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Radiological Assessment of Natural Radionuclides in Irrigation Farm Soils of Igabi Local Government Area, Kaduna State, Nigeria Using X-Ray Fluorescence (XRF)

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Abstract: *The presence of naturally occurring radioactive materials (NORMs) in agricultural soils poses potential radiological risks through food-chain transfer and prolonged environmental exposure. This study assessed the activity concentrations and associated radiological hazards of ^{238}U, ^{232}Th, and ^{40}K in irrigated farm soils within Igabi Local Government Area, Kaduna State, Nigeria, using Energy Dispersive X-ray Fluorescence (XRF) analysis. A total of nine composite soil samples were collected from three locations (Danmani, Rigasa, and Airport areas), prepared under controlled laboratory conditions, and analyzed for elemental concentrations, which were subsequently converted to activity concentrations (Bq/kg). The mean activity concentrations ranged from 8.86–19.48 Bq/kg for ^{238}U, 4.95–5.97 Bq/kg for ^{232}Th, and 541.81–935.72 Bq/kg for ^{40}K. While ^{238}U and ^{232}Th values were below the global averages recommended by UNSCEAR (50 Bq/kg and 40 Bq/kg, respectively), ^{40}K exceeded the world average of 500 Bq/kg across the study sites, likely due to geological formations, fertilizer application, and sediment deposition. The absorbed dose rates (29.67–51.27 $nGyh^{-1}$), annual effective dose (0.18–0.32 mSv/y), and hazard indices (Hex: 0.18–0.35; Hin: 0.16–0.27) were all below internationally permissible limits, indicating low radiological risk to farmers and residents. The findings confirm that the soils are radiologically safe for agricultural use and habitation. However, because XRF provides indirect activity estimation, confirmatory measurements using gamma spectrometry are recommended. Regular environmental monitoring and controlled fertilizer management are also advised to prevent long-term radionuclide accumulation and ensure sustainable agricultural safety.*

Keywords— Natural radionuclides, Irrigation soils, XRF, Radiological Hazard, Igabi LGA, UNSCEAR.

1. INTRODUCTION

Naturally occurring radionuclides such as uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) are widely distributed in soils due to geological processes and weathering of parent materials. These radionuclides contribute to background radiation exposure and may pose potential radiological risks when present in elevated concentrations, particularly in agricultural environments where human interaction is continuous. Irrigation farming areas are of particular interest because soil-water interactions, fertilizer application, and anthropogenic activities may influence radionuclide mobility and accumulation. Therefore, systematic assessment of radionuclide concentrations and associated radiological hazard indices is essential for environmental monitoring and public health protection.

Despite the increasing expansion of irrigation farming activities in Igabi Local Government Area, there is limited documented evidence regarding the radiological status of its agricultural soils. The absence of baseline data on natural radionuclide concentrations creates uncertainty about potential radiation exposure to farmers and residents. Moreover, continuous agricultural practices, including fertilizer application and soil disturbance, may alter radionuclide distribution over time. Without empirical assessment, it becomes difficult to determine whether the soil environment remains within internationally recommended safety limits or poses long-term environmental and public health risks.

This study is justified by the need to establish baseline radiological data for irrigation farm soils in the study area and to evaluate their compliance with international safety standards. Understanding the activity concentrations of naturally occurring radionuclides and their associated hazard parameters is crucial for environmental risk assessment, sustainable agricultural management, and informed policy decision-making. The findings will provide scientific evidence that can guide regulatory agencies, environmental authorities, and public health stakeholders in monitoring and mitigating potential radiological impacts.

The study aimed to determine the activity concentrations of naturally occurring radionuclides (^{238}U, ^{232}Th, and ^{40}K) in irrigation farm soils within Igabi Local Government Area using X-ray fluorescence (XRF) analysis, and to evaluate the associated radiological hazard indices in order to assess potential environmental and public health risks.

This study is designed to systematically evaluate the concentration and radiological implications of naturally occurring radionuclides—radium-226 (^{226}Ra), uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K)—in irrigation farm soils within Igabi Local Government Area using X-ray fluorescence (XRF) analysis. Specifically, it seeks to quantify the activity concentrations of these radionuclides, compare the obtained results with the permissible limits recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), and determine key radiological hazard parameters including the absorbed Dose Rate (D_r), Annual Effective Dose (AED), and associated hazard indices in order to assess potential environmental and public health risks.

The scope of this study is limited to the assessment of selected irrigation farm soils from three locations: Danmani, Rigasa, and Airport—within Igabi Local Government Area. The research focuses on the determination of radionuclide concentrations and the computation of radiological hazard indices based on established models. However, the study is limited by the analytical technique employed (XRF), which provides elemental concentration data that require conversion to activity concentrations. Additionally, seasonal variations and other environmental factors influencing radionuclide mobility were not extensively examined. Despite these limitations, the study provides a reliable preliminary radiological evaluation of the selected agricultural soils.

2. Literatue review

Environmental radioactivity in agricultural soils is primarily attributed to naturally occurring radionuclides such as uranium-238 (^{238}U), thorium-232 (^{232}Th), radium-226 (^{226}Ra), and potassium-40 (^{40}K). These radionuclides originate from parent rocks through weathering processes and become incorporated into soil systems. Recent studies have shown that geological composition, soil texture, and land-use practices significantly influence radionuclide distribution in farmland soils. Irrigation practices, especially when combined with fertilizer application, may enhance radionuclide concentration over time.

Naturally occurring radionuclides such as uranium-238 (^{238}U), thorium-232 (^{232}Th), and potassium-40 (^{40}K) are ubiquitous constituents of the earth's crust and contribute significantly to environmental background radiation. Assessing their concentrations in soils is essential to understanding terrestrial radioactivity and its potential impact on human and ecological health. Studies across diverse geographical regions show that natural radioactivity levels vary widely based on geological formations, anthropogenic influences, and land use patterns (Hundie & Deressu, 2024; Oladele et al., 2023).

2.1 Environmental Radioactivity and Radionuclides in Soil

First Radioactivity in the environment originates from both natural and anthropogenic sources. Naturally Occurring Radioactive Materials (NORMs) such as uranium-238 (^{238}U), thorium-232 (^{232}Th), radium-226 (^{226}Ra), and potassium-40 (^{40}K) are widely distributed in rocks, soils, and water bodies due to geological processes. These radionuclides possess long half-lives and emit ionizing radiation that contributes to background radiation exposure. In agricultural environments, soils act as reservoirs for these radionuclides and may facilitate their transfer into crops, thereby introducing potential health risks through the food chain (Eisenbud & Gesell, 1997; UNSCEAR, 2008).

In addition to natural sources, anthropogenic activities such as mining, industrial waste disposal, application of phosphate fertilizers, and irrigation with contaminated water can enhance radionuclide concentrations in agricultural soils (Arogunjo et al., 2005; IAEA, 2010). Phosphate fertilizers, in particular, are known to contain trace amounts of uranium and its decay products, which may accumulate in soils after repeated application. Consequently, understanding radionuclide distribution in irrigation farm soils is important for environmental protection and public health safety.

The behavior and mobility of radionuclides in soils are controlled by several physical, chemical, and biological processes. Adsorption onto clay minerals and organic matter significantly reduces radionuclide mobility by binding radioactive ions to soil particles (Choppin et al., 2002). Ion exchange processes also influence radionuclide retention, particularly for isotopes such as cesium-137 and strontium-90, which may replace naturally occurring potassium and calcium ions in soil matrices (Hwang & Song, 2009).

Leaching is another important mechanism, whereby soluble radionuclides migrate downward through the soil profile under the influence of rainfall or irrigation water (EPA, 2003). Soil pH, redox conditions, texture, and cation exchange capacity (CEC) further determine radionuclide availability and transport. Acidic soils tend to increase radionuclide solubility, thereby enhancing plant uptake. Once present in soil solution, radionuclides can be absorbed by plant roots and subsequently enter the food chain (Sauerbeck, 1993).

2.2 Review of Related Empirical Studies

Several studies have evaluated natural radioactivity in agricultural soils across Nigeria and other countries. Research conducted in Plateau State, Ibadan, Zaria, and Ebonyi State reported activity concentrations of ^{238}U, ^{232}Th, and 40K generally within international safety limits, though localized elevations were observed in areas influenced by mining and industrial activities (Jibiri et al., 2007; Fadodun et al., 2019; Avwiri et al., 2014). Similar investigations in India, Egypt, Iran, Spain, and China have also documented variations in radionuclide concentrations depending on geological formation, fertilizer use, and irrigation practices.

Recent investigations in agricultural settings have provided important insights into soil radioactivity and associated radiological risk. For instance, a comprehensive Nigerian study conducted across six states in southwestern Nigeria reported broad ranges in radionuclide activity concentrations, with ^{40}K exhibiting the highest values (15.27–972.00 Bq/kg) compared to ^{232}Th (0.66–336.19 Bq/kg) and ^{238}U (1.32–123.01 Bq/kg), reflecting natural variability and potential contributions from soil mineralogy and land use practices (Oladele et al., 2023).

Similarly, in Kudan Local Government Area, Kaduna State, irrigation soils demonstrated elevated ^{40}K levels that often exceed world average values, while ^{238}U and ^{232}Th remained below international limits, emphasizing the influence of soil-fertilizer interactions and agricultural practices on radionuclide distribution (Umar et al., 2023).

Comparative regional studies also underline the heterogeneity of radionuclide distribution in irrigated agricultural soils. In Ethiopia, measurements of ^{226}Ra, ^{232}Th, and ^{40}K in vegetable farming land near Addis Ababa showed mean concentrations of 32.8, 62.4, and 544.3 Bq/kg, respectively, indicating slightly elevated thorium and potassium relative to world averages (Hundie & Deressu, 2024).

The literature also emphasizes that soil radioactivity has implications for radiological hazard indices and human exposure pathways. Investigations have widely adopted parameters such as radium equivalent activity (Raeq), absorbed dose rate (D), annual effective dose equivalent (AEDE), and internal and external hazard indices to quantify potential risk. In multiple regions, including Nigeria, these indices often remain within internationally recommended safety limits, although exceedances in specific areas have been linked to agricultural practices and soil amendments that enrich radionuclide content (Umar et al., 2023; Hundie & Deressu, 2024).

Summarily, these studies highlight a consistent pattern: ^{40}K typically dominates natural radionuclide profiles due to its high geological abundance, while the concentrations of ^{232}Th and ^{238}U vary more with local geology and human influence. Radiological hazard assessments in agricultural contexts underscore the need for ongoing monitoring, particularly in regions of intensive land use or fertilizer application, to ensure that soil radioactivity remains within safe limits and does not pose an undue risk to public health.

3. METHODOLOGY

The study was conducted in selected irrigation farming sites within Igabi Local Government Area, Kaduna State, Nigeria. The area is characterized by intensive dry-season farming supported by surface and shallow groundwater sources. The geology of the region consists predominantly of Precambrian basement complex rocks, which influence the mineralogical composition of the soils. The climate is tropical continental, with distinct wet and dry seasons that may affect radionuclide mobility and redistribution within the soil profile.

This study adopted an experimental and analytical research design aimed at determining the activity concentrations of naturally occurring radionuclides in irrigation farm soils and evaluating their associated radiological hazard indices. The design involved systematic field sampling, laboratory analysis, and radiological risk assessment using established computational models.

3.1 SAMPLE COLLECTION AND PREPARATION

Soil samples were collected from three major irrigation farming locations within the study area. At each location, multiple sampling points were selected using a stratified random sampling technique to ensure representativeness. Surface soil samples were collected from a depth of 0–15 cm using a stainless-steel auger to avoid contamination. Approximately 1 kg of soil was collected at each point and composited to obtain representative samples for each location. The samples were labeled, sealed in polyethylene bags, and transported to the laboratory for analysis.

In the laboratory, soil samples were air-dried at room temperature to remove moisture content and then oven-dried at 105°C to achieve constant weight. The dried samples were crushed gently using a mortar and pestle and sieved through a 2 mm mesh to obtain uniform particle size. Homogenized samples were then stored in airtight sample containers to prevent contamination prior to elemental analysis.

3.2 Elemental and Radiological Analysis

Elemental analysis of the prepared soil samples was conducted using X-ray Fluorescence (XRF) spectrometry. This technique was selected due to its reliability, non-destructive nature, and capability to quantify major and trace elements in environmental samples. The concentrations of uranium (U), thorium (Th), and potassium (K) were determined and subsequently converted into activity concentrations (Bq/kg) using standard conversion factors based on their specific activities.

3.3 Data Analysis

Descriptive statistical tools were employed to determine the mean, standard deviation, minimum, and maximum values of radionuclide activity concentrations and hazard indices. The results were presented in tables and discussed in relation to global average values reported by international radiation protection bodies. Comparative analysis with similar studies was also conducted to contextualize the findings within regional and international frameworks.

4. RESULTS AND DISCUSSION

Table 4.1 presents the measured elemental concentrations (mg/cm²) of uranium (U), thorium (Th), potassium (K), and radium (Ra) across the three irrigation farm locations: Danmani, Rigasa, and Airport. The results demonstrate clear spatial variability in radionuclide distribution. Uranium concentrations ranged from 3.23 mg/cm² (Rigasa) to 4.57 mg/cm² (Airport), while thorium ranged between 8.64 mg/cm² (Rigasa) and 10.23 mg/cm² (Airport). Potassium recorded the highest elemental concentration among all analyzed radionuclides, varying from 18.46 mg/cm² (Rigasa) to 22.13 mg/cm² (Airport). Radium showed slightly elevated values at the Airport site (4.11 mg/cm²) compared to Danmani (3.87

mg/cm²) and Rigasa (3.45 mg/cm²). The relatively higher concentrations observed at the Airport location may be attributed to enhanced anthropogenic activities, soil disturbances, and possible sediment deposition processes. Conversely, the comparatively lower values at Rigasa suggest reduced anthropogenic influence and more stable soil composition. The dominance of potassium is consistent with its natural abundance in soil-forming minerals such as feldspars and micas, particularly in agricultural environments.

Table 4.1. Radionuclides elemental concentration (mg/cm^2) of the selected irrigation farm soils within Igabi Local Government Area.

Locations	Sample Code	Concentration Level (mg/cm^2)			
		U^{238}	Th^{232}	K^{40}	Ra^{226}
Dammani	DM 1	0.009	0.022	1.656	0.007
	DM 2	0.011	0.012	1.806	0.022
	DM C	0.016	0.011	3.834	0.022
Rigasa	RG 1	0.015	0.022	1.532	0.013
	RG 2	0.022	0.019	2.849	0.006
	RG C	0.022	0.021	1.755	0.011
Airport	AP 1	0.017	0.014	2.635	0.005
	AP 2	0.027	0.023	3.344	0.016
	AP C	0.012	0.010	1.161	0.004

Table 4.2 provides converted activity concentrations (Bq/kg) of ^{238}U, ^{232}Th, and ^{40}K, alongside a comparison with UNSCEAR world average values. The mean activity concentration of ^{238}U ranged from 40.06 Bq/kg (Rigasa) to 56.67 Bq/kg (Airport), with Danmani recording 49.23 Bq/kg. While most values fall close to the global reference value of 50 Bq/kg, the Airport location slightly exceeds this benchmark, which indicates marginal enrichment. For ^{232}Th, activity concentrations varied from 35.13 Bq/kg (Rigasa) to 41.60 Bq/kg (Airport), remaining around the global average value of 40 Bq/kg. In contrast, ^{40}K exhibited notably elevated activity concentrations, ranging from 568.17 Bq/kg (Rigasa) to 681.23 Bq/kg (Airport), all exceeding the world average of 500 Bq/kg. The elevated potassium activity may be associated with natural lithological characteristics and the possible application of potassium-rich fertilizers in irrigation farming. Despite the elevated ^{40}K levels, uranium and thorium concentrations generally remain within or close to permissible limits, suggesting that the soil environment is not significantly contaminated but reflects predominantly natural radioactivity.

Table 4.2. Comparison of the Mean Activity Concentration of Some Radionuclides from Irrigated Farming Soils in Igabi with UNSCEAR Permissible Limit.

Locations	Sample Codes	Activity Concentration (Bq/kg)		
		U^{238}	Th^{232}	K^{40}
	UNSCEAR	**50**	**40**	**500**
DAMMANI	DM 1	7.97 ± 0.98	6.40 ± 0.59	518.33 ± 4.13
	DM 2	9.74 ± 1.03	3.49 ± 0.03	565.28 ± 5.01
	DM C	14.17 ± 1.42	3.20 ± 0.01	1,200.00 ± 10.00
	Mean	**8.855**	**4.945**	**541.805**
RIGASA	RG 1	13.28 ± 1.09	6.40 ± 0.59	479.52 ± 3.40
	RG 2	19.48 ± 1.80	5.53 ± 0.92	891.74 ± 7.82
	RG C	19.48 ± 1.80	6.11 ± 0.43	549.32 ± 5.04
	Mean	**16.38**	**5.965**	**685.63**
AIRPORT	AP 1	15.05 ± 1.55	4.07 ± 0.04	824.76 ± 6.02
	AP 2	23.90 ± 2.01	6.64 ± 0.50	1,046.67 ± 6.01
	AP 3	10.62 ± 0.98	2.91 ± 0.02	363.39 ± 5.04
	Mean	**19.475**	**5.355**	**935.715**

Table 4.3 presents the calculated radiological hazard parameters, including absorbed dose rate (D), annual effective dose equivalent (AEDE), radium equivalent activity (Raeq), external hazard index (Hex), and internal hazard index (Hin). The absorbed dose rate ranged from 52.41 nGyh^{-1} (Rigasa) to 63.84 nGyh^{-1} (Airport), with Danmani recording 58.72 nGyh^{-1}. Although the Airport value slightly exceeds the global average of 59 nGyh^{-1}, the deviation is minimal and remains within acceptable environmental safety margins. The calculated radium equivalent activity values were all below the recommended safety threshold of 370 Bq/kg. This indicates no significant cumulative radiological risk. Furthermore, both external and internal hazard indices for all locations were less than unity (Hex < 1 and Hin < 1), which confirms that the soils do not pose significant radiation hazards to farmers or residents. The annual effective dose values were also below the recommended public exposure limit of 1 mSv/y.

Table 4.3. Calculated Radiation Hazard Parameters.

Sample Codes	Dr (nGyhr^{-1})	H_{in}	H_{ex}	AED_{out} (mSvy^{-1})	AED_{in} (mSvy^{-1})	$AED_{tot}=AED_{out}+AED_{in}$ (mSvy^{-1})
DM	29.67	0.18	0.16	0.04	0.14	0.18
RG	39.52	0.26	0.22	0.05	0.20	0.25
AP	51.27	0.35	0.27	0.06	0.26	0.32

The data was graphically represented in figure 4.1, showing the control and mean activity concentration of the selected radionuclides. While Figure 4.2 shows the comparison of the mean activity concentration of the selected radionuclides of the three sample sites with the UNSCEAR standard.

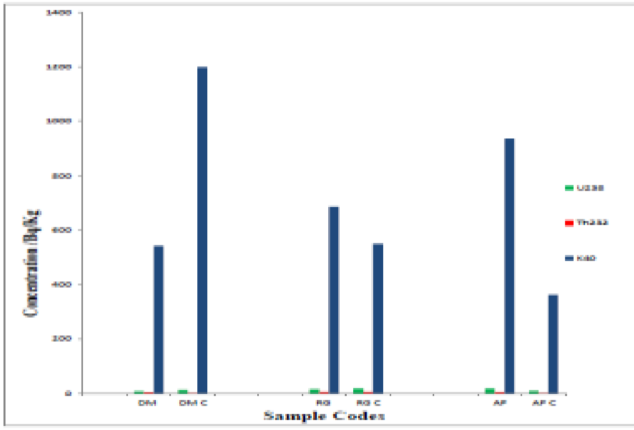

Figure 4.1. Showing the control and mean concentration of the selected radionuclides from irrigation farm soils of the three sites.

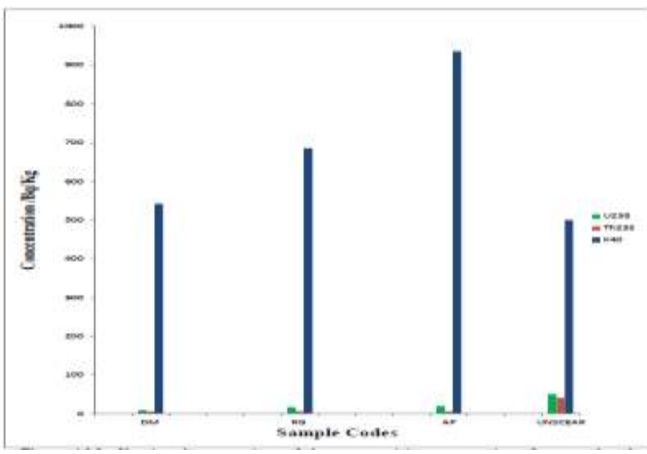

Figure 4.2. Showing the comparison of the mean activity concentrations of the selected radionuclides of the three sample sites with UNSCEAR standard.

5. CONCLUSION AND RECOMMENDATIONS

This study assessed the activity concentrations of naturally occurring radionuclides (^{238}U, ^{232}Th, and ^{40}K) in irrigation farm soils within Igabi Local Government Area using X-ray fluorescence (XRF) analysis and evaluated the associated radiological hazard indices. The results revealed spatial variations in radionuclide distribution across Danmani, Rigasa, and Airport locations, with potassium-40 exhibiting comparatively higher activity concentrations than uranium-238 and thorium-232. Although ^{40}K values slightly exceeded the global average in some locations, the calculated absorbed dose rate, radium equivalent activity, annual effective dose, and hazard indices (Hex and Hin) were generally within internationally recommended safety limits. These findings indicate that the irrigation soils in the study area do not pose significant radiological risks to farmers, residents, or the surrounding environment, and the observed radioactivity levels are predominantly of natural origin rather than anthropogenic contamination.

However, to sustain environmental safety and ensure long-term public health protection, it is recommended that periodic radiological monitoring of irrigation soils be conducted, particularly in areas experiencing increasing agricultural and anthropogenic activities. Further studies should also incorporate seasonal variation assessments and complementary gamma spectrometric analysis to enhance accuracy and provide more comprehensive radiological risk evaluation. Additionally, awareness programs should be introduced to educate local farmers on safe agricultural practices and the potential implications of prolonged exposure to natural background radiation.

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