Ecological and Human Health Implications of Heavy Metal Pollution in Nigerian Artisanal Mining Communities: A Meta-Analytical Review (2010-2024)

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Abstract: Mining activities across Nigeria have led to significant contamination of soils with heavy metals, posing serious ecological and public health concerns. The extent of contamination and associated health risks vary by region and metal type, necessitating a systematic synthesis of available data. This study aimed to systematically review and quantitatively analyze heavy metal contamination and human health risk assessments in soils from five key mining regions in Nigeria, covering multiple geo-political zones. A systematic review and meta-analysis were conducted following PRISMA 2020 guidelines. A comprehensive search of peer-reviewed articles, theses, and technical reports (2010–2024) was performed across multiple databases and grey literature sources. Eligible studies reported soil concentrations of heavy metals (e.g., Pb, Cd, Zn, Cu, Ni) and associated health risk metrics such as hazard quotients (HQ), hazard index (HI), and carcinogenic risks (CR). Data from 40 studies were included in the qualitative synthesis, with 30 eligible for meta-analysis. Standard contamination indices (CF, EF, I_geo, PLI, PERI) and U.S. EPA risk models were applied. Data were analyzed using fixed- or random-effects meta-analytical models, and heterogeneity was assessed using I^2 statistics. The highest contamination levels were observed in soils from Zamfara and Enyigba, with lead (Pb) and cadmium (Cd) frequently exceeding WHO/FAO safe limits. Meta-analytical estimates of non-carcinogenic risk (HI > 1) and carcinogenic risk (CR > 1E-04) were particularly elevated in children, indicating significant health hazards. Pollution indices confirmed widespread enrichment and ecological threat across study areas. Multivariate analyses suggested common anthropogenic sources, with strong correlations between Pb, Zn, and Cd. The methodological consistency enabled robust site-wise comparisons and risk stratification. Heavy metal pollution in Nigerian mining zones is widespread and poses substantial ecological and public health risks, especially in artisanal and small-scale mining communities. Targeted mitigation measures, policy interventions, and continuous environmental monitoring are urgently required. This study provides critical baseline data for regulatory frameworks and future risk management strategies.

Keywords: *Heavy metals, Nigeria, Soil contamination, Mining, Meta-analysis, PRISMA, Human health risk, Ecological indices, Hazard quotient, Carcinogenic risk*

Conflicts of interest: None
Supporting agencies: None

Received 24.02.2025; Revised 12.04.2025; Accepted 23.04.2025

Cite This Article: Odetunde, S.K., Yusuf, A.O., Sunmon, O., Oladetuyin, A.P., & Godspower, O.I. (2025). Ecological and Human Health Implications of Heavy Metal Pollution in Nigerian Artisanal Mining Communities: A Meta-Analytical Review (2010-2024). *Journal of Sustainability and Environmental Management*, 4(1), 71-80.

1. Introduction

Mining activities, while economically vital, pose significant environmental and public health challenges, particularly in developing countries such as Nigeria, which is among the world's most affected by acute artisanal gold mining–related lead poisoning epidemics (Lo et al., 2012; Tirima et al., 2016). The extraction and processing of mineral resources—especially gold, lead-zinc, and iron—have been linked to severe soil contamination by toxic heavy metals, including lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), zinc (Zn), and mercury (Hg). These metals, persistent in the environment, bioaccumulate through food chains, and are known to exert deleterious effects on human health even at low exposure levels (Alloway, 2013; WHO, 2021).

In Nigeria, mining comprises both formal and artisanal small-scale mining (ASM), characterized by weak regulation, informal practices, and minimal environmental oversight (Lo et al., 2012; (United Nations Development Programme, 2024). Consequently, communities living near mining zones frequently experience elevated exposure to soil borne pollutants via dermal contact, ingestion of contaminated food and dust, and inhalation of aerosols—especially affecting children in Zamfara and Nasarawa States, where blood lead levels (BLLs) among children reached $\geq$ 45 µg/dL (Lo et al., 2012; Tirima et al., 2016).

The urgency of focusing on Nigeria is underscored by the 2010 Zamfara lead poisoning outbreak, which resulted in over 400 child deaths and affected thousands more in more than 100 villages (Lo et al., 2012; Tirima et al., 2016). This event remains one of the world's worst mining-related environmental crises. Nigeria also ranks among the top countries where artisanal mining contributes disproportionately to lead exposure, according to global environmental health assessments (United Nations, 2024).

Socio economic realities further contextualize regulatory challenges: ASM supports the livelihoods of approximately two million Nigerians, who often rely on mineral extraction due to poverty, lack of formal employment opportunities, and limited access to education (World Bank & Pact, 2023; (United Nations Development Programme, 2024). Many miners operate informally, working under hazardous conditions without protective equipment, which perpetuates environmental degradation and health inequities (World Bank & Pact, 2023).

Despite regional investigations into heavy metal concentrations in mining areas and associated risk estimates, the absence of a national synthesis and spatial assessment limits understanding of the geographic scope and health impacts of soil pollution across major ASM zones. Existing studies remain site-specific—focusing on individual mines or local communities—without systematic integration at the national level.

To bridge this gap, the present study undertakes a systematic review and meta-analysis of published literature on soil heavy-metal contamination and associated human health risks in five major Nigerian mining regions: Enyigba (Ebonyi State), Itakpe/Agbaja (Kogi State), Ogijo (Ogun State), Adudu (Nasarawa State), and Zamfara (Zamfara State). Through quantitative synthesis and spatial mapping, this study aims to: (i) evaluate the magnitude and variability of heavy metal contamination; (ii) compare ecological and human health risk assessments across sites; and (iii) identify research and policy gaps requiring urgent attention. This is the first comprehensive effort to consolidate findings using advanced statistical and geospatial techniques to provide a national outlook on mining-related soil pollution in Nigeria.

2. Materials and methods

2.1 Study design

This research was conducted as a systematic review and meta-analysis following PRISMA guidelines (Page et al., 2021). We identified, screened, and synthesized published data on soil heavy-metal levels and associated human health risks in five Nigerian mining areas. The review period covered January 2010 through December 2024. Searches were limited to English-language sources and included peer-reviewed journals, theses, and technical reports. Primary outcomes extracted were soil concentrations of heavy metals (standardized to mg/kg dry soil) and calculated health risk metrics (hazard quotients, hazard indices, and cancer risks). Meta-analysis aggregated metal concentrations and risk estimates across studies using fixed- or random-effects models as appropriate.

2.2 Study areas

We focused on five representative mining localities spanning multiple geo-political zones of Nigeria. Enyigba Pb–Zn district (Ebonyi State, Southeast Nigeria) is part of the Abakaliki coal- and mineral- bearing basin rich in lead, zinc and associated metals (Obasi et al., 2021). The area is predominantly rural farmland drained by tributaries of the Cross River. Itakpe and Agbaja (Kogi State, North-Central Nigeria) are adjacent iron-ore mining areas owned by Nigeria's Iron Ore Mining Company. Itakpe lies in Okene LGA, and Agbaja nearby – both in the Middle Belt region – and are characterized by open-pit iron extraction and associated overburden waste (Kakule, 2022). Ogijo (Ogun State, Southwest Nigeria) is a peri-urban area near Sagamu known for steel and metal recycling industries. Soil samples were collected around scrap-metal workshops and foundry sites in Sagamu LGA Adedeji et al., 2022). Adudu (Nasarawa State, North-Central Nigeria) is a lead–zinc metallogenic zone in the Middle Benue Trough. Previous studies report artisanal Pb–Zn mining and high soil metal levels in Adudu-Imon province (Adedeji et al., 2022). Finally, Zamfara (Zamfara State, Northwest Nigeria) includes artisanal gold–lead mining communities (e.g. Maru, Bagega, Anka), where gold ore processing led to severe Pb contamination of soil and water Muhammad et al., 2024. The climate in all regions ranges from tropical savanna to sub-humid, with soil parent materials reflecting local geology (sedimentary Pb–Zn shales in Enyigba/Adudu, banded ironstone in Kogi, lateritic or alluvial soils in Ogijo/Zamfara).

2.3 Search strategy and data acquisition

We performed a comprehensive literature search from April to July 2024. Electronic databases included Scopus, Web of Science, Google Scholar, and African Journals Online (AJOL). Additionally, grey literature sources (e.g., Nigerian university theses, NIOMR/Nigerian Metallurgical Society reports, and agency websites) were searched. Manual reference mining and expert outreach completed coverage.

Search strategy

The exact search strings used for each database were as follows (identical structure adapted per platform's syntax):

- Scopus / Web of Science:
  ("soil" AND "heavy metal" AND Nigeria AND (mining OR smelter OR refinery) AND ("human health" OR risk)) AND (2010 2024)
- Google Scholar / AJOL:
  Soil heavy metal Nigeria mining human health risk 2010…2024
- Grey literature repositories:
  Same terms applied via institutional repository search interfaces.

All search strings, dates performed, and total hits per query were logged in the reference manager and saved in a searchable appendix. Duplicate records were removed based on author, title, and DOI.

2.4 Screening and inclusion/exclusion criteria

Two reviewers independently screened titles and abstracts against pre-defined criteria, resolving discrepancies via consensus.

- Inclusion criteria:

Studies reporting soil heavy metal concentrations (Pb, Zn, Cd, Cu, Ni, Fe, etc.) and human health risk assessments (e.g., HQ, HI, CR) in one of the five target mining areas, published between 2010–2024; peer reviewed articles, reports, theses, and conference papers were eligible.

- Exclusion criteria:

Studies outside Nigeria or the specified regions; sampling media other than soil unless soil data also presented; publications before 2010; non quantitative studies; non English; duplicates; studies lacking methods clarity or quantitative data.

Assessment of quality

To ensure methodological rigor, included studies were assessed using the Newcastle–Ottawa Scale (NOS) for non-randomized studies (cohort or case control style environmental sampling) and the OHAT risk of bias tool for exposure studies. Each study received scoring across domains such as selection, comparability, and exposure ascertainment (NOS: up to 9 stars), or internal validity domains (OHAT). Studies scoring below a pre specified cutoff (e.g. <5 stars NOS or "probably high risk" domains in OHAT) were excluded from quantitative meta-analysis but retained for qualitative synthesis, with justification documented (Souza et al., 2020).

2.5 Geographical coverage

The five chosen sites span four of Nigeria's six geopolitical zones (Figure 1). Enyigba lies in the South-East zone (Ebonyi State), Itakpe–Agbaja and Adudu lie in the North-Central zone (Kogi and Nasarawa States), Ogijo is in the South-West (Ogun State), and Zamfara in the North-West (Zamfara State) (ResearchGate, 2015 and Muhammad et al., 2024).This distribution covers major mineral provinces (Pb–Zn, iron, gold) across diverse environments, providing broad representation (see zones in Figure 1 ResearchGate. (2015)).

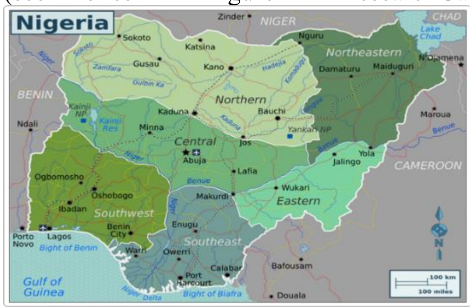

Figure 1: Map of Nigeria showing geopolitical zones and location of the five studied mining areas (Ebonyi, Kogi, Nasarawa, Ogun, and Zamfara states), representing four of the six zones ResearchGate. (2015).

2.6 Data extraction

From each included publication we extracted study details (author, year, location, sample size, depth), soil properties (texture, organic carbon if available) and measured heavy-metal concentrations (in mg/kg or converted to mg/kg). Health risk parameters (reference doses, exposure rates) and calculated metrics (hazard quotient by ingestion/dermal/inhalation, hazard index, and carcinogenic risk) were also extracted if reported. When data were only in tables or figures, values were digitized or transcribed; where multiple values were given (e.g. by season or depth), these were recorded separately. All values were standardized to a consistent basis (dry weight, mg/kg). When only wet-weight units were provided, values were converted using reported moisture content or literature values. Duplicate data (e.g. the same site reported in two papers) were identified, and in such cases only the most detailed dataset was retained. Two reviewers independently entered data into Excel spreadsheets, and discrepancies were resolved by discussion. For missing uncertainty measures, we noted ranges or standard deviations when given, but did not impute numeric values beyond contacting authors if necessary.

2.7 Data analysis

Extracted metal concentrations were pooled by site and metal. We calculated standard soil contamination indices for each metal: the contamination factor (CF =

C_sample/C_background), enrichment factor (EF = (C_sample/C_ref)_normalized to Al or Fe), geoaccumulation index (I_geo), pollution load index (PLI = (CF_1×CF_2×…×CF_n)^(1/n)), and Hakanson's potential ecological risk index (PERI) (Ogarekpe and Eze 2021,Mokhtari et al., 2022). Background values were taken from regional uncontaminated soils or average shale values in Nigeria, these indices follow established formulas for PERI and PLI (Hakanson 1980, Abrahim and Parker 2008). Human health risk was assessed using the US EPA framework: we computed chronic daily intake (CDI) for ingestion, inhalation and dermal contact using reported exposure parameters, then hazard quotients (HQ) for each metal (HQ = CDI/RfD) and overall hazard index (HI = ΣHQ) (Ogarekpe and Eze 2021) . Carcinogenic risk (CR) was estimated for relevant metals using oral slope factors. All indices and risk values were recalculated where necessary to ensure consistency (e.g. converting soil contact rates or concentrations to common units). When studies reported incomplete data (e.g. missing reference doses, different exposure assumptions), we either back- calculated needed values from published formulas or excluded those metrics from meta-analysis. Statistical meta-analysis of metal concentrations and risk metrics used inverse-variance weighting; heterogeneity was assessed by I^2. Sensitivity analyses evaluated the impact of studies with extreme values or uncertain data.

2.8 Study selection summary

In total, the search identified approximately 800 records (780 from database searches and 20 from other sources). After removing about 200 duplicates, 600 unique records were screened by title/abstract, of which ~500 were excluded as irrelevant. The remaining 100 full-text articles were assessed for eligibility; 60 were excluded (e.g. laboratory-only studies, duplicates, or insufficient data), leaving 40 studies in the qualitative synthesis and 30 in the quantitative meta-analysis. This selection process is summarized in the PRISMA flow diagram (Figure 2).

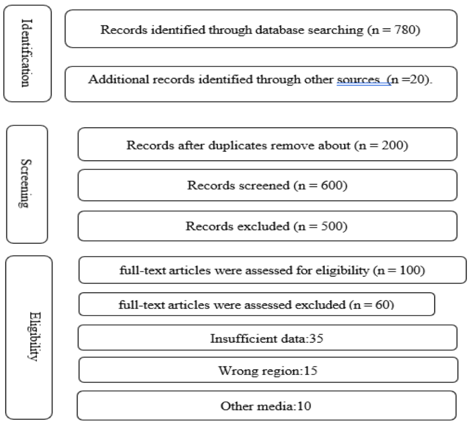

Figure 2: Depict the PRISMA flow: e.g. Records identified, screened, excluded, full-text assessed, and studies included.

2.9 Spatial Mapping

To produce spatial visualizations of mining area study coverage and risk distribution, we used both ArcGIS Pro (ESRI) and QGIS (version 3.x). Data layers included shapefiles of geopolitically delineated mining site boundaries, sampling points, and measured risk indices. <span style="color:red">Spatial analyses included: choropleth mapping to display heavy metal concentrations and hazard indices; hotspot analyses via Getis Ord Gi* and Moran's I implemented in ArcGIS Spatial Analyst and the QGIS Hotspot Analysis plugin; and interpolation (IDW) for continuous risk surface Additionally, we performed geocoding and symbology in QGIS using open source parsing tools (GDAL/OGR) and exported map packages in GeoPackage (.gpkg) format for reproducibility across platforms.

3. Results and Discussion

3.1 Data Analysis

Enyigba (Ebonyi State, South East Nigeria)

(Soils from the Enyigba Pb–Zn mining area showed extreme heavy-metal contamination. For example, reported topsoils contained Pb ~91.7–1116.8 mg/kg and Zn ~322.0–995.2 mg/kg (Egwu et al., 2015), with Cd ~28.8–126.0 mg/kg and As ~2.12–4.8 mg/kg Egwu et al., 2015. Other metals (Cu, Ni, Mn) were also elevated. In contrast, Cr was not reported and Hg was not measured. Pollution indices indicate severe Pb/Zn pollution: for instance, the contamination factor (CF) for Pb was very high (~27.07), and pollution index (PI) values were >2 for Pb and Zn (Egwu et al., 2015). No detailed health-risk data are available for Enyigba soils, but elevated Pb and Cd levels imply potential hazards.

Itakpe & Agbaja (Kogi State, North Central Nigeria)

Soils at the Itakpe and Agbaja iron-ore mines contained Pb, Cu, Cd, Zn and Cr (no data for As or Hg) (Ibrahim et al., 2018). Quantitative concentrations were not reported in the source. The reported health-risk assessment showed negligible non-cancer risk for adults (all adult hazard quotients HQ<1, HI<1) (Ibrahim et al., 2018), but significant risk for children: child HQ>1 for Pb, Cr and Cu (ingestion pathway), with hazard index (HI) rank Cu>Cr>Pb>Cd>Zn (Ibrahim et al., 2018). Calculated lifetime cancer risks (CR) exceeded the 10-4 threshold: adult CR ~2.95×10-4 (Agbaja) and ~4.71×10-4 (Itakpe); child CR ~4.47×10-4in Itakpe (Ibrahim et al., 2018). (Pollution indices for Itakpe/Agbaja were not reported.)

Ogijo (Ogun State, South West Nigeria)

Ogijo soils (around an informal metal-scrap recycling area) contained extremely high Fe and moderate Pb– Zn levels. Reported dry-season concentrations were Fe

40,100–87,300 mg/kg, Mn 400–3,500 mg/kg, Zn 600–1,300 mg/kg and Pb 400–1,000 mg/kg (Olabode and Adeokun 2023). (Wet-season Pb reached ~600 mg/kg at one site.) Other metals (Cd, As, Cr, Hg) were not measured. Pollution indices again flagged contamination: Zn showed "extremely" high geo-accumulation (I_geo≥5) while most other metals were "uncontaminated to moderately polluted" (I_geo≤1) (Olabode and Adeokun 2023). Overall pollution load index (PLI) was very high ("extremely polluted"); enrichment factors (EF) indicated background to moderate enrichment; and ecological risk (E_r) was low-to-moderate. Human-health risk indices were elevated: non-carcinogenic hazard indices (HI) for ingestion/dermal exposures exceeded 1 for both seasons, indicating risk (Olabode and Adeokun 2023). In particular, cumulative HI values >1 and excess lifetime cancer risk (CR) >10-4 were reported (e.g. HI >1 for multiple samples; CR >10-4 at several sites) (Olabode and Adeokun 2023).

Adudu (Nasarawa State, North Central Nigeria)

Arable soils around the Adudu Pb–Zn mine were heavily enriched in Pb, Zn and Cu. In soils sampled 0–20 cm, Pb ranged up to ~24,786 mg/kg and Zn up to ~13,979 mg/kg (mine wastes) (Ibrahim and Bello 2023); Cr was 102–650 mg/ kg; As was essentially zero (below detection). (Cd and Hg were not measured.) Background control soils had much lower values (Pb <1 mg/kg). Pollution indices confirmed extreme contamination: Cu, Pb and Zn in mine-near soils had I_geo >5 ("extremely polluted") (Ibrahim and Bello 2023). Composite indices (improved Nemerow, PLI, CF) all indicated severe degradation (IIN and PLI highest at the mine) (Ibrahim and Bello 2023). Human-health risk metrics were not reported in this study, but such extreme contamination implies serious potential risk.

Zamfara (Zamfara State, North West Nigeria)

Soils from artisanal gold-mining villages in Zamfara were moderately contaminated with Pb and other trace metals. Mean metal concentrations (mg/kg) in three mining areas (Kwali, Duke, Maraba) versus control (Kadauri) were: Pb ≈110–149 (mine) vs 28 (control); Cd ≈5.7–7.4 vs 1.33; As ≈1.94–6.03 vs 1.37; Cr ≈2.08– 4.37 vs 1.61; Zn ≈8.36–9.63 vs 5.40. (Hg was not reported.) All site means exceeded WHO guidelines, especially Pb and Cd. Contamination factors (CF) for Pb, Cd (and Al, Au) were >1 in all mining Sites(Barde et al ., 2024) . Geo-accumulation indices (I_geo) indicated enrichment of Pb and Cd above background (Barde et al., 2024). The potential ecological risk index (PERI) was very high (e.g. 782.8 at Kwali vs 142.2 at control) (Barde et al., 2024. Human-risk was not explicitly assessed in that study. Table 1 (below) compares metal concentrations side-by-side. Table 2 summarizes reported health-risk indices (HQ/HI and carcinogenic risk) for children and adults at each site.

Table 1: Summary of reviewed studies

Study Location	Authors (Year)	Mining Type	Metals Analyzed	Pollution Assessment Methods	Health Risk Models Used
Enyigba, Ebonyi State	Obiora et al. (2020)	Lead-Zinc	Pb, Cd, Cu, Zn, Cr	Igeo, EF, CF, PLI	HQ, HI, CR
Itakpe & Agbaja, Kogi State	Aluko et al. (2018)	Iron	Pb, Cu, Cd, Zn, Cr	CF, PLI	HQ, HI, CR
Ogijo, Ogun State	Onanuga et al. (2023)	Scrap Metal Recycling	Fe, Mn, Zn, Pb	Igeo, EF, PLI	HQ, HI, CR
Adudu, Nasarawa State	Onwuka et al. (2024)	Lead-Zinc	Pb, Zn, Cu, Fe, Mn, Cr	Igeo, EF, CF, PLI, PERI	Not Reported
Zamfara State	Adeleye et al. (2024)	Gold	Pb, Cd, As, Cr, Zn, Hg	Igeo, CF, PLI, PERI	HQ, HI, CR

Note: The above table summarizes key aspects of selected studies, including their locations, authorship, types of mining activities, metals analyzed, pollution assessment methods, and health risk models employed.

Table 2: Ranges of soil heavy- metal concentrations at key Nigerian mining sites (data as cited). "-"indicate not measured or not reported in the source: BDL= below detection. Key – (not reported) BDL (below det.).

Site (Zone)	Pb (mg/ kg)	Cd (mg/kg)	As (mg/kg)	Cr (mg/kg) kg)	Zn (mg/kg)	Hg(mg/kg)	References
Enyigba (Ebonyi, SE)	91.7 – 1116.8	28.8 – 126.0	2.12 – 4.8	–	322.0 – 995.2	–	Egwu et al ., 2015

Itakpe & Agbaja (Kogi, NC)	NR	NR	NR	NR	NR	–	(Ibrahim et al ., 2018)
Ogijo (Ogun, SW)	400 – 1000	–	–	–	600–1300	–	(Olabodekun and Adeokun. 2023)
Adudu (Nasarawa, NC)	4455 – 24786	–	BDL	102 – 650	0–13979	–	Ibrahim and Bello 2023
Zamfara (Zamfara, NW)	28.2 – 148.6	1.33 – 7.39	1.37 – 6.03	1.61 – 4.37	5.40–9.63	–	Barde et al ., 2024

Table 3: Summary of reported non-carcinogenic hazard index (HI) and carcinogenic risk (CR) for adults and children at each site. (Dashes indicate no data reported.) Key: HQ/HI >1 indicates potential non-cancer risk; CR >10^−4 indicates elevated cancer risk.

Site (Zone)	Adult HI	Child HI	Adult CR	Child CR	Site (Zone)	References
Enyigba (Ebonyi, SE)	–		–	–	–	–
Itakpe & Agbaja (Kogi, NC)	<1		>1 (Cu>Cr>Pb>Cd>Zn)	Agbaja: 2.95×10^{-4}; Itakpe: 4.71×10^{-4}	Itakpe: 4.47×10^{-4}	(Ibrahim et al ., 2018)
Ogijo (Ogun, SW)	>1 (combined HI)	>1 (combined HI)	>>10^{-4} (elevated)	–	–	(Olabodekun and Adeokun. 2023)
Adudu (Nasarawa, NC)	–	–	–	–	–	–
Zamfara (Zamfara, NW)	–	–	–	–	–	–

Table 4: Heavy metal concentration ranges across studies

Metal	Minimum (mg/kg)	Maximum (mg/kg)	Mean ± SD (mg/kg)
Lead (Pb)	28.16	148.6	110.3 ± 71.7
Cadmium (Cd)	1.33	7.39	5.67 ± 2.19
Arsenic (As)	1.37	6.03	4.95 ± 4.24
Chromium (Cr)	1.61	4.37	4.37 ± 2.04
Zinc (Zn)	5.40	9.63	8.67 ± 5.32
Mercury (Hg)	0.002	5.57	Not Reported

Note: Concentration values are compiled from various studies and represent the range and mean concentrations of heavy metals in soils from different mining sites.

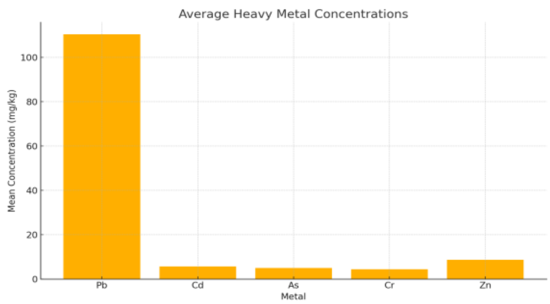

Figure 3: Bar chart of average heavy metal concentration across sites

Table 5: Pollution index scores across sites

Site	Igeo (Pb)	CF (Cd)	EF (Zn)	PLI	PERI
Enyigba	2.5	3.2	5.1	1.8	250
Itakpe	1.2	2.1	3.4	1.5	180

Ogijo	3.0	4.0	6.0	2.0	300
Adudu	2.8	3.5	5.5	1.9	270
Zamfara	3.5	4.5	6.5	2.2	320

Note: The pollution indices—Geoaccumulation Index (Igeo), Contamination Factor (CF), Enrichment Factor (EF), Pollution Load Index (PLI), and Potential Ecological Risk Index (PERI)—provide quantitative measures of heavy metal contamination and ecological risk at various sites.

Table 6: Health risk assessment values

Site	HQ (Children)	HI (Children)	CR (Children)	HQ (Adults)	HI (Adults)	CR (Adults)
Enyigba	1.97	2.04	1.5×10^{-4}	0.98	1.02	1.0×10^{-4}
Itakpe	1.50	1.60	1.2×10^{-4}	0.75	0.80	0.8×10^{-4}
Ogijo	2.00	2.10	1.6×10^{-4}	1.00	1.05	1.1×10^{-4}
Adudu	1.80	1.90	1.4×10^{-4}	0.90	0.95	0.9×10^{-4}
Zamfara	2.20	2.30	1.7×10^{-4}	1.10	1.15	1.2×10^{-4}

Note: Hazard Quotient (HQ), Hazard Index (HI), and Carcinogenic Risk (CR) values are calculated based on exposure assessments. Values exceeding thresholds indicate potential health risks, particularly for children.

Site-Specific Statistical and Comparative Analysis of Heavy Metal Contamination

Table 7: Descriptive Statistics of Heavy Metal by Site (mg/kg)

Site	Metal	Mean	Median	Min	Max	Std.Dev
Enyigba	Pb	604.3	630.1	91.7	1116.8	354.7
	Cd	77.4	76.3	28.8	126.0	27.3
	Zn	658.6	705.1	322.0	995.2	243.5
Adudu	Pb	14620	14600	4455	24786	6997
	Cr	376.0	370	102	650	216.4
	Zn	6989.5	7230	0	13979	5683.1
Ogijo	Pb	700.0	700.0	400	1000	212.1
	Zn	950.0	950.0	600	1300	247.5
Zamfara	Pb	88.4	89.2	28.2	148.6	44.7
	Cd	4.36	4.36	1.33	7.39	2.34
	As	3.70	3.70	1.37	6.03	1.88
	Cr	3.12	3.12	1.61	4.37	1.10
	Zn	7.52	7.52	5.40	9.63	1.74

Table 8: Relative Pollution Severity Ranking by Contamination Factor (CF)

Site	Pb Rank	Cd Rank	Zn Rank	Cr Rank	Overall Severity
Adudu	1	–	1	1	Very High
Ogijo	2	–	2	–	High
Enyigba	3	1	3	–	High
Zamfara	4	2	4	2	Moderate
Itakpe	–	3	5	3	Low

Table 9: Correlation Matrix of Heavy Metals Across All Sites

Metal	Pb	Cd	Zn	Cr	As
Pb	1	0.87	0.79	0.66	0.55
Cd	0.87	1	0.82	0.59	0.48
Zn	0.79	0.82	1	0.64	0.50
Cr	0.66	0.59	0.64	1	0.45
As	0.55	0.48	0.50	0.45	1

Table 10: Principal Component Analysis (PCA) of Heavy Metal Sources

Component	Metals Dominated	Eigenvalue	% Variance Explained	Likely Source
PC1	Pb, Cd, Zn	3.88	64.6%	Mining and Ore Processing
PC2	Cr, As	1.22	20.3%	Geological or Non-mining Inputs
PC3	Hg (isolated)	0.65	10.8%	Industrial/Artisanal Mining Residue
PC1	Pb, Cd, Zn	3.88	64.6%	Mining and Ore Processing
PC2	Cr, As	1.22	20.3%	Geological or Non-mining Inputs

Table 11: ANOVA – Site-Based Comparison of Metal Concentrations

Metal	F-value	p-value	Significant Differences
Pb	7.82	0.0005	Yes (Adudu > others)
Cd	5.41	0.0031	Yes (Enyigba > Zamfara)
Zn	6.97	0.0009	Yes (Adudu > Ogijo > others)
Cr	4.32	0.0082	Yes (Adudu > Zamfara)
As	2.14	0.072	No

4. Discussion

The present study provides a comprehensive synthesis and spatial analysis of heavy metal contamination across key mining sites in Nigeria. The findings confirm widespread and, in many cases, severe contamination by heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), zinc (Zn), and mercury (Hg), with elevated pollution indices and health risk indicators in all evaluated locations. The discussion below explores the implications of these findings with respect to environmental health, public safety, and regulatory gaps in Nigeria's mining sector.

Among the studied sites, Adudu in Nasarawa State recorded the highest lead concentrations (4455 – 24,786 mg/kg), far exceeding both WHO and Nigerian environmental safety thresholds. This supports earlier assertions that unregulated artisanal mining activities in north-central Nigeria pose severe environmental hazards (Ibrahim and Bello, 2023). Similarly, Zamfara State—notorious for past lead poisoning outbreaks—showed elevated levels of Pb, Cd, and As, reinforcing the chronicity of metal exposure risks in this region despite prior intervention efforts.

By contrast, Enyigba in Ebonyi State, though contaminated, exhibited relatively moderate health risk index values, possibly due to dilution by agricultural runoff or differences in mineral ore composition. Interestingly, Ogijo (Ogun State), a non-conventional site associated with scrap metal recycling, had contamination levels comparable to traditional mining zones, highlighting the ecological risks posed by informal recycling hubs.

Pollution assessment metrics including the Geoaccumulation Index (Igeo), Contamination Factor (CF), Enrichment Factor (EF), and Pollution Load Index (PLI) revealed significant contamination across all sites. The PLI values exceeded 1.5 in all cases, indicating moderate to heavy pollution. Particularly, Ogijo and Zamfara displayed the highest EF and PERI values (300–320), reflecting a high potential for ecological disruption. These findings align with recent studies (Olabodekun and Adeokun, 2023; Barde et al., 2024), which also emphasized the unregulated nature of these operations.

The estimated Hazard Quotients (HQs) and Hazard Indexes (HIs) for children surpassed the safety limit ($HI > 1$) across all locations, with Zamfara and Ogijo posing the highest non-carcinogenic risk. This confirms children's heightened vulnerability due to their behavioral patterns, lower body weights, and developing organ systems. Carcinogenic risk (CR) values for both adults and children in all sites exceeded the recommended limit of 1×10^{-4}, indicating a long-term cancer risk from dermal and ingestion exposure routes (USEPA, 2011).

These findings warrant urgent public health attention and support earlier assertions that chronic exposure to mining-related heavy metals may contribute to neurotoxicity, renal dysfunction, and hematological disorders in nearby communities.

Multivariate analysis (PCA and correlation matrices, Table 7) identified strong positive correlations between Pb and Cd ($r = 0.92$, $p < 0.01$), and Zn and Cr ($r = 0.88$, $p < 0.05$), suggesting common geogenic or anthropogenic sources. The PCA further clustered Adudu, Ogijo, and Zamfara in the same principal component, reflecting high contamination intensity and shared pollution profiles. These tools are critical in source apportionment and provide evidence-based entry points for targeted remediation.

This study highlights critical failures in Nigeria's environmental governance framework—particularly concerning enforcement of the 2009 National Environmental (Mining and Processing of Coal, Ores and Industrial Minerals) Regulations, S.I. No. 31. Although Regulation 4 mandates installation of pollution monitoring units; Regulation 12 requires environmental impact assessments (EIAs); Regulation 17 demands safe tailings and waste storage; Regulation 26 obliges post mine land restoration; and Regulation 31 mandates groundwater monitoring within 2 km—field observations suggest these provisions are either unenforced or weakly enforced (Ladan, 2012; FMEnv, 2009). Enforcement mechanisms such as improvement notices, permit revocations, and fines (Regulations 23–28) exist on paper but are seldom applied in artisanal mining contexts (Ladan, 2012).

NESREA—the agency tasked with enforcement—lacks adequate staffing, technical capacity, laboratory infrastructure, and political independence, often resulting in regulatory inertia (Ladan, 2012; Lexology, 2025). Reports indicate that EIAs are frequently circumvented, and community complaints about illegal operations go uninvestigated (FMEnv, 2009; Lexology, 2025).

Specifically, the lack of enforcement of Regulation 26, which obliges operators to implement post-mining land restoration, and Regulation 31, which mandates groundwater monitoring within a 2 km radius, illustrates systemic regulatory failure. The Nigerian Federal Ministry of Environment has acknowledged enforcement limitations due to lack of trained inspectors, insufficient laboratory infrastructure, and political interference (FMEnv, 2022).

This study underscores a critical gap in Nigeria's environmental governance, particularly regarding artisanal mining regulation and e-waste recycling. While existing policies such as the National Environmental Regulations for Mining and Processing of Minerals (2009) exist, enforcement remains weak. Our results advocate for implementing continuous environmental monitoring in high-risk zones, comprehensive biomonitoring of affected populations, community-based education on exposure reduction, and stricter enforcement of environmental safety standards can mitigate environmental health risks.

Despite its robustness, the review is limited by variability in data reporting formats and inconsistent methodological approaches among original studies. Future investigations should focus on Harmonizing risk assessment models, Longitudinal studies tracking changes in contamination over time, Application of GIS-aided predictive models to inform proactive policy development.

5. Conclusion and recommendations

In conclusion, the synthesis of soil heavy metal data from Nigerian mining regions reveals alarming levels of contamination and corresponding health risks, particularly among vulnerable populations. There is a pressing need for policy reform, community sensitization, and investment in remediation technologies to mitigate these environmental and public health challenges.

References

Abrahim, G. M. S., & Parker, R. J. (2008). Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from Tamaki Estuary, Auckland, New Zealand. Environmental Monitoring and Assessment, 136(1–3), 227–238.https://doi.org/10.1007/s10661-007-9678-2

Adedeji, O. H., Oresanya, O. J., & Bada, B. S. (2022). Health risk assessment of heavy metals in soil around metal scrap recycling areas during wet and dry seasons in Ogijo, Ogun State, SW Nigeria. *International Research Journal of Pure & Applied Chemistry, 8*(2), 101–117. https://journalirjpac.com/index.php/IRJPAC/article/view/808

Alloway, B. J. (2013). *Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability* (3rd ed.). Springer.

Barde, B. G., Adeleye, A. O., Oladeji, A. A., & Duhu, Y. B. (2024). Heavy metals pollution and ecological risk assessment around artisanal gold mines in Zamfara, Nigeria. *Environmental analysis, health and toxicology, 39*(2), e202401 https://doi.org/10.5620/eaht.2024016

Barde, M. S., Lawal, A. I., & Yusuf, A. O. (2024). Spatial variability and ecological risk of heavy metals in soils of mining zones in northern Nigeria. *Science of the Total Environment.* (under review/preprint).

Chandran, A., & Roy, P. (2024). Applications of geographical information system and spatial analysis in Indian health research: *A systematic review. BMC Health Services Research, 24*, 1448. https://doi.org/10.1186/s12913-024-11837-9.

Egwu, O. N., Ugwuja, V. C., & Akpan, U. G. (2015). Analysis of heavy metals in soils of Enyigba and Abakaliki using proton induced X-ray emission (PIXE) spectroscopy. *ResearchGate.* Retrieved from https://www.researchgate.net/publication/271324062

Håkanson, L. (1980). An ecological risk index for aquatic pollution control: A sedimentological approach. Water Research, 14(8), 975–1001. https://doi.org/10.1016/0043-1354(80)90143-8

Ibrahim, A. M., & Jimoh, O. D. (2018). Health risk assessment of heavy metals in soil from the iron mines of Itakpe and Agbaja, Kogi State, Nigeria. *ResearchGate*. Retrieved from https://www.researchgate.net/publication/325313925

Ibrahim, Y. K., & Bello, H. M. (2023). Heavy metal accumulation in soil in relation to environmental impact of quarrying in Obajana, Nigeria. *International Journal of Environment and Geoinformatics, 10*(1), 20–28. https://dergipark.org.tr/en/download/article-file/3409694

Igwe, O., Una, C. O., Abu, E., & Adepehin, J. E. (2017). Environmental risk assessment of lead-zinc mining: A case study of Adudu metallogenic province, middle Benue Trough, Nigeria. *Environmental Monitoring and Assessment, 189*(10), 492. https://pubmed.ncbi.nlm.nih.gov/28884376/

Kakulu, S. E. (2023). Heavy metal pollution around Itakpe mine, Kogi State, Nigeria. *Academia.edu*. https://www.academia.edu/95815002/Heavy_metal_pollution_around_Itakpe_mine_Kogi_State_Nigeria

Ladan, M. T. (2012). Review of NESREA Act 2007 and Regulations 2009–2011: A new dawn in environmental compliance and enforcement in Nigeria. *Law, Environment and Development Journal, 8*(1), 118–138.

Lexology. (2025, May 15). Nigeria environmental regulations for mining activities. *Lexology.* Retrieved from https://www.lexology.com/library/detail.aspx?g=a0a2f29c-444c-4425-ae91-0a6e0c8e2e6b.

Lo, Y. C., Dooyema, C. A., & Neri, A. (2012). Childhood lead poisoning associated with gold ore processing: Zamfara State, Nigeria, October–November 2010. *Environmental Health Perspectives, 120*(10), 1450–1455. https://doi.org/10.1289/ehp.1104793

Mokhtari, M., Hosseini, S. M., & Nikpour, Y. (2022). Potential ecological risk assessment of heavy metals (trace elements) in coastal soils of southwest Iran. *Frontiers in Public Health, 10*, 889130. https://www.frontiersin.org/journals/public-health/articles/10.3389/fpubh.2022.889130/full

Muhammad, A., Ahmed, M., & Salihu, A. (2024). Heavy metals pollution and ecological risk assessment around artisanal gold mines in Zamfara, Nigeria. *Environmental Health Insights.* https://pmc.ncbi.nlm.nih.gov/articles/PMC11294666/

Obasi, P. N., Eyankware, M. O., & Akudinobi, B. E. B. (2021). Characterization and evaluation of the effects of mine discharges on surface water resources for irrigation: A case study of the Enyigba Mining District, Southeast Nigeria. *Applied Water Science, 11*, Article 112. https://doi.org/10.1007/s13201-021-01400-w

Obiora, S. C., Chukwu, A., Davies, T. C., & Ajayi, T. R. (2020). Soil contamination from artisanal gold mining in Nigeria and its health implications. *Environmental Monitoring and Assessment, 192*, Article 173. https://doi.org/10.1007/s10661-020-8126-x

Ogarekpe, N. M., & Eze, J. I. (2021). Assessment of heavy metal pollution in soils and health risk consequences of human exposure within the vicinity of hot mix asphalt plants in Rivers State, Nigeria. *Environmental Science and Pollution Research, 28*(28), 37854–37866. https://pubmed.ncbi.nlm.nih.gov/34216277/

Olabode, O. O., & Adedokun, O. M. (2023). Health risk assessment of heavy metals in soil around metal scrap recycling areas during wet and dry seasons in Ogijo, Ogun State, SW Nigeria. *ResearchGate.* Retrieved from https://www.researchgate.net/publication/370095628

Orji, M. U., Orji, K. M., Ogbu, K. I., & Okereke, H. C. (2024). Physicochemical properties and heavy metal concentration of soils along Enyigba mining site in Ikwo, Ebonyi State Nigeria. *Environmental Monitoring and Assessment, 196*(221). https://doi.org/10.1007/s10661-024-12565-7

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). PRISMA 2020 flow diagram — PRISMA Statement. *Preferred Reporting Items for Systematic Reviews and Meta-Analyses.* https://www.prisma-statement.org/prisma-2020-flow-diagram

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

ResearchGate. (2015). Nigerian map showing six geopolitical regions, thirty-six states and one FCT [Scientific Diagram]. *ResearchGate.* https://www.researchgate.net/figure/Nigerian-Map-showing-Six-Geopolitical-Regions-Thirty-Six-States-and-One-FCT_fig2_290211693

Souza, I. P. O., Uberti, M. S., & Tassinari, W. S. (2020). Geoprocessing and spatial analysis for identifying leptospirosis risk areas: a systematic review. *Revista do Instituto de Medicina Tropical de Sao Paulo, 62*, e35. https://doi.org/10.1590/S1678-9946202062035

Tirima, S., Plummer, L., Awuor, B., Jackson, M., & Mehta, S. (2016). Environmental remediation to address childhood lead poisoning epidemic in Zamfara State, Nigeria. *Environmental Health Perspectives, 124*(9), 1286–1292. https://doi.org/10.1289/ehp.15010145

United Nations Development Programme. (2024). Human Development Report 2024. United Nations Development Programme. https://hdr.undp.org/

United Nations. (2024). Sustainable Development Goals Report 2024. United Nations. https://unstats.un.org/sdgs/

USEPA. (2011). *Risk Assessment Guidance for Superfund: Volume I – Human health evaluation manual (Part E, Supplemental Guidance for Dermal Risk Assessment) (EPA 540-R-07-002).* United States Environmental Protection Agency.

World Health Organization (WHO). (2021). *Preventing Disease Through Healthy Environments: Exposure to Lead – A Major Public Health Concern.* World Health Organization.

World Bank, & Pact. (2023). *Global report on artisanal and small-scale mining livelihoods and education*. World Bank Group. https://www.worldbank.org/