Volume 23, No 3 | International Journal of Radiation Research, July 2025

Potential radiological risks associated with artisanal mining activities and the use of tailings from Kuru District as building materials

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► ***Original article***

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Received: March 2024
Final revised: October 2024
Accepted: November 2024

Int. J. Radiat. Res., July 2024; 23(3): 593-600

DOI: 10.61186/ijrr.23.3.12

Keywords: *Mining activities, tailings, building material, radiation hazard indices, gamma spectrometry.*

ABSTRACT

Background: This study evaluated the radiological risks associated with mining and living in buildings constructed with tailings. ***Materials and Methods:*** A NaI detector was used to determine the specific activity of ^{238}U, ^{232}Th, and ^{40}K in tailings, and radiological hazard indices were estimated. ***Results:*** The mean specific activities of ^{238}U, ^{232}Th, and ^{40}K were 84.27 ± 13.62 Bq/kg, 11.65 ± 0.69 Bq/kg, and 193.26 ± 9.98 Bq/kg, respectively. The mean values for ^{232}Th and ^{40}K were about 74% and 54% lower than their corresponding average world values, while that of ^{238}U was 155% higher than its average world value. The hazards indices: radium equivalent (Ra_{eq}), absorbed dose rate (D_{out} and D_{in}), annual effective dose equivalent (ADE_{out} and ADE_{in}), annual gonadal dose equivalent (AGDE), external hazard index (Hex), internal hazard index (Hin), and excess lifetime cancer risk ($ELCR_{out}$ and $ELCR_{in}$) were estimated from the specific activity of the radionuclides. Their mean values were 249.74 Bq/kg, 54.03 nGy/h, 106.00 nGy/h, 66.31 µSv/y, 520.35 µSv/y, 369.78 µSv/y, 0.31, 0.54, 0.232×10^{-3} and 1.821×10^{-3} respectively. Ra_{eq}, D_{out}, ADE_{out}, H_{ex} and H_{in} were about 32%, 5%, 17.11%, 69%, and 46% lower, while D_{in}, ADE_{in}, and AGDE were about 26.19%, 24%, and 24.09% higher than their respective reference values. $ELCR_{out}$ is about 80%, while $ELCR_{in}$ is almost six times higher than the reference ELCR from all carcinogens. ***Conclusion:*** The high specific activity of ^{238}U, D_{in}, ADE_{in}, AGDE, and $ELCR_{in}$ indicates that tailings are unsuitable for building and that there are potential radiological risks associated with artisanal mining activities in Kuru district.

INTRODUCTION

Ionizing radiation is an intrinsic component of the Earth's environment, and humans have been exposed to it throughout history [1]. Environmental radioactivity arises from natural radioactive materials present on Earth, either through natural processes or anthropogenic activities. Radiation levels can be influenced by geological formation, soil mineral concentrations [2], and human activities such as nuclear power, nuclear research, radiography, cement and paint production, fertiliser manufacturing, oil exploration, and mining [3]. Workers in these industries are subject to continuous radiation exposure, primarily through inhalation and dermal contact.

In addition, residential, and occupational environments, such as houses and offices, can contribute significantly to external radiation exposure. This is largely due to gamma-ray emissions from building materials that contain radionuclides such as ^{238}U, ^{232}Th, and ^{40}K and their decay products [4]. While the importance of shelter cannot be overemphasised, building constructed with materials containing high levels of radiation will contribute significantly to the radiation exposure of the occupants. Various construction materials contain differing levels of naturally occurring radionuclides that release radon [5].

Continuous exposure to radon, a decay product of ^{238}U, affects indoor air quality and has been linked to the induction of lung cancer [6]. Therefore, building materials with higher levels of naturally occurring radionuclides will lead to increased radon concentrations over time as these radionuclides accumulate. It is essential to assess the levels of radionuclides in building materials to evaluate the population exposure, especially given that people spend approximately 78% of their time indoors [7].

Mining activities in Jos began around I904, and the city has long been known for its mining activities. Although formal mining operations have ceased, illegal artisanal mining continues [8]. This type of mining is associated with serious risks, including fatalities, injuries, and significant environmental disruptions [9-12]. Despite these dangers, artisanal mining remains a vital means of livelihood in the region [13], with its economic benefits often

[DOI: 10.61882/ijrr.23.3.12]

outweighing concerns about its consequences.

In the Kuru District, mineral ore extraction is now largely done through manual centrifugation, with mining tailings (waste products) left in piles around the mining sites. These tailings contain various minerals, some of which are carcinogenic [14]. These soil-rich wastes materials are often collected for use in building local ovens and shelters, as they are inexpensive [14]. While the radiological effects of mining activities in Jos have been widely studied-focusing on population exposure through water consumption, the food chain [11, 15], dose rates in the air at active mining sites [16], and the impact of tin mining on different soil types and concrete blocks [17, 18], there is limited research on the radiological risks associated with artisanal mining. Specifically, little attention has been given to the risks faced by residents living in homes built with mining tailings. This study aims to assess the potential long-term radiological risks posed by artisanal mining activities in the Kuru District, focusing on miners and residents living in homes constructed using tailings from mining sites in Jos.

MATERIALS AND METHODS

Study area

This study was conducted in three mining locations: Kuru-Jenta (KJ), Kanikon (KK) and Zakong-Soil (ZS), all all located in the Kuru District (figure 1) of Jos South Local Government Area of Plateau State. The area is situated at an elevation of about 1318.20 m, with coordinates at 9.7184° North and 8.8359° East.

While agriculture is the main occupation in Jos, Plateau State is widely known for its mining industry. Historically, it has been Nigeria's leading region for mining, especially in the extraction and exportation of tin and columbite. In the Kuru District, miners work manually digging pits with basic tools like shovels, diggers, and spades to extract minerals. The minerals mined here include cassiterite, tin, wolframite, ilmenite, and columbite.

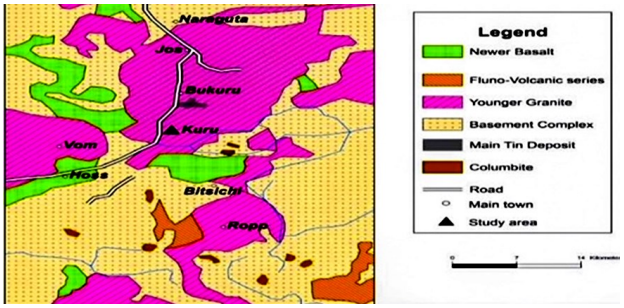

Figure 1. Map of Kuru District and its environs (adapted from [19]).

Collection and preparation of samples

A total of 21 samples were collected from the three mining locations. Six samples were obtained from Kuru-Jenta (KJ), five from Kanikon (KK), and ten from Zakong-soil (ZS). The number of samples collected at each site was proportional to the area's size. Approximately 1 kg of tailings was collected from the surface (about 0-30 cm) of randomly selected heaps at each location. The samples were placed in plastic bags, clearly labelled, and transported to the laboratory. Stones were manually removed from each sample before placing them in pre-cleaned plastic trays. The samples were air-dried in the laboratory for six weeks to ensure all moisture was removed. After drying, the samples were pulverised using a laboratory mortar and pestle and then passed through a 1 mm sieve for homogeneity. About 300 g of each sieved sample was transferred to a clean, pre-weighed cylindrical plastic container. The filled containers were weighed to determine the exact mass of each sample. All containers were hermetically sealed and left for four weeks to allow the ^{238}U and ^{232}Th and their progenies to reach secular equilibrium.

Sample measurement and analysis of spectral.

The specific activities of ^{238}U, ^{232}Th, and ^{40}K in the tailing samples were measured using a gamma-ray spectrometer. This spectrometer was equipped with a 76 mm by 76 mm sodium iodide doped with thallium (NaI (Tl)), Model 802-series (Canberra inc., USA). The NaI (Tl) detector was shielded with thick lead blocks and connected to a Canberra Multichannel Analyser (MCA), Model 2007P, through a pre-amplifier base for data acquisition. The operating voltage of the detector was set to 600 V with a resolution of 7.5% full width half maximum (FWHM) at the 0.662 MeV peak of ^{137}Cs. Energy and efficiency calibrations were performed using gamma sources provided by the International Atomic Energy Agency (IAEA), following IAEA Document No. 385 [20].

To determine the laboratory's background radiation, an empty beaker identical in size to the sample beaker was placed in the detector and counted under the same conditions. Each sample was then placed in the detector and counted for 25200 s (7 h). The net counts for each sample were obtained by subtracting the background counts, and the spectra were analysed using GENIE-2000 software (Canberra Inc., USA). The specific activities of ^{238}U, ^{232}Th, and ^{40}K were calculated based on the concentrations of ^{214}Bi (at the 1764.5 keV gamma peak), ^{208}Tl (2614.7 keV gamma peak), and the gamma peak of ^{40}K (1460.8 keV), respectively. The minimum detectable activity (MDA) of the detector for the chosen gamma peaks were calculated from the background radiation count rate, as as described in literature [21, 22], and is presented in table 1.

Specific activity (A)

The specific activity A (Bq/kg) for all samples was determined using equation 1 [20, 23].

[DOI: 10.61882/ijrr.23.3.12]

$$A = \frac{C}{t \times m \times \varepsilon \times P_\gamma} \quad (1)$$

Where; A is the specific activity of the radionuclide in Bq/kg, C is the net count for the sample in the peak energy range, m is the mass of the sample in kg, t is the counting lifetime in seconds, ε is the detector energy-dependent efficiency, and P_Y is the gamma-ray yield per disintegration of radionuclides.

Table 2. Specific activity of ^{238}U, ^{232}Th and ^{40}K in tailings from Kanikon (mean ± SD).

Sample	^{238}U (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
KK1	99.66± 16.21	8.81±0.52	151.21±7.97
KK2	161.05±25.59	6.97±0.41	217.84±11.40
KK3	92.48±14.89	7.16±0.42	158.95±8.28
KK4	79.89± 13.13	11.13±0.65	229.90±11.93
KK5	22.50± 4.05	7.16±0.42	185.79±9.74
Mean	91.12±14.77	8.25±0.48	188.74±9.86
World's average	33.00	45.00	420.00
P	0.058	0.001	0.001

Radiological hazard indices

Various radiological hazard indices were calculated to assess potential radiological risks associated with mining in Kuru and the use of tailings in building construction. These indices include radium equivalent (Ra_{eq}), absorbed dose rate (D), annual effective dose equivalent (E), annual gonadal dose equivalent (AGDE), external hazard index (Hex), internal hazard index (Hin), and excess lifetime cancer risk (ELCR) and have been described fully elsewhere [22].

Radium equivalent (Ra_{eq})

Radium equivalent provides a single index to estimate the gamma radiation output from a mix of radionuclides in samples. It was calculated using equation 2 [24, 25]:

$$Ra_{eq} = A_U + 1.43A_{Th} + 0.77A_K \quad (2)$$

Where; A_U, A_{Th}, and A_K are the specific activities for ^{238}U, ^{232}Th, and ^{40}K, respectively.

Absorbed dose rate (D)

The outdoor absorbed dose rate in air was calculated using equation 3 [25], while the indoor absorbed dose rate was calculated using equation 4 [26, 27]:

$$D_{outdoor}(nGy\ h{-}1) = 0.462A_U + 0.604A_{Th} + 0.0417A_K \quad (3)$$

$$D_{indoor}(nGy\ h{-}1) = 0.92A_U + 1.1A_{Th} + 0.08A_K \quad (4)$$

Where; A_U, A_{Th}, and A_K are the specific activities of ^{238}U, ^{232}Th, and ^{40}K in Bq/kg, respectively.

Annual effective dose (AED)

AED_{in} accounts for dwellers' exposure, while AED_{out} accounts for miners' exposure. The outdoor and indoor annual effective (AED_{out} and AED_{in}) doses were calculated using equations 5 and 6 [28]:

$$AED_{out}\ (\mu Sv/y) = D_{out}\ (\times 0.2 \times 0.7 \times 8766 \times 10^{-3} \quad (5)$$

$$AED_{in}\ (\mu Sv/y) = D_{in}\ (\times 0.8 \times 0.7 \times 8766 \times 10^{-3} \quad (6)$$

Where; D_{out} and D_{in} are the outdoor and indoor absorbed dose rate respectively in nGy/h, 0.2 is the outdoor occupancy, 0.8 is the indoor occupancy factor, 0.7 Sv/Gy is the conversion factor from absorbed dose rate to the effective dose rate, and 8766 is the number of hours in a year.

Annual gonadal dose equivalent (AGDE)

The AGDE (for miners and dwellers) has been calculated using equation 7 [25, 29]:

$$AGDE\ (\mu Sv/y) = 3.09A_U + 4.18A_{Th} + 0.314A_K \quad (7)$$

Where; A_U, A_{Th}, and A_K are the specific activities of ^{238}U, ^{232}Th, and ^{40}K in Bq/kg, respectively.

Hazard indices (H_{ex} and H_{in})

External and internal index H_{ex} and H_{in} were calculated using the specific activities of ^{238}U, ^{232}Th, and ^{40}K in sampled tailings using equations 8 and 9, respectively [28]:

$$H_{ex} = \frac{A_U}{370\ Bq/kg} + \frac{A_{Th}}{259\ Bq/kg} + \frac{A_K}{4810\ Bq/kg} \quad (8)$$

$$H_{in} = \frac{A_U}{185\ Bq/kg} + \frac{A_{Th}}{259\ Bq/kg} + \frac{A_K}{4810\ Bq/kg} \quad (9)$$

Where; A_U, A_{Th}, and A_K are the values for the specific activities of ^{238}U, ^{232}Th, and ^{40}K.

Excess lifetime cancer risk (ELCR)

Excess lifetime cancer risk (ELCR) from outdoor and indoor exposures have been calculated using equations 10 and 11 [22] to estimate the potential carcinogenic effects of exposure to radionuclides by miners and dwellers resulting from mining activities and the use of tailings as a building material, respectively.

$$ElCR_{out} = AED_{out} \times RF \times DL \quad (10)$$

$$ElCR_{in} = AED_{in} \times RF \times DL \quad (11)$$

Where; AED_{out} and AED_{in} are the outdoor and indoor annual effective dose, DL is the duration of life (70 years), and RF is the fatal cancer risk factor per Sievert, which is 0.05 for the public.

Statistical Analysis

A one-sample t-test using the Statistical Package for Social Science (SPSS) version 23 (IBM, Armonk, NY) to compare the obtained values with global reference values and other relevant data. A p-value of less than 0.05 ($p<0.05$) was considered statistically significant.

RESULTS

The lowest level of radioactivity of ^{238}U, ^{232}Th, and

[DOI: 10.61882/ijrr.23.3.12]

^{40}K that the detector can reliably measure under the analysis conditions are shown in Table 1. The minimum detectable activities (MDA) of ^{238}U, ^{232}Th, and ^{40}K of the detector are 0.022, 0.020, and 0.080 Bq/kg, respectively. Table 2 presents the specific activities of ^{238}U, ^{232}Th, and ^{40}K in tailings from Kanikon. The values for ^{238}U ranged from 22.50 ± 4.05 to 161.05 ± 25.59 Bq/kg, for ^{232}Th ranged from 6.97 ± 0.41 to 11.13 ± 0.65 Bq/kg, and for ^{40}K ranged from 151.21 ± 7.97 to 229.90 ± 11.93 Bq/kg. The mean values are 91.12 ± 14.77, 8.25 ± 0.48, and 188.74 ± 9.86 Bq/kg for ^{238}U, ^{232}Th, and ^{40}K in tailing from Kanikon, respectively.

For the tailings collected from Kuru-Jenta (table 3), the specific activity of ^{238}U ranged from 44.54 ± 7.03 to 366.73 ± 57.44 Bq/kg, ^{232}Th ranged from 6.68 ± 0.39 to 60.20 ± 3.46 Bq/kg, and ^{40}K ranged from 251.46 ± 13.06 to 419.87 ± 20.79 Bq/kg. The mean specific activities of ^{238}U, ^{232}Th, and ^{40}K are 125.30 ± 19.85, 18.46 ± 1.07, and 304.44 ± 15.61 Bq/kg, respectively.

Table 4 shows the specific activities of ^{238}U, ^{232}Th, and ^{40}K in tailings from Zagong-soil, where the largest number of samples were analysed. The values of ^{238}U ranged from 29.46 ± 5.05 to 90.97 ± 14.84 Bq/kg, with an average value of 55.93 ± 18.69 Bq/kg. The values of ^{232}Th ranged from 4.35 ± 0.42 to 13.82 ± 0.81 Bq/kg, and ^{40}K ranged from 4.75 ± 0.23 to 226.67 ± 11.26 Bq/kg. The mean values are 55.93 ± 18.69, 9.27 ± 0.56, and 128.82 ± 6.65 Bq/kg for ^{238}U, ^{232}Th and ^{40}K.

Table 2. Specific activity of ^{238}U, ^{232}Th, and ^{40}K in tailings from Kanikon (mean ± SD).

Sample	^{238}U (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
KK1	99.66±16.21	8.81±0.52	151.21±7.97
KK2	161.05±25.59	6.97±0.41	217.84±11.40
KK3	92.48±14.89	7.16±0.42	158.95±8.28
KK4	79.89± 13.13	11.13±0.65	229.90±11.93
KK5	22.50± 4.05	7.16±0.42	185.79±9.74
Mean	91.12±14.77	8.25±0.48	188.74±9.86
World's average	33.00	45.00	420.00
P	0.058	0.001	0.001

Table 3. Specific activity of ^{238}U, ^{232}Th, and ^{40}K in tailings from Kuru-Jenta (mean ± SD).

Sample	^{238}U (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
KJ1	56.41±8.99	6.68±0.39	256.47±13.23
KJ2	97.14±15.84	11.42±0.67	251.46±13.06
KJ3	44.54±7.03	9.03±0.52	318.13±15.78
KJ4	81.01±12.71	10.75±0.61	419.87±20.79
KJ5	105.98±17.07	12.70±0.74	277.97±14.44
KJ6	366.73±57.44	60.20±3.46	302.75±16.38
Mean	125.30±19.85	18.46±1.07	304.44±15.61
World's average	33.00	45.00	420.00
P	0.130	0.070	0.019

As seen in tables 2 to 4, the specific activities of ^{238}U, ^{232}Th, and ^{40}K in the samples from the study areas are compared to world averages. Figures 2, 3, and 4 highlight the distribution of ^{238}U, ^{232}Th, and ^{40}K across all sampled tailings from the three mining fields. For ^{238}U, the specific activity ranges from 22.50 ± 4.05 Bq/kg in sample KK5 to 366.73 ± 57.44 Bq/kg in sample KJ6. The specific activity of ^{232}Th varies, with the lowest being 4.35 ± 0.42 Bq/kg in sample ZS2 and the highest at 60.20 ± 3.46 Bq/kg in sample KJ6. For ^{40}K, the specific activity spans from 4.75 ± 0.23 Bq/kg in sample ZS2 to 419.87 ± 20.79 Bq/kg in sample KJ4. Figure 5 compares the overall mean specific activities of ^{238}U, ^{232}Th, and ^{40}K in all the sampled tailings from the selected mining sites in Kuru District with the world average values. The overall mean specific activities of ^{238}U, ^{232}Th, and ^{40}K are recorded as 84.27 ± 13.62, 11.65 ± 0.69, and 193.26 ± 9.98 Bq/kg, respectively.

Table 4. Specific activity of ^{238}U, ^{232}Th, and ^{40}K in tailings from Zagong-Soil (mean ± SD).

Sample	^{238}U (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
ZS1	54.83±9.17	8.13±0.48	6.26±0.32
ZS2	32.05±5.54	4.35±0.42	166.24±8.62
ZS3	29.46±5.05	7.73±0.45	87.30±4.57
ZS4	45.58±7.22	8.44±0.48	4.75±0.23
ZS5	90.97±14.84	10.14±0.60	176.59±9.24
ZS6	76.82±12.08	11.85±0.68	226.67±11.26
ZS7	57.47±9.87	13.82±0.81	145.69±7.61
ZS8	53.91±9.01	5.73±0.34	121.01±6.27
ZS9	52.97±8.95	9.41±0.55	155.17±8.08
ZS10	65.20±11.26	13.10±0.77	198.48±10.32
Mean	55.93±18.69	9.27±0.56	128.82±6.65
World's average	33.00	45.00	420.00
P	0.004	0.001	0.001

Note: World average values refer to the global average activity concentration of radionuclides in soils as reported by UNSCEAR [28].

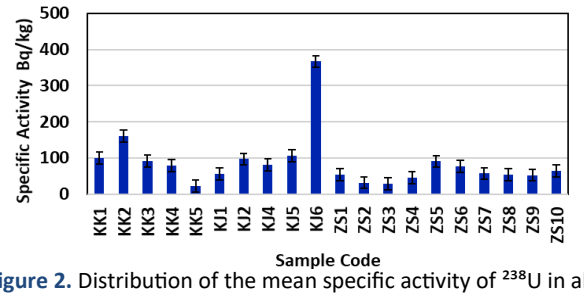

Figure 2. Distribution of the mean specific activity of ^{238}U in all sampled tailings.

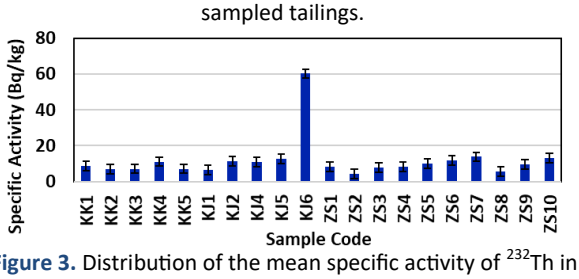

Figure 3. Distribution of the mean specific activity of ^{232}Th in all sampled tailings.

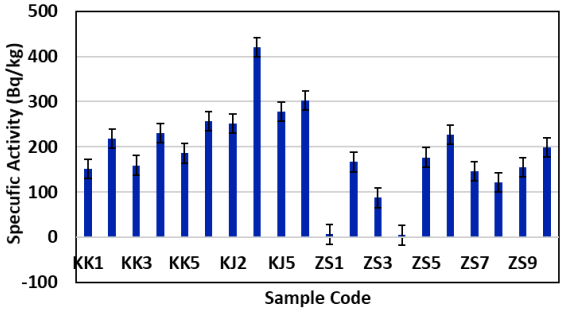

Figure 4. Distribution of the mean specific activity of 40K in all sampled tailings.

[DOI: 10.61882/ijrr.23.3.12]

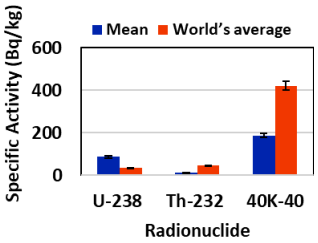

Figure 5. Average specific activities of 238U, 232Th, and 40K (Bq/kg) versus the world's average values.

Table 6 presents the values of the estimated radiological hazard indices and their corresponding reference or world's average values. Ra_{eq} ranges from 61.30 to 685.93 Bq/kg, with a mean of 249.74 Bq/kg. The outdoor absorbed dose rate in air D_{out} ranges from 21.92 to 218.41 nGy/h with a mean value of 54.03 nGy/h. The indoor absorbed dose rate in air D_{in} to assess the absorbed dose of residents of homes built with these tailings ranges from 42.68 to 428.13 nGy/h; the mean value is 106.00 nGy/h. The indoor annual effective dose equivalent AED_{in} has values from 209.50 to 2101.69 µSv/y with an average value of 520.35 µSv/y.

Table 5. Mean specific activities of ^{238}U, ^{232}Th, and ^{40}K (Bq/kg) in the soil of some previously studied mining sites and results from the current study.

^{238}U	^{232}Th	^{40}K	Location	Reference
7220.00	16800	-	Plateau, Nigeria	[8]
55.30	26.40	505.10	South-west Nigeria	[25]
3867.50	8301.90	1251.70	Plateau, Nigeria	[30]
132.60	351.4	319.60	Plateau, Nigeria	[31]
49.71	4.98	615.21	Plateau, Nigeria	[32]
84.27± 13.62	11.65± 0.69	193.26± 9.98	Plateau, Nigeria	Present study
p=0.204	p=0.201	p=0.170		

Table 6. Summary of some estimated radiological indices from the specific activity of ^{238}U, ^{232}Th and ^{40}K measured from sampled tailings and their corresponding reference values.

Sample	Ra_{eq} (Bq/kg)	D_{out} (nGy/hr)	D_{in} (nGy/hr)	AED_{out} (µSv/y)	AED_{in} (µSv/y)
KK1	228.69	57.67	113.63	70.77	557.79
KK2	338.75	87.70	173.48	107.62	851.60
KK3	225.11	53.68	105.83	65.88	519.53
KK4	272.83	53.22	104.36	65.32	512.32
KK5	175.80	22.47	43.62	27.57	214.15
KJ1	263.44	40.79	80.20	50.06	392.81
KJ2	307.09	62.26	122.30	76.41	600.36
KJ3	302.41	39.30	76.68	48.23	376.41
KJ4	419.68	61.43	120.36	75.38	590.86
KJ5	338.18	68.22	133.99	83.73	657.74
KJ6	685.93	218.41	428.13	268.04	2101.69
ZS1	71.28	30.50	59.89	37.43	294.02
ZS2	166.28	24.36	47.74	29.90	234.34
ZS3	107.73	21.92	42.68	26.90	209.50
ZS4	61.30	26.35	51.60	32.34	253.31
ZS5	241.44	55.52	109.15	68.13	535.81
ZS6	271.30	53.49	104.83	65.64	514.60
ZS7	189.41	40.97	79.88	50.28	392.10
ZS8	155.28	33.41	65.70	41.01	322.53
ZS9	185.91	36.63	71.65	44.94	351.74
ZS10	236.76	46.32	90.47	56.83	444.12
Mean	249.74	54.03	106.00	66.31	520.35
World's average reference level	370.00	NA	NA	NA	NA
P	0.001	0.745	0.228	0.230	0.261

Table 7. Measured Indoor AED (mSv/yr) from different studied building materials across the world and the current study.

AED	Sample	Location	Reference
0.81	Concrete blocks	Jos, Nigeria	[17]
1.20	Soil	Jos, Nigeria	[18]
0.33	Sand	Pakistan	[33]
0.68	Soil	India	[34]
0.40-0.83	Sediments	South-west, Nigeria	[35]
0.53	Soil	Iran	[36]
0.88	Sediment	China	[37]
0.36	Tailings	Nasarawa, Nigeria	[38]
0.11	Sediment	Italy	[39]
0.52	Tailings	Jos, Nigeria	Present study
p = 0.430			

Table 8. estimated annual gonadal dose equivalent, external and internal hazard indices, and excess life cancer risks from studied samples.

Sample	AGDE (µSv/y)	H_{ex}	H_{in}	$ELCR_{out} \times 10^{-3}$	$ELCR_{in} \times 10^{-3}$
KK1	392.26	0.33	0.60	0.248	1.953
KK2	595.18	0.51	0.94	0.377	2.981
KK3	365.60	0.31	0.56	0.231	1.818
KK4	365.57	0.31	0.52	0.229	1.793
KK5	157.79	0.13	0.19	0.097	0.750
KJ1	282.76	0.23	0.38	0.175	1.375
KJ2	426.86	0.37	0.62	0.267	2.101
KJ3	275.27	0.22	0.34	0.169	1.317
KJ4	427.10	0.35	0.57	0.264	2.068
KJ5	467.85	0.39	0.68	0.293	2.302
KJ6	1479.90	1.29	2.28	0.938	7.356
ZS1	205.37	0.18	0.33	0.131	1.029
ZS2	169.42	0.14	0.22	0.105	0.820
ZS3	150.76	0.13	0.21	0.094	0.733
ZS4	177.61	0.16	0.28	0.113	0.887
ZS5	378.93	0.32	0.57	0.238	1.875
ZS6	367.35	0.31	0.52	0.230	1.801
ZS7	281.10	0.24	0.39	0.176	1.372
ZS8	228.53	0.19	0.34	0.144	1.129
ZS9	251.73	0.21	0.35	0.157	1.231
ZS10	318.55	0.27	0.44	0.199	1.554
Mean	369.78	0.31	0.54	0.232	1.821
Refence value	300.00	1.00	1.00	0.290	0.290
P	0.265	0.001	0.001	0.150	0.001

The estimated annual gonadal dose equivalent AGDE from this study ranges from 150.76 to 1479.90 µSv/y with a mean value of 369.78 µSv/y (table 8). H_{ex} ranges from 0.13 to 1.29 with a mean of 0.31, and H_{in} ranges from 0.19 to 2.28 with a mean of 0.54. Obtained values for outdoor and indoor excess life cancer risks ($ELCR_{out}$ and $ELCR_{in}$) range from 0.094 to 0.938×10^{-3} and 0.733 to 7.356×10^{-3} with mean values of 0.232 and 1.821×10^{-3}, respectively.

DISCUSSION

Tables 2 to 4 present a comparative analysis of the specific activities of radionuclides ^{238}U, ^{232}Th and ^{40}K from samples collected in the study areas against global averages. The findings reveal significant

[DOI: 10.61882/ijrr.23.3.12]

variations, particularly in the concentrations of ^{238}U. Samples from Kuru-Jenta show notably high mean specific activity for ^{238}U, averaging 125.30 Bq/kg, which is substantially above the global average of 33 Bq/kg. In tailings from Kanikon, the mean specific activity of ^{238}U is about three times higher than the global average. Sample KJ6 from Kuru-Jenta exhibits an exceptional increase, with ^{238}U levels roughly 11 times above the global average. The overall mean concentration in Kuru-Jenta is over four times higher than the global standard.

Although the mean specific activity of tailings from Zagong-soil (table 4) is lower than the values for tailings for Kuru-Jenta, about 80% of the samples from Zangong-soil still show ^{238}U concentrations that exceed the world's average. The mean specific activity obtained for ^{238}U in these samples is about 70% higher than the world's average, while the mean values for ^{232}Th and ^{40}K are 79% and 69% lower than their respective world's average values in soil. Generally, the specific activities of ^{232}Th and ^{40}K across all samples are lower than global averages of 45 and 420 Bq/kg, respectively [28]. For instance, tailings from Kanikon show mean values approximately 82% lower for ^{232}Th and 65% lower for ^{40}K. In Kuru-Jenta, the specific activities of ^{232}Th, and ^{40}K are about 59% and 32% lower than the global averages. Tailings from Zagong-Soil also show lower concentrations for ^{232}Th and ^{40}K compared to Kuru-Jenta.

Statistical analysis, represented by the p-values, indicates that the deviations from world averages are significant for ^{238}U in some locations ($p < 0.05$), while ^{232}Th and ^{40}K generally show lower levels of significance. The specific activities of ^{238}U, ^{232}Th, and ^{40}K observed in this study are comparable to those reported for other mining fields (table 5). However, some variations in data have been noted, with the specific activity values in this study being lower than those reported in earlier studies from the same region [8, 30, 31]. Despite this, the mean ^{238}U value from this study is higher than those reported by [25, 32], although those studies recorded higher values for ^{40}K. The variations may be due to differences in mining intensity, the types of mined minerals, as well as climatic conditions and erosion levels during sample collection. Additionally, the solubility of certain radionuclides in water could contribute to the differences in observed values.

The radiological hazard indices estimated in Table 6 show that the Ra_{eq} and D_{out}, and AED_{out} are lower than their corresponding world's average and reference values by about 32%, 5.21%, and 17.11%, respectively. However, certain samples still exceed safety thresholds, raising concerns about their use as building materials. The mean indoor absorbed dose D_{in} is about 26.19% higher than the population-weighted average value of 84 nGy/h [28], with the highest value obtained being about four times higher than the world's average value. Similarly, the mean annual effective dose indoors (AED_{in}) is approximately 24% higher than the global average of 420 μSv/y, and 52.4% of the samples have values exceeding this average, with the highest being five times the world average. These results further reveal that tailings are not materials suitable for building.

The AED_{in} values obtained from this study are comparable to those reported for other building materials worldwide (table 7). The value from the present study is within the range of the values obtained by some similar studies [35, 36], above the results obtained by others [34, 38, 39], but lower than the results of some others [17, 18, 34, 37].

The radiological hazard indices indicate that while the mean values for the internal and external hazard indices (Hex and Hin) remain within acceptable limits, certain samples exceed these thresholds. The effective dose equivalents (AEDin and AGDE) are higher than global averages, implying potential genetic radiation effects and an increased risk of cancer for individuals exposed to these tailings. The estimated excess lifetime cancer risk (ELCR) for outdoor exposure is about 80% of the total ELCR for all carcinogens, while the indoor ELCR is approximately six times higher than the reference value for all carcinogens. The ELCR values for residents living in homes built with these tailings are particularly concerning, indicating a significantly higher probability of cancer compared to global averages.

The mean values of $ELCR_{out}$ and $ELCR_{in}$ from this study are 0.232×10^{-3} and 1.82110^{-3}, respectively. This suggests that mining activities in Kuru District add an additional risk of 232 cancer cases per million people for outdoor exposure and 1821 cancer cases per million for indoor exposure in homes constructed with these tailings. The elevated levels of ^{238}U, particularly in Kuru-Jenta, present significant health hazards. Prolonged exposure to uranium is known to cause damage to various organs, including the cardiovascular system, liver, kidneys, and nervous system, and increase the risk of cancer [40, 41]. This concern is heightened when uranium-contaminated tailings are used in construction. From a radiation protection standpoint, the primary concern is the increased likelihood of cancer over an individual's lifetime. The elevated specific activity of ^{238}U in tailings from Kuru mining sites and the associated health risks underscore the unsuitability of these materials for construction and the potential significant rise in cancer risks to miners because of mining activities.

CONCLUSION

The findings reveal that the mean specific activity of ^{238}U in tailings, as well as mean values of D_{in}, AED_{in},

[DOI: 10.61882/ijrr.23.3.12]

and AGDE, and Ra_{eq}, D_{out}, and AED_{out} for some samples exceed global average or reference values. The elevated specific activity of ^{238}U indicates an increased risk of internal radiation exposure for miners and residents primarily due to inhalation. The study also estimates an additional cancer risk of 2053 cases per 1 million people as derived from the Excess Lifetime Cancer Risk (ELCR) directly linked to mining activities in the Kuru District. From a radiation protection perspective, both the mining operations and the use of tailings as construction materials pose significant radiological risks. The heightened cancer risk underscores the need for enhanced safety measures and alternative materials to reduce these risks.

ACKNOWLEDGMENT

None.

Ethical consideration: None.

Funding: No funding was provided for this work.

Data Availability: Not Applicable.

Conflict of Interest: The authors declare that they have no competing interest in this study.

Author Contributions: A.M.B., contributed to the concept and design of the study, data collection analysis and interpretation, and wrote part of the manuscript. I.A.Z., contributed to the design of the study, wrote part of the manuscript, and reviewed and edited the first draft of the manuscript critically for intellectual content. O,K,I,, took part in data analysis and interpretation. All authors read and approved the final manuscript.

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[DOI: 10.61882/ijrr.23.3.12]

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[DOI: 10.61882/ijrr.23.3.12]