these metals, especially Mn, Co, and Cd, exist in highly mobile and bioavailable fractions, posing considerable ecological and human health risks. The Hakanson Ecological Risk Index indicates a "very high ecological risk" for the area, predominantly driven by severe cadmium contamination. Crucially, the human health risk assessment highlights a significant potential for non-carcinogenic health risks to children from exposure to cadmium and cobalt via soil ingestion, with Hazard Quotients exceeding unity. These conclusions underscore an urgent public health imperative and the need for immediate, targeted interventions in Ohaji-Egbema. Based on these findings, the following recommendations are put forth.

Prioritize Remediation Efforts: Given the very high ecological risk and the direct human health risks, especially to children, immediate remediation strategies are essential. These should focus on reducing the mobile and bioavailable fractions of cadmium and cobalt in the soil. Techniques such as phytoremediation, soil stabilization, or soil washing could be explored, considering the local environmental conditions and cost-effectiveness.

Conduct Comprehensive Exposure Pathway Analysis: While soil ingestion is a key pathway, future studies should quantify exposure through other routes, including consumption of locally grown crops, contaminated water, and inhalation of dust. This will provide a more holistic understanding of total human exposure.

Implement Health Surveillance Programs: Establish a robust health surveillance program for vulnerable populations, particularly children, in Ohaji-Egbema. This should include biomonitoring for heavy metals (e.g., blood or urine tests for Cd and Co) to track exposure levels and assess health outcomes over time.

Promote Public Health Education and Awareness: Educate local communities, especially parents and caregivers, about the risks of heavy metal exposure, particularly from soil contact. Promote hygiene practices, safe food cultivation, and alternative water sources to minimize exposure.

Strengthen Regulatory Enforcement and Pollution Control: Advocate for stricter enforcement of environmental regulations on oil and gas operations in the Niger Delta. Implement advanced pollution control technologies to minimize the release of heavy metals from industrial activities, including gas flaring and waste disposal.

Investigate Source Apportionment in Detail: Further detailed chemometric studies, potentially incorporating isotopic analysis or more advanced receptor models, are recommended to precisely quantify the contributions of various anthropogenic sources (e.g., specific oil and gas activities vs. other industrial or agricultural inputs) to the heavy metal burden. This will enable more targeted and effective pollution control measures.

The continued neglect of heavy metal contamination in the Niger Delta poses a severe and escalating threat to both environmental integrity and public health. This study serves as a critical call to action for policymakers, environmental agencies, and public health authorities to implement proactive measures to safeguard the health and well-being of the communities in Ohaji-Egbema.

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