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ORIGINAL RESEARCH ARTICLE

Assessment of Natural Radionuclides and Radiological Hazards in Oil Palm Plantation Soils of Southern Ondo State, Nigeria

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ABSTRACT
This study presents a comprehensive evaluation of naturally occurring radionuclides and the associated radiological hazards in soils collected from major oil-palm plantations in southern Ondo State, Nigeria. Twenty composite top-soil samples (0–15 cm) were obtained from four representative sites (Aye, Lofo, Kajola and Ayadi) and analyzed using a calibrated NaI(Tl) γ-ray spectrometer. Activity concentrations of ^{40}K, ^{232}Th and ^{238}U were quantified to determine terrestrial radioactivity and to estimate radiological dose indices. The mean activities of ^{40}K (126.40 ± 2.74 Bq/kg), ^{232}Th (29.20 ± 1.19 Bq/kg) and ^{238}U (18.64 ± 0.97 Bq/kg) were all below the global averages of 420, 50 and 33 Bq/kg respectively, as reported by UNSCEAR (2000). The corresponding radiological hazard parameters; radium equivalent activity (76.8 Bq/kg), absorbed dose rate (35.4 nGy/h), annual effective dose equivalent (0.04 mSv/y), external hazard index (0.21) and internal hazard index (0.27) were also within internationally accepted limits. Spatial variations in radionuclide levels reflect lithologic and pedogenic controls rather than anthropogenic influence. Statistical evaluation revealed weak positive correlations between ^{232}Th and ^{238}U activities, suggesting a common geogenic origin. The results indicate negligible radiological risk to farmers and consumers and confirm the radiological safety of agricultural soils in the investigated area. This baseline dataset provides reference information for environmental radioactivity monitoring and sustainable agricultural planning in Ondo State and contributes to national radioecological databases. Continuous periodic surveillance is nevertheless recommended to track possible changes arising from fertilizer use, waste deposition, or other anthropogenic activities.

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INTRODUCTION
Naturally occurring radionuclides are ubiquitous constituents of the earth's crust and form a major source of ionizing radiation to which humans are continuously exposed (UNSCEAR, 2000). The principal naturally occurring radionuclides are uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K) and are primordial in origin, having persisted since the formation of the earth. These isotopes are distributed heterogeneously in soils, rocks, and sediments according to the underlying geological formations and pedogenic processes (Abbasi & Mirekhtiary, 2018). As such, terrestrial gamma radiation constitutes the most significant contribution to the natural background radiation dose received by humans, accounting for about 85% of total exposure from natural sources (Adegoke, 2000; Obed et al., 2005).

In agricultural environments, soil radioactivity plays a crucial role because radionuclides may enter the human body indirectly through soil-to-plant transfer and food-chain accumulation (Jibiri et al., 2007). The magnitude of exposure from these sources depends on several factors, including soil mineralogy, organic content, moisture, and anthropogenic influences such as the application of phosphate fertilizers, sewage sludge, and agrochemicals (Alexandre & Kyser, 2006). Elevated concentrations of uranium and thorium decay-series isotopes in soils have been linked to increased gamma dose rates, which may lead to potential health risks if concentrations exceed recommended safety limits (Agbalagba et al., 2012; Babatunde et al., 2019).

Globally, extensive research has been conducted to quantify soil radioactivity and assess the associated hazards. Studies in India (Taskin et al., 2009), and Ghana have reported mean activity concentrations of ^{40}K, ^{232}Th, and ^{238}U ranging from 200 – 500, 20–60, and 15–45 Bq/kg, respectively. In Nigeria, several regional investigations have also been undertaken. (Diab et al., 2008) observed mean values of 326 Bq/kg for ^{40}K, 43 Bq/kg for ^{232}Th, and 27 Bq/kg for ^{238}U in southwestern

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soils. Similarly, Agbalagba et al. (2012) reported comparable results from the Niger Delta oil-field environments. These studies reveal that while most soils exhibit activity levels below the global averages of 420, 50, and 33 Bq/kg (for ^{40}K, ^{232}Th, and ^{238}U, respectively), localized enrichment can occur in areas underlain by granitic or phosphate-rich lithologies.

Southern Ondo State, located in the southwestern zone of Nigeria, is characterized by intensive oil-palm cultivation, representing one of the major agricultural activities sustaining local livelihoods. Despite the economic importance of palm oil production, limited attention has been given to the radiological implications of long-term soil use in these plantations. Continuous cultivation, fertilizer application, and organic waste accumulation could alter the natural radionuclide equilibrium of the soils. Previous studies in neighboring states such as Delta, Ekiti, and Ogun have established baseline radioactivity levels (Agbalagba et al., 2012; Odudu et al., 2022; Jibiri et al., 2007), but no comprehensive study had been conducted to characterize the radiological status of oil-palm soils in Ondo State prior to this investigation.

Understanding the natural radioactivity levels in such agricultural soils is essential for ensuring food safety, environmental protection, and compliance with radiationsafety standards. The assessment of radionuclide activity and derived hazard indices provides a scientific basis for evaluating potential health risks to farmers and consumers. It also contributes to the broader national effort of establishing a radiological baseline for Nigeria's agricultural landscapes (UNSCEAR, 2000; Eganoosi, 2021).

The present study, therefore, aims to: quantify the activity concentrations of ^{40}K, ^{232}Th, and ^{238}U in soils from major oil-palm plantations in southern Ondo State; evaluate radiological hazard indices including absorbed dose rate, annual effective dose equivalent, radiumequivalent activity, and external and internal hazard indices; and compare the results with international safety standards and previously reported values from other regions of Nigeria and beyond.

This work provides baseline information for environmental radioactivity monitoring and radiological health assessment in agricultural systems within the region.

2. Location and Geology of the Study Area

The study was conducted within the oil palm–growing belt of southern Ondo State, Nigeria, specifically within the Irele and Okitipupa local government areas (LGAs). Geographically, the study area lies approximately between latitudes 6°35'N and 6°45'N and longitudes 4°50'E and 4°55'E, covering an average elevation of 60 – 120 m above sea level. The region is drained by several seasonal streams and tributaries of the Oluwa and Ogbese Rivers, which enhance soil fertility and support extensive palm cultivation. Major sampled settlements include Aye, Lofo, Kajola, and Ayadi,(within Irele and Okitipupa local government areas), all of which fall within the tropical rainforest zone (Figure 1).

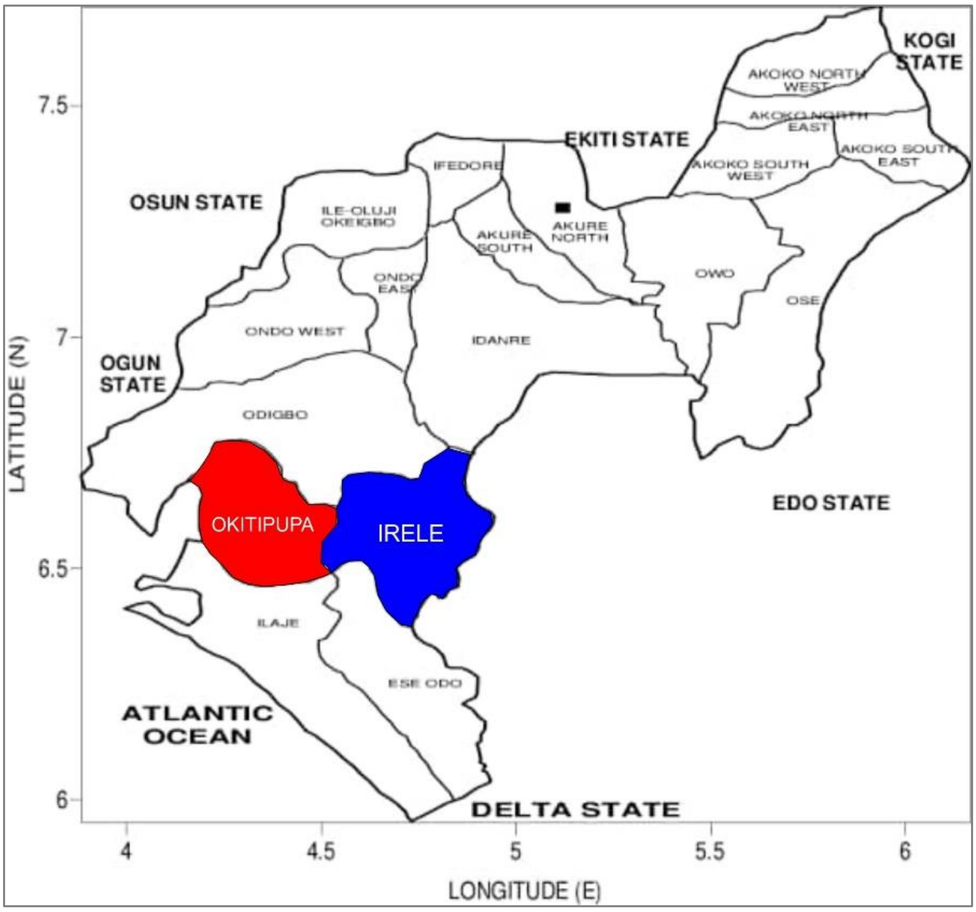

Figure 1: Map of Ondo State showing the local government area of study

Climatically, the area experiences two distinct seasons: the wet season (April–October) and the dry season (November–March), with an annual mean rainfall of about 1,800–2,200 mm and average temperature of 27–29 °C (Fasasi *et al.*, 2003). The soils are generally ferrallitic and lateritic, derived mainly from weathered Precambrian basement complex rocks and coastal sedimentary formations (Gbadamosi *et al.*, 2018a). These soils exhibit moderate clay content, low organic carbon, and are well-drained, which makes them suitable for perennial crops such as oil palm and cocoa.

Geologically, the study area lies within the Eastern Dahomey Basin, consisting of sandstones, shales, claystones, and limestone intercalations. The lithologic units include the Abeokuta Formation, Ewekoro Formation, and Okitipupa Ridge, which are known to contain variable concentrations of uranium- and thorium-bearing minerals (Omatsola & Adegoke, 1981). These geological formations influence the distribution of naturally occurring radionuclides in soils, particularly those of potassium and the uranium–thorium decay series.

MATERIALS AND METHODS

3.1 Sample Collection and Preparation

Twenty topsoil samples were collected from the major oil-palm plantations distributed across the four sampling locations. At each plantation, soil samples were collected from five different points within a 20 m × 20 m grid at a depth of 0–15 cm, using a stainless-steel auger. The subsamples were homogenized to form composite samples, which were then air-dried for 48 hours, pulverized, and sieved through a 2 mm mesh to remove debris and ensure uniform grain size. Each sample was packed in 1 L Marinelli beakers, sealed to prevent radon escape, and stored for 4 weeks to achieve secular equilibrium between parent and progeny radionuclides (Girigisu *et al.*, 2013).

3.2 Gamma-Ray Spectrometric Analysis

The activity concentrations of ^{40}K, ^{232}Th, and ^{238}U were determined using a sodium iodide [NaI(Tl)] scintillation detector system coupled to a multichannel analyzer. The detector was housed in a 10 cm thick lead shield to minimize background radiation. Energy calibration was carried out using reference standards from the International Atomic Energy Agency (IAEA), while efficiency calibration was conducted using a standard soil matrix traceable to Analytics Inc., USA. Each sample was counted for 36,000 seconds, and the photopeaks corresponding to 1.46 MeV (^{40}K), 1.76 MeV (^{214}Bi for ^{238}U), and 2.62 MeV (^{208}Tl for ^{232}Th) were used for quantitative analysis.

3.3 Calculation of Activity Concentrations

The specific activity concentration A (in Bq/kg) of each radionuclide was determined using:

$$A = \frac{C}{\varepsilon \times P_\gamma \times M} \quad [1]$$

where C is the net count rate (s^{-1}), ε is the detector efficiency at the specific energy, $P\gamma$ is the gamma-ray emission probability, and M is the sample mass (kg). The uncertainties associated with counting statistics were propagated following Poisson statistics (Isinkaye *et al.*, 2018).

3.4 Radiological Hazard Indices

The absorbed dose rate (D) in air at 1 m above ground surface, in nGy/h, was calculated using the conversion factors provided by UNSCEAR (2000):

$$D=0.462C_U+0.604C_{Th}+0.0417C_K \quad [2]$$

where C_U,C_{Th}, and C_K are the activity concentrations of ^{238}U, ^{232}Th, and ^{40}K respectively.

The radium equivalent activity (Raeq), which represents a single radiological index combining the effects of the three radionuclides, was computed using (Beretka & Mathew, 1985):

$$Raeq=C_U+1.43C_{Th}+0.077C_K \quad [3]$$

The external hazard index (Hex) and internal hazard index (Hin) were evaluated to ensure radiation safety in accordance with the criteria of ICRP (1993):

$$H_{ex} = \frac{C_U}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad [4]$$

$$H_{in} = \frac{C_U}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \quad [5]$$

The annual effective dose equivalent (AEDE), expressed in mSv/y, was derived using a dose conversion factor of 0.7 Sv/Gy and an outdoor occupancy factor of 0.2, as recommended by UNSCEAR (2000):

$$AEDE=D\times 8760\times 0.7\times 0.2\times 10^{-6} \quad [6]$$

3.5 Data Analysis

Descriptive and inferential statistics, including correlation analysis, were performed using SPSS software (version 22). Correlations between radionuclide activities and derived hazard indices were examined to identify potential relationships among variables. Graphical representations, such as bar charts and spatial trend plots, were produced in MATLAB and Microsoft Excel.

3.6 Excess Lifetime Cancer Risk (ELCR)

The Excess Lifetime Cancer Risk (ELCR) was estimated to evaluate the probability of developing cancer over a lifetime due to exposure to natural radionuclides in the studied soils. It is calculated using the relation:

$$ELCR = AEDE \times DL \times RF$$

where AEDE is the annual effective dose equivalent (Sv/y), DL is the average duration of life (70 years), and RF is the fatal cancer risk factor (0.05 Sv^{-1}) as recommended by the International Commission on Radiological Protection (ICRP).

Using the mean AEDE value obtained in this study (0.04 mSv/y = 0.00004 Sv/y), the ELCR is calculated as:

$$ELCR = 0.00004 \times 70 \times 0.05 = 1.4 \times 10^{-4}$$

This value falls within the acceptable safety range of 10^{-4} to 10^{-3} recommended by international radiological protection standards, indicating that the radiological risk to the population from soil exposure in the study area is within permissible limits and does not pose significant health concerns.

RESULTS AND DISCUSSION

4.1 Activity Concentrations of Natural Radionuclides

The measured activity concentrations of ^{40}K, ^{232}Th, and ^{238}U in soil samples from the study area are presented in Tables 1 and 2. The concentrations varied spatially across the sampled oil palm plantations, reflecting differences in lithology, pedogenesis, and agricultural inputs. The activity concentrations of ^{40}K ranged from 62.0 to 228.12 Bq/kg, with a mean of 126.40 ± 2.74 Bq/kg; ^{232}Th ranged from 11.65 to 57.24 Bq/kg with mean of 29.20 ± 1.19 Bq/kg); and ^{238}U ranged from 7.88 to 31.15 Bq/kg with mean of 18.64 ± 0.97 Bq/kg).

These mean values are below the worldwide averages reported by UNSCEAR (2000): 420 Bq/kg for ^{40}K, 50 Bq/kg for ^{232}Th, and 33 Bq/kg for ^{238}U. The lower activity levels implies minimal enrichment of uranium and thorium series nuclides within the soil matrix. Similar low values were reported by Jibiri et al. (2007) for soils in southwestern Nigeria and by Agbalagba et al. (2012) in the Niger Delta region. The distribution pattern indicates that the soils are largely influenced by natural geological sources rather than anthropogenic contamination.

4.2 Radiological Hazard Indices

The derived radiological parameters: Radium Equivalent Activity (Raeq), Absorbed Dose Rate (D), Annual Effective Dose Equivalent (AEDE), External Hazard Index (Hex), and Internal Hazard Index (Hin)were computed and are summarized in Table 2.

Table 1: Mean Activity Concentrations of Natural Radionuclides in Southern Ondo Soils

Radionuclide	Mean Activity (Bq/kg)	World Limit (Bq/kg)	Remark
^{40}K	126.40 ± 2.74	420	Below limit
^{232}Th	29.20 ± 1.19	50	Below limit
^{238}U	18.64 ± 0.97	33	Below limit

Table 2: Comparison of Mean Radiological Hazard Indices with Global Averages

Hazard Index	Value	Permissible Limit	Reference
Radium Equivalent (Raeq)	76.8 Bq/kg	370 Bq/kg	UNSCEAR (2000)
Absorbed Dose Rate (D)	35.4 nGy/h	59 nGy/h	UNSCEAR (2000)
Annual Effective Dose (AEDE)	0.04 mSv/y	0.07 mSv/y	ICRP (1993)
External Hazard Index (Hex)	0.21	<1	ICRP (1993)
Internal Hazard Index (Hin)	0.27	<1	ICRP (1993)

Table 3: Correlation Matrix of Radionuclide Concentrations and Radiological Indices

Parameter	^{40}K	^{232}Th	^{238}U	Raeq	D	AEDE
^{40}K	1.000	0.218	0.182	0.356	0.362	0.341
^{232}Th	0.218	1.000	0.611	0.879	0.875	0.864
^{238}U	0.182	0.611	1.000	0.812	0.794	0.788
Raeq	0.356	0.879	0.812	1.000	0.996	0.990
D	0.362	0.875	0.794	0.996	1.000	0.997
AEDE	0.341	0.864	0.788	0.990	0.997	1.000

Table 4: Comparison of Mean Activity Concentrations (Bq/kg) with Other Studies

Location / Study	^{40}K	^{232}Th	^{238}U	Reference
Southern Ondo (Present study)	126.4	29.2	18.6	This work
Niger Delta, Nigeria	290.0	37.0	22.0	Agbalagba et al. (2012)
Ogun State, Nigeria	302.0	41.0	27.0	Jibiri & Agomuo (2007)
Egypt	250.0	28.0	19.0	(El-Taher et al., 2010)
India	400.0	45.0	32.0	(Taskin et al., 2009)
UNSCEAR Global Average	420.0	50.0	33.0	UNSCEAR (2000)

All measured indices are below the recommended limits, confirming that the soils are radiologically safe for agricultural and occupational exposure. According to UNSCEAR (2000), a Raeq value below 370 Bq/kg corresponds to an annual effective dose of less than 1 mSv/y, which is within the public exposure guideline.

These results agree with those reported for similar agricultural soils in Ode-Irele (Odudu et al., 2022), Delta (Agbalagba et al., 2012), and Ogun (Jibiri et al., 2007), indicating that southern Ondo soils are characterized by moderate natural radioactivity without significant anthropogenic enhancement.

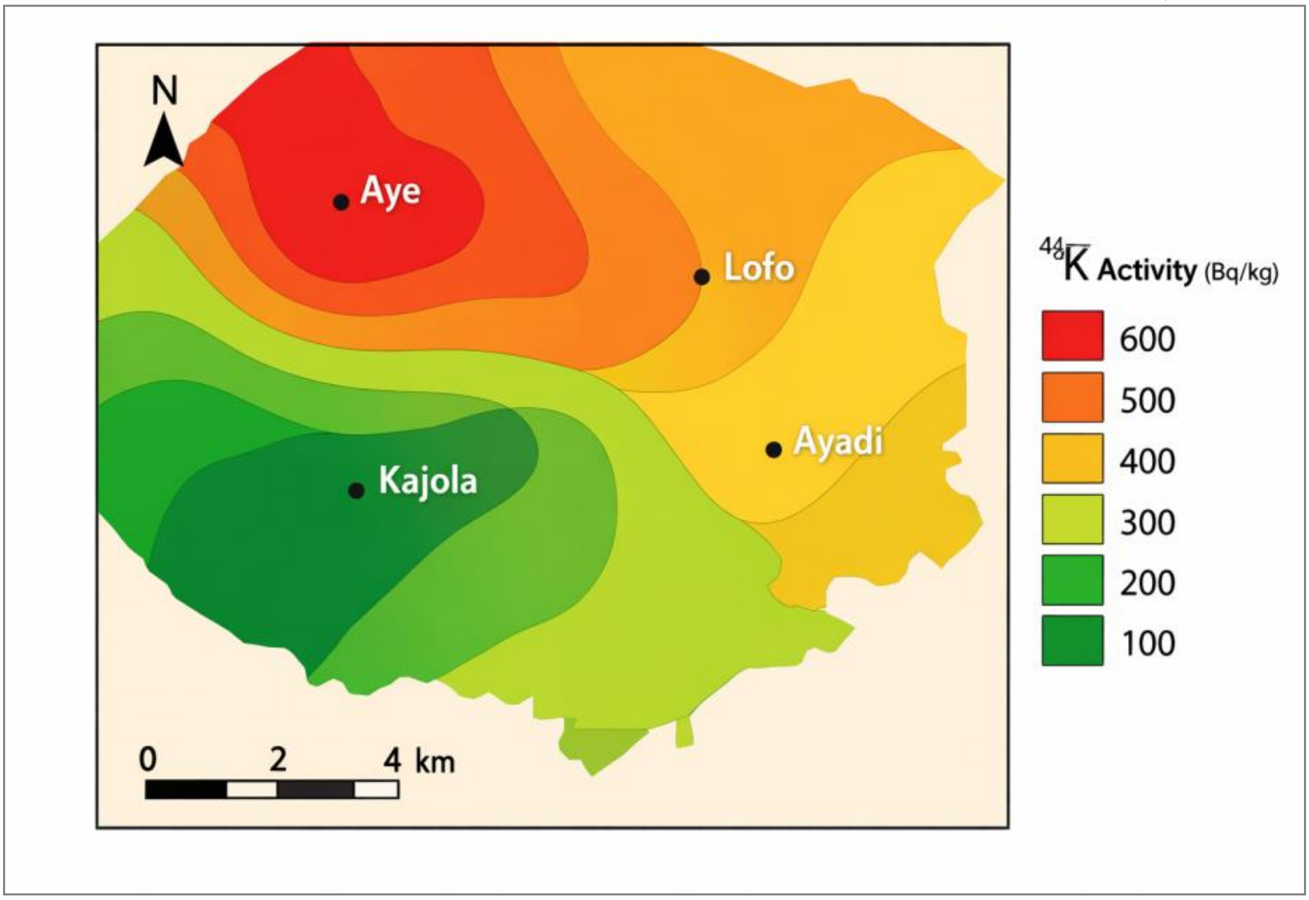

Figure 2: Spatial distribution map of ^{40}K activity concentration (Bq/kg) in soils of southern Ondo State using IDW interpolation.

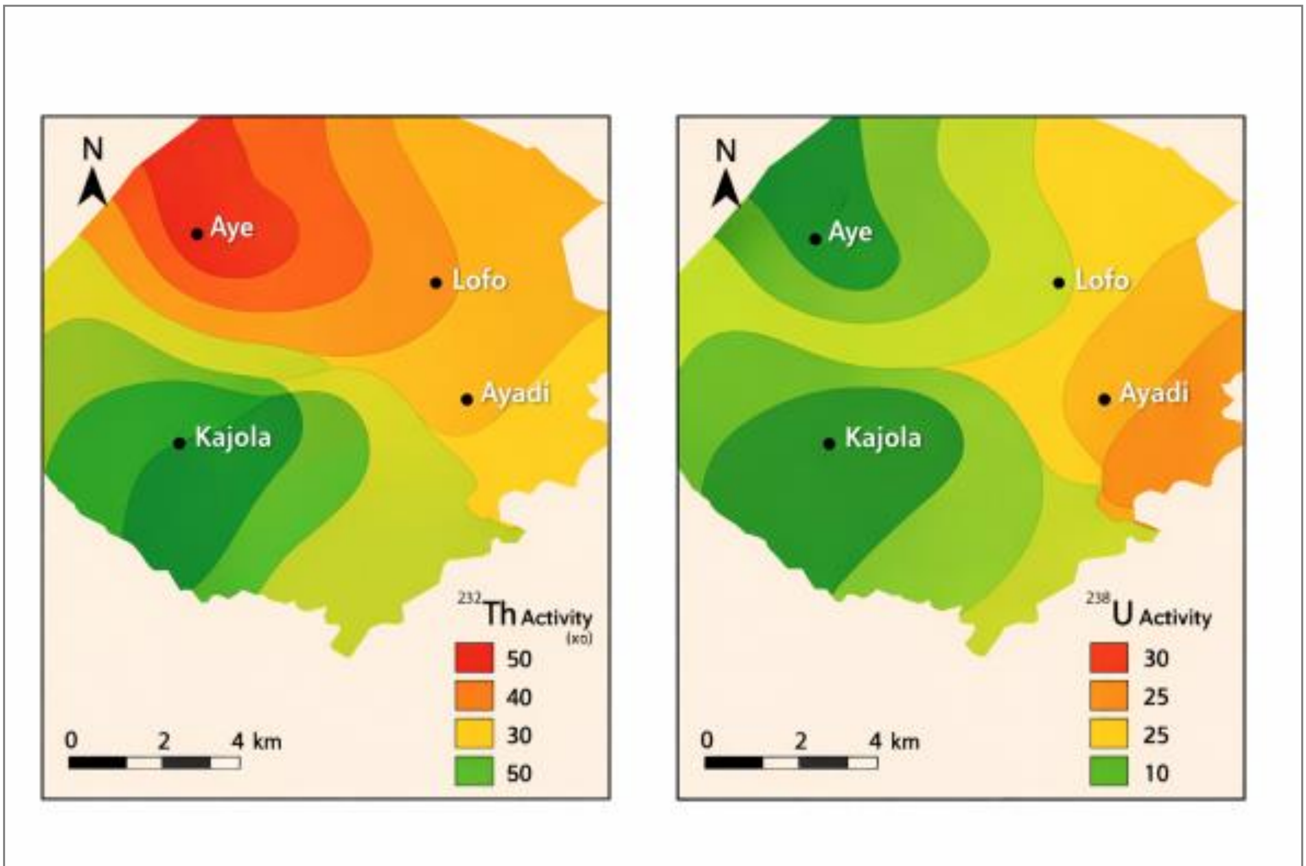

Figure 3: Spatial distribution map of ^{232}Th activity concentration (Bq/kg) in soils of southern Ondo State using IDW interpolation.

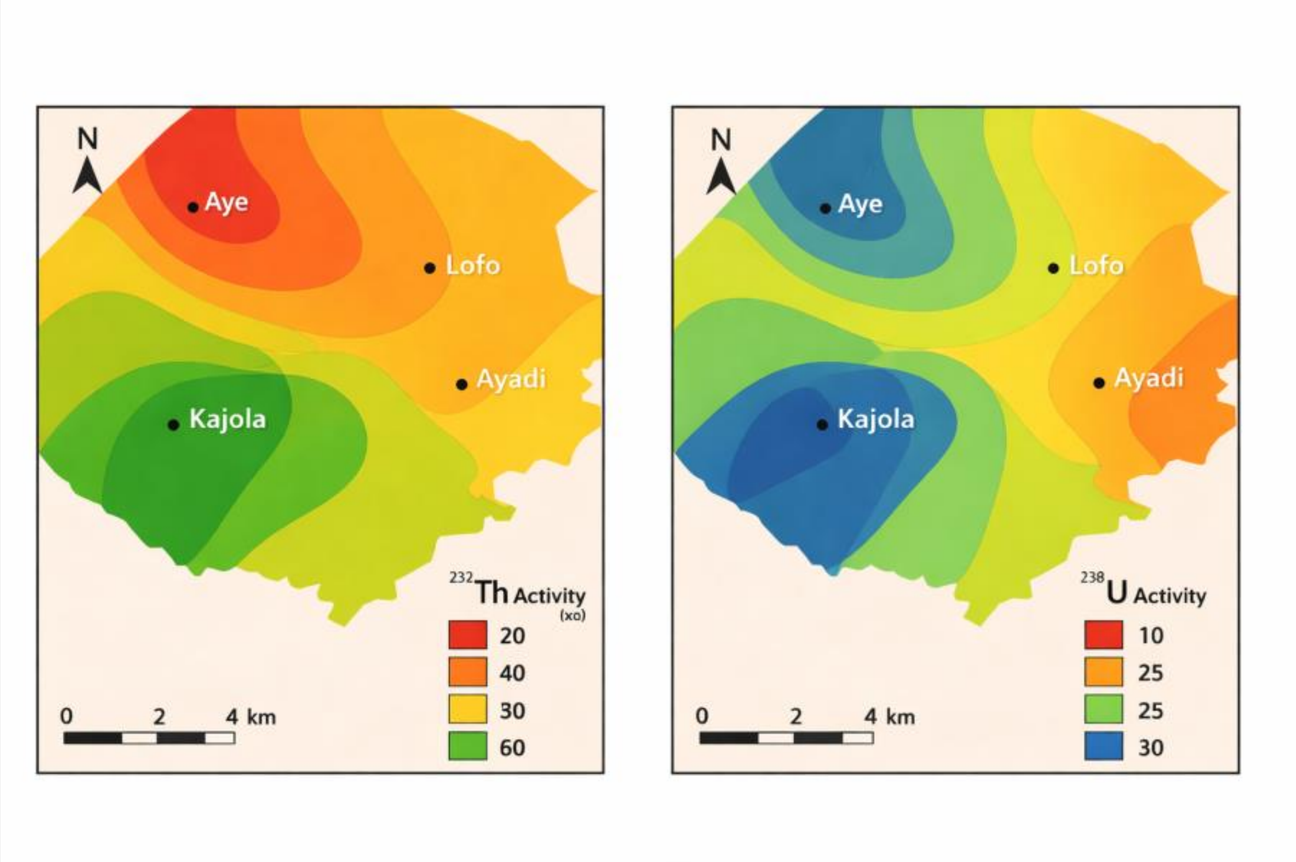

Figure 4: Spatial distribution map of ^{238}U activity concentration (Bq/kg) in soils of southern Ondo State using IDW interpolation.

4.3 Spatial Variations and Correlation Analysis

Spatial variations among sampling locations showed that the highest activities of ^{40}K and ^{232}Th occurred at Aye and Ayadi, which are located near zones of ferruginous sandstones, while the lowest values were recorded at Kajola (Table 3). The enrichment of ^{40}K in these areas can be attributed to the presence of potassium-bearing feldspar minerals and the influence of organic fertilizers commonly used in oil palm plantations.

The correlation analysis shows a strong positive relationship between ^{232}Th, ^{238}U, and the hazard indices ($r > 0.79$), indicating that the thorium and uranium series are the major contributors to the absorbed dose rate in the study area. The relatively weaker correlation between ^{40}K and the indices suggests its minor contribution to the overall dose due to its comparatively lower specific activity (Kang *et al*., 2020).

4.4 Comparative Analysis with Other Regions

To evaluate regional variations, the mean activity concentrations of radionuclides in southern Ondo soils were compared with data from other parts of Nigeria and selected global locations (Table 4).

From the comparison, the radionuclide activity levels in the study area are among the lowest reported both within Nigeria and globally, implying a low radiological baseline typical of sedimentary terrains with limited granitic intrusions.

4.5 Radiological Implications

The low activity levels observed suggest that farmers and residents of the study area are not exposed to significant external or internal radiological hazards. The calculated AEDE (0.04 mSv/y) is substantially lower than the global limit of 1 mSv/y for public exposure recommended by the ICRP (1993). Additionally, the hazard indices (Hex and Hin) being far below unity indicate that soil utilization for agricultural purposes poses no significant risk of gamma radiation exposure.

The low uranium–thorium ratio (U/Th ≈ 0.64) also reflects the dominance of thorium in the lithological matrix, a feature consistent with weathered basement and sedimentary soils of southwestern Nigeria (Otwoma et al., 2013). These findings support the interpretation that radionuclide distribution in the study area is geogenically controlled, with minimal influence from anthropogenic inputs.

4.6 Environmental Significance and Monitoring Implications

Although current levels are within safe limits, long-term agricultural activities such as the application of phosphate fertilizers and biomass ash can elevate soil radioactivity (Ajayi et al., 2018). Continuous environmental monitoring is therefore recommended to track any progressive changes. Establishing such baseline data is vital for developing national radioecological maps and for assessing soil quality in agricultural ecosystems.

4.7 Spatial Distribution of ^{40}K Activity

The spatial distribution of ^{40}K activity concentration across the study area was generated using the Inverse Distance Weighting (IDW) interpolation technique based on the measured values at the four sampling locations (Figure 2). The resulting contour map provides a visual representation of the variation in ^{40}K distribution across the oil-palm plantation soils.

The map reveals relatively higher ^{40}K concentrations around Aye and Ayadi, while lower values are observed toward Kajola. This spatial trend may be attributed to variations in soil mineral composition, particularly the presence of potassium-bearing feldspar minerals, as well as localized agricultural practices such as organic fertilizer application.

4.8 Spatial Distribution of ^{232}Th Activity

The spatial distribution of ^{232}Th activity concentration across the study area was generated using the Inverse Distance Weighting (IDW) interpolation method based on the measured values at the four sampling locations (Figure 3). This approach provides a clear visualization of thorium variability within the oil-palm plantation soils.

The distribution pattern indicates relatively elevated ^{232}Th concentrations around Aye, while lower concentrations are observed toward Kajola. This variation may be linked to differences in underlying lithology and the natural abundance of thorium-bearing minerals within the soil matrix.

4.9 Spatial Distribution of ^{238}U Activity

The spatial variation of ^{238}U activity concentration was also mapped using the IDW interpolation technique to illustrate its distribution across the study area (Figure 4). The resulting contour map highlights areas of uranium enrichment and depletion.

The map shows moderate ^{238}U concentrations around Ayadi and Lofo, with comparatively lower values toward Kajola. These variations may be influenced by soil-forming processes, drainage patterns, and localized geochemical conditions affecting uranium mobility.

CONCLUSION AND RECOMMENDATIONS

This study assessed the activity concentrations of naturally occurring radionuclides ^{40}K, ^{232}Th, and ^{238}U) in agricultural soils from major oil-palm plantations in southern Ondo State, Nigeria, using gamma-ray spectrometry. The results revealed that all measured radionuclide concentrations and derived radiological hazard indices were below the corresponding global permissible limits. The mean activity concentrations of ^{40}K (126.4 Bq/kg), ^{232}Th (29.2 Bq/kg), and ^{238}U (18.6 Bq/kg) were lower than the worldwide averages of 420, 50, and 33 Bq/kg, respectively (UNSCEAR, 2000). The computed values of radium equivalent activity (76.8 Bq/kg), absorbed dose rate (35.4 nGy/h), annual effective dose equivalent (0.04 mSv/y), and hazard indices (Hex = 0.21, Hin = 0.27) confirm that soils in the study area present no significant radiological threat to farmers or consumers.

The observed spatial variability in activity concentrations was attributed mainly to lithological differences, particularly the distribution of feldspathic and clay minerals that host uranium and thorium. The correlation analysis established that ^{232}Th and ^{238}U are the dominant contributors to external and internal dose rates, while ^{40}K plays a comparatively minor role. When compared with results from other parts of Nigeria and abroad, southern Ondo soils exhibit relatively low natural radioactivity levels, characteristic of sedimentary and lateritic terrains.

From a radiological protection perspective, the study concludes that oil-palm plantation soils in southern Ondo State are radiologically safe for agricultural activities. Nonetheless, continuous environmental monitoring is recommended to detect potential changes arising from agricultural practices, fertilizer applications, or industrial activities. It is also advised that future studies incorporate radionuclide transfer factors into crops and conduct multi-seasonal surveys to account for possible temporal variations.

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