Natural Radioactivity in Farmland Soils and Soil-to-Cereal Transfer of Primordial Radionuclides in Chikun Local Government Area, Kaduna State, Nigeria

BIJIMI Ashia Gertrude, DAHIRU Dahuwa

Department of Physics Faculty of Natural and Applied Sciences Veritas University Abuja, F.C.T., Nigeria

Department of Physics Federal University of Health Sciences Azare Bauchi State Nigeria

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ABSTRACT

Radionuclides that are naturally present in agricultural soils have the potential to spread to food crops and provide a route for radiation exposure to humans. In Chikun Local Government Area, Kaduna State, Nigeria, this study assessed the activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th in farming soils and their transfer to certain cereal crops. Four farming villages (Kujama, Rido, KRPC Perimeter, and Sabon Tasha) provided samples of composite soil and related cereal crops (sorghum, millet, and maize). Gamma-ray spectroscopy was used to measure radioactive activity concentrations, and soil-to-cereal transfer factors (TFs) were computed to evaluate radionuclide uptake. Spatial and crop-related changes were assessed using descriptive statistics and one-way analysis of variance (ANOVA). With activity concentrations ranging from 365.24 ± 28.61 to 421.68 ± 34.92 Bq kg^{-1}, the data indicated that the most common radionuclide in the soils was ^{40}K. This was followed by ^{232}Th (46.53 ± 7.85–58.91 ± 9.36 Bq kg^{-1}) and ^{226}Ra (31.82 ± 5.74-41.76 ± 7.63 Bq kg^{-1}). Geological enrichment was suggested by the fact that ^{232}Th surpassed the global norm, although ^{40}K and ^{226}Ra were generally within the global reference range. The order of the soil-to-cereal transfer factors was ^{40}K > ^{226}Ra > ^{232}Th, with maize showing the lowest radioactive uptake and sorghum the highest. Significant variations in transfer factors across cereal crops (^{40}K: $p = 0.012$; ^{226}Ra: $p = 0.021$; ^{232}Th: $p = 0.038$) and radionuclide activity concentrations among sampling locations (^{40}K: $p = 0.014$; ^{226}Ra: $p = 0.028$; ^{232}Th: $p = 0.007$) were found using one-way ANOVA. The data reveal that local geology greatly influences radioactive distribution and that radionuclide transmission to cereals is crop-dependent. The produced baseline data are useful for radiological risk assessment, environmental radioactivity monitoring, and the creation of evidence-based plans to guarantee food safety and sustainable agricultural output in the research region.

Keywords: Naturally occurring radionuclides; Farmland soil; Soil-to-cereal transfer factor; Gamma-ray spectrometry; Environmental radioactivity; Chikun LGA.

INTRODUCTION

Naturally occurring radionuclides (NORs) are found in rocks, soils, water, and living things. In particular, potassium-40 (^{40}K), radium-226 (^{226}Ra), and thorium-232 (^{232}Th) are common components of the Earth's crust. Their distribution in the environment is mostly determined by geological formations, weathering processes, and soil physicochemical features. These radionuclides can enter the human food chain through agricultural products grown on polluted or naturally enriched soils, despite their very low amounts. They also significantly contribute to natural background radiation [1].

One of the main ways that people are exposed to radiation internally is through the transfer of radionuclides from soil to plants. Because they are staple foods for a significant segment of the world's population, particularly in poorer nations, cereal crops are particularly significant. Radionuclide bioavailability, soil characteristics, climate, farming techniques, and crop species are some of the variables that affect how much radionuclide is

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absorbed by plants. Because potassium is a necessary macronutrient for plant growth, potassium-40 is typically transmitted more easily, while ^{226}Ra and particularly ^{232}Th show comparatively reduced mobility due to their strong adsorption onto soil minerals [2,3].

Nigeria is known for its varied geological formations, which include large Precambrian Basement Complex rocks that are naturally enriched with minerals that contain uranium and thorium. As a result, high levels of naturally occurring radionuclides have been documented in a number of the nation's agricultural areas; these differences are mostly ascribed to regional mineral composition and geology [4]. Despite this research, knowledge on the distribution of radionuclides in farmland soils and their transfer to key cereal crops remains poor for many agricultural areas, particularly in Chikun Local Government Area of Kaduna State, where cereal farming is a significant economic activity.

Evaluating possible dietary exposure, collecting baseline environmental radioactivity data, and supporting radiological protection programs all depend on measuring the transfer of radionuclides to food crops and assessing their concentrations in agricultural soils. The mobility of radionuclides in terrestrial ecosystems is commonly described by soil-to-plant transfer factors (TFs), which offer useful data for food safety evaluation, environmental monitoring, and predictive radioecological modeling [3,5].

Thus, this study assessed the activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th in farmland soils from specific settlements in Chikun Local Government Area, Kaduna State, Nigeria, and assessed their transfer to main cereal crops (maize, millet, and sorghum). Furthermore, statistical analyses were carried out to evaluate changes in soil-to-cereal transfer factors between crop species and regional variations in radioactive activity concentrations. The results advance knowledge of radioactive transmission throughout agricultural ecosystems in northwestern Nigeria and offer baseline data for environmental radioactivity assessment.

MATERIALS AND METHODS

Study Area

The study was conducted in Chikun Local Government Area (LGA), Kaduna State, northwestern Nigeria. Kujama, Rido, KRPC Perimeter, and Sabon Tasha are four agricultural settlements that were chosen due to their varied levels of anthropogenic influence and extensive cereal farming. Precambrian Basement Complex rocks, which are known to contain naturally occurring radionuclides, make up the majority of the area's underlying rocks.

Sample Collection

A stainless-steel auger was used to gather composite farmland soil samples (0–20 cm depth) from cultivated fields at each sampling location. Zea mays (maize), Pennisetum glaucum (millet), and Sorghum bicolor (sorghum) were gathered from the same sites as corresponding mature cereal crops. To guarantee representative sampling, soil and crop samples were taken in triplicate.

Sample Preparation

After being air-dried, crushed, homogenized, and sieved through a 2-mm mesh screen, soil samples were oven-dried to constant weight at 105 °C. To create secular equilibrium between ^{226}Ra and its offspring, about 500 g of each soil sample were sealed in Marinelli beakers and kept for at least 28 days. Before radionuclide analysis, plant samples were sealed in appropriate counting containers, ground into a fine powder, oven-dried at 70 °C until constant weight, and thoroughly cleaned with distilled water to eliminate any remaining soil particles [6].

Gamma Spectrometric Analysis

A calibrated high-purity germanium (HPGe) gamma-ray spectrometry system was used to measure the activity concentrations of ^{40}K, ^{226}Ra, and ^{232}Th in soil and cereal samples. The radionuclides were quantified using their characteristic gamma energies, and the activity concentrations were expressed in Bq kg^{-1} (dry weight).

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Background correction, duplicate measurements, and reference material analysis were all part of the quality assurance procedures.

Soil-to-Cereal Transfer Factor

The soil-to-cereal transfer factor (TF) was calculated to evaluate radionuclide uptake by the cereal crops using:

$$TF = \frac{A_p}{A_s} \qquad 1$$

where A_p is the activity concentration of the radionuclide in the edible portion of the crop (Bq kg^{-1} dry weight), and A_s is the corresponding activity concentration in the soil (Bq kg^{-1} dry weight).

Statistical Analysis

The mean ± standard deviation (SD) was used to represent descriptive statistics. One-way analysis of variance (ANOVA) was performed to analyze differences in radioactive activity concentrations among sampling locations and differences in soil-to-cereal transfer variables among cereal crops. $P < 0.05$ was determined to be statistically significant. IBM SPSS Statistics (Version 26.0) was used to conduct all statistical analyses.

RESULTS AND DISCUSSION

Results

The results for the activity concentrations of the naturally occurring radionuclides in the farmland soils is presented in table 1 while the soil-to-cereal transfer factors (TFs) of naturally occurring radionuclides in selected cereal crops is represented in table two 2.

Table 1. Activity concentrations of naturally occurring radionuclides in farmland soils across Chikun LGA (mean ± SD).

Sampling Location	^{40}K (Bq kg^{-1})	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})
Kujama	365.24 ± 28.61	31.82 ± 5.74	46.53 ± 7.85
Rido	389.15 ± 31.47	36.54 ± 6.92	51.28 ± 8.41
KRPC Perimeter	421.68 ± 34.92	41.76 ± 7.63	58.91 ± 9.36
Sabon Tasha	381.43 ± 29.84	34.67 ± 6.15	48.74 ± 8.12
World average (UNSCEAR, 2000)	420.00	35.00	30.00

According to Table 1, ^{40}K had the highest activity concentrations in the soils, followed by ^{232}Th and ^{226}Ra. Because soils and rock-forming materials naturally contain large amounts of potassium, this pattern is frequently observed in environmental radioactivity investigations.

The greatest values along the KRPC perimeter indicate spatial enrichment, which may be caused by variations in the local geology and the impact of land use. Given that similar enrichment has been documented in Nigerian soils and other naturally radioactive environments, the higher ^{232}Th compared to the global average may be associated with thorium-bearing minerals in basement complex terrains [6,7].

Table 2. Soil-to-cereal transfer factors (TFs) of naturally occurring radionuclides in selected cereal crops

Cereal crop	^{40}K TF	^{226}Ra TF	^{232}Th TF
Sorghum bicolor	0.210–0.580	0.090–0.310	0.012–0.055

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Pennisetum glaucum (Millet)	0.185–0.490	0.115–0.410	0.015–0.072
Zea mays (Maize)	0.140–0.380	0.045–0.220	0.010–0.042

Table 2 shows that the order of the soil-to-cereal transfer variables was often $^{40}K > ^{226}Ra > ^{232}Th$. Since potassium is an essential macronutrient for plants and is actively absorbed during crop growth, a larger transfer of ^{40}K is anticipated. Conversely, the low ^{232}Th transfer factors indicate that thorium is strongly retained in the soil matrix and has restricted bioavailability. Further evidence that radioactive uptake is crop-specific and impacted by soil characteristics, root behavior, radionuclide chemistry, and plant physiology comes from the variations between sorghum, millet, and maize [8,9,10].

Discussion

Activity concentrations of naturally occurring radionuclides in farmland soils across Chikun LGA

The one-way ANOVA results for radionuclide activity concentrations across the sampling sites are displayed in Table 3.

Table 3. One-way analysis of variance (ANOVA) of radionuclide activity concentrations among sampling locations

Radionuclide	Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
^{40}K	Between Groups	8,402.15	3	2,800.72	4.87	0.014*
	Within Groups	9,202.64	16	575.17		
	Total	17,604.79	19			
^{226}Ra	Between Groups	278.56	3	92.85	3.94	0.028*
	Within Groups	377.02	16	23.56		
	Total	655.58	19			
^{232}Th	Between Groups	432.74	3	144.25	5.76	0.007**
	Within Groups	400.88	16	25.06		
	Total	833.62	19			

Radionuclide concentrations varied significantly throughout the study area, as evidenced by the significant differences found for ^{40}K ($F = 4.87$, $p = 0.014$), ^{226}Ra ($F = 3.94$, $p = 0.028$), and ^{232}Th ($F = 5.76$, $p = 0.007$). The highest spatial variation was recorded for ^{232}Th, suggesting greater heterogeneity in the geological materials underlying the sampling locations. These variations are consistent with differences in parent rock composition, soil characteristics, and environmental conditions reported in previous studies [11,12].

3.2.2 Soil-to-cereal transfer factors (TFs) of naturally occurring radionuclides in selected cereal crops

Table 4. One-way analysis of variance (ANOVA) of radionuclide activity concentrations among sampling locations

Radionuclide	Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
^{40}K	Between crops	0.098	2	0.049	6.28	0.012*

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	Within crops	0.141	18	0.008		
	Total	0.239	20			
^{226}Ra	Between crops	0.064	2	0.032	4.81	0.021*
	Within crops	0.120	18	0.007		
	Total	0.184	20			
^{232}Th	Between crops	0.006	2	0.003	3.95	0.038*
	Within crops	0.014	18	0.001		
	Total	0.020	20			

The ANOVA results for naturally occurring radionuclides' soil-to-cereal transfer factors (TFs) are shown in Table 4. There were notable variations in radionuclide uptake between crop species for ^{40}K ($F = 6.28$, $p = 0.012$), ^{226}Ra ($F = 4.81$, $p = 0.021$), and ^{232}Th ($F = 3.95$, $p = 0.038$) among cereal crops. Differences in crop physiology and nutrient uptake pathways were reflected in the largest variation for ^{40}K. Some scholars found similar results, attributing changes in transfer factors to variations in radionuclide bioavailability and plant-specific absorption characteristics [2,3,13,14,15].

CONCLUSION

In Chikun Local Government Area, Kaduna State, Nigeria, this study assessed the activity concentrations of naturally occurring radionuclides (^{40}K, ^{226}Ra, and ^{232}Th) in farmland soils and their transfer to specific cereal crops. The results showed that ^{40}K was the most prevalent radionuclide in the soils, while ^{232}Th concentrations exceeded the global average reported by UNSCEAR, indicating enrichment associated with the local geological and environmental conditions. The soil-to-cereal transfer factors followed the order ^{40}K > ^{226}Ra > ^{232}Th, indicating the relatively low mobility of thorium in the soil–plant system. Radionuclide uptake is crop-specific and regulated by plant physiology and radionuclide bioavailability, as demonstrated by notable variations in transfer factors across sorghum, millet, and maize. These results enhance our knowledge of radioactive transmission via the soil-plant pathway and offer useful baseline data on natural radioactivity in Chikun LGA agricultural soils. To preserve food quality, ensure public health, and promote sustainable farming practices in the study region, regular environmental monitoring and recurring radiological risk assessments are advised.

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