

Article

Heavy Metal Contamination, Source Identification, Human Health Risk and Sustainability Assessment of Soils Across Industrial, Agricultural, and Residential Land-Use Areas in Rivers State, Nigeria

Chinazo Ndidiamaka Anunobi *, Qingyue Wang *, Miho Suzuki, Tochukwu Oluwatosin Maduka , Christian Ebere Enyoh  and Afia Sultana 

Graduate School of Science and Engineering, Saitama University, 255 Shimo-Okubo, Sakura-ku, Saitama 338-8570, Japan; miho@fms.saitama-u.ac.jp (M.S.); tochukwumaduka.edu@gmail.com (T.O.M.); cenyoh@gmail.com (C.E.E.); sultana.a.052@ms.saitama-u.ac.jp (A.S.)

* Correspondence: chinazoanunobi@gmail.com (C.N.A.); seiyo@mail.saitama-u.ac.jp (Q.W.); Tel.: +81-070-8520-9646 (Q.W.)

Abstract

Heavy metal contamination poses significant ecological and public health concerns due to its persistence, toxicity, and bioaccumulative potential of toxic metals, threatening environmental quality and sustainable development. This study evaluated the distribution, pollution status, health risks, and sources of heavy metals in soils from industrial, agricultural, and residential areas of Rivers State, Nigeria, using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS). Elevated concentrations of As, Mn, Se, Zn, and Co were detected across the study locations. Arsenic recorded the highest concentration in the Trans-Amadi industrial area (366.8 mg/kg), while Mn and Zn reached maximum concentrations of 1312 mg/kg and 327.9 mg/kg in Woji and Egi, respectively, exceeding the DPR limits for soil HMs. Pollution indices, including contamination factor, geo-accumulation index, enrichment factor, pollution load index, and Nemerow Integrated Pollution Index, revealed moderate to severe contamination, with the industrial zone exhibiting a *NIPi* value of 12.5. Health risk assessment identified ingestion as the dominant exposure pathway. Hazard quotient values for As (9.15) in the children category exceeded USEPA-acceptable limits, indicating potential non-carcinogenic risks. Carcinogenic risk assessment identified arsenic as the principal carcinogenic contaminant, with ingestion-derived Incremental Lifetime Cancer Risk (*ILCR*) values in the industrial area exceeding the USEPA maximum acceptable lifetime cancer risk threshold (1×10^{-4}), particularly among children, whereas the carcinogenic risks associated with the other investigated metals generally remained within acceptable or tolerable limits. Source identification indicated that industrial emissions, vehicular activities, waste disposal, and agricultural practices were the primary contributors to heavy metal accumulation. These findings provide critical scientific evidence for targeted remediation, pollution prevention, and informed health-risk environmental management to protect soil quality, ecosystem integrity, and public health. The study supports evidence-based policies that advance sustainable land management, environmental protection, and progress in Rivers State, Nigeria.



Academic Editor: Iason Verginelli

Received: 17 June 2026

Revised: 20 July 2026

Accepted: 23 July 2026

Published: 27 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

Keywords: heavy metals; environmental sustainability; soil pollution; health risk assessment; environmental pollution; industrial and agricultural soils; Niger Delta; Rivers State

1. Introduction

Heavy metals (HMs) are a highly dense and toxic group of elements that pose as a pervasive threat to global ecosystems. While they exist naturally within the Earth's crust, human activities, primarily industrial manufacturing, resource extraction, and modern farming, frequently release these pollutants into the environment [1,2]. Despite its status as Africa's most populous country and a major economic powerhouse, Nigeria possesses substantial crude-oil reserves estimated at approximately 35–36 billion barrels; while the nation's vast mineral and oil resources have propelled its economy forward, however, Nigeria faces severe environmental crises driven by heavy metal pollution [3,4]. Decades of petroleum exploration and production, gas flaring, unregulated artisanal petroleum refining, oil bunkering, pipeline vandalism, sabotage, spill events, and other anthropogenic activities in the Niger Delta have resulted in extensive HM contamination by Pb, Cd, Ni, Cr, Cu, Zn, and other potentially toxic elements. These persistent pollutants have accelerated soil degradation, biodiversity loss, and ecosystem dysfunction, while posing serious risks to human health, agricultural productivity, and water quality. Consequently, they undermine environmental sustainability and compromise sustainable land use [5,6]. Inappropriate means of waste disposal, municipal landfill solid waste, organic and inorganic fertilizer, pesticides and organic manure application are the major contributors to heavy metal contamination in residential and agricultural areas [7–9]. This widespread contamination severely alters environmental health and human well-being. HMs like arsenic, cadmium, chromium, lead, and mercury are especially hazardous because of their high toxicity and tendency to accumulate in the tissues of living organisms over time [10,11]. Chronic exposure to heavy metals has been widely reported to induce adverse biological effects through damage to cellular organelles and critical macromolecules, particularly DNA and nuclear proteins, resulting in oxidative stress, disrupted cell-cycle regulation, apoptosis, genotoxicity, and an increased risk of carcinogenesis [12]. The toxicological effects of heavy metals are both metal-specific and systemic. For instance, lead (Pb) is associated with neurological, skeletal, cardiovascular, endocrine, immune, and hematological dysfunction, whereas cadmium (Cd) is classified as a human carcinogen because of its cumulative toxicity and carcinogenic potential [13]. Cardiovascular toxicity has also been reported for cobalt (Co) and barium (Ba), with chronic cobalt exposure linked to progressive cardiomyopathy and heart failure, while soluble barium compounds may induce hypokalaemia and potentially fatal cardiac arrhythmias [14]. Furthermore, arsenic (As) exposure during pregnancy has been associated with fetal growth restriction, preterm birth, developmental neurotoxicity, and impaired reproductive outcomes, whereas excessive manganese (Mn) exposure has been implicated in fetal developmental impairment and reduced cognitive function during childhood [15]. These health concerns are particularly relevant in the Niger Delta, where continuous exposure through contaminated soil may increase the vulnerability of pregnant women and children. Moreover, residents are frequently exposed to complex mixtures of heavy metals rather than individual contaminants, and increasing evidence suggests that the combined toxicity of multiple metals may produce additive or synergistic adverse health effects that exceed those associated with single HM exposure [16].

Several studies have investigated HM pollution in soils across Rivers State and the wider Niger Delta region using different analytical approaches. For example, Edori et al. [17] reported varying concentrations of HMs in soils collected from higher institutions in Rivers State, with some HMs exceeding recommended guideline values. Okechukwu et al. [18] assessed heavy metal contamination in municipal dumpsites using contamination factor (CF), pollution load index (PLI), and geo-accumulation index (I_{geo}), reporting generally low to moderate contamination levels. Similarly, Iyama et al. [19] documented elevated cadmium concentrations in agricultural soils within Port Harcourt,

whereas Ohiagu et al. [20] identified anthropogenic activities as the dominant source of HM contamination in soils surrounding dumpsites in Onne. Comparable studies conducted across the Niger Delta have consistently demonstrated that land-use practices and anthropogenic activities exert a strong influence on HM pollution in soils. Agbai and Agbai [21] reported significant variations in HM concentrations among four land-use types, including palm plantation, plantain plantation, fallow land, and virgin land in Bayelsa State, identifying land use as a primary determinant of soil pollution. Similarly, Iwegbuo et al. [22] observed significant spatial variations in HM concentrations across nineteen urban land-use categories in Benin, Niger Delta, encompassing industrial, residential, agricultural, and commercial areas, further confirming the dominant role of land-use characteristics in controlling soil HM distribution. However, their investigation was restricted to surface soils (0–15 cm) sieved to ≤ 2 mm particle size. Likewise, Okoye et al. [23] reported that HM accumulation in Niger Delta soils was governed by both lithogenic processes and anthropogenic inputs, particularly crude oil exploitation and industrial emissions. Izah et al. [24] investigated cassava mill effluent-contaminated soils and demonstrated localized HM enrichment associated with agro-industrial activities, whereas Kudamnya et al. [25] evaluated HMs in soils and water using atomic absorption spectrophotometry (AAS) and integrated geochemical indices with multivariate statistical techniques to identify pollution sources and environmental risks in the eastern Niger Delta. Although HM pollution across the Niger Delta has been widely documented, the majority of existing regional investigations have relied on bulk surface-soil characterization (typically ≤ 2 mm particle size) using relatively lower-resolution analytical techniques such as AAS or X-ray fluorescence (XRF). Consequently, these studies provide limited information on the vertical migration, fine-particle-associated enrichment, and depth-dependent geochemical behavior of HMs throughout the soil profile. Moreover, the influence of ultra-fine soil fractions, which possess greater specific surface area, enhanced adsorption capacity, and stronger affinity for HMs, remains largely unexplored despite their critical role in pollutant retention, mobility, and potential human exposure. Consequently, previous investigations in Rivers State and other parts of the Niger Delta have predominantly focused on individual pollution sources (e.g., oil spills, dumpsites, agricultural lands, or cassava-processing sites), single land-use categories, or shallow surface soils, with comparatively little emphasis on integrated assessments spanning multiple contrasting land-use systems and subsurface horizons. As a result, a comprehensive understanding of the three-dimensional spatial distribution, vertical transport, source characterization, and environmental behavior of HMs within the Niger Delta remains limited. To overcome these limitations, the present study establishes a high-resolution, three-dimensional geochemical assessment framework by integrating ultra-fine particle fraction analysis ($\leq 32 \mu\text{m}$) with Inductively Coupled Plasma–Mass Spectrometry (ICP-MS) across three soil horizons (0–10, 10–50, and 50–100 cm) within industrial, agricultural, and residential environments. This analytical strategy enables more sensitive detection of HMs, improved discrimination of anthropogenic signatures, and enhanced characterization of HM pollutant migration pathways. HM pollution was further evaluated using complementary pollution indices, including the contamination factor (CF), enrichment factor (EF), geo-accumulation index (I_{geo}), pollution load index (PLI), Integrated Pollution Index (IPI), and Nemerow Integrated Pollution Index (NIPI). Unlike previous studies conducted in Rivers State and the wider Niger Delta, this study provides a comparative, depth-resolved, multi-land-use, and multi-index assessment within a unified analytical framework. By coupling high-resolution ICP-MS with ultra-fine particle characterization and comprehensive pollution assessment, the study offers a more robust understanding of heavy metal distribution, source identification, contamination status, and potential human health risks. The findings provide valuable baseline information

for long-term environmental monitoring while generating scientific evidence to support sustainable land-use management, pollution mitigation strategies, environmental policy formulation, and the protection of soil quality, ecosystem integrity, and public health in Rivers State, the Niger Delta region.

2. Materials and Methods

2.1. Study Area and Soil Sampling

This study was conducted in Rivers State, Niger Delta, Nigeria (Figure 1). The Niger Delta, which supports a population of approximately 25 million people, is one of the world's most important petroleum-producing regions and has experienced extensive industrialization, urbanization, and agricultural development. These activities have contributed to increasing concerns regarding HM contamination of soils. Three land-use categories were investigated, namely industrial (Trans-Amadi), agricultural (Egi), and residential (Woji). A stratified purposive sampling strategy was adopted to ensure that the dominant land-use types and their associated anthropogenic activities were adequately represented. Sampling locations were selected based on (i) the intensity of human activities, (ii) proximity to potential heavy metal sources, (iii) accessibility, and (iv) the representativeness of the predominant land-use characteristics within each area. Egi (agricultural area), located between 6.80° E– 7.30° E longitude and 5.20° N– 5.50° N latitude, is characterized predominantly by cultivated farmlands, natural vegetation, and scattered rural settlements. Agricultural activities in this area include intensive crop cultivation with regular application of fertilizers, pesticides, and organic manure. Sampling sites were established within active farmland and were generally located within the cultivated fields, away from major roads and industrial facilities. Woji (residential area), located between 7.20° E– 7.50° E longitude and 5.00° N– 5.30° N latitude, is a densely populated urban environment comprising residential buildings, commercial centers, markets, and road networks. Trans-Amadi (industrial area), located between 7.10° E– 7.40° E longitude and 4.50° N– 4.80° N latitude, is one of the largest industrial estates in Rivers State and hosts petrochemical industries, oil servicing companies, manufacturing facilities, mechanical workshops, and heavy vehicular traffic.

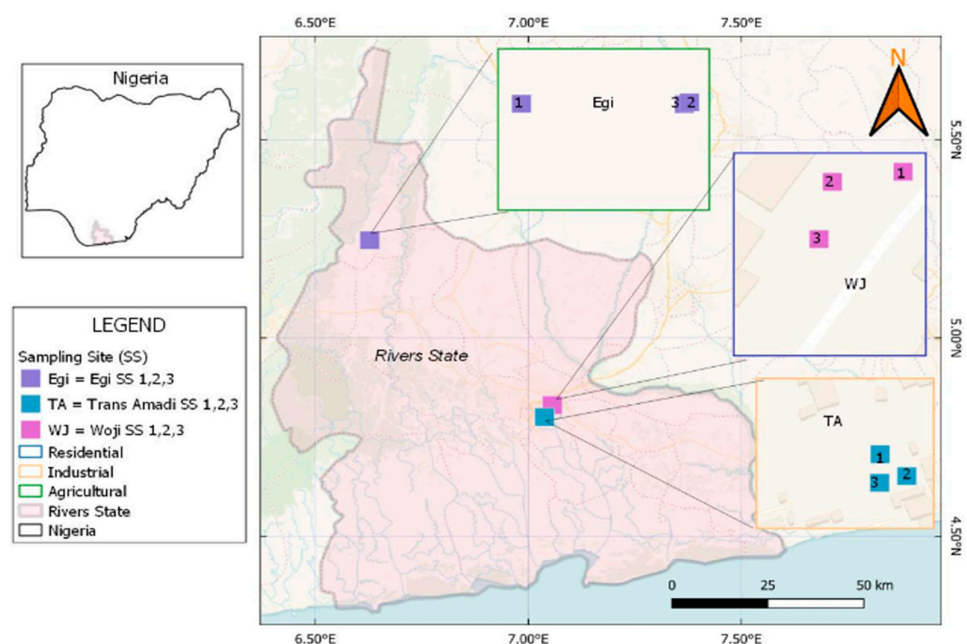


Figure 1. Location of the study area and soil sampling sites in Rivers State, Nigeria. Sampling was conducted across three land categories: Trans-Amadi (TA) industrial area, Egi agricultural area, and

Woji (WJ) residential area. Three sampling sites (SS1–SS3) were established within each location, yielding a total of 27 soil samples collected at three depth intervals (0–10 cm, 10–50 cm, and 50–100 cm). Each land area category contributed nine samples. The inset map shows the location of Rivers State within Nigeria, while the main map displays the spatial distribution of sampling sites used for assessing HM contamination.

2.2. Soil Sampling and Collection

Sampling locations were selected using a stratified purposive sampling strategy to ensure adequate representation of the three dominant land-use categories in Rivers State, namely industrial (Trans-Amadi), agricultural (Egi), and residential (Woji). The selected locations were chosen because they represent areas with contrasting anthropogenic activities and varying potential sources of HM contamination. Specifically, Trans-Amadi is characterized by intensive petrochemical operations, manufacturing industries, automobile workshops, and heavy vehicular traffic; Egi is predominantly an agricultural area where crop cultivation is supported by the routine application of fertilizers, pesticides, and organic manure; while Woji is a densely populated residential area influenced by urban activities, commercial establishments, municipal waste generation, and road traffic. Within each land area category, three spatially separated sampling sites, designated as Sampling Site 1 (SS1), Sampling Site 2 (SS2), and Sampling Site 3 (SS3), were established to account for spatial variability in soil HM concentrations. Sampling sites were selected to represent the predominant land zone characteristics of each area while remaining in close proximity to potential pollution sources. In the industrial area (Trans-Amadi), sampling sites were located approximately 100–300 m from major industrial facilities and principal road corridors. In the residential area (Woji), sampling sites were situated approximately 50–100 m from major roads, commercial centers, and residential developments. Agricultural sampling sites in Egi were established within actively cultivated farmlands and away from direct industrial influences, where agricultural inputs constitute the primary potential source of heavy metals. Soil sampling was conducted between December 2024 and January 2025. At each sampling site, soil samples were collected using a calibrated stainless-steel hand auger from three depth intervals (0–10 cm, 10–50 cm, and 50–100 cm) to evaluate the vertical distribution of heavy metals. Approximately 50 g of soil was collected from randomly selected locations within a 1 m × 1 m quadrat. A minimum of five subsamples were collected at each depth and thoroughly homogenized to produce one composite representative sample. This compositing approach was adopted to minimize small scale spatial heterogeneity and provide representative soil samples for each sampling location. Overall, 27 composite soil samples were collected, comprising three land-use categories, three sampling sites and three sampling depths. Approximately 500 g of homogenized soil was obtained for each composite sample, wrapped in pre-labeled aluminum foil and stored at 4 °C until analysis. Prior to transportation of the samples to Japan, the necessary import permit was obtained from the Ministry of Agriculture, Forestry and Fisheries, Yokohama Plant Protection Station, Japan. Although the stratified purposive sampling approach improved the representativeness of each sampling site, the relatively limited number of sampling locations may not fully capture the spatial heterogeneity of HM distribution across Rivers State.

2.3. Sample Pre-Treatment and Preparation

For the determination of HM concentrations illustrated in Figure 2, the soil samples, were initially dried, then ground to a fine homogenous particle size, before they were transferred into a Retsch AS 200-digit vibrating sieve shaker (Retsch GmbH, Tokyo, Japan) to separate the soil particles using a sieve size of $\leq 32 \mu\text{m}$, set to an amplitude of 60 Hz, for 20 min. Fifty milligrams of each of the resulting soil samples obtained after the sieving

process were weighed using a weighing balance. Each sample was placed in a 100 mL glass beaker. Subsequently, analytical grade reagents (HCL and HNO₃) of aqua regia consisting of 15 mL of 36% HCL and 5 ml of 63% HNO₃ were prepared in a 1000 mL beaker, then 20 mL of the aqua regia were measured and poured into each of the 100 mL beakers containing the weighed soil samples. The mixture (samples + aqua regia) was heated using a hotplate set at 150 °C for 90 min until no traces of reddish-brown fumes were observed. The digest realized after the digestion process was reduced to 1 ml or left until almost dry. The digest was allowed to cool to room temperature, and a diluted solution was prepared using of 20 mL of 2% nitric acid and an appropriate percentage of Type-1 Milli-Q water or distilled water. Subsequently, 20 mL of the solution was added to each of the digest, and allowed to sit for some time. Whatman filter paper (5C, 110 mm diameter, 11 µm pore size) was used to filter the samples. The filtered samples were stored in the refrigerator at a temperature of 4 °C until heavy metal analysis. The concentrations of heavy metals were quantified using Inductively Coupled Plasma–Mass Spectrometry (ICP-MS NexION 350D, Perkin Elmer, Waltham, MA, USA) at the Center for Environmental Science, Saitama, Japan. Analytical measurements were conducted at a plasma gas flow rate of 18.00 L min^{−1}, auxiliary gas flow rate of 1.20 L min^{−1}, nebulizer gas flow rate of 0.98 L min^{−1}, and RF power of 1600 W. Prior to instrumental determination of the HM digested samples, sample solutions were diluted with 3% HNO₃ and spiked with a yttrium (Y) internal standard to improve measurement reliability and correct for instrumental drift. During the HM analysis, the ICP-MS was switched on using a tuning standard solution. This was performed to set up the analytical conditions. Multi-elemental standard XSTC-662 solutions (Spex CertiPrep, Metuchen, NJ, USA) were used to create calibration curves. Acceptable curves for calculating the concentrations of the selected metals were those within the 0.999 range. Quality assurance/quality control (QA/QC) procedures were performed for HM estimation in the soil samples. After acid washing, deionized water was used to rinse the glassware during and after the digestion process. Certified reference materials (CRMs) (Gobi Kosa Dust, NIES CRM No. 30) which were digested and analyzed were used to evaluate method accuracy [26]. Analytical precision was assessed by triplicate analysis of each digested sample solution, and the relative standard deviation (RSD) of replicate measurements was mostly below 5%, indicating excellent analytical precision and repeatability of the ICP-MS measurements. Procedural blanks were included throughout the digestion and analytical procedures to monitor potential contamination, and no significant contamination was detected. Method accuracy was evaluated based on CRM recoveries, which were 107% for Cu, 100% for Zn, 93% for Mn, 85% for Cr, 95% for Co, 86% for Pb, 97% for Cd, and 85% for Ni [26]. These recovery values fall within the generally accepted range (80–120%) for HM analysis, confirming the reliability of the analytical procedure. Multi-element calibration standards were used for instrument calibration, and the calibration curves generated by external multi-point linear regression exhibited excellent linearity for all analytes, with coefficients of determination (R²) ranging from 0.997 to 0.999, indicating a strong linear relationship between analyte concentration and instrumental response. Instrument calibration was verified by recalibrating the ICP-MS after every ten sample measurements to minimize instrumental drift and maintain analytical stability throughout the analytical sequence. The method limits of detection (LODs) for Mn, Cr, Cu, Ni, Co, Zn, Pb, and Cd were 0.041, 0.018, 0.048, 0.088, 0.009, 0.067, 0.085, and 0.001 ng mL^{−1}, respectively, demonstrating the high sensitivity of the analytical method for HM determination in soil samples.

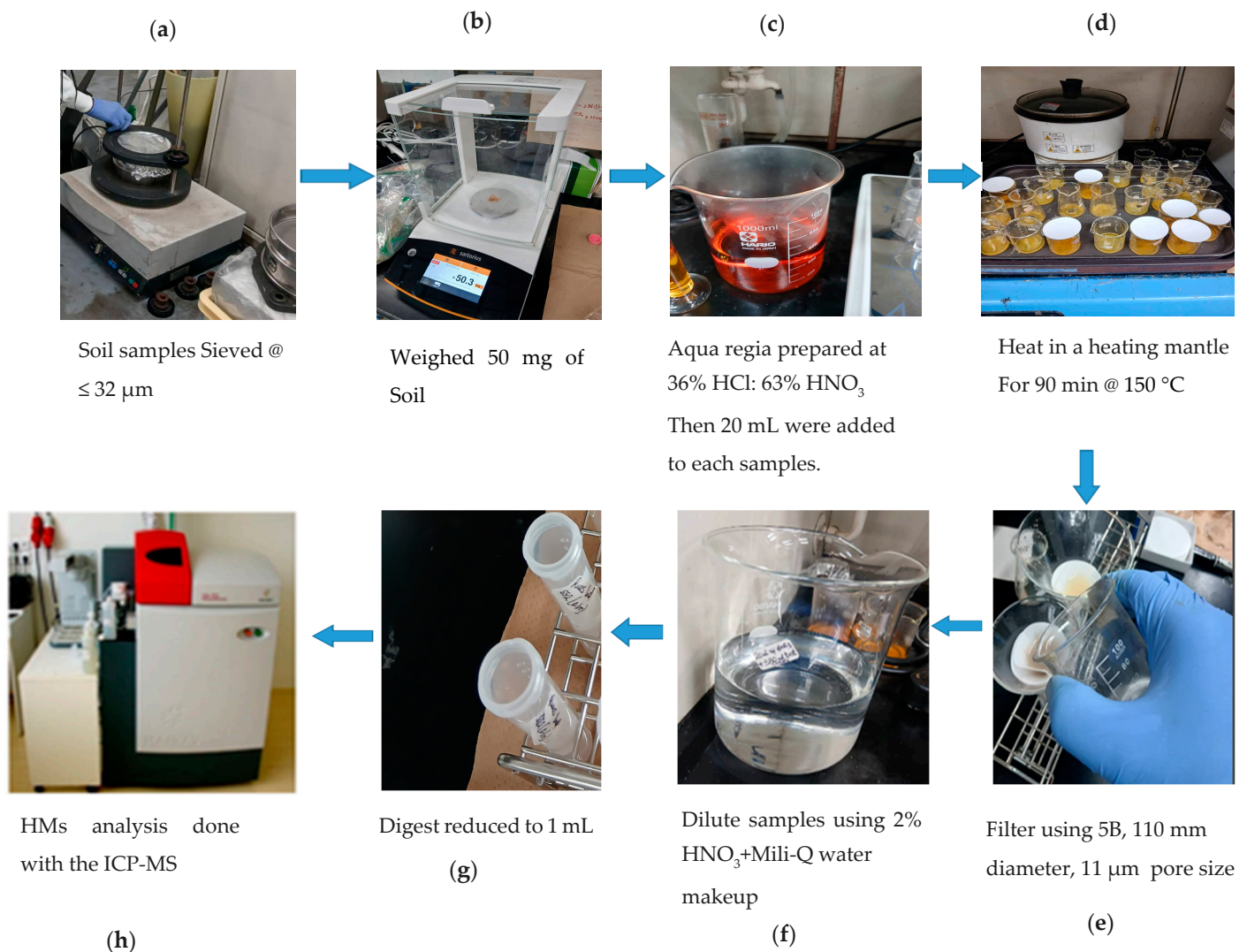


Figure 2. Schematic representation of the soil sample preparation and analytical procedure used for HM determination. (a) Soil samples were sieved to $\leq 32 \mu\text{m}$ and (b) 50 mg aliquots were accurately weighed. (c) Samples were digested with 20 mL of freshly prepared aqua regia (36% HCl:63% HNO_3), (d) at 150°C for 90 min, (e) filtered through $11 \mu\text{m}$ pore-size filter paper, (f) diluted with 2% HNO_3 and Milli-Q water, (g) reduced to a final volume of 1 mL and (h) analyzed for heavy metal concentrations using ICP-MS.

2.4. Data Analysis and Statistics

Statistical analysis was performed on the heavy metal data using MS Excel 2013 and SAS on demand for academics software (SAS 9.4). To evaluate whether HM concentrations differed significantly among land-use categories, soil depths, and sampling locations, a three-way analysis of variance (ANOVA) was performed using land-use type (industrial, agricultural, and residential), soil depth, and sampling site as fixed factors. Correlation analysis was used to assess the relationships between the analyzed heavy metals. The contamination factor (CF), index of accumulation (I_{geo}) and enrichment factor (EF) were used to determine the pollution condition of the soil. The pollution load index (PLI), Integrated Pollution Index (IPI) and Nemerow Integrated Pollution Index (NIPI) were employed to determine the degree of soil degradation and pollution risk at the study locations. Principal component analysis (PCA) and hierarchical cluster analysis (HCA) were used to determine the precise origin of HM pollutants in soil [27]. PCA was subsequently performed on the standardized correlation matrix to identify the major patterns of association among the

investigated HMs and to explore potential sources of pollution. Principal components with eigenvalues greater than 1.0 (Kaiser's criterion) were retained for interpretation, and the scree plot was used to verify the number of meaningful components retained. Consequently, the interpretation of the PCA was based on the standardized variables, eigenvalues, percentage of explained variance, and loading patterns of the retained components. The resulting loading structure provides qualitative insights into the relationships among HMs and the environmental processes potentially influencing their distribution.

2.5. Contamination Factor (CF), Geo-Accumulation Index (I_{geo}) and Enrichment Factor (EF) of the Analyzed Heavy Metals at the Three Different Land Zones of Rivers State, Nigeria

Contamination factor quantifies the extent of HM pollution in soil and is calculated as the ratio of the measured metal concentration to its background concentration. C_n is the HM concentration in soil samples, and C_{ref} represents the reference value of the Department of Petroleum Resources (DPR) and adopted referenced limits of HMs. The CF is classified as follows: $CF < 1$ means 'low contamination', $1 < CF < 3$ indicates 'moderate contamination', $3 < CF < 6$ shows 'considerable contamination', and $CF > 6$ denotes 'very high contamination' [27].

The geo-accumulation index (I_{geo}), as shown in Table 1, was proposed by Müller and has been widely used in studies of HMs. HM pollution in the soil can be calculated by comparing the HM values with the background values.

Where C_n is the measured concentration (mg/kg) of each HM found at study location, and B_n represents the background value (mg/kg) of the HMs found in soil [28,29].

Table 1. Müller's geo-accumulation index (I_{geo}) classes and corresponding pollution intensity levels (Müller [30,31]).

I_{geo} Value	I_{geo} Class	Pollution Intensity
$I_{geo} \leq 0$	0	Unpolluted
$0 < I_{geo} \leq 1$	1	Unpolluted to moderately polluted
$1 < I_{geo} \leq 2$	2	Moderately polluted
$2 < I_{geo} \leq 3$	3	Moderately to heavily polluted
$3 < I_{geo} \leq 4$	4	Heavily polluted
$4 < I_{geo} \leq 5$	5	Heavily to extremely polluted
$I_{geo} > 5$	6	Extremely polluted

The EF for the HMs were obtained by estimating the ratio between the metal concentration and the baseline or background value. In EF determination, a metal of geological origin is mostly considered in determination of the reference metal [31]. In this study, manganese was used as the reference HMs, similar to [32]. The permissible limit of 437 was utilized as the background value of Mn in this study.

Where C_{ref} is the reference metal concentration, C_n is the concentration of the HMs of interest in the soil sample. EF is grouped based on these categories: deficiency to minimal pollution; $EF > 2$, moderate pollution; $2 \leq EF < 5$, significant pollution; $5 \leq EF < 20$, very high pollution; $20 \leq EF < 40$ and extremely high pollution is when $EF \geq 40$ [31,33].

The CF, I_{geo} and EF of the soil samples was calculated using the equations below.

$$CF = \frac{C_n}{C_{ref}} \quad (1)$$

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 \times B_n} \right) \quad (2)$$

$$EF = \left(\frac{C_{n\text{metal}}}{M_n} \right)_{\text{sample}} \div \left(\frac{C_{n\text{metal}}}{M_n} \right)_{\text{background}} \quad (3)$$

2.6. Pollution Load Index (PLI), Integrated Pollution Index (IPI) and Nemerow Integrated Pollution Index (NIPI or P_N) of the Heavy Metal Concentrations at Different Locations of Rivers State

To comprehensively evaluate the overall degree of HM pollution in the investigated soils, three integrated pollution indices, namely the pollution load index (PLI), Integrated Pollution Index (IPI), and Nemerow Integrated Pollution Index (NIPI, also referred to as P_N), were employed. These indices provide an integrated assessment of HM pollution status by combining the concentrations of multiple HMs into a single pollution metric, thereby facilitating comparison among different sampling locations. These indices assess the extent of pollution in the study area. The pollution load index (PLI) was used to evaluate the overall level of HM pollution at each sampling location by integrating the contamination factors (CFs) of the analyzed HMs [33]. The CF for each HM was calculated relative to its corresponding background concentration of the Department of Petroleum Resources (DPR) target values and referenced geochemical background values. The PLI was calculated using Equation (4) below:

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{1/2} \quad (4)$$

where n represents the number of analyzed HMs and CF is the contamination factor of each HM.

Based on the criteria proposed by Tomlinson et al. [34], a pollution load index (PLI) value ≤ 1 indicates an unpolluted or baseline condition, whereas a PLI value > 1 reflects progressive deterioration of soil quality resulting from heavy metal (HM) contamination. The Integrated Pollution Index (IPI) was employed to evaluate the cumulative pollution level resulting from all analyzed HMs. Unlike individual contamination factors, the IPI provides an overall measure of pollution intensity by averaging the pollution indices of all HMs at each sampling location. According to the classification of subsequent studies [27], the pollution levels are categorized as follows: $IPI \leq 1$: Low pollution; $1 < IPI \leq 2$: Moderate pollution; and $IPI > 2$: High pollution.

The Nemerow Integrated Pollution Index (NIPI, also denoted as P_N) was used to provide a more comprehensive assessment of soil pollution by simultaneously considering both the average pollution level and the maximum pollution index among all analyzed HMs. Consequently, the Nemerow Integrated Pollution Index (NIPI) is widely regarded as a more sensitive and comprehensive indicator of overall HM pollution than indices based solely on mean pollution levels, as it incorporates both the average pollution status and the maximum pollution intensity, allowing for the detection of localized pollution hotspots [27]. The NIPI was calculated using Equation (5):

$$NIPI = \frac{\sqrt{P_{imax}^2 + P_{iave}^2}}{2} \quad (5)$$

where P_{imax} is the maximum pollution index and P_{iave} is the average pollution index for all analyzed HMs. The pollution status based on NIPI was classified according to the following criteria [27]: $NIPI \leq 0.7$: Unpolluted; $0.7 < NIPI \leq 1.0$: Warning level; $1.0 < NIPI \leq 2.0$: Slight pollution; $2.0 < NIPI \leq 3.0$: Moderate pollution; and $NIPI > 3.0$: Heavy pollution.

Compared with PLI and IPI, the NIPI provides a more balanced evaluation of contamination status because it incorporates both the average pollution level and the highest pollution intensity observed among the analyzed HMs. Both geochemical background concentrations and Department of Petroleum Resources (DPR/EGASPIN) regulatory threshold values were employed as background reference concentrations in the calculation of the

pollution indices. This approach ensured a comprehensive and consistent evaluation of all investigated HMs by applying the most appropriate and scientifically justifiable background reference concentration for each HM.

2.7. Human Health Risk Assessment of the Analyzed HMs from Rivers, State Locations

Human exposure to HMs in soil was evaluated by the estimating of risk, determined through average daily dose (*ADD*), hazard quotient (*HQ*), hazard index (*HI*), and lifetime carcinogenic risk (*LCR*) coefficients. Average daily dose, *ADD*, of three exposure pathways of soil including ingestion (*ADD_{ing}*), inhalation (*ADD_{inh}*), and dermal (*ADD_{dermal}*) in mg/kg/day of metals including V, Cr, Mn, Zn, Co, Ni, Cu, As, Mo, Pb, Cd and Se was calculated by using these formulas below.

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

$$ADD_{inh} = C \times \frac{InhR \times EF \times ED}{PEF \times BW \times AT} \quad (7)$$

$$ADD_{dermal} = C \times \frac{SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (8)$$

where *C* is the concentration of heavy metals (mg kg⁻¹); *IngR* is the soil ingestion rate (200 mg d⁻¹ y⁻¹ for children and 100 mg⁻¹ day⁻¹ for adults); *EF* is the exposure frequency (350 day⁻¹ year⁻¹); *ED* is the exposure duration (6 years for children and 24 years for adults); *BW* is the average body weight (15 kg for children and 70 kg for adults); *AT* is the averaging time, calculated as *ED* × 365 days for non-carcinogenic risk assessment and 70 × 365 days (25,550 days) for carcinogenic risk assessment; *InhR* is the inhalation rate (20 m³ day⁻¹ for both adults and children); *PEF* is the particle emission factor (1.36 × 10⁹ m³ kg⁻¹); *SA* is the exposed skin surface area (2800 cm² for children and 5700 cm² for adults); *AF* is the soil-to-skin adherence factor (0.2 mg cm⁻² for children and 0.07 mg cm⁻² for adults); and *ABS* (dermal absorption factor) is 0.001. The average daily dose via ingestion (*ADD_{ing}*), inhalation (*ADD_{inh}*), and dermal contact (*ADD_{derm}*) for V, Cr, Mn, Co, Ni, Cu, Zn, As, Mo, Cd, Pb, and Se were calculated using the corresponding exposure equations described above. For carcinogenic risk assessment, the Lifetime Average Daily Dose (*LADD*) was calculated using the lifetime averaging time (25,550 days), and the Incremental Lifetime Cancer Risk (*ILCR*) was subsequently estimated using the corresponding cancer slope factors. Unless otherwise specified, identical exposure parameters were applied across all exposure pathways. The selected exposure parameters were adopted from the U.S. Environmental Protection Agency (USEPA) human health risk assessment guidance and the related literature [33].

2.7.1. Non-Carcinogenic Health Risk Assessment of Rivers Industrial, Agricultural and Residential Locations

The *HQ* was calculated as the ratio of average daily dose to reference dose (*HQ* = *ADD*/*RfD*) of the HMs presented in Table 2 [33,35]. The hazard index (*HI*) was computed by the summation of the total expected *HQs* (non-carcinogenic risks) through inhalation, oral, and dermal pathways, and the non-carcinogenic risks of different contaminants through the 3 exposure routes mentioned above are computed through its utilization. The *HQ* and *HI* were computed through the utilization of the equations below:

$$HQ = \frac{ADD_{ing}}{RfD} \quad (9)$$

$$HQ = \frac{ADD_{inh}}{RfD} \quad (10)$$

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

$$HI = \sum HQ = HQ_{ingestion} + HQ_{inhalation} + HQ_{dermal} \quad (12)$$

Table 2. Toxicological reference values (*RfD* and *CSF*) for heavy metal exposure via ingestion, inhalation, and dermal pathways.

HMs	<i>RfD</i> (mg/kg × d)			<i>CSF</i> (mg/kg × d)			References
	Ingestion	Inhalation	Dermal	Ingestion	Inhalation	Dermal	
Cr	3.00×10^{-3}	2.86×10^{-5}	6.00×10^{-5}	8.50×10^{-3}	4.20×10^1		[36]
Mn	4.60×10^{-1}	1.43×10^{-5}	1.84×10^{-3}				[36,37]
Co	2.00×10^{-2}	5.71×10^{-6}	1.84×10^{-3}				[36,37]
Ni	2.06×10^{-2}	2.06×10^{-2}	5.40×10^{-3}		8.4×10^{-1}		[36]
Cu	4.00×10^{-2}	4.02×10^{-2}	1.20×10^{-2}				[36,37]
Zn	3.00×10^{-1}	3.00×10^{-1}	6.00×10^{-2}				[36,37]
As	3.00×10^{-4}	1.23×10^{-4}	1.23×10^{-4}	1.50	1.50	3.66	[36]
Cd	1.00×10^{-3}	1.00×10^{-5}	1.00×10^{-5}	6.1	6.30		[36,37]
Pb	3.50×10^{-3}	3.52×10^{-3}	5.2×10^{-4}	8.50×10^{-3}			[36]
Se	5×10^{-3}	na	na				[35,38]
Mo	5×10^{-3}	na	1.9×10^{-3}				[35,39]
V	7×10^{-3}	na	7×10^{-3}				[35,40,41]

na denotes not available.

2.7.2. Carcinogenic Risk (CR) of the Analyzed HMs from the Study Locations of Rivers State

The *ILCR* was calculated by multiplying the *LADD* and the cancer slope factor (Table 2) for each HM for all exposure routes [33], as given by Equations (13)–(15).

$$ILCR = LADD_{ingestion} \times SF \quad (13)$$

$$ILCR = LADD_{inhalation} \times SF \quad (14)$$

$$ILCR = LADD_{dermal} \times SF \quad (15)$$

The human health risk assessment was based on total metal concentrations determined by ICP-MS following acid digestion. HM speciation (e.g., Cr (III)/Cr (VI) and inorganic/organic arsenic) and bio-accessibility analyses were not performed. Accordingly, the exposure assessment assumes that the measured metal concentrations are fully available for human uptake, consistent with the conservative screening methodology recommended by the USEPA. Therefore, the estimated average daily dose (*ADD*), hazard quotient (*HQ*), hazard index (*HI*), and Incremental Lifetime Cancer Risk (*ILCR*) were interpreted as screening-level estimates intended to identify potential health concerns rather than definitive measures of actual human exposure [33].

3. Results and Discussion

3.1. Heavy Metal Concentration at Different Locations of Rivers State

Tables 3–5 summarize the concentration of analyzed HMs in mg/kg. The pattern of distribution of the HMs in the Trans-Amadi industrial area (Table 3) shows high HM concentrations, with Zn and As having mean concentrations of 222.5 mg/kg and 366.8 mg/kg respectively across the sampling depths, exceeding the DPR permissible limits of 140 mg/kg and 20 mg/kg, respectively. Mn, Se, Cd and Co were all low in the industrial area, while moderate levels of Cr and Cu were observed at this land use. This connotes the impact of industrial activities such as metal fabrication, petrochemical operations, and vehicular

emissions [6,8,30]. In the Egi agricultural area (Table 4), Mn exhibits the highest concentration of HMs at the 0–10 cm depth (874.5 mg/kg), far exceeding the DPR limit of 437 mg/kg. There was a significant decrease in Mn at lower depths. The values of Zn (327.9 mg/kg), Cr (210.8 mg/kg) and Se (2.6 mg/kg) were high compared to the DPR and Dutch/CCME permissible limits. A similar study by Fatoba et al. [42], around the flow stations in Kokori and Kolo Creek, Niger Delta, Nigeria, observed high values of Zn, Pb, Ni, Cr, and Cd.

Table 3. Spatial and vertical distribution of heavy metal concentrations (mg/kg) across Trans-Amadi industrial area sampling sites and soil depths in Rivers State, Nigeria.

Sampling Site	Depth (cm)	V	Cr	Mn	Ni	Co	Cu	Zn	As	Mo	Cd	Pb	Se
SS1	0–10	27.0 ± 3.66	103.7 ± 5.06	123.5 ± 5.59	4.8 ± 1.59	41.1 ± 3.81	31.6 ± 2.99	138.8 ± 3.13	287.6 ± 2.25	4.6 ± 2.96	0.3 ± 0.04	32.1 ± 2.7	0.2 ± 0.03
	10–50	16.4 ± 3.85	73.7 ± 1.54	267.3 ± 5.49	4.6 ± 0.85	27.1 ± 3.72	41.8 ± 4.66	174.0 ± 2.80	100.0 ± 4.02	2.0 ± 1.41	0.5 ± 0.41	40.1 ± 3.0	0.6 ± 0.01
	50–100	4.9 ± 0.57	44.0 ± 3.67	30.8 ± 2.76	2.9 ± 0.14	7.9 ± 0.43	10.8 ± 1.81	58.9 ± 6.54	366.8 ± 4.17	2.2 ± 0.22	0.3 ± 0.06	20.5 ± 5.0	0.3 ± 0.02
SS2	0–10	20.9 ± 5.56	143.7 ± 2.78	103.0 ± 4.76	3.7 ± 0.77	20.2 ± 2.04	24.8 ± 2.14	68.0 ± 5.35	217.8 ± 2.31	2.5 ± 1.04	0.3 ± 0.07	35.8 ± 2.3	0.8 ± 0.01
	10–50	13.6 ± 1.79	219.5 ± 3.21	175.0 ± 6.01	5.1 ± 0.53	27.6 ± 3.36	33.8 ± 4.83	78.8 ± 1.56	80.7 ± 3.01	1.8 ± 0.03	0.3 ± 0.07	37.2 ± 1.1	0.5 ± 0.03
	50–100	7.7 ± 2.75	83.3 ± 3.71	83.1 ± 2.95	4.0 ± 1.00	23.2 ± 3.05	20.9 ± 2.64	68.9 ± 1.17	49.1 ± 3.09	1.4 ± 0.48	0.3 ± 0.08	44.8 ± 1.2	0.4 ± 0.59
SS3	0–10	18.5 ± 3.39	87.4 ± 1.72	66.9 ± 2.39	3.3 ± 0.47	17.7 ± 4.74	27.7 ± 0.81	66.5 ± 5.48	173.4 ± 2.44	2.9 ± 0.25	0.3 ± 0.01	20.4 ± 1.1	0.1 ± 0.01
	10–50	13.2 ± 1.32	75.9 ± 0.93	166.5 ± 1.96	4.8 ± 1.02	25.0 ± 4.59	30.7 ± 1.47	88.0 ± 3.20	351.2 ± 2.72	1.8 ± 0.15	0.3 ± 0.08	32.9 ± 1.4	0.6 ± 0.02
	50–100	8.1 ± 2.66	56.9 ± 2.62	45.7 ± 1.46	3.8 ± 1.02	29.4 ± 3.33	20.7 ± 1.68	222.4 ± 3.56	306.0 ± 2.31	2.6 ± 0.39	0.4 ± 0.11	21.5 ± 3.1	0.3 ± 0.02

SS1, SS2, and SS3 denote Sampling Sites 1, 2, and 3 respectively within each study area. Values are presented as Mean/Standard Deviation (SD) of triplicate analyses.

Table 4. Concentrations of heavy metals (mg kg^{−1}, mean ± SD, *n* = 3) in agricultural soils (Egi) at different sampling sites and depths.

Sampling Site	Depth (cm)	V	Cr	Mn	Ni	Co	Cu	Zn	As	Mo	Cd	Pb	Se
SS1	0–10	8.8 ± 0.7	60.4 ± 4.0	874.5 ± 5.0	5.5 ± 0.6	26.3 ± 4.9	25.6 ± 3.8	81.1 ± 3.0	3.4 ± 0.3	2.2 ± 0.1	0.2 ± 0.02	17.7 ± 1.7	1.2 ± 0.1
	10–50	9.7 ± 3.7	59.0 ± 4.3	420.1 ± 4.5	5.9 ± 2.2	12.8 ± 2.0	21.3 ± 3.0	85.1 ± 4.4	2.6 ± 1.6	0.9 ± 0.1	0.1 ± 0.09	28.4 ± 2.0	1.5 ± 0.4
	50–100	9.7 ± 1.3	67.2 ± 2.0	490.6 ± 1.8	5.4 ± 0.5	12.2 ± 2.4	24.8 ± 3.5	86.6 ± 3.0	2.7 ± 0.6	0.1 ± 0.02	0.2 ± 0.01	31.0 ± 1.5	1.9 ± 0.3
SS2	0–10	5.8 ± 0.8	46.5 ± 2.1	145.6 ± 3.6	3.2 ± 0.1	11.1 ± 1.9	18.2 ± 2.7	73.1 ± 4.9	1.6 ± 0.2	0.6 ± 0.04	0.1 ± 0.05	20.5 ± 1.7	1.5 ± 0.2
	10–50	9.5 ± 0.8	84.4 ± 2.5	249.7 ± 1.5	3.7 ± 1.9	10.2 ± 4.0	25.9 ± 3.0	71.7 ± 3.6	2.7 ± 0.5	0.2 ± 0.08	0.2 ± 0.01	29.2 ± 2.0	1.9 ± 0.2
	50–100	11.3 ± 2.0	81.6 ± 3.5	134.9 ± 4.8	4.1 ± 0.9	14.3 ± 1.1	26.9 ± 3.5	98.6 ± 4.4	2.5 ± 1.0	0.1 ± 0.02	0.2 ± 0.01	31.8 ± 1.8	1.7 ± 0.2
SS3	0–10	13.0 ± 2.4	165.4 ± 3.0	662.1 ± 5.9	19.1 ± 2.6	56.3 ± 2.6	53.9 ± 2.8	327.9 ± 3.5	3.3 ± 0.7	0.6 ± 0.2	0.2 ± 0.08	56.6 ± 6.2	2.0 ± 0.2
	10–50	8.7 ± 0.1	41.3 ± 1.0	152.5 ± 2.8	4.0 ± 0.7	17.0 ± 3.9	17.0 ± 1.9	51.2 ± 0.9	2.7 ± 0.9	1.9 ± 0.1	0.1 ± 0.02	15.8 ± 0.4	1.2 ± 0.2
	50–100	16.7 ± 2.2	210.8 ± 3.4	260.5 ± 5.9	7.6 ± 1.9	25.4 ± 1.8	41.6 ± 5.2	116.3 ± 6.1	7.4 ± 0.6	0.6 ± 0.2	0.2 ± 0.01	56.9 ± 2.5	2.6 ± 0.2

Values are expressed as mean ± standard deviation (SD) of triplicate measurements (*n* = 3). Concentrations are reported on a dry-weight basis. Units for all metals are mg kg^{−1}.

Table 5. Heavy metal concentrations (mg kg^{−1}, mean ± SD) in soils from the residential area (Woji).

Sampling Site	Depth (cm)	V	Cr	Mn	Ni	Co	Cu	Zn	As	Mo	Cd	Pb	Se
SS1	0–10	7.8 ± 0.39	62.0 ± 3.55	1312.4 ± 9.58	6.0 ± 1.63	13.7 ± 4.69	34.5 ± 5.61	281.3 ± 4.23	7.1 ± 0.67	1.6 ± 0.06	1.3 ± 0.04	65.8 ± 3.8	3.4 ± 0.07
	10–50	5.0 ± 2.40	41.7 ± 3.68	162.9 ± 6.10	2.1 ± 0.16	11.5 ± 3.36	21.0 ± 2.67	95.0 ± 3.24	11.2 ± 1.29	0.5 ± 0.05	0.5 ± 0.51	12.1 ± 0.8	1.7 ± 0.58
	50–100	12.8 ± 1.97	66.3 ± 3.25	391.4 ± 4.52	3.6 ± 1.27	18.8 ± 2.16	21.8 ± 1.64	63.1 ± 4.45	3.7 ± 0.18	2.2 ± 0.33	0.1 ± 0.02	9.9 ± 1.4	1.1 ± 0.30
SS2	0–10	11.9 ± 2.94	109.5 ± 5.41	786.5 ± 4.20	6.1 ± 1.16	20.7 ± 1.13	38.9 ± 3.66	178.7 ± 4.22	13.1 ± 2.18	1.8 ± 0.20	1.2 ± 0.10	72.5 ± 3.7	3.1 ± 0.48
	10–50	6.4 ± 0.96	63.3 ± 3.51	798.6 ± 3.36	4.3 ± 2.46	19.8 ± 0.45	24.2 ± 2.78	161.4 ± 3.69	12.5 ± 1.15	3.0 ± 1.04	1.2 ± 0.11	36.7 ± 1.0	2.6 ± 0.68
	50–100	9.9 ± 2.27	51.2 ± 3.03	169.3 ± 3.44	3.9 ± 0.55	14.1 ± 2.40	14.6 ± 4.62	55.6 ± 3.32	2.7 ± 1.23	2.1 ± 0.47	0.1 ± 0.02	18.2 ± 1.4	1.4 ± 0.64
SS3	0–10	6.6 ± 0.53	56.7 ± 3.54	902.0 ± 6.07	4.5 ± 2.38	10.0 ± 2.62	26.7 ± 5.68	150.4 ± 2.07	25.9 ± 1.68	1.7 ± 0.21	1.2 ± 0.09	38.4 ± 1.9	2.7 ± 0.36
	10–50	7.9 ± 1.85	57.4 ± 3.19	443.6 ± 2.30	4.9 ± 1.10	17.4 ± 0.73	24.8 ± 3.74	90.6 ± 3.08	32.4 ± 1.54	1.8 ± 0.89	1.1 ± 0.02	20.9 ± 2.0	2.6 ± 0.56
	50–100	6.7 ± 1.73	66.0 ± 5.80	428.2 ± 2.68	3.0 ± 1.42	8.0 ± 3.74	30.3 ± 3.52	118.7 ± 2.99	29.4 ± 2.02	1.6 ± 0.57	1.1 ± 0.13	32.4 ± 2.0	2.5 ± 0.48

The high Zn levels might be attributed to the repeated application of phosphate fertilizers or pesticides [9]. In addition to the natural triggers of HMs deposition in the Niger Delta region, the elevated Se concentrations observed in the agricultural soils are likely associated with the long-term application of phosphate fertilizers and other agrochemicals, which are recognized sources of selenium and other HMs in cultivated soils [43]. As and Cd were observed at minimum concentration levels at the Egi location. Generally, there was a vertical attenuation pattern 0–10 cm > 10–50 cm > 50–100 cm in most of the HMs at the Egi agricultural location. At the Woji residential area presented in Table 5, Mn had the highest HM value of 1312.4 mg/kg observed at the topsoil layer of 0–10 cm, which surpasses the DPR regulatory limit of 437 mg/kg as shown in Table 6. Zn (281.3 mg/kg) and Se (3.4 mg/kg) concentrations were also high, exceeding the DPR and CCME permissible limit of 140 mg/kg and 1 mg/kg respectively. Mn, Zn and Se therefore emerged as the most dominant HMs in the residential area. Pb, V and Co show low concentrations, with their

highest values (65.8 mg/kg, 12.8 mg/kg and 6.1 mg/kg respectively) below the DPR, CCME and Dutch permissible limit (Table 6) of 85 mg/kg, 130 mg/kg and 24 mg/kg respectively. Se pollution in the residential area is likely attributable to mixed anthropogenic inputs, including domestic waste disposal, atmospheric deposition, vehicular emissions, fossil fuel combustion, and diffuse urban contamination. Similar observations have been reported in the Niger Delta, where HM accumulation in soils was attributed to complex interactions between petroleum-related activities, urbanization, agricultural practices, and natural environmental processes [20]. The elevated Se concentrations observed in the agricultural and residential soils suggest that Se pollution across the investigated soils is likely driven by a combination of geogenic influences from selenium-bearing sedimentary materials and anthropogenic inputs associated with agricultural practices, petroleum-related activities, urbanization, and atmospheric deposition [43]. The environmental behavior of Se differs markedly from that of most HMs because its mobility is primarily controlled by oxidation–reduction conditions, soil pH, and mineralogical composition. Consequently, variations in soil physicochemical conditions can substantially influence Se bioavailability, transport, and environmental pollution risk [43]. There is vertical profiling of HMs across the three land uses and the three sampling depths (0–10 cm, 10–50 cm, and 50–100 cm), revealing two distinct trends. HMs such as Cr, V and Ni exhibited surface attenuation patterns (0–10 cm > 10–50 cm > 50–100 cm) that imply surface-dominated anthropogenic inputs [7,8]. Conversely, elevated subsurface concentrations were observed for As at Trans-Amadi (SS3), reaching 306.0 mg/kg, while Zn attained 116.3 mg/kg at Egi (SS3) within the 50–100 cm soil layer. These elevated concentrations at depth indicate significant vertical translocation of HM pollutants through the soil profile, reflecting long-term accumulation and the persistence of HM pollution [6,12].

Table 6. Department of Petroleum Resources (DPR) guideline values and literature-derived background concentrations for selected heavy metals.

Metal	DPR Target Value (mg/kg)	Dutch/CCME Background Limit	Adopted Geochemical Background Value (mg/kg)	References
As	20–29	—	20	[44]
Cd	0.8		0.8	[45,46]
Cr	100		100	[45,46]
Cu	36		36	[45,46]
Ni	35		35	[45,46]
Pb	85		85	[45–47]
Zn	140		140	[45]
Mn	437–850		437	[45,48,49]
Se		1–3.9	0.5–0.7	[48,50,51]
Mo		253	10	[49,50]
V		130	20–120	[50,52–54]
Co		24	20	[50,52,55]

The Department of Petroleum Resources (DPR) guideline values, the Dutch National target/Canadian Council of Ministers of environment (CCME) values and referenced geochemical background concentrations were employed as HM background references in this study. (DPR and Dutch/CCME background) Reference values were used to evaluate the measured heavy metal concentrations, while the DPR and the referenced geochemical background adopted values from Kabata-Pendias [48] were employed for the evaluation of pollution indices.

The interpretation of V, Mo, Se, and Co concentrations represents a limitation of this study because these HMs are not assigned regulatory threshold values in the current Nigerian NUPRC/EGASPIN and other soil quality guidelines in Nigeria. Consequently, their pollution status was assessed using internationally recognized guideline values and published background concentrations. Although this approach provides a scientifically accepted framework for HM evaluation, it may not fully capture site-specific environmental conditions in Nigeria, underscoring the need to establish national regulatory thresholds for these HMs.

3.1.1. Effects of Land Use, Soil Depth, and Sampling Site on Heavy Metal Concentrations

The three-way ANOVA (Table 7) demonstrated that HM concentrations were significantly influenced by land use, soil depth, sampling site, and their interactions, although the magnitude of these effects differed among metals. The overall models were highly significant for all investigated HMs ($p < 0.001$), with coefficients of determination (R^2) ranging from 0.724 (Mo) to 0.999 (As), indicating that the selected factors were explained between 72.4% and 99.9% of the observed variability. The highest explanatory power was obtained for As ($R^2 = 0.999$), Zn ($R^2 = 0.997$), Mn ($R^2 = 0.996$), Pb ($R^2 = 0.956$), Se ($R^2 = 0.924$), and Ni ($R^2 = 0.920$), reflecting strong environmental control over their spatial and vertical distributions. Land use exerted significant effects on nearly all HMs, with the strongest responses observed for Se ($F = 238.16$, $p < 0.001$), Cd ($F = 76.77$, $p < 0.001$), and As, Zn, Mn, Cr, Co, and Ni. In contrast, Cu showed no significant land-use effect, while Pb exhibited a comparatively weaker but significant response ($p = 0.0085$). A similar study [56] of crude-oil-impacted soil analyzed a one-way ANOVA, and the results demonstrated significant differences ($p < 0.05$) in Pb, As, and Cd concentrations, indicating strong anthropogenic pollution associated with petroleum exploration and production activities [56].

Table 7. Summary of three-way ANOVA showing the effects of land-use (Treatment), soil depth, sampling site, and their interactions on heavy metal concentrations in soils of Rivers State, Nigeria.

Metal	Model F	R^2	Treatment	Depth	Sampling Site	Treatment $\times$ Depth	Treatment $\times$ Site	Depth $\times$ Site	Treatment $\times$ Depth $\times$ Site
V	10.95 ***	0.841	***	***	ns	***	*	*	**
Cr	19.35 ***	0.903	***	***	***	***	***	***	***
Mn	482.74 ***	0.996	***	***	***	***	***	***	***
Co	13.10 ***	0.863	***	***	***	***	***	***	***
Ni	23.73 ***	0.92	***	***	***	***	***	***	***
Cu	18.14 ***	0.897	ns	***	***	***	***	***	***
Zn	650.57 ***	0.997	***	***	***	***	***	***	***
As	3423.98 ***	0.999	***	***	***	***	***	***	***
Mo	5.47 ***	0.724	***	**	ns	**	*	**	*
Cd	16.02 *	0.885	***	***	ns	***	***	***	***
Pb	45.80 *	0.956	**	***	***	***	***	***	***
Se	25.14 *	0.924	***	**	**	***	ns	**	***

ns means not significant ($p > 0.05$); * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Treatment represents land-use type (industrial, agricultural, and residential). Model statistics are based on Type III sums of squares.

These results indicate that differences among industrial, agricultural, and residential areas contributed substantially to variations in HM pollution. Soil depth significantly affected all investigated HMs, demonstrating pronounced vertical variability within the soil profile [57]. The strongest depth effects were observed for Pb ($F = 66.49$, $p < 0.001$) and Cd ($F = 29.62$, $p < 0.001$), whereas Mo and Se exhibited relatively weaker depth-dependent variation. These findings suggest that HM distributions are influenced by differences in surface inputs, retention processes, and vertical migration within the soil profile [57,58]. Sampling site significantly affected the concentrations of Cr, Mn, Co, Ni, Cu, Zn, As, Pb, and Se, indicating considerable spatial heterogeneity across the study area. Conversely, V, Mo, and Cd showed no significant site effect, suggesting relatively uniform distributions across sampling locations. Significant two-way (land use $\times$ depth and depth $\times$ site) and three-way (land use $\times$ depth $\times$ site) interactions for all HMs further demonstrate that the effects of individual environmental factors were interdependent rather than acting independently. Among the investigated HMs, As (3423.98), Zn (650.57), and Mn (482.74) exhibited the strongest overall model responses, followed by Pb (45.80), Se (25.14), and Cd (16.02), highlighting their high sensitivity to the combined influence of land use, soil depth, and site characteristics.

Overall, the three-way ANOVA provides robust statistical evidence that HM distributions in Rivers State soils are controlled by the combined effects of land use, soil depth, and local environmental conditions. These findings support the observed spatial and vertical variability in HM concentrations and indicate that HM pollution reflects the interaction of

anthropogenic influences with site-specific environmental processes rather than the effect of any single factor alone.

3.1.2. Correlation of Heavy Metals in Rivers State Study Areas

The correlation coefficients between HMs in soil samples from the industrial, agricultural, and residential zones of Rivers State are presented in Table 8. Strong positive correlations were observed between Cu and Co ($r = 0.620^{***}$), Zn and Ni ($r = 0.620^{***}$), Zn and Cu ($r = 0.580^{***}$), Cu and Ni ($r = 0.570^{***}$), Mn and Se ($r = 0.620^{***}$), and Pb and Zn ($r = 0.560^{***}$). These associations suggest that these elements may share similar distribution patterns and may originate from related environmental inputs, including industrial activities, petroleum-related operations, vehicular emissions, and urban pollution sources prevalent within the Niger Delta region [5,7,12]. Moderate positive correlations were observed between V and Ni ($r = 0.510^{**}$), Co and Ni ($r = 0.500^{**}$), and Pb and Co ($r = 0.500^{**}$), indicating possible partial similarities in their sources or geochemical behavior. Conversely, weak positive relationships observed between V and Cr ($r = 0.350^{*}$), Cr and Co ($r = 0.360^{*}$), and other HMs pairs indicate weaker associations and potentially different controlling factors. Significant negative correlations between As and Se ($r = -0.410^{**}$) and Mo and Se ($r = -0.400^{**}$) suggest contrasting geochemical behavior or differential environmental mobility under the prevailing soil conditions. Overall, the correlation matrix indicates that Ni, Cu, Zn, Co, Pb, and Mn exhibit similar distribution patterns, suggesting possible shared influences from anthropogenic activities such as petroleum-related pollution, industrial emissions, vehicular sources, and urban waste inputs [5,12]. Therefore, the observed correlations are considered supportive indicators of potential associations among HMs and were interpreted together with complementary approaches, including enrichment factors, pollution indices, and multivariate analyses, such as principal component analysis (PCA), for more robust source identification.

Table 8. Pearson correlation matrix of heavy metals showing inter-element relationships and potential source associations in the study area.

HMs	V	Cr	Mn	Co	Ni	Cu	Zn	As	Mo	Cd	Pb	Se
V	1											
Cr	0.350 *	1										
Mn	−0.170	−0.054	1									
Co	0.17	0.360 *	0.420 **	1								
Ni	0.510 **	0.320 *	0.12	0.500 **	1							
Cu	0.450 **	0.360 *	0.470 **	0.620 ***	0.570 ***	1						
Zn	0.099	0.11	0.480 **	0.450 **	0.620 ***	0.580 ***	1					
As	0.017	−0.094	−0.240	−0.180	−0.190	−0.280	−0.120	1				
Mo	0.510 **	0.035	0.037	−0.100	0.340 *	0.06	0.086	0.22	1			
Cd	−0.150	−0.080	0.490 **	−0.017	−0.056	0.25	0.380 *	−0.050	0.18	1		
Pb	0.15	0.330 *	0.620 ***	0.500 **	0.310 *	0.700 ***	0.560 ***	−0.230	−0.084	0.370 *	1	
Se	−0.260	0.007	0.620 ***	0.25	−0.120	0.29	0.27	−0.410 **	−0.400 **	0.540 ***	0.490 **	1

* $p < 0.05$ denotes significance, ** indicates highly significance ($p < 0.01$), and *** shows very highly significance ($p < 0.001$).

3.2. Environmental Index Evaluation of the Heavy Metal Contaminants Across Industrial, Agricultural and Residential Area of Rivers State, Nigeria

3.2.1. Index of Geo-Accumulation (I_{geo})

The results of the I_{geo} of the study area in Table 9 indicate that the study area is predominantly uncontaminated to moderately contaminated for most HMs. Trans-Amadi exhibited the highest overall geo-accumulation levels among the study locations. As, with an I_{geo} of 3, is the most critical contaminant, exhibiting heavy contamination of the HMs, particularly in the Trans-Amadi industrial area. Se, with an I_{geo} of 0 at 10–50 cm, showed unpolluted condition, while Cr, Zn, Cu, Ni, and Cd were characterized as unpolluted. In a similar study by Fatoba et al. [42], the index of I-geo results generally showed no pollution to low pollution, except the Cr in Kolo Creek that indicated strong pollution [42].

Table 9. Geo-accumulation index (I_{geo}) values of HMs in surface and subsurface soils from industrial (Trans-Amadi), agricultural (Egi), and residential (Woji) areas of Rivers State, Nigeria, at different sampling depths (0–10 cm, 10–50 cm, and 50–100 cm), indicating the degree of metal enrichment relative to geochemical background concentrations.

Metal	Trans-Amadi			Egi			Woji		
	0–10 cm	10–50 cm	50–100 cm	0–10 cm	10–50 cm	50–100 cm	0–10 cm	10–50 cm	50–100 cm
V	−3	−3	−4	−4	−4	−3	−4	−4	−4
Cr	0	0	−1	−1	−1	−1	−1	−1	−1
Mn	−3	−2	−4	−1	−1	−1	1	−1	−1
Co	−3	−3	−3	−2	−3	−2	−2	−3	−3
Ni	−1	−1	−2	−1	−2	−2	−2	−2	−2
Cu	−1	−1	−2	−1	−1	−1	−1	−1	−1
Zn	−1	−1	−1	−1	−2	−1	0	−1	−1
As	3	2	3	−4	−3	−3	−1	−1	−2
Mo	−2	−3	−3	−4	−4	−7	−3	−3	−3
Cd	−2	−2	−2	−3	−3	−3	0	0	−3
Pb	−2	−2	−2	−2	−2	−2	−1	−3	−3
Se	−2	0	−1	1	1	1	2	2	1

The background colour shows HMs with moderate to high I_{geo} .

Egi predominantly showed negative I_{geo} for almost all investigated HMs. V, As, Mo, Cd, Mn, Co, Cu, Ni, and Pb exhibited $I_{geo} < 0$, which connotes an absence of pollution. Se consistently produced an I_{geo} value of 1 across all depths at Egi. This corresponds to moderately polluted conditions. Se represents the principal contaminant in the Woji area. Observed values ranged between I_{geo} values between 1 and 2, which are classified under the moderate pollution condition. Mn with an I_{geo} of 1 at 0–10 cm depth indicates moderate pollution of surface soils likely due to recent anthropogenic deposition [5,12]. Cd had an $I_{geo} = 0$ at shallow depths (0–10 cm and 10–50 cm), corresponding to unpolluted conditions. Most remaining HMs (V, Cr, Co, Ni, Cu, Zn, Pb, Mo, As) recorded negative values thus, they are classified as unpolluted ($I_{geo} \leq 0$). Overall, the I_{geo} results demonstrate that while the majority of analyzed HMs remain within geogenic background levels, anthropogenic influence is evident through the significant pollution of As at the Trans-Amadi industrial area [19]. The spatial variability underscores distinct pollution sources, with industrial, agricultural, and residential activities contributing differently to soil quality degradation in the study area.

3.2.2. Contamination Factor (CF) of the Heavy Metal Pollutants Across the Three Land Areas of Rivers State, Nigeria

To assess HM pollution within the study area, the contamination factor (CF) was computed by comparing the measured concentrations of HMs in soil samples with their respective background concentrations (DPR target values and referenced geochemical background values). The CF results (Figure 3) revealed distinct spatial variations in HM pollution across the industrial, residential, and agricultural soils. Trans-Amadi exhibited the most pronounced contamination pattern among the investigated sites. As was identified as the dominant contaminant, displaying very high contamination across all depths, with the highest pollution ($CF = 12.04$) observed at 50–100 cm depth. This strongly suggests intense industrial- or petroleum-derived contamination [6]. Conversely, other HMs, including Se, Pb, Cd, Mo, Zn, Cu, Ni, Co, Mn, Cr, and V, showed low contamination levels ($CF < 1$), although minor/moderate contamination occurred for Zn, Se and Cr. A similar study [59] classified the CF for Pb as extremely contaminated. Pb, As, and Cd were observed as the principal contaminants in that study, whereas Cu and Zn exhibited comparatively low CF [59].

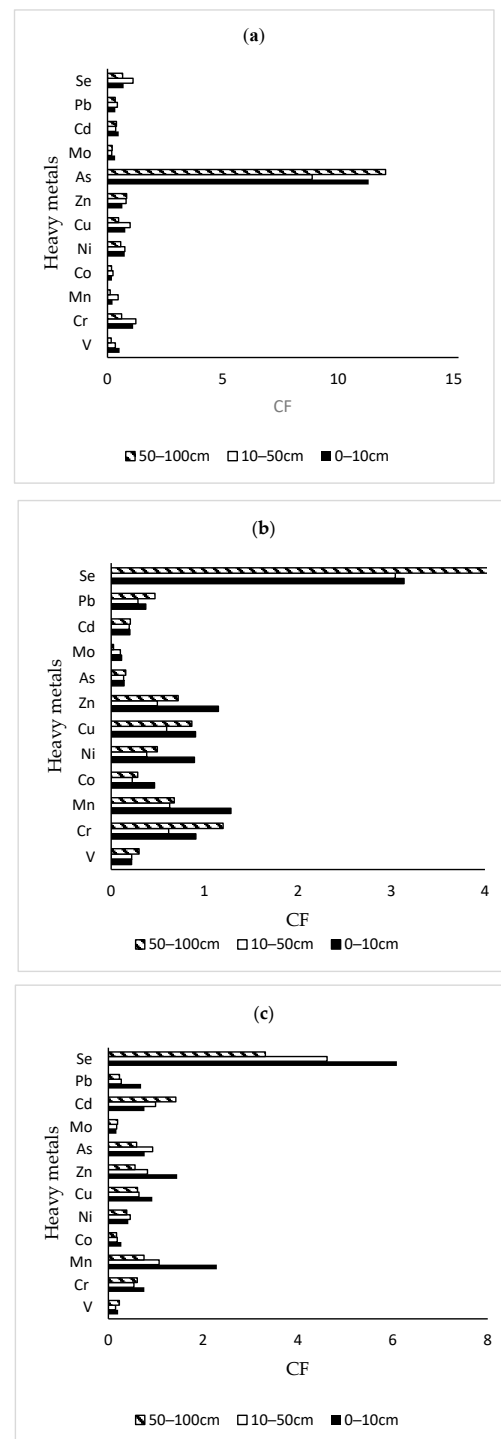


Figure 3. Heavy metal contamination factors (CF) across (a) industrial, (b) agricultural and (c) residential soil zones, citing the studied heavy metals CF across the three land areas.

At the Egi area, CF were comparatively lower than those of Woji but still demonstrated notable HM pollution. Se (4.15) remained the dominant contaminant at Woji, showing considerable contamination across all soil depths. Zn, Cr, and Cu exhibited low pollution; the CF range between 0 and 1, particularly within the surface soil (0–10 cm), indicating recent anthropogenic influence [5,12]. Other HMs, including Pb, Cd, Mo, Ni, Co, and V, predominantly showed low contamination ($CF < 1$), suggesting minor HM contamination. The Woji location exhibited considerable for Se across all depths ($3 < CF < 6$), with the most elevated CF of 6.08 recorded at the surface layer (0–10 cm). Mn also demonstrated

considerable contamination, particularly at 0–10 cm, suggesting substantial anthropogenic pollution sources [6,7]. Zn, Pb, Cd, Cr, Cu, Ni, Co, Mo, and V generally exhibited low contamination levels ($CF < 1$), although Pb and Cd displayed localized moderate contamination at some depths. The elevated surface contamination implies recent industrial, vehicular, or petroleum-related inputs [5]. Hence, the *CF* pattern across the three land zones are as follows: Industrial > Residential > Agricultural. Surface soils (0–10 cm) generally exhibited higher *CF* values for most HMs, supporting the influence of anthropogenic activities such as industrial operations, petroleum exploitation, vehicular emissions, and urbanization [5].

3.3. Pollution Load Index, Integrated Pollution Index (IPI) and Nemrow Integrated Pollution Index (NIPI)

To further assess the HM pollution in the study location of Rivers State, pollution load index, Integrated Pollution Index and Nemrow Integrated Pollution Index were utilized. The results of the *PLI* Figure 4 show that the values across the study sites ranged between 0.4 and 0.7, indicating varying degrees of pollution intensity with depth and land area. In the Trans-Amadi, *PLI* reached 0.6 at 10–50 cm and 50–100 cm, indicating unpolluted conditions, while slightly lower values (0.5) were observed at 0–10 cm, suggesting vertical redistribution of HM pollutants [5]. The Woji and Egi area also recorded low *PLI* values (0.4 to 0.7), indicating an overall minimal pollution condition. Similar to [22], where *PLI* values for all investigated HMs were below 1 ($PLI < 1$), which indicated that the studied soils were not polluted by HMs. The results showed that the observed HM concentrations primarily reflected natural geochemical processes, including the weathering of parent rocks and soil-forming materials, rather than substantial anthropogenic contamination [5,8].

Overall, the *PLI* results suggest that there are no severe pollution in all the study locations, although there is a possibility for localized HM pollution. The *IPI* result (Figure 4) revealed that the Trans-Amadi area had the highest *IPI* value of 2.0, indicating moderate pollution. The Woji area recorded *IPI* values between 0.8 and 1.2, suggesting low to moderate pollution, while the Egi area exhibited the lowest *IPI* values between 0.6 and 0.8, indicating low pollution levels. The decreasing *IPI* trend from industrial to residential to agricultural areas highlights a dominant influence of industrial activities on soil contamination. The relatively high *IPI* values further imply that pollution are attributed to long-term accumulation [5,6]. The *NIPI* values (Figure 4), suggest a more critical pollution scenario. The Trans-Amadi industrial area exhibited extremely high *NIPI* values (12.5 at 10–50 cm), indicating heavy pollution conditions ($NIPI > 3.0$). This implies that although average pollution (*PLI*) may appear moderate, the presence of highly polluted individual HMs can significantly elevate HM pollution in a given location. Despite having relatively low *PLI* values, the *NIPI* values at the Woji residential area was between 2.4 and 4.3, indicating heavy pollution. This may be a result of the influence of specific pollutants rather than widespread pollution. In the Egi agricultural area, *NIPI* values ranged from 2.2 to 3.0, indicating moderate pollution, likely driven by agrochemical inputs or localized petroleum activities such as artisanal petroleum mining common in Rivers State [5,6].

The combined application of *IPI*, *PLI*, and *NIPI*, showed a clear gradient of pollution across the three land areas. The industrial area (Trans-Amadi) exhibits high to extreme pollution, driven by both surface deposition and subsurface accumulation, as evidenced by moderate *IPI* ($1 \leq IPI \leq 2$) and extremely high *NIPI* (> 3). The residential area (Woji) demonstrated moderate pollution, reflecting mixed anthropogenic sources, while the agricultural area (Egi) remain largely unpolluted to slightly polluted, indicating minimal environmental contamination. Among the indices, *NIPI* proved most sensitive, capturing peak pollution levels, whereas *PLI* provided a conservative estimate of overall site quality, and *IPI* reflected a cumulative HM pollution load. The convergence of the pollution indices enhances the robustness of the HM pollution indices assessment, collectively demonstrating

that industrial activities constitute the primary driver of soil HM pollution across the Rivers State study area.

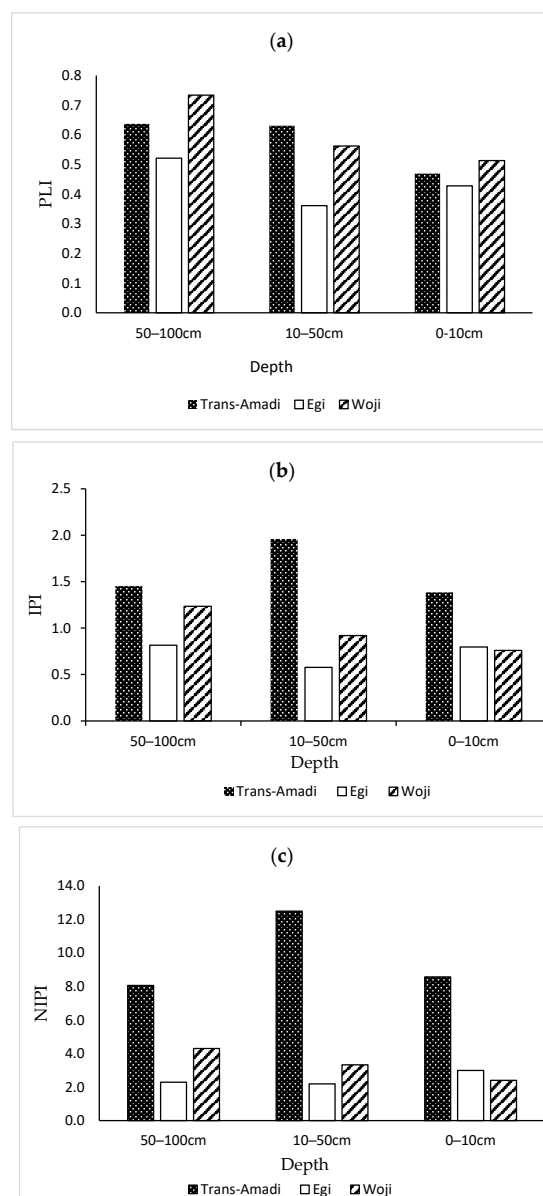


Figure 4. Spatial and vertical distribution of (a) pollution load index (PLI), (b) Integrated Pollution Index (IPI) and (c) Nemerow Integrated Pollution Index (NIPI) values of the HM pollutants in industrial (Trans-Amadi), agricultural (Egi), and residential (Woji) soils.

3.4. Enrichment Factor (EF)

The EF result obtained as presented in Figure 5, show that the Trans-Amadi industrial area had an EF of 70.8 for As, which denotes extreme high HM enrichment. This indicates dominant anthropogenic sources, probably from crude oil refining and spills, industrial waste discharge and combustion residues [6]. Most of the investigated HMs, including Cr (4.5), Zn (4.2), Se (3.8), Ni (3.3), Cu (3.4) had moderate HM enrichment factor; this entails strong anthropogenic input such as industrial emissions, HM processing, oil-related activities and artisanal mining [6]. Cd, Co and V with an EF of 2.3, 1.7 and 1.6 respectively, showed minimal enrichment in the industrial area, likely from mixed sources (natural and human activities). Se with an EF of 5.9 stands out as the dominant contaminant at the Egi area, likely due to anthropogenic activities such as agrochemicals (fertilizers, pesticides)

application and oil exploration activities in surrounding areas [6,55]. Minor HM pollution was observed for Cr (1.4), Cu and Zn (1.1), while V, As, Mo and Cd showed deficiency to minimal pollution, likely linked to natural or slight influences by human activity [6]. At the Woji area, Se (4.4) showed significant enrichment ($2 \leq EF < 5$), which may be due to domestic waste burning, traffic emissions and atmospheric deposition [6,12]. There were minor to no HM enrichment for Cu (1.2), Zn (0.8) and Pb (0.8), while minimal HM enrichment was observed for Co (0.3), Cr (0.7) and Ni (0.5), while V and Mo had an EF of 0.2, indicating deficiency to minimal enrichment. The Woji area generally showed low EF , reflecting relatively less impact of the HM pollutants. In summary, the EF reveals spatial variability in anthropogenic HM inputs, with the Trans-Amadi industrial area having the highest EF , particularly for As, indicating severe industrial influence [6]. In contrast, the Woji residential area reflects predominantly geogenic HM pollution source, while Egi agricultural soils show selective enrichment of Se, likely linked to anthropogenic processes reflecting regional petroleum exploration and production activities, gas flaring, and weathering of geological materials [6,60].

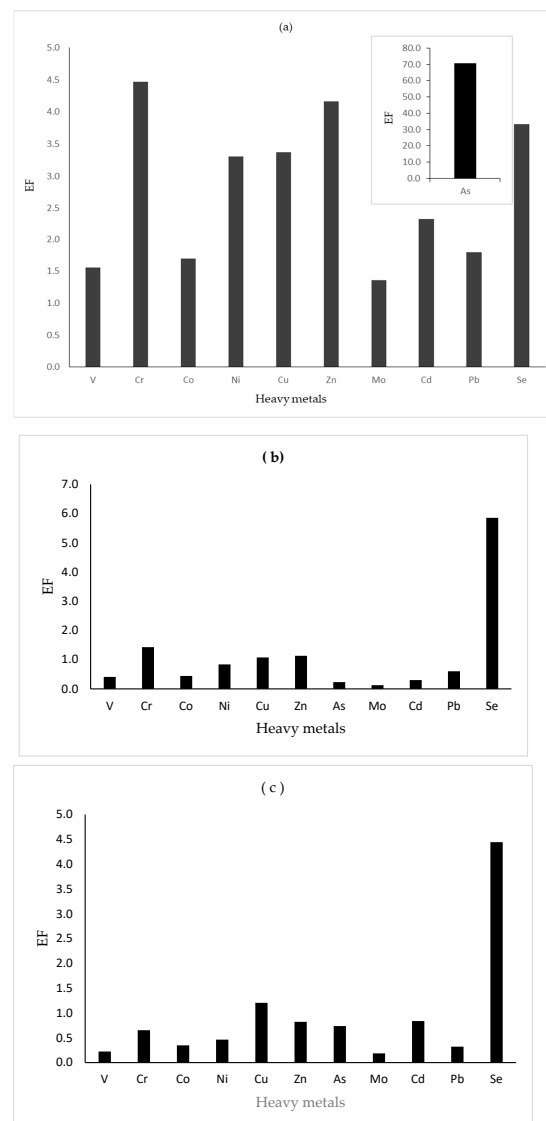


Figure 5. Spatial comparison of HM enrichment factor (EF) values in (a) Trans-Amadi. The inset graph in (a) shows extremely high EF of As ($EF \geq 40$) in the Trans-Amadi industrial area. (b) Egi, and (c) Woji residential area, illustrating HM-specific enrichment factor trends and potential anthropogenic influence across industrial, agricultural, and residential locations.

3.5. Source Identification of HM Pollutants in Rivers State Industrial, Agricultural and Residential Areas

3.5.1. Principal Component Analysis

The three-dimensional Principal Component Analysis (3D PCA) (Figure 6) extracted three principal components (PC1–PC3), collectively explaining 67.91% of the total variance in the dataset. Specifically, PC1 accounted for 34.92% of the total variance, PC2 explained 20.91%, and PC3 contributed 12.08% (Table S1). Principal components with eigenvalues greater than 1.0 (Kaiser's criterion) were retained for interpretation, and the scree plot (Figure S1) was used to verify the number of meaningful components retained. Consequently, the interpretation of the PCA was based on the standardized variables, eigenvalues, percentage of explained variance, and loading patterns of the retained components (Table S2). The observed loading patterns provide valuable preliminary insights into the principal environmental processes governing the distribution and co-occurrence of the investigated metals. PC1 exhibited strong positive loadings for Cu (0.4227), Pb (0.4089), Zn (0.3710), Co (0.3464), Mn (0.3402), Ni (0.2926), and Se (0.2817), suggesting potential influence from anthropogenic activities. These HMs are commonly associated with industrial emissions, vehicular traffic, fossil fuel combustion, metal processing, improper waste disposal, and agricultural inputs such as fertilizers and pesticides [8,19]. Their co-occurrence in PC1 therefore suggests that these anthropogenic activities may have influenced the observed HM distribution within the study area. PC2 explained 20.91% of the total variance and exhibited a bipolar loading pattern characterized by positive loadings of V (0.4953), Ni (0.3848), Mo (0.3648), and Cr (0.2570), together with negative loadings of Se (−0.4441) and Mn (−0.2810). This component is interpreted as reflecting possible influence from both geogenic and anthropogenic processes [8,12]. The association of V, Ni, Cr, and Mo may be related to fossil fuel combustion, petroleum exploration and production, vehicular emissions, and waste disposal, while simultaneously reflecting contributions from the natural geochemical composition of the parent material [12]. The opposing loadings of Se and Mn further suggest differing environmental controls or variations in their mobility under contrasting geochemical conditions. PC3 accounted for 12.08% of the total variance and was characterized by high positive loadings of Mo (0.5777), Cd (0.5146), and As (0.3441). This component reflects predominantly lithogenic and pedogenic influences associated with parent material composition and natural soil-forming processes, while also indicating localized anthropogenic enrichment rather than representing a purely geogenic source [6,12]. The relatively strong loading of Cd, which is commonly associated with industrial and agricultural activities, together with the significant land-use effects identified by the three-way ANOVA, suggests that both natural and anthropogenic processes contribute to the variability represented by this component [6]. Similarly, the occurrence of As within this component may reflect a combination of geochemical background conditions and land-use-related inputs. Although Se did not load strongly on PC3, its relatively independent behavior and significant response to land use, soil depth, and sampling location indicate the influence of secondary environmental controls, potentially associated with agricultural amendments, residential activities, or localized geochemical conditions [8,12,55]. Also, Se in the soil may be predominantly present in the reduced immobile phase, elemental Se (Se⁰) [61]. Consequently, PC3 represents a mixed lithogenic–anthropogenic influence rather than an exclusively natural source. Overall, the 3D PCA model revealed three broad HM associations comprising (i) Cu, Pb, Zn, Co, and Ni; (ii) Mn, Se, Cr, and V; and (iii) Mo, Cd, and As. These groupings likely reflect differing environmental controls and source identifications. The first group appears to be associated predominantly with anthropogenic activities, including industrial, petroleum-related, transportation, and urban influences. The second group reflects the combined influence of geogenic and anthropogenic processes,

modulated by site-specific environmental conditions. The third group is primarily associated with lithogenic and pedogenic processes, with additional localized anthropogenic inputs [12].

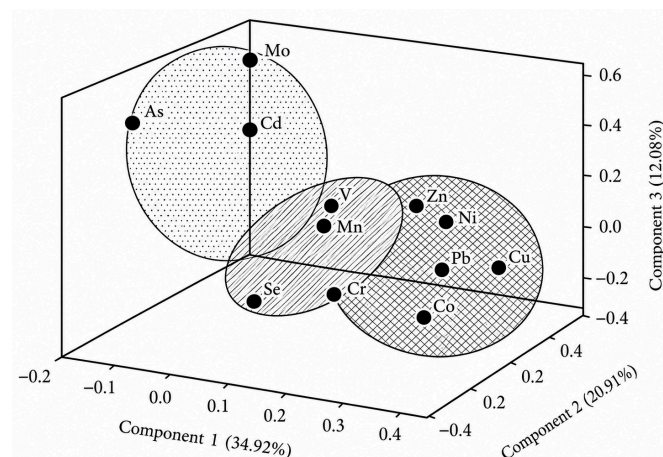


Figure 6. Three-dimensional rotated PCA plot showing the relationships among HMs and their potential sources in soils from Rivers State, Nigeria. The first three principal components explained 67.91% of the total variance, with contributions of 34.92% (PC1), 20.91% (PC2), and 12.08% (PC3). The black dots represent the individual HMs, the lines and grid represent the 3D coordinate axis, while the shaded ovals highlight the specific source groupings. PC1 represents predominantly anthropogenic contamination arising from industrial, petroleum-related, and traffic activities; PC2 reflects mixed geogenic–anthropogenic influences; whereas PC3 is associated mainly with lithogenic inputs derived from natural geological and pedogenic processes.

Therefore, the identified principal is representative of indicative evidence of HM pollution sources. The consistency observed among the PCA loading patterns, three-way ANOVA, Pearson correlation analysis, enrichment factor, pollution indices, and hierarchical cluster analysis nevertheless strengthens the inferred source identification.

3.5.2. Cluster Analysis of Heavy Metal in Trans-Amadi, Egi and Woji Land Areas

Hierarchical cluster analysis (HCA) results, illustrated in Figure 7, grouped the sampling locations into two statistically significant clusters based on similarities in HM composition. Cluster I comprised Res10 and Agri10, indicating comparable pollution values at surface soil depth within the Woji and Egi locations. The observed similarity may be a result of mixed anthropogenic inputs such as agrochemicals, domestic emissions, and atmospheric deposition [8]. Cluster II consisted of Ind10 and Ind50, demonstrating minimal differences at the surface and subsurface industrial soils. This indicates that soil contamination is persistent and might have resulted in vertical mobility of the HMs within the Trans-Amadi industrial environment, reflecting continuous industrial discharge and accumulation [5]. The broad distance link which separates Cluster I and Cluster II implies that there are notable dissimilarities between the Trans-Amadi industrial soil and the Egi and Woji land areas. This confirms that anthropogenic inputs such as industrial activities represent a significant and major source of HM pollution in the study area. The clustering pattern aligns with findings from PCA and enrichment factor analyses, indicating combined anthropogenic and geogenic influences, with the Trans-Amadi industrial areas exhibiting higher pollution intensity [12].

Although the PCA and HCA produced internally consistent patterns that agreed with correlation analysis and pollution indices, one limitation of this study is that the multivariate analyses were conducted using a relatively modest number of soil samples.

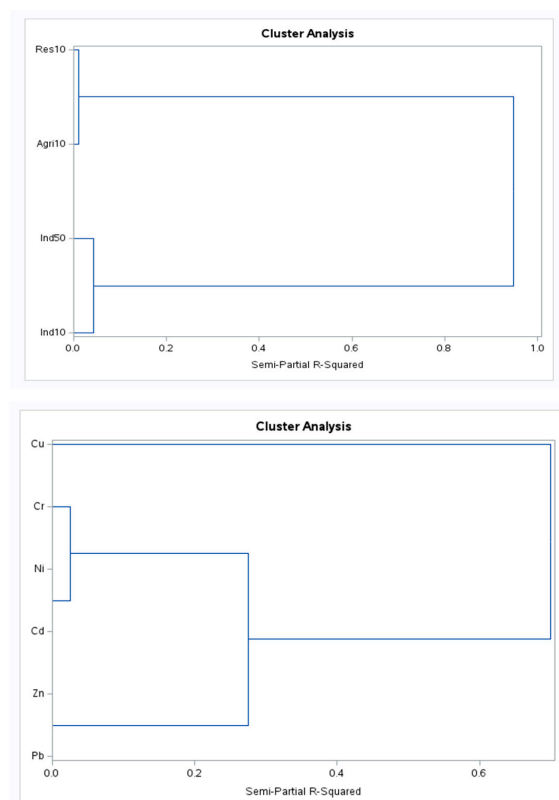


Figure 7. Dendrogram of hierarchical cluster analysis (HCA) using Semi-Partial R^2 distance was applied to classify sampling locations according to similarities in heavy metal concentrations. Res10, Agri10, Ind10 and Ind50 denotes residential at 0–10 cm, agricultural 0–10 cm, industrial 0–10 cm, and industrial 10–50 cm respectively.

3.6. Health Risk Assessment of the Heavy Metal Pollutants at Different Land Zones of Ivers State

The average daily dose (ADD) (Tables 10–12) values for HMs in soils from the Trans-Amadi, Egi and Woji locations revealed marked variations across exposure pathways. Among the exposure routes, inhalation and ingestion were the dominant pathway of exposure for both adults and children, while dermal absorption contributed the least exposure dose [61]. Generally, children exhibited substantially higher ADD values than adults for all analyzed HMs, indicating increased vulnerability of children to HM exposure due to lower body weight, higher soil ingestion rates, and increased hand-to-mouth activities commonly associated with childhood behavior [22,61,62]. The estimated average daily dose (ADD) for HMs in the Trans-Amadi industrial area (Table 10) demonstrated clear differences among exposure pathways, and groups. Overall, ingestion represented the dominant exposure pathway for both adults and children, while dermal absorption contributed the least to total exposure. Children consistently exhibited higher ADD values than adults through all exposure routes, owing to their lower body weight and greater exposure factors incorporated into the USEPA exposure model [63]. For adult ingestion exposure, Zn (5.14×10^{-2} mg/kg/day) produced the highest ADD values, followed closely by As (2.75×10^{-3} mg/kg/day) in the child ingestion category, indicating that these HMs constitute the principal source to ingestion exposure within the industrial environment. It has been observed by different studies that exposure to As on higher levels are a result of its natural abundance in soil, and despite the low levels of As in some cases, its harmful impacts in children are more notable [64]. Other HMs including V (1.85×10^{-4} mg/kg/day), Cr (1.26×10^{-3} mg/kg/day), Mn (1.51×10^{-3} mg/kg/day) and Cu (3.45×10^{-4} mg/kg/day) also had elevated values of ADD in the child ingestion pathway. Conversely, Se, Mo, Pb

and Cd exhibited the lowest *ADD* values across all exposure pathways, reflecting their relatively low non-carcinogenic health risk. Inhalation *ADD* values were several orders of magnitude lower than ingestion doses, while the dermal pathway consistently represented the least significant pathway for both adults and children, indicating limited transdermal transfer of HMs from polluted soils. In general, the *ADD* profile suggests that industrial activities within the Trans-Amadi area significantly influence HM exposure patterns, with children constituting the most vulnerable population group.

Table 10. Average daily dose (*ADD*) in mg/kg/day of heavy metals in the Trans-Amadi industrial region of Rivers State through ingestion, inhalation and dermal exposure for adults and children.

Heavy Metal	Adult Ingestion	Adult Inhalation	Adult Dermal	Child Ingestion	Child Inhalation	Child Dermal
V	1.98×10^{-5}	1.11×10^{-9}	4.74×10^{-13}	1.85×10^{-4}	8.71×10^{-9}	3.11×10^{-12}
Cr	1.35×10^{-4}	7.59×10^{-9}	3.23×10^{-12}	1.26×10^{-3}	5.94×10^{-8}	3.53×10^{-12}
Mn	1.62×10^{-4}	9.07×10^{-9}	3.86×10^{-12}	1.51×10^{-3}	2.47×10^{-9}	2.53×10^{-11}
Co	5.64×10^{-6}	3.16×10^{-10}	1.35×10^{-13}	5.26×10^{-5}	1.47×10^{-8}	8.84×10^{-13}
Ni	8.01×10^{-4}	1.87×10^{-9}	7.99×10^{-13}	3.11×10^{-4}	1.62×10^{-8}	5.23×10^{-12}
Cu	3.69×10^{-5}	2.07×10^{-9}	8.85×10^{-13}	3.45×10^{-4}	6.45×10^{-8}	5.79×10^{-12}
Zn	5.14×10^{-2}	8.24×10^{-9}	3.51×10^{-12}	1.37×10^{-3}	1.29×10^{-7}	2.30×10^{-11}
As	4.38×10^{-5}	1.65×10^{-8}	7.05×10^{-12}	2.75×10^{-3}	1.46×10^{-9}	4.61×10^{-11}
Mo	3.33×10^{-6}	1.87×10^{-10}	7.98×10^{-14}	3.11×10^{-5}	1.99×10^{-10}	5.22×10^{-13}
Cd	4.54×10^{-7}	2.54×10^{-11}	1.08×10^{-14}	4.24×10^{-6}	1.91×10^{-8}	7.12×10^{-14}
Pb	4.34×10^{-5}	2.44×10^{-9}	1.04×10^{-12}	4.05×10^{-4}	2.48×10^{-10}	6.81×10^{-12}
Se	6.22×10^{-13}	3.17×10^{-11}	1.35×10^{-14}	5.28×10^{-6}	2.03×10^{-6}	8.86×10^{-14}

ADD (mg/kg/day) represents the heavy metals intake dose over the specific exposure duration. Values formatting using scientific notation (e.g., 1.13×10^{-8}) reflect pathway specific calculation *ADD* inputs for adult and children in the study region. Bold values indicate comparatively elevated *ADD* levels across exposure pathways.

Table 11. *ADD* values of HMs at the Egi area of Rivers State through ingestion, inhalation and dermal exposure for adults and children.

Heavy Metal	Adult Ingestion	Adult Inhalation	Adult Dermal	Child Ingestion	Child Inhalation	Child Dermal
V	1.42×10^{-5}	7.95×10^{-10}	3.40×10^{-13}	1.32×10^{-4}	6.23×10^{-9}	2.22×10^{-12}
Cr	9.19×10^{-6}	6.97×10^{-9}	2.98×10^{-12}	1.16×10^{-3}	5.45×10^{-8}	3.25×10^{-12}
Mn	5.16×10^{-4}	2.89×10^{-8}	1.24×10^{-11}	4.82×10^{-3}	2.27×10^{-7}	8.09×10^{-11}
Co	8.91×10^{-6}	4.99×10^{-10}	2.13×10^{-13}	8.32×10^{-5}	3.91×10^{-9}	1.40×10^{-12}
Ni	6.78×10^{-4}	1.58×10^{-9}	6.76×10^{-13}	2.64×10^{-4}	1.24×10^{-8}	4.43×10^{-12}
Cu	3.89×10^{-5}	2.18×10^{-9}	9.30×10^{-13}	3.63×10^{-4}	1.71×10^{-8}	6.09×10^{-12}
Zn	5.28×10^{-2}	8.47×10^{-9}	3.77×10^{-12}	3.61×10^{-4}	6.63×10^{-8}	2.37×10^{-11}
As	3.92×10^{-6}	2.20×10^{-10}	9.40×10^{-14}	3.66×10^{-5}	1.72×10^{-9}	6.15×10^{-13}
Mo	1.09×10^{-6}	6.11×10^{-11}	2.61×10^{-14}	1.02×10^{-5}	4.78×10^{-10}	1.71×10^{-13}
Cd	2.20×10^{-7}	1.24×10^{-11}	5.27×10^{-15}	2.06×10^{-6}	9.67×10^{-11}	3.45×10^{-14}
Pb	4.38×10^{-5}	2.46×10^{-9}	1.05×10^{-12}	4.09×10^{-9}	1.93×10^{-8}	6.87×10^{-12}
Se	3.02×10^{-13}	9.99×10^{-7}	5.65×10^{-14}	2.20×10^{-5}	1.04×10^{-9}	3.70×10^{-13}

All pathway values (Ingestion, Inhalation, and Dermal) are expressed in (mg/kg/day). Bold *ADD* values denote high *ADD* values.

Table 12. *ADD* values in mg/kg/day of heavy metals at the Woji residential area through ingestion, inhalation and dermal exposure for adults and children.

HMs	Adult Ingestion	Adult Inhalation	Adult Dermal	Child Ingestion	Child Inhalation	Child Dermal
V	1.14×10^{-5}	6.40×10^{-10}	2.73×10^{-13}	1.07×10^{-4}	5.01×10^{-9}	1.79×10^{-12}
Cr	8.74×10^{-5}	4.90×10^{-9}	2.09×10^{-12}	8.16×10^{-4}	3.84×10^{-8}	2.28×10^{-12}
Mn	8.21×10^{-4}	4.61×10^{-8}	1.97×10^{-11}	7.66×10^{-3}	3.60×10^{-7}	1.29×10^{-10}
Co	5.84×10^{-6}	3.28×10^{-10}	1.40×10^{-13}	5.45×10^{-5}	2.57×10^{-9}	9.16×10^{-13}
Ni	4.90×10^{-4}	1.15×10^{-9}	4.89×10^{-13}	1.90×10^{-4}	8.96×10^{-9}	3.20×10^{-12}
Cu	3.60×10^{-5}	2.02×10^{-9}	8.62×10^{-13}	3.36×10^{-4}	1.58×10^{-8}	5.65×10^{-12}
Zn	6.36×10^{-2}	1.02×10^{-8}	4.35×10^{-12}	1.70×10^{-3}	7.99×10^{-8}	2.85×10^{-11}
As	2.10×10^{-5}	1.18×10^{-9}	5.03×10^{-13}	1.96×10^{-4}	9.22×10^{-9}	3.29×10^{-12}
Mo	2.48×10^{-6}	1.39×10^{-10}	5.94×10^{-14}	2.31×10^{-5}	1.09×10^{-9}	3.89×10^{-13}
Cd	1.16×10^{-6}	6.52×10^{-11}	2.78×10^{-14}	1.09×10^{-5}	5.10×10^{-10}	1.82×10^{-13}
Pb	4.67×10^{-5}	2.62×10^{-9}	1.11×10^{-12}	4.36×10^{-4}	2.05×10^{-8}	7.32×10^{-12}
Se	1.59×10^{-12}	1.79×10^{-10}	7.66×10^{-14}	2.99×10^{-5}	1.40×10^{-9}	5.02×10^{-13}

Bold *ADD* values indicate high *ADD* values.

Although industrial activities substantially increased environmental HM concentrations, the calculated *ADD* values remained relatively low, indicating limited daily human exposure under the current exposure assumptions.

The *ADD* estimates in Table 11, for HMs in soils collected from the Egi agricultural area, revealed that ingestion was the dominant exposure pathway, whereas dermal absorption contributed minimally to overall exposure. Children consistently experienced considerably higher exposure doses than adults across all investigated HMs because of age-dependent exposure parameters. Among the investigated HMs, Mn exhibited the highest child ingestion *ADD* values, with an *ADD* ingestion value of 4.82×10^{-3} mg/kg/day in children. Elevated Mn exposure may be associated with agricultural inputs, natural soil composition, or atmospheric deposition [5,8]. There are also elevated *ADD* values of Cr (1.16×10^{-3} mg/kg/day) while Pb and Cd exhibited the lowest *ADD* values, suggesting relatively limited exposure from these HM pollutants. Although the agricultural environment generally displayed lower exposure doses than the industrial site for several HMs, the results indicate that agricultural soils still represent an important exposure medium, particularly through ingestion of contaminated soil generated during farming activities. Ni, Cr, V, Cu and Zn demonstrated moderate *ADD* values across the ingestion child exposure groups. The relatively elevated ingestion doses of these HMs suggest influences from agrochemical inputs, soil amendments, vehicular emissions, and long-term accumulation within cultivated soils [5,19]. The dermal pathway of exposure consistently represented the least significant pathway. The *ADD* profile therefore demonstrates that agricultural activities within the Egi area are the major source of HM accumulation, and human exposure, with children representing the most vulnerable population group. The dominance of ingestion exposure highlights the need for sustainable agricultural practices, periodic environmental monitoring, and control of agrochemical inputs to reduce long-term human health risks.

The *ADD* results (Table 12) at the Woji residential area exhibited exposure characteristics comparable to the other land-use categories, with ingestion representing the principal exposure pathway, while the dermal contact exhibited the least. Children consistently showed higher *ADD* values than adults for every HMs because of their greater exposure sensitivity. Mn (7.66×10^{-3} mg/kg/day) and Zn (1.70×10^{-3} mg/kg/day) exhibited the largest ingestion exposure doses within the residential environment, whereas Ni, Co, Cu, Cd and Se produced comparatively lower exposure estimates. The relatively elevated ingestion doses suggest that vehicular emissions, domestic activities, and urban atmospheric deposition may contribute to metal exposure within the residential environment [19]. The results generally indicate that low-level HM exposure exists in Woji, which may contribute to cumulative human health risks over prolonged periods of exposure. The comparatively higher exposure of children further emphasizes the importance of implementing public health interventions aimed at minimizing contact with these HMs at the Woji residential environments.

3.6.1. The Hazard Quotient (*HQ*) Assessment of the Analyzed HM Pollutants

The hazard quotient assessment demonstrated in Table 13 explains that ingestion was the principal exposure pathway contributing to non-carcinogenic health risks across the investigated locations. Children consistently exhibited higher *HQ* values than adults, highlighting their increased susceptibility to environmental pollutants due to physiological sensitivity and greater exposure frequency [19]. Among the investigated locations, Trans-Amadi recorded the highest overall non-carcinogenic risk burden, followed by Woji and Egi. The hazard quotient (*HQ*) values (Table 13) observed for the Trans-Amadi industrial area showed substantial variability among HMs and exposure pathways. Inhalation consistently generated the highest *HQ* values for both adults and children, whereas ingestion and dermal exposure produced extremely low *HQ* values. Among child ingestion pathway, As (9.15) exhibited the highest *HQ* value, suggesting persistent anthropogenic pollution

arising from industrial emissions, vehicular activities, agricultural practices, and poor waste management [8,19]. Importantly, most individual HMs' *HQ* values in the Trans-Amadi area remained below the USEPA safety threshold of 1.0, with an exception of As (9.15) in the child ingestion category, indicating that most of the investigated HMs are expected to produce significant non-carcinogenic health effects through a single exposure pathway. The *HQ* values (Table 13) calculated for the Egi agricultural soils demonstrated that ingestion remained the dominant exposure route, while inhalation and dermal contact contributed only marginally to non-carcinogenic risk. Children again exhibited substantially higher *HQ* values than adults. Zn (0.18×10^{-1}) produced the highest *HQ* ingestion values in children. The elevated *HQ* of Zn in children indicates that this metal is the major pollutant to non-carcinogenic risk within the Egi agricultural environment, this suggests influences from soil amendments and other agricultural practices in the agricultural area [6,8]. The remaining HMs exhibited relatively low *HQ* values, indicating minimal individual health concerns. The *HQ* values (Table 13) calculated for the Woji residential area demonstrated that ingestion remained the dominant exposure route, while inhalation and dermal contact contributed only marginally to non-carcinogenic risk. Children again exhibited substantially higher *HQ* values than adults. As (6.53×10^{-1}) produced the highest ingestion *HQ* in children and Zn in the adult ingestion (2.12×10^{-1}); this shows that these HM pollutants come from improper domestic waste management, proximity to landfills and industrial emissions [8]. The exceptionally high *HQ* values of As in children shows that this metal is the dominant pollutant to non-carcinogenic risk within the Woji residential environment. Other HMs showed relatively low *HQ* values, indicating minimal individual health risk. Overall, As contributed disproportionately to the overall non-carcinogenic risk profile, with the most elevated value in the industrial area, therefore warranting continued environmental monitoring within the study areas.

3.6.2. Hazard Index (*HI*) of the Selected Heavy Metals Across the Three Land Areas

The hazard index assessment revealed varying degrees of non-carcinogenic health risks across industrial, agricultural, and residential land areas in Rivers State, Nigeria as presented in Table 14. The *HI* assessment of most HMs' exhibited values below the recommended safety threshold, except for As (9.16) at the Trans-Amadi industrial area, in the child category which showed elevated level of *HI* non-carcinogenic risk. Other HMs including Zn, Pb and Cr showed significant values in both adults and children. Elevated non-carcinogenic risks of the *HI* values, particularly for Cr, Zn and As of the child and adult population, were observed at the agricultural and residential location. The Trans-Amadi area presented the greatest environmental health concern due to excessive arsenic exposure, while the Woji and Egi locations also demonstrated significant non-carcinogenic risks. The findings emphasize the influence of industrialization, petroleum-related activities, agricultural practices, and urbanization on HM pollution within the study location of Rivers State, Niger Delta, Nigeria [5]. The cumulative *HI* results indicate that children, particularly in the agricultural and residential areas, may experience non-carcinogenic risks above recommended safety limits. These findings underscore the need for targeted environmental sustainability management, regular monitoring, and measures to reduce children's exposure to HM-polluted soils in the study area.

Table 13. Non-carcinogenic health risk assessment (*HQ*) of heavy metals via inhalation, ingestion, and dermal pathways in the study areas, with bold values indicating high non-carcinogenic health risk assessment (*HQ*) of heavy metals in the study area.

Location	Population	Pathway	V	Cr	Mn	Co	Ni	Cu	Zn	As	Mo	Cd	Pb	Se
Trans-Amadi (Industrial Area)	Adult	Inhalation	NA	2.65×10^{-6}	6.47×10^{-8}	5.50×10^{-5}	9.08×10^{-8}	5.16×10^{-8}	2.70×10^{-8}	5.50×10^{-5}	NA	2.54×10^{-6}	4.68×10^{-6}	NA
		Ingestion	2.83×10^{-3}	4.51×10^{-2}	1.15×10^{-3}	2.80×10^{-4}	3.89×10^{-2}	9.24×10^{-4}	1.70×10^{-1}	9.81×10^{-7}	6.66×10^{-4}	4.54×10^{-4}	1.24×10^{-2}	1.24×10^{-10}
		Dermal	6.80×10^{-9}	5.39×10^{-8}	2.10×10^{-9}	7.30×10^{-11}	1.48×10^{-10}	7.37×10^{-11}	5.90×10^{-11}	5.73×10^{-8}	4.20×10^{-8}	1.09×10^{-9}	1.99×10^{-9}	NA
	Child	Inhalation	NA	2.08×10^{-5}	5.07×10^{-7}	4.30×10^{-4}	7.11×10^{-7}	4.04×10^{-7}	2.10×10^{-7}	4.31×10^{-4}	NA	1.99×10^{-5}	5.42×10^{-6}	NA
		Ingestion	2.64×10^{-2}	4.21×10^{-1}	1.08×10^{-2}	2.63×10^{-3}	1.51×10^{-2}	8.62×10^{-3}	4.57×10^{-3}	9.15	6.22×10^{-3}	4.24×10^{-3}	1.16×10^{-1}	1.06×10^{-3}
		Dermal	4.44×10^{-8}	5.89×10^{-8}	1.38×10^{-8}	4.80×10^{-10}	9.69×10^{-10}	4.83×10^{-10}	3.80×10^{-10}	3.75×10^{-7}	2.75×10^{-10}	7.12×10^{-9}	1.31×10^{-8}	NA
Egi (Agricultural Area)	Adult	Inhalation	NA	2.44×10^{-6}	2.06×10^{-7}	8.80×10^{-5}	7.69×10^{-8}	5.42×10^{-8}	2.80×10^{-8}	7.34×10^{-7}	NA	1.24×10^{-6}	6.99×10^{-7}	NA
		Ingestion	2.03×10^{-3}	3.06×10^{-3}	3.69×10^{-3}	4.50×10^{-4}	3.29×10^{-2}	9.71×10^{-4}	0.18×10^{-1}	1.31×10^{-2}	2.20×10^{-4}	2.20×10^{-4}	1.25×10^{-2}	8.03×10^{-11}
		Dermal	4.85×10^{-9}	4.96×10^{-8}	6.71×10^{-9}	1.20×10^{-10}	1.25×10^{-10}	7.75×10^{-11}	6.00×10^{-11}	7.64×10^{-10}	1.37×10^{-11}	5.27×10^{-10}	2.02×10^{-9}	NA
	Child	Inhalation	NA	1.91×10^{-5}	1.62×10^{-6}	6.90×10^{-4}	6.02×10^{-7}	4.24×10^{-7}	2.20×10^{-7}	5.75×10^{-6}	NA	9.67×10^{-6}	5.47×10^{-6}	NA
		Ingestion	1.89×10^{-2}	3.87×10^{-1}	3.44×10^{-2}	4.16×10^{-3}	1.28×10^{-2}	9.07×10^{-3}	4.70×10^{-3}	1.22×10^{-1}	2.03×10^{-3}	2.06×10^{-3}	1.17×10^{-1}	4.40×10^{-3}
		Dermal	3.18×10^{-8}	5.41×10^{-8}	4.40×10^{-8}	7.60×10^{-10}	8.20×10^{-10}	5.08×10^{-10}	3.90×10^{-10}	5.00×10^{-9}	8.99×10^{-11}	3.45×10^{-9}	1.32×10^{-8}	NA
Woji (Residential Area)	Adult	Inhalation	NA	1.71×10^{-6}	3.29×10^{-7}	5.70×10^{-5}	5.56×10^{-8}	5.03×10^{-8}	3.40×10^{-8}	3.93×10^{-6}	NA	6.52×10^{-6}	7.44×10^{-7}	NA
		Ingestion	1.63×10^{-3}	2.91×10^{-2}	5.87×10^{-3}	2.90×10^{-4}	2.38×10^{-2}	9.01×10^{-4}	2.12×10^{-1}	7.00×10^{-2}	4.96×10^{-4}	1.16×10^{-3}	1.33×10^{-2}	3.19×10^{-10}
		Dermal	3.90×10^{-9}	3.49×10^{-8}	1.07×10^{-8}	7.60×10^{-11}	9.05×10^{-11}	7.19×10^{-11}	7.30×10^{-11}	4.09×10^{-9}	3.12×10^{-11}	2.78×10^{-9}	2.15×10^{-9}	9.57×10^{-11}
	Child	Inhalation	NA	1.34×10^{-5}	2.58×10^{-6}	4.50×10^0	4.35×10^{-7}	3.94×10^{-7}	2.70×10^{-7}	3.07×10^{-5}	NA	5.11×10^{-5}	5.83×10^{-6}	NA
		Ingestion	1.52×10^{-2}	2.72×10^{-1}	5.47×10^{-2}	2.73×10^{-3}	9.25×10^{-3}	8.41×10^{-3}	5.7×10^{-3}	6.53×10^{-1}	4.63×10^{-3}	1.09×10^{-2}	1.25×10^{-1}	5.97×10^{-3}
		Dermal	2.55×10^{-8}	3.26×10^{-8}	1.84×10^{-6}	1.30×10^{-8}	4.57×10^{-8}	8.07×10^{-8}	4.10×10^{-7}	4.7×10^{-8}	5.60×10^{-9}	2.61×10^{-9}	1.05×10^{-7}	NA

HQ < 1 indicates no significant non-carcinogenic health risk, while *HQ* > 1 indicates potential adverse health effects. NA connotes not available because of the non-availability of *RfD* values.

Table 14. Non-carcinogenic hazard index (*HI*) values of potentially toxic elements for adult and child populations in different land zones of Rivers State.

Location/ Population	V	Cr	Mn	Co	Ni	Cu	Zn	As	Mo	Cd	Pb	Se
Trans-Amadi	Adult	2.83×10^{-3}	4.51×10^{-2}	1.15×10^{-3}	2.82×10^{-4}	3.89×10^{-2}	9.24×10^{-4}	1.17×10^{-1}	6.67×10^{-4}	4.54×10^{-4}	1.24×10^{-2}	1.24×10^{-10}
	Child	2.64×10^{-2}	4.21×10^{-1}	1.08×10^{-2}	3.06×10^{-3}	1.51×10^{-2}	8.62×10^{-3}	4.57×10^{-3}	9.16	6.22×10^{-3}	1.16×10^{-1}	1.06×10^{-3}
Egi	Adult	2.03×10^{-3}	3.07×10^{-3}	3.69×10^{-3}	5.33×10^{-4}	3.29×10^{-2}	9.71×10^{-4}	1.76×10^{-1}	1.31×10^{-2}	2.18×10^{-4}	2.21×10^{-4}	1.25×10^{-2}
	Child	1.89×10^{-2}	3.87×10^{-1}	3.44×10^{-2}	4.84×10^{-3}	1.28×10^{-2}	9.07×10^{-3}	4.69×10^{-3}	1.22×10^{-1}	2.03×10^{-3}	2.07×10^{-3}	1.17×10^{-1}
Woji	Adult	1.63×10^{-3}	2.91×10^{-2}	5.87×10^{-3}	3.49×10^{-4}	2.38×10^{-2}	9.01×10^{-4}	2.12×10^{-1}	6.99×10^{-2}	4.96×10^{-4}	1.17×10^{-3}	1.33×10^{-2}
	Child	1.15×10^{-2}	2.71×10^{-1}	5.47×10^{-2}	3.18×10^{-3}	9.25×10^{-3}	8.41×10^{-3}	5.66×10^{-3}	6.53×10^{-1}	4.62×10^{-3}	1.09×10^{-2}	1.25×10^{-1}

Values greater than 1 indicate potential non-carcinogenic health risks. Bold values indicate high *HI* values.

3.7. Carcinogenic Risk (CR) of the Studied Heavy Metals at the Three Land Areas

The estimated Incremental Lifetime Cancer Risk (ILCR) Table 15 varied considerably among heavy metals, exposure pathways, receptors, and land-use types. Consistent with the Lifetime Average Daily Dose (LADD) estimates (Tables S3–S5), soil ingestion constituted the dominant exposure pathway, producing substantially greater carcinogenic risks than dermal contact and inhalation. The elevated ingestion-derived ILCR values directly reflect the higher LADD values estimated for this pathway (Tables S3–S5), confirming that incidental soil ingestion is the primary route of carcinogenic HM exposure in the study area. According to the United States Environmental Protection Agency (USEPA), ILCR values $< 1.0 \times 10^{-6}$ represent negligible cancer risk, and values between 1.0×10^{-6} and 1.0×10^{-4} are considered within the acceptable or tolerable lifetime cancer risk range, whereas values $> 1.0 \times 10^{-4}$ indicate an unacceptable carcinogenic risk requiring regulatory intervention [63]. Among all carcinogenic metals investigated, As was the predominant contributor to lifetime cancer risk across all land-use categories, which aligns with [64]’s identified carcinogenic HM pollutants. The highest ILCR values were recorded through the ingestion pathway in the industrial area (Trans-Amadi), reaching 1.51×10^{-4} for adults and 3.53×10^{-4} for children. These values exceeded the internationally accepted USEPA maximum acceptable lifetime cancer risk threshold (1.0×10^{-4}), indicating an unacceptable carcinogenic risk associated with chronic arsenic exposure. The markedly elevated ILCR values correspond closely with the comparatively high arsenic LADD observed for the industrial soils (Tables S3–S5). This suggests that prolonged anthropogenic activities, including petroleum refining, petrochemical processing, metal fabrication, fossil fuel combustion, and atmospheric deposition of industrial emissions, are the principal drivers of arsenic accumulation [65]. Residential soils (Woji) also exhibited relatively elevated arsenic-associated carcinogenic risks, with ingestion ILCR values of 1.08×10^{-5} for adults and 2.52×10^{-5} for children. Although these values remained below the unacceptable risk threshold (1.0×10^{-4}), they exceeded the acceptable carcinogenic risk level (1.0×10^{-6}) and therefore fall within the USEPA tolerable carcinogenic risk range, indicating that chronic exposure may still contribute to cumulative lifetime cancer risk. Cd represented the second most significant carcinogenic contaminant. The highest Cd ingestion carcinogenic risks occurred in the residential area, where ILCR values reached 2.43×10^{-6} for adults and 5.68×10^{-6} for children. These findings are consistent with the elevated cadmium LADD values reported in Tables S3–S5 and indicate a tolerable yet non-negligible carcinogenic risk. Given cadmium’s persistence, long biological half-life, and tendency to bioaccumulate, continued environmental surveillance remains essential. Conversely, Cr and Pb exhibited comparatively lower ILCR values, generally ranging from 10^{-7} to 10^{-6} , indicating acceptable carcinogenic risks under current exposure conditions. Likewise, inhalation-derived risks for Cr, As, Cd, and Ni were consistently below 10^{-8} , while dermal arsenic carcinogenic risks level remained below 10^{-6} , reflecting the substantially lower LADD values estimated for these pathways. These results demonstrate that inhalation and dermal contact contribute minimally to the overall carcinogenic burden relative to soil ingestion. Children consistently exhibited higher ILCR values than adults across all land-use types. This observation agrees with the receptor-specific LADD estimates and reflects the higher soil ingestion rates, lower body weight, and greater exposure intensity assumed in the USEPA exposure model [63]. Consequently, children constitute the most vulnerable population to carcinogenic risks arising from contaminated soils. Overall, the ILCR assessment identifies Arsenic as the principal carcinogenic driver in the study area, particularly within the industrial environment where cancer risks exceeded internationally accepted thresholds. USEPA carcinogenic risk threshold (1.0×10^{-4}) in the industrial area indicates that chronic exposure to arsenic-contaminated soils may pose a significant lifetime

cancer risk, particularly for children [35,64]. The results generally suggest that continuous anthropogenic activities, including industrial emissions, agricultural practices, vehicular pollution, and inadequate waste management, significantly contribute to the accumulation of HM pollutants within the study environment [65]. These findings underscore the urgent need for effective industrial emission control, routine environmental monitoring, soil remediation, and sustainable land-use management strategies to reduce long-term human exposure, especially among vulnerable populations such as children. The results also point out the importance of prioritizing arsenic in environmental risk management and public health intervention programs within Rivers State, Niger Delta region.

Table 15. Incremental Lifetime Cancer Risk (*ILCR*) associated with exposure to carcinogenic heavy metals through ingestion, inhalation, and dermal contact across different land-use types, with bold values indicating high *ILCR* values.

Land-Use	Pathway	Receptor	Cr	As	Cd	Pb	Ni
Industrial (Trans-Amadi)	Ingestion	Adult	3.9399×10^{-7}	1.5134×10^{-4}	9.4917×10^{-7}	1.2653×10^{-7}	—
		Child	9.1931×10^{-7}	3.5312×10^{-4}	2.2147×10^{-6}	2.9524×10^{-7}	—
	Inhalation	Adult	1.8323×10^{-9}	1.4243×10^{-8}	9.2263×10^{-11}	—	9.0409×10^{-10}
		Child	1.2742×10^{-9}	9.9054×10^{-9}	6.4164×10^{-11}	—	6.2875×10^{-10}
	Dermal	Adult	—	1.4733×10^{-6}	—	—	—
		Child	—	2.4125×10^{-6}	—	—	—
Agricultural (Egi)	Ingestion	Adult	3.6217×10^{-7}	2.0183×10^{-6}	4.6056×10^{-7}	1.2774×10^{-7}	—
		Child	8.4507×10^{-7}	4.7094×10^{-6}	1.0747×10^{-6}	2.9805×10^{-7}	—
	Inhalation	Adult	1.6843×10^{-9}	1.8996×10^{-10}	4.4768×10^{-11}	—	7.6586×10^{-10}
		Child	1.1713×10^{-9}	1.3210×10^{-10}	3.1134×10^{-11}	—	5.3261×10^{-10}
	Dermal	Adult	—	1.9649×10^{-8}	—	—	—
		Child	—	3.2174×10^{-8}	—	—	—
Residential (Woji)	Ingestion	Adult	2.5469×10^{-7}	1.0796×10^{-5}	2.4322×10^{-6}	1.3610×10^{-7}	—
		Child	5.9428×10^{-7}	2.5192×10^{-5}	5.6752×10^{-6}	3.1758×10^{-7}	—
	Inhalation	Adult	1.1845×10^{-9}	1.0161×10^{-9}	2.3642×10^{-10}	—	5.5316×10^{-10}
		Child	8.2372×10^{-10}	7.0667×10^{-10}	1.6442×10^{-10}	—	3.8469×10^{-10}
	Dermal	Adult	—	1.0511×10^{-7}	—	—	—
		Child	—	1.7211×10^{-7}	—	—	—

Incremental Lifetime Cancer Risk calculated using the United States Environmental Protection Agency (USEPA) human health risk assessment model. Values $< 1.0 \times 10^{-6}$ indicate negligible carcinogenic risk; values between 1.0×10^{-6} and 1.0×10^{-4} represent the acceptable or tolerable lifetime cancer risk range; and values $> 1.0 \times 10^{-4}$ indicate an unacceptable carcinogenic risk according to USEPA guidelines. “—” denotes that carcinogenic risk was not evaluated because a cancer slope factor was unavailable for the respective exposure pathway.

4. Conclusions

The observed distribution pattern of the HMs and the integrated application of I_{geo} , CF , EF , PLI , IPI , and $NIPi$ demonstrated that industrial activities constitute the primary source of HM pollution within the study area, while agricultural and residential locations experience comparatively lower pollution intensity. The strong agreement among the pollution indices confirms the effectiveness of combined pollution assessment approaches in evaluating contamination severity, identifying anthropogenic influences, and supporting sustainable environmental management strategies aimed at mitigating HM pollution and protecting soil quality. Human health risk characterization demonstrated that exposure pathways and toxicological outcomes vary according to land-use type and target demographic group. Non-carcinogenic risk assessment revealed that the average daily doses (ADD) for most HMs generally fall within acceptable safety limits, except for As (9.15) in the child ingestion category, which exceeded the USEPA safety threshold. Children exhibit greater susceptibility, predominantly through the ingestion pathway. The Incremental Lifetime Cancer Risk (*ILCR*) assessment indicated unacceptable long-term carcinogenic risks across all investigated land-use categories, with As and Cr identified as the principal contributors. For these two HMs, ingestion-related *ILCR* values consistently exceeded the USEPA-acceptable carcinogenic risk threshold (1×10^{-4}), reaching the critical level of 1×10^{-3} for children. The Trans-Amadi industrial area exhibited the highest oral cancer risk for As (1.65×10^{-3} in children) and also showed elevated inhalation cancer risks, high-

lighting the cumulative impacts of intensive industrial emissions. Overall, these findings demonstrate that land-use practices and anthropogenic activities strongly influence the accumulation, spatial distribution, and behavior of HMs in soils of Rivers State, the study area. The results underscore the need for adaptive, science-based environmental governance that integrates continuous environmental monitoring, stringent industrial emission control, sustainable waste management practices and strategic land-use planning. Implementing these measures is fundamental to minimizing anthropogenic pollution source of the HMs, preserving soil ecosystem functionality, advancing the Sustainable Development Goals (SDGs), and promoting resilient industrial, agricultural, and residential development without compromising long-term environmental quality and public health. The findings were based on site-specific assessment of the investigated industrial, agricultural, and residential land use locations. Nevertheless, the study provides valuable baseline data for future investigations involving broader spatial coverage, larger sample sizes and long-term environmental monitoring to better characterize HM dynamics across the region.

Prioritizing the remediation of HM-polluted sites, strengthening environmental regulatory enforcement, and adopting cleaner production technologies will reduce soil degradation, safeguard ecosystem services, and minimize long-term human health risks. Consequently, this study provides valuable scientific evidence to support policymakers and environmental managers in developing integrated, science-based strategies that promote sustainable industrial operations, environmentally responsible agricultural practices, and sustainable residential land-use planning while ensuring long-term soil quality, environmental sustainability, and public health protection.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18157621/s1>, Table S1: Different loadings of heavy metals on Varimax rotated factors of the principal component analysis; Figure S1: Scree plot of PCA illustrating the extent of importance of each factor in a descending order, which expresses when the obtained eigenvalue of an individual factor is sufficient to be considered a relevant factor. It shows a sharp drop from PC1–PC2, a moderate drop at PC2–PC3, and a clear flattening after PC3; Table S2: Summary of principal component eigenvalues and explained variance for the investigated potentially toxic elements; Table S3: Lifetime Average Daily Dose (LADD) via ingestion exposure ($\text{mg kg}^{-1} \text{ day}^{-1}$) for adults and children across different land-use types; Table S4: Lifetime Average Daily Dose (LADD) via inhalation exposure ($\text{mg kg}^{-1} \text{ day}^{-1}$) for adults and children across different land-use types; Table S5: Lifetime Average Daily Dose (LADD) via dermal exposure to heavy metals for adults and children across different land-use types ($\text{mg kg}^{-1} \text{ day}^{-1}$).

Author Contributions: C.N.A.: Contributed to the conceptual design of the research, methodology formulation, and preparation of the original manuscript draft. Q.W.: Supervision and review. M.S.: Supervisory role and review. T.O.M.: Manuscript evaluation, revision, and editing. C.E.E.: Contributed to manuscript review and refinement. A.S.: Contributed to review. All authors have read and agreed to the published version of the manuscript.

Funding: This study was partially supported by the Grant-in-Aid for Scientific Research (KAKENHI), including Special Funds for Innovative Area Research and Basic Research (Category B), provided by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. The funding was awarded under grant numbers 22H03747 (FY2022–FY2024), 24K20941 (FY2024–FY2026), and 25K03267 (FY2025–FY2028).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in this published article/Supplementary Materials. Additional information and materials can be obtained from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Li, Y.; Mei, L.; Zhou, S.; Jia, Z.; Wang, J.; Li, B.; Wang, C.; Wu, S. Analysis of Historical Sources of Heavy Metals in Lake Taihu Based on the Positive Matrix Factorization Model. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1540. [\[CrossRef\]](#) [\[PubMed\]](#)
- Coetzee, J.J.; Bansal, N.; Chirwa, E.M.N. Chromium in Environment, Its Toxic Effect from Chromite-Mining and Ferrochrome Industries, and Its Possible Bioremediation. *Expo. Health* **2020**, *12*, 51–62. [\[CrossRef\]](#)
- Ipeaiyeda, A.R.; Ogungbemi, A.O. Decontamination of automobile workshop soils containing heavy metals and PAHs using chelating agents. *Int. J. Environ. Pollut. Remediat.* **2020**, *8*, 37–45. [\[CrossRef\]](#)
- Chinedu, E.; Chukwuemeka, C.K. Oil spillage and heavy metals toxicity risk in the Niger Delta, Nigeria. *J. Health Pollut.* **2018**, *8*, 180905. [\[CrossRef\]](#) [\[PubMed\]](#)
- Anyanwu, I.N.; Beggel, S.; Sikoki, F.D.; Okuku, E.O.; Unyimadu, J.-P.; Geist, J. Pollution of the Niger Delta with total petroleum hydrocarbons, heavy metals and nutrients in relation to seasonal dynamics. *Sci. Rep.* **2023**, *13*, 14079. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ogbeide, O.; Henry, B. Addressing heavy metal pollution in Nigeria: Evaluating policies, assessing impacts, and enhancing remediation strategies. *J. Appl. Sci. Environ. Manag.* **2024**, *28*, 1007–1051. [\[CrossRef\]](#)
- Andre-Obayanju, O.; Pajiah, J.A. Assessment of heavy metal pollution in soils of Ifie Community, Warri, Delta State, Nigeria. *Glob. J. Pure Appl. Sci.* **2025**, *31*, 25–35. [\[CrossRef\]](#)
- Afonne, O.J.; Chukwuka, J.U.; Ifediba, E.C.; Obi, E. Pollution indices of heavy metal contaminants in typical agrarian soil samples in Ihiala, South-East Nigeria. *Health Environ.* **2022**, *3*, 176–185. [\[CrossRef\]](#)
- Magaji, Y.; Mohammed, A.S.; Appah, J.A.; Mohammed, M. Assessment of Physicochemical Properties and Heavy Metal Contamination of Soils from selected Dumpsites in Gwagwalada Area Council, Abuja, Nigeria. *J. Basic Environ. Res.* **2025**, *3*, 50–58.
- Anthony, T. Assessment of heavy metal contamination in wetlands soils around an industrial area using combined GIS-based pollution indices and remote sensing techniques. *Air Soil Water Res.* **2023**, *16*, 1–11. [\[CrossRef\]](#)
- Mu, L.; Zha, F.; Guo, H.; Bokade, M.; Pandey, S.; Singh, D.N.; Wang, Q.; Chen, T.; Tai, H.; Cai, P.; et al. A multiscale perspective on the occurrence, transport mechanisms, and molecular interactions of heavy metals in contaminated soils. *Environ. Res.* **2026**, *296*, 124042. [\[CrossRef\]](#) [\[PubMed\]](#)
- Akuru, U.B.; Nwachoko, N.; Tetam, J.G.; Jamabo, M.; Amadi, C.S.; Peter-Osah, E. Exploring the levels of heavy metals in soil: A case study of Ahoada West Local Government Area in Rivers State, Nigeria. *Asian J. Environ.* **2025**, *24*, 9–18. [\[CrossRef\]](#)
- Lemessa, F.; Simane, B.; Seyoum, A.; Gebresenbet, G. Analysis of the concentration of heavy metals in soil, vegetables, and water around the Bole Lemi Industrial Park, Ethiopia. *Heliyon* **2022**, *8*, e12429. [\[CrossRef\]](#) [\[PubMed\]](#)
- Zhao, D.; Wang, P.; Zhao, F.-J. Toxic metals and metalloids in food: Current status, health risks, and mitigation strategies. *Curr. Environ. Health Rep.* **2024**, *11*, 468–483. [\[CrossRef\]](#) [\[PubMed\]](#)
- Su, R.; Jiang, Y.; Li, W.; Ding, W.; Feng, L. Effects of Prenatal Arsenic, Cadmium, and Manganese Exposure on Neurodevelopment in Children: A Systematic Review and Meta-Analysis. *Medicina* **2025**, *61*, 1143. [\[CrossRef\]](#) [\[PubMed\]](#)
- Issah, I.; Duah, M.S.; Arko-Mensah, J.; Bawua, S.A.; Agyekum, T.P.; Fobil, J.N. Exposure to metal mixtures and adverse pregnancy and birth outcomes: A systematic review. *Sci. Total Environ.* **2024**, *908*, 168380. [\[CrossRef\]](#) [\[PubMed\]](#)
- Edori, O.S.; Iyama, W.A.; Edori, E.S. Comparative assessment of heavy metals in soils of designated institutions in Rivers State, Nigeria. *Fac. Nat. Appl. Sci. J. Basic Environ. Res.* **2025**, *2*, 47–68.
- Okechukwu, V.U.; Onwukeme, V.I.; Eze, V.C. Concentration levels and pollution status of selected heavy metals in active dumpsites in Port Harcourt, Rivers State, Nigeria. *Chem. Rep.* **2024**, *5*, 275–284. [\[CrossRef\]](#)
- Iyama, W.A.; Okpara, K.; Techato, K. Assessment of heavy metals in agricultural soils and plant (*Vernonia amygdalina* Delile) in Port Harcourt Metropolis, Nigeria. *Agriculture* **2022**, *12*, 27. [\[CrossRef\]](#)
- Ohiagu, F.O.; Lele, K.C.; Chikezie, P.C.; Verla, W.A.; Enyoh, E.E. Pollution profile and ecological risk assessment of heavy metals from dumpsites in Onne, Rivers State, Nigeria. *Chem. Afr.* **2021**, *4*, 207–216. [\[CrossRef\]](#)
- Agbai, W.; Efenudu, U. Land use types and their influence on heavy metals concentration in soils of Yenagoa and Southern Ijaw local government area of Bayelsa State. *Bulg. J. Soil Sci. Agrochem. Ecol.* **2022**, *56*, 3–16.
- Iwegbue, C.M.; Martincigh, B.S. Ecological and human health risks arising from exposure to metals in urban soils under different land use in Nigeria. *Environ. Sci. Pollut. Res.* **2018**, *25*, 12373–12390. [\[CrossRef\]](#) [\[PubMed\]](#)
- Okoye, E.A.; Ezejiofor, A.N.; Nwaogazie, I.L.; Frazzoli, C.; Orisakwe, O.E. Heavy metals and arsenic in soil and vegetation of Niger Delta, Nigeria: Ecological risk assessment. *Case Stud. Chem. Environ. Eng.* **2022**, *6*, 100222. [\[CrossRef\]](#)
- Izah, S.C.; Bassey, S.E.; Ohimain, E.I. Assessment of pollution load indices of heavy metals in cassava mill effluents contaminated soil: A case study of small-scale processors in a rural community in the Niger Delta, Nigeria. *Biosci. Methods* **2017**, *8*, 1–17. [\[CrossRef\]](#)

25. Kudamnya, E.; Edet, A.; Bassey, B. Appraisal of sources, pollution and risks of some metals in soil and water using geochemical and multivariate statistical approach, eastern Niger Delta, Nigeria. *Discov. Geosci.* **2026**, *4*, 94. [[CrossRef](#)]
26. Kabir, M.H.; Rashid, M.H.; Wang, Q.; Wang, W.; Lu, S.; Yonemochi, S. Determination of Heavy Metal Contamination and Pollution Indices of Roadside Dust in Dhaka City, Bangladesh. *Processes* **2021**, *9*, 1732. [[CrossRef](#)]
27. Mansouri, M.S.; Payandeh, K.; Koushfar, A.; Goosheh, M.; Mohammadi Rouzbahani, M. Level of heavy metals and environmental pollution index in Ahvaz, Southwest Iran. *Sci. Rep.* **2024**, *14*, 14754. [[CrossRef](#)] [[PubMed](#)]
28. Zhao, H.; Wu, Y.; Lan, X.; Yang, Y.; Wu, X.; Du, L. Comprehensive assessment of harmful heavy metals in contaminated soil in order to score pollution level. *Sci. Rep.* **2022**, *12*, 3552. [[CrossRef](#)] [[PubMed](#)]
29. Duru, C.E.; Enyoh, C.E.; Enedoh, M.C.; Duru, I.A.; Ibe, F.C.; Verla, A.W.; Isiuku, B.O. Assessment of heavy metals in soils from reclaimed section of Nekede Mechanic Village, Owerri, Southeastern Nigeria. *Chem. Afr.* **2021**, *4*, 429–441. [[CrossRef](#)]
30. Muller, G. Index of geoaccumulation in sediments of the Rhine River. *Geojournal* **1969**, *2*, 108–118.
31. Kowalska, J.B.; Mazurek, R.; Gasiorek, M.; Zaleski, T. Pollution indices as useful tools for the comprehensive evaluation of the degree of soil contamination—A review. *Environ. Geochem. Health* **2018**, *40*, 2395–2420. [[CrossRef](#)] [[PubMed](#)]
32. Bello, S.; Nasiru, R.; Garba, N.N.; Adeyemo, D.J. Quantification of pollution levels associated with heavy metals in Shanono and Bagwai artisanal gold mines, Kano State, Nigeria. *FUDMA J. Sci.* **2019**, *3*, 97–102. [[CrossRef](#)]
33. Rana, M.S.; Wang, Q.; Wang, W.; Enyoh, C.E.; Islam, M.R.; Isobe, Y.; Kabir, M.H. Sources, Distribution, and Health Implications of Heavy Metals in Street Dust across Industrial, Capital City, and Peri-Urban Areas of Bangladesh. *Atmosphere* **2024**, *15*, 1088. [[CrossRef](#)]
34. Tomlinson, D.L.; Wilson, J.G.; Harris, C.R.; Jeffrey, D.W. Problems in the Assessment of Heavy-Metal Levels in Estuaries and the Formation of a Pollution Index. *Helgoländer Meeresunters.* **1980**, *33*, 566–575. [[CrossRef](#)]
35. Miletić, A.; Lučić, M.; Onjia, A. Exposure factors in health risk assessment of heavy metal(loid)s in soil and sediment. *Metals* **2023**, *13*, 1266. [[CrossRef](#)]
36. Yang, S.; Zhao, J.; Chang, S.X.; Collins, C.; Xu, J.; Liu, X. Status assessment and probabilistic health risk modeling of metals accumulation in agricultural soils across China: A synthesis. *Environ. Int.* **2019**, *128*, 165–174. [[CrossRef](#)] [[PubMed](#)]
37. Gu, Y.G.; Lin, Q.; Gao, Y.P. Metals in exposed lawn soils from 18 urban parks and their human health implications in Guangzhou, southern China's largest city. *J. Clean. Prod.* **2016**, *115*, 122–129. [[CrossRef](#)]
38. EPA US. *EPA Integrated Risk Information System (IRIS) Electronic Database*; US Environmental Protection Agency: Washington, DC, USA, 1996.
39. ur Rehman, I.; Ishaq, M.; Ali, L.; Khan, S.; Ahmad, I.; Din, I.U.; Ullah, H. Enrichment, Spatial Distribution of Potential Ecological and Human Health Risk Assessment via Toxic Metals in Soil and Surface Water Ingestion in the Vicinity of Sewakht Mines, District Chitral, Northern Pakistan. *Ecotoxicol. Environ. Saf.* **2018**, *154*, 127–136. [[CrossRef](#)] [[PubMed](#)]
40. Alsafran, M.; Usman, K.; Al Jabri, H.; Rizwan, M. Ecological and Health Risks Assessment of Potentially Toxic Metals and Metalloids Contaminants: A Case Study of Agricultural Soils in Qatar. *Toxics* **2021**, *9*, 35. [[CrossRef](#)] [[PubMed](#)]
41. Wang, J.; Gao, B.; Yin, S.; Xu, D.; Liu, L.; Li, Y. Simultaneous Health Risk Assessment of Potentially Toxic Elements in Soils and Sediments of the Guishui River Basin, Beijing. *Int. J. Environ. Res. Public Health* **2019**, *16*, 4539. [[CrossRef](#)] [[PubMed](#)]
42. Fatoba, P.O.; Ogunkunle, C.O.; Folarin, O.O.; Oladele, F.O. Heavy metal pollution and ecological geochemistry of soil impacted by activities of oil industry in the Niger Delta, Nigeria. *Environ. Earth Sci.* **2016**, *75*, 297. [[CrossRef](#)]
43. Natasha, N.; Shahid, M.; Niazi, N.K.; Khalid, S.; Murtaza, B.; Bibi, I.; Rashid, M.I. A critical review of selenium biogeochemical behavior in soil–plant system with an inference to human health. *Environ. Pollut.* **2018**, *234*, 915–934. [[CrossRef](#)] [[PubMed](#)]
44. Li, K.-Y.; Charron, G.; Pelletier, J.; Bravo, M. Distribution of geogenic arsenic in European topsoil and potential concerns for food safety. *J. Hazard. Mater.* **2025**, *497*, 139523. [[CrossRef](#)] [[PubMed](#)]
45. Department of Petroleum Resources (DPR). *Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN)*, Revised ed.; Ministry of Petroleum Resources: Abuja, Nigeria, 2002.
46. Jones, O.; Openiyi, E.O.; Thompson, S.O.; Orija, D.; Babaniyi, B.R.; Ajayi, O.O. Heavy Metals Distribution in Soils of Selected Dumpsite and Scrap Yard in Akure, Nigeria. *J. Environ. Prot. Sustain. Dev.* **2021**, *7*, 30–36.
47. Alo, A.U.; Tse, A.; Vatuva, A.; Ugulu, S.; Giadom, F.; Ehibor, I.O.; Nnurun, E.; Akaha-Tse, V.H. Multi-Criteria Risk Assessment and Prediction of Heavy Metal Pollution of Soils Around Pb–Zn Artisanal Mining Hotspots in Southeastern Nigeria. *Water Air Soil Pollut.* **2025**, *236*, 887. [[CrossRef](#)]
48. Kabata-Pendias, A. *Trace Elements in Soils and Plants*, 4th ed.; CRC Press: Boca Raton, FL, USA, 2011.
49. Caleb, P.A.; Adedotun, A. Heavy metals accumulation in soils within mechanic village at Bodija, Ibadan, Nigeria. In Proceedings of the 7th NSCB Biodiversity Conference, Online, 27–29 October 2020.
50. Crommentuijn, T.; Polder, M.D.; van de Plassche, E.J. *Maximum Permissible Concentrations and Negligible Concentrations for Metals, Taking Background Concentrations into Account*; Report No. 601501001; National Institute for Public Health and the Environment (RIVM): Bilthoven, The Netherlands, 1997.

51. Canadian Council of Ministers of the Environment (CCME). *Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health: Selenium*; CCME: Winnipeg, MB, Canada, 2009. Available online: <https://ccme.ca/en/res/selenium-canadian-soil-quality-guidelines-for-the-protection-of-environmental-and-human-health-en.pdf> (accessed on 19 July 2026).
52. Baken, S.; Larsson, M.A.; Gustafsson, J.P.; Cubadda, F.; Smolders, E. Ageing of vanadium in soils and consequences for bioavailability. *Eur. J. Soil Sci.* **2012**, *63*, 839–847. [[CrossRef](#)]
53. Canadian Council of Ministers of the Environment (CCME). *Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health: Vanadium*; CCME: Winnipeg, MB, Canada, 2007. Available online: <https://ccme.ca/en/res/vanadium-canadian-soil-quality-guidelines-for-the-protection-of-environmental-and-human-health-en.pdf> (accessed on 19 July 2026).
54. Yang, J.; Teng, Y.; Wu, J.; Chen, H.; Wang, G.; Song, L.; Yue, W.; Zuo, R.; Zhai, Y. Current status and associated human health risk of vanadium in soil in China. *Chemosphere* **2017**, *171*, 635–643. [[CrossRef](#)] [[PubMed](#)]
55. Adagunodo, T.A.; Sunmonu, L.A.; Emetere, M.E. Heavy metals' data in soils for agricultural activities. *Data Brief.* **2018**, *18*, 1847–1855. [[CrossRef](#)] [[PubMed](#)]
56. Akinpelumi, V.K.; Onyena, A.P.; Abdulai, P.M.; Ossai, C.M.; Orisakwe, O.E. Seasonality and ecological risks of heavy metals in diverse environmental matrices from Niger Delta, Nigeria. *Int. J. Environ. Sci. Technol.* **2026**, *23*, 335. [[CrossRef](#)]
57. Lv, J.; Liu, Y.; Zhang, Z.; Dai, J. Factorial kriging and stepwise regression approach to identify environmental factors influencing spatial multi-scale variability of heavy metals in soils. *J. Hazard. Mater.* **2013**, *261*, 387–397. [[CrossRef](#)] [[PubMed](#)]
58. Liu, W.; Li, Y.; Ma, L.; Kong, L.; Abuduwalli, J. Integrating horizontal-vertical heterogeneity and environmental factors to unravel heavy metal distributions and phytoaccumulation in a soil-maize system. *J. Hazard. Mater.* **2026**, *512*, 142382. [[CrossRef](#)] [[PubMed](#)]
59. Afolabi, O.O.; Adesope, O.M. Ecotoxicological risk assessment of heavy metals from remediated oil spill site in Niger Delta region, Nigeria. *Environ. Chem. Ecotoxicol.* **2022**, *4*, 186–193. [[CrossRef](#)]
60. Edegbai, A.J.; Owonaro, J.B.; Pajiah, J.A.; Omietimi, E.J.; Lenhardt, N.; Ukpebor, J.E. Baseline data on selenium micronutrient concentration in parts of Southern Nigeria show provenance and paleodepositional controls. *Acta Geochim.* **2026**, 1–23. [[CrossRef](#)]
61. McLoughlin, S.L.; Patrick, R.A.D.; Mosselmans, J.F.W.; Kelleher, J.; van Dongen, B.E. Selenium uptake from livestock pasture extremely enriched in selenium, molybdenum and uranium: A field and X-ray absorption study. *Soil Syst.* **2023**, *7*, 24. [[CrossRef](#)]
62. Wang, L.; Liu, Q.; Bai, R. Soil heavy metal pollution and health risk assessment based on Monte Carlo simulation: Case study of Xicheng lead–zinc mining area. *Sustainability* **2025**, *17*, 3963. [[CrossRef](#)]
63. U.S. Environmental Protection Agency (EPA). *Guidelines for Carcinogen Risk Assessment*; U.S. Environmental Protection Agency: Washington, DC, USA, 2005.
64. Benjamin, O.D.; Adewole, M.G.; Adewale, M.T.; Olatunbosun, S.S.; Moses, O.D. Carcinogenic and non-carcinogenic health risk assessment of heavy metals in water from selected oil pollution-prone communities in the Niger Delta region. *J. Trace Elem. Miner.* **2025**, *14*, 100266. [[CrossRef](#)]
65. Amadi, A.N.; Olasehinde, P.I.; Yisa, J.; Shaibu, I.; Okoye, N.O. Environmental geochemistry and heavy metal assessment in soils, surface and groundwater from Eastern Niger Delta, Nigeria using multivariate pollution indices. *Int. J. Sci. Glob. Sustain.* **2016**, *2*, 15. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.