

SPATIAL VARIABILITY AND ECOLOGICAL RISK OF HEAVY METALS IN SOIL
FROM ARTISANAL AND SMALL-SCALE MINING SITES IN THE CENTRAL
ZONE OF TARABA STATE, NIGERIA: A GEO-ACCUMULATION INDEX
APPROACH

ABSTRACT

Artisanal and small-scale mining (ASM) activities have increasingly contributed to environmental degradation through the unregulated release of toxic metals into soils, particularly in mineral-rich regions such as Taraba State, Nigeria. This study assessed the spatial variability and ecological risks of selected heavy metals including Cadmium (Cd), Lead (Pb), Cobalt (Co), Copper (Cu), Chromium (Cr), Zinc (Zn), Nickel (Ni), Manganese (Mn), and Iron (Fe) in soils collected from seven ASM sites in the central zone of the state. Soil samples were analyzed using Atomic Absorption Spectrophotometry (AAS), and the geo-accumulation index (Igeo) was applied to evaluate contamination intensity. The results revealed significant spatial heterogeneity in metal distribution, with Mayo-Sinna exhibiting the lowest contamination levels, while Lambangu, Gidan Kara, and Maijankasa showed elevated concentrations of Pb, Co, Ni, Mn, and Fe. Cu, Cr, and Cd were below detection limits in all sites. The Igeo values classified Lambangu and Gidan Kara as moderately to heavily polluted with respect to multiple metals, signaling ecological risk hotspots. The study stresses the pressing need for environmental regulation, continuous monitoring, and remediation programs to mitigate the health and ecological hazards posed by ASM activities. These findings provide empirical evidence to inform sustainable mining practices and soil quality management in Nigeria and other developing regions facing similar challenges.

Keywords: Heavy metal, contamination, geo-accumulation index, artisanal mining, soil pollution, Taraba State, ecological,

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1. INTRODUCTION

Heavy metal contamination in soils has emerged as a pressing environmental concern worldwide, particularly in regions with intensive artisanal and small-scale mining (ASM) activities. These mining practices, often unregulated and mechanized at a rudimentary level, significantly contribute to the release of toxic heavy metals into terrestrial ecosystems. Once introduced, heavy metals such as lead (Pb), cadmium (Cd), cobalt (Co), nickel (Ni), and zinc (Zn) can persist in soils for extended periods, posing risks to plants, animals, and human health through bioaccumulation and trophic transfer (Fosu-Mensah *et al.*, 2020; Kabir *et al.*, 2021).

The soil acts both as a reservoir and a conduit for heavy metal pollutants. The spatial variability of these contaminants is influenced by factors such as topography, soil pH, mining methods, and proximity to waste dumps and processing units (Ali *et al.*, 2022). Understanding the

distribution and concentration of heavy metals is critical for environmental monitoring, land-use planning, and implementing remediation strategies. Particularly in sub-Saharan Africa, ASM has intensified over the years, often driven by economic needs but accompanied by significant ecological degradation (Bempah *et al.*, 2020; Ezeaku & Davidson, 2023).

Taraba State, located in northeastern Nigeria, is endowed with abundant mineral resources including gold, barytes, and zinc. The central zone of the state has witnessed an increase in ASM activities over the past decade, particularly in areas like Mayo-Sinna, Langalanga, Maibokati, and Lambangudu. These mining sites are largely operated by local miners with minimal environmental controls, making them potential hotspots for soil pollution. While mining enhances local economies, the associated ecological consequences especially heavy metal pollution, require comprehensive assessment (Okoro *et al.*, 2021; Suleiman *et al.*, 2024).

To assess contamination levels, the geo-accumulation index (Igeo) introduced by Müller (1969) provides a robust quantitative measure. It compares current metal concentrations to pre-industrial baselines, classifying the degree of pollution across various scales. The Igeo method has been widely applied in recent studies for its reliability and ease of interpretation (Omoriegbe *et al.*, 2022; Yusuf *et al.*, 2023). This study evaluates the spatial distribution and ecological risks of heavy metals in soils from selected ASM sites in the central zone of Taraba State.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the Central Senatorial Zone of Taraba State, Nigeria, an area characterized by diverse geological formations and an increasing number of artisanal and small-scale mining (ASM) activities. Seven specific sites were selected based on their active or historical mining status: Langalanga and Maibokati (Bali LGA), Mayo-Sinna (Sardauna LGA), and Quenty Gate, Gidan Kara, Maijankasa, and Lambangudu (Gashaka LGA). These locations represent a mix of ecological zones, land uses, and mining intensities, providing a comprehensive spatial representation of heavy metal contamination in the region.

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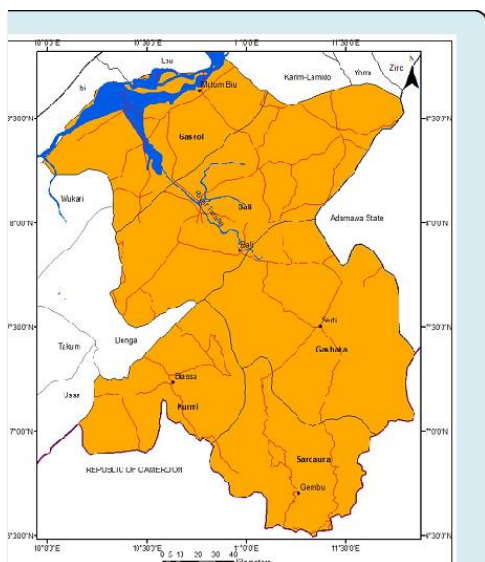


Figure 1: Map of the Study Area

2.2 Soil Sample Collection

Soil samples were collected during the 2024 dry season to ensure minimal interference from surface runoff or leaching. At each site, composite soil samples were collected from five randomly selected points within a 100 m × 100 m grid. Samples were taken from the topsoil layer (0–20 cm depth), where contamination is typically most pronounced. Stainless steel augers were used to avoid trace metal interference. Each composite sample was homogenized, air-dried at room temperature, and passed through a 2 mm sieve before laboratory analysis.

2.3 Laboratory Analysis of Heavy Metals

The prepared soil samples were subjected to acid digestion using a mixture of nitric acid (HNO₃) and perchloric acid (HClO₄) by APHA (2017) protocols. Concentrations of nine heavy metals including cadmium (Cd), lead (Pb), cobalt (Co), copper (Cu), chromium (Cr), zinc (Zn), nickel (Ni), manganese (Mn), and iron (Fe) were determined using Atomic Absorption Spectrophotometry (AAS; Model AA-7000, Shimadzu, Japan). Quality control measures included the use of reagent blanks, certified reference materials, and sample duplicates to ensure analytical accuracy and precision.

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2.4 Geo-accumulation Index (Igeo) Calculation

The geo-accumulation index (Igeo) was used to assess the degree of heavy metal contamination. Igeo was calculated using the formula proposed by Müller (1969):

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

where: C_n = Measured concentration of the heavy metal in the soil or sediment sample

B_n = Geochemical background value of the metal (typically from average shale or crustal values)

1.5 = Background matrix correction factor to account for natural fluctuations in the environment and lithogenic effects

\log_2 = Logarithm to base 2

C_n is the measured concentration of the metal in the soil sample,

B_n is the geochemical background concentration of the metal (typically based on average crustal values), and 1.5 is a correction factor that accounts for natural variations in the background values. The Igeo values were classified into seven pollution categories, ranging from Class 0 (uncontaminated) to Class 6 (extremely contaminated), following Müller's classification system.

3. RESULTS

Table 1: Geo-Accumulation Index (Igeo) of Heavy Metals in Soil Samples Across Seven ASM Sites in Central Taraba State

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Site	Cd	Pb	Co	Cu	Cr	Zn	Ni	Mn	Fe
Langalanga	0.00	5.1089	-0.63	0.00	0.00	0.00	0.0635	4.4275	4.4600
Maibokati	0.00	4.3517	-1.26	0.00	0.00	0.00	-0.41	3.9357	4.6128
Mayo-Sinna	0.00	0.5327	0.00	0.00	0.00	-5.70	-1.33	-0.1520	2.0911
Quenty Gate	0.00	8.2403	5.4075	0.00	0.00	1.4697	5.8997	13.5628	8.2742
Gidan Kara	0.00	8.3775	5.6756	0.00	0.00	1.7797	5.6797	13.5617	8.2498
Maijankasa	0.00	8.2084	4.8524	0.00	0.00	1.5021	5.3847	13.6304	8.2675
Lambangudu	0.00	8.3574	5.0589	0.00	0.00	1.7640	5.5328	13.6502	8.2760

Table 1 presents Igeo values for nine heavy metals (Cd, Pb, Co, Cu, Cr, Zn, Ni, Mn, and Fe) across seven artisanal and small-scale mining (ASM) sites in Central Taraba State. Cd, Cu, and Cr values are 0.00, indicating that these metals are below detection limits or completely uncontaminated across all sites. Lead (Pb) ranges from 0.5327 (Mayo-Sinna) to 8.3775 (Gidan Kara). All sites except Mayo-Sinna fall into the "extremely contaminated" category ($I_{geo} > 5$). Cobalt (Co) negative values at Langalanga (-0.63) and Maibokati (-1.26) suggest no contamination, while others exceed $I_{geo} = 5$, classifying them as extremely contaminated. Zinc (Zn) was undetected at Langalanga, Maibokati, and Mayo-Sinna. Igeo values at Quenty Gate (1.4697), Gidan Kara (1.7797), Maijankasa (1.5021), and Lambangudu (1.7640) suggest moderate to heavy contamination. Nickel (Ni) presented very high values at most sites (e.g., 5.8997 at Quenty Gate, 5.6797 at Gidan Kara), indicating extreme contamination. Manganese (Mn) and Iron (Fe): Exceptionally high Igeo values at four sites (Quenty Gate, Gidan Kara, Maijankasa, and Lambangudu) all above $I_{geo} = 13$ for Mn and $I_{geo} = 8$ for Fe, indicating severe contamination and potential ecological risks. Mayo-Sinna: Exhibits the lowest Igeo values across all metals, highlighting it as the least contaminated site (Table 1).

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Table 2. The geo-accumulation index (I_{geo}) values for heavy

Metal	Range	Mean	Variance
Cd	0.0000	0.0000	0.0000
Pb	7.8448	6.1681	9.0517
Co	6.9356	2.7292	10.0728
Cu	0.0000	0.0000	0.0000
Cr	0.0000	0.0000	0.0000
Zn	7.4797	0.1165	7.1817
Ni	7.2297	2.9743	11.1144
Mn	13.8022	8.9452	35.8310
Fe	6.1849	6.3188	6.5699

Mn shows the widest range (13.80) and the highest variance, indicating significant differences in contamination between sites. Pb, Co, Ni, and Zn also exhibit large ranges and variances, suggesting considerable spatial variation. Cd, Cu, and Cr have values of zero across all sites, indicating no contamination detected by Igeo. Fe demonstrates a noticeable spread across sites, although it is less pronounced than that of Mn or Ni (Table 2).

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4. DISCUSSION

The findings of this study, which evaluated the spatial variability and ecological risk of heavy metals in soil from artisanal and small-scale mining (ASM) sites in Central Taraba State, provide compelling evidence of environmental contamination across various sites with significant implications for human health and ecosystem sustainability. Utilizing the geo-accumulation index (I_{geo}) approach, the research assessed levels of Cadmium (Cd), Lead (Pb), Cobalt (Co), Copper (Cu), Chromium (Cr), Zinc (Zn), Nickel (Ni), Manganese (Mn), and Iron (Fe) across seven mining locations. The results reveal critical patterns of metal distribution and

intensity of contamination, highlighting certain sites as ecological risk hotspots. From the Igeo data presented in Table 1, it is immediately evident that Cd, Cu, and Cr were below detection limits across all sites, as all their Igeo values stood at 0.00. This suggests either the natural absence of these metals in the geological matrix or effective natural immobilization processes such as adsorption to clay particles or oxides. While their absence minimizes the composite ecological risk, it is important to acknowledge that undetected does not imply insignificant, as their mobilization under altered soil chemistry (e.g., acidic leachates) cannot be ruled out in future environmental assessments. On the other hand, the contamination from Pb, Co, Ni, Mn, Zn, and Fe was notably high, with Igeo values in several sites exceeding the “extremely contaminated” threshold of >5.

Gidan Kara, Maijankasa, Quenty Gate, and Lambangudu emerged as severely contaminated locations with high Igeo values for multiple metals. For instance, Pb at Gidan Kara recorded an Igeo of 8.3775, indicating extreme contamination. This high concentration may be attributed to the local processing of lead-rich ores, smelting residues, and poor tailing management. Lead, a neurotoxic metal, is particularly dangerous due to its persistence in the environment and ability to bioaccumulate in crops and local food chains. Similar extreme lead contamination has been reported in Zamfara State (Aliyu *et al.*, 2021) and Ghanaian mining zones (Bempah *et al.*, 2020), further confirming that uncontrolled ASM operations consistently lead to hazardous lead concentrations in topsoils.

Manganese emerged as the most widely variable and spatially dominant contaminant. With Igeo values exceeding 13 in Lambangudu, Maijankasa, and Quenty Gate, Mn showed the highest range (13.80) and variance (35.83) among all metals studied. These values far exceed normal geochemical background levels and suggest intensive anthropogenic loading, likely from ore beneficiation processes such as washing and grinding. Although Mn is an essential trace element, its elevated presence in soil has been linked to disrupted microbial processes, inhibition of enzymatic soil functions, and toxicity in crops. The findings are in alignment with those of Gideon and Daniel (2023), who reported similar Mn toxicity patterns in North-Central Nigeria. The implications for human health are also concerning, as Mn overexposure has been linked to neurodevelopmental disorders in children and cognitive deficits in adults.

Nickel and cobalt were also significantly elevated across sites, with Igeo values reaching 5.8997 and 5.6756 respectively at Quenty Gate and Gidan Kara. These values place both metals in the extremely contaminated category. Given their occurrence in sulfide-rich ores often mined for gold or polymetallic content, the high values may be linked to ore roasting or leaching processes common in informal mining settings. Both metals are known to induce oxidative stress in plants and are potentially carcinogenic to humans when ingested through contaminated water or crops. Ezeaku and Davidson (2023) emphasized that ASM zones lacking tailings dams or leachate control systems often become sources of persistent Co and Ni pollution, corroborating the findings of this research.

Zinc, while less ubiquitous, demonstrated moderate to heavy contamination at Maijankasa, Quenty Gate, Gidan Kara, and Lambangudu, with Igeo values between 1.47 and 1.77. These values fall within the “moderately to heavily contaminated” range. Although zinc is an essential

micronutrient, excessive concentrations can alter microbial nitrogen fixation and suppress crop yields. Spatial variability in Zn distribution reflects both lithogenic factors and site-specific anthropogenic inputs, such as discarded batteries or smelting waste. The selective presence of Zn in certain locations suggests localized pollution sources rather than background enrichment. This pattern is consistent with the findings of Okoro *et al.* (2021), who noted that zinc contamination in Nigerian mining sites often coincides with gold tailings and ore concentration residues.

Iron, though a naturally abundant soil element, also showed extreme contamination in several locations, with Igeo values as high as 8.2760 in Lambangudu. While iron is less toxic compared to other metals, its high levels may interfere with soil redox conditions and microbial activities, particularly in waterlogged or low-pH environments. Excessive iron can hinder the uptake of phosphorus and other micronutrients, leading to soil fertility imbalance. The elevated iron values also serve as indicators of the degree of soil disturbance caused by ASM activities, especially where iron-bearing rocks are exposed and processed without environmental safeguards.

In sharp contrast to the other sites, Mayo-Sinna recorded the lowest Igeo values across all metals. With Pb at 0.5327, Mn at -0.1520, and Fe at 2.0911, the site appears to be uncontaminated to only slightly contaminated. This stark difference suggests limited mining activity or effective natural attenuation processes in this location. The lower contamination levels at Mayo-Sinna underscore the strong correlation between mining intensity and heavy metal pollution levels. It may also reflect better vegetation cover, soil structure, or distance from tailings dumps, as suggested in the spatial assessments of Ali *et al.* (2022). Mayo-Sinna can therefore serve as a reference or control site for long-term ecological monitoring in the region.

Statistical trends presented in Table 2 further strengthen the interpretations derived from Table 1. The high variance in Mn (35.83), Ni (11.11), and Co (10.07) indicates significant spatial heterogeneity, which is characteristic of ASM-impacted landscapes. The findings validate the assertion by Suleiman *et al.* (2024) that artisanal mining introduces intense but spatially localized metal contamination patterns, often influenced by topography, proximity to processing units, and tailings disposal methods. Moreover, the zero mean and variance for Cd, Cu, and Cr in Table 2 reinforce their non-detection and negligible ecological impact within the context of this study.

The ecological and human health risks posed by the contamination patterns observed are significant. Chronic exposure to Pb, Ni, Co, and Mn through inhalation of dust, ingestion of soil particles, or consumption of contaminated crops and water has been associated with various health conditions, including cancer, kidney dysfunction, and developmental disorders. The cumulative presence of multiple heavy metals may also lead to synergistic toxicity effects, amplifying their harmful impacts. The unregulated nature of ASM activities in Central Taraba State exacerbates these risks, especially in the absence of protective legislation or remediation infrastructure.

In terms of policy and environmental management, the findings of this study highlight the urgent need for integrated mitigation strategies. These include enforcement of environmental impact assessments before mining, the creation of community-managed waste containment systems, and the implementation of phytoremediation programs using metal-accumulating plants. The success of such initiatives has been demonstrated in other parts of Nigeria and Ghana, where community-led soil restoration projects have significantly reduced metal concentrations over time (Omoregie *et al.*, 2022; Yusuf *et al.*, 2023). Furthermore, there is a pressing need to raise awareness among miners and local populations about the long-term risks of metal pollution and promote safer mining practices through training and incentives.

5. CONCLUSION

In conclusion, the geo-accumulation index analysis conducted in this research clearly identifies Quenty Gate, Gidan Kara, Maijankasa, and Lambangudu as environmental hotspots with extreme heavy metal contamination. These findings emphasize the ecological vulnerability of Central Taraba State's mining zones and the critical need for immediate remediation and regulatory intervention. The results serve not only as a scientific basis for policy development but also as a call to action for stakeholders including government agencies, academic institutions, and local communities, to collaborate in mitigating the adverse impacts of artisanal mining. Ultimately, this study contributes to a broader understanding of the environmental dynamics of heavy metal pollution in sub-Saharan Africa and offers a framework for future assessments and sustainable land use planning.

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