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NATURAL RADIOACTIVITY AND ASSOCIATED RADIATION HAZARDS IN SOIL OF PIMAK AND FARIN-DUTSE TIN MINES, WESTERN NASARAWA STATE, NIGERIA

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Abstract

Radiological effects were carried out in the soil of the Farin-Dutse and Pimak mining sites in western Nasarawa State as a result of both internal and external exposure to radiation from natural sources related to ^{226}Ra, ^{232}Th, and ^{40}K radionuclides. The activity concentrations of Ra, Th, and K activities in soil samples were measured using the sodium iodide thallium activated (NaI(Tl)) gamma detector. The activity concentrations of Ra, Th, and K for Farin-Dutse and Pimak were found to be within the range of 11 - 57 Bq kg^{-1}, 9 - 40 Bq kg^{-1}, and 434 - 856 Bq kg^{-1}; 12 - 42 Bq kg^{-1}, 27 - 63 Bq kg^{-1}, and 186 - 2086 Bq kg^{-1} respectively; the potassium concentrations were found to be increasing with depth in all the locations and higher than the recommended limit except for Pimak1(0ft) and Pimak1 (1ft) respectively as reported by United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2000). The annual gonadal dose equivalent (AGDE), annual effective dose rate (AEDE), radium equivalent (Ra_{eq}), and absorbed dose rate (DR) were the radiological health hazards indicators for Farin-Dutse and Pimak were found to be within the range of 0.21- 0.56 mSv yr^{-1}, 0.35 – 0.97 mSv yr^{-1}, 338 - 752 Bq kg^{-1}, and 29 - 79 nGy hr^{-1}; 0.34 – 0.83 mSv yr^{-1},0.60 – 1.39 mS yr^{-1}, 237 - 1657 Bq kg^{-1}, and 49 - 113 nGy hr^{-1} respectively. The external and internal hazard index (H_{ex} and H_{in}) for both mines are below the recommended limit of unity.

Keywords: Activity, Ionizing Radiation, Mining, Radionuclides, Soil.

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1.0 INTRODUCTION

A large portion of the land-atmosphere interface is made up of relatively thin coatings of fibrous materials and heterogeneous particulate matter called soils. The diverse array of soil micro- and macroflora and fauna inhabits these intricate mixtures of minerals, carbonaceous materials, and water. A common characteristic of both naturally occurring and artificially created isotopes is radioactivity, which is the nucleus's spontaneous disintegration along with particle emission. The process is present in soil minerals, plant fibers, animal tissues, air, and water, all of which contain minute amounts of radioactive elements. (Raymond, 2000). The standard has been the ALARA concept, which seeks to guarantee the lowest possible level of radiation exposure for humans. "ALARA" is the guiding concept of radiation safety. The acronym ALARA represents "as low as reasonably achievable." ALARA refers to avoiding radiation exposure, especially at low doses, that does not directly benefit you. Time, distance, and shielding are the three fundamental radiation safety precautions to accomplish this. The Nigerian government has repeatedly shown its disapproval of artisanal mining operations and the promotion of human health by enacting laws, decrees, and initiatives. The most recent example of this is the introduction of the Presidential Artisanal Gold Mining Development Initiative (PAGMI) by the previous administration of President Muhammadu Buhari. (https://statehouse.gov.ng).

Farin-Dutse and Pimak are local community settlements in the western part of Nasarawa State endowed with tin deposits, a major asset to the surrounding area's economic development. Additionally, the settlements are blessed with many streams and rivers passing across them. The population is largely young men and women between 20 – 40 years old. They use their family farmlands and any available land within the community settlement for the extraction of tin without recourse to their well-being. Since they employed crude techniques, they washed out the dug soil into the streams and rivers, in a few cases they dug wells within the farmlands in search of water to wash out the tin from the soil and the dispersed water eventually got into the streams and rivers which are the primary sources of drinking water and for other domestic use. These practices are on the premise that mining will generate more economic benefits to the community than traditional farming. Nonetheless, an upsurge in illicit and artisanal mining operations may worsen the local ecology and raise background radioactivity levels, which might impact the general well-being of the community.

This research endeavor was conducted to examine the radiological health risks related to the indiscriminate mining and artisanal mining activities widespread among the inhabitants of these villages. As a result, this groundbreaking study reported the concentrations of Ra, Th, and K utilizing UNSCEAR-established standard protocols along with the associated potential health implications.

Solid mineral mining in Nigeria has been linked to the environmental release of primordial radionuclides because of the removal of sizable amounts of radioactively contaminated soil (Ibeanu, 2003). The consequences of mining and tailing dumps in Nigeria have been brought to light by Odunmbaku, Adewumi, and Musa (1999), Abdulkarim and Musa (2013), Abdulkarim et al (2018), Abubakar et al (2015a, 2015b), Gomina, Kola, and Awojoyobge (2019), Termizi et al (2014), Jibiri, Alausa, and Farai (2009), and Nuradden et al (2018) posited that there is a significant radiological risk to people and the environment from exposure to ionizing radiation from natural radioactivity as a result of the ongoing release of mining wastes and tailings into the environment. These releases cause radionuclides to accumulate in the biosphere, air, water, and soil. They found that the extraction of tin and other minerals, along with other mining-related activities, contribute to environmental degradation, deforestation, air and water pollution, and the extinction of aquatic life. These effects are particularly felt by those who work in and around mines. They reaffirmed the necessity for workers and public protection and recommended continuous and thorough evaluation, appropriate control, monitoring, and remediation techniques to prevent the radiological effects of radiation exposure. They corroborated that ongoing evaluation of radiological hazards would provide a baseline for future assessments of other exposures and act as a guide for dosimetry and decontamination in cases of radiation poisoning.

2.0 METHOD

Study Area

Farin-Dutse and Pimak are local community settlements in Nasarawa West Senatorial District of Nasarawa State, Nigeria, and are predominantly farmers and hunters. Small, medium, informal, legal, and illicit miners who employ crude techniques and protocols to extract natural resources are all considered artisanal (small-scale) miners (Sabo, Sadiq, and Gamba, 2018). The senatorial district presently has a large number of artisanal miners, although only a few of them are operational and accessible because of local security issues.

According to the World Nuclear Association (WNA), radiation protection standards assume that any radiation dose, no matter how small, presents a potential risk to human health (WNA, 2014; Njinga, Jonah, and Gomina, 2015). Therefore, a compelling need to investigate the activity concentration of naturally occurring radioactive elements in the artisanal Farin-Dutse and Pimak tin mines. This will provide radiological parameters to ascertain the radiological risk associated with small-scale mining in the district. Figure 1 shows the area of investigation.

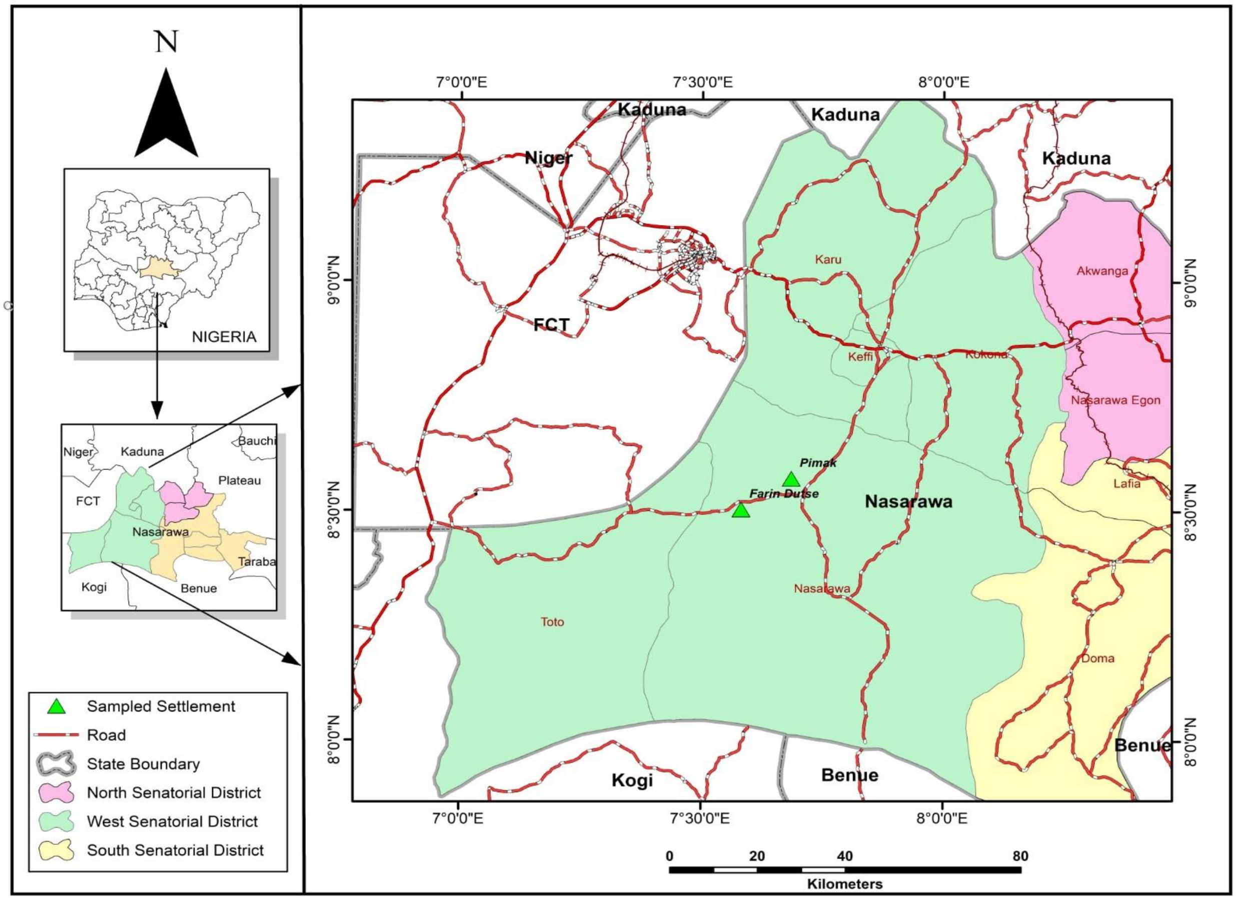

Figure 1. Map of Nasarawa State Indicating Study Area with ▲
(Source: Adapted from Google Earth Imagery and Administrative Map of Nasarawa State, 2023)

Sample collection preparation

The preliminary survey, which used a radiation alarm meter to identify regions with elevated ionizing radiation within the mining sites, served as the foundation for the in-situ survey for this study. This measure, however, only evaluates the background radiation level in a given area and does not account for the amount of ionizing radiation that is emitted from the soil, making it unreliable for estimating radiation levels. All it does is point out the best place to collect samples for further investigation.

Twelve (12) soil samples altogether, weighing around 6 kg, were taken from these locations (Farin-Dutse and Pimak). Two spots were chosen as identified by the radiation alert meter as having high background radiation within the mining areas. Using a global positioning system (GPS), the sampling locations were noted, and samples were taken at the topsoil, one foot, and two feet above ground level, respectively, to achieve a fully representative sampling of the areas. After being gathered, the samples were placed in clearly labeled plastic take-away containers and brought to the laboratory for examination.

Sample Preparation

The low background radiation laboratory of the Centre for Energy Research and Training (CERT), Ahmadu Bello University Zaria was utilized. After the samples were free of rocks and pebbles in the laboratory, they were left to dry for 48 hours at room temperature. To achieve secular equilibrium between radium and its progeny, the dried samples were crushed, ground into a fine powder, and then sieved through a 2-mm mesh screen to create a homogenized sample. These homogenized samples were then weighted, packed, and kept in standard 500ml Marinelli beakers for approximately 30 days (Ibeanu, 1999, Veiga et al., 2006).

Sample Analysis

Following secular equilibrium, the sealed samples were counted using a Canberra model A65-B1 version 3.20, sodium iodide (thallium) activated gamma detector made by EG&G Ortec, with an energy resolution of 72% at the peak of Cs-137 at 661.16 keV. The samples were enclosed in a 6 cm thick lead shield, cadmium-lined assembly with copper sheets to minimize background radiation. The NaI(Tl) crystal is linked to a photomultiplier tube (PMT). There is an external voltage source (1Kv) and an internal preamplifier in the configuration. Efficiency and energy calibrations were performed for the detector. Computer-based MCA software, Maestro for Windows, developed by EG&G Ortec and Canberra, was used for the gamma spectra acquisition and processing.

The gamma-ray emission of ^{214}Bi (1764 keV) was used to calculate the activity of ^{226}Ra, the emission of ^{208}Tl (2614.5 keV) was used to determine the activity of ^{232}Th and the emission energy of 1460 keV was used to determine the activity of ^{40}K over a counting duration of 29,000 s (8 hrs). Figure 2 shows the set-up used for this investigation.

Figure 2: Picture of the CERT, A.B.U Zaria NaI(Tl) Gamma Spectrometry Section.

3.0 RESULTS AND DISCUSSION

The results obtained from the NaI(Tl) detector showed different activity concentrations of the radionuclides ^{226}Ra, ^{232}Th, and ^{40}K as analyzed by the acquired spectrum.
The gross area count G_c is related to the area count (Okeyode and Akanni, 2009)

$$N_c = G_c - B_c \qquad (1)$$

where B_c is the background area count (area count recorded by the detector in the absence of the samples) and N_c is the net area count.
Using equation (1), the net area count N_c was calculated from the gross area counts G_c generated by the gamma spectroscopy system. Consequently, the net count per second (CPS) was also calculated for the three radionuclides (^{40}K, ^{226}Ra, and ^{232}Th). Table 1 shows the background count rate and conversion factors used in the evaluation of the samples.

Table 1: Background count rate and conversion factor (σ) used in the evaluation of the samples

S/N	Nuclides	Background Count (CPS)	CPS/Bq-Kg^{-1})
1	226Ra	0.0169±0.0102	0.000643
2	232Th	0.1000±0.0074	0.000863
3	40K	0.2174±0.0157	0.000877

The activity concentrations for the naturally occurring radionuclides in the measured samples were computed using the relation below (Okeyode and Akanni, 2009).

$$A_c = \frac{N_c}{L_t}\sigma - 1 \qquad (2)$$

where L_t is the lifetime of the counting, and σ is the conversion factor – it is constant for each radionuclide at a constant geometry, and it is the characteristics of the efficiency of the NaI (Tl) detector used in the analysis of the samples in this work. All the raw data obtained from the detector were converted to conventional units using calibration factors to determine the activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th respectively. Table 2 shows the result of the activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th in soil samples from Farin-Dutse and Pimak mines.

	K-40			Ra-226			Th-22		
	Top Soil	**1 Feet**	**2 Feet**	**Top Soil**	**1 Feet**	**2 Feet**	**Top Soil**	**1 Feet**	**2 Feet**
Farin Dutse 1	690±5.4	703±5.6	856±9.9	57±4.5	32±2.1	33±3.0	40±1.3	29±3.5	42±1.2
Farin Dutse 2	434±8.0	612±10.4	-	11±1.7	45±3.8	-	9±3.4	29±1.4	-
Pimak 1	186±7.9	195±5.4	516±6.9	42±1.9	15±0.9	21±1.9	36±2.4	63±2.4	52±1.2
Pimak 2	1839±11.1	2086±9.7	1788±8.8	21±0.7	12±2.5	18±1.8	44±2.1	27±3.1	31±1.8

It is noteworthy to note that the soil samples from Farin-Dutse and Pimak mine had activity concentrations of ^{40}K increasing with depth, ranging from 434 to 856 Bq kg^{-1} and from 186 to 2086 Bq kg^{-1}, respectively. These values are more than twice and five times the global average for ^{40}K respectively. These high values can be explained by the high rate of farming activity in the surrounding areas, which will further increase the ^{40}K concentration because of the high fertilizer application rates. The ^{226}Ra activity concentrations for mines were within the recommended value of 35 Bq kg^{-1} except for Farin-Dutse1(0ft), Farin-Dutse2 (1ft), and Pimak1 (0ft). The activity concentrations of ^{232}Th are higher than the recommended limit in both mines except in Farin-Dutse1 (1ft), Farin-Dutse2 (0ft), Farin-Dutse2 (1ft), and Pimak2 (1ft) as reported by UNSCEAR (2000).

Assessment of Radiation Hazard Indices

For the natural radionuclides ^{226}Ra, ^{232}Th, and ^{40}K, the radiological effects of exposure to external and internal radiation can be evaluated by calculating the absorbed dose rate (D), radium equivalent (Ra_{eq}), external hazard index (H_{ex}), annual effective dose equivalent (AEDE), and annual gonadal dose equivalent (AGDE).

Absorbed Dose Rate (DR)

By assuming secular equilibrium between ^{238}U and ^{226}Ra in the surface soil and using the dose coefficients factors 0.462, 0.604, and 0.0417 (UNSCEAR, 2000; Munyaradzi, Anna, and Makondelele, 2018) for the ^{226}Ra sub-series, ^{232}Th series, and ^{40}K, respectively, the gamma absorbed dose rates in the air were determined from ^{226}Ra, ^{232}Th, and ^{40}K activities. Equation (3) provides the absorbed dose rate (DR):

$$DR\ (nGy\ hr^{-1}) = 0.462C_{Ra} + 0.604C_{Th} + 0.0417C_k \quad (3)$$

where C_{Ra}, C_{Th}, and C_k denote the activity concentrations of Ra, Th, and K, respectively in Bq kg^{-1}. It should be mentioned that the ^{226}Ra sub-series delivers roughly 90% of the external dose from the ^{238}U series. Consequently, the dose estimate derived from the measurement of ^{226}Ra is unaffected by any disequilibrium that may exist between ^{226}Ra and ^{238}U (Nuraddeen et al.,2018). Table 3 presents the absorbed dose values that were determined in this manner. The computed values range from 28.62 to 112.96 $nGyhr^{-1}$. Three of the eleven locations have D_R values greater than the recommended limits of 84 $nGyhr^{-1}$ (UNSCEAR, 2000), Pimak2 (0ft) has 112.96 $nGyhr^{-1}$, Pimak2 (1ft) has 108.84 $nGyhr^{-1}$, and Pimak2 (2ft) has 101.60 $nGyhr^{-1}$. The locations with D_R within the suggested limit are Farin-Dutse1 (0ft) with 79.27 $nGyhr^{-1}$, Farin-Dutse1 (1ft) with 61.62 $nGyhr^{-1}$, Farin-Dutse1 (2ft) with 76.31 $nGyhr^{-1}$, Farin-Dutse2 (0ft) with 28.62 $nGyhr^{-1}$, Farin-Dutse2 (1ft) with 63.83 $nGyhr^{-1}$, Pimak1 (0ft) with 48.90 $nGyhr^{-1}$, Pimak1 (1ft) with 53.11 $nGyhr^{-1}$, and Pimak1 (2ft) with 62.63 $nGyhr^{-1}$. The proportion of naturally occurring radionuclides to the absorbed dose rates varies based on the different radionuclide concentrations in the sediment (Erenturk et al, 2014).

Radium Equivalent (Ra_{eq})

The term radium equivalent (Ra_{eq}) in Bq kg^{-1} will be useful to compare the average activity concentrations containing varying amounts of ^{226}Ra, ^{232}Th, and ^{40}K as the diversity levels of natural radionuclides in soil samples are not uniform. Materials containing natural radionuclides, such as ^{226}Ra, ^{232}Th, and ^{40}K, are evaluated for their potential risk of gamma radiation using Ra_{eq}. It is expected that the gamma radiation dosage rates for ^{226}Ra, ^{232}Th, and ^{40}K are comparable at 370 Bq kg^{-1}, 259 Bq kg^{-1}, and 4810 Bq kg^{-1}, respectively (Beretka and Mathew, 1985). Equation (4) yields Ra_{eq} (Bq kg-1):

$$Ra_{eq}\ (Bq\ kg^{-1}) = C_{Ra} + 1.43C_{Th} + 0.77C_k \quad (4)$$

where C_{Ra}, $C_{Th,}$ and C_k are the mean activity of ^{226}Ra, ^{232}Th, and ^{40}K in Bq kg^{-1}respectively.

To maintain the annual radiation dosage below 2.4mSv, the maximum value needs to be less than 370 Bq kg^{-1} (Tufail et al., 2006). Ra_{eq} was calculated at eleven different locations and found to range from 255.24 to 1656.83 Bq kg^{-1}. Three locations Farin-Dutse2 (1ft) with 338.05 Bq kg^{-1}, Pimak1 (0ft) with 236.70 Bq $kg^{-1,}$ and Pimak1 (1ft) with 255.24 Bq kg^{-1} had Ra_{eq} values below the recommended limits of 370 Bq kg^{-1} defined for this index (UNSCEAR, 2000). Therefore, only the soils from these two places are suitable for use as building materials from the perspective of radiation protection. The sites with values higher than the suggested limit are Farin-Dutse1 (0ft) with 645.50 Bq kg^{-1}, Farin-Dutse1 (1ft) with 614.78 Bq kg^{-1}, Farin-Dutse1 (2ft) with 752.18 Bq kg^{-1}, Farin-Dutse2 (2ft) with 557.71 Bq kg^{-1}, Pimak1 (2ft) with 492.68 Bq kg^{-1}, Pimak2 (0ft) with 1499.95 Bq kg^{-1}, Pimak2 (1ft) with 1656.83 Bq kg^{-1}, and Pimak2 (2ft) with 1439.09 Bq kg^{-1} as Table 3 illustrates.

Annual Effective Dose Equivalent (AEDE)

The annual effective dose equivalent (also called the outdoor annual effective dose - OAED) is estimated as the product of the gamma radiation dose, DR (nGy/hr), dose conversion factor of 0.7Sv/Gy, and occupancy factor of 20% (0.2) for outdoor exposure (duration the miners spend on the field in a year) using the equation

$$AEDE = DR\ (nGy\ hr^{-1}) \times a\ (hr\ d^{-1}) \times b\ (d\ yr^{-1}) \times q \times ɗ \quad (5)$$

The variables a, b, q, and ɗ represent the number of hours in a day (24 hours per day), days in a year (365.25 days per year), outdoor occupancy factor (0.2), and conversion factor (0.7Sv Gyr^{-1}) between the effective dose that an adult receives and the absorbed dose in the air. 500 µSv yr^{-1} is the global average. Only Farin-Dutse2 (0ft) out of the eleven locations had an AEDE of 0.35 mSv yr^{-1} within the suggested limits of 0.50 mSv yr^{-1} specified for this index (UNSCEAR, 2000). The computed values of AEDE varied from 0.35 to 1.39 mSv yr^{-1}. The sites with values higher than the suggested value are Farin-Dutse1 (oft) with 0.97 mSv yr^{-1}, Farin-Dutse1 (1ft) with 0.76 mSv yr^{-1}, Farin-Dutse1 (2ft) with 0.94 mSv yr^{-1}, Farin-Dutse2 (1ft) with 0.78 mSv yr^{-1}, Pimak1 (0ft) with 0.60 mSv yr^{-1}, Pimak1 (1ft) with 0.65 mSv yr^{-1}, Pimak1 (2ft) with 0.77 mSv yr^{-1}, Pimak2 (0ft) with 1.39 mSv yr^{-1}, Pimak2 (1ft) with 1.34 mSv yr^{-1}, and Pimak2 (2ft) with 1.25 mSv yr^{-1}. The high values from these sites are directly related to the higher values of the absorbed dose rate from the locations as presented in Table 3.

Annual Gonadal Dose Equivalent (AGDE)

According to UNSCEAR (UNSCEAR, 1988), the bone marrow and bone surface cells were identified as organs of interest when calculating the AGDE resulting from the average activity of ^{226}Ra, ^{232}Th, and ^{40}K. AGDE is computed using equation (6) (Mamont-Ciesla et al., 1982; Xinwei et al., 2006):

$$AGDE\ (mSv\ yr^{-1}) = 3.09C_{Ra} + 4.18C_{Th} + 0.314C_k \quad (6)$$

where C_{Ra}, C_{Th}, and C_k are the mean activity of ^{226}Ra, ^{232}Th, and ^{40}K in Bq kg^{-1}respectively.

Only Farin-Dutse2 (0ft) out of the eleven locations had an AGDE of 0.21 mSv yr^{-1} which is within the suggested limit of 0.30 mSv yr^{-1} specified for this index (UNSCEAR, 2000). The computed values of AGDE ranged from 0.21 – 0.83 mSv yr^{-1}. The locations with values higher than the suggested limit are Farin-Dutse1 (0ft) with 0.56 mSv yr^{-1}, Farin-Dutse1 (1ft) with 0.44 mSv yr^{-1}, Farin-Dutse1 (2ft) with 0.55 mSv yr^{-1}, Farin-Dutse2 (1ft) with 0.45 mSv yr^{-1}, Pimak1 (0ft) with 0.34 mSv yr^{-1}, Pimak1 (1ft) with 0.37 mSv yr^{-1}, Pimak1 (2ft) with 0.44 mSv yr^{-1}, Pimak2 (0ft) with 0.83 mSv yr^{-1}, Pimak2 (1ft) with 0.80 mSv yr^{-1}, and Pimak2 (2ft) with 0.75 mSv yr^{-1}. Elevations of the suggested limit could lead to increased genetic risks of harm to the lungs, female breast, active bone marrow, and bone surface (UNSCEAR, 2000).

External and Internal Hazard Index (H_{ex}, H_{in})

The risk posed by naturally occurring gamma radiation from primordial radionuclides is evaluated by the external H_{ex} and Internal H_{in} hazard index. The primary goal is to determine whether the hazard index is smaller than unity (ICPR, 2000). The H_{ex} and H_{in} are evaluated by equations 6 and 7 respectively (Viega et al., 2006):

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

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \qquad (8)$$

where C_{Ra}, C_{Th}, and C_k are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in Bq kg^{-1}respectively.

The value for the H_{ex} and H_{in} should be less than 1, for the radiation hazard to be considered acceptable for the public (Berekta and Mathew, 1985; Kumar et al., 1999; Amrani and Tahtat, 2001; Al-Hamarneh and Awadallah, 2009). The H_{ex} and H_{in} (as presented in Table 3) in all the locations were found to be less than the suggested limit value of unity (ICRP 2000).

Table 3. Radiological Health Risk Indicators for Farin-Dutse & Pimak Mines

Name of Mine	DR (nGy hr^{-1})	Ra-eq (Bq/Kg)	Hex	Hin	AEDE (mSv yr^{-1})	AGDE (mSv yr^{-1})
Farin-Dutse1(0ft)	79.27	645.50	0.45	0.61	0.97	0.56
Farin-Dutse1(1ft)	61.62	614.78	0.34	0.43	0.76	0.44
Farin-Dutse1(2ft)	76.31	752.18	0.43	0.52	0.94	0.55
Farin-Dutse2(0ft)	28.62	338.05	0.15	0.18	0.35	0.21
Farin-Dutse2(1ft)	63.83	557.71	0.36	0.48	0.78	0.45
Farin-Dutse2(2ft)	-	-	-	-	-	-
Pimak1(0ft)	48.90	236.70	0.29	0.40	0.60	0.34
Pimak1(1ft)	53.11	255.24	0.32	0.36	0.65	0.37
Pimak1(2ft)	62.63	492.68	0.36	0.42	0.77	0.44
Pimak2(0ft)	112.96	1499.95	0.61	0.67	1.39	0.83
Pimak2(1ft)	108.84	1656.83	0.57	0.60	1.34	0.80
Pimak2(2ft)	101.60	1439.09	0.59	0.59	1.25	0.75
World Average	**84**	**370**	**≤ 1**	**≤ 1**	**0.5**	

Minimum Depth for Hazard and Health Indices

Furthermore, using regression analysis, expressions for the depth dependence of different hazard indices were carried out with equations (9) to (14) obtained as stated

Dose Rate (DR)

$$DR = A\begin{cases}63.386\\35.674\end{cases} \times Depth,\ R^2 = \begin{cases}0.8326\\0.5575\end{cases} \qquad (9)$$

Radium Equivalent Activity (Ra_{eq})

$$Raeq = A\begin{cases}907.00\\248.12\end{cases} \times Depth,\ R^2 = \begin{cases}0.5821\\0.8459\end{cases} \qquad (10)$$

Annual Effective Dose Equivalent (AEDE)

$$AEDE = A\begin{cases}0.780\\0.438\end{cases} \times Depth,\ R^2 = \begin{cases}0.8324\\0.6974\end{cases} \qquad (11)$$

Annual Gonadal Dose Equivalent (AGDE)

$$AGDE = A\begin{cases}0.46\\0.25\end{cases} \times Depth,\ R^2 = \begin{cases}0.5594\\0.7005\end{cases} \qquad (12)$$

External Hazard Index (H_{ex})

$$Hex = A\begin{cases}0.360\\0.208\end{cases} \times Depth,\ R^2 = \begin{cases}0.8521\\0.6843\end{cases} \quad (13)$$

Internal Hazard Index (H_{in})

$$Hin = A\begin{cases}0.480\\0.240\end{cases} \times Depth,\ R^2 = \begin{cases}0.8767\\0.6180\end{cases} \quad (14)$$

Table 4 can be obtained from these equations.

Table 4: Minimum Depth Determined for Radiation Hazard Indices Based on Recommended Limits

	DR_{min}	Ra_{eqMin}	$AEDE_{Min}$	$AGDE_{Min}$	H_{exMin}	H_{inMin}
SR1	1.96042	0.87299	0.94697	0.97403	4.16667	3.40136
SR2	1.31600	0.66343	0.64103	0.66667	2.77778	2.08333
SR3	1.34598	1.49121	1.14155	1.20000	4.80769	4.16667
SR4	2.35459	0.40794	0.65104	0.65217	3.03030	2.80899

(SR1 = Farin-Duste 1, SR2 = Farin-Dutse 2, SR3 = Pimak 1, and SR4 = Pimak 2)

In Table 4, the minimum depth determined for Dose Rate (DR), Radium Equivalent (Ra_{eq}), Annual Effective Dose Equivalent (AEDE), Annual Gonadal Dose Equivalent (AGDE), External Hazard Index (H_{ex}) and Internal Hazard Index (H_{in}) has been determined and reported. The minimum depth is the depth in feet beyond which the miners will be exposed to the limit of a specific hazard index. These minimum depths are determined based on UNSCEAR (2000) recommended limits for soil sample types.

From Table 4, the miner must not exceed 2.35459ft, 1.49121ft, 1.14155ft, 1.2000ft, 4.80769ft, and 4.16667ft to be within the recommended safety limits for Dose Rate (DR), Radium Equivalent (Ra_{eq}), Annual Effective Dose Equivalent (AEDE), Annual Gonadal Dose Equivalent (AGDE), External Hazard Index (H_{ex}) and Internal Hazard Index (H_{in}) respectively. This implies that mining operations beyond these depth limits should be considered unsafe without adapting other components of the ALARA Principle.

4,.0 CONCLUSION

This study evaluated the impact of radiological health hazards associated with natural radioactivity in the Farin-Dutse and Pimak tin mines, western Nasarawa State, Nigeria. The activity concentrations of ^{226}Ra were within the suggested limit of 35 Bq kg^{-1} in all the locations except in Farin-Dutse1 (0ft), Farin-Dutse2 (1ft), and Pimak1 (0ft). For ^{232}Th, the activity concentrations were above the suggested limit of 30 Bq kg^{-1} with the exceptions of Farin-Dutse1 (1ft), Farin-Dutse2 (0ft), Farin-Dutse2 (2ft), and Pimak2 (1ft). The evaluated activity concentrations of ^{40}K increased with increasing depth and were higher than the suggested limit in all the locations except in Pimak1 (0ft) and Pimak1 (1ft). Additionally, using conventional formalism as suggested by the most current UNSCEAR report, the collected values were used to determine health hazard parameters. The results of comparing the values obtained for these parameters with the prescribed limits showed that there is no generally substantial risk of radiation from the Farin-Dutse and Pimak tin mines to human health, except for a few places with elevated levels of radioactivity and hazard indices. In addition, regression analysis was employed for the depth dependence of the different hazard indices which suggested the minimum depth (in feet) beyond which the miners will be exposed to the limit of a specified hazard index as recommended by UNSCEAR (2000) for soil sample types.

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