Pollution Study 2025, 6(1), 3155.
https://doi.org/10.54517/ps3155

Article

Quarry operations and soil health: Tracing metal pollution in Awi and Njagachan communities, Nigeria

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CITATION

Udiba UU, Modey DK, Ama J, et al. Quarry operations and soil health: Tracing metal pollution in Awi and Njagachan communities, Nigeria. Pollution Study. 2025; 6(1): 3155. https://doi.org/10.54517/ps3155

ARTICLE INFO

Received: 12 December 2024
Accepted: 8 January 2025
Available online: 8 February 2025

Abstract: This study investigated the influence of quarry operations on soil health by evaluating the metal pollution status of soils around major quarry communities (Awi and Njagachan) in Akamkpa, Nigeria. Soil samples were subjected to wet digestion and quantified using an Atomic Absorption Spectrophotometer (Model AA-6800, Japan). The concentrations of lead (63.34–96.34 mg/kg), cadmium (4.29–7.40 mg/kg), mercury (2.34–3.76 mg/kg), arsenic (2.48–5.21 mg/kg), and selenium (1.22–2.75 mg/kg) were all below the U.S. Environmental Protection Agency (US-EPA), Dutch remediation levels, and other soil guidelines. However, significant spatial variation in metal levels across quarry sites points to anthropogenic influences, with quarries likely contributing to the elevated metal concentrations. Contamination factors indicated moderate contamination by lead, considerable contamination by cadmium, and very high contamination by mercury. The degree of contamination was high for all quarries except Ding Zing quarry, which showed a very high degree during the wet season. Ecological risk assessment revealed low potential risk from lead and arsenic, moderate to high risk from cadmium, and very high risk from mercury. Geo-accumulation indices suggested that soils were largely unpolluted by lead and arsenic but ranged from unpolluted to moderately polluted by cadmium and mercury. The study concludes that quarry activities contribute to elevated metal concentrations, posing varying levels of ecological risk. Continuous monitoring is strongly recommended to prevent potential long-term human and environmental health risks, with a focus on addressing mercury contamination. Regulatory measures should be enforced to mitigate further pollution.

Keywords: quarry operations; soil health; heavy metals; pollution status; ecological risk

1. Introduction

Cross River State is rich in rock deposits that extend throughout its entire expanse. However, apart from the Akamkpa, Biase, Obudu, and Obanlinku Local Government Areas (LGAs), the majority of these rock formations remain largely unexplored. Akamkpa LGA has the state's greatest landmass and stone deposit [1]. Because of its abundant mineral resources, Akampka is one of the places where quarrying has grown to be a major economic sector. Communities like Awi and Njagachan host major quarries that supply construction materials locally and beyond. Quarrying entails the drilling, blasting, crushing, screening, washing, and stockpiling of rocks located on the surface or below the earth's surface. Dimension and crushed stone quarrying are the two primary branches of the industry. Dimension quarrying extracts blocks or sheets of stone in various shapes and sizes, whereas the crushed stone industry crushes granites, stones, or basaltic rocks primarily for use as concrete aggregate or road stone [2]. Quarrying operations are essential to the development of infrastructure and economic expansion. It is significant because it contributes to the nation's economic growth by providing building and construction materials, and tax and royalty revenue for the government and the rural populace in particular [1]. Additionally, the sector supports many urban and rural households by creating employment possibilities for both skilled and unskilled people, contributing to their socioeconomic well-being and means of subsistence. However, there are worries about how these quarries are affecting the environment, especially with regard to heavy metal contamination of the soil. The extraction of rocks and its subsequent processing releases fine dust and waste materials rich in various contaminants, especially heavy metals into surrounding soils and poses potential threats to local ecosystems and human health [3]. Thirty-five (35) metals are of concern because of issues with homes and workplaces. Of these, 23 have been designated as heavy metals (specific gravity > 1.5 mg/kg). It's interesting to note that while some of these metals are necessary in trace amounts for the proper functioning of living systems, metals like lead, cadmium, and mercury are exceedingly poisonous even at extremely low quantities and have no known biological role in living things. Soil contamination by heavy metals from quarrying is a significant environmental concern because metals like lead (Pb), cadmium (Cd), nickel (Ni), and zinc (Zn) do not degrade naturally and can accumulate in soils, adversely affecting soil fertility and eventually find their way into the food chain through the crops [4]. Runoff into adjacent water bodies from this accumulation could also be harmful to aquatic life. This is in addition to other serious environmental concerns such as disturbance of land and vegetation, noise and ground vibrations arising from the movement of heavy-duty equipment, extraction and blasting of rocks. Quarry contamination has been an issue in the vicinity of most quarries [5]. Residents in Awi and Njagachan, as well as the nearby farming communities, run the risk of being exposed to these pollutants. A research study by Adewole and Adesina [6], claims that heavy metals and particulate matter released by quarrying operations contaminate neighbouring farmlands. In a similar vein, research conducted elsewhere in Nigeria, Ogundele et al., [7] has demonstrated that quarrying operations raise the levels of heavy metals (Pb, Cd, and Zn) in the soils around the quarries. Quarries have been operating for decades in Akamkpa, a region renowned for its biodiversity and agricultural production, but little attention has been paid to comprehending the precise impact of these operations on the status of soil metal pollution. While studies like Nwachukwu et al. [8], have documented the broader environmental consequences of quarries in Cross River State, detailed investigations focusing on localized impacts on smaller communities like Awi and Njagachan where four active quarries are operating have been overlooked. This study was designed to assess the influence of quarry operations on soil health by tracing metal pollution in soils around major quarry communities (Awi and Njagachan) in Akamkpa, Nigeria. Soil health refers to the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans [9]. Healthy soil is characterized by its ability to regulate water, cycle adequate nutrients, support plant growth, and provide a stable habitat for diverse organisms. Quarrying often disrupts these functions, resulting in degraded soil conditions. Studies conducted near granite quarries in Ikole-Ekiti, Nigeria, found elevated levels of heavy metals such as iron (Fe), chromium (Cr), and nickel (Ni), posing risks to soil and human health [10]. Similar findings were observed in limestone quarry sites in Oyo State, Nigeria, where soils showed increased concentrations of lead (Pb), cadmium (Cd), and zinc (Zn) [11]. In a study on the environmental impacts of quarrying in Ogun State, Nigeria, quarry activities were linked to decreased soil fertility and structure degradation [12]. Heavy metals disrupt microbial communities essential for nutrient cycling and organic matter decomposition. Studies in Gombe State, Nigeria, showed that quarrying increased soil contamination, negatively impacting microbial biomass and diversity [13]. In India, quarry operations near open mining sites in Orissa led to heavy metal accumulation in soils, negatively affecting local ecosystems and agriculture [14].

2. Materials and methods

2.1. The study area

Cross River State Nigeria is located at latitude 5.8702° N and longitude 8.5988° E. Calabar is the capital of the State. Cross River State has a total area of 20,156 km^2 square kilometres and is bordered in the east by Cameroon, in the north by Benue state, on the west by Ebonyi State and Akwa Ibom State on the south west. Cross River State is made up of 18 Local Government Areas. Akamkpa the largest local governments in Cross River state and is located between latitude 5.1667° N and 5.5333° N, and Longitude 8.2333° E and 8.6333° E (**Figure 1**). It has an area of 5003 km^2 (1.932 m^2) with an elevation of 50–200 m above sea level and a projected population of 200,100 [15]. The vegetation of Akamkpa Local Government Area ranges from mangrove swamps through rainforest, to derived Savannah. The geology of Akamkpa region is made up of rocks of the Oban Massif belonging to the Precambrian Basement Complex rocks of Nigeria. These rocks are overlain by the sedimentary rocks of Cretaceous age [16]. Akamkpa has the largest stone deposit in the state with both small- and large-scale quarries scattered the length and breadth of the local government. The major occupations of the people living in the study area include farming (in subsistent and commercial scale), mining (quarrying), fishing and trading.

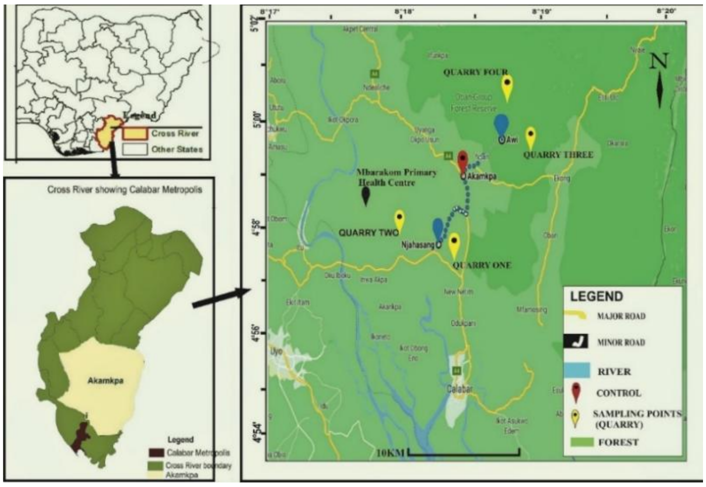

Figure 1. Map of study area showing sample locations.

2.2. Sample collection

Two quarries (Saturn quarry and Twin Brother quarry) at Awi and two quarries at Njagachang (Fuhua and Ding-zing quarries) were chosen for the study. Soil samples were collected from five selected points (50 m apart) within the vicinity of each quarry once a month for six months (January 2023 and July 2023). The samples were collected at a depth of 1–10cm using a hand auger into labelled polyethylene bags. A total of 120 samples (30 from each of the four quarries) was used for the study. The collected samples were transported to the Zoology and Environmental Biology laboratory at the University of Calabar. Soil was collected from Akamkpa main town, where there are no quarries, and used as a control.

2.3. Sample preservation and preparation

The five samples from each quarry were pooled together to form a composite sample for the quarry, air-dried in the laboratory for five days, then crushed into fine powder using laboratory mortar and pestle. 1 g of the ground sample for each quarry was digested using 20 mL of hydrofluoric acid, nitric acid, and perchloric acid in a ratio of 1:3:1 on a hot plate.

2.4. Sample analysis

Metal concentration in the digest was determined by Atomic Absorption Spectrophotometry using Shemadu Atomic Absorption Spectrophotometry (model AA-6800, Japan).

2.5. Analytical quality assurance

Samples were handled carefully to guarantee the reliability and accuracy of the research findings. To prevent cross-contamination, thorough cleaning protocols were followed for the hand auger, mortar, and pestle after each sample. Three replicate analyses on subsamples from the same composite were run to confirm uniformity. Analytical grade nitric acid, perchloric acid, and hydrofluoric acid (Riedel-deHaen, Germany) were the reagents employed for the digestion and preservation of the sample. For every heavy metal under analysis, certified standard solutions were used to calibrate the Shemazu Atomic Absorption Spectrophotometer (AA-6800). The same process was used to digest and analyze Standard Reference Materials, lichen designated IAEA-336, in order to validate the analysis's outcome. The dependability of the analytical procedures used was determined by comparing the analyzed results with the certified reference values of the elements determined.

2.6. Evaluation of pollution status and potential ecological risk

The potential ecological risk posed by lead, cadmium, mercury, arsenic, and selenium in soils around the quarries was evaluated using quantitative pollution indices. These include the contamination factor and contamination degree, the ecological risk factor, the index of geo-accumulation, and the Pollution Load Index.

2.6.1. Contamination factor (Cf)

Contamination factor (Cf) was computed using Equation (1) [17,18].

$$\mathrm{Cf} = \frac{\mathrm{Cs}}{\mathrm{Cp}} \tag{1}$$

where Cs is the mean content of a given metal from at least 5 sample sites and C_p is the pre-industrial reference level for the metal. The pre-industrial reference level of the metals was obtained from Hakanson [17] as 50 µg/g, 1.0 µg/g, 0.25 µg/g, and 15 µg/g for lead, cadmium, mercury, and arsenic, respectively.

2.6.2. Index of geo-accumulation

The index of geo-accumulation (I_{geo}) was used to determine the metal pollution status of the soils by comparing current concentrations with the pre-industrial levels. It was computed using Equation (2).

$$I_{\mathrm{geo}} = \log_2[C_1/(1.5\mathrm{C}_{rl})] \tag{2}$$

where C_1 is the measured concentration of the examined metal in soil, and C_{rl} is the geochemical background concentration or reference value of the metal. The factor 1.5 was introduced because of possible variation in background value for a given metal in the environment as well as very small anthropogenic influences on the value.

2.6.3. Pollution Load Index

The Pollution Load Index of soils around the quarries was evaluated using Equation (3) [19].

$$\mathrm{PLI} = n\sqrt{(\mathrm{CF1} \times \mathrm{CF2} \times \mathrm{CF3} \times \ldots \mathrm{CF}n)} \tag{3}$$

where;

PLI = Pollution Load Index;
n = Number of metals studied;
PL1 < 1—Perfection;
PL1 = 1—shows that only pollutants at baseline levels are present;
PL1 > 1—shows deterioration of site quality.

2.6.4. Ecological risk factor

An ecological risk factor (Er) is used to quantitatively express the potential ecological risk posed by the heavy metal on the other components of the environment. It was computed using Equation (4) [17,18]. The formula

$$\mathrm{Er} = \mathrm{TrxCf} \tag{4}$$

where Tr is the toxic-response factor for a given substance and Cf the contamination factor. The toxic-response factor of the metals was obtained from Hakanson [17] as 5 µg/g, 30 µg/g, 40 µg/g, and 10 µg/g for lead, cadmium, mercury and arsenic, respectively.

2.7. Statistical analysis

Statistical analysis was done using IBM SPSS 23.0 software for Windows. Data collected were subjected to a statistical test of significance using the Analysis of Variance (ANOVA) test to assess significant variation in soil metal levels across the quarries. Probabilities less than 0.05 ($p < 0.05$) were considered statistically significant. Independent T Test were used to assess significant variation of metal levels in soil between the dry and wet seasons. Probabilities less than 0.05 ($p < 0.05$) were considered statistically significant. Pearson product moment correlation coefficient was used to determine the association between metal levels in soil at $a = 0.05$.

3. Results

3.1. Analytical quality assurance

To evaluate the accuracy and precision of the analytical procedure employed, standard reference materials coded Lichen IAEA-336 were analyzed in like manner to our samples. The analyzed values and the certified reference values of the elements determined were very close, suggesting the reliability of the method employed (**Table 1**).

Table 1. Results of analyzed reference material (Lichen IAEA-336) compared to the certified reference values (mg/kg).

Element (mg/kg)	Pb	Cd	Cu	Ni	Cr
Analyzed value	5.25	0.140	4.00	1.20	29.18
Reference value	4.2–5.5	0.1–2.34	3.1–4.1	1.00–1.50	27.00–30.00

3.2. Total heavy metal concentration in soil

Results obtained from the determination of total heavy metal concentration in the soil around Saturn and Twin Brothers Quarries, Awi and Fuhua and Ding Zing Quarries, Njagachang, Cross River State, during dry and wet seasons are presented in **Table 2,** and a comparison of metal concentration in soil across the different quarries for both wet and dry seasons is presented in **Figures 2** and **3**.

Mean soil metal levels across the quarries for both dry and wet seasons were of the ranges 63.4 ± 1.02–78.67 mg/kg, 4.29–7.40 mg/kg, 2.34–3.76 mg/kg, 2.48–5.21 mg/kg, and 1.22–2.75 mg/kg for lead, cadmium, mercury, arsenic, and selenium, respectively (**Table 2**). The differences in the concentration of each metal between the quarries were found to be significant both in dry and wet seasons (ANOVA, $p \leq 0.05$; **Figures 2** and **3**). Each of the metals also displayed significant differences in soil levels between the quarries and the control stations (ANOVA, $p \leq 0.05$). The difference in soil metal concentrations between dry and wet seasons was also significant at the 95% confidence level (**Table 2**).

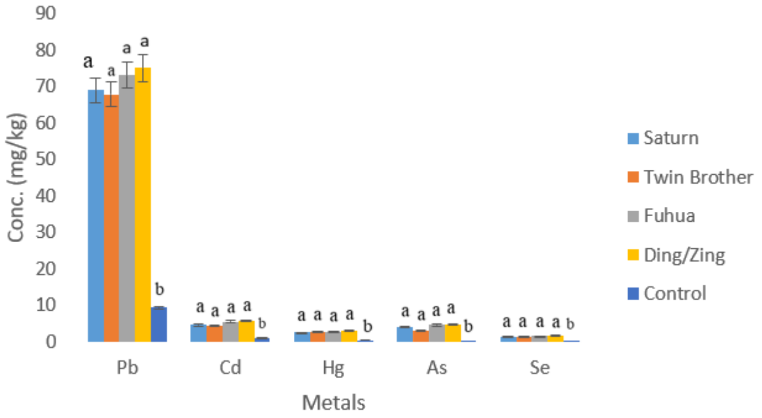

Figure 2. Comparison of heavy metal concentration in soil across quarries and control for dry season.

Quarries with different superscript per metal indicates significant difference (ANOVA, $p < 0.05$) in concentration.

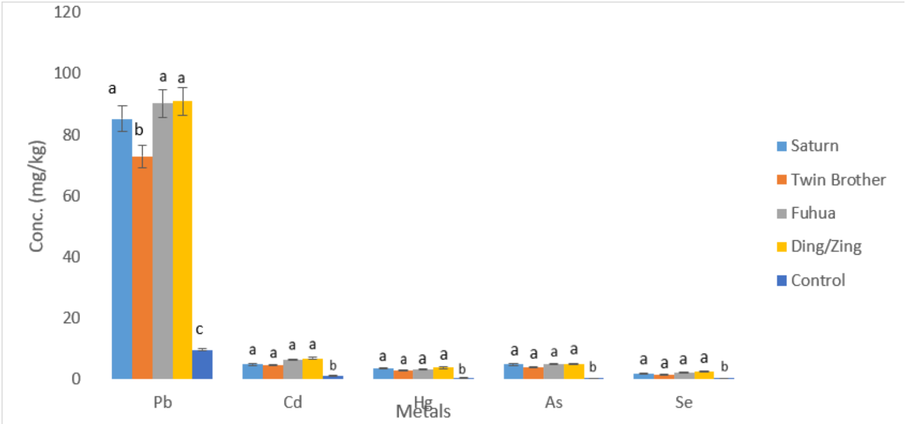

Figure 3. Comparison of heavy metal concentration in soil across quarries and control for wet season.

Quarries with different superscript per metal indicates significant difference (ANOVA, $p < 0.05$) in concentration.

Table 2. Total heavy metal concentration in soil around quarries for both dry and wet season.

		Dry Season					**Wet Season**				
Station	**Metals**	**Jan**	**Feb**	**March**	**Mean ± SD**	**Range**	**May**	**June**	**July**	**Mean ± SD**	**Range**
Saturn	Pb	63.34	71.46	72.24	69.01 ± 1.02 ^{a}	63.34–72.24	83.98	85.45	86.24	85.22 ± 0.93 ^{b}	83.98–86.34
	Cd	4.56	4.61	4.59	4.59 ± 0.02 ^{a}	4.56–4.61	4.74	4.81	4.79	4.78 ± 0.03 ^{b}	4.74–4.81
	Hg	2.47	2.76	2.34	2.52 ± 0.17 ^{a}	2.34–2.76	3.45	3.67	3.34	3.49 ± 0.14 ^{b}	3.34–3.67
	As	4.49	3.85	3.57	3.97 ± 0.39 ^{a}	3.57–4.49	4.58	4.67	5.08	4.78 ± 0.22 ^{a}	4.58–5.08
	Se	1.24	1.46	1.56	1.42 ± 0.13 ^{a}	1.24–1.56	1.93	1.93	1.98	1.95 ± 0.02 ^{b}	1.93–1.98
Twin Brother	Pb	66.35	69.45	68.01	67.94 ± 1.27 ^{a}	66.35–68.45	72.34	72.58	74.05	72.99 ± 0.76 ^{b}	72.34–74.05
	Cd	4.37	4.29	4.47	4.38 ± 0.07 ^{a}	4.29–4.47	4.56	4.59	4.62	4.59 ± 0.02 ^{b}	4.56–4.62
	Hg	2.56	2.51	2.73	2.60 ± 0.09 ^{a}	2.51–2.73	2.67	2.76	2.98	2.80 ± 0.13 ^{a}	2.67–2.98
	As	2.48	3.54	3.04	3.02 ± 0.43 ^{a}	2.48–3.54	3.84	3.87	3.61	3.77 ± 0.12 ^{a}	3.61–3.87
	Se	1.22	1.36	1.31	1.30 ± 0.06 ^{a}	1.22–1.36	1.35	1.57	1.36	1.43 ± 0.10 ^{a}	1.35–1.57

Table 2. (*Continued*).

		Dry Season					Wet Season				
Station	**Metals**	**Jan**	**Feb**	**March**	**Mean ± SD**	**Range**	**May**	**June**	**July**	**Mean ± SD**	**Range**
Fuhua	Pb	71.76	73.76	73.98	73.17 ± 1.00 ^{a}	71.76–73.98	84.56	87.76	98.67	90.33 ± 1.04 ^{b}	84.56–98.67
	Cd	5.34	5.45	5.67	5.49 ± 0.14 ^{a}	5.34–5.67	5.75	6.45	6.86	6.35 ± 0.46 ^{b}	5.75–6.86
	Hg	2.78	2.79	2.86	2.81 ± 0.04 ^{a}	2.78–2.86	2.87	3.27	3.45	3.20 ± 0,24 ^{a}	2.87–3.45
	As	4.52	4.57	4.52	4.54 ± 0.02 ^{a}	4.52–4.57	4.89	4.91	4.96	4.92 ± 0.03 ^{b}	4.89–4.96
	Se	1.47	1.49	1.58	1.51 ± 0.05 ^{a}	1.47–1.58	1.94	2.46	2.51	2.30 ± 0.23 ^{b}	1.94–2.51
Ding/Zing	Pb	74.45	74.34	76.45	75.08 ± 0.97 ^{a}	74.34–76.45	86.78	89.95	96.34	91.0 ± 1.97 ^{b}	86.78–96.34
	Cd	5.63	5.71	5.83	5.72 ± 0.08 ^{a}	5.63–5.83	6.46	6.73	7.40	6.86 ± 0.40 ^{b}	6.46–7.40
	Hg	2.96	2.98	3.04	2.99 ± 0.03 ^{a}	2.96–3.04	3.67	3.75	3.76	3.73 ± 0.04 ^{b}	3.67–3.76
	As	4.58	4.62	4.76	4.65 ± 0.08 ^{a}	4.58–4.76	4.83	4.96	5.21	5.00 ± 0.16 ^{b}	4.83–5.21
	Se	1.76	1.64	1.64	1.68 ± 0.06 ^{a}	1.64–1.76	1.86	2.56	2.75	2.39 ± 0.38 ^{a}	1.86–2.75
Control	Pb	9.23	9.34	9.36	9.31 ± 0.06 ^{a}	9.23–9.36	9.65	9.66	9.61	9.64 ± 0.02 ^{a}	9.61–9.66
	Cd	0.98	1.03	1.06	1.02 ± 0.03 ^{a}	0.98–1.06	1.07	1.09	1.06	1.07 ± 0.01 ^{a}	1.06–1.09
	Hg	0.39	0.39	0.38	0.39 ± 0.00 ^{a}	0.38–0.39	0.48	0.46	0.49	0.48 ± 0.01 ^{a}	0.46–0.49
	As	0.16	0.17	0.16	0.16 ± 0.00 ^{a}	0.16–0.17	0.16	0.19	0.19	0.18 ± 0.01 ^{a}	0.16–0.19
	Se	0.11	0.21	0.11	0.14 ± 0.04 ^{a}	0.11–0.21	0.12	0.24	0.12	0.16 ± 0.06 ^{a}	0.11–0.21

Means with the different superscripts (a and b) across the row indicates significant ($p < 0.05$) difference in metals concentration.

3.3. Relationship between heavy metal in soil around quarries

A significant ($p \leq 0.01$), strong positive correlation was observed between lead and cadmium ($r = 0.960$), lead and mercury ($r = 0.980$), lead and arsenic ($r = 0.971$), and between lead and selenium ($r = 0.960$) (**Table 3**). A significant ($p \leq 0.01$), strong positive correlation was also observed between cadmium and mercury ($r = 0.941$), cadmium and arsenic ($r = 0.952$), and between cadmium and selenium ($r = 0.958$). Strong positive correlation was also observed between mercury and arsenic ($r = 0.963$), mercury and selenium ($r = 0.949$), and between arsenic and selenium ($r = 0.932$); the correlations were significant at the 99% confidence level (3).

Table 3. Relationship between heavy metals concentrations in soil around quarries.

		lead soil	**cadmium soil**	**mercury soil**	**arsenic soil**	**selenium soil**
lead soil	Pearson Correlation	1				
	Sig. (2-tailed)					
	N	30				
cadmium soil	Pearson Correlation	0.960**	1			
	Sig. (2-tailed)	0.000				
	N	30	30			
mercury soil	Pearson Correlation	0.986**	0.941**	1		
	Sig. (2-tailed)	0.000	0.000			
	N	30	30	30		

Table 3. (*Continued*).

		lead soil	**cadmium soil**	**mercury soil**	**arsenic soil**	**selenium soil**
arsenic soil	Pearson Correlation	0.971**	0.952**	0.963**	1	
	Sig. (2-tailed)	0.000	0.000	0.000		
	N	30	30	30	30	
selenium soil	Pearson Correlation	0.960**	0.958**	0.949**	0.932**	1
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	
	N	30	30	30	30	30

** Correlation is significant at the 0.01 level (2-tailed).

3.4. Evaluation of pollution status and potential ecological risk

The results of Pollution indices and ecological risk assessment posed lead, cadmium, mercury, arsenic, and selenium in soils around the quarries under study are presented in **Tables 4–7**.

Table 4. Contamination factor and (CF) and Contamination degree (CD).

	Pb		**Cd**		**Hg**		**AS**		**Contamination Degree**		**Status of Contamination factor**	**Status Contamination Degree**
	Dry season	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Cf < 1: low contamination factor**	**Cd 7: Low contamination of degree**
Saturn	0.99	1.22	4.59	4.78	10.08	13.96	0.26	0.32	15.92	20.28	1 < Cf ≤ 3: moderate contamination	7 > Cd ≤ 14: Moderate of degree contamination
Twin Brother	0.97	1.04	4.38	4.59	10.4	11.2	0.2	0.25	15.95	17.08	3 < Cf ≤ 6: considerable contamination	14 > Cd ≤ 21: High degree of contamination
Fuhua	1.05	1.29	5.49	6.35	11.24	12.8	0.3	0.33	18.08	20.77	Cf > 6: Very high contamination factor	Cd > 21: Very high degree of contamination
Ding Zing	1.07	1.3	5.72	6.86	11.96	15	0.31	0.33	19.06	23.49		
Average	**1.02**	**1.21**	**5.045**	**5.645**	**10.92**	**13.24**	**0.27**	**0.31**	**17.25**	**20.41**		
Control	0.13	0.14	1.02	1.07	1.52	1.92	0.01	0.01	2.68	3.14		

Table 5. Index of geo-accumulation (I_{geo}).

	Pb		**Cd**		**Hg**		**AS**		**Range**	**Pollution Status**
	Dry season	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**$I_{geo} \leq 0$**	**Unpolluted**
Saturn	−0.14	−0.07	0.644	0.658	0.636	0.745	−0.579	−0.653	$0 < I_{geo} \leq 1$	unpolluted to moderately polluted
Twin Brother	−0.145	−0.121	0.628	0.644	0.646	0.671	−0.872	−0.596	$1 < I_{geo} \leq 2$	moderately polluted

Table 5. (*Continued*).

	Pb		Cd		Hg		AS		Range	Pollution Status
	Dry season	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**$I_{geo} \leq 0$**	**Unpolluted**
Fuhua	−0.121	−0.05	0.916	0.979	0.672	0.716	−0.534	−0.66	$2 < I_{geo} \leq 3$	moderately polluted to strongly polluted
Ding Zing	−0.112	−0.048	0.717	0.898	0.68	0.767	−0.685	−0.502	$3 < I_{geo} \leq 4$	strongly polluted
Average	**−0.130**	**−0.072**	**0.726**	**0.795**	**0.659**	**0.725**	**−0.668**	**−0.602**	$4 < I_{geo} \leq 5$	strongly polluted to extremely polluted
Control	−0.809	−0.797	0.142	0.157	0.013	0.082	−1.652	−1.612	$I_{geo} > 6$	extremely polluted

Table 6. Pollution Load Index (PLI).

	Saturn	Twin Brothers	Fuhua	Ding Zing	Control	Status of pollution load index: Range	Status
Dry season	1.86	1.72	2.1	2.18	0.21	PLI < 1	perfect state
Wet season	2.26	1.91	2.4	2.58	0.23	PLI = 1	pollutants at baseline levels
Average	2.06	1.82	2.25	2.38	0.22	PLI > 1	Deterioration of site quality

Table 7. Ecological risk factor (EC).

	Pb		Cd		Hg		AS		Status of Ecological of Risk factor	
	Dry season	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Dry season**	**Wet season**	**Range**	**Status**
Saturn	4.95	6.1	137.7	143.4	403.2	558.4	2.6	3.2	Er < 40	Low potential ecological risk
Twin Brother	4.85	5.2	131.4	137.7	416	448	2	2.5	40 < Er ≤ 80	Moderate potential ecological risk
Fuhua	5.25	6.45	164.7	190.5	449.6	512	3	3.3	80 < Er ≤ 160	Considerable potential ecological risk
Ding Zing	5.35	6.5	171.6	205.8	478.4	600	3.1	3.3	160 < Er ≤ 320	High potential ecological risk
Average	**5.1**	**6.06**	**151.35**	**169.35**	**436.8**	**529.6**	**2.68**	**3.08**	Er > 320	Very high potential ecological risk
Control	0.65	0.7	30.6	32.1	60.5	76.8	0.1	0.1		

3.4.1. Contamination factor and contamination degree

The average contamination factors for both wet and dry seasons were 1.02 and 1.21 for lead, 5.05 and 5.65 for cadmium, 10.92 and 13.24 for mercury, and 0.27 and 0.31 for arsenic. The highest contamination factor (15.00) was recorded at Ding Zing Quarry in the wet season by mercury, while the lowest was recorded at Twin Brother Quarry by arsenic in the dry season (**Table 4**). The average contamination factors of the metals followed the trend Hg > Cd > Pb > As. The contamination degree for the dry and wet seasons was 15.92 and 20.28 for Saturn, 15.95 and 17.08 for Twin Brother, 18.08 and 20.77 for Fuhua, and 19.06 and 23.49 for Ding Zing.

3.4.2. Index of geo-accumulation (I_{geo})

Table 5: Indicates that the average values of the index of geo-accumulation for both dry and wet seasons were −0.129, −0.072 for lead, 0.726 and 0.795 for cadmium, 0.659 and 00.725 for mercury, and −0.668 and −0.603 for arsenic. The highest value of the index of geo-accumulation (0.979) was recorded at Fuhua quarry in the wet season by cadmium, while the lowest (−0.048) was recorded at Ding Zing quarry by lead in the wet season. The index of geo-accumulation of the metals also followed the trend Cd > Hg > As > Pb.

3.4.3. Pollution Load Index (PLI)

Average value of Pollution Load Index was 2.06, 1.82, 2.25 and 2.38 for Saturn, Twin Brother, Fuhua and Ding Zing respectively (**Table 6**). The PLI therefore followed the trend Ding Zig > Fuhua > Saturn > Twin Brother.

3.4.4. Ecological risk factor (EC)

The average values of ecological risk factors for both dry and wet seasons were 5.10 and 6.06 for lead, 151.35 and 169.35 for cadmium, 436.58 and 529.6 for mercury and 2.68, and 3.08 for arsenic. The highest ecological risk factor (600) was recorded at Ding Zing quarry in the wet season by mercury while the lowest (2.00) was recorded at Twin Brother Quarry by arsenic in the dry season (**Table 7**). The average ecological risk factors of the metals also followed the trend Hg > Cd > Pb > As.

4. Discussion

4.1. Total heavy metal concentration in soil

Through its Regional Screening Levels (RSLs), which are risk-based concentrations used to evaluate possible threats to human health, the United States Environmental Protection Agency (US-EPA) offers guidelines for metals levels in soil. The guideline values vary based on the land use. The screening levels for lead, cadmium, mercury, arsenic, and selenium in residential soil are 400 mg/kg, 70 mg/kg, 1.1 mg/kg, 0.6 mg/kg, and 390 mg/kg. These thresholds are for long-term exposure in areas where there is frequent human contact with the soil, such as in homes or playgrounds and farms [20]. The mean soil lead, cadmium, and selenium during dry and wet seasons (**Table 3**) were found to be below the screening values. Mean levels of mercury and arsenic in the study, however, exceeded the screening levels. RSLs are not enforceable regulatory limits but serve as guidance for risk assessment and site clean-up decisions. Mercury and arsenic in the study area, therefore, pose potential ecological risk.

The Department of Petroleum Resources (DPR) in Nigeria adopts, the Dutch standards for the assessment of soil pollution in the country. Target and intervention values are used by the Dutch soil remediation policy to evaluate soil contamination. The remediation intervention value indicates the metal.

Level at which the soil’s ability to sustain plant, animal, and human life is gravely jeopardized or compromised. The concentration of soil metals over which the soil is considered to be significantly polluted is represented by this value. The soil metal level below which a sustainable soil quality exists is indicated by the target value. The target value is the soil metal level that must be attained to fully recover all the functional properties of the soil for humans, animal, and plant life, thus the benchmark for environmental quality on the assumption of negligible risk to the ecosystem [21]. The target and intervention values for the metal studies are: 85 mg/kg and 530 mg/kg for lead, 0.8 mg/kg and 12 mg/kg for cadmium, 0.3 mg/kg and 10 mg/kg for mercury, 29 mg/kg and 55 mg/kg for arsenic, and 0.7 mg/kg and 100 mg/kg for selenium. The mean concentration of all the metals studied was below remediation intervention values. However, soil lead, Cadmium, mercury, and selenium levels exceeded the Dutch target values, especially in the wet season. The findings suggest impairment of some of the functional properties of the soil for humans, animal, and plant life, thus posing a potential ecological risk.

Soil metal levels were also assessed using Soil Guideline values (SGVs). SGVs are benchmarks used to assess the risk of contamination in soils, particularly with regard to human health, under the United Kingdom law [22]. These values serve as indicative limits beyond which remedial action might be needed to protect human health [23]. The SGVs for the Pb, Cd, Hg, As, and Se for residential areas with homegrown plant produce are: 200 mg/kg for lead, 1.8 mg/kg for cadmium, 1 mg/kg for mercury, 32 mg/kg, and 35 mg/kg [24]. Cadmium and mercury in studied soils exceeded the SGVs suggesting that the soils around the quarries under investigation possess potential ecological risk with respect to cadmium and mercury intoxication to the other components of the ecosystem.

The high spatial variation in soil metal levels observed across the quarries suggests anthropogenic influence, as the metal may not have entirely originated from natural processes or crustal materials. The significantly higher metals concentration in soils around all the quarries when compared to the control suggests that quarry activities may be responsible for the elevated concentration of the metal at the quarries. The significantly higher metals concentration observed during the wet season may be due to the influence of moisture on the soil chemistry, which in turn enhances absorption of the metal. There is therefore a serious cause for concern especially in the wet season, as uptake by plants, leaching into the ground, and runoff into surface water cannot be ruled out given favorable physical, chemical, and physiological conditions. The chemical form of these metals in soil depends on a number of factors, including pH, soil organic matter content, redox potentials, and chloride ion concentration. Phytoavailability and toxicity in soil-plant systems are determined by several environmental factors, including soil properties, plant type and stage of development, climate, and the chemical form of the metal. Excessive uptake of arsenic by plants disrupts enzyme function and impairs phosphate flow in the plant system [24]. Workers and residents of these quarries may be exposed to health risks, particularly children who may get infected chronically through their normal hand-to-mouth behavior as they play in the dust. Lower mean soil lead (0.04 mg/kg), mercury (0.09 mg/kg), and arsenic (0.105 mg/kg) have been reported for Asonomaso quarry in Ashanti region of Ghana [5]. Lower soil lead (12.26 mg/kg) and a higher cadmium concentration were reported for soils within the quarry environment in Akamkpa Local Government Area, Nigeria [25]. The mean cadmium concentrations in this study align with those reported in quarry sites in India [26]. Selenium concentrations in studied soils surpass those in quarrying sites in the United Kingdom, where levels typically range below 1 mg/kg [24], suggesting that selenium pollution here is uniquely tied to local quarry activities.

4.2. Relationship between heavy metal in soil around quarries

The significant, strong, and positive correlation observed between lead and cadmium, lead and mercury, lead and arsenic, and between lead and selenium (**Table 4**) indicates that an increase in the concentration of lead in the soils around the quarries under study is accompanied by a corresponding increase in the concentration of cadmium, mercury, arsenic, and selenium, suggesting that the same source may be responsible for their presence at the concentration determined. Similarly, the significant, strong, and positive correlation observed between cadmium and mercury, cadmium and arsenic, and between cadmium and selenium indicates that an increase in the concentration of cadmium in the soils is accompanied by a corresponding increase in mercury, arsenic, and selenium, suggesting that some are responsible for their presence at the concentrations determined. The significant, strong, and positive correlations observed between mercury and arsenic, mercury and selenium, and between arsenic and selenium also suggest that the same source may be responsible for their presence at the concentrations determined.

4.3. Evaluation of potential ecological risk

4.3.1. Contamination factor and contamination degree

Metal contamination factor and contamination degree were used to determine the contamination status of the soils around the quarries under study. The contamination factor for lead across the quarries (**Table 5**) showed moderate contamination except in Saturn and Twin Brothers during the dry season, which showed low contamination. The contamination factor for cadmium across the different quarries during both the dry and wet seasons corresponded to considerable contamination with mercury corresponding to very high contamination. On the other hand, the contamination factor for arsenic corresponds to low contamination all through the study. This high contamination factor for mercury, cadmium, and lead in the study suggests anthropogenic contribution of lead in soil around the quarries.

The degree of contamination computed for all the quarries under study (**Table 5**) corresponds to high degree of contamination except Ding Zing quarry during wet season which correspond to very high degree of contamination.

4.3.2. Ecological Risk Factor (EC)

The ecological risk factor in this study represents the sensitivity of various biological communities to metal contamination and illustrates the potential ecological risk caused by the heavy metals. The ecological risk factor computed in this study (**Table 6**) reveals that lead and arsenic pose low potential ecological risk to other components of the environment across the four quarries under study. Cadmium poses considerable ecological risk at Saturn and Twin Brother quarries and high potential ecological risk at Fuhua and Ding Zing quarries. Mercury poses a very high potential ecological risk to other components of the ecosystem across all the quarries being investigated.

4.3.3. Index of Geo-accumulation (I_{geo})

An index of geo-accumulation (I_{geo}) was used to determine and define Pb contamination in soil by comparing current concentrations with the “pre-industrial levels”. The geo-accumulation index (I_{geo}) was distinguished into seven classes as described by Muller [18] Based on the values of the Index of geo-accumulation (I_{geo}), the four quarries could be said to be unpolluted with respect to lead and arsenic (Classified as group 0) and from unpolluted to moderately polluted by cadmium and mercury (Classified as group 1). The ranking of intensity of metal pollution of soil across the quarries is as follows: cadmium > mercury > arsenic > lead.

4.3.4. Pollution Load Index (PLI)

The Pollution Load Index was applied in the study to assess the pollution quality of the soils around Saturn, Twin Brother, Fuhua, and Ding Zing quarries. The following terms will be used to explain the Pollution Load Index (PLI): PLI > 1 Polluted; PL1 = 1 pollutant at baseline levels is present; PLI < 1 = Not polluted. The PLI therefore indicates that all the quarries are not polluted. It is worthy to note that the PLI values for cadmium and mercury across the different quarries significantly approach unity, indicating that the pollutants are present at base levels. This is a cause for concern because both metals are cumulative poisons and have the tendency to bioaccumulate at successively higher trophic levels in ecological geochemical environments.

5. Linkages with existing literature and knowledge gaps

The study aligns with global findings on heavy metal contamination due to quarry activities, corroborating the role of anthropogenic activities in environmental degradation. However, it uniquely demonstrates significant seasonal variability, with higher concentrations observed during the wet season. This finding highlights the role of moisture in enhancing the mobility and solubility of heavy metals, a factor relatively overlooked in previous studies. The strong positive correlations observed among metals (e.g., Pb and Cd, Hg and As) provide new insights into their potential shared sources or synergistic effects on soil properties. Such inter-metal relationships remain underexplored in prior research and offer valuable data for risk assessment models. Furthermore, by comparing soil concentrations to international benchmarks (e.g., Dutch, US-EPA, UK SGV), this study situates local findings within a global context, emphasizing the need for region-specific remediation strategies. The study underscores the inadequacy of existing policies in mitigating heavy metal contamination from quarrying activities. Findings suggest the need for stricter enforcement of environmental regulations and adoption of sustainable quarrying practices

6. Study limitations and future research

The study acknowledges the following limitations:

- Sample size: Limited sampling stations may not capture broader variability across the region. Future studies should increase sample points to enhance generalizability.

- Research scope: The research focuses solely on topsoil (1–10 cm) contamination, excluding subsurface layers or water bodies, which are crucial for understanding broader ecological and public health implications.
- Chemical speciation: This study does not investigate the speciation of heavy metals, which is critical for assessing bioavailability and toxicity. Future research should explore the interaction between heavy metals and soil chemistry, such as pH and organic matter, to provide deeper insights into toxicity and bioavailability.

7. Conclusion

The concentrations of all the metals were below the United States Environmental Protection Agency (US-EPA) guidelines for soil, the Dutch remediation intervention levels, and the soil guideline values. However, the high spatial variation in metal concentrations across the quarries suggests significant anthropogenic influence. The notably higher metal concentrations in soils around the quarries compared to the control indicate that quarry activities likely contribute to the elevated metal levels. Higher heavy metal concentrations in quarry soils during the wet season compared to the dry season were also revealed. The contamination factor for lead showed moderate contamination across the quarries, while cadmium indicated considerable contamination, and mercury exhibited very high contamination. The overall degree of contamination at most quarries corresponded to a high level, except for the Ding Zing quarry during the wet season, which showed a very high degree of contamination. Ecological risk assessments revealed that lead and arsenic pose low potential ecological risks to the environment, while cadmium presents a range of risks from considerable to high potential ecological risks. Mercury was found to pose a very high potential ecological risk. The geo-accumulation index (Igeo) indicates that the quarries are unpolluted concerning lead and arsenic but range from unpolluted to moderately polluted by cadmium and mercury. Continuous monitoring of metal levels around the quarries is recommended to safeguard both human and environmental health.

Author contributions: Conceptualization, UUU and DKM; methodology, UUU, DKM and JA; software, UUU and JEA; validation, UUU, DKM, JA and NOSU; formal analysis, UUU and EOE; investigation, DKM, UUU, CIC and JEA; writing—original draft preparation, UUU, DKM, JA, JEA, NOSU, EOE and CIC; writing—review and editing, UUU, DKM, JA, JEA, NOSU, EOE and CIC; supervision, UUU; project administration, DKM and UUU. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

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