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RESEARCH ARTICLE

Radiological Impact Assessment of Mine-Residue from Coal Mining Sites at Awulu-Ika, in Kogi, North-central Geopolitical Region of Nigeria

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Abstract: Coal, as a fossil fuel, plays a vital role in the economic development of nations globally. However, the radiological impact due to coal mining may pose significant health risks to humans. Consequently, it is important to evaluate the radiological impact of coal mining in various regions worldwide. This study focuses on Awulu-Ika in Kogi, Nigeria's north-central geopolitical region, as a representative case. Sixty-two (62) mine-residue samples were randomly collected from the study area, and the activity concentrations of ^{40}K, ^{226}Ra and ^{232}Th were measured using a well-calibrated NaI (Tl) detector. Radiological parameters, including gamma absorbed and effective dose rates as well as hazard indices, were calculated using the activity concentrations of the radionuclides obtained in the study. The activity concentrations of ^{40}K ranged from below detectable levels (BDL) to 504.2 Bq/kg, ^{226}Ra ranged from BDL to 193.8 Bq/kg, and ^{232}Th ranged from BDL to 115.8 Bq/kg. The mean activity concentration of each radionuclide in the samples was lower than the world-recommended values. The mean effective dose rate of 26.21 µSv/year obtained in the study is significantly below the value recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Although the radioactivity levels in the mine residues are low and may not pose any short-term radiological health effects, long-term exposure to radiation in the area, as well as in similar regions globally, may be detrimental to human health. This underscores the importance of continuous monitoring and assessment of radiological impacts in coal mining areas worldwide to ensure public health safety.

Keywords: *Awulu-Ika, coal mining, mine-residue, Nigeria, north-central, Radiological assessment*

Introduction

Coal is a sedimentary rock (Greb *et al.*, 2017), that is either black or brownish-black, and mostly comprising carbon of about 50% to 70% by mass (Wang *et al.*, 2019). Coal is formed through the heat, pressure, and chemical alteration of plant remains (Alpern and Lemos de Sousa, 2002, Suárez-Ruiz *et al.*, 2019). During this process, plant first transforms into peat, and then undergoes progressive coalification stages including lignite, sub-bituminous coal, bituminous coal, and finally anthracite. The formation of peat from plant is associated with bio-chemical processes and formation of coal from peat is linked to physical and geological processes (Bao *et al.*, 2023). Coal is widely used for electricity generation on a large scale and, due to its combustibility, serves as a primary heating source in households across developing countries such as Nigeria, India, and Bangladesh Michael *et al.*, (2020). In 2016, it was reported that coal contributed about 44% of world carbon dioxide emitted to the atmosphere which exceeded both the oil and natural gas emission (IEA, 2018). Apart from the burning of coal that releases carbon dioxide, the mining and processing of coal may be detrimental to the environment and human health (Juciano and Kátia, 2021).

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Nigeria has been known for commercial mining of coal and other minerals such as tin and tantalum since early 20th century (Nwadialor, 2011). The occurrence of coal was first discovered in 1909 at the Udi Ridge in Enugu. The revenues from coal contributed approximately 0.3% of the Gross Domestic Product (GDP) of Nigeria. However, with the discovery of crude oil in Olobiri in 1956, the attention of the government shifted towards the production of petroleum; as a result, the mining of coal and other minerals was not patronized.

In recent years, there has been growing concern about coal mining activities due to the potential radiological health hazards, including increased risks of cancer, genetic mutations, and organ damage due to prolonged exposure to radioactive elements such as uranium, thorium, and radon, to the general public (Itodo *et al.*, 2020, Wysocka *et al.*, 2022). Kolo *et al.*, (2017) reported that the ionizing radiation doses potentially ingested by residents near coal plants could pose significantly higher long-term health risks than those in the vicinity of nuclear power plants. Cortes-Ramirez *et al.*, (2022) and Michael *et al.*, (2020) reported that people living around coal deposits mined as open pits suffer from cardiovascular, kidney, respiratory, dental, and cancer diseases. These diseases can occur because human cells are highly significant and their function is defined by the structure of their constituent molecules; thus, exposure to ionizing radiation may perturb the chemical balance and functions of the cell. The objective of this work was to assess the radiological impact of coal mining on the inhabitants of Awulu-Ika in Kogi, Nigeria's north-central geopolitical region, and to compare the results with globally recommended values for primordial radionuclides, thereby providing insights applicable to coal mining regions worldwide.

Materials and Methods

The Study Area

Awulu-Ika consists of two adjacent villages in Ofugbo, located approximately 170.5 km from Lokoja in Kogi's north-central geopolitical zone of Nigeria (Fig. 1). The area has an estimated population of around 115,100 and has substantial sub-bituminous coal deposits, which contribute significantly to the local economy through small- and large-scale mining activities. Also, many residents engage in crop farming and livestock rearing, and in addition, Awulu-Ika is one of the more accessible regions in the area, benefiting from relatively good road networks that facilitate transportation and trade. Figure 1 shows the geological map of the study (Nigerian Geological Survey, 2023).

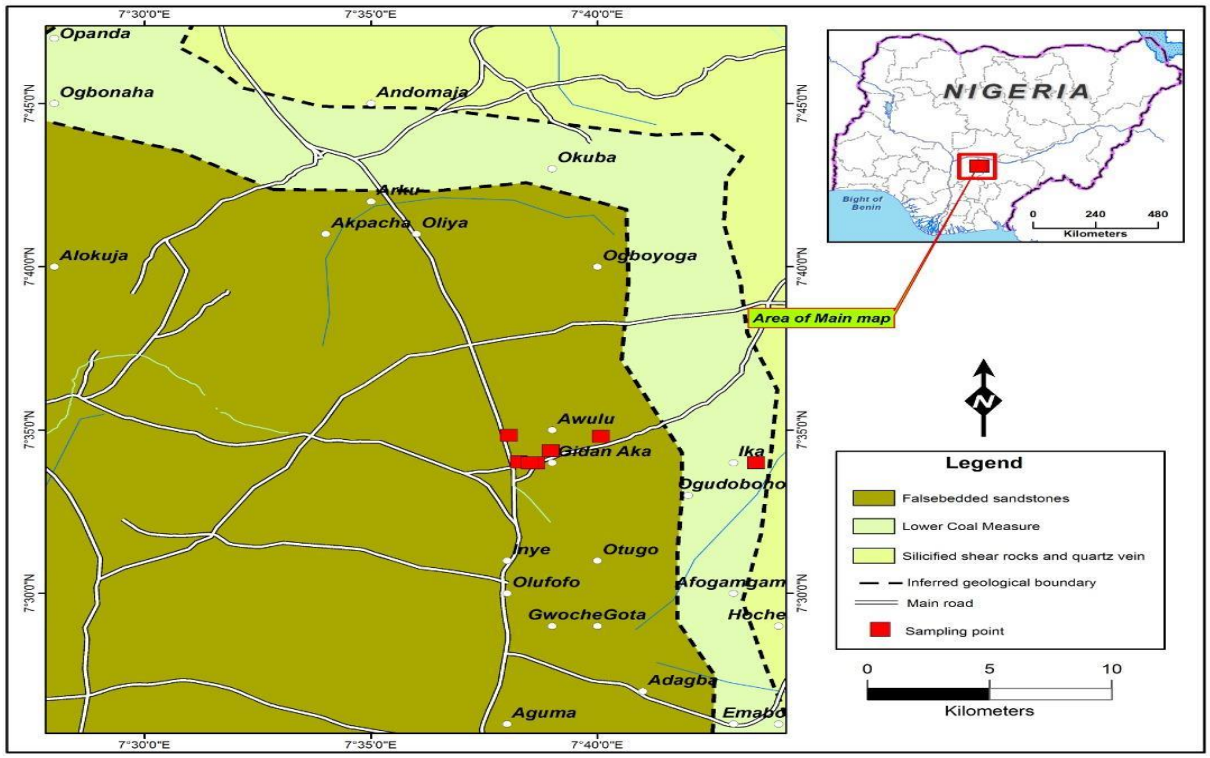

Figure 1. Map of Kogi showing the mining area samples were taken

Sample Collection

Samples of mine residues were collected from the mining sites in Awulu-Ika community, Kogi State, in the north-central region of Nigeria (Fig. 1). Sixty-four mine-residue samples were collected in the study area covering 80% of the mining site for large sample representation. Each of the samples collected was kept in clean nylon bags, numbered for easy identification.

Sample Preparation

Each sample was dried in an oven at 110 °C for four hours to remove moisture before being thoroughly pulverized to a powdery form to attain a constant mass. A 2.0 mm mesh sieve was used to ensure all samples matched the grain size of the reference soil samples used for calibration; this was to ensure accuracy and reliability of the analysis. Only 200 g of each sample was weighed into a clean plastic container of uniform dimensions and sealed. The gamma spectroscopy was followed after the sample was kept for four weeks to attain secular equilibrium of Rn-222 (^{222}Rn) with its daughter radionuclide.

Radioactivity measurements

The setup consists of a NaI (Tl) gamma-ray spectrometry and a multichannel computer-resident quantum. NaI (Tl) is the commonest scintillating detector suitable for counting the radioactivity levels in environmental samples because it has sufficient energy resolution to distinguish different radionuclides in environmental samples, particularly low-level environmental radioactivity measurements (Aruna *et al.*, 2025) The detector system uses a high voltage of 550 volts with Amplifier Coarse gain of 3.6 and Shaping Time of 0.75µs. The system has energy resolution of 8% (^{137}Cs) and 20% counting efficiency. The detector was kept in a vertical position in a lead cylindrical shield of 10 cm thickness, 55 cm height and a removable shielded cover. NaI(TI) exhibited a typical resolution (full width at half maximum) of 60 keV at 1.33 MeV ^{60}Co (El-Gamal *et al.*, 2019). The Multichannel Analyzer programme (MCA8K-01) examined the accumulated spectra data after each sample was analyzed for naturally occurring radionuclide activity for 36000s. Prior to the counting of the samples, the background gamma-ray was measured using empty sample container and the efficiency of the detector was determined using a reference standard mixed source traceable to Analytical Quality Control Service (AQCS, USA) that has confirmed activities of the specified radionuclide and a geometrical configuration equal to the sample container, the efficiency calibration of the detector was carried out. Equation 1 (Dedawan *et al.*, 2022)shows the determination of the activity concentration of a radionuclide in the samples.

$$C = \frac{C_R}{\sum I_\gamma m_s} \quad (1)$$

where:

C represents the activity concentration (in Bq/kg) of the radionuclide in the mine-residue, C_R represents the disintegration per second, ε represents the efficiency, and I_γ represents the gamma-ray yield, while m_s represents the mass of the sample (kg). The activity concentrations of radionuclides in the sample and the detection limits (DL) were obtained using software (Quantum MCA software). The DLs were 12.5 Bq/kgfor ^{40}K, 2.3 Bq/kg for ^{226}Ra, and 1.8 Bq/kg for ^{232}Th. According to Mbonu and Ben, (2021)When the concentration of any radionuclide is below the detection limit required, one-half of the DL is used in calculating the radiological risks or effects.

Outdoor gamma absorbed dose

Outdoor gamma absorbed dose is an expression of risk assessments related to radionuclide interactions in environmental matrices, including water, soils, sediment, plants, and aquatic ecosystems. It is determined to assess radiation risks to the population living in areas with naturally occurring radionuclides or anthropogenic radioactive contamination. According to ICRP, one (1) meter as a standard height for gamma radiation monitoring, representing the breathing zone and average human trunk level, where most of the body's vital organs are located. The outdoor gamma absorbed dose in the study is determined using the model expressed in equation 2.

$$D_R = 0.416C_{Ra} + 0.623C_{Th} + 0.0414_{Ck} \quad (2)$$

where:

D_R (nGy/h) represents the outdoor gamma absorbed dose and C_{Ra}, represents the activity concentration of ^{226}Ra, C_{Th} represents the activity concentration of ^{232}Th and C_K represents the activity concentration of ^{40}K.

Effective dose

The effective dose H_E due to activity concentrations of radionuclides in the samples was evaluated using a model from (UNSCEAR, 2000)

$$H_E = D_R x 0.7\ x 0.2 x 8760 \quad (3)$$

where: D_R (nGy/h) represents the gamma absorbed dose, 0.2 represents the occupancy factor, 0.7 represents the conversion factor recommended by

UNSCEAR and 8760 (h/y) is the number of hours per year

Radium equivalent activity

Radium equivalent activity (Ra_{eq}) is commonly used as an index to compare the activity concentrations of radionuclides in a sample. Ra_{eq} provides a single value to estimate the external radiation hazard posed by a material. It is the addition of the activity concentrations of the natural radionuclide in the sample, which is based on the evaluation that 130 Bq/kg (^{40}K), 10 Bq/kg (^{226}Ra), and 7 Bq/kg (^{232}Th) will give the same absorbed gamma dose (Júnior *et al.*, 2021). The internationally accepted safety limit is 370 Bq/kg**,** high Ra_{eq} values indicate that the material is not suitable and may pose long-term radiation risks to occupants. However, the radium equivalent was determined using (Devanesan *et al.*, 2020) for the present study.

$$Ra_{eq} = 0.077C_k + C_{Ra} + 1.43C_{Th} \quad (4)$$

where:

C_K represents the activity concentration of ^{40}K; C_{Ra} represents the activity concentration of ^{226}Ra, and C_{Th} represents the activity concentration of ^{232}Th.

External hazard index

External hazard due to emission of natural gamma radiation, which must not exceed a unit (1.0), is a decisive standard used to assess the radiological suitability of any material; it helps identify regions with radiological contamination from natural sources or anthropogenic activities such as mining. For radiological safety, H_{ex} must be ≤ 1 to ensure that the external radiation hazard remains within safe limits; otherwise, remediation, restricted use, or further radiological analysis may be recommended**.** This index was determined using Purnama and Damayanti, (2020) model:

$$H_{ex} = \frac{C_k}{4810} + \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} \leq 1 \quad (5)$$

where:

C_K, represents the activity concentration of ^{40}K, C_{Ra} represents the activity concentration of ^{226}Ra and C_{Th} represents the activity concentration of ^{232}Th.

Internal hazard index

Human respiratory organs are at risk when exposed to ^{222}Rn gas due to the decay of ^{226}Ra. Prolonged radon inhalation is linked to lung cancer**,** The Internal hazard index is a crucial index for health risk assessments in homes and workplaces. If H_{in}> 1, the material may pose serious internal exposure risks**,** requiring ventilation measures or material substitution**.** This is referred to as the internal hazard index and it was calculated using Purnama and Damayanti, (2020) model:

$$H_{ex} = \frac{C_k}{4810} + \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} \leq 1 \quad (6)$$

where:

C_K, represents the activity concentration of ^{40}K, C_{Ra} represents the activity concentration of ^{226}Ra, and C_{Th} represents the activity concentration of ^{232}Th.

Gamma index

A hazard factor used to compare the annual dose rate due to the excess external gamma radiation dose caused by any superficial materials is referred to as the gamma index (I_γ). It is a useful screening instrument to identify any radiologically unsafe building material for dwelling construction (Najam *et al.,* 2015). The index was determined using the European Commission's proposed model as referenced by John *et al.*, (2022):

$$H_\gamma = \frac{C_k}{3000} + \frac{C_{Ra}}{300} + \frac{C_{Th}}{200} \quad (7)$$

where:

C_K, represents the activity concentration of ^{40}K, C_{Ra} represents the activity concentration of ^{226}Ra, and C_{Th} represents the activity concentration of ^{232}Th. This was calculated using equation 7. The activity concentrations of ^{40}K were divided by 3000, which is the equivalent conversion value while the concentrations of ^{226}Ra were also divided by 300 and the concentrations of ^{232}Th were also divided by 200 which is the equivalent conversion value, and three values were added together to give gamma index value. This calculation was aided by excel spread sheet for easy calculation.

Results and Discussion

Activity concentrations of ^{40}K, ^{226}Ra and ^{232}Th in the mine residues from the study area

The activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th in the samples were measured and the results are as presented in Table 1. The error noted in each sample is the uncertainty from the spectrometry detector, while the errors on each mean value are the standard deviations (SD).

The activity concentrations of ^{40}K ranged from below detectable level (BDL) to 504.2 Bq/kg with a mean of 94.2 Bq/kg (SD: ±10.1 Bq/kg). The ^{226}Ra ranged from BDL to 193.8 Bq/kg with a mean of 37.9 Bq/kg (SD: ±6.3 Bq/kg), and ^{232}Th between BDL and 15.75 Bq/kg with a mean of 6.3 Bq/kg (SD: ±2.5 Bq/kg). However, the results showed that ^{40}K has the widest range (BDL to 504.2 Bq/kg), indicating significant variability in its concentration across the samples while ^{226}Ra has a moderate range (BDL to 193.8 Bq/kg) and ^{232}Th has the narrowest range (BDL to 15.75 Bq/kg), suggesting more consistent concentration levels. Further, the mean concentration of ^{40}K (94.1 Bq/kg) is significantly higher than that of ^{226}Ra (37.9 Bq/kg) and ^{232}Th (6.3 Bq/kg). This shows that ^{40}K is more in the samples compared to the other radionuclides; meanwhile, ^{226}Ra decays into ^{222}Rn (radon), a radioactive gas that can accumulate in enclosed spaces, increasing lung cancer risks. making it the most hazardous, ^{232}Th is less bioavailable with its longest half-life (approximately 14 billion years) compared to ^{226}Ra, ^{232}Th, which is also hazardous in specific conditions, particularly if inhaled or ingested in fine particulate form**,** while ^{40}K is the least detrimental due to its short biological half-life. The findings in the study are comparable to a few others, as shown in Table 2. However, the results clearly indicate that the activity concentrations of the radionuclides are lower than the world recommended values of 400 Bq/kg for ^{40}K, 40 Bq/kg for ^{226}Ra, and 35 Bq/kg for ^{232}Th. The lower concentrations suggest negligible radiation exposure with insignificant possible adverse health effects. However, the activity concentrations of 155.8 ± 32 Bq/kg and 160.6 ± 5.9 Bq/kg reported for ^{40}K in coal wastes from Palembang and Kalimantan, respectively (Marpaung *et al.*, 2018) and 120 Bq/kg reported for ^{40}K in coal from Serbia (Janković *et al.*, 2011) are higher than values in this study. Marpaung *et al.*, (2018) reported the activity concentration of 112.8±13.1 Bq/kg and 52.0±2.3 Bq/kg for ^{232}Th in coal waste from Palembang and Kalimantan, respectively. The present study showed that the results of ^{232}Th are over 33% and 12% lower than the respective values for ^{232}Th in coal waste from Palembang and Kalimantan from Indonesia (Humaira *et al.,* 2019). The activity concentration of 18.40 Bq/kg for ^{232}Th reported in coal around Turkey(Akkurt and Günoğlu, 2014) was three times higher than the values obtained in this study. The activity concentration of ^{226}Ra in this study is slightly lower than the world recommended value of 40 Bq/kg. (Ismael *et al.*, 2018), reported the activity concentration of 378 ± 2 Bq/kg for ^{226}Ra in coal ash from Kiwira, Tanzania; this value is approximately ten times higher than the value obtained in this study. It is important to note that activity concentrations of natural radionuclides in any region of the world depend on factors such as geological formations, mineral composition, weathering processes, and human activities, including mining and industrial waste disposal.

Outdoor gamma absorbed and effective doses in the study

The outdoor gamma absorbed dose (D_R) due to radiation exposure in the study area has been calculated, and the results are presented in Table 1. The least absorbed dose rate was 10.64 while the highest value was 72.30 nGy/h, and the mean 30.69 nGy/h; thus, the average absorbed dose obtained in the present study is lower compared to the 55 nGy/h recommended by the United Nation's Scientific Committee on Effects of Atomic Radiation (UNSCEAR, 2000).The mean effective dose (H_R) rate value of 26.21 µSv/y presented in Table 1 is lower than 0.460 µSv/y value from terrestrial radionuclides in normal background areas (UNSCEAR, 2000). The values of D_R, H_R, indicate that the radiation exposure from the studied area is significantly lower than the global average, and this suggests minimal radiological health risks to the populace.

From Table 1, the activity concentration of ^{40}K was the highest among the three radionuclides, indicating that ^{40}K is abundant in the study area, followed by ^{226}Ra, with a mean of 37.45, indicating a lower average concentration, and ^{232}Th, which had the lowest concentration**.** This result is reflected in standard deviation (SD) value of 117.78 for ^{40}K, to indicating high variability in the concentration in all the samples and ^{226}Ra with (SD) of 29.05, showing moderate variability, whereas ^{232}Th of (SD) 3.23, this means that a lower concentration value compared to the other two radionuclides. When comparing the sampling points, sample 19 has the highest values of 504.2 ± 15.1**,** 193.8 ± 5.2, and 15.8 ± 7.5 for ^{40}K, ^{226}Ra, and ^{232}Th, respectively. Samples 8 and 19 have higher values in contrast to other sampling points. However, some samples were below the detectable limit, indicating areas with very low radioactivity.

Table 1. Activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th, absorbed dose, and effective dose in the study.

Sample points	^{40}K (Bq/kg)	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	D_R (nGy/h)	H_R (μSv/y)
1	226.2±10.1	38.4±4.7	2.0±0.3	37.42	30.52
2	204.5±10.2	33.7±4.2	1.8±0.2	30.88	25.17
3	293.4±10.2	42.3±2.3	12.4±1.3	48.12	39.23
4	265.4±10.1	33.5±4.4	11.0±2.2	40.69	33.17
5	333.1±10.13	34.3±5.8	11.4±2.6	44.91	36.62
6	301.8±10.2	26.5±6.3	5.08±1.8	34.18	27.87
7	BDL	BDL	1.42±0.2	10.64	0.86
8	BDL	BDL	BDL	72.30	0.59
9	113.8±34.0	37.9±2.1	6.9±2.2	32.44	26.45
10	114.1±10.3	29.9±3.4	6.2±3.5	27.37	22.32
11	BDL	37.0±1.1	7.35±0.2	26.42	21.54
12	34.7±15.2	36.9±4.2	6.6±4.3	25.78	21.02
13	232.4±45.1	58.3±8.2	11.8±0.2	53.69	43.78
14	210.1±65.0	46.3±3.4	10.6±0.4	44.83	36.55
15	BDL	79.1±1.2	6.1±4.3	49.29	40.19
16	BDL	63.2±8.6	5.4±2.7	39.82	32.47
17	16.1±15.1	32.7±5.3	6.2±3.7	23.97	19.55
18	14.5±14.2	26.6±2.7	5.5±0.9	19.94	16.25
19	504.2±15.1	193.8±5.2	15.8±7.5	22.13	180.49
20	456.7±10.3	155.88±4.3	10.29±0.2	18.81	153.47
21	59.62±15.12	55.92±4.6	2.8±0.2	36.80	30.01
22	53.9±12.4	44.6±4.7	2.5±1.3	29.85	24.34
23	223.7±14.1	38.6±3.1	10.5±2.5	41.13	33.54
24	202.7±15.2	31.3±1.7	9.0±1.3	34.76	28.35
25	67.2±14.1	46.5±6.1	7.2±3.4	35.13	28.65
26	60.9±65.3	37.7±4.1	6.4±3.2	29.21	23.82
27	71.2±15.1	20.9±2.1	4.73±3.4	18.96	15.46
28	64.7±13.1	16.7±2.0	4.21±1.3	15.86	12.93
29	84.9±13.5	29.8±2.1	12.34±1.2	30.38	24.77
30	77.5±25.2	63.7±2.0	10.98±1.1	48.18	39.29
31	67.1±15.1	53.7±2.7	7.2±3.2	39.19	31.95
32	60.7±15.2	70.3±2.7	6.43±1.7	47.69	38.89
33	42.6±15.1	57.0±5.0	10.92±2.2	42.57	34.71
34	38.2±45.2	63.5±3.1	9.8±1.7	45.23	36.88
35	BDL	50.3±15.2	5.5±1.5	32.56	26.55
36	BDL	47.2±2.6	4.82±1.8	30.31	24.71
37	BDL	38.5±5.3	5.43±1.9	25.85	21.08
38	BDL	44.6±10.2	4.85±2.1	28.85	23.52
39	35.6±15.2	35.2±9.2	6.94±1.8	25.09	20.45
40	BDL	28.4±5.1	6.2±2.2	20.65	16.84
41	34.7±11.2	22.2±11.2	3.9±1.7	15.45	12.60
42	56.7±25.1	20.6±5.1	3.4±2.3	14.23	11.60
43	62.1±15.2	16.7±5.2	8.0±3.1	18.56	15.13
44	56.3±17.2	36.3±9.2	7.2±1.1	28.76	23.45
45	178.7±15.12	20.8±9.2	4.1±2.7	23.96	19.54
46	161.6±14.2	16.8±9.2	4.2±2.3	20.87	17.01
47	96.3±12.1	36.3±9.2	4.38±1.3	23.82	19.42
48	BDL	28.6±9.2	3.9±2.3	19.09	15.57
49	54.3±10.5	BDL	3.9±1.7	28.64	2.33
50	53.8±25.1	BDL	3.4±2.6	25.53	2.08
51	58.9±16.1	28.3±9.1	5.6±1.3	20.22	16.48

Table 1 continued

52	BDL	22.1±9.7	5.0±2.4	16.27	13.27
53	18.3±2.5	27.6±9.1	3.5±3.2	19.16	15.62
54	16.6±3.2	22.6±8.2	3.1±2.1	15.98	13.03
55	BDL	20.4±9.3	6.4±3.2	16.32	13.31
56	BDL	17.4±6.3	5.7±1.9	14.09	11.49
57	78.2±22.1	33.0±9.3	4.4±2.0	25.95	21.16
58	70.7±21.1	25.9±5.0	3.9±1.5	21.16	17.26
59	68.4±15.2	25.8±9.1	8.7±2.2	24.59	20.05
60	57.42±15.12	29.8±3.1	7.79±4.2	25.59	20.86
61	BDL	5.4±2.7	4.49±2.7	63.84	5.20
62	BDL	4.3±1.9	4.0±1.2	54.17	4.41
63	97.1±35.1	46.1±5.2	6.98±3.1	36.27	29.57
64	86.3±31.2	36.5±5.2	6.2±1.1	29.70	24.22
Mean ± SD	**94.2±10.1**	**37.9±6.3**	**6.3±2.5**	**30.69±26**	**26.71±3.6**

BDL = below detection limit

Table 2. Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the study compared with the values in some similar studies from other countries.

Country	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	References
Serbia	29.8	21.4	120	Janković *et al.*, (2011)
Turkey	110.37	18.4	191.45	Akkurt and Günoğlu, (2014)
Indonesia	3604	112.5	115.8	Marpaung *et al.*, (2018))
Tanzania	41.3	37.2	293.8	Ismael *et al.*, (2018)
Egypt	82	112	776	Akortia *et al.*, (2021)
Cyprus	363.5	370.43	1168	Butt *et al.*, (1998)
India	110.34	22.56	321.9	Janković *et al.*, (2011)
Ghana	356	33.2	-	Nisha *et al.*, (2016)
Pakistan	111.2	98.7	-	Xinwei *et al.*, (2005)
Nigeria	37.9	6.3	94.2	Present study

Table 3. Radium equivalent (Ra_{eq}), internal hazard index (H_{in}), external hazard index (H_{ex}), and gamma (I_γ) representative index in the study.

	Ra_{eq} (Bq/kg)	H_{in}	H_{ex}	I_γ
Minimum	0.19	0.01	0.01	0.01
Maximum	790.19	1.59	1.07	2.97
Mean	139.59	0.25	0.16	0.46
SD	145.03	0.24	0.16	0.62

Radiological hazard indices in the study

The results of the radium equivalent obtained in the study are presented in Table 3. The maximum radium equivalent in the study was 790.19 Bq/kg, while the minimum was 0.19 Bq/kg. The mean radium equivalent value of 139.59 Bq/kg is about 38% lower than the world average of 370 Bq/kg reported by UNSCEAR, (2000). The range of 4.5 – 49.8 Bq/kg for radium equivalent in coal from the Maiganga coal field in North-Eastern Nigeria (Matthew et al., 2017) is lower than the values obtained in this study. However, the radium equivalent value of 150.09 Bq/kg (Akkurt and Günoğlu, 2014) in coal from Turkey is very close to the mean value obtained in the present study. Table 3 presents the internal hazard index, external hazard index, and gamma hazard index in the study. However, the criterion demands that each of the three indices must be less than or equal to one ($H_{in} \leq 1$; $H_{ex} \leq 1$ and $I_\gamma \leq 1$) as a radiological safety rule for using any material for the construction of living homes. The values range widely, indicating significant variability in the radioactivity of the samples, and it shows that most samples have a H_{in} well below the safety threshold, although some samples having values ($H_{in} > 1$) that exceed the safety limit and this suggests that certain samples may pose a radiological health risk if used for dwellings. In general, the average values for H_{in}, H_{ex}, and I_γ indices in the study are within acceptable limits.

Conclusion

The activity concentrations of the natural radionuclides (^{40}K, ^{226}Ra, and ^{232}Th) in the mine residue from Awulu-Ika are lower compared to the world-recommended limits. The average absorbed dose and effective dose in the study are also lower than the recommended world average limits. However, the three indices used to assess the radiological safety of building materials remain within the acceptable limit (≤1). This showed that radiation hazards associated with the mine residue may not have much health impact when used for building dwellings. The radioactivity from the study area will have no serious health impact on individuals in the vicinity of the mining sites. Although the study showed low radioactivity levels, but long-term investigation of radiation exposure is required in the area. A more detailed study should be conducted to assess these risks and determine appropriate safety measures for residents in mining areas. In addition, illegal mining should be regulated to safeguard the miners and the general populace from continuous radiation exposure.

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Competing Interest declaration: no conflict of interest

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