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Radiometric Evaluation of Naturally Occurring Radionuclides in Soil Around Mining Areas in Nasarawa State, Nigeria

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Abstract: This study investigates the activity concentrations of naturally occurring radionuclides in soil samples collected from mining areas in Nasarawa, Nasarawa State, Nigeria. A total of thirty-one soil samples were analyzed, comprising fifteen each from active and abandoned mining sites, along with one control sample. The samples were prepared and analyzed by gamma spectroscopy method using Sodium Iodide (NaI(TI))- detector with 7.62cm^2 by 7.62cm^2 geometry to determine the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K. The mean activity concentrations for the active (abandoned) mining sites were 38.32 ± 2.51 Bq/kg (39.26 ± 2.71 Bq/kg), 31.57 ± 1.97 Bq/kg (37.80 ± 2.91 Bq/kg), and 59.59 ± 3.51 Bq/kg (69.83 ± 3.93 Bq/kg) for ^{226}Ra, ^{232}Th, and ^{40}K, respectively. Radiological hazard indices were evaluated to assess potential health risks. The calculated mean values for absorbed dose rate (D), radium equivalent activity (Raeq), external hazard index (Hex), annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR) for the active (abandoned) sites were 39.32 nGy/h (43.90 nGy/h), 88.20 Bq/kg (98.73 Bq/kg), 0.238 (0.267), 48.22 µSv/y (53.83 µSv/y), and 168.76 × 10^{-6} (188.42 × 10^{-6}), respectively. The AEDE values surpass recommended global safety limits, indicating a potential radiological health risk for residents and workers in the area. It is therefore recommended that mitigation measures, including shielding, environmental remediation, or site restrictions, be implemented to reduce long-term exposure and safeguard public health.

Keywords: Mining sites, sodium iodide doped thallium detectors, activity concentration analysis, and radiological hazard indices.

1. Introduction

Mining activities are pivotal to Nigeria's economic development, especially in mineral-rich regions like Nasarawa State. However, these operations often disrupt the natural geological environment, leading to the redistribution and enhanced exposure to naturally occurring radioactive materials (NORMs) [1, 2- 5]. These materials, primarily uranium-238, thorium-232, and potassium-40, are present in varying concentrations in the Earth's crust and can pose significant health risks when their activity levels exceed safety thresholds. Radiometric evaluation of soil in mining areas is therefore essential to assess environmental radiation hazards and inform strategies for radiation protection and environmental management [2, 6- 15].

In Nasarawa State, extensive artisanal and mechanized mining has raised public health concerns regarding prolonged exposure to elevated radiation levels. Radiological assessments of soils surrounding mining areas provide insight into potential external exposure risks to both local populations and mine workers. Such evaluations also help establish baseline data for environmental monitoring and regulatory control in accordance with international safety standards [3, 15- 20].

Several studies across Nigeria have underscored the importance of radiometric evaluations in mining regions. For instance, Obed, Ademola, and Ogundare [4] conducted a radiological assessment of soil samples from mining areas in southeastern Nigeria and reported high activity concentrations of ^{238}U and ^{40}K, with estimated hazard indices surpassing global safety limits. Similarly, Jibiri, Farai, and Alausa [5] investigated natural radioactivity in industrial and mining zones in southwestern Nigeria, revealing elevated radionuclide concentrations and highlighting the radiological risks to residents and occupational workers in those areas. These findings emphasize the need for localized studies to evaluate site-specific radiation exposure levels, particularly in regions with intensive mining activities like Nasarawa State.

Specifically, in Nasarawa State, studies have been conducted to assess the radiological impact of mining activities. Eghaghe et al. [3] evaluated the risks of exposure to ionizing radiation from ^{226}Ra, ^{232}Th, and ^{40}K in the Udege Mbeki mining area, finding that the estimated effective dose in the soil samples exceeded the International Commission on Radiological Protection's recommended reference levels for public exposure. Similarly, Aliyu et al. [1] conducted a radiometric survey in the Azara

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development area, reporting significant activity concentrations of radionuclides and associated gamma-radiation dose rates. Furthermore, Rilwan et al. [6] assessed radionuclide concentrations in ongoing drilled boreholes across Keffi town, highlighting elevated exposure levels that pose health concerns for local miners.

Given the increasing mining operations in Nasarawa and the known geologic richness of the region, this study aims to assess the levels of naturally occurring radionuclides in soil samples from both active and abandoned mining sites. The evaluation involves determining the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, and calculating associated radiological hazard indices such as absorbed dose rate, radium equivalent activity, external hazard index, annual effective dose equivalent, and excess lifetime cancer risk. The outcomes are expected to provide valuable data for radiation safety planning and support the implementation of appropriate environmental health mitigation strategies.

2. Materials and Methods

2.1 Study Area

Nasarawa, located in central Nigeria, is geologically positioned within the mineral-rich Benue Trough, comprising mainly sedimentary rocks such as sandstone, shale, and limestone, along with sections of the Precambrian Basement Complex. These formations make the area a hub for solid mineral resources, including barite, coal, lead-zinc, and marble. The town has a population estimated between 60,000 and 70,000, with the broader Nasarawa State experiencing steady growth due to mining and agricultural activities. While farming remains the primary livelihood producing crops like maize, yam, and rice, there has been a notable shift towards artisanal and small-scale mining, which now employs a large portion of the population. This growing mining sector, although economically beneficial, raises environmental and radiological safety concerns, highlighting the need for continuous monitoring and evaluation [14].

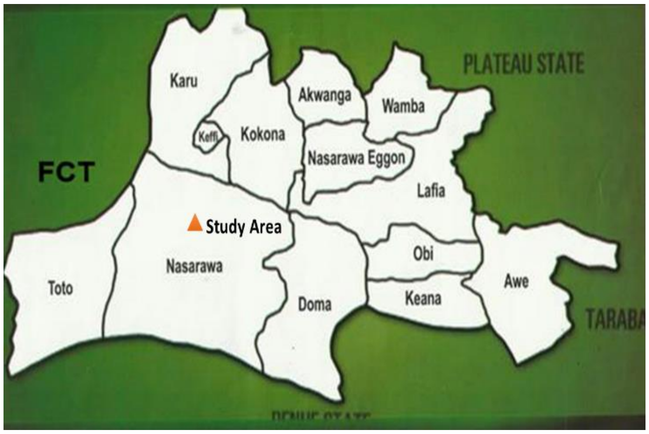

Fig. 1: Map of study area.

2.2 Sample and Sampling Techniques

A total of thirty one (31) soil samples comprising of fifteen (15) soil samples each from around active and abandoned coal mining sites were randomly collected using systematic random sampling. One sample was collected from non-coal mining sites which serve as controls.

2.3 Method of Soil Sample Collection

Soil samples from the selected coal active and abandoned mining sites were collected into polyethylene bag using hand trowel. The opening of the polythene bags were well tightened to prevent contamination and were labelled for easy identification. The soil samples were collected at a depth of about 5 cm. Each composite soil sample collected weighed about 400g of mass. A control soil sample from non-coal mining sites area was collected as control.

2.4 Method of Soil Sample Preparation

The soil samples collected were air dried to remove moisture content. The samples were pulverized and sieved with 2mm mesh to remove bigger particles such as stones, plants roots, coarse materials, and other debris to obtained homogenous, fine-texture powder. Approximately, 200g of each texture was poured into a new polyethylene bag tightly sealed with rubber band and correctly labelled for ease of identification according to the locations and sent for analysis.

2.5 Method of Soil Sample Analysis

Gamma spectroscopy method using Sodium Iodide (NaI(TI))- detector with 7.62cm^2 by 7.62cm^2 was used to determine the activity concentration of ^{238}U, ^{232}Th, and ^{40}K at Centre for Energy Research and Training A.B.U Zaria Nigeria. Geometry as a factor was used at the time of measurement, so that samples that have been prepared will have the same standard geometry for height, density and volume. At the laboratory, the background radiation was taken before measurement with an empty container under the same environmental condition and the value were subtracted during activity concentration computation. In each batch of samples quality assurance measured such as blanks, standards, duplicates and certified reference materials were included. The detector displays a wide range of energy for the analysis of a greater number of radionuclides. Specific gamma ray lines were used to determine the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K.

2.6 Radiological Hazard Indices Equations

i. Activity concentration

The gamma spectroscopy analysis were in count per second (cps), we now use equation (1)to converted from count per second (cps) to activity concentration be in Becquerel per kilogram (Bqkg^{-1}) used by UNSCEAR [21].

$$C(Bqkg^{-1}) = \frac{c_n}{c_{fk}} \quad (1)$$

C = activity concentration of the radionuclides in the sample given in $BqKg^{-1}$

Cn = count rate (counts per second) **Count per second (cps) =** $\frac{\textbf{Net Count}}{\textbf{Live Time}}$

C_{fk}= Calibration factor of the detecting system.

ii. Gamma Absorbed Dose Rate: Gamma Absorbed Dose Rate (D) were determined from the activity concentration and by applying the conversion factors of 0.462, 0.604 and 0.0417 for ^{226}Ra, ^{232}Th and ^{40}K respectively as expressed by UNSCEAR [21] as:

$$D = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \quad (2)$$

A_U, A_{Th} and A_K are the Activity Concentrations for ^{238}U, ^{232}Th and ^{40}K respectively.

It is assumed that the contribution from other radionuclides, such as 137Cs, 235U, 87Rb, 90Sr, ^{138}La, ^{147}Sm and ^{176}Lu to the total dose rate are negligible. UNSCEAR reported that the world average absorbed gamma dose rate mean is $55nGyh^{-1}$ [21].

iii. Measurement of Radium Equivalent Activity: Radium Equivalent Activity (Ra_{eq}) were determine using the weighted sum of activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K:

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (3)$$

Where A_{Ra}, A_{Th} and A_K are the specific activities of ^{226}Ra, ^{232}Th and ^{40}K in $Bqkg^{-1}$ respectively.

iv Measurement of External Hazard Index: External hazard index (Hex) were evaluated to limit the activity concentration (A) of ^{226}Ra, ^{232}Th and ^{40}K to ensure that a permissible dose rate of less than 1 mSv/y as expressed by UNSCEAR [21] as:

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1 \quad (4)$$

Where A_{Ra}, A_{Th} and A_K are the specific activities of ^{226}Ra, ^{232}Th and ^{40}K in Bq/kg respectively.

v. Measurement of Annual Effective Dose Rate: Annual Effective Dose Rate (AEDR) were evaluated using the absorbed dose rate (D) data obtained and a conversion factor value of 0.7 Sv/Gy of absorbed dose in air to effective dose an adults receives as expressed by UNSCEAR [21] as:

$$AEDR = D \times 8760 \times 0.2 \times 0.7 \times 10^{-3} \quad (5)$$

Where, D(nGy/hr) is the absorbed dose, 8760h/yr is the working hours per year, 0.2 is the occupancy factor, and 0.7 is the conversion coefficient.

vi. Measurement of Excess Life Cancer Risk: Excess Life Cancer Risk (ELCR) were determined by the product of determined AED R with Duration of Life (DL), 70 years for children and 50 years for adult and low dose background radiation Risk Factor (RF) of 5% for public exposure considered to produce stochastic effect as expressed:

$$ELCR = AEDR \times RF \times DL \quad (6)$$

Where, AEDE is the Annual effective Dose Equivalent, DL is the Duration of Life which is 70 yrs for children and 50 yrs for adult, RF is the Risk Factor which is $0.05Sv^{-1}$ (5%) for public exposure considered to produce stochastic effects.

3. Results and Discussion

The results of activity concentration level in soil from both the active and abandoned mining sites of the study area are determined. Figure 2 presents the raw results of activity concentration level of soil from active mining sites and abandoned mining sites respectively in the study area.

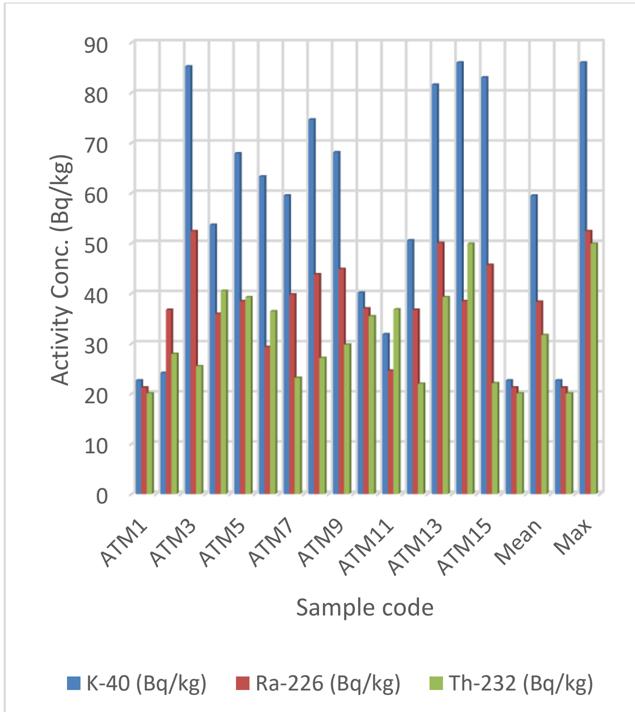

Fig. 2: Comparison of raw result of activity concentration level of soil from active mining sites in the study area

Figure 2 present the raw result of activity concentration level of soil from active mining sites in the study area. The study assessed the activity concentrations of natural radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) in soil samples collected from active mining sites in Benue State, Nigeria. The measured concentrations were 38.33 Bq/kg for ^{226}Ra, 31.67 Bq/kg for ^{232}Th, and 3.52 Bq/kg for ^{40}K. These values were compared to global averages established by the United Nations Scientific Committee on the Effects of Atomic Radiation [21-23] and findings from other studies in Nigerian mining regions. The results showed that ^{226}Ra and ^{232}Th concentrations were slightly above the global average, while ^{40}K levels were significantly lower than typical values reported in similar studies.

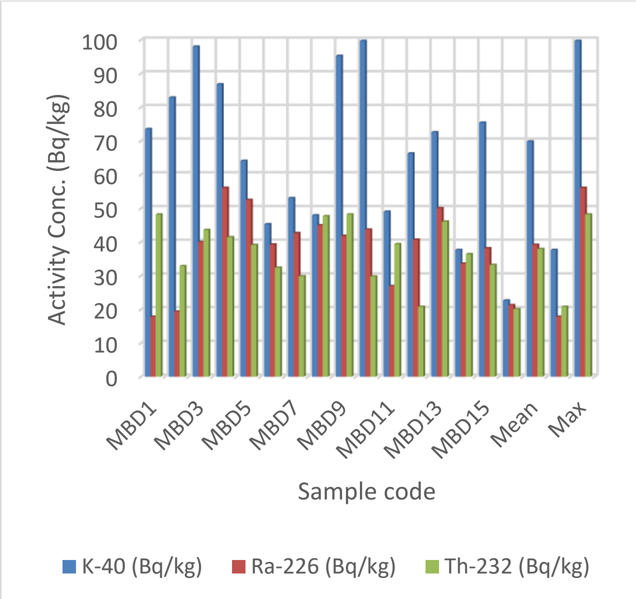

Fig. 3: Comparison of raw result of activity concentration level of soil from abandoned mining sites in the study area.

Figure 3 present raw result of activity concentration level of soil from abandoned mining sites in the study area. The study assessed the activity concentrations of naturally occurring radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) in soil from active mining sites in Benue State, Nigeria. The measured values were 39.16 Bq/kg for ^{226}Ra, 37.90 Bq/kg for ^{232}Th, and 69.82 Bq/kg for ^{40}K. When compared to global average values reported by UNSCEAR (35 Bq/kg for ^{226}Ra, 30 Bq/kg for ^{232}Th, and 400 Bq/kg for ^{40}K), the results indicate slightly elevated levels of ^{226}Ra and ^{232}Th, while the concentration of ^{40}K is significantly lower than the global average. These findings suggest that mining activities may have influenced the distribution of these radionuclides in the soil, particularly the lower-than-expected ^{40}K concentration, which may be due to the mineralogical composition of the site.

Table 1: Calculated radiological hazard indices of sample collected from the active mining sites in the study area

Sample code	D (nGy/h)	Ra_{eq} (Bq/kg)	Hex	AEDE (mSv/y)	ELCR (x10^{-6})
ATM1	22.86107	51.64099	0.139488	0.02803	98.12885
ATM2	34.83784	78.50977	0.212076	0.04272	149.5379
ATM3	43.14787	95.38764	0.257688	0.05291	185.2079
ATM4	43.28225	97.93744	0.264528	0.05308	185.7847
ATM5	44.30489	99.81102	0.269594	0.05433	190.1743
ATM6	38.17417	86.2539	0.232965	0.04681	163.8588
ATM7	34.84882	77.48293	0.209312	0.04273	149.5851
ATM8	39.72641	88.32349	0.238592	0.04872	170.5217
ATM9	41.53367	92.64636	0.250266	0.05093	178.2791
ATM10	40.16098	90.74135	0.245102	0.04925	172.387
ATM11	34.91022	79.65359	0.215131	0.04281	149.8486
ATM12	32.35376	72.0553	0.194649	0.03967	138.8753
ATM13	50.22365	112.4407	0.303725	0.06159	215.58
ATM14	51.47663	116.3987	0.314381	0.06313	220.9583
ATM15	37.90862	83.66222	0.226012	0.04649	162.719
CS01	22.86107	51.641	0.139488	0.02803	98.12887
Mean	**39.31672**	**88.19636**	**0.238234**	**0.04821**	**168.7631**

Table 2: Calculated radiological hazard indices of sample collected from the active mining sites in the study area

Sample code	D (nGy/h)	Ra_{eq} (Bq/kg)	Hex	AEDE (mSv/y)	ELCR (x10^{-6})
MBD1	40.36796	92.30599	0.249274	0.04950	173.2754
MBD2	32.22965	72.68944	0.196314	0.03952	138.3426
MBD3	48.85948	109.7992	0.296566	0.05992	209.7244
MBD4	54.52353	121.9418	0.329395	0.06686	234.0368
MBD5	50.54011	113.3411	0.306163	0.06198	216.9383
MBD6	39.57265	89.02328	0.240469	0.04853	169.8617
MBD7	39.92421	89.37108	0.241417	0.04896	171.3707
MBD8	51.5634	116.8191	0.315533	0.06323	221.3308
MBD9	52.38473	118.0307	0.318796	0.06424	224.8562
MBD10	42.3155	93.92001	0.253702	0.05189	181.6351
MBD11	38.24495	86.95901	0.234862	0.04690	164.1626
MBD12	34.09542	75.46583	0.203868	0.04181	146.3512
MBD13	53.95532	121.4711	0.328107	0.06617	231.5978
MBD14	39.05529	88.49714	0.239033	0.04789	167.6409
MBD15	40.7955	91.37118	0.246805	0.05003	175.1106
CS01	22.86107	51.641	0.139488	0.02803	98.12887
Mean	**43.89518**	**98.73373**	**0.266687**	**0.05383**	**188.4157**

Table 1 and 2 presents the calculated radiological hazard indices of sample collected from the active mining sites in the study area. The calculated absorbed dose rate (D), radium equivalent activity (Ra_{eq}), external hazard index (Hex), annual effective dose equivalent (AEDE), and excess lifetime cancer risk (ELCR) are 39.32 nGy/h (43.89518 nGy/h**)**, 88.20 Bq/kg (98.73373 Bq/kg**)**, 0.238 (0.266687), 0.048 mSv/y (0.053.83 mSv/y), and 168.76 × 10^{-6} (188.4157x10^{-6}**)**, respectively, for the active (abandoned) mining sites.

The reported value of absorbed dose value for both active and abandoned mining sites are lower than the global average outdoor value (60 nGy/h), suggesting that the radiation exposure from the studied environment is relatively moderate. Similar studies in other countries have reported varying dose rates, such as 55.7 nGy/h in Tunisia [19], 51.5 nGy/h in Turkey [20], and 47.2 nGy/h in Nigeria [18]. Compared to these studies, the current absorbed dose rate is on the lower end of the spectrum, indicating minimal radiation exposure from external gamma radiation.

The recommended safety limit for Raeq in building materials is 370 Bq/kg. The reported Raeq value for both active and abandoned coal mining sites are significantly below this limit, indicating that the soil samples studied do not pose a significant radiological threat. For comparison, studies in Egypt, Iran, and Turkey reported Raeq values of 95.2 Bq/kg [16], 132.5 Bq/kg [2], and 107.9 Bq/kg [20], respectively. The current value is lower than these, reinforcing the conclusion of a low radiological hazard from naturally occurring radionuclides.

The external hazard index (Hex) is another important parameter that estimates the potential external radiation exposure from materials. To ensure safety, Hex should be less than 1. The reported external hazard index for both the active and abandoned coal mining sites are well within this safe limit, suggesting negligible external radiation risk. In comparison, reported values from other regions include

0.312 in Nigeria [18], 0.411 in Egypt [16], and 0.359 in Iran [2]. The current Hex value is significantly lower, indicating that radiation exposure from these materials is minimal and does not pose a significant hazard to human health.

Annual Effective Dose Equivalent is a critical parameter for evaluating human exposure to radiation. The global average outdoor AEDE is 0.07 mSv/y [21], and the recommended public dose limit is 1 mSv/y (ICRP, 1990). The reported AEDE value for both active and abandoned mining sites are below the recommended public dose limit. This suggests that individuals in the studied area are safe. In comparison, studies in Turkey and Nigeria reported AEDE values of 0.0632 mSv/y [20] and 0.057 mSv/y [17], respectively. The current AEDE in Benue State are within close range, indicating the populace living in close proximity to the coal mining sites are safe.

Excess Lifetime Cancer Risk measures the probability of developing cancer due to radiation exposure over a lifetime. The acceptable ELCR value is 0.29×10^{-3}. The reported ELCR the active and abandoned coal mining sites appears to be within this limit. However, since ELCR is derived from AEDE, and AEDE is extraordinarily high, the actual cancer risk could be much greater than currently estimated. Studies in Turkey and Nigeria reported ELCR values of 0.22×10^{-3} [20] and 0.17×10^{-3} [17], respectively, which are comparable to the current value.

4. Conclusion

The activity concentration analysis of soil samples collected from active and abandon coal mining site in Benue state reveals results that showed that ^{226}Ra and ^{232}Th concentrations were slightly above the global average, while ^{40}K levels were significantly lower than typical values reported in similar studies. The radiological assessment of the active and abandon mining sites indicates that all calculated parameters such as absorbed dose rate, radium equivalent activity, external hazard index, annual effective dose equivalent, and excess lifetime cancer risk are below the recommended safety limits. Although slightly higher values were observed at the abandoned sites compared to the active ones, both remain within acceptable radiological risk levels. Continuous monitoring is recommended to ensure long-term environmental and public safety.

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