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Spatial Distribution of Natural Radionuclides and Statistical Analysis of Radiological Hazards in Relation to Soil Classification in Katsina State

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ABSTRACT
This study assessed the influence of soil type on the distribution of naturally occurring radionuclides and the associated radiological hazards in southern Katsina State, Nigeria. A total of 25 soil samples were collected from six dominant soil types - Acrisols, Arenosols, Cambisols, Lixisols, Luvisols, and Leptosols - and analyzed using gamma-ray spectrometry for activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K. Radiological hazard parameters including absorbed dose rate (D_R), annual effective dose (AED), and hazard indices were evaluated. The mean activity concentrations were 31.46 ± 3.53 Bq/kg for ^{226}Ra, 91.38 ± 5.08 Bq/kg for ^{232}Th, and 312.93 ± 7.10 Bq/kg for ^{40}K. While ^{40}K and ^{226}Ra levels were below global averages, ^{232}Th exceeded the recommended limit. The absorbed dose rate ranged from 46.12 to 107.58 nGy/h, and AED values ranged from 56.54 to 132 µSv/y, all below the global threshold of 480 µSv/y. Hazard indices remained under unity, indicating negligible radiological risk. Statistical analysis using one-way ANOVA revealed significant variation ($p = 0.03843$) in AED among the soil types, with Leptosols showing the highest mean dose rate (224.5 µSv/y), suggesting a greater radiological contribution. An R^2 value of 0.4379 indicated a moderate correlation between soil type and AED variability. Additionally, soil pH ranged from 6.15 to 6.51, indicating generally acidic conditions. A moderate negative correlation was found between pH and the activity concentrations of ^{226}Ra and ^{232}Th, while ^{40}K showed a strong positive correlation with pH. The findings contribute critical baseline data for environmental radiation monitoring and suggest that soil type significantly influences dose rate distribution. These insights are vital for land-use planning, environmental safety, and public health risk assessment in Katsina State.

Keywords: Radioactivity, Soil type, Soil pH, ANOVA

1.0 INTRODUCTION

The distribution of naturally occurring radioactive materials (NORMs), specifically ^{238}U, ^{232}Th, and ^{40}K, in soil is influenced by the presence of primordial radionuclides—uranium (U), thorium (Th), and potassium (K)—in the bedrock (Hillel, 2007; S. M. Johar et al., 2016), as well as the chemical and mechanical processes involved in the formation of sands (Alsaffar & Kabir, 2024). The radioactivity present in the surface layers of soil is derived from the decay of these radionuclides (Zorer, 2019). The level of gamma radiation resulting from natural environmental radioactivity is influenced by geological and geographical factors. These factors, in turn, affect the absorbed dose received by inhabitants and can be observed in varying concentrations in soils globally (Almayahi et al., 2012; Saffuwan Mohamed Johar et al., 2016). Igneous rocks containing dark-colored heavy minerals are usually characterized as having higher radiation, whereas lower-level radiation comes from sedimentary rocks (Abdulkadir et al., 2023; Sandesh et al., 2022; Shahul Hameed et al., 2012).

In evaluating the health risks of a population, it is crucial to estimate the distribution of radiation doses. This estimation serves as a reference for documenting changes in soil radioactivity levels resulting from both natural and anthropogenic activities (Obed et al., 2005). Over the years, a substantial body of research has been conducted due to concerns regarding the health risks associated with exposure to radioactivity from soil in various locations worldwide (Abba et al., 2017; Abd El-mageed et al., 2011; Agbalagba & Onoja, 2011; Ahmed & El-Arabi, 2005; Alam et al., 1999; Almayahi et al., 2012; Atsue & Adegboyega, 2017; Beretka & Mathew, 1985; Dowdall et al., 2003; Garba, Abdulkadir, et al., 2023; Osman et al., 2008; Ramli, 1997; Saleh et al., 2013; Sandesh et al., 2022). The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) asserts that additional data is necessary regarding exposures from natural, anthropogenic, and occupational sources of radiation at low levels (Garba, Abdulkadir, et al., 2023).

The most likely hazard associated with natural radiation involves either external exposure to soil, direct exposure to certain building materials, or the transfer of radionuclides from soil to plants. Factors influencing this transfer include soil type, electrical conductivity, soil pH, and the organic matter content of the soil (Saleh et al., 2015; Thabayneh, 2014). There is a paucity of studies that estimate the terrestrial gamma radiation dose levels at various locations within Katsina State, Nigeria (Abdulkadir et al., 2023; Atsue & Adegboyega, 2017; Garba, Abdulkadir, et al., 2023; Najib et al., 2016). Nevertheless, the existing studies solely focus on examining the background radiation levels of the areas. The activity of primordial radionuclides within the soil of the study area, which the inhabitants utilize for various activities such as agriculture and construction, has not been evaluated.

Hence, the aim of this study is to evaluate the activity of radionuclides in relation to the various soil types within the study area. Subsequently, the estimated radiological hazards will be examined using descriptive statistics and analysis of variance with OriginPro. Additionally, the study will inform the local population about appropriate environmental management and the selection of soil for agricultural or construction purposes. This is crucial as it will contribute to the existing radiological baseline data for both the study area and the country at large.

2.1 Location of the study area

The study area is located in the southern region of Katsina State, Nigeria, situated between Latitude 11° 10´ N and 12° 23´ N and Longitude 06° 52´ E and 07° 54´ E. This region encompasses 11 local government areas and is bordered to the north by the Dan-Musa local government area, to the east by Kano State, to the west by Zamfara State, and to the south by Kaduna State (Figure 1). According to the FAO-UNESCO soil classification, the study area is underlain by eight distinct soil types. The predominant soil types, which primarily originate from parent rocks through natural processes such as weathering, include arenosols, formed from calcareous or residual sandstones or siliceous rock; fluvisols, derived from lacustrine or marine deposits (acidic soil); leptosols, resulting from siliceous rock; regosols, formed from unconsolidated finely grained materials; cambisols, typically originating from colluvial or alluvial deposits; acrisols, formed due to acid rock weathering; lixisols, resulting from unconsolidated and strongly weathered material; and luvisols, formed from unconsolidated material of glacial till, alluvial, and colluvial deposits (Chesworth, 2007). Table 1 delineates the soil types present within the study area, as well as the parent materials from which these soils originated.

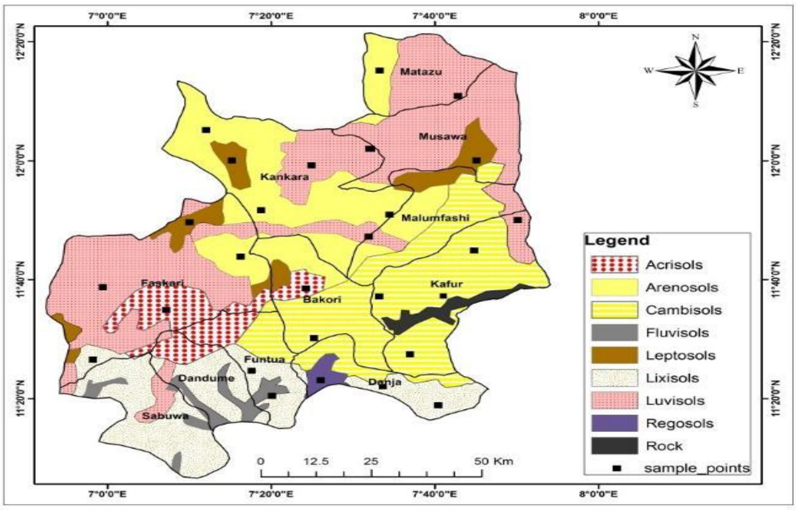

Figure 1: Study Area Indicating Sample Collection Points

2.2 Sample Collection

Soil samples, each weighing 2 kg, were randomly collected from 25 locations, corresponding to the various soil types within the study area (Figure 1). The samples were extracted at a depth of 10-20 cm using a hand auger, and the coordinates of each sampling point were recorded using a Global Positioning System (Garmin - etrex 10). The coordinates of the sampling points are detailed in Table 1. The collected samples were securely packed and sealed in well-labeled polyethylene bags to prevent cross-contamination. Subsequently, they were transported to the Center for Energy Research and Training (CERT) at Ahmadu Bello University, Zaria, for preparation and gamma-ray spectroscopy analysis.

2.3 Measurement of ^{226}Ra, ^{232}Th And ^{40}K Concentration

The gamma-ray spectrometry utilized in this study employed a NaI (Tl) detector. The activity concentration of the soil samples was calculated using Equation 1. The samples were positioned on the surface of the detector, and each sample was counted for 29,000 seconds in a reproducible sample detector geometry. Differential spectrometry was conducted in three channels, facilitated by a computer-based multichannel analyzer (MCA), with data acquisition and gamma spectra analysis performed using MAESTRO software from ORTEC. The 1764 keV gamma line of ^{214}Bi was used to assess the activity concentration of ^{226}Ra for ^{238}U, while the 2614.5 keV gamma line of ^{208}Tl was employed for ^{232}Th. The single 1460 keV gamma line of ^{40}K was utilized for its content evaluation. Following the subtraction of the background count from the raw data, the data were subsequently converted from counts per second to Bq/kg. This conversion utilized specific factors for each nuclide, namely 6.431 for ^{40}K, 8.632 for ^{226}Ra, and 8.768 for ^{232}Th (Garba et al., 2022; Ibeanu, 1999).

$$C(Bqkg^{-1}) = kC_n \tag{1}$$

where $k = \frac{1}{\varepsilon P_\gamma M_s}$, C is the activity concentration of the radionuclide in the sample given in Bq/kg, C_n is the count rate under the corresponding peak, ε is the detector efficiency at the specific γ-ray energy, P_γ is the absolute transition probability of the specific γ-ray, and M_s is the mass of the sample (kg) (Jibiri & Esen, 2011).

2.4 Radiological Hazards Assessment

2.4.1 Absorbed Dose Rate (D_R)

Terrestrial sources predominantly contribute to gamma radiation in the environment, demonstrating a significant correlation between terrestrial gamma radiation and radionuclide concentration. The total absorbed dose rate (DR) in air was determined using the dose conversion factors (0.427, 0.662, and 0.043 for ^{226}Ra, ^{232}Th, and ^{40}K, respectively), as specified in Equation 2 (UNSCEAR, 2000a).

$$D_R(nGy/h) = (0.462C_{Ra} + 0.604C_{Th} + 0.0417C_K) \tag{2}$$

WhereC_{Ra}, C_{Th} and C_K are the activity concentration (Bq/kg) of radium, thorium and potassium respectively in the samples.

2.4.2 Annual Effective Dose (AED)

The annual effective dose (AED) to the population, attributable to the activity concentrations of radionuclides in the samples, was calculated using only the outdoor annual effective dose. This calculation relies on a conversion coefficient from absorbed dose to effective dose of 0.7 Sv/Gy and an outdoor occupancy factor of 0.2, as specified by (UNSCEAR, 2000a). The annual effective dose was calculated using Equation 3:

$$AED(mSv/y) = D_R(nGy/h) \times 24\ \times 365\ \times 0.2\ \times 0.7\ \times\ 10^{-6} \tag{3}$$

Where $D_R(nGy/h)$ is the absorbed dose rate

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

The hazard associated with external radiation exposure was quantified using the measured activity concentration and calculated through Equation 4, referred to as the external hazard index or indoor radiation hazard index, denoted as (H_{ex}). Additionally, the internal hazard index, denoted as (H_{in}), was estimated to assess the internal exposure to carcinogenic radon, utilizing Equation 5 for its calculation (Beretka & Mathew, 1995).

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \tag{4}$$

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \tag{5}$$

where C_{Ra}, C_{Th} and C_K are the activity concentration (Bq/kg) of radium, thorium and potassium respectively from the samples. The value of these indices should be less than one (1) in order for the radiation hazard to have a negligible effect on the respiratory organs of the public (Beretka & Mathew, 1985).

3.0. MATERIALS AND METHOD

The subsequent sections present the findings regarding the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, as well as the associated radiological hazards, derived from soil samples collected in the study area.

3.1 Activity concentration

The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K measured from the soil samples are presented in Table 2. The activity concentration of 40K in all samples ranges from 61.46 to 709.93 Bq/kg, with a mean value of 327.49 ± 7.35 Bq/kg. A higher mean activity concentration of ^{40}K was reported for a similar soil type in Malaysia (Almayahi et al., 2012; Saffuwan Mohamed Johar et al., 2016). Garba et al. (2023) reported a lower mean concentration of ^{40}K in certain soils, which are utilized as building materials, sourced from various regions in Katsina State. Additionally, six out of the twenty-five samples analyzed exhibited a high activity of ^{40}K, exceeding the global mean value of 420 Bq/kg in soil as recommended by UNSCEAR (UNSCEAR, 2000b). Nevertheless, the cumulative mean of all analyzed samples was determined to be below the global average value of ^{40}K in soil. Several sampling locations were farmlands where residents utilize fertilizers enriched with potassium (K), which may contribute to the elevated levels of ^{40}K observed in certain samples from the study area. Furthermore, ^{40}K is recognized as being more prevalent in nature compared to other radionuclides (UNSCEAR, 2000b).

The activity concentration of ^{226}Ra in all soil samples ranges from 5.55 to 129.78 Bq/kg, with an average value of 30.37 ± 3.94. These findings are lower than the reported mean activity concentration of ^{226}Ra in various soil types in Malaysia (Almayahi et al., 2012; Saffuwan Mohamed Johar et al., 2016). Furthermore, the mean activity concentration of ^{226}Ra observed in the present study was determined to be lower than the activity concentration of ^{226}Ra found in certain soils (utilized for building materials) in various regions of Katsina State, as documented by (Garba, Rabi'u, et al., 2023). Furthermore, six (6) out of the twenty-five (25) samples analyzed exhibited a high activity concentration of ^{226}Ra, exceeding the mean level of exposure to ^{226}Ra in soil as recommended by UNSCEAR (UNSCEAR, 2000b). However, the overall mean of all the samples analyzed was found to be below the world average value of ^{226}Ra in soil.

The activity concentration of ^{232}Th in all samples ranges from 11.21 to 474.27 Bq/kg, with a mean concentration of 85.47 ± 5.23 Bq/kg. The mean activity concentration of ^{232}Th observed in this study is higher than the mean activity concentration of ^{232}Th in various soil types in Malaysia (Almayahi et al., 2012; Saffuwan Mohamed Johar et al., 2016). Moreover, the average activity concentration of ^{232}Th identified in the present study was found to exceed the activity concentration of ^{232}Th in certain soils (utilized for construction purposes) from specific regions in Katsina State, as documented by (Garba, Rabi'u, et al., 2023). Furthermore, ten (10) out of the twenty-five (25) samples analyzed exhibited a high activity concentration of ^{232}Th, exceeding the global average concentration of ^{232}Th in soil as recommended by (UNSCEAR, 2000b). Even so, the collective mean of all the samples analyzed was found to be above the world average value of ^{232}Th in soil.

Overall, the mean activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K observed in the present study were found to be higher than those reported in other studies conducted in certain regions of Nigeria. (Alias et al., 2008; Garba, Rabi'u, et al., 2023; Omeje et al., 2016). The study area experiences a rainy season for an average period of five (5) months (Hassan & Abdulhamed, 2012). Radionuclides are deposited on the soil surface as a result of flooding and erosion. During the rainy season, characterized by high precipitation, the likelihood of radionuclides reaching the soil surface is increased through processes such as filtration and leaching.

The mean activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K for each soil type were estimated and are presented in Table 3. Leptosols exhibited the highest activity concentration of ^{226}Ra, measuring 59.87 ± 3.20 Bq/kg, whereas Cambisols demonstrated the lowest activity concentration of ^{226}Ra at 16.04 ± 4.64 Bq/kg. The overall mean activity concentration of ^{226}Ra across all soil types was 31.46 ± 3.53 Bq/kg. Cambisols were found to have the highest activity concentration of ^{232}Th, with a value of 150.92 ± 7.12 Bq/kg, while Arenosols recorded the lowest concentration of ^{232}Th at 32.34 ± 4.80 Bq/kg. The average concentration of ^{232}Th across all soil types was 91.38 ± 5.08 Bq/kg. Luvisols exhibited the highest concentration of ^{40}K, with a measurement of 506.65 ± 7.32 Bq/kg, whereas Leptosols recorded the lowest concentration of ^{40}K at 167.47 ± 7.32 Bq/kg. The average concentration of ^{40}K across all soil types was estimated to be 312.93 ± 7.1 Bq/kg.

Table 1: Activity Concentration Of ^{226}Ra, ^{232}Th And ^{40}K From Soil Samples With Coordinates

Sample ID	Coordinates		Activity concentration (Bq/kg)		
	Latitude	Longitude	K-40	Ra-226	Th-232
Acrisols-1	N11°34′41.21″	E7°7′12.83″	506.89 ± 8.63	29.89 ± 1.52	32.01 ± 5.62
Acrisols-2	N11°38′48.2″	E7°24′6.41″	206.47 ± 4.24	19.74 ± 0.68	210.16 ± 3.58
Arenosols-1	N12°5′31″	E7°12′4.24″	395.99 ± 10.46	19.06 ± 4.99	21.47 ± 5.03
Arenosols-2	N12°15′20.15″	E7°33′11.22″	365.42 ± 10.46	26.53 ± 6.51	14.98 ± 5.03
Arenosols-3	N11°52′0.14″	E7°18′30.67″	294.58 ± 6.49	24.73 ± 4.36	18.24 ± 4.68
Arenosols-4	N11°51′3.12″	E7°34′20.90″	267.34 ± 3.43	25.93 ± 2.36	74.31 ± 3.85
Arenosols-5	N11°43′52.35″	E7°16′11.30″	315.87 ± 8.90	39.36 ± 4.16	32.83 ± 5.43
Cambisols-1	N11°44′55.7″	E7°44′35.38″	145.06 ± 7.83	27.69 ± 1.20	170.96 ± 4.52
Cambisols-2	N11°37′19.59″	E7°32′58.55″	182.01 ± 7.24	18.86 ± 3.92	66.21 ± 4.80
Cambisols-3	N11°30′21.48″	E7°24′57.09″	299.03 ± 9.06	18.30 ± 3.12	25.03 ± 5.82
Cambisols-4	N11°27′43.11″	E7°36′52.94″	348.05 ± 7.78	9.67 ± 6.23	18.24 ± 4.68
Cambisols-5	N11°38′56″	E7°41′17″	107.68 ± 11.32	5.55 ± 8.75	474.27 ± 15.77
Lixisols-1	N11°26′27.09″	E6°58′20.70″	117.02 ± 2.95	6.19 ± 2.24	131.99 ± 3.66
Lixisols-2	N11°24′52.07″	E7°17′33.65″	274.09 ± 8.90	50.55 ± 4.83	290.33 ± 9.16
Lixisols-3	N11°18′57.32″	E7°40′15.65″	346.76 ± 8.10	24.33 ± 3.80	32.83 ± 5.43
Lixisols-4	N11°22.345′	E7°34.468′	472.57 ± 8.37	22.66 ± 1.04	30.59 ± 0.87
Luvisols-1	N12°11′0.42″	E7°42′35.02″	581.65 ± 4.72	26.49 ± 2.44	76.59 ± 3.22
Luvisols-2	N12°2′8.28″	E7°31′55.20″	318.01 ± 10.03	24.73 ± 3.52	24.02 ± 5.35
Luvisols-3	N11°59′23.58″	E7°24′57″	411.49 ± 8.21	55.86 ± 5.59	43.09 ± 5.50
Luvisols-4	N11°50′6.11″	E7°50′11.13″	532.04 ± 7.88	52.74 ± 4.95	36.29 ± 5.47
Luvisols-5	N11°47′27.74″	E7°31′48.8″	709.93 ± 6.70	27.13 ± 6.39	44.31 ± 5.82
Luvisols-6	N11°38′54.61″	E6°59′30.39″	486.89 ± 6.44	23.77 ± 6.51	25.64 ± 5.19
Leptosols-1	N12°0′7.9″	E7°44′54.39″	61.46 ± 7.72	129.78 ± 4.56	129.75 ± 6.45
Leptosols-2	N12°0′26.93″	E7°15′7.95″	370.89 ± 7.62	36.88 ± 3.76	18.87 ± 5.54
Leptosols-3	N11°49′53.44″	E7°9′57.54″	70.03 ± 0.29	12.94 ± 1.20	93.85 ± 0.31
Mean			327.48 ± 7.35	30.37 ± 3.94	85.47 ± 5.23

3.2 Assessment of Radiological Hazards

The present study determined the radiological hazard parameters associated with the activity of radionuclides by employing equations (2) - (5). The findings are detailed in Table 3.

Table 2: Mean Activity Concentration (^{226}Ra, ^{232}Th And ^{40}K), Absorbed Dose Rate (D_R), Annual Effective Dose (AED) And Soil pH Based On Soil Types

Soil type	Ra-226 (Bq/kg)	Th-232 (Bq/kg)	K-40 (Bq/kg)	D_R (nGy/h)	AED (µSv/y)	Soil pH
Acrisols	24.70 ± 1.05	121.10 ± 4.60	356.70 ± 6.40	99.45	121.95	6.38 ± 0.05
Arenosols	27.12 ± 4.48	32.34 ± 4.80	327.82 ± 7.96	46.12	56.54	6.51 ± 0.11
Cambisols	16.04 ± 4.64	150.92 ± 7.12	216.36 ± 8.64	107.58	131.96	6.26 ± 0.13
Leptosols	59.87 ± 3.20	80.87 ± 4.07	167.47 ± 5.20	83.47	102.33	6.15 ± 0.16
Lixisols	25.93 ± 2.95	121.40 ± 4.80	302.63 ± 7.08	97.93	120.10	6.33 ± 0.17
Luvisols	35.12 ± 4.88	41.65 ± 5.08	506.65 ± 7.32	62.53	75.06	6.44 ± 0.12
Mean	31.46 ± 3.53	91.38 ± 5.08	312.93 ± 7.1	82.84	101.32	6.35 ± 0.12

3.2.1 Absorbed Dose Rate (D_R)

The mean absorbed doses for all soil types in the study area were determined using Equation 2, with the results detailed in Table 3. The absorbed dose values range from 29.99 to 293.56 nGy/h, with an average of 82.84 nGy/h. notably, both the maximum and minimum absorbed dose readings were observed in Cambisols, potentially due to variations in activities across different sampling locations. Among the various soil types, the highest absorbed dose was recorded at 107.58 nGy/h in Cambisols, which may be attributed to natural processes such as erosion and weathering, or anthropogenic activities like fertilizer application and waste disposal. Arenosols exhibited the lowest absorbed dose value of 46.12 nGy/h. five of the soil types were found to have mean absorbed doses exceeding the global average of 59 nGy/h, while one soil type was below this global mean. The absorbed dose results, although exceeding the global average value of 59 nGy/h, were observed to be lower than those reported for certain other local government areas in Katsina State (Abdulkadir et al., 2023) and similarly lower than the values documented for soil in Malaysia (Almayahi et al., 2012). Contrary to previous findings, the estimated absorbed doses in the present study were found to be higher than the mean absorbed doses measured from various soil types used for construction purposes in certain regions of Katsina State (Garba, Rabi'u, et al., 2023).

3.2.2 Annual effective dose equivalent (AED)

The annual effective dose equivalent for all samples was assessed using Equation 3, with the results detailed in Table 4. The values range from 36.80 to 360 µSv/y, with an average of 97.34 µSv/y. The mean annual effective doses for different soil types were calculated and are presented in Table 3. Cambisols exhibited the highest mean annual effective dose of 132 µSv/y, whereas Arenosols showed the lowest mean value of 56.54 µSv/y. The overall mean annual effective dose across all soil types was determined to be 101.32 µSv/y. The absorbed dose rate values were utilized to derive the annual effective dose equivalent, thus reflecting a similar trend. The overall mean annual effective dose from this study aligns with the mean annual effective dose reported for soil in Malaysia (Almayahi et al., 2012). Furthermore, the mean values for all annual effective dose equivalents for the various soil types in the study area are below the global average of 480 µSv/y (UNSCEAR, 2000b). Consequently, the samples are free from radioactive contamination and pose a negligible radiological hazard to both farmers and the general population.

3.2.3 Hazard Index

The primary aim of the hazard index is to maintain a value below unity (ICRP, 2004). The internal and external hazard indices were calculated for each sample using Equations 4 and 5, respectively, and the results are presented in Table 4. The hazard indices (internal and external) for all samples ranged from 0.2 to 1.9. The mean value for the internal hazard index was estimated to be 0.56, while the average value for the external hazard index was 0.48. Among all recorded hazard indices (internal and external), five samples exhibited values exceeding unity, surpassing the limit recommended by ICRP (2004). Nevertheless, the overall mean hazard index (internal and external) from the present study was found to be below the acceptable limit of unity (1).

Table 3: Absorbed Dose, Internal And External Hazard Indices from Soil Samples

Sample ID	D_R (nGy/h)	AED (µSv/y)	H_{in}	H_{ex}	Soil pH
Acrisols-1	54.28	66.60	0.40	0.30	6.47
Acrisols-2	144.58	177.30	0.90	0.90	6.30
Lixisols-1	87.41	107.20	0.60	0.60	5.79
Luvisols-4	68.46	83.90	0.50	0.40	5.60
Leptosols-3	65.59	80.40	0.40	0.40	5.51
Cambisols-2	56.31	69.10	0.40	0.30	6.73
Cambisols-3	36.02	44.20	0.30	0.20	6.89
Cambisols-4	29.99	36.80	0.20	0.20	5.73
Luvisols-1	82.76	101.50	0.60	0.50	6.80
Luvisols-2	39.17	48.00	0.30	0.20	6.53
Luvisols-3	69.02	84.60	0.60	0.40	5.97
Arenosols-1	38.32	46.90	0.30	0.20	6.51
Arenosols-2	36.48	44.70	0.30	0.20	6.29
Arenosols-3	36.69	44.90	0.30	0.20	5.95
Leptosols-1	140.93	172.80	1.20	0.90	6.44
Leptosols-2	43.93	53.80	0.30	0.20	6.51
Arenosols-4	67.99	83.40	0.50	0.40	7.21
Arenosols-5	51.19	62.80	0.40	0.30	6.57
Cambisols-1	122.07	149.70	0.80	0.80	6.01
Luvisols-5	68.88	84.50	0.50	0.40	6.75
Luvisols-6	46.76	57.30	0.30	0.30	7.02
Lixisols-4	48.68	59.70	0.30	0.30	6.96
Lixisols-2	210.10	257.70	1.50	1.30	6.73
Lixisols-3	45.49	55.80	0.30	0.30	5.84
Cambisols-5	293.56	360.00	1.90	1.90	5.93

3.2.4 Soil pH

The pH of soil is a critical factor influencing the availability of soil nutrients. The pH values for the collected soil samples, representing various soil types, range from 5.51 to 7.21, with an average value of 6.36. Among the analyzed samples, Leptosols-3 exhibited the lowest pH of 5.51 ± 0.007, indicating acidity, whereas Arenosols-4 displayed the highest pH of 7.21 ± 0.006, indicating alkalinity. Variations in soil pH at individual sampling points may occur due to anthropogenic activities. However, the estimated mean pH values for each soil type within the study area range from 6.15 ± 0.16 to 6.51 ± 0.11, with an overall mean of 6.35 ± 0.12. Leptosols recorded the lowest pH of 6.15 ± 0.16, while Arenosols recorded the highest pH of 6.51 ± 0.11. As illustrated in Table 3, all mean soil pH values fall within the acidic range on the pH scale. Table 4 provides the results of the soil pH analysis for all samples from the study area.

4.0 RESULTS AND INTERPRETATION

4.1 Descriptive Statistics and One-way ANOVA for Dose Rate

According to the descriptive statistics outlined in Table 4, Leptosols exhibited the highest mean dose rate at 183.05 nGy/h, followed by Acrisols at 99.43 nGy/h, whereas Cambisols demonstrated the lowest mean dose rate at 51.85 nGy/h. The substantial variation in mean dose rates is visually represented in the box plot in Figure 2 and is corroborated by the relatively high coefficient of variation (65.4%), which indicates a significant degree of variability within the dataset.

Table 4: Descriptive Statistics of Dose Rate for Soil Types

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Acrisols	2	0	99.43	63.85	45.15
Arenosols	5	0	62.76	18.74	8.38
Cambisols	5	0	51.85	22.76	10.18
Lixisols	4	0	64.51	51.07	25.53
Luvisols	6	0	67.59	28.39	11.59
Leptosols	3	0	183.05	126.23	72.88

The analysis of variance (ANOVA) was conducted to assess whether the dose rates significantly differ across the six soil types: Acrisols, Arenosols, Cambisols, Lixisols, Luvisols, and Leptosols. The results, as presented in Table 5, reveal a statistically significant difference among the means (F = 2.96, p = 0.03851) at the 0.05 significance level. This finding indicates that at least one of the soil types exhibits a dose rate that is significantly different from the others.

Table 5: One-Way ANOVA of Dose Rate for Soil Types

	DF	Sum of Squares	Mean Square	F Value	P
Model	5	39934.90	7986.98	2.96	0.03851
Error	19	51274.17	2698.64		
Total	24	91209.07			

As illustrated in Table 6, the relatively high standard deviation and standard error of the mean for Leptosols (126.23 and 72.88, respectively) indicate a broad distribution and the presence of potential outlier values. This variability may be attributed to localized geologic or anthropogenic factors influencing natural radioactivity. Conversely, Arenosols and Cambisols demonstrated lower variability and reduced dose rates, which could be linked to their comparatively lower radionuclide content and retention capacity.

Table 6: Fit Statistics of Dose Rate for Soil Types

R^2	Coefficient Variance	Root MSE	Data Mean
0.4378	0.65	51.95	79.39

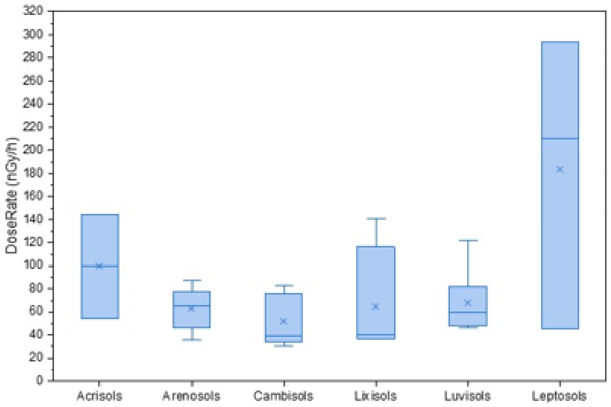

Figure 2: Boxplot Of Dose Rate For Soil Types

The R^2 value of 0.4378 suggests that approximately 43.78% of the variation in dose rate can be attributed solely to soil type. Although this indicates a moderate effect, it also suggests that additional factors, such as mineralogical composition, radionuclide concentration, or land use practices, may contribute to the observed dose rates.

The findings are crucial for comprehending the radiological risks associated with various soil types, particularly in the context of land-use planning and environmental radiation protection. The notably elevated dose rate detected in Leptosols warrants further investigation to ascertain its origin and potential health implications.

4.2 Descriptive Statistics and One-Way ANOVA for Annual Effective Dose Rate

An analysis of variance (ANOVA) was performed to assess whether the annual effective dose rate (AED, μSv/y) exhibits significant differences among various soil types. The descriptive statistics reveal variability in the annual effective dose rate across the six soil types examined. As presented in Table 7, Leptosols demonstrated the highest annual effective dose rate of 224.5 μSv/y, accompanied by substantial variability (SD of 154.79 μSv/y), whereas Cambisols exhibited the lowest annual effective dose rate of 63.56 μSv/y. These findings suggest that certain soil types may be associated with elevated radiation dose rates, potentially due to their mineral composition or geological background.

Table 7: Descriptive Statistics Of Annual Effective Dose Rate For Soil Types

	N Analysis	N Missing	Mean	Standard Deviation	SE of Mean
Acrisols	2	0	121.95	78.28	55.35
Arenosols	5	0	76.96	22.96	10.27
Cambisols	5	0	63.56	27.92	12.49
Lixisols	4	0	79.05	62.64	31.32
Luvisols	6	0	82.9	34.82	14.22
Leptosols	3	0	224.5	154.79	89.37

The ANOVA test results, as depicted in Table 8, revealed an F-value of 2.96 and a p-value of 0.03843. Given that the p-value is below the significance threshold of 0.05, this finding suggests a statistically significant difference in the annual effective dose rates among at least some of the soil types.

Table 8: One-Way ANOVA of Annual Effective Dose Rate for Soil Types

	DF	Sum of Squares	Mean Square	F Value	P
Model	5	60091.64	12018.33	2.96	0.03843
Error	19	77112.19	4058.54		
Total	24	137203.84			

The R^2 value of 0.4379, as presented in Table 9, indicates that approximately 43.8% of the variability in dose rate can be attributed to soil type, suggesting a moderate influence of soil type on the annual effective dose rate. The coefficient of variation (CV) of 65.45% and the Root Mean Square Error (RMSE) of 63.71 μSv/y further demonstrate moderate dispersion around the predicted values.

The boxplot depicted in Figure 3 corroborates the ANOVA results, illustrating significant differences in dose rate distributions among various soil types. Notably, Leptosols exhibit a higher median and greater variability, indicating the presence of potential outliers or a broader range of natural variation within this group.

Table 9: Fit Statistics of Dose Rate for Soil Types

R^2	Coefficient of Variance	Root MSE	Data Mean
0.4379	0.65	63.71	97.34

4.3 Correlation Analysis

This section presents the results of the linear correlation between soil pH and the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K across various soil types in the study area, as depicted in Figures 4, 5, and 6. The correlation between soil pH and the activity concentrations of ^{226}Ra and ^{232}Th yielded correlation coefficients of $R = -0.48$ and $R = -0.55$, respectively, indicating a moderate negative correlation. In contrast, the linear correlation between soil pH and the activity concentration of ^{40}K was found to be $R = 0.79$, suggesting a strong positive correlation between these variables (Pandis, 2016). The observed correlations between soil pH and the activity concentrations of ^{226}Ra and ^{232}Th are consistent with the findings of (S. M. Johar et al., 2016) whereas the correlation between soil pH and the activity concentration of ^{40}K presents a divergent result.

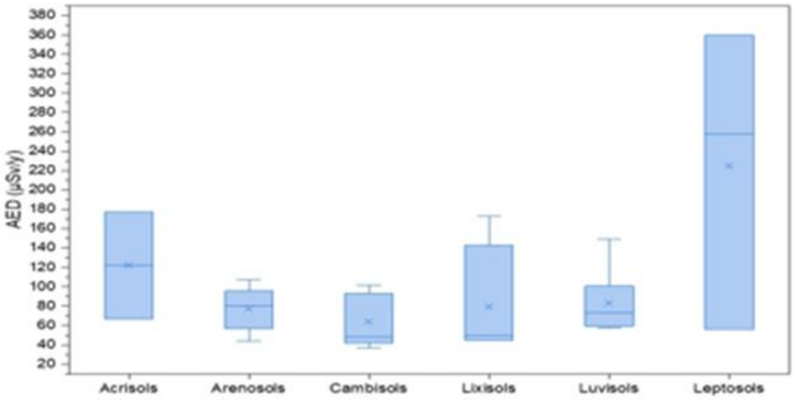

Figure 3: Boxplot of Animal Effective Dose Rate for Soil Types

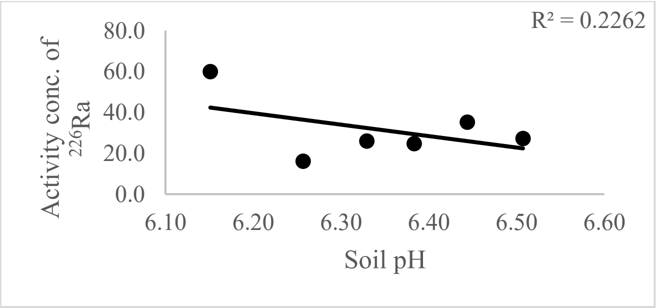

Figure 3: Correlation Between Activity Concentration of ^{226}Ra and Soil pH

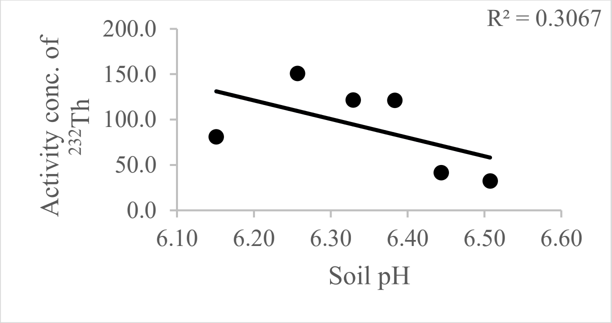

Figure 4: Correlation between Activity concentration of ^{232}Th and Soil pH

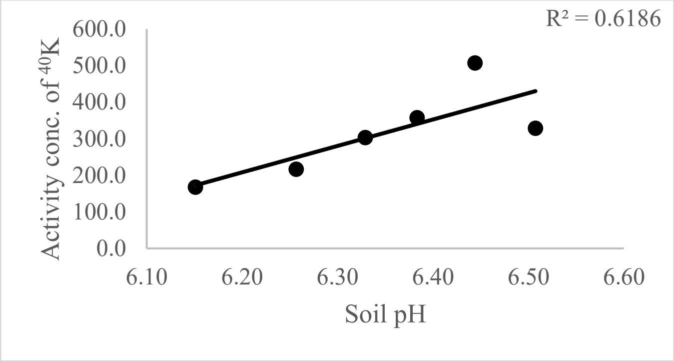

Figure 5: Correlation Between Activity Concentration of ^{40}K and Soil pH

5.0 CONCLUSION

The activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th in the soil samples from the study area were assessed. Results from certain sampling locations exceeded the average recommended values for these radionuclides in soil. However, the mean activity concentrations across different soil types were found to range between 167.47 and 356.70 Bq/kg, with a mean of 312.93 ± 7.1 Bq/kg for ^{40}K; between 16.04 and 59.87 Bq/kg, with a mean of 31.46 ± 3.53 Bq/kg for ^{226}Ra; and between 32.34 and 150.92 Bq/kg, with a mean of 91.38 ± 5.08 Bq/kg for ^{232}Th. The mean values for ^{40}K and ^{226}Ra across all soil types analyzed were below the global mean values of 420 Bq/kg and 35 Bq/kg, respectively (ICRP, 2004; UNSCEAR, 2000b). Conversely, the mean value of ^{232}Th across all analyzed soil types was determined to be twice the global average of 45 Bq/kg. The activity concentrations of ^{40}K and ^{232}Th observed in the present study were found to exceed those reported for various soil types used in construction in certain states of northern Nigeria (Garba, Rabi'u, et al., 2023), The concentration of ^{226}Ra in this study was found to be higher than that reported in previous research. Conversely, the activity concentrations of ^{40}K and ^{226}Ra in the soil observed in this study were lower than those reported in Malaysia, Thailand, Argentina, Jordan, and Yemen (Abd El-mageed et al., 2011; Al-Kharouf et al., 2008; Alias et al., 2008; Almayahi et al., 2012; Montes et al., 2012; Santawamaitre et al., 2011), at the same time, they all have mean activity concentration of ^{232}Th higher than the result of the present study. While some of the mean values for ^{226}Ra and ^{232}Th were found to be higher than the recommended values of 33, and 45 Bq/kg for ^{226}Ra and ^{232}Th in soil respectively, as reported by UNSCEAR, (2000). The estimated radiological hazard parameters associated with the measured mean activity concentrations of ^{40}K, ^{226}Ra and

^{232}Th are; absorbed dose rate, annual effective dose equivalent, and hazard indices (internal and external). The mean absorbed dose from the current study was found to exceed the world average value of 59 nGy/h. similar results were obtain from Thailand and Jordan (Al-Kharouf et al., 2008; Santawamaitre et al., 2011). In contrast to the findings of the present study, higher mean absorbed doses have been reported in studies conducted in Malaysia, Serbia, Yemen, and Turkey (Abd El-mageed et al., 2011; Almayahi et al., 2012; Zorer, 2019; Žunić et al., 2007). The mean hazard index, both internal and external, and the mean annual effective dose were observed to be below the global average, with values ranging from 46.12 to 107.58 nGy/h for absorbed dose rate, 56.54 to 132 μSv/y for annual effective dose equivalent, and 0.2 to 1.9 for hazard indices (internal and external), respectively. The considerable variation in dose rates across different soil types holds significant implications for environmental radiation monitoring and radiological risk assessments. Soil types such as Leptosols, which exhibit elevated dose rates, may contribute more substantially to background radiation exposure. This factor should be taken into account in land use planning and environmental health assessments. Soil pH was also assessed for all samples, with mean values indicating acidity on the pH scale, ranging from 6.15 to 6.51 across the various soil types in the study area. A linear correlation analysis revealed a moderate negative correlation between soil pH and the activity concentrations of ^{226}Ra and ^{232}Th, whereas a strong positive correlation was identified between soil pH and the activity concentration of ^{40}K.

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