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Mapping heavy metal contamination in soils around Ikpeshi marble mining sites in Southern Nigeria using the regression kriging spatial prediction approach

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Abstract

Determining the geospatial distribution and level of heavy metals (HMs) pollution in the soil is crucial for the management and restoration of heavy metal-polluted soils around mining sites. This study analyzed the content of heavy metals (HMs) such as arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), manganese (Mn), nickel (Ni), zinc (Zn), and iron (Fe) in soils around the Ikpeshi marble mining sites in Southern Nigeria. The degree of contamination and several pollution indices, including enrichment, contamination, and geo-accumulation index, were calculated to assess the soil contamination level around the marble-mining sites. Average concentrations of As, Cd, and Cu exceeded Clarke's and crustal values, indicating significant contamination near mining sites. Cd ranged from 0.01–12.8 mg kg^{-1} (mean 4.7 mg kg^{-1}), and Cu from 0.09–84.6 mg kg^{-1} (mean 31.0 mg kg^{-1}). Metal concentrations decreased with distance from mining activities, confirming their anthropogenic origin. Overall, soils were highly to extremely contaminated with Cd, highly contaminated with Cu and As, moderately contaminated with Pb and Zn, and uncontaminated with Fe, Ni, and Mn. Contamination ranked as Cd > Cu > As > Pb > Zn > Fe > Ni > Mn. This study offers a strong scientific foundation for the clean-up and management of heavy metal-contaminated soils in marble mining regions of Nigeria.

Keywords: Soil contamination; pollution indices; concentration maps; mining sites; Southern Nigeria

Introduction

Exploiting mineral deposits offers job opportunities to the local communities and makes a substantial contribution to the local economy. However, the discharge of several air, water, and soil contaminants as illustrated in Figure 1 taints this significant activity. Mining extraction and processing release heavy metals into surrounding soils (Wang *et al*., 2020; Zhang *et al*., 2023), which may accumulate in crops and livestock (Nwankwoala *et al*., 2023) and pose serious ecological and health risks. For instance, exposure to Pb can lead to neurological damage, especially in children, causing developmental issues, learning disabilities, and behavioural problems. It can also affect adults, leading to high blood pressure, kidney damage, and reproductive problems. Exposure to As is linked to various health problems, including skin lesions, cardiovascular diseases, diabetes, and an increased risk of certain cancers, such as skin, lung, bladder, and kidney cancer (Zheng *et al*., 2020). It is important to note that the severity of the health risks depends on the level and duration of exposure to these heavy metals (Unuevho *et al*., 2021; Al-Raad and Hanafiah, 2022).

Due to the harmful effects that HMs have on human health and the environment, as well as the possibility that mining sites may release these pollutants, it is essential to monitor and regulate mining sites, particularly if they are close to densely populated areas or sensitive habitats (Amadi *et al*., 2020; Vuong *et al*., 2023). The spatial distribution of HMs in soil can vary depending on factors such as the type of mining activity, the composition of the

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ore, and the surrounding environment. Typically, the highest concentrations of HMs are found in close proximity to the mining sites or areas where mineral processing takes place. However, wind and water can also transport these metals over longer distances, leading to contamination in nearby regions. It is important to conduct thorough soil testing and monitoring to assess the extent of heavy metal contamination and implement appropriate remediation measures (Udoh and Amadi, 2020; Bhuiyan *et al*., 2021).

To determine the probable origins of soil HMs contamination, a number of techniques have been used, including principal component analysis (Yang *et al*., 2020, Nwankwoala *et al*., 2022), positive matrix factorization (Bhuiyan *et al*., 2021), and UNMIX modelling (Tan *et al*., 2020). It is necessary to clarify the equivalent pollution level resulting from various heavy metals (HMs) from various sources in addition to identifying the sources of metals. HMs pollution indices are commonly used to assess and quantify the level of HMs pollution in a given area. They take into account various factors such as the concentration of heavy metals in soil or water, the potential health risks associated with these metals, and the environmental impact (Banch *et al*., 2019). Common indices include the Pollution Load Index (PLI), the Contamination Factor (CF), and the Potential Ecological Risk Index (PERI). These indices help researchers and environmental agencies understand the severity of heavy metal pollution and prioritize remediation efforts (Cheng *et al*., 2007). They're valuable tools for monitoring and managing environmental quality.

The Geoaccumulation Index (I_{geo}) is another important index used to assess HMs pollution in soil. It measures the degree of contamination by comparing the current concentration of a particular HM with its background concentration. The index ranges from 0 (no pollution) to 6 (extremely polluted). By analysing the I_{geo} values for different metals, researchers can determine the pollution level and potential ecological risks associated with heavy metal contamination in a specific area (Ackah, 2019; Zakari *et al.,* 2021). It's a useful tool in evaluating the impact of HMs on soil quality.

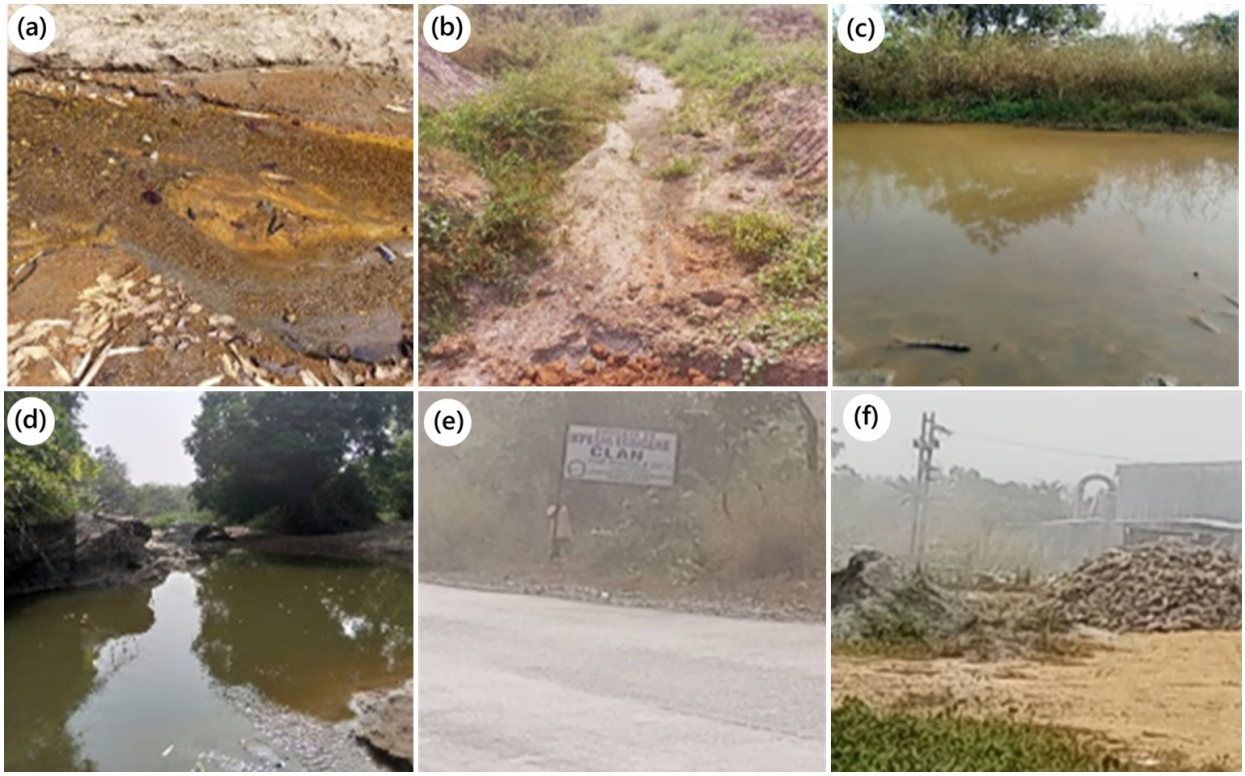


Figure 1: Images showing physical features of around Ikpeshi mining sites in the study area (a) contaminated soil, (b) degraded soil, (c) and (d) contaminated rivers, and rock dust arising from (e) blasting operations, and (f) milling operations

Marble mining is a common practice in Southern Nigeria. As a result of miners' attention being drawn primarily to the main deposits of interest and with little to no consideration for the environment and public health, a significant number of heavy metals (HMs) and other various toxic by-products are released into the surrounding environment (Harun *et al.,* 2025; Agoha *et al*., 2021). For instance, as seen in Figure 1(e), between March and June 2010, at least 163 persons, including 111 children, tragically died as a result of exposure to rock dust during rock milling, crushing, and other related hazardous practices. A comparable incident took place in Niger State's Rafi Local Government Area, where at least 28 children under the age of five were officially declared dead. The two scenarios (Adeoti and Okonkwo, 2016; Adepoju and Asiwaju-Bello, 2021) were ascribed to significant environmental contamination resulting from informal processing of lead-rich ore. Consequently, the Ikpeshi marble mining sites in Southern Nigeria were chosen as the study region. There, 45 soil samples were taken in order to determine the presence of heavy metals (HMs) including As, Cd, Cu, Pb, Mn, Ni, Zn, and Fe. The assessment of soil pollution in a region was carried out using environmental pollution indices, such as the elemental contamination index, degree of contamination, contamination factor, index of geo-accumulation, and metal pollution index.

Exploiting mineral deposits offers local communities job opportunities and makes a substantial contribution to the local economy. However, the discharge of several air, water, and soil contaminants, as illustrated in Figure 1, taints this significant activity. For instance, in mining areas, the extraction and processing of minerals can release heavy metals into the soil (Wang *et al*., 2020; Zhang *et al*., 2023). These metals can enter the food chain, affecting crops and livestock (Nwankwoala *et al*., 2023), and pose significant risks to human health and the environment. Despite the well-documented impacts of mining activities on environmental pollution and human health globally, there is a notable lack of research on the specific environmental and health risks associated with marble mining in Southern Nigeria. This knowledge gap is particularly concerning, given the severity of incidents related to informal mining practices in the region (Adeoti and Okonkwo, 2016; Adepoju and Asiwaju-Bello, 2021). Therefore, this study examined the level of heavy metal pollution in soils surrounding the Ikpeshi marble mining sites and evaluate the associated environmental and health risks.

In addition, concentration maps were constructed for fascinating visual representations of the distribution of HMs across the study area. This is necessary to establish the pollution level soils arising from the age long mining and blasting operations and unravel the pollutants.

Given the severity of these incidents, it is hypothesized that the Ikpeshi marble mining sites in Southern Nigeria are significantly contaminated with heavy metals, posing a

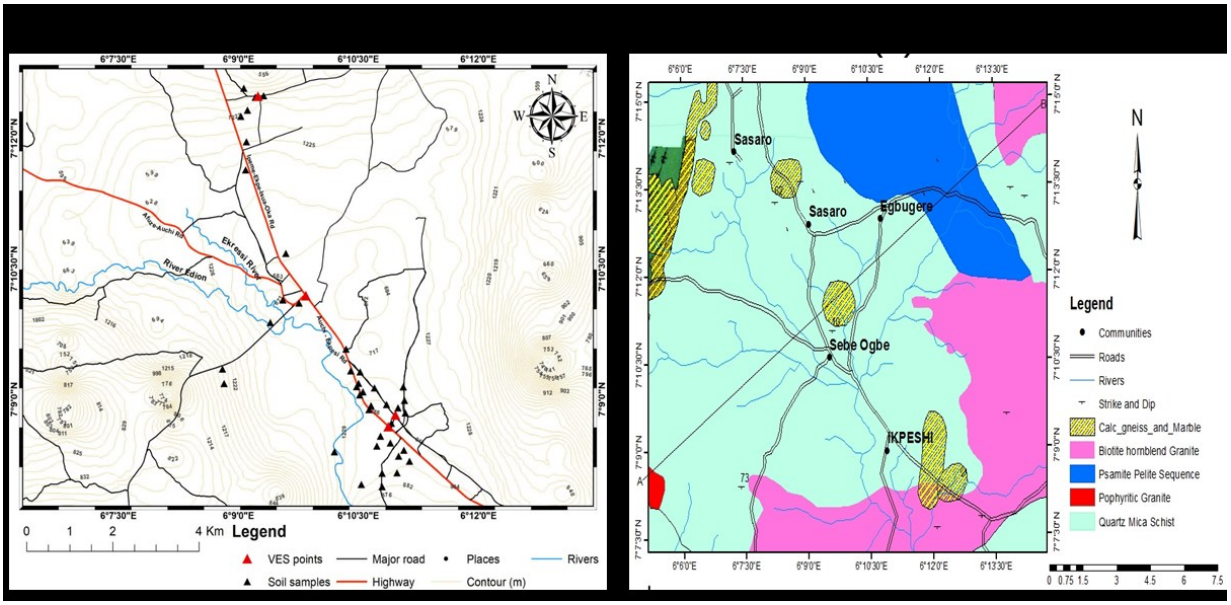


Figure 2: (a) Map showing the soil sampling location in the study area, and (b) Geology map of Ikpeshi and environs

substantial risk to the environment and public health. This study hypothesizes that the soils surrounding the Ikpeshi marble mining sites are heavily contaminated with heavy metals, exceeding permissible limits and posing significant environmental and health risks. The key objectives of this study are to assess the level of heavy metal pollution in the soils surrounding the Ikpeshi marble mining sites and evaluate the associated environmental and health risks. To achieve this, 45 soil samples were analyzed for the presence of heavy metals (HMs), including As, Cd, Cu, Pb, Mn, Ni, Zn, and Fe. The study utilized environmental pollution indices, such as the elemental contamination index, degree of contamination, contamination factor, index of geo-accumulation, and metal pollution index, to determine the pollution level and identify the key pollutants.

Materials and Methods

Study area description

Ikpeshi mining site in southern Nigeria as shown in Figure 2(a) was selected as a study area. The geological map of the study area is displayed in Figure 2(b). It's an interesting place known for its rich mineral deposits. The site is located in Edo State, Nigeria, and is famous for its significant reserves of limestone, marble, and other minerals. Figure 2 shows the samples of marble collected from study area. The mining activities in Ikpeshi have contributed to the local economy and provided employment opportunities for the community. The limestone extracted from the site is used in various industries, including cement production. It is accessible through the Auchi-Ibilo Expressway and lies between latitude 7°06′ N to 7°11′ N of the Equator and longitude 6°08′ E to 6°15′ E of Greenwich Meridian.

Geology of the study area

Ikpeshi and its surrounding falls within the Igarra Schist Belt of Southwestern Nigeria and the major rocks in the study area comprised of schist, granite and marble (Figure 2c). The granites around Ikpeshi are coarse-grained and it has one of the largest marble deposits in Nigeria (Ailegbo *et al*., 2021).

Sample collection, preparation and analysis

For the current investigation, a total of forty-five (45) soil samples were obtained. In polythene bags, 40 samples from the area around the mining sites and 5 control samples were gathered 50 meters away from the sites (Figure 1a). Each 50 cm^3 digestion tube contained 2 g of ground sample and 10 cm^3 of aqua regia (a mixture of HCl and HNO_3 in a 3:1 ratio). The programmable digestion block was then set to gradually increase from 75 °C (30 min) to 110 °C (60 min) and finally 140 °C (40 min). To make sure the digestion processes were moving along smoothly, the procedure was tested every 20 minutes within these temperature and time ranges.

After the digestion, tubes were removed from the block and allowed to cool at room temperature. 25 cm^3 of 0.1 % of HNO_3 were mixed with a vortex stirrer. The mixture was then transferred to a 50 cm^3 centrifuge tube, sealed, and centrifuged for 15 minutes at 1500 revolutions per minute. The sample was prepared in compliance with the USEPA (2016) standard for metal analysis. In order to prepare for microwave plasma atomic emission spectrometry (MP-AES) at Usmanu Danfodio University's central laboratory in Sokoto, Nigeria, 10 cm^3 of the digested solution was decanted. Agilent MP-AES outperform traditional atomic absorption spectroscopy (AAS) in terms of sensitivity, speed, and lower detection limits (down to sub-ppb levels). To achieve high precision, the analytical procedures were performed three times, with the average value being used.

To ensure the accuracy and precision of the analytical results, the following quality control measures were implemented:

a. Triplicate analysis: The analytical procedures were performed in triplicate to ensure high precision.

b. Blank and standard samples: Blank and standard samples were included in each batch of analysis to ensure accuracy.

c. Instrument calibration: The MP-AES instrument was calibrated regularly to ensure optimal performance.

The following pollution assessment indices were used to evaluate the level of heavy metal contamination in the soil:

a. Geo-accumulation index (Igeo): This index was used to quantify the heavy metal pollution in the soil.

b. Contamination factor (Cf): This index was used to evaluate the quantity and quality of anthropogenic heavy metal deposition on the soil.

c. Pollution load index (PLI): This index was used to assess the degree of heavy metal contamination in the soil.

d. Enrichment factor (EF): This index was used to differentiate between anthropogenic and natural sources of heavy metal contamination in the soil.

The data was analysed using statistical methods, including descriptive statistics and correlation analysis. The repeatability of the analytical results was determined using the t-test with a 95% confidence interval (CI). The geographic distributions of the heavy metals were mapped using the regression kriging (RK) spatial prediction approach. The mapping exercise yielded results that allowed for the identification of areas where the environment or human health are at risk due to heavy metal deposition.

Pollution assessment

Geo-accumulation index (Igeo)

The I_{geo} proposed by Muller (1969) was applied to quantify the HMs pollution in soil around Ikpeshi mining sites. The I_{geo} for the soil samples was calculated using the Eq. (1).

$$I_{geo} = \log_2 \left[\frac{C_n}{1.5B_n}\right] \qquad (1)$$

where B_n is the metal's background value, C_n is the concentration of the metal found in soil samples from the Ikpeshi mining sites, and 1.5 is the background matrix correction based on lithological effects.

Contamination factor (C_f^i)

The contamination factor is the ratio of a certain heavy metal concentration in a soil sample to its reference value, which is usually the metal's concentration prior to industrialization (Hakanson, 1980). The C_f^i was computed using the formula provided in Eq. (2).

$$C_f^i = {C^i}/{C_n^i} \qquad (2)$$

where C_n^i is the typical pre-industrial reference level of HMs (mg kg^{-1}) Pb = 70; Cd = 1.0; Cr = 90; Cu = 50; Zn = 175; As = 15.0; Ni = 68; Mn = 850 (Hakanson, 1980; Rahman *et al*., 2022) and C_f^i is the observed concentration of HMs in soil samples.

Pollution load index (PLI)

The *PLI* of the Ikpeshi mining sites was calculated using Eq. (3). PLI can be obtained from the n-root from the n-CFs that were determined for the HMs (Thomlinson *et al*., 1980).

$$PLI = \sqrt[n]{(C_{f1} \times C_{f2} \times C_{f3} \times \cdots\cdots\cdots\cdots \times C_{fn})} \qquad (3)$$

where *n* is the concentration of studied metals and C_f is the contamination factor, as mentioned in the prior condition (Eq. (3)). The PLI provides a straightforward but sensible method for assessing the quality of a site. An estimation of PLI < 1 means perfection; PLI = 1 indicates that only baseline levels of contaminants are known; and PLI > 1 would indicate a worsening in site quality.

Enrichment factor

Based on the work of Mokhtarzadeh *et al*., (2020) enrichment factors (EFs) were calculated using the Eq. (4) to determine the extent of contamination of soil in Ikpeshi mining sites with heavy metals.

$$EF = \frac{\left(\frac{C_i}{C_{ref}}\right) sample}{\left(\frac{C_i}{C_{ref}}\right) background} \qquad (4)$$

Where C_i denotes the targeted metal concentration in the soil, and C_{ref} is the reference metal (As) concentration.

Comparison with average crustal value

The laboratory analysis results were contrasted with the average crustal value for each element found in Wedepohl (1995) and Taylor and McLaennan (2001). This is due to the fact that soils are the result of upper crustal rocks weathering, and Wedepohl, Taylor and McLaennan employed the upper continental crust background values in their postulation. In addition to other climatic and human influences, distinct rock types give rise to diverse soil types, which is how soils get their bearings.

Statistical analysis

The data was collected for triplicate samples to reduce the chances of errors. The repeatability was determined using t-test with a 95% confidence interval (CI). The data was summarized, and the mean values and standard deviation were reported.

Spatial distribution prediction

The geographic distributions of the HMs were mapped using the regression kriging (RK) spatial prediction approach

using ArcGIS 10.8. The mapping exercise that we conducted for our study yielded results that allowed us to identify places where the environment or human health are at risk due to heavy metal deposition. We applied evaluation thresholds to every map in order to identify the locations that are at risk due to elevated concentrations of heavy metals. Regardless of the origin, soil covers with element concentrations above the thresholds are displayed. In our delineation, elevated quantities of harmful substances observed in topsoil that is likely of being

Table 1: Mean values of HMs concentration, their comparison with Clark's value and contamination status of the soil

HMs	HMs concentration (mg kg^{-1})			Comparison with Clarks' value and literature			Contamination Status
	Min	Max	Mean	Clarke's Value	Wedepohl (1995)	Taylor and McLennan (2001)	
Cadmium	0.01	12.83	4.71	0.1	0.01	0.98	Very high
Iron	0.25	199.54	88.71	35,000.0	30890.0	37,000.0	Low
Copper	0.09	84.56	31.03	25.0	14.3	25.0	Very high
Nickel	0.01	9.88	3.63	44.0	18.6	20.0	Low
Manganese	0.12	109.82	40.36	600.0	527.0	600.0	Low
Lead	0.04	34.67	13.72	17.0	17.0	20.0	High
Zinc	0.15	130.74	47.98	71.0	52.0	71.0	High
Arsenic	0.01	4.05	1.52	1.5	0.06	0.05	Very high
pH	5.4	7.9	6.3	—	—	—	—

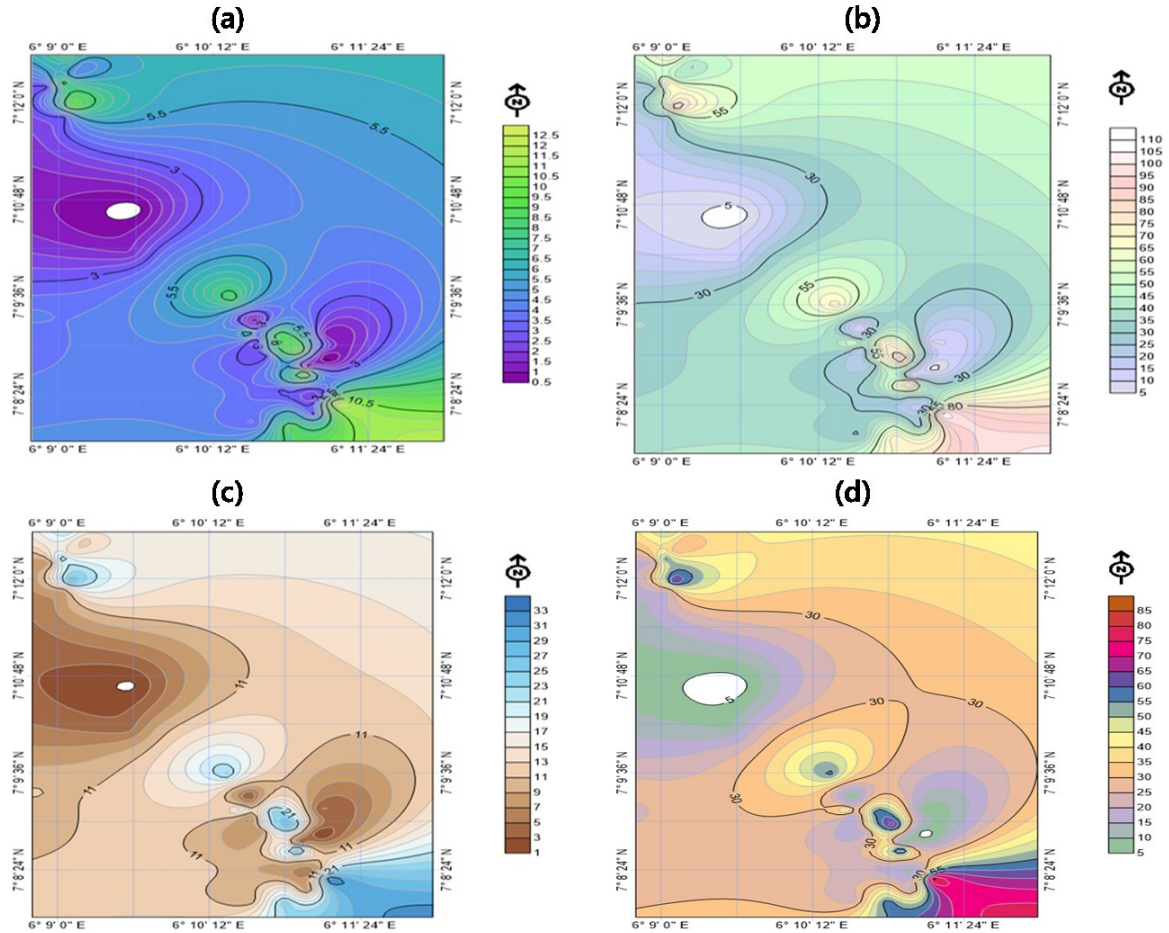


Figure 3: Maps showing concentration of heavy metals in soil of Ikpeshi and environs (a) Cadmium, (b) Manganese, (c) Lead, and (d) Copper

polluted, as well as the naturally occurring normal values (background concentrations), are treated equally.

This study highlights the importance of integrating spatial analysis with land-use planning and management strategies to effectively manage heavy metal pollution in mining areas. The study also proposes a comprehensive approach that incorporates risk assessment mapping, zoning regulations, remediation requirements, and stakeholder engagement to mitigate environmental and health risks.

Results and Discussion

Heavy metals concentration in the soil

Mining activities are a major source of soil HM pollution, posing serious environmental and health risks (Akoto, 2023; Han *et al*., 2023; Hoque *et al*., 2023; Haghighizadeh *et al*., 2024). Eight HMs (Mn, Cd, Pb, Cu, Zn, Ni, As, and Fe) were analyzed in 45 soil samples collected from the Ikpeshi mining area in Southern Nigeria, considering the site's lithologic characteristics. The minimum, maximum, and mean concentrations of these metals are presented in Table 1.

The mean concentrations of Cd (4.7 mg kg^{-1}), As (4.0 mg kg^{-1}), and Cu (31.0 mg kg^{-1}) exceeded the average crustal abundances reported by Wedepohl (1995), Taylor and McLennan (2001), and Clarke's value, indicating significant enrichment in the study area. These metals likely originated from host-rock weathering and dissolution, followed by migration into the surrounding soils, surface water, and groundwater (Adnan *et al*., 2022; Wang *et al*., 2025). Other HMs showed mean values below their respective crustal abundances. Cd levels were notably higher than those reported by previous studies (Wedepohl, 1995; Taylor and McLennan, 2001), signifying severe contamination near the marble-mining zone.

As illustrated in Figure 3(a), Cd concentrations were highest near the mining sites and declined with distance, confirming the influence of mining activities. The slightly acidic soil pH (5.4; Table 1) likely enhanced Cd solubility and mobility (Chaanda *et al*., 2019; Flores *et al*., 2021), resulting in greater accumulation in the northeastern and southeastern zones that coincide with the active marble mines. Similar spatial Cd enrichment near mining sites has also been observed in recent investigations in Ghana and India (Akoto, 2023; Hoque *et al*., 2023).

Manganese concentrations ranged from 0.1 to 109.8 mg kg^{-1} (mean = 40.4 mg kg^{-1}), below crustal reference values (Wedepohl, 1995; Taylor and McLennan, 2001), indicating no Mn contamination. Mn adsorption varies with temperature, pH, cation-exchange capacity, and organic matter (Duarte *et al*., 2019; Casagrande *et al*., 2020; Nurul *et al*., 2020). As shown in Figure 3(b), Mn concentration slightly increased near the mining zones despite remaining below crustal levels.

Lead concentrations were highest around the mining sites, exceeding the reference limits set by Wedepohl (1995) and Taylor and McLennan (2001). Elevated Pb levels are attributed to the weathering of galena (PbS) and its migration into nearby soils. Pb solubility is influenced by soil pH (5.4–7.9) and organic matter content: higher pH favors Pb-carbonate formation or adsorption on clay, while near-neutral pH promotes organo-lead complexation (Beulah *et al*., 2021; Amaral *et al*., 2021). The Figure 3(c) map confirms greater Pb contamination near mining sites compared to control locations, consistent with other global mining regions (Hokonya *et al*., 2022; Haghighizadeh *et al*., 2024).

Copper concentrations were also elevated, with mean values exceeding Clarke's value (25.0 mg kg^{-1}) and crustal abundances, indicating Cu contamination of nearby soils. Figure 3(d) identifies the mining sites as Cu hotspots. Weathering of Cu-bearing rocks and dissolution processes likely contributed to this enrichment. Chronic exposure to elevated Cu can cause pulmonary oedema, lung carcinoma, and transient fever. Mafic rocks generally contain more Cu than felsic types, explaining higher crustal Cu content in the area (Nurul *et al*., 2020; Amadi *et al*., 2020). The silty-sand texture of the soil promotes permeability and facilitates metal transport, while slightly low pH enhances Cu release from parent rocks. Similar Cu distribution trends near mining sites were recently reported by Akoto (2023) and Vuong *et al*. (2023).

Figures 4(a–d) display the spatial distributions of Zn, Ni, As, and Fe, which show patterns similar to those of Cd, Mn, Pb, and Cu, indicating elevated HM concentrations near the marble-mining zones. Both the spatial maps and measured concentrations confirm mining as the dominant HM source in the study area. Recent global analyses also found analogous contamination trends in soils near mine tailings and quarry zones (Adnan *et al*., 2022; Haghighizadeh *et al*., 2024; Wang *et al*., 2025).

Overall, although the origin of HMs in soil remains the same, their enrichment levels vary according to metal mobility, pH, organic matter, and soil structure (Obiora *et al*., 2016; Amadi *et al*., 2017). Arsenic mobility increases under higher pH and lower redox conditions when As(III) predominates (Obiora *et al*., 2016). Iron occurs mainly as Fe^{3+} (oxidized, insoluble) and Fe^{2+} (reduced, soluble); its distribution reflects the geochemical background and mining impact. The elevated Fe content in sediments likely results from iron-stained soil being leached and transported by water movement (Han *et al*., 2023; Haghighizadeh *et al*., 2024).

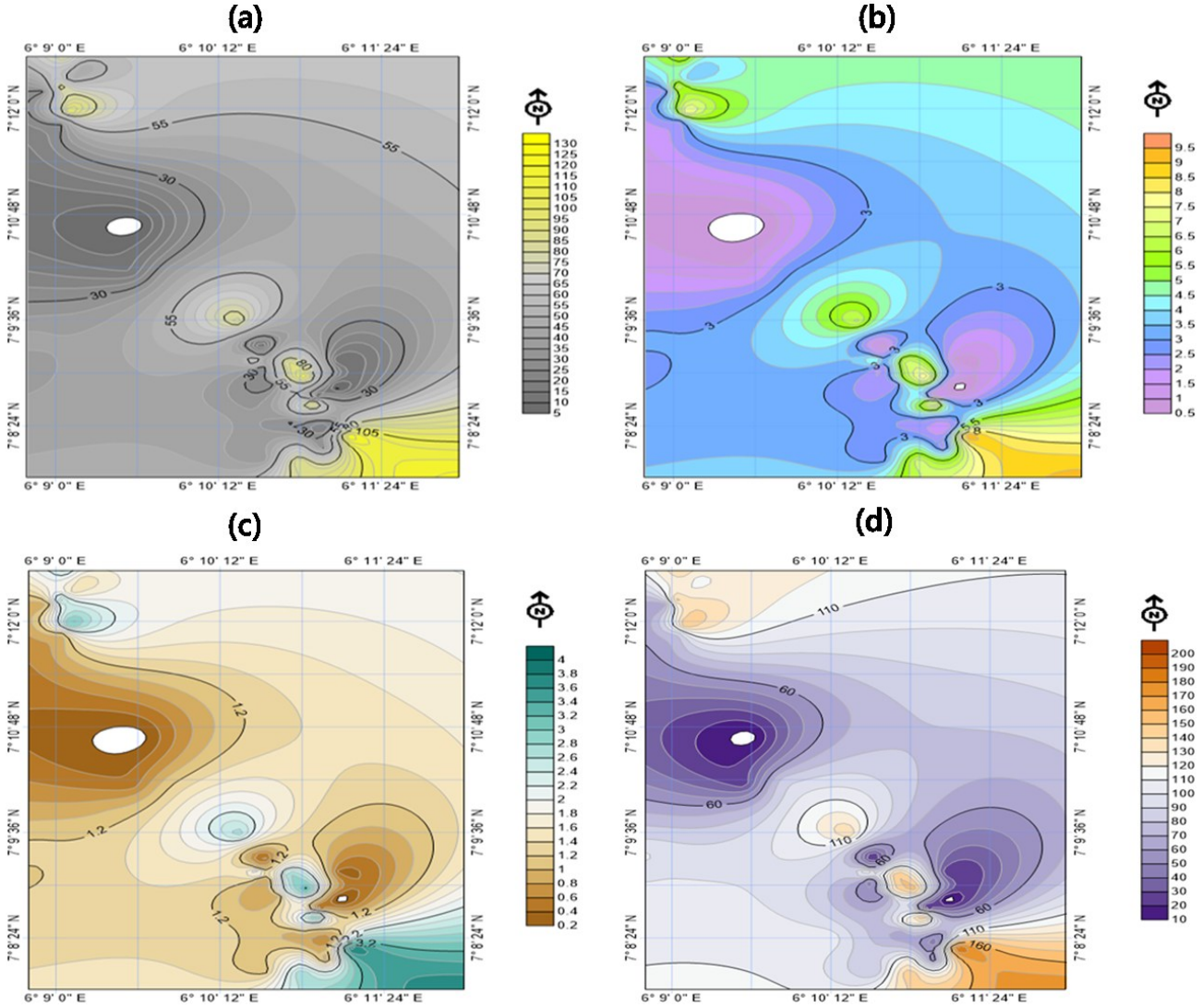


Figure 4: Maps showing concentration of heavy metals in soil of Ikpeshi and environs (a) Zinc, (b) Nickel, (c) Arsenic, and (d) Iron

Table 2: Classification of geo-accumulation index (I_{geo}), categorization of enrichment factor (EF), and grouping of contamination factor (CF) of the heavy metals' concentration in soil of the study area

HMs	I_{geo}	Pollution Intensity	EF value	Enrichment Intensity	CF value	Contamination Intensity
Cadmium	4.25	Strongly to extremely polluted	25.40	Very severe enrichment	6.15	Very high contamination
Iron	0.21	Unpolluted to moderately Polluted	0.65	No enrichment	0.40	Low contamination
Copper	4.18	Strongly to extremely polluted	13.24	Severe enrichment	4.28	Considerable contamination
Nickel	0.24	Unpolluted to moderately Polluted	0.78	Minimal enrichment	0.48	Low contamination
Manganese	0.16	Unpolluted to moderately Polluted	0.43	Minimal enrichment	0.51	Low contamination
Lead	2.24	Moderately to strongly polluted	3.40	Moderate enrichment	1.75	Moderate contamination
Zinc	2.16	Moderately to strongly polluted	2.86	Minor enrichment	1.80	Moderate contamination
Arsenic	4.12	Strongly to extremely polluted	12.87	Severe enrichment	4.15	Considerable contamination

According to (Sutherland, 2000 and cited in Obiora *et al*., 2016): The classification of EF: EF < 1 indicates no enrichment, EF < 3 is minor enrichment, EF = 3–5 is moderate enrichment, EF = 5–10 is moderately severe enrichment, EF = 10–25 is severe enrichment, EF = 25–50 is very severe enrichment, and EF > 50 is extremely severe enrichment. According to (Hakason, 1980 and cited in Amadi *et al*., 2017): CF<1 low contamination; 1≤CF<3 moderate contamination; 3≤CF<6 considerable contamination; CF≥6 very high contamination.

Soil pollution assessment

Geo-accumulation index

In order to evaluate the degree of soil contamination within the vicinity of the mining sites, geo-accumulation index (I_{geo}) was computed for each of the analyzed heavy metals using the Eq. (1). The accumulation index (I_{geo}) values and related description is given in Table 2. According to Muller (1979), the soil can be classified as follows based on the geo-accumulation index: i) $I_{geo} > 5$ = extremely polluted, (ii) $I_{geo} = 4–5$ = strongly to extremely polluted, (iii) $I_{geo} = 3–4$ = strongly polluted, (iv) $I_{geo} = 2–3$ = moderately to strongly polluted, (v) $I_{geo} = 1–2$ = moderately polluted, (vi) $I_{geo} = 0–1$ = unpolluted to moderately polluted, and (vii) $I_{geo} < 0$ = practically unpolluted. The results in Table 2 showed that the soil surrounding marble mining areas was strongly to extremely polluted with As, Cd, and Cu indicated by their I_{geo} values of 4.12, 4.25 and 4.18, respectively. The soil was moderately to strongly polluted with Pb and Zn exhibiting I_{geo} values of 2.24 and 2.16, respectively, while Fe, Ni, and Mn were determined to be unpolluted.

Enrichment factor

An efficient method for differentiating between anthropogenic and natural sources of HMs contamination in soil is the enrichment factor (EF). Eq. (4) was used in this investigation to estimate the EF for the chosen HMs, and the results are shown in Table 2. The fact that the EF for Cd, Cu, Pb, Zn, and As is more than 1 suggests that human activity, as opposed to natural sources, is the cause of the HM contamination in the soil (Morillo *et al*., 2004). It's interesting to note that the soil near mining sites exhibited extremely severe enrichment in Cd, Cu, and As. It has been demonstrated that the pH and volume of incoming contaminated water affect the enrichment of Cd and Pb in soil (Hokonya *et al*., 2022). Estimating the amount of effluent from mining sites is therefore desirable and requires research in order to ascertain the soil's capacity to enrich heavy metals. Pb displayed low enrichment while HMs like Ni and Mn showed minor enrichment. This implies that the enrichment phenomenon in the soil in relation to the earth's crust may be caused by mining operations, as indicated by all of the HMs exhibiting extremely severe enrichment. Thus, the EF (25.40) found in the current study clearly indicates a high degree of Cd pollution in the soil surrounding Ikpeshi mining sites.

Contamination factor

Another significant metric that is employed in the current study to evaluate the quantity and quality of anthropogenic heavy metal (HM) deposition on the soil surrounding Ikpeshi mining sites is the contamination factor (CF). According to Table 2, the soil has extremely high levels of Cd contamination, significant levels of Cu and As contamination, moderate levels of Pb and Zn contamination, and low levels of Fe, Ni, and Mn contamination.

Pollution load index

The pollution load index (PLI) was used to assess the degree of HMs contamination in the soil of Ikpeshi mining sites. This index is a convenient tool for comparing the levels of pollution in various locations. The list as presented provides a fundamental and applicable framework for evaluating a region: A score of zero indicates perfection, and a score of one indicates the availability of only benchmark amounts of HMs. On the other hand, multiple characteristics would indicate the site's dynamic collapse and the soil quality (Rahman *et al*., 2022). According to this study, the mean PLI value for eight distinct HMs was 1.15, which suggests that, given the HMs under investigation, there is now a high amount of pollution at the Ikpeshi mining sites. Consequently, continuous monitoring ought to be necessary to more accurately ascertain the PLI driven by HMs contamination as a result of dust and other particular procedures.

Degree of contamination

The degree of contamination (CD), which represents the overall current level of heavy metal contamination, was determined by calculating the contamination factor of all metals in a sample. This would yield an estimate of the total level of contamination in the surface layers at a certain sampling location. CD can be divided into four categories of contamination which are as follows: (i) $Cd < 6$: low degree, (ii) $6 \leq Cd < 12$ moderate, (iii) $12 \leq Cd < 24$: considerable and (iv) very high degree. The matching values of 30.25 were obtained by adding up the contamination factors found in Table 4. According to the estimated value, these results are within the very high degree of contamination class. The level of metal pollution indicates that the soil surrounding the Ikpeshi marble mining sites is heavily contaminated with metals.

Visualization of soil contamination

The contamination map for the study area (Ikpeshi marble mining sites) as shown in Figure 5 was produced using the results of the calculated environmental pollution indices. The degree of contamination determined the four categories for the area. Cadmium dominates the very high contamination region, copper and arsenic the high contamination area, lead and zinc the moderate

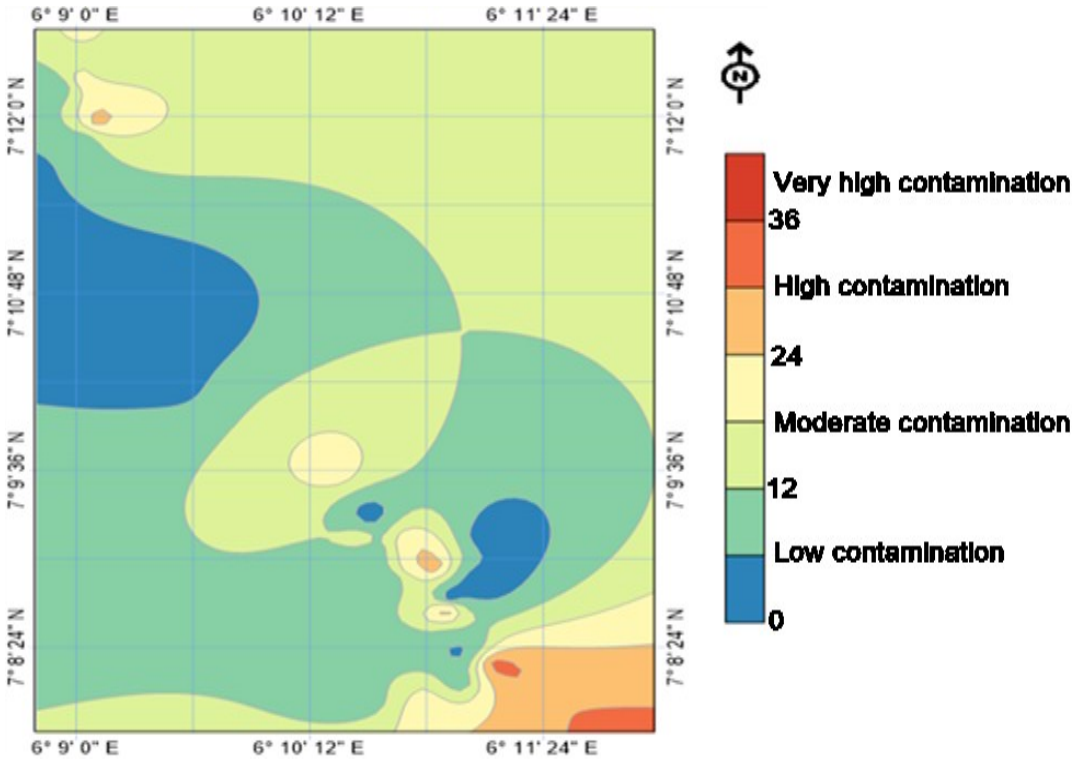


Figure 5: Map showing the soil contamination level in the Ikpeshi marble mining sites

contamination zone, and iron, nickel, and manganese the low contamination area. The elements concentration maps (Figures 3 and 4) and the environmental calculated indices (Tables 2) agree with the study area contamination level map.

To effectively mitigate heavy metal pollution in the Ikpeshi mining area, a multifaceted approach is necessary. The following remediation measures can be considered:

a. Phytoremediation: Plant species selection: Identify and cultivate hyperaccumulator plant species that can absorb and tolerate high levels of heavy metals like Cd, Cu, and As. In parallel, employ phytostabilization techniques using vegetation to immobilize heavy metals in the soil, thereby reducing their bioavailability and leaching potential.

b. Soil Amendments: Beyond plant-based strategies, soil amendments can also be employed. Adding organic matter such as compost, manure, or biochar can improve soil structure, increase cation exchange capacity, and reduce heavy metal mobility.

c. Liming: Apply lime to increase soil pH, thereby reducing the solubility and bioavailability of heavy metals like Cd and Pb.

d. Policy and Regulatory Interventions: Strengthen and enforce environmental regulations governing mining activities, including comprehensive environmental-impact assessments and strict waste-management practices, to minimize future pollution.

e. Monitoring and enforcement: Regularly monitor soil and water quality and enforce penalties for non-compliance with environmental regulations.

f. Community engagement: Educate local communities about the risks associated with heavy metal pollution and involve them in the remediation process.

g. Additional Measures: In severely contaminated areas, soil excavation and secure landfill disposal may be necessary. Physical and chemical soil-washing methods can further reduce metal concentrations, while ecological restoration can

rehabilitate degraded ecosystems and promote biodiversity recovery.

A comprehensive approach that integrates biological, chemical, and policy-based strategies is likely to be the most effective means of addressing heavy-metal contamination in the Ikpeshi mining area. Implementing these remediation measures will help mitigate environmental and health impacts and support the long-term restoration of the ecosystem to a safe and sustainable condition.

Conclusion

The current study has unequivocally shown that the extraction of marble is a significant cause of pollution in the area surrounding the Ikpeshi mining sites, particularly in the soils, which act as heavy metal sinks. The study also showed that the metal concentrations decreased farther from the mining locations, suggesting that the mining operation caused the metals to end up in the soil. The soils in the study area are very highly polluted with cadmium, highly polluted with copper and arsenic, moderately polluted with lead and zinc, and low (unpolluted) with iron, nickel, and manganese in the following decreasing order: Cd > Cu > As > Pb > Zn > Fe > Ni > Mn. These findings are supported by the computed geo-accumulation index, enrichment factor, contamination factor, and degree of contamination.

Significance and Contribution

This study fills an important gap in the literature by providing comprehensive insights into the environmental impacts of marble mining in Nigeria. The findings of this study have significant implications for policymakers, regulatory agencies, and the mining industry, highlighting the need for effective measures to mitigate the environmental and health risks associated with marble mining.

Based on the study's findings, the following recommendations are proposed:

a. Regular monitoring and assessment: Regular monitoring and assessment of heavy metal pollution in soils and water sources should be conducted to ensure early detection and mitigation of pollution.

b. Implementation of best practices: Mining companies should implement best practices, such as proper waste management and rehabilitation of mined lands, to minimize environmental impacts.

c. Development of policies and regulations: Policymakers should develop and enforce policies and regulations that ensure environmental sustainability and protect public health.

Future research should focus on:

a. Long-term monitoring: Conducting long-term monitoring of heavy metal pollution in the study area to assess the effectiveness of mitigation measures.

b. Human health risk assessment: Conducting human health risk assessments to determine the potential health impacts of heavy metal pollution on local communities.

c. Development of cost-effective remediation technologies: Developing cost-effective remediation technologies to mitigate heavy metal pollution in soils and water sources.

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Disclosure statement

The authors declare no conflict of interest.

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

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