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PHYSICOCHEMICAL CHARACTERIZATION AND ECOLOGICAL RISK ASSESSMENT OF MIXED TOXIC METALS AND RADIONUCLIDES IN CONTAMINATED TIN MINE TAILINGS IN SELECTED AREAS AROUND JOS, PLATEAU STATE, NIGERIA

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Abstract: Tin-mine tailings in Jos Plateau State, Nigeria, contain elevated levels of toxic metals (Pb, Cd, Cr) and naturally occurring radionuclides (U, Th, K), yet few studies have quantified the ecological risks associated with these wastes. This study characterizes physicochemical properties and contaminant levels in tailings collected from four dumpsites, Zawan A, Kuru A, Sharubutu, and Rim, and compares them with adjacent farmland soils. Tailings and control samples (500 g each) were pretreated and analyzed via atomic absorption spectrophotometry and gamma spectrometry. Soil pH, electrical conductivity, bulk density, organic matter, texture, and cation exchange capacity (CEC) were assessed. Toxic metals were evaluated using contamination indices: Contamination Factor (CF), Metal Pollution Index (MPI), Pollution Load Index (PLI), Geo-accumulation Index (Igeo), Nemerow Pollution Index, Enrichment Factor (EF), Degree of Contamination (Cd), and Potential Ecological Risk Index (PERI). Principal Component Analysis (PCA) was conducted to explore relationships among metals and soil properties, and radionuclide activity (^{238}U, ^{232}Th, ^{40}K), absorbed dose rates, and annual effective dose were quantified. Heavy metal concentrations (Pb: 11.5–50.5 mg/kg; Cd: 1.8–5.1 mg/kg; Cr: 1.2–5.1 mg/kg) varied by site, with Pb highest in Kuru A and Cd highest in Rim. Ecological risk indices indicated moderate to high pollution at Zawan A and Rim (Cd > Cr > Pb). While most farmland soils remained of acceptable quality, dumpsites exhibited moderate contamination and localized ecological risk (total degree-of-contamination: Rim > Zawan A > Kuru A > Sharubutu). PCA revealed correlations between Cd and CEC/silt content, highlighting anthropogenic origins. Radionuclide activity at dumpsites exceeded adjacent farmland levels, but remained below global average values; absorbed dose and effective

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annual dose rates were within safe thresholds (<1), indicating non-controlled radiation risk. However, ecological indices flagged localized ecological concerns. This study underscores the need for targeted remediation and environmental management interventions at contaminated tailing sites, especially those near communities. It also recommends continuous monitoring of contaminant migration, evaluation of human exposure pathways, and policy-based controls on tailings management in mining-impacted regions.

Keywords: Tin-Mine Tailings, Toxic Metals, Radionuclides, Ecological Risk Indices, Jos Plateau State, Nigeria

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1.0 Introduction

Tin mining activities have long been recognized as a major contributor to environmental contamination, primarily through the release of naturally occurring radionuclides and toxic heavy metals into surrounding ecosystems. During the extraction and processing of tin ore, substantial quantities of residual waste materials known as mine tailings are generated. These tailings frequently contain elevated concentrations of hazardous substances that can pose significant threats to both environmental sustainability and public health [1]. Mine tailings typically consist of various mineral fractions, including magnetic minerals such as iron ore and columbite, as well as non-magnetic minerals like cassiterite, monazite, zircon, and silica. In many mining regions, these residues are disposed of without further treatment or recovery. However, in some instances, they are repurposed for industrial or agricultural applications, including their use in fertilizer production, animal feed additives, refractory materials, road construction, and as backfill material in storage facilities [2];[3].

Historically, Nigeria ranked among the world's leading producers of tin, particularly during the 1960s. Despite the decline in large-scale production, mining activities continue in several regions of the country, resulting in the continuous generation and accumulation of large volumes of mining waste. Tailings can constitute a substantial proportion of the total material generated during mining operations, accounting for approximately 90–98% of the processed material in copper mining and between 20–50% in the extraction of other mineral ores [4]. These mine residues frequently contain radionuclides such as uranium and thorium, which emit ionizing radiation capable of causing severe biological damage. Exposure to such radiation has been associated with increased risks of cancer and genetic abnormalities in humans. Moreover, heavy metals, including lead, cadmium, arsenic, and mercury, present in tailings can enter ecological systems through leaching and bioaccumulation, thereby contaminating soil, water, and the food chain. Prolonged exposure to these toxic metals has been linked to numerous health complications, including neurological impairment, kidney dysfunction, and developmental abnormalities [6]. Mining activities also lead to the formation of large tailings ponds or waste dumps, which can further accelerate environmental degradation and adversely affect surrounding ecosystems and nearby human settlements.

Mine tailings may also facilitate the migration of radioactive and metallic contaminants into the environment through processes such as erosion, leaching, and wind dispersion. As a result, radionuclides like uranium and thorium can enter surface water, groundwater, soils, and agricultural systems, thereby increasing the potential for human exposure through inhalation of contaminated dust, dermal contact, or consumption of contaminated food and water. Consequently, understanding the potential environmental and health implications associated with these contaminants is essential for effective environmental monitoring and risk management.

Assessing the potential human health risks associated with tin mine tailings, therefore, requires a systematic evaluation of the levels of toxic metals and radionuclides present within these waste materials. Such assessments typically involve preliminary investigations into the physicochemical characteristics of the tailings, the concentration and distribution of heavy metals, and the interactions of these contaminants within environmental media. These evaluations are particularly important for populations directly involved in mining activities as well as communities residing in close proximity to mining sites [7].

Accordingly, this study seeks to evaluate the ecological risks associated with toxic metals present in tin mine tailings collected from selected mining communities, namely Zawan A (ZS1), Kuru A (KS2), Sharubutu (SS3), and Rim (RS4), located within Jos South and Riyom Local Government Areas of Plateau State, Nigeria.

2. Materials and Methods

2.1 Study Area Description

Tailings and farmland soils were sampled from Zawan A, Kuru A, Sharubutu, and Rim, all in Jos South and Riyom Local Government Areas, Plateau State, Nigeria. Analytical methods included atomic absorption spectrophotometry and gamma photometry. Ecological risk indices were calculated using the measured contaminant concentrations alongside reference data.

Plateau State is located in the middle belt of Nigeria, with an area of 30.91 km (11936 sq mi). The state has an estimated population of about three million people. It is located between latitude 9051’30” N to 1002’00” N and longitude 8048’00” E to 9051’00E. The name PlateauStatee emerged due to its mountainous topography with captivating rock formations. The mountain's attitude ranges from around 1,200 meters (about 400 feet) to a peak of 1,829 meters above sea level. The predominant occupation of the people here is mining and subsistence farming, 500 g of each of the sample was taken.

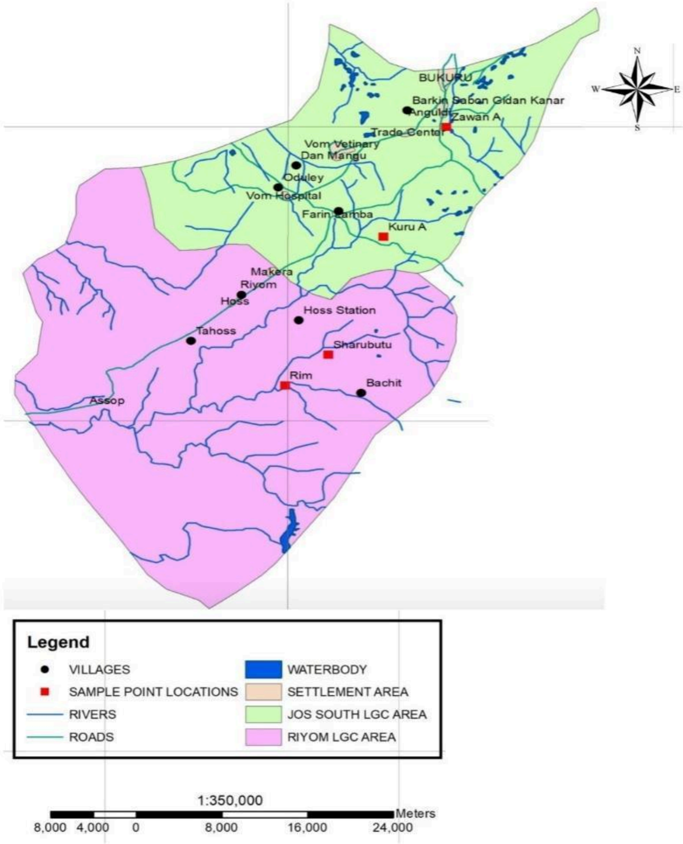

Figure 1: Map Showing the Location of the Study Area

Source: Cartographic, GIS and Remote Sensing Studio Department of Geology University of Jos, 2023.

Figure 1 shows the sampling points where the tailing samples were taken from in Jos South and Riyom L.G.A. of Plateau State. The Geographical Positioning System (GPS) was used to locate the sampling area to ensure consistency. Each sample was taken from the mining site in Zawan A (ZS1) and Kuru A (KS2) of Jos-South Local Government Area, Sharubutu (SS3) and Rim (RS4) of Riyom Local Government Area of Plateau State, Nigeria.

2.2 Sampling Locations and Sample Collection

2.3 Sample Preparation

Four samples of 500 g each were taken from the mining and the control sites, respectively. The Tin mine tailing and soil samples was pretreated through washing, drying and in some cases grinding to size particles of 2 mm to distinguish between small and large particles. The goal of the pretreatment procedure was to prepare a test sample in which the concentration of the original soil was provided; however, this procedure did not alter the chemical species analyzed.

3.0 Results and Discussion

3.1 Physicochemical Analysis of Soil and Tailings

Soil contamination by toxic metals is a significant environmental concern, primarily resulting from activities like mining, fluid leaks, and metal corrosion [8].

Mining areas in Jos South and Riyom Local Government Area, Plateau State, display similar physical traits. Ongoing mining activities have impacted soil properties such as pH, conductivity, and bulk density, as noted in this study. The soil around these regions is loose and prone to erosion, mainly due to continuous excavation for economic minerals. The soil's structure and fragmentation patterns suggest a high risk of erosion and leaching, negatively affecting the surrounding vegetation, as shown in Plate 1. Therefore, the soil in these areas does not support plant growth.

Plate 1: Pictorial Images of Sample, Sampling Sites and Mine Activities

(A) and (B), washing/separation of Tin mine tailings, (C) and (D) Tin mine tailings from study area, (E), Tin mine tailing deposit and (F) Tin mine tailings site within farm lands.

Table 1: Physicochemical Characteristics of Tin Mine Tailings

	Mean ± SD			
Parameters	**Zawan A**	**Kuru A**	**Sharubutu**	**Rim**
pH	6.74 ± 0.30	7.01 ± 0.04	7.00 ± 0.06	6.68 ± 0.34
Electrical Conductivity (S/m)	12.00 ± 2.91	10 ± 2.55	10.00 ± 2.55	13.00 ± 3.54
Organic matter (%)	BDL	BDL	BDL	BDL
Bulk density (g/cm^3)	1.28 ± 0.67	1.13 ±1.19	1.01 ± 1.31	2.24 ± 0.31
Sand (%)	92.1 ± 0.01	93 ± 0.03	87.4 ± 0.02	90.2 ± 0.01
Clay (%)	BDL	BDL	BDL	BDL
Silt (%)	BDL	BDL	BDL	BDL
Particle size class	Sandy soil	sandy soil	sandy soil	Sandy
CEC (meq/100g)	5.00 ± 1.00	6.00 ± 0.01	6.00 ± 0.01	5.00 ± 1.00

*SD = Standard deviation for 3 determination

*BDL= Below Detection Limit

3.1.1 Soil Organic Matter (SOM):

Organic matter significantly impacts soil structure, water retention, nutrient availability, biological activity, and pesticide efficiency. A higher organic matter content suggests better soil fertility, as it facilitates nutrient exchange and supports plant growth [8]. The organic matter content of the samples ranged from 2.40 ± 0.02% to 3.81 ± 0.01%. The highest concentration was found in soil samples from farmland. Soils with less than 1% organic matter are typically found in desert areas. The trend in organic matter concentration was: Zawan A > Rim > Sharubutu > Kuru A.

3.1.2 Electrical Conductivity (EC):

Soil conductivity reflects the soil's ability to conduct electricity, which is influenced by soluble salts in the soil. Conductivity values for the samples ranged from 8.00 ± 3.00 to 13.00 ± 3.54 S/m. The highest conductivity value was observed in Rim, while the lowest was found in Sharubutu. The higher conductivity values compared to previous studies suggest that mining activities and agricultural processes have contributed to these levels [9].

3.1.3 pH Levels:

Soil pH measures acidity or alkalinity. pH values above 7 are considered alkaline, while values below 7 indicate acidity. The pH in the studied samples ranged from 6.60 ± 0.03 to 7.01 ± 0.04, with the highest value found at the tin mine tailing dumpsites. The pH values for these sites were within the optimal range for plant growth, as higher pH values limit metal mobility, which can be beneficial for plant life.

3.1.4 Bulk Density:

Soil bulk density is a measure of soil compaction, which impacts root penetration, water infiltration, and solute movement. The ideal bulk density for sandy soils is typically less than 1.6g/cm³. The bulk density of the samples ranged from 1.12 ± 0.02 to 1.55 ± 0.03 g/cm³, which falls within the expected range for plant growth. The lowest density was found in Kuru A, while the highest was found in Rim.

3.1.5 Texture:

Soil texture influences water infiltration and drainage. The textural analysis revealed that all the tailing samples were predominantly sandy, with Zawan A containing 92.1% sand, Kuru A 93.0%, Sharubutu 87.4%, and Rim 90.2%. Clay and silt were not detected in any sample. The presence of heavier metals in smaller soil particles (clay and silt) was noted, but the sandy nature of the soils in these areas makes them more prone to erosion.

3.1.6 Cation Exchange Capacity (CEC):

CEC refers to the soil's ability to absorb and exchange cations (positively charged ions). Soils with high CEC are typically more fertile and can better retain essential nutrients. The CEC values for the tailings samples ranged from 5.00 meq/100g to 7.00 meq/100g. The highest CEC was observed in Zawan A, which also had a high organic matter content.

Table 2: Concentration (mg/kg) of Toxic Metals from the Tin Mine Tailing Dump Sites before Washing Experiment

Location	Pb	Cd	Cr
Zawan A	41.62±0.03	2.91±0.02	6.50±0.03
Kuru A	50.53±0.03	2.23±0.02	5.11±0.02
Sharubutu	23.12±0.01	1.81±0.01	3.12±0.02
Rim	11.45±0.01	2.98.11±0.03	1.21±0.01
Average	31.68±0.02	2.48±0.02	3.99±0.02
WHO/FAO (2001)	**50**	**3**	**50**

3.2 Toxic Metal Analysis

The concentrations of heavy metals in tin mine tailings varied across sampling locations. Lead (Pb) ranged from 11.45–50.53 mg/kg**,** with the highest concentration recorded in Kuru **A**, while **Rim** showed the lowest levels. Cadmium (Cd) concentrations ranged from 1.81–5.11 mg/kg**,** with the highest values observed in Rim, whereas Sharubutu recorded the lowest [10]. Chromium (Cr) levels varied between 1.21–5.11 mg/kg, with Kuru **A** showing the highest concentration [15]. Across most sites, the metals followed the order Pb > Cr > Cd, indicating Pb dominance in the tailings [11];[12]. Elevated Pb levels were likely linked to anthropogenic activities such as improper disposal of petroleum products, batteries, and industrial materials [14]. Heavy metals can persist in soils and accumulate in biological systems through the food chain, potentially causing neurological, kidney, and developmental disorders in humans[13].

Statistical analysis using a two-sample t-test ($p < 0.05$) indicated no significant difference between tailing and farmland samples ($p = 0.44$) [16], suggesting common contamination sources. Principal Component Analysis (PCA) revealed strong relationships between metal distribution and soil physicochemical properties, with cadmium positively correlated with cation exchange capacity and silt content[16].

Table 3: Activity Concentration (Bq/kg) of Radionuclides (Uranium, Thorium and Potassium) from Tin Mine Tailing Dump Sites before Washing Experiment with Blended SDS/EDTA

Location	**^{238}U**	**^{232}Th**	**^{40}K**
Zawan A	19.25±1.51	112.41±6.21	ND
Kuru A	21.37±1.68	159.02±8.82	ND
Sharubutu	30.98±2.41	26.65±1.48	ND
Rim	3.92±0.32	4.71±0.26	1.88±0.10
Average	18.88±1.48	75.70±4.19	0.47±0.03
UNSCEAR, 2000	**35**	**30**	**420**

ND: Not Detected

3.3 Radionuclide Analysis

Radionuclide activity concentrations in the tin mine tailings varied across the study area due to geological differences, with ^{232}Th contributing the highest activity in most samples. The maximum activities recorded were 30.98 ± 2.41 Bq/kg for ^{238}U (Sharubutu), 159 ± 8.82 Bq/kg for ^{232}Th (Kuru), and 1.88 ± 0.10 Bq/kg for ^{40}K (Rim) [17]. Mean activity concentrations were slightly higher in tailings than in nearby agricultural soils, likely due to mining-related dust and exposure to naturally occurring radioactive materials associated with minerals such as monazite and zircon [18].

However, the measured radionuclide concentrations and absorbed dose rates were below the global average values reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), which estimates an average outdoor terrestrial radiation dose of about 49–60 nGy/h [18].

Radiological indices, including radium equivalent (Ra_eq) and hazard indices (H_ex and H_in), were all below recommended safety limits, and the estimated annual effective dose was below 6 mSv/year, indicating low radiological risk and suggesting that the mining dumpsites do not constitute controlled radiation areas [19][20].

3.4 Ecological Risk Assessment Indices

Table 4: Ecological Risk Assessment of Toxic Metals in Tin Mine Tailings

Mine tailing Dump sites	**MPI**	**CF**	**Igeo**	**EF**
Zawan A	$4.12\text{x}10^{0}$	$5.95\text{x}10^{-1}$	$8.53\text{x}10^{-1}$	$9.74\text{x}10^{-1}$
Pd	(Excessively	Low contaminated	Unpolluted	Minimal
Significance	contaminated)	$3.91\text{x}10^{0}$	$1.24\text{x}10^{0}$	$1.55\text{x}10^{0}$
Cd	$1.40\text{x}10^{1}$	Severe contaminated		Minimal

Significance	(Slightly	$7.22x10^{-2}$	Moderately	$9.48x10^{-1}$
Cr	contaminated)	Low contaminated	polluted	Minimal
Significance	$5.09x10^{0}$		$1.03x10^{0}$	
	(Severely		From unpolluted to	
	contaminated)		moderately	
			polluted	
Kuru A	$1.10x10^{1}$	$7.22x10^{-1}$	$7.98x10^{-1}$	$7.51x10^{-1}$
Pd	Slightly contaminated	Low contaminated	Unpolluted	Minimal
Significance	$9.89x10^{1}$	$2.23x10^{0}$	$1.23 x10^{0}$	$2.70x10^{0}$
Cd	Severely contaminated	Slightly contaminated	Moderately	Minimal
Significance	$6.55x10^{0}$	$5.68x10^{-2}$	polluted	$1.24x10^{0}$
Cr	Severely contaminated	Low contaminated	$1.05x10^{0}$	Moderate
Significance			Between polluted	
			to moderately	
			polluted	

Mine tailing Dump sites	MPI	CF	Igeo	EF
Sharubutu	$1.01x10^{1}$	$3.30x10^{-1}$	$1.01x10^{0}$	$2.10x10^{0}$
Pd	Slightly contaminated	Low contaminated	Between polluted to	Moderate
Significance	$2.83x10^{0}$	$1.18 x10^{0}$	moderately polluted	$6.41x10^{0}$
Cd	Moderately	Suspected	$2.32x10^{0}$	Significant
Significance	contaminated	contaminated	Between polluted to	$2.64x10^{0}$
Cr	$1.03x10^{2}$	$3.47x10^{-2}$	moderately polluted	Moderate
Significance	Severely	Low contaminated	$1.38x 10^{0}$	
	contaminated		Moderately polluted	
Rim	$5.73x10^{1}$	$1.64 x 10^{-1}$	$1.47x10^{0}$	$5.95x10^{0}$
Pd	Severely	Low contaminated	Between polluted to	Significant
Significance	contaminated	$5.11 x10^{0}$	moderately polluted	$1.02x10^{0}$
Cd	$2.56x10^{1}$	Moderately	$1.06x10^{0}$	Minimal
Significance	Moderately	contaminated	Between polluted to	$1.73x10^{1}$
Cr	contaminated	$1.18 x10^{-1}$	moderately polluted	Minimal
Significance	$4.84x10^{0}$	Low contaminated	$3.51x 10^{0}$	
	Excessively		Between polluted to	
	contaminated		moderately polluted	

3.4.1 Contamination Factor (CF)

Contamination factors (CF) for Pb, Cd, and Cr in tailings from four Jos dump sites indicate generally low to moderate contamination when benchmarked against world median pre-industrial background levels. At **Zawan A**, CF values for Pb and Cr were below 1, indicating low contamination, whereas Cd showed considerable contamination. **Kuru A** samples similarly exhibited low contamination for Pb and Cr, with slight contamination for Cd. In **Sharubutu**, Pb and Cr remained low while Cd was moderately contaminated. At **Rim**, Pb and Cr again had low CF values (<1), with Cd indicating moderate contamination. Overall, the CF trend for Cd followed: *Kuru A > Zawan A > Rim > Sharubutu*, while for Pb and Cr the order varied among sites.

Compared with other Nigerian studies, which have reported higher CF values in some soils near dumpsites, the present results indicate minimal heavy metal contamination across these tailings, likely due to site-specific soil characteristics and analytical differences. Variations across studies may reflect differences in soil type, sampling methodology, and analytical procedures.

3.4.2 Metal Pollution Index (MPI)

The Metal pollution index (MPI) for mine tailings at various dump sites in Jos, Nigeria, is presented in Table 4. The results indicate that at the Zawan A site, Pb had an MPI value of 4.12×10^0, Cd had 1.40×10^1, and Cr recorded 5.09×10^0, all suggesting contamination.

At the Kuru A site, the MPI values for Pb, Cd, and Cr were 1.10×10^1, 9.86×10^0, and 6.55×10^0, respectively, also indicating contamination.

At the Sharubutu mine tailings dumpsite, the soil appeared slightly polluted, with an MPI value of 1.01×10^1 for Pb. Cd and Cr recorded MPI values of 2.83×10^0 and 1.03×10^2, respectively, suggesting moderate and severe contamination.

For the Rim mine tailings dumpsite, Pb and Cr showed contamination with MPI values of 5.73×10^1 and 2.56×10^1, respectively. Cr also recorded an MPI of 4.84×10^0, indicating excessive contamination. An analysis of MPI values across the four sampling locations showed the contamination trend as: Zawan A > Kuru A > Rim > Sharubutu. In contrast, farmland soils showed no signs of metal pollution [27].

Table 5: Ecological Risk Assessment of Toxic Metals in Tin Mine Tailings

Mine tailing Dump sites	PLI	C_d	$PI_{Nemerow}$
Zawan A	5.52×10^{-1}	4.58×10^0	1.92×10^0
Significance	Not Polluted	High degree	Precaution domain
Kuru A	4.51×10^{-1}	3.01×10^0	1.61×10^0
Significance	Not Polluted	High degree	Precaution domain
Rim	2.41×10^{-1}	1.54×10^0	2.62×10^0
Significance	Not Polluted	Low degree	Moderately polluted Domain
Sharubutu	2.24×10^{-1}	5.29×10^0	4.59×10^{-1}
Significance	Not Polluted	Very high degree	Seriously polluted domain

3.4.3 Pollution Load Index (PLI)

The **Pollution Load Index (PLI)** results indicate that soils from the tin mine dumpsites at Zawan **A,** Kuru **A,** Rim**,** and Sharubutu are largely unpolluted, with PLI values all below 1, reflecting minimal overall heavy metal contamination across sites. Similarly, farmland soils also displayed PLI values <1, consistent with a lack of significant pollution based on this integrated index, which compares heavy metal burdens relative to background levels [13].

3.4.4 Geo-accumulation Index (Igeo)

The Geo-accumulation Index (Igeo) results show that toxic metal accumulation at all dumpsites generally falls within the range from unpolluted to moderately polluted, with trends suggesting greater enrichment of Cd relative to Pb and Cr across most locations [26].

3.4.5 Nemerow Pollution Index (PINemerow)

Using the Nemerow Pollution Index (PINemerow), the Rim site was classified as highly polluted, Sharubutu as moderately polluted, and Zawan **A** and Kuru **A** as precautionary, reflecting combined effects of multiple metal pollutants [23];[24].

3.4.6 Enrichment Factor (EF)

Enrichment Factor (EF) values indicate deficiency to minimal enrichment at all sites, suggesting limited anthropogenic influence on overall metal accumulation, although Sharubutu and Rim showed the highest EF values [23].

3.4.7 Degree of Contamination (Cd)

Finally, the Degree of Contamination (Cd) values indicate the highest contamination at Rim, followed by Zawan **A**, Kuru **A**, and Sharubutu, highlighting spatial variability in cumulative heavy metal burdens across the studied dumpsites.

Together, these indices provide a multifaceted assessment of soil contamination, with most sites showing low to moderate pollution levels when benchmarked against established geochemical criteria [28].

4.0 Conclusion

This study comprehensively assessed the ecological risks associated with mixed contaminants, specifically toxic metals (Cd, Cr, Pb) and radionuclides (U, Th, K), in tin mine tailing dumpsites across the Jos Plateau State, Nigeria. Analytical results revealed varying levels of contamination among the sampled sites, with Rim and Zawan A dumpsites exhibiting the highest pollution and ecological risk indices. Although the tailings generally exhibited moderate pollution and low ecological risk overall, notable anthropogenic contributions were observed, particularly at Zawan A and Rim.

The ecological risk indices (PLI, Cd, PINemerow) emphasized localized environmental threats, while farmlands adjacent to the dumpsites showed relatively good soil quality, indicating limited contaminant migration. Based on these findings, there is an urgent need for preventive and remedial actions such as controlled access to contaminated sites, soil remediation programs, and ongoing environmental monitoring. Future research should focus on long-term contaminant migration, bioavailability studies, and the effectiveness of remediation strategies in reducing ecological and human health risks.

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