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Evaluation of Radiological Health Hazard Indices of Natural Radioactivity in Vegetables from Irrigation Farms in Soba Local Government Area, Kaduna State, Nigeria

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Abstract

Natural radionuclides in agricultural products may contribute to long-term radiological health risks through dietary intake. This study assessed the activity concentrations of U-238, Th-232, and K-40 in vegetables cultivated in irrigation farms within Soba Local Government Area, Kaduna State, Nigeria, and evaluated the associated radiological health risks. Pepper, onion, and tomato samples collected from nine locations were analyzed using NaI(Tl) gamma-ray spectrometry. Radiological parameters, including committed effective dose (CED), lifetime cancer risk (LCR), and internal hazard index (H_i), were estimated for adults and children using standard ICRP dose conversion coefficients. The highest radionuclide concentrations were recorded in Kinkiba, with values of 2.45, 7.93, and 556.84 Bq kg^{-1} for U-238, Th-232, and K-40, respectively. Total CED values ranged from 4.86×10^{-5} to 2.85×10^{-4} mSv yr^{-1} for adults and 1.97×10^{-5} to 1.37×10^{-4} mSv yr^{-1} for children. The maximum LCR obtained was 1.42×10^{-2}, while all H_i values remained below the recommended safety threshold. Although spatial variations in radionuclide concentrations were observed, the evaluated radiological indices indicate low ingestion-related health risk under current exposure conditions. The study provides baseline radiological data for environmental monitoring and food safety assessment in agricultural communities.

Keywords: Natural radioactivity; Food safety; Vegetables; Gamma spectrometry; Committed effective dose; Lifetime cancer risk; Soba Local Government Area; Kaduna State; Nigeria.

I. INTRODUCTION

Naturally occurring radioactive materials (NORMs) are widely distributed in the environment and constitute a major source of human exposure to ionizing radiation. Natural radionuclides such as uranium-238 (U-238), thorium-232 (Th-232), and potassium-40 (K-40) occur naturally in rocks, soils, water bodies, and agricultural systems through geological weathering and geochemical processes [1–4]. Their concentrations may be enhanced by anthropogenic activities, including agriculture, mining, industrial operations, and waste disposal, resulting in elevated environmental radiation levels and potential health risks [5].

Food consumption represents one of the principal pathways through which radionuclides enter the human body. Vegetables are particularly important because they readily absorb radionuclides from soils, irrigation water, and fertilizers during growth. The extent of radionuclide accumulation in edible plants depends on several factors, including soil composition, water quality, agricultural practices, and plant species [6]. Recent studies in Nigeria have demonstrated measurable transfer of naturally occurring radionuclides from agricultural soils and irrigation systems into edible vegetables, highlighting the importance of continuous radiological monitoring of food crops and associated health risks [7]. Similarly, measurable concentrations of naturally occurring radionuclides have been reported in irrigation water used for vegetable cultivation, indicating a potential pathway for radionuclide transfer into the food chain [8]. Long-term ingestion of radionuclide-containing food may contribute to internal radiation exposure and increase the risk of adverse health effects, including genetic mutations, organ damage, and cancer development [9-10].

Radiological assessment of food crops is therefore essential for evaluating environmental contamination and ensuring food safety, particularly in agricultural communities where irrigation farming is extensively practiced. Despite growing concern regarding radiological contamination of agricultural products, comprehensive data on radionuclide concentrations and associated health risks in vegetables cultivated within irrigation farming systems in Nigeria remain limited. Recent reviews have emphasized the need for continued assessment of food-chain contamination and its public health implications [6].

This study evaluates the activity concentrations of U-238, Th-232, and K-40 in commonly consumed vegetables grown on irrigation farms within the Soba Local Government Area, Kaduna State, Nigeria. The associated radiological health hazards were assessed using committed effective dose (CED), lifetime cancer risk (LCR), and internal hazard index (H_i). The study provides baseline radiological data for environmental monitoring, food safety evaluation, and public health risk assessment in agricultural communities.

II. MATERIALS AND METHODS

A. *Geology of the Study Area*

Fig. 1 shows the map of Soba Local Government Area (LGA), Kaduna State, Nigeria, which covers approximately 2,955 km² and lies between latitudes 9°00′–11°00′ N and longitudes 7°00′–8°30′ E. Makarfi LGA bounds it to the north, Zaria and Sabon Gari LGAs to the northwest, Igabi LGA to the southwest, Kauru LGA to the south, and Ikara LGA to the northeast. The study area experiences a tropical climate characterized by distinct wet and dry seasons, including the dry Harmattan period associated with northeastern trade winds. The mean annual rainfall is approximately 1,099.3 mm, while peak temperatures occur between February and April [11].

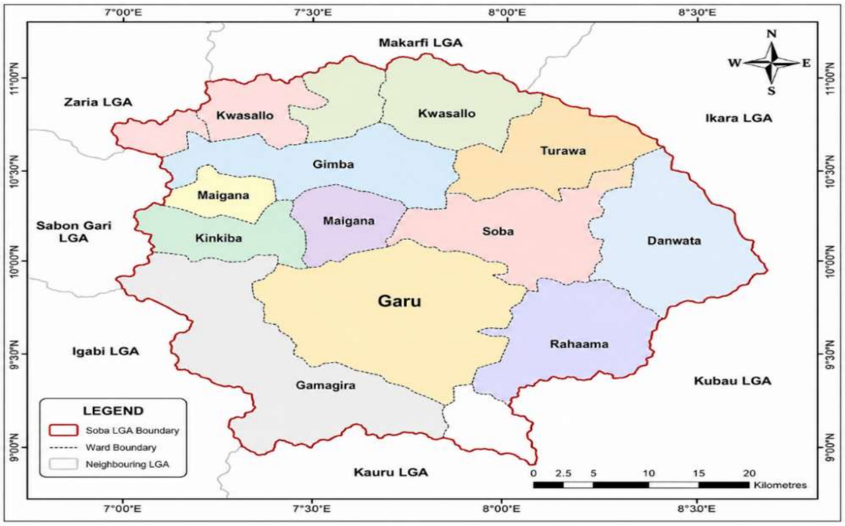

Fig. 1. Map of the study. Source: GEO–INVEST (NIG) LTD, Kaduna, Nigeria, 2014.

The area supports extensive agricultural activities, with irrigation farming sustained by surface water resources and earth dams that also serve the domestic and fishing needs of surrounding communities [12]. Geologically, the area is dominated by crystalline basement rocks, including schists, gneisses, and granites, which are locally overlain by sedimentary and alluvial deposits [13]. These geological formations may contribute to the natural occurrence and mobility of radionuclides within soils and irrigation systems. The presence of agricultural and geological factors that can enhance radionuclide transfer into the food chain underscores the need for radiological assessment within the study area. However, systematic data on environmental radioactivity in the area remain limited.

B. *Sampling*

Vegetable samples comprising pepper, onion, and tomato were randomly collected from irrigation farms across nine sampling locations within the study area. Sample collection was carried out using clean, sterile knives and hand gloves to minimize contamination. The collected samples were properly labeled for identification and transported to the laboratory for preparation and radiological analysis. During sampling, the geographical coordinates of each sampling location were recorded using a Global Positioning System (GPS) device to ensure accurate spatial referencing of the study sites.

C. *Sample Preparation*

The collected vegetable samples were cleaned and dried at room temperature (approximately 37 °C) to remove moisture content. The dried samples were then pulverized into fine powder and sieved to obtain a uniform particle size for analysis. Each processed sample was packaged in a radon-impermeable cylindrical plastic container with dimensions of 7.6 cm × 7.6 cm, corresponding to the detector geometry. To prevent the escape of radon-222 and ensure radioactive equilibrium between parent radionuclides and their progenies, the containers were triple-sealed before analysis. The prepared samples were subsequently analyzed for radionuclide concentrations using gamma spectrometry. Sample preparation procedures were conducted in accordance with the standard guidelines outlined in the IAEA Technical Report Series No. 295 [14].

D. *Gamma Spectrometric Analysis*

Gamma-ray spectrometry was employed to determine the activity concentrations of radionuclides in the vegetable samples. Each prepared sample was analyzed using a 7.62 cm × 7.62 cm NaI(Tl) scintillation detector coupled to a photomultiplier tube and enclosed within a thick lead shield to reduce background radiation by approximately 95%. The samples were counted for 29,000 s (approximately 8 h) to obtain adequate counting statistics.

Activity concentrations of U-238, Th-232, and K-40 were determined from the acquired gamma-ray spectra using their characteristic photopeaks and expressed in Bq kg^{-1}. Energy and efficiency calibrations of the detection system were performed using standard Cs-137 and Co-60 reference sources. The detector system achieved an energy resolution of approximately 7.2% at the 661.6 keV gamma line of Cs-137, with calibration measurements conducted for 30 min.

Quality assurance and calibration verification were carried out using IAEA gamma spectrometric reference materials: RGU-1 for U-238 (via Bi-214 peak), RGTh-1 for Th-232 (via Tl-208 peak), and RGR-1 for K-40.

E. *Activity Concentration Determination (Bq kg^{-1})*

The activity concentration of a radionuclide, A, in the vegetable samples was calculated using (1).

$$A = \frac{N}{\varepsilon P_\gamma t m} \qquad (1)$$

Where A is the activity concentration (Bq kg^{-1}), N is the net count rate (counts per second), ε is the detector efficiency, P_γ is the gamma emission probability, t is the Counting time (seconds), and m is the mass of the sample (kg).

F. *Radium Equivalent Activity Concentration Index (Ra$_{eq}$)*

To represent the activity concentration levels of ^{238}U, ^{232}Th, and ^{40}K by a single quantity that takes into account the radiation hazards associated with each component, a common radiological index was introduced [15]. This index is called the Radium Equivalent Activity (Ra$_{eq}$). The radium equivalent index in B kg^{-1} is a widely used radiological hazard index. It is a convenient index to compare the specific activities of samples containing different concentrations of ^{238}U, ^{232}Th, and ^{40}K. This radium equivalent concept was used to describe the gamma output from different mixtures of uranium, thorium, and potassium in sediments from [16]. It was calculated using (2).

$$Ra_{eq} = A_u + 1.43A_{Th} + 0.077A_K \qquad (2)$$

Where A_u, A_{Th} and A_K are the specific activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in Bq kg^{-1}, respectively. In the above relation, it has been assumed that 10 Bq kg^{-1} of ^{226}Ra, 7 Bq kg^{-1} of ^{232}Th, and 130 Bq kg^{-1} of ^{40}K produce an equal gamma dose, and the value detected was less than the safety limit of 370 Bq kg^{-1} recommended by UNSCEAR [17].

G. *The Absorbed Gamma Dose Rate*

The input of natural radionuclides to the absorbed dose rate in air (D$_R$) at the average height of one meter above the ground surface depends on the natural specific activity concentration of ^{238}U, ^{232}Th, and ^{40}K. If a radionuclide activity is known, then its exposure dose rate in air at 1 m above the ground can be estimated using (3) [18-19].

$$D_R(nGyh^{-1}) = 0.43A_U + 0.666A_{Th} + 0.042A_K \qquad (3)$$

Where D_R, A_U, A_{Th} and A_K are the absorbed dose rate, and specific activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in Bq kg^{-1}, respectively.

H. *Committed Effective Dose (CED)*

The committed effective dose (CED) estimates the amount of radiation absorbed by a person through vegetable consumption over a year. The formula for computing this is given by (4).

$$CED = A \cdot IR \cdot DCF \qquad (4)$$

Where A is the Activity concentration (Bq kg^{-1}), IR is the ingestion rate (kg/year). For adults, this is ~ 0.175 kg day^{-1} and ~ 64 kg year^{-1}, and for children, this is ~ 0.081 kg day^{-1} and ~ 30kg year^{-1}. Finally, DCF is the dose conversion factor (Sv/Bq) provided by [20] and [21].

I. *Radiological Risk Indices*

The radiological risk indices evaluated across the sampled locations and the internal exposure to radon and its daughter progenies are quantified by the internal hazard index (H_{in}) [21], which is given by (5):

$$H_{in} = ({}^{A_{Ra}}/_{185} + {}^{A_{Th}}/_{259} + {}^{A_K}/_{4819}) \leq 1 \qquad (5)$$

The values of the internal hazard indices (H_{in}) must be less than unity for the radiation hazard to be negligible [14].

1) Lifetime Cancer Risk (LCR)

The LCR quantifies the probability of developing cancer over a lifetime from ingesting radionuclides [13].

$$LCR = CED \cdot RF \qquad (6)$$

Where CED is the Committed Effective Dose (Sv/y), and RF is the Risk Factor for cancer induction (per Sv), typically around 0.05 Sv^{-1} for the general public.

III. RESULTS AND DISCUSSION

A. Radionuclide Concentrations

This study assessed the concentrations of naturally occurring radionuclides, ^{238}U, ^{232}Th, and ^{40}K, in commonly consumed vegetables (pepper, onion, and tomato) collected from nine distinct locations within Soba Local Government Area, Kaduna State. The results, summarized in Table I, reveal spatial and crop-specific variations in radionuclide uptake.

1) Uranium-238 (^{238}U) Concentration

The activity concentration of ^{238}U ranged from 2.45 ± 0.25 Bq kg^{-1} in tomato from Kinkiba (V6) to 9.21 ± 0.90 Bq kg^{-1} in pepper from Maigana (V5). Elevated uranium concentrations were also observed in onion samples from Gimba (V2), which recorded a value of 4.44 ± 0.59 Bq kg^{-1}. The observed variations among sampling locations may reflect differences in local geological characteristics, soil composition, irrigation water quality, and radionuclide mobility within the agricultural environment. The measured values indicate a non-uniform distribution of ^{238}U across the study area, suggesting that site-specific environmental factors influence radionuclide uptake by vegetables.

2) Thorium-232 (^{232}Th) Concentration

The activity concentration of ^{232}Th varied considerably among the sampled vegetables. The highest concentration was recorded in tomato from Kinkiba (V6) at 7.93 ± 0.39 Bq kg^{-1}, followed by pepper samples from Maigana (V5) and Dinya (V3) with values of 5.86 ± 0.18 Bq kg^{-1} and 5.68 ± 0.20 Bq kg^{-1}, respectively. The lowest concentration was observed in pepper from Soba (V10) at 0.95 ± 0.17 Bq kg^{-1}. Although thorium is generally characterized by low solubility and limited mobility in soils, localized geological conditions and variations in soil properties may influence its transfer to crops. The observed spatial variability, therefore, suggests differences in environmental conditions across the study area.

Table I. Activity Concentration of Radionuclides in Vegetable Samples.

Location	Sample ID	Vegetable Type	U-238 (Bq Kg^{-1})	Th-232 (Bq Kg^{-1})	K-40 (Bq Kg^{-1})
Tudun Saibu	V1	Pepper	7.48±0.65	1.29±0.26	364.25±8.23
Gimba	V2	Onion	4.44±0.59	1.88±0.19	461.23±12.78
Dinya	V3	Pepper	3.11±0.29	5.68±0.20	159.34±9.03
Maigana	V5	Pepper	9.21±0.90	5.86±0.18	151.89±6.49
Kinkiba	V6	Tomato	2.45±0.25	7.93±0.39	556.84±15.63
Kwasallo	V7	Onion	5.25±1.08	1.24±0.11	322.94±13.23
Awai	V8	Tomato	3.49±0.47	1.71±0.28	221.83±11.99
Wanka	V9	Onion	3.49±0.47	1.67±0.23	750.13±7.58
Soba	V10	Pepper	4.50±0.92	0.95±0.17	445.55±13.82

3) Potassium-40 (^{40}K) Concentration

^{40}K was the most abundant radionuclide across all samples, consistent with its role as an essential nutrient for plant growth. The highest concentration was found in onion from Wanka (V9) at 750.13±7.58 Bq kg^{-1}, followed by tomato from Kinkiba (V6) at 556.84±15.63 Bq kg^{-1}. The lowest concentration was recorded in pepper from Maigana (V5) at 151.89±6.49 Bq kg^{-1}. The elevated ^{40}K levels in onions and tomatoes reflect their metabolic demand for potassium and efficient uptake mechanisms.

4) Spatial and Crop-Specific Trends

The results demonstrate both spatial and crop-dependent variations in radionuclide concentrations across the study area. Elevated activity concentrations were observed in samples collected from Kinkiba, Wanka, and Maigana, suggesting the influence of local geological characteristics, soil properties, and irrigation practices on radionuclide uptake. Onion samples from Wanka exhibited the highest K-40 concentration, while pepper samples from Maigana recorded the highest U-238 activity concentration. Tomato samples from Kinkiba showed elevated levels of Th-232 and comparatively high K-40 concentrations. These findings indicate that radionuclide accumulation in vegetables is influenced by a combination of environmental conditions and plant-specific uptake mechanisms.

5) Health and Environmental Implications

While ^{40}K is biologically essential and naturally abundant, elevated concentrations of ^{238}U and ^{232}Th may contribute to radiological health risks through long-term dietary exposure. The observed variability in radionuclide concentrations across sampling locations underscores the importance of routine environmental monitoring, particularly in agricultural areas where geological and anthropogenic factors may influence radionuclide uptake by crops. These findings support the implementation of site-specific radiological assessments, farmer awareness programs, and appropriate regulatory measures to ensure food safety and protect public health.

The activity concentrations obtained in the present study are generally comparable to values reported in similar environmental radioactivity investigations conducted in Nigeria and other regions, although variations may arise from differences in geology, soil characteristics, irrigation practices, agricultural inputs, and radionuclide mobility [7], [22–24]. Such differences highlight the importance of localized radiological assessments for accurate evaluation of food safety and potential health risks associated with the consumption of agricultural products.

B. Committed Effective Dose (CED)

The committed effective dose (CED) values for adults and children resulting from the ingestion of radionuclides in vegetable samples are presented in Tables II and III, respectively. The results indicate spatial variations in radiological exposure across the sampled locations due to differences in radionuclide concentrations.

For adults, K-40 was the major contributor to the total committed effective dose in all locations, reflecting its relatively high activity concentration in the analyzed vegetable samples. The highest total CED was recorded in Kinkiba (Sample V6) with a value of 2.85 × 10^{-4} mSv yr^{-1}, primarily due to elevated concentrations of Th-232 and K-40. In contrast, U-238 contributed the least to the total dose across all locations, with values ranging from 2.76 × 10^{-6} to 2.07 × 10^{-5} mSv yr^{-1}. Wanka (V9) also exhibited relatively elevated dose values, mainly associated with high K-40 concentrations.

For children, similar trends were observed, with K-40 remaining the dominant contributor to the total dose. The highest K-40 contribution was obtained in Kinkiba (V6) at 8.63 × 10^{-5} mSv yr^{-1}, corresponding to the highest total CED for children of 1.37 × 10^{-4} mSv yr^{-1}. Uranium-238 consistently contributed the lowest dose values, ranging from 1.40 × 10^{-7} to 1.38 × 10^{-6} mSv yr^{-1} across the sampled locations.

Although children recorded lower total CED values than adults, their higher biological sensitivity to ionizing radiation remains an important consideration. Nevertheless, all calculated CED values for both adults and children were significantly below the recommended public exposure limit of 1 mSv yr^{-1} established by the International Commission on Radiological Protection (ICRP) [25]. These findings indicate that the ingestion of vegetables cultivated within the study area poses minimal radiological health risk under current exposure conditions. However, the relatively elevated dose values observed in Kinkiba and Wanka suggest the need for continued environmental monitoring and further investigation of possible sources of radionuclide enrichment.

Table II. Committed Effective Dose (CED) for adults.

Location	Sample ID	Committed Effective Dose (mSv yr^{-1})			Total CED (mSv yr^{-1})
		U-238	Th-232	K-40	
Tudun Saibu	V1	4.26E-06	5.95E-06	4.52E-05	5.54E-05
Gimba	V2	8.41E-06	1.08E-05	7.15E-05	9.07E-05
Dinya	V3	4.00E-06	2.61E-05	1.98E-05	4.99E-05
Maigana	V5	2.80E-06	2.69E-05	1.88E-05	4.86E-05
Kinkiba	V6	2.07E-05	9.12E-05	1.73E-04	2.85E-04
Kwasallo	V7	2.76E-06	7.10E-06	5.01E-05	5.99E-05
Awai	V8	1.18E-05	1.97E-05	6.88E-05	1.00E-04
Wanka	V9	3.93E-06	9.60E-06	1.16E-04	1.30E-04
Soba	V10	4.05E-06	4.37E-06	5.52E-05	6.37E-05

Table III Committed Effective Dose (CED) for children (1-10).

Location	Sample ID	Committed Effective Dose (mSv yr^{-1})			Total CED (mSv yr^{-1})
		U-238	Th-232	K-40	
Tudun Saibu	V1	2.13E-07	2.43E-06	1.69E-05	1.96E-05
Gimba	V2	5.61E-07	5.88E-06	3.57E-05	4.22E-05
Dinya	V3	2.00E-07	1.07E-05	7.41E-06	1.83E-05
Maigana	V5	1.40E-07	1.10E-05	7.06E-06	1.82E-05
Kinkiba	V6	1.38E-06	4.95E-05	8.63E-05	1.37E-04
Kwasallo	V7	1.84E-07	3.86E-06	2.50E-05	2.91E-05
Awai	V8	7.87E-07	1.07E-05	3.44E-05	4.59E-05
Wanka	V9	2.62E-07	2.62E-07	5.81E-05	5.87E-05
Soba	V10	2.02E-07	1.78E-06	2.07E-05	2.27E-05

C. Radiological Risk Indices

Table IV presents the calculated Lifetime Cancer Risk (LCR) and Internal Hazard Index (H_i) values for the sampled locations. These indices were used to evaluate the potential radiological health implications associated with exposure to naturally occurring radionuclides in the investigated vegetable samples.

The LCR values ranged from 2.43×10^{-3} in Maigana (V5) to 1.42×10^{-2} in Kinkiba (V6), indicating relatively higher radiological risk in Kinkiba compared with the other sampled locations. Similarly, the H_i values varied from 6.26×10^{-2} to 1.72×10^{-1}, with the highest values observed in Wanka (V9) and Kinkiba (V6). The elevated H_i values in these locations may be associated with comparatively higher activity concentrations of naturally occurring radionuclides.

Despite these variations, all H_i values remained below the recommended safety threshold of unity, indicating negligible internal radiological hazard according to internationally accepted radiological safety criteria. Overall, the radiological risk indices suggest that the investigated vegetables pose a low radiological health risk under current exposure conditions. Nevertheless, the relatively elevated values observed in Kinkiba and Wanka highlight the importance of continued environmental monitoring and periodic radiological assessment to ensure long-term food safety and public health protection.

Table IV. Radiological Risk Indices.

Location	Sample ID	LCR	Internal Hazard Index (H_{in})
Tudun Saibu	V1	2.77E-03	9.35E-02
Gimba	V2	4.54E-03	1.23E-01
Dinya	V3	2.50E-03	6.71E-02
Maigana	V5	2.43E-03	6.26E-02
Kinkiba	V6	1.42E-02	1.71E-01
Kwasallo	V7	3.00E-03	7.85E-02
Awai	V8	5.01E-03	6.69E-02
Wanka	V9	6.49E-03	1.72E-01
Soba	V10	3.18E-03	1.08E-01

IV. CONCLUSION

This study evaluated the activity concentrations of naturally occurring radionuclides (U-238, Th-232, and K-40) in vegetable samples collected from irrigation farming communities within Soba Local Government Area, Kaduna State, Nigeria. The results revealed spatial variations in radionuclide distribution across the sampled locations, indicating that local environmental and geological conditions influence radionuclide concentrations. The measured activity concentrations of U-238 and Th-232 were within internationally accepted limits, while K-40 exhibited relatively higher values in some locations. Among the sampled sites, Kinkiba and Wanka showed comparatively elevated radiological parameters, suggesting localized enrichment of natural radionuclides. However, the calculated committed effective dose (CED), internal hazard index (H_i), and lifetime cancer risk (LCR) values for both adults and children remained below recommended safety limits for public exposure. Overall, the evaluated radiological indices indicate low ingestion-related radiological risk associated with the consumption of vegetables cultivated within the study area under current exposure conditions. The findings provide important baseline data for environmental radiation monitoring, food safety assessment, and public health protection in agricultural communities. Continuous environmental monitoring is important for early detection of radionuclide accumulation within agricultural systems and for maintaining food safety standards.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

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