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Assessment of Naturally Occurring Radionuclides in Soil around Coal Mining Areas in Benue State, Nigeria

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Abstract: In this study, the assessment of naturally occurring radionuclides in soil around coal mining areas in Benue State, Nigeria was determined. A total of thirty-one soil samples, which comprised fifteen each from the active and abandoned mining sites and one control sample, were collected, prepared, and sent for activity concentration analysis using Sodium Iodide (NaI) crystal doped with Thallium detector at the Centre for Research and Training, Zaria, Nigeria. The detector displayed specific gamma ray lines to determine the activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K. The raw results of activity concentration level in soil from both the active (abandoned) mining sites for ^{226}Ra, ^{232}Th, and ^{40}K are 38.3273$\pm$2.605083 Bq/kg (39.15679$\pm$2.697869 Bq/kg), 31.67017$\pm$1.98358 Bq/kg (37.9024$\pm$2.899206 Bq/kg), and 59.48989$\pm$3.52307 Bq/kg (69.82478$\pm$3.94225 Bq/kg), respectively. The results obtained were used to calculate radiological health hazard indices. The mean values of radiological hazard for active (abandoned) mining sites in the study area such as absorbed dose rate (D), radium equivalent activity (Raeq), 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), 48.22 mSv/y (53.83305 mSv/y), and 168.76 × 10^{-6} (188.4157x10^{-6}), respectively. The AEDE value is excessively high, posing a significant risk to human health. Mitigation measures, such as shielding or phytoremediation, should be implemented to reduce radiation exposure and prevent long-term health risks.

Keywords: Coal mining sites, activity concentration analysis, sodium iodide doped with thalium detector, and radiological hazard indices.

1 Introduction

The availability of mineral resources in an area serves to add to its economic growth through job creation, energy usage, and wealth generation [1]. The mining of mineral resources, such as coal, for economic growth often leads to radiological hazards that affect man and his environment [2].

Naturally occurring radionuclides, including uranium-238, thorium-232, and potassium-40, are present throughout the Earth's crust. However, human activities such as mining can significantly disturb their natural balance and lead to elevated levels in the environment. In coal mining regions, the disturbance of geological materials may enhance the release of these radionuclides into the surrounding soil, potentially increasing radiation exposure to humans and ecosystems [3-6]. Evaluating the presence and concentration of NORMs in soils near mining sites is therefore essential for understanding environmental radiation levels and guiding appropriate safety measures.

The study area is a region known for its coal and other mineral deposits. There have been a number of studies examining the environmental impact of mining activities. One such study by Jibiri and Temaugee [5] focused on the radiological properties of raw minerals and soils collected from various mining locations. Their findings indicated that soil samples had relatively high concentrations of ^{40}K, ^{238}U, and ^{232}Th, with values averaging 425.92 Bq/kg, 40.34 Bq/kg, and 33.69 Bq/kg, respectively. While the radiation dose rates observed (ranging from 52.25 to 64.00 nGy/h) were within international safety limits, the researchers emphasized the importance of continued monitoring due to

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the potential health risks associated with prolonged exposure.

In a related investigation, Agba, Onjefu, and Ugwuanyi [6]

examined radiation levels in the vicinity of mining operations involving salt, clay, and stone extraction in Benue State. They reported varying exposure rates across different sites, with the Mkar quarry exhibiting the highest recorded dose equivalent rate of 0.33 mSv/year. Despite the values falling below the 1.0 mSv/year exposure limit set by international guidelines, the study highlighted the necessity for ongoing assessment to ensure environmental safety and reduce long-term health risks [7].

These previous studies highlight the importance of tracking radioactive elements in mining regions. This research seeks to further investigate the concentrations of ^{238}U, ^{232}Th, and ^{40}K in soils near coal mining areas in Benue State. The goal is to provide updated data that can support risk assessment and contribute to sustainable environmental management.

2 Materials and Methods

2.1 Study Area

The study area of this research work is Effa Community, Okpokwu Local Government Area, Benue State, Nigeria, where coal mining is ongoing. There are two active and one abandoned coal mining site at the moment, a sizeable water body called the River Umabe, and streams in the community. The Effa community has boundaries with Awo and Okoko villages in Ankpa Local Government Area of Kogi State, North Central Nigeria, Ohimini and Ogbadibo Local Government Areas of Benue State. It is located to the right along the Otukpo – Ugbokolo – Okwungaga – Otukpa branch road in Ogbadibo, shortly after Ugbokolo.

Okpokwu Local Government is surrounded by Ogbadibo, Ohimini, Otukpo, and Ado Local Government Areas of Benue State. The Local Government also has boundaries with Enugu, Ebonyi, and Cross River States of Nigeria.

Okpokwu has three (3) districts of Edumoga, Ichama, and Okpoga. Effa is a community in the Edumoga district.

Benue State has a land mass of 34,059 square kilometres and is situated on longitude 7° 47' and 10° 0' East. Latitude 6° 25' and 8° 8' North with a population of 4.253,641 people based on the 2006 National Population Census. The rainy days are 160.01 annually, with a temperature of 29.38 °C (84.88 °F). The compositions of soil in the state are loamy, clay, sandy, and silt, and agriculture is a major occupation, with varieties of crops being the “food basket of the nation”. Benue state has about thirty-four (34) solid minerals, with major ones as limestone, coal, and granite [8]. Figure 1 shows the map of Benue State depicting the study area, Okpokwu Local Government Area.

Fig. 1: Map of Nigeria and Benue State showing the Study Area

2.2 Sample Collection, Preparation, and Analysis

In the study area at the moment, it is only in Effa Community, Okpokwu Local Government Area, that coal mining activities are taking place. The community has three coal mining sites, with one being abandoned, having exhausted its coal deposits, and two 2 active ones. The soil samples collected were air-dried to remove moisture content.

The samples were pulverized and sieved with a 2mm mesh to remove bigger particles such as stones, plant roots, coarse materials, and other debris to obtain a homogenous, fine-texture powder. Approximately 200 g of each texture was poured into a new polyethylene bag, tightly sealed with a rubber band, and correctly labelled for ease of identification according to the locations and sent for analysis at the Centre for Energy Research and Training, Zaria.

A Sodium Iodide crystal doped with Thallium detector was used to determine the activity concentration of ^{238}U, ^{232}Th, and ^{40}K. Geometry as a factor was put to use at the time of measurement, so that samples that had been prepared had the same standard geometry for height, density, and volume. At the laboratory, the background radiation was measured before measurement with an empty container under the same environmental conditions, and the value was subtracted during activity concentration computation. In each batch of samples, quality assurance measures such as blanks, standards, duplicates, and certified reference materials were included. The detector displayed a wide range of energy for the analysis of a larger number of radionuclides. Specific gamma ray lines were used to determine the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K [9-12].

2.3 Radiological Hazard Indices

2.3.1 Gamma Absorbed Dose Rate

Gamma Absorbed Dose Rate (D) was 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 [13] as:

$$D = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_{K} \quad (1)$$

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 ^{137}Cs, ^{235}U, ^{87}Rb, ^{90}Sr, ^{138}La, ^{147}Sm, and ^{176}Lu to the total dose rate is negligible. UNSCEAR reported that the world average absorbed gamma dose rate mean is 55nGyh^{-1}.

2.3.2 Measurement of Radium Equivalent Activity

Radium Equivalent Activity (Ra_{eq}) was determined using the weighted sum of activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, as expressed by Balogun et al. [14] as:

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_{K} \quad (2)$$

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

2.3.3 Measurement of 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 1mSv/y, as expressed by UNSCEAR [13], as:

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \leq 1 \quad (3)$$

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

2.3.4 Measurement of Annual Effective Dose Rate

Annual Effective Dose Rate (AEDR) was 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 that adults receive, as expressed by UNSCEAR [13] as:

$$AEDR = D \times 8760 \times 0.2 \times 0.7 \times 10^{-3} \quad (4)$$

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.

2.3.5 Measurement of Excess Life Cancer Risk

Excess Life Cancer Risk (ELCR) was determined by the product of AEDR with Duration of Life (DL), 70 years for children and 50 years for adults, and a low dose background radiation Risk Factor (RF) of 5% for public exposure considered to produce stochastic effect as expressed in Jibiri, & Okeyode. [14] as :

$$ELCR = AEDR \times RF \times DL \quad (5)$$

Where AEDE is the Annual Effective Dose Equivalent, DL is the Duration of Life, which is 70 years for children and 50 years for adults, 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 the soil from both the active and abandoned mining sites of the study area are determined. Figures 2 and 3 present the raw results of the activity concentration level of soil from active mining sites and abandoned mining sites, respectively, in the study area.

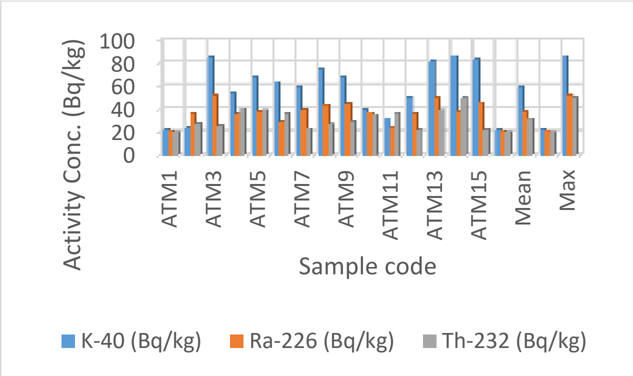

Fig. 2: Comparison of the raw result of the activity concentration level of soil from the active mining site in the study area.

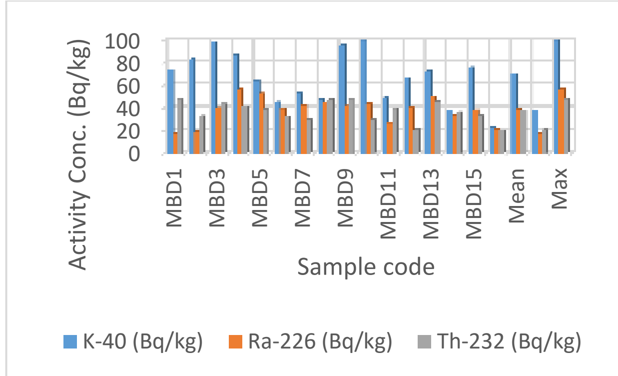

Fig. 3: Comparison of the raw result of the activity concentration level of soil from abandoned mining sites in the study area.

Figure 2 presents the raw result of the 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 (UNSCEAR) 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.

Figure 3 presents the raw results of the 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 abandoned 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 [14-20].

Table 1: Calculated radiological hazard indices of samples collected from the active mining site in the study area.

Sample Code	GPS (N/E)	D (nGy/h)	Ra_{eq} (Bq/kg)	Hex	AEDE (mSv/y)	ELCR ($x10^{-6}$)
ATM1	$07^0$93.736’/$03^0$59.350’	22.86107	51.64099	0.139488	0.02803	98.12885
ATM2	$07^0$93.724’/$03^0$59.345’	34.83784	78.50977	0.212076	0.04272	149.5379
ATM3	$07^0$93.714’/$03^0$59.343’	43.14787	95.38764	0.257688	0.05291	185.2079
ATM4	$07^0$93.704’/$03^0$59.343’	43.28225	97.93744	0.264528	0.05308	185.7847
ATM5	$07^0$93.693’/$03^0$59.346’	44.30489	99.81102	0.269594	0.05433	190.1743
ATM6	$07^0$93.681’/$03^0$59.350’	38.17417	86.2539	0.232965	0.04681	163.8588
ATM7	$07^0$93.668’/$03^0$59.352’	34.84882	77.48293	0.209312	0.04273	149.5851
ATM8	$07^0$93.676’/$03^0$59.339’	39.72641	88.32349	0.238592	0.04872	170.5217
ATM9	$07^0$93.674’/$03^0$59.332’	41.53367	92.64636	0.250266	0.05093	178.2791
ATM10	$07^0$93.666’/$03^0$59.326’	40.16098	90.74135	0.245102	0.04925	172.387
ATM11	$07^0$93.655’/$03^0$59.320’	34.91022	79.65359	0.215131	0.04281	149.8486
ATM12	$07^0$93.653’/$03^0$59.310’	32.35376	72.0553	0.194649	0.03967	138.8753
ATM13	$07^0$93.647’/$03^0$59.300’	50.22365	112.4407	0.303725	0.06159	215.58
ATM14	$07^0$93.636’/$03^0$59.294’	51.47663	116.3987	0.314381	0.06313	220.9583

ATM15 07^{0}93.645’/03^{0}59.283’	37.90862	83.66222	0.226012	0.04649	162.719
CS01 07^{0}93.170’/03^{0}62.212’	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 samples collected from the abandoned mining site in the study area.

Sample Code GPS (N/E)	D (nGy/h)	Ra_{eq} (Bq/kg)	Hex	AEDE (mSv/y)	ELCR (x10^{-6})
MBD1 07^{0}93.820’/03^{0}59.633’	40.36796	92.30599	0.249274	0.04950	173.2754
MBD2 07^{0}93.821’/03^{0}59.685’	32.22965	72.68944	0.196314	0.03952	138.3426
MBD3 07^{0}93.821’/03^{0}59.671’	48.85948	109.7992	0.296566	0.05992	209.7244
MBD4 07^{0}93.822’/03^{0}59.659’	54.52353	121.9418	0.329395	0.06686	234.0368
MBD5 07^{0}93.816’/03^{0}59.631’	50.54011	113.3411	0.306163	0.06198	216.9383
MBD6 07^{0}93.818’/03^{0}59.616’	39.57265	89.02328	0.240469	0.04853	169.8617
MBD7 07^{0}93.814’/03^{0}59.594’	39.92421	89.37108	0.241417	0.04896	171.3707
MBD8 07^{0}93.812’/03^{0}59.578’	51.5634	116.8191	0.315533	0.06323	221.3308
MBD9 07^{0}93.826’/03^{0}59.566’	52.38473	118.0307	0.318796	0.06424	224.8562
MBD10 07^{0}93.825’/03^{0}59.520’	42.3155	93.92001	0.253702	0.05189	181.6351
MBD11 07^{0}93.825’/03^{0}59.527’	38.24495	86.95901	0.234862	0.04690	164.1626
MBD12 07^{0}93.826’/03^{0}59.511’	34.09542	75.46583	0.203868	0.04181	146.3512
MBD13 07^{0}93.823’/03^{0}59.485’	53.95532	121.4711	0.328107	0.06617	231.5978
MBD14 07^{0}93.820’/03^{0}59.471’	39.05529	88.49714	0.239033	0.04789	167.6409
MBD15 07^{0}93.809’/03^{0}59.439’	40.7955	91.37118	0.246805	0.05003	175.1106
CS01 07^{0}93.170’/03^{0}62.212’	22.86107	51.641	0.139488	0.02803	98.12887
Mean	**43.89518**	**98.73373**	**0.266687**	**0.05383**	**188.4157**

Tables 1 and 2 present the calculated radiological hazard indices of samples collected from the active (abandoned) mining sites in the study area. The calculated absorbed dose rate (D), radium equivalent activity (Raeq), 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 values of absorbed dose for both active and abandoned mining sites are lower than the global average outdoor value (60nGy/h), suggesting that the radiation exposure from the studied environment is relatively moderate [21]. Similar studies in other countries have reported varying dose rates, such as 55.7nGy/h in Tunisia [22], 51.5nGy/h in Turkey [23], and 47.2nGy/h in Nigeria [24]. 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 370Bq/kg. The reported Raeq value for both active and abandoned coal mining sites is 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 95.2Bq/kg [14], 132.5Bq/kg [15], and 107.9Bq/kg [23], 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), 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 is well within this safe limit, suggesting negligible external radiation risk. 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 radiation exposure. The global average outdoor AEDE is 0.07mSv/y [13], and the recommended public dose limit is 1mSv/y [8]. The reported AEDE value for both active and abandoned mining sites is below the recommended public dose limit. These suggest that individuals in the studied area are safe. In comparison, studies in Turkey and Nigeria reported AEDE values of 0.0632mSv/y [23] and 0.057mSv/y [24], respectively. The current AEDE in Benue State is within range, indicating that the populace living near the coal mining sites is 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} [8]. The reported ELCR around 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} [23] and 0.17×10^{-3} [24], respectively, which are comparable to the current value.

4 Conclusions

The activity concentration analysis of soil samples collected around the active and abandoned coal mining sites in Benue state 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 abandoned 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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