EVALUATION OF PRIMORDIAL RADIONUCLIDES AND HEALTH IMPACTS IN SOIL FROM THE EFFA AREA, BENUE STATE, NIGERIA

BY

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Abstract

This study evaluates the concentrations of naturally occurring radionuclides (226Ra, 232Th, and 40K) and their associated health impacts in soil samples from Effa communities surrounding the Abache coal mine in Benue State, Nigeria. Mining activities redistribute these radionuclides, increasing environmental exposure to ionizing radiation. Sixteen soil samples were randomly collected and analysed using NaI (Tl) gamma spectrometry at the Centre for Energy and Research Training (CERT), Ahmadu Bello University, Zaria. The mean activity concentrations of 226Ra, 232Th, and 40K were 33.33 ± 2.56 Bq/kg, 41.06 ± 2.40 Bq/kg, and 51.53 ± 2.71 Bq/kg, respectively. The 226Ra value slightly exceeded the global average by a factor of 1.01, while 232Th and 40K were below. Most radiological hazard indices were within permissible limits, except for the annual gonadal dose equivalent (AGDE) which exceeded safety thresholds at specific sites and excess lifetime cancer risk (ELCR) with the average value of $0.91x\ 10^{-3}$ higher than the world average of $0.29\ x\ 10^{-3}$ which would be considered as moderate to high risk. The results of radium equivalent activity do not show any radiological implications if the soils are used domestically. These findings emphasize the need for regular environmental monitoring and mitigation measures.

Keywords: Radionuclides, Health Risk, Radiological Parameters, Effa, Nigeria

Introduction

Radiation and its potential hazards to human health have become global concerns. While natural radiation is unavoidable, mining activities significantly alter its distribution [1,2]. The International Atomic Energy Agency (IAEA) notes that exposure from natural radioactivity is generally negligible for the public, except those working with mineral ores or naturally occurring radioactive materials (NORMs) [3]. However, the World Nuclear Association (WNA) emphasizes that any radiation dose carries some risk [4,5]. Coal mining operations began in the Abache Effa community in 2019, aiming to provide an alternative energy source for industrial processes. These activities result in environmental degradation and potential radiological threats. Excavation, blasting, and dust emissions can redistribute radionuclides, increasing radiation exposure in surrounding environments. Dust and particulate matter also contribute to air pollution, affecting local flora, fauna, and water bodies [**6**]. Exposure to radioactive contaminants may lead to elevated radiation levels and health risks for residents [**9**,**10**, **11**]. Inhalation of coal dust can result in diseases like pneumoconiosis (black lung disease) [**12**,**11**], and there is increased cancer risk due to gamma radiation exposure [**7**, **8**]. While radiological surveys have been conducted in several Nigerian mining areas [**13**], such as Shanono, Bagwai [**14**], Maiganga [**7**], Barakinladi, Enugu [**8**], Okobo [**15**], and Zabili, Chad [**16**]—no such assessment has been done in the Abache Effa coal mine. It is against this backdrop that this study was carried out to evaluate soil radionuclide concentrations and their health implications in Effa, Efewu, and Abache.

Materials and Method

Study Area

Effa lies within the Lower River Benue Trough in Benue State, Nigeria, between longitudes 7°47’ to 10°00’E and latitude 6°25’ to 8°08’N. It has a tropical climate with two distinct seasons: a rainy season (April–October) and a dry season (November–March). The geology includes sandstones, shales, mudstones, and coal seams, which influence radionuclide distribution due to their varying permeability and composition.

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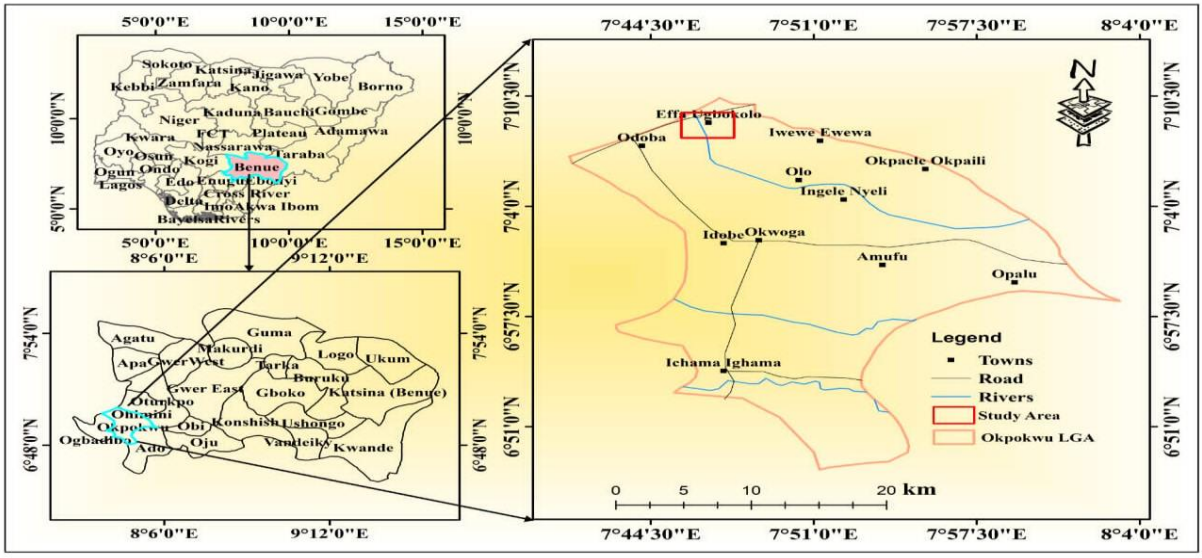

Fig 1a Map of Nigeria, Benue and Effa area.

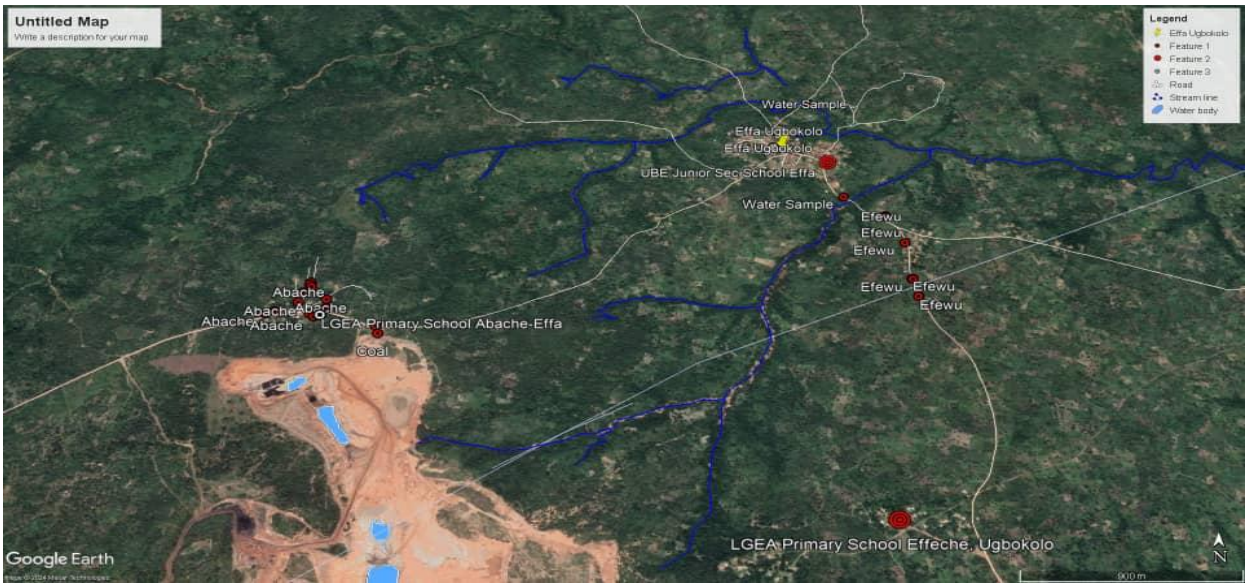

Fig. 1b The Google Map of study area

Sample collection and preparation

Sixty soil samples were collected from a depth of 0–15 cm using hand tools. Samples were labeled according to GPS coordinates and sealed in polythene bags. At CERT, samples were air-dried for 72 hours, pulverized, sieved through a 100-micron mesh, and packed in radon-impermeable containers. The samples were stored for 30 days to achieve secular equilibrium before countiong using NaI based gamma spectroscopy.

Gamma Spectrometric Measurements

Samples were analyzed using a NaI (Tl) detector housed in a lead shield to reduce background radiation. Calibration was performed using IAEA-315 [**19**] sediment standards. Gamma peaks from 214Bi and 214Pb (for 238U), 228Ac and 208Tl (for 232Th), and 40K were used for activity concentration analysis. To determine the baseline count, an empty beaker with the same dimensions as the sample containers was counted. The baseline spectrum was subsequently subtracted from the sample spectra to yield the overall radio-isotope count. Sample and background counting were performed for a duration of over 28,800 seconds, resulting in gamma spectra with good statistical reliability. The gamma-ray photo peaks of ^{228}Ac and ^{208}Tl were used for determining the activity of ^{232}Th. The, ^{214}Bi and ^{214}Pb peaks were used for the activity of ^{238}U and the activity of ^{40}K was determined from its single gamma line. The specific activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in respective sample, expressed in Bqkg^{-1}, were calculated using Equation1[**20**] and [**18**]

$$A(C) = \frac{C_{net}}{\varepsilon(E) \times I_{\gamma} \times t \times m} \qquad (1)$$

Where A(C) is the specific activity (Bq/kg), C_net is the net count rate, ε is the photopeak efficiency, Iγ is the gamma intensity, t is the counting time, and m is the sample mass.

Radiation hazard estimation

Several radiological parameters were calculated:

Absorbed Dose Rate (ADR)

Determination of absorbed dose rate is essential for assessing the health-related risks associated with radiation exposure. Radiological hazards due to radiation exposure from radionuclides in soil can be assessed using equation 2 [21]. The effects depend largely on the absorbed dose rate in the air at 1.0m above ground level ([22].

$$\mathrm{ADR}\left(\frac{\mathrm{nGy}}{\mathrm{h}}\right) = (0.462\mathrm{C_{Ra}} + 0.604\mathrm{C_{Th}} + 0.0417\mathrm{C_K}) \quad (2)$$

Where, *C* is the activity concentration of the primordial radionuclides in Bq/kg.

Radium Equivalent Activity (Ra_{eq})

Radium equivalent is defined as the weighted sum of activities of primordial radionuclides (^{226}Ra, ^{232}Th and ^{40}K) and is shown in equation (3) ([23]. The equation is based on the theory that 259 Bq/kg of ^{232}Th, 370 Bq/kg of ^{226}Ra and 4810 Bq/kg of ^{40}K generally produce similar gamma radiation dose rates.

$$\mathrm{Ra}_{eq}\left(\frac{Bq}{kg}\right) = C_{Ra} + 1.43C_{Th} + 0.077C_K \quad (3)$$

Where, Ra_{eq} is the radium equivalent activity and *C* is the activity concentration of each radionuclides in Bq/kg. The allowable highest value of radium equivalent activity is 370 Bq/kg [24, 21].

Annual effective dose equivalent (AEDE)

The absorbed dose rate is not sufficient to estimate the human radiological risk. As a result of radiation exposure, the conversion factor from absorbed dose in the air to effective dose for both outdoor and indoor occupancy factor should be considered to obtain the annual effective dose. For the purposes of calculation, a conversion factor of 0.7 Sv/Gy is used to convert the absorbed dose rate to human effective dose with an outdoor occupancy of 20% and 80% for indoor [21]. The expression for determining annual effective dose equivalent is;

$$\mathrm{H_E} = \mathrm{D} \times \mathrm{T} \times \mathrm{F} \quad (4)$$

Where $H_E$is the annual effective dose (mSv), *D* is the absorbed dose rate ($\mathrm{nGy/h}$), T is the outdoor occupancy time (365 days x 24h x 0.2) and (365 days x 24h x 0.8) for indoor occupancy, and F is the conversion factor (0.7 x 10^3 mSv/10^9nGy). It implies;

$$\mathrm{AEDE(outdoor)}(\mu\mathrm{Svy^{-1}}) = \mathrm{D(nGyh^{-1})} \times 8760\mathrm{h} \times 0.7\mathrm{SvGy^{-1}} \times 0.2 \times 10^{-3} \quad (5)$$

$$\mathrm{AEDE(outdoor)}(\mu\mathrm{Svy^{-1}}) = \mathrm{D(nGyh^{-1})} \times 8760\mathrm{h} \times 0.7\mathrm{SvGy^{-1}} \times 0.8 \times 10^{-3} \quad (6)$$

The Hazard Indices

The hazard indices which includes the external (H_{ex}) and internal (H_{in}) radiation hazard indices were a model proposed to ensure that the public exposure to radiation from primordial radionuclides does not exceed the allowable equivalent dose of 1 mSv/yr. The external hazard index has to be below unity in order to ensure that the radiation threat is insignificant; it is expressed according to [25] as;

$$\mathrm{H_{ex}} = \frac{\mathrm{C_{Ra}}}{370} + \frac{\mathrm{C_{Th}}}{259} + \frac{\mathrm{C_K}}{4810} \leq 1 \quad (7)$$

Alternatively, the internal exposure due to radon and its short-lived daughters is given by the internal hazard index (H_{in}) ([22] and is calculated as;

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad (8)$$

Where, *C* represents the activity concentration in Bq/kg of each radionuclide. To neglect radiological effects on the human population, both $H_{ex\ and}$ H_{in} must be below unity ([26].

Annual Gonadal Dose Equivalent (AGDE)

According to [27] gonads are considered as organs of interest for dosimetry purposes. These are primary reproductive organs; testes in the male and the ovaries in the female. The International Commission for Radiation Protection [28] gave the number 0.2 as the Tissue Weighting Factor for Gonads. Because gonads are highly radio-sensitivity, every effort must be done to reduce gonadal dose to the general population. An elevation of the levels of AGDE is also known to affect the bone marrow that produces red blood cells. This may lead to cancer of the blood called leukaemia, which is often fatal. Other organs of interest are the thyroid, lungs, liver, colon, and bladder ([27]. The annual gonadal dose equivalent (AGDE) in µSv.y-1 is determined using (9) [29]:

$$AGDE(\mu Svy^{-1}) = 3.09C_{Ra} + 4.19C_{Th} + 0.314C_K \quad (9)$$

Where, C is activity concentration of radionuclides (Ra, Th and K).

Gamma Representative Index (RLI)

The gamma radioactivity Representative Level Index associated with naturally occurring radioactive elements and can be measured using Equation (10) [30]

$$RLI = \frac{1}{150C_{Ra}} + \frac{1}{100C_{Th}} + \frac{1}{150C_K} \quad (10)$$

Activity Utilization Index (AUI)

The natural radionuclides activity utilization index (AUI) was used to express the dose rate in the air from different combinations of the three primordial radionuclides in the studied sample. The appropriate factor to the measured specific activity of the respective nuclides was applied and the AUI was calculated from the equation 11 [21]

$$AUI = \left(\frac{C_U}{50Bqkg^{-1}}\right)F_U + \left(\frac{C_{Th}}{50Bqkg^{-1}}\right)F_{Th} + \left(\frac{C_K}{500Bqkg^{-1}}\right)F_K \quad (11)$$

Where; F_U, F_{Th} and F_K are 0.462, 0.604 and 0.041 respectively, which are the respective fractional contribution from the actual activities of these radionuclides to the total gamma radiation dose rate in air.

The Excess Lifetime Cancer Risk (ELCR)

The excess lifetime cancer risks (ELCR), caused by the annual effective dose due to external exposure is estimated using equation 12 [31]:

Excess lifetime cancer risk, $ELCR = E \times ALT \times RF$ (12)

Where, ALT is the average life time (70 years) and RF is risk factor. Fatal cancer risk per Sievert and for stochastic effects, ICRP uses values of 0.5×10^{-4} for the public exposure [31]. This risk represents the number of extra cancers expected in a given number of people exposed to a carcinogen at a given dose.

Results

Radioactivity concentration in soil

Activity concentrations for 226Ra ranged from 19.70 to 48.40 Bq/kg (mean: 33.33 ± 2.56), 232Th ranged from 25.31 to 49.94 Bq/kg (mean: 41.06 ± 2.40), and 40K ranged from 36.55 to 78.07 Bq/kg (mean: 51.53 ± 2.71). The 226Ra values slightly exceeded the world average (33 Bq/kg), while 232Th and 40K were below their respective averages (45 and 420 Bq/kg) as presented in Table 1.

Table 1: Activity concentration of ^{226}Ra (^{238}U), ^{232}Th and ^{40}K in soil

Sample ID	**^{226}Ra(^{238}U) (Bq/kg)**	**^{232}Th (Bq/kg)**	**^{40}K (Bq/kg)**
Mine soil sample 1	24.4450±2.12	49.1448±2.85	66.7185±2.02
Mine soil sample 2	23.2186±2.24	39.2064±2.68	73.0964±3.48
Mine soil sample 3	19.6987±1.62	38.1984±2.51	50.0778±2.80
Mine soil sample 4	23.1750±2.43	39.2246±2.74	77.9160±3.73
Effa point A	37.7926±3.24	31.4709±1.48	38.5692±2.80
Effa point B	38.5863±3.59	39.4527±2.17	49.6112±3.89
Effa point C	25.4925±1.16	49.94299±2.39	41.3686±3.11
Effa point D	37.8911±2.43	38.76853±1.82	38.2582±2.64
Efewu point A	39.1657±2.20	43.32953±2.05	36.5474±2.02
Efewu point B	25.8401±1.27	25.31357±2.17	38.2582±2.18
Efewu point C	48.4013±3.52	47.63968±3.40	47.7449±2.95
Efewu point D	33.3836±2.72	34.21893±2.75	51.0109±2.66
Abache point A	38.0070±2.84	49.60091±2.54	78.0715±3.27
Abache point B	36.5585±3.70	44.25314±2.51	38.5692±1.71
Abache point C	43.2445±3.72	42.98746±1.69	48.3670±2.01
Abache point D	38.3546±2.12	44.24173±2.57	50.2333±2.08
Range	48.40±3.52-19.70±1.62	49.94±2.39-25.31±2.17	78.07±3.27-36.55±2.02
Mean	33.33±2.56	41.06±2.40	51.53±2.71
WAV	33	45	420

Radiological hazard parameters

The estimated values of the radiological parameters obtained are shown in Table 2. These parameters are; Absorbed Dose rate (Dr), Radium equivalent activity (Raeq), Annual Effective Dose Equivalents (AEDE outdoor and AEDE indoor) and External (Hex) and internal (Hin) hazard indices, Annual Gonadal Dose Equivalent, Representative Gamma Index (Iγr), Activity Utilization Index (AUI) and Excess Life Time Cancer Risk (ELCR). The values ranges as; 28.82 – 53.13 nG.h^{-1} with average value of 42.35 nG.h^{-1}, 64.98-120.20 Bq.kg^{-1} with average value of 96.02 Bq.kg^{-1}, 0.04 – 0.07 mSvy^{-1} with average value of 0.05, 0.14 – 0.26 mSvy^{-1} with average value of 0.21, 0.18 -0.33 with the average value of 0.26, 0.25 – 0.46 with the average value of 0.35, 197.67 – 363.69 mSvy^{-1} with an average value of 290.80 mSvy^{-1}, 0.45 – 0.83 with average value of 0.67, 0.55-1.03 with the average value of 0.81 and 0.62 x 10^{-3} - 1.14 x 10^{-3} with average value of 0.91x 10^{-3} respectively.

Table 2: Radiological health hazard parameters estimated

Sample ID	ADR (nGh^{-1})	Raq ($Bqkg^{-1}$)	AEDo($mSvy^{-1}$)	AEDin ($mSvy^{-1}$)	H_{ex}	H_{in}	AGDE ($mSvy^{-1}$)	RLI	AUI	ELCR x 10^{-3}
MSP 1	43.7592	99.8594	0.054	0.215	0.2697	0.3358	301.9099	0.6989	0.8250	0.9392
MSP 2	37.4558	84.9122	0.046	0.184	0.2293	0.2921	258.5805	0.5956	0.6941	0.8039
MSP 3	34.2609	78.1784	0.042	0.168	0.2111	0.2644	236.2627	0.5467	0.6476	0.7353
MSP 4	37.6476	85.2657	0.046	0.185	0.2303	0.2929	260.0352	0.5987	0.6943	0.8080
EPA	38.0769	85.7658	0.047	0.187	0.2317	0.3338	260.4382	0.5924	0.7325	0.8172
EP B	43.7251	98.8237	0.054	0.214	0.2669	0.3712	299.7219	0.6848	0.8372	0.9384
EPC	43.6682	100.0964	0.054	0.214	0.2703	0.3392	300.5233	0.6970	0.8423	0.9372
EPD	42.5173	96.2760	0.052	0.209	0.2600	0.3625	291.1490	0.6658	0.8216	0.9125
EFP A	45.7896	103.9411	0.056	0.225	0.2807	0.3866	313.6153	0.7188	0.8883	0.9827
EFP B	28.8229	64.9844	0.035	0.141	0.1755	0.2454	197.6697	0.4509	0.5477	0.6186
EFP C	53.1267	120.2024	0.065	0.261	0.3247	0.4555	363.6858	0.8309	1.0266	1.1402
EFPD	38.2186	86.2445	0.047	0.187	0.2330	0.3232	262.2079	0.5988	0.7260	0.8202
AB A	50.7738	114.9478	0.062	0.249	0.3105	0.4132	349.2879	0.8014	0.9568	1.0897
ABB	45.2273	102.8103	0.055	0.222	0.2777	0.3765	310.0546	0.7120	0.8755	0.9707
ABC	47.9603	108.4408	0.059	0.235	0.2929	0.4098	328.5003	0.7504	0.9228	1.0293
ABD	46.5366	105.4882	0.057	0.228	0.2849	0.3886	319.2194	0.7316	0.8930	0.9988
Mean	42.35	96.02	0.05	0.21	0.26	0.35	290.80	0.67	0.81	0.91
Range	28.82-53.13	64.98-120.20	0.04-0.07	0.14-0.26	0.18-0.33	0.25-0.46	197.67-363.69	0.45-0.83	0.55-1.03	0.62-1.14
WAV	60	370	1	1	1	1	300	1	1	0.29

Table 3: Comparison of activity concentration of ^{226}Ra and ^{232}Th and ^{40}K in soil from the study area with data from other published work with world average value

Area/Country	^{238}U	^{232}Th	^{40}K	Reference
Benue, Nigeria	33.33	41.06	51.53	Present study
Walvisbay, Namibia	30.38	35.58	203.62	[32]
China	11.9	9.6	39.6	[33]
Delta, Nigeria	8.66	11.66	302.15	[34]
N. Pakistan, Pakistan	50.66	70.15	531.70	[35]
Makoko Lagoon, Nigeria	4.39	10.15	41.04	[36]
Villanueva-Kolombia	44.25	62.8	1596.3	[37]
Tanjun Enim- Indonesia	79.21	100.21	1443.28	[17]
WAV	33	45	420	[38]

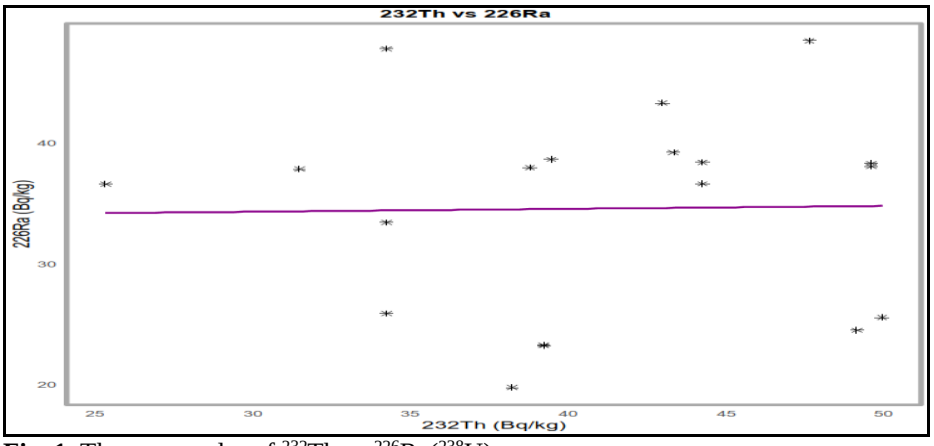

Fig. 1. The scatter plot of ^{232}Th vs ^{226}Ra(^{238}U).

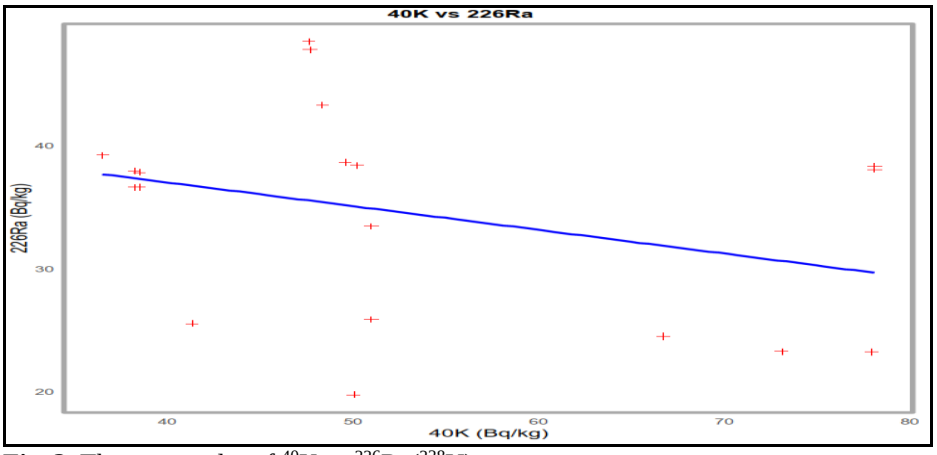

Fig. 2. The scatter plot of ^{40}K vs ^{226}Ra(^{238}U).

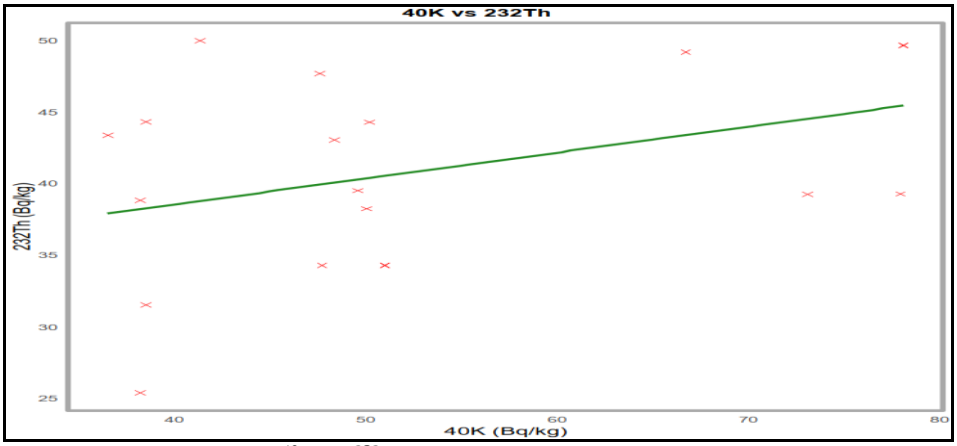

Fig. 3. The scatter plot of ^{40}K vs ^{232}Th

Table 4. The correlation and *p*-values for the three radionuclide pairs.

Pair	Correlation	*p*-value
^{40}K vs ^{226}Ra(^{238}U)	-0.3329	0.1637
^{40}K vs ^{232}Th	0.3822	0.1064
^{232}Th vs ^{226}Ra(^{238}U)	0.0197	0.9363

Discussion

The results indicated that the activity concentration of the radionuclides varied in various soil samples. The average activity concentration determined for ^{226}Ra in this present study was higher than the world average values by a factor of 1.01 which may be due to leaching from the top soil. However, the values were lower than the world average values by a factor of 0.9124 for ^{232}Th and 0.1227 for ^{40}K [**38**] as shown in Table 3. The trend here showed that ^{40}K > ^{232}Th > ^{226}Ra which is in line with the studies carried out by [**36**] in Nigeria, [**32**] in Namibia and [**35**] in Pakistan. The results also agreed with the notion that the average activity concentration of ^{232}Th in soil is greater than that of ^{238}U as per [**21**]. It has been observed that ^{40}K is the highest naturally occurring radionuclide element in nature [**39**]. The results compared with other works in Table 3, showed that the current average concentrations of the radionuclides were higher than the values recorded from China [**33**] and Nigeria [**36**] while there were found to be lower than values reported in Pakistan [**35**] in Kolombia ([**37**] and in Indonesia [**17**]. The average activity concentration of ^{226}Ra and ^{232}Th are greater than were record in Namibia and Nigeria [**32**, **34**] whereas the value of ^{40}K was lower than the values reported for the Namibia and Nigeria. The variation in radionuclides concentrations may be due to mineralization and geological formation of the area. The sandstone is responsible for the distributions of the radionuclides due to its high permeability and low attachment ability just as coal seams which act as sink for radionuclides. Shale and mudstone concentrate radionuclides due to their low permeability, fine-grain texture and high surface area.

The radiological health hazard parameters shown in Table 2 recorded values that shows AGDE though having average value lower than the world average value of 300 mSvy^{-1} had values higher than the world average value at Abache and other parts of the study area implying that the community may be exposed to radiological hazard, which might affect the functionality of their sensitive organs most especially the reproductive organs, and the bone marrows [**40**]. Excess Life Time Cancer Risk (ELCR) recorded higher values for all locations in study area than the world average value of 0.29 x 10^{-3} [**41**] which agrees [**42**]. The result implies that approximately 0.91out of 1000 (or 1 in 1,099) may develop cancer due to the exposure which would be considered as moderate to high risk. This calls for concern as regular monitoring will be required for adequate radiation protection. The values of the other parameters evaluated as shown in Table 2 were found lower than the world average value but preventive measures should be put in place to avoid enrichment that can lead to higher and long- time cumulative effects.

In order to test the correlations between the activity concentrations of ^{232}Th versus ^{226}Ra, ^{40}K versus ^{226}Ra and ^{40}K versus ^{226}Th, the activity obtained for ^{226}Ra, ^{232}Th and ^{40}K were illustrated in Figures 1,2 and 3 respectively. None of the radionuclide pairs show statistically significant correlations (all *p*-values > 0.05). The strongest observed trend is between ^{40}K and ^{232}Th, with a moderate positive correlation, though it still falls short of significance as shown in Table 4. A weak positive correlation was found to exist between ^{232}Th and ^{226}Ra indicating a weak natural abundance of ^{232}Th versus ^{226}Ra over period of times through their decay process whereas a very weak negative correlation exists between ^{40}K versus ^{226}Ra which show the anomaly of potassium existence in earth crust due to human activity.

Conclusion

This study assessed the levels of natural radionuclides in soils around the Abache, Effa, Efewu and coal mine, Benue State. While most values were within permissible limits, AGDE exceeded safety thresholds at specific sites in the area and ELCR obtained was found higher than the world average value. Regular monitoring and control measures are recommended to protect public health. The results provide a valuable baseline for radiological assessments in the region and can guide future policy and environmental safety strategies.

Data availability statement

Data included in articles/supp. material/referenced in articles

Conflict of interest

There is no conflict of interest

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