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Age-Dependent Radiological Risk and Organ Dosimetry from Consumption of Staple Crops in the Sokoto Basin, Nigeria

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Abstract- ***The study examined radionuclide concentrations, soil-to-crop transfer factors and age-specific organ doses from the consumption of maize, beans and pepper in the Sokoto Basin, North-West Nigeria. Activity concentrations of 226Ra, 232Th and 40K were determined by gamma-ray spectrometry in a total of 24 soil and 26 crop samples from eight Local Government Areas. The most significant finding was anomalous thorium transfer factors, near unity and 10–100 times larger than IAEA reference values, challenging the established paradigm of thorium immobility in agricultural systems. Infants showed the highest age-dependent committed effective doses, with doses 3.7-4.0 times the ICRP public limit of 1,000 µSv/yr, and excess lifetime cancer risk values were 236-2,347 times greater than UNSCEAR benchmarks. The highest organ-specific dose rates were recorded in the testes, bone marrow and lungs. The mean ingestion doses from maize consumption were significantly higher than the ICRP limits (48-52 %). These results demonstrated that the high transfer of thorium in calcareous semi-arid soils, combined with high maize consumption, pose significant risks of dietary exposure for the most vulnerable populations, emphasising the necessity for site-specific, age-segregated radiological assessment rather than generic international values.***

Keywords: Age-dependent Dosimetry, Transfer Factors, Sokoto Basin, Organ doses, Excess Lifetime Cancer Risk, Dietary Exposure

I. INTRODUCTION

Naturally occurring radioactive materials (NORMs) such as uranium-238 (238U), thorium-232 (232Th) and potassium-40 (40K) are widely distributed in the Earth's crust with their concentrations affected by geological origin and weathering processes (IAEA, 2019). Activities like phosphate mining, fertilizer application, and artisanal gold recovery have been found to elevate background radiation levels leading to mobilization of radionuclides in agricultural systems and food chains (Abayiga et al., 2022; Orosun et al., 2022).

The Sokoto Basin in North-West Nigeria provides a unique geological setting for radionuclide transfer studies. It is underlain by phosphate-bearing sediments of the Sokoto Group, and artisanal mining activities are being carried out in the area. The semi-arid climate, calcareous soils, and high evapotranspiration of the area create conditions that may enhance radionuclide mobility and plant uptake (Hamidu et al., 2016; Saidu et al., 2024). Soil characterization studies indicate sandy textures, low organic matter (0.33-0.93%) and neutral pH (5.2-6.7), which decrease radionuclide sorption and could increase bioavailability (Patrick et al., 2024).

Transfer factors (TFs), the ratio of radionuclide activity in plant tissue to that in soil, are important in assessing the food chain mobility (IAEA, 2010). The IAEA has set the reference ranges for 40K, 226Ra and 232Th as 0.1-10, 0.01-0.5 and 0.001-0.1, respectively (Balonov et al., 2010; Vandenhove et al., 2009). However, TFs are highly variable with respect to soil type, plant species and environmental conditions and require site-specific assessments (Ehlken & Kirchner, 2002).

After ingestion, radionuclides preferentially deposit in certain organs, such as radium in bone (chemically similar to calcium), thorium in the liver, and potassium-40 uniformly in soft tissue (ICRP, 2012). Children and infants are at higher risk due to their high metabolic rates, higher radiosensitivity and higher consumption rates relative to their body weight (ICRP, 2007, 2024). The long-term carcinogenic potential was evaluated by estimating the Excess Lifetime Cancer Risk (ELCR) using ICRP risk coefficient of 5 × 10-2 per Sv (Abbasi & Bashiry, 2020; UNSCEAR, 2020).

While previous Nigerian studies have investigated the radionuclide transfer at different locations such as, southwestern region of Nigeria (Oladele et al., 2023), Niger Delta (Avwiri et al., 2021), Ebonyi State (Ugbede & Osahon, 2021), Kano tin-mining areas (Muhammad et al., 2024), and Enugu coal-mining areas (Amakom et al., 2023), there are no reports of age-distributed risk assessments for the Sokoto Basin using site-specific empirical measurements. The study provides quantitative data on activity concentrations of radionuclides in soils and staple crops (maize, beans and pepper), soil-to-crop transfer factors, and age dependent radiological health risks such as committed effective dose, organ-specific dose rates and ELCR in different population groups.

II. MATERIALS AND METHODS

2.1 Study Area

Sokoto and Kebbi States are located within latitudes 10° – 14° N and longitudes 3o -7o E and are part of the southwestern region of the Iullemmeden Basin. The area is over 65,000 km 2 with an altitude of 250-400 m above sea level. The Sudano-Sahelian climate is characterised by an average annual rainfall of 500-800 mm and average daily maximum temperature of over 40°C (Hamidu et al., 2016).

The Sokoto Basin is a Cretaceous-Tertiary sedimentary basin consisting of Illo /Gundumi Formation (continental sandstones), Rima Group (Taloka Sandstone, Dukamaje Shale, Wurno Sandstone), Sokoto Group (Dange Shale, Kalambaina Limestone, Gamba Sand) and Gwandu Formation (continental sands and clays). The phosphate-rich formations of the Sokoto Group have higher radionuclides concentrations than the quartz-dominated sands of the Gwandu Formation (Joseph et al., 2022; Saidu et al., 2024).

2.2 Sampling and Analysis

Eight Local Government Areas (LGAs) were sampled. These are Wamakko, Dange-Shuni, Sokoto South and Kware in Sokoto State; Dandi, Zuru, Birnin Kebbi and Jega in Kebbi State. 24 soil samples (0-20 cm depth) and 26 crop samples (maize, beans, and pepper) were collected. The samples were air-dried, ground to a fine powder and packed into cylindrical radon-impermeable containers. Samples were kept for 30 days to reach secular radioactive equilibrium (IAEA, 2014).

Activity concentrations of 226Ra, 232Th and 40K were measured using a 76 × 76 mm thallium-doped sodium iodide (NaI(Tl)) gamma-ray spectrometer (Canberra, Model 727) at the Centre for Energy Research and Training, Ahmadu Bello University, Zaria. Radionuclides were identified in the following characteristic energy windows: 1620-1820 keV for 226Ra (1764.0 keV from 214Bi), 2480-2820 keV for 232Th (2614.5 keV from 208Tl), and 1380–1550 keV for 40K (1460.0 keV). The counting time per sample was 29,000 seconds. Calibration used IAEA reference materials RGK-1 (40K), RGU-1 (226Ra) and RTG-1 (232Th). The detection limits were 14.54 Bq/kg for 40K, 3.84 Bq/kg for 226Ra, and 9.08 Bq/kg for 232Th (Currie, 1968).

2.3Transfer Factor Calculation

The soil-to-plant transfer factor (TF) for 232Th was estimated as:

$$TF = {}^{A_{plant}}\!/_{A_{soil}} \qquad (1)$$

where Aplant is the activity concentration of 232Th in the edible section of the crop (Bq/kg dry weight) and Csoil is the activity concentration in the matching soil (Bq/kg dry weight) (IAEA, 2010). The IAEA (2010) reference range for 232Th is 0.001-0.1.

2.4 Age-Dependent Dose Assessment

Daily intake was calculated using Nigerian dietary consumption rates: beans (0.15 kg/day), maize (0.35 kg/day), and pepper (0.05 kg/day) (Hassan et al., 2021). According to ICRP (2012), the ingestion dose is estimated as:

$$Ingestion\,Dose = A_{crop} \times CR \times 365 \times DCF$$

(2)

where Acrop is the activity concentration of the radionuclide in the crop (Bq/kg), CR is the daily consumption rate of the crop (kg/day), 365 is the number of days in a year, DCF is the ingestion dose conversion factor (Sv/Bq) for the radionuclide

The age-specific dose conversion factors (WHO, 2004) is given in Table 1:

Table 1: Age-Specific Dose Conversion Factors (WHO, 2004)

Radionuclide	Infant (≤1 yr)	Child (1–12 yrs)	Teenager (12–17 yrs)	Adult (≥17 yrs)
^{226}Ra	4.7×10^{-6}	6.2×10^{-7}	1.5×10^{-6}	2.8×10^{-7}
^{232}Th	-	-	-	2.2×10^{-7}
^{40}K	6.2×10^{-8}	2.1×10^{-8}	7.6×10^{-9}	6.2×10^{-9}

2.5 Excess Lifetime Cancer Risk

Excess lifetime cancer risk (ELCR) can be expressed as follows (Abbasi & Bashiry, 2020):

$$ELCR = AEDE \times DL \times RF \quad (3)$$

where AEDE is annual effective dose (Sv/yr), DL is 70 years, and RF is 0.05 Sv-1 (ICRP, 2007).

2.6 Organ-Specific Dose Rates

The effective dose rate delivered to a particular organ can be calculated using the relation:

$$Dorgan = AEDE \times A \times K \quad (4)$$

where AEDE is the annual effective dose, A is the occupancy factor (0.8), and K is the conversion factor of organ dose from ingestion (ICRP, 1996)

The organ conversion factors (K) are testes (0.82), bone marrow (0.69), lungs (0.64), kidneys (0.62), ovaries (0.58), liver (0.46), and whole body (0.68) (ICRP, 1996)

III. RESULTS AND DISCUSSION

3.1 Soil Activity Concentrations

Soil activity concentrations showed considerable spatial heterogeneity as presented in Tables 2 to 3. Potassium-40 concentration value range from 21.71-125.55 Bq/kg withn mean of 71.68 ± 28.64 Bq/kg, ^{226}Ra content varied from 10.95 to 41.40 Bq/kg with mean of 26.71 ± 8.66 Bq/kg and ^{232}Th from 11.04 to 61.04 Bq/kg with mean of 28.10 ± 11.80 Bq/kg. Sokoto State had significantly higher K-40 concentrations with concentration of 85.66 ± 31.04

Bq/kg than Kebbi State with concentration of 56.13 ± 13.96 Bq/kg, which is attributed to the phosphate-rich Sokoto Group formations that are rich in potassium-bearing minerals. Localised hotspots of thorium in Sokoto South were 61.04 Bq/kg and 60.65 Bq/kg, that is, approximately 2 times the global average of 30 Bq/kg (UNSCEAR, 2020). These hotspots are in agreement with artisanal mining activities recorded in the region (Orosun et al., 2022; Saidu et al., 2024).

Table 2: Soil Activity Concentrations for Sokoto State

Sample ID	K-40 (Bq/kg)	Ra-226 (Bq/kg)	Th-232 (Bq/kg)	Raeq (Bq/kg)
SOK-SL-01	125.55 ± 3.56	34.81 ± 3.86	11.04 ± 1.45	60.26
SOK-SL-02	111.20 ± 4.37	12.39 ± 1.86	12.59 ± 1.85	38.96
SOK-SL-03	52.23 ± 5.65	21.97 ± 2.86	32.35 ± 3.05	72.25
SOK-SL-04	34.58 ± 3.95	39.40 ± 3.24	20.35 ± 2.57	71.16
SOK-SL-05	86.73 ± 4.20	16.08 ± 1.15	15.64 ± 2.31	45.12
SOK-SL-06	48.55 ± 4.71	21.97 ± 3.99	61.04 ± 4.97	113.00
SOK-SL-07	110.56 ± 4.68	41.40 ± 4.14	60.65 ± 4.44	136.64
SOK-SL-08	114.48 ± 3.56	27.96 ± 2.05	24.63 ± 2.04	71.99
SOK-SL-09	56.24 ± 1.21	30.23 ± 2.10	24.10 ± 2.11	69.02

SOK-SL-10	98.21 ± 2.12	31.91 ± 3.01	28.02 ± 1.34	79.54
SOK-SL-11	96.23 ± 2.11	30.11 ± 2.10	30.11 ± 1.43	80.58
SOK-SL-12	112.34 ± 2.10	32.10 ± 1.97	31.01 ± 1.34	85.09
Mean	85.66 ± 31.04	28.06 ± 8.86	26.74 ± 12.06	72.89 ± 19.91

Table 3: Soil Activity Concentrations for Kebbi State

Sample ID	K-40 (Bq/kg)	Ra-226 (Bq/kg)	Th-232 (Bq/kg)	Raeq (Bq/kg)
KBB-SL-01	21.71 ± 2.07	10.95 ± 1.59	22.19 ± 2.39	44.35
KBB-SL-02	81.12 ± 5.94	13.10 ± 3.83	17.38 ± 3.54	44.20
KBB-SL-03	52.23 ± 5.65	21.97 ± 2.86	32.35 ± 3.05	72.25
KBB-SL-04	34.58 ± 3.95	39.40 ± 3.24	20.35 ± 2.57	71.16
KBB-SL-05	60.45 ± 2.64	23.03 ± 2.34	26.22 ± 1.23	65.18
KBB-SL-06	60.46 ± 2.61	18.34 ± 3.10	28.21 ± 1.22	63.34
KBB-SL-07	60.47 ± 2.51	22.17 ± 2.01	30.33 ± 2.32	70.20
KBB-SL-08	60.48 ± 2.80	25.20 ± 3.20	28.12 ± 2.10	70.07
KBB-SL-09	60.49 ± 4.51	30.20 ± 2.40	29.56 ± 3.08	77.13
KBB-SL-10	60.50 ± 3.62	33.20 ± 3.21	27.10 ± 1.56	76.61
KBB-SL-11	60.51 ± 2.10	28.92 ± 3.12	30.09 ± 2.10	76.61
KBB-SL-12	60.52 ± 5.11	34.12 ± 2.11	31.01 ± 1.09	83.12
Mean	56.13 ± 13.96	25.05 ± 8.10	26.91 ± 4.40	67.85 ± 11.71

3.2 Crop Activity Concentrations

Crop activity concentrations showed distinct physiological preferences as shown in Tables 4 and 5. The potassium-40 ranged from 26.08 to 193.27 Bq/kg in beans with mean of 137.81 ± 36.23 Bq/kg, 64.19 to 193.27 Bq/kg in maize with mean of 138.97 ± 58.15 Bq/kg and 26.08 to 73.12 Bq/kg in pepper with mean of 58.66 ± 21.29 Bq/kg. Beans and maize had higher values of K-40 than pepper. This is consistent with the importance of potassium in legumes (fixation of nitrogen) and cereals (development of grain).

Radium-226 concentrations varied from 10.74 to 40.15 Bq/kg in beans with a mean of 23.82 ± 13.28 Bq/kg for both states, 12.39 to 34.21 Bq/kg in maize with a mean of 21.53 ± 9.53 Bq/kg) and 10.95 to 37.99 Bq/kg in pepper with a mean of 19.69 ± 11.29 Bq/kg. The concentration of thorium-232 in beans ranged from 10.49 to 45.36 Bq/kg with a mean of 29.15 ± 10.38 Bq/kg, in maize from 10.80 to 29.62 Bq/kg with a mean of 22.33 ± 10.03 Bq/kg and for pepper it ranged from 20.20 to 38.72 Bq/kg with a mean of 27.38 ± 6.78 Bq/kg which were significantly higher than the concentrations in crops in Nigeria (5 - 15 Bq/kg) (Oladele et al., 2023).

Table 4: Crop Activity Concentrations in Sokoto State

Sample ID	K-40 (Bq/kg)	Ra-226 (Bq/kg)	Th-232 (Bq/kg)	Raeq (Bq/kg)
		Beans		
SOK-BN-01	110.54	37.99	22.19	78.23
SOK-BN-02	172.27	40.15	32.54	99.95
SOK-BN-03	185.85	10.74	45.36	89.92
SOK-BN-04	112.21	32.01	32.12	86.58
SOK-BN-05	108.20	38.22	30.21	89.75
Mean	137.81 ± 36.23	31.82 ± 12.88	32.48 ± 8.95	88.89 ± 7.79
		Maize		

SOK-MZGR-01	64.19	32.54	10.80	52.93
SOK-MZGR-02	193.27	25.43	11.52	56.79
SOK-MZGR-03	111.20	12.39	10.49	35.95
SOK-MZGR-04	187.22	34.21	29.62	90.98
Mean	138.97 ± 58.15	26.14 ± 9.80	15.61 ± 8.98	59.16 ± 23.08
		Pepper		
SOK-PPR-01	26.08	10.95	22.19	44.69
SOK-PPR-02	73.12	10.95	36.01	68.07
SOK-PPR-03	67.23	21.10	26.02	63.49
SOK-PPR-04	68.22	12.32	20.20	46.46
Mean	58.66 ± 21.29	13.83 ± 4.84	26.11 ± 7.11	55.68 ± 11.32

Table 5: Crop Activity Concentrations for Kebbi State

Sample ID	K-40 (Bq/kg)	Ra-226 (Bq/kg)	Th-232 (Bq/kg)	Raeq (Bq/kg)
		Beans		
KBB-BN-01	138.35	16.08	15.64	49.10
KBB-BN-02	89.48	12.03	19.75	47.16
KBB-BN-03	185.85	10.74	45.36	89.92
KBB-BN-04	122.03	18.20	30.11	70.65
KBB-BN-05	130.21	19.24	18.21	55.31
Mean	133.18 ± 35.49	15.26 ± 3.81	25.81 ± 11.97	62.43 ± 18.38
		Maize		
KBB-MZGR-01	122.40	12.53	29.53	64.18
KBB-MZGR-02	47.84	18.91	29.55	64.85
KBB-MZGR-03	98.21	16.02	30.10	66.63
KBB-MZGR-04	86.75	20.22	27.02	65.54
Mean	88.80 ± 30.92	16.92 ± 3.20	29.05 ± 1.36	65.30 ± 1.07
		Pepper		
KBB-PPR-01	110.54	37.99	22.19	78.23
KBB-PPR-02	21.98	13.97	38.72	71.03
KBB-PPR-03	89.21	26.02	28.03	72.97
KBB-PPR-04	76.20	24.21	25.67	66.79
Mean	74.48 ± 38.13	25.55 ± 10.07	28.65 ± 7.31	72.26 ± 4.73

3.3 Soil-to-Crop Transfer Factors

The transfer factors as presented in Table 6 represent the most significant scientific contribution of this study.

Table 6: Soil-to-Crop Transfer Factors

Sample ID	TF K-40	TF Ra-226	TF Th-232
Sokoto Beans	1.58 ± 0.42	1.12 ± 0.42	1.11 ± 0.29
Sokoto Maize	1.59 ± 0.65	0.92 ± 0.36	0.53 ± 0.32
Sokoto Pepper	0.67 ± 0.23	0.49 ± 0.17	0.89 ± 0.24
Kebbi Beans	2.37 ± 0.67	0.61 ± 0.15	0.96 ± 0.46
Kebbi Maize	1.58 ± 0.56	0.68 ± 0.13	1.08 ± 0.05
Kebbi Pepper	1.33 ± 0.68	1.02 ± 0.40	1.06 ± 0.28

Potassium-40 transfer factors of values ranging from 0.67–2.37 were within the IAEA reference range of 0.1–10 (Balonov et al., 2010). Beans showed the highest K-40 transfer factors (1.58-2.37), followed by maize (1.58-1.59) and pepper (0.67-1.33). Kebbi beans recorded high transfer factor (2.37) which indicates adaptive uptake efficiency in which plants increase potassium absorption in a setting of low availability (Thien et al., 2020) although soil K-40 concentrations were lower.

The radium-226 transfer factors were significantly higher than the IAEA reference range of 0.01–0.5 (Balonov et al., 2010) exceeding the reference values by factors of 2–100. Sokoto beans had transfer factors greater than unity (1.12), suggesting active accumulation of radium in the edible bean tissues. Maize had intermediate values (Sokoto 0.92, Kebbi 0.68) while in Kebbi, pepper was above unity (1.02). The high transfer factors are important as radium is a bone seeking radionuclide with high radiotoxicity (Al-Hamarneh et al., 2016). Higher TFs for Ra-226 could be due to competition for calcium in calcareous soils because radium behaves similar to calcium (Vandenhove et al., 2009).

The most significant finding is the transfer factors of thorium-232 with values close to or greater than unity for different crops: Sokoto beans (1.11), Kebbi pepper (1.06), Kebbi maize (1.08) and Kebbi beans (0.96). These values are 10–100 times higher than the IAEA reference range of 0.001–0.1 (Balonov et al., 2010; Vandenhove et al., 2009), which fundamentally challenges the established paradigm that thorium is essentially immobile in soil-plant systems.

Thorium normally hydrolyses to Th(OH)4 with a solubility product constant of approximately 10-45 and adsorbs strongly to soil particles, indicating negligible uptake by plants (Lilley, 2013; Whicker et al., 1997). The high TFs indicate increased bioavailability in the semi-arid calcareous soils of the Sokoto Basin through several mechanisms: (1) formation of soluble carbonate complexes in alkaline soils (Vandenhove et al., 2009); (2) microbial production of siderophores and organic acids in the rhizosphere (Ehlken & Kirchner, 2002); (3) concentration of radionuclides in surface soils resulting from low rainfall and high evapotranspiration (Thien et al., 2020); and (4) mechanical disturbance due to artisanal mining activities (Orosun et al., 2022; Saidu et al., 2024).

These observations are consistent with findings in other calcareous environments (Al-Hamarneh et al., 2016) and contrast with other regions of Nigeria where Th-232 TFs were considerably lower, with geometric means of 0.43 in southwestern Nigeria (Oladele et al., 2023) and 0.28–0.31 in mining sites (Orosun et al., 2022). This indicates that geochemical environment of the Sokoto Basin plays fundamental role in changing the behaviour of thorium in agricultural systems.

3.4 Daily Intake and Ingestion Doses

Daily intake calculations presented in Table 7 revealed that maize consumption contributes the highest radionuclide intake, with Ra-226 daily intakes reaching 11.97 Bq/day and Th-232 daily intakes reaching 10.54 Bq/day

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Table 7: Daily Intake and Ingestion Doses

Sample	Daily Intake (Bq/day)			Ingestion Dose (µSv/yr)		
	K-40	Ra-226	Th-232	K-40	Ra-226	Th-232
Sokoto Beans	20.67 ± 5.37	4.77 ± 1.81	4.87 ± 1.26	46.78 ± 12.16	487.83 ± 184.62	391.27 ± 101.22
Sokoto Maize	48.64 ± 20.35	9.15 ± 3.43	5.46 ± 3.14	110.07 ± 46.05	935.12 ± 350.56	438.65 ± 252.02
Sokoto Pepper	2.93 ± 1.06	0.69 ± 0.24	1.31 ± 0.36	6.64 ± 2.41	70.67 ± 24.71	104.81 ± 28.54
Kebbi Beans	19.98 ± 5.32	2.29 ± 0.57	3.87 ± 1.80	45.21 ± 12.04	233.91 ± 58.34	310.93 ± 144.49
Kebbi Maize	31.08 ± 10.82	5.92 ± 1.14	10.17 ± 0.51	70.34 ± 24.48	605.23 ± 116.76	816.45 ± 40.63
Kebbi Pepper	3.73 ± 1.91	1.28 ± 0.50	1.43 ± 0.36	8.43 ± 4.33	130.55 ± 50.99	115.04 ± 28.97

The calculated ingestion doses showed that maize contributed most to the internal radiation exposure, with average ingestion doses of 1,484 µSv/yr for Sokoto and 1,492 µSv/yr for Kebbi, which were 48–52% higher than the ICRP public limit of 1,000 µSv/yr. The highest individual ingestion dose (SOK-MZGR-04 at 2,204 µSv/yr) is 220% of the annual limit. The values obtained were much higher than the world average ingestion dose of 290 µSv/yr (UNSCEAR, 2020) and are above those reported for

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Kano tin-mining farms (151 µSv/yr; Muhammad et al., 2024) and Lagos food crops (less than 1,000 µSv/yr; Olaoye et al., 2024), but similar to Enugu coal-mining cassava (2,030 µSv/yr; Amakom et al., 2023).

Maize was the most dominant in the ingestion dose due to a combined effect of high consumption rates

(0.35 kg/day) and high Th-232 concentration in Kebbi maize (29.05 Bq/kg) and Ra-226 in Sokoto maize (26.14 Bq/kg). Maize can take up radionuclides from subsoil layers due to its deep root system (IAEA, 2010) and its high biomass production and potassium demand aids in the accumulation of radionuclides (Uchida et al., 2009).

3.5 Age-Dependent Committed Effective Doses

Age dependent committed effective doses presented in Table 8 showed that infants receive the highest doses per unit intake, with mean infant doses from maize reaching 3,710 µSv/yr in Sokoto and 3,991 µSv/yr in Kebbi, which are 3.7-4.0 times the ICRP public limit of 1,000 µSv/yr (ICRP, 2007).

Table 8: Committed Effective Doses by Age Group (µSv/yr)

Sample	Infant (≤1 yr)	Child (1–12 yrs)	Teenager (12–17 yrs)	Adult (≥17 yrs)
Sokoto Beans	2,245.00 ± 230.21	679.66 ± 86.78	2,076.90 ± 577.27	943.67 ± 105.87
Sokoto Maize	3,709.87 ± 1,508.20	1,431.72 ± 535.70	4,030.68 ± 1,517.05	1,503.78 ± 571.78
Sokoto Pepper	688.83 ± 135.90	157.34 ± 30.04	303.50 ± 81.58	186.89 ± 37.76
Kebbi Beans	1,450.61 ± 337.42	435.69 ± 91.62	1,107.87 ± 167.48	604.18 ± 137.48
Kebbi Maize	3,990.54 ± 200.96	1,392.16 ± 71.16	3,040.21 ± 426.36	1,529.13 ± 84.54
Kebbi Pepper	936.20 ± 79.69	221.17 ± 30.42	504.25 ± 150.15	259.24 ± 27.27

Teenagers also showed increased doses ranging from 1,588 to 3,723 µSv/yr, which are reflective of the larger dose coefficients for this age group compared to adults. Beans provided the intermediate infant doses (1,977-2,548 µSv/yr), and pepper gave the lowest doses (566-937 µSv/yr).

The age-dependent pattern agrees with ICRP metabolic models (ICRP, 2012, 2024) and previous findings (Akinkpulemi et al., 2025). Infants are more vulnerable due to (1) higher metabolic rates leading to increased radionuclide absorption, (2) developing tissues with greater radiosensitivity, (3) longer life expectancy for stochastic effects to manifest, and (4) higher consumption rates relative to body weight (WHO, 2017). Maize is also a primary complementary food introduced from 6 months in Nigeria (Hassan et al., 2021), making infants especially vulnerable to radionuclide exposure associated with maize.

3.6 Excess Lifetime Cancer Risk

The ELCR values for infants presented in Table 9 ranged from 1,982 × 10-3 to 19,715 × 10-3 which is 236–2,347 times higher than the UNSCEAR global benchmark value of 8.4 × 10-3. These values are far greater than the USEPA acceptable risk levels of 1 × 10-4 to 1 × 10-6 (USEPA, 1989).

Table 9: Excess Lifetime Cancer Risk by Age Group (×10-3)

Sample	Infant ELCR	Child ELCR	Teenager ELCR	Adult ELCR
Sokoto Beans	7,857.50 ± 805.74	2,378.80 ± 303.74	7,269.15 ± 2,020.45	3,302.83 ± 370.55
Sokoto Maize	12,984.54 ± 5,278.70	5,011.01 ± 1,875.00	14,107.37 ± 5,309.67	5,263.22 ± 2,000.94
Sokoto Pepper	2,410.91 ± 475.65	550.70 ± 105.15	1,062.26 ± 285.52	654.10 ± 132.16
Kebbi Beans	5,077.15 ± 1,180.95	1,524.90 ± 320.72	3,877.56 ± 585.94	2,114.62 ± 481.05
Kebbi Maize	13,966.88 ± 703.36	4,872.59 ± 249.03	10,640.74 ± 1,492.27	5,351.93 ± 295.75
Kebbi Pepper	3,276.69 ± 278.69	774.10 ± 106.48	1,764.88 ± 525.52	907.36 ± 95.39

The important potential genetic effects that may manifest in the future generations are the hereditary risk values for infants (396 × 10-3 to 3,943 × 10-3) (ICRP, 2007; UNSCEAR, 2001). Although the hereditary risk is less than the risk for cancer, the ICRP (2007) says that the hereditary risk is important for the protection of public health, particularly in populations where exposure occurs in childhood.

The high ELCR values, thousands of times above acceptable levels, show that the current way of consuming is associated with an unacceptably high risk of cancer for vulnerable populations. These results are in agreement with those reported from Enugu coal mining areas (Amakom et al., 2023) and petroleum impacted areas (Eyibio et al., 2022) but the magnitude of exceedance in the present study is unprecedented for non-mining agricultural zones in Nigeria.

3.7 Organ-Specific Effective Dose Rates

Organ-specific effective dose rates presented in Table 10 and Figure 1 resulted in the highest doses to testes (0.000546 mSv/yr, 18%), bone marrow (0.000460 mSv/yr, 16%), lungs (0.000426 mSv/yr, 15%), whole body (0.000453 mSv/yr, 16%) and kidneys (0.000413 mSv/yr, 14%).

Table 10: Organ-Specific Effective Dose Rates (mSv/yr)

Organ	Mean Dose (mSv/yr)	Percentage Contribution
Testes	0.000546	18%
Whole Body	0.000453	16%
Bone Marrow	0.000460	16%
Lungs	0.000426	15%
Kidneys	0.000413	14%
Ovaries	0.000386	13%
Liver	0.000307	10%

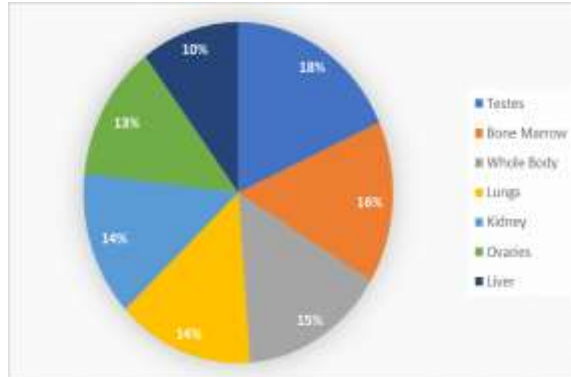

Figure 1: Organ-Specific Dose Rate Distribution

The higher dose to testes raises concerns about possible effects on male fertility and heritable genetic damage. Germ cell damage from ionising radiation can result in a decrease in fertility and an increased risk of heritable diseases (ICRP, 2007; UNSCEAR, 2001). The dose to bone marrow is of concern because of its role in haematopoiesis and the possibility of radiation-induced leukaemia. Ra-226, actively accumulated by some crops (up to a TF of 1.52), is chemically similar to calcium and preferentially deposited in bone, thus resulting in prolonged irradiation of bone surfaces and bone marrow (Harrison & Muirhead, 2003). The IARC (2001) has classified Ra-226 and Ra-228 as carcinogenic to humans (Group 1).

The dose to kidneys are of note as thorium can accumulate in renal tissues and cause nephrotoxicity at high doses (ICRP, 2012). The doses observed are quite low but the possibility of additive effects with other nephrotoxic substances (e.g., heavy metals) should be considered in comprehensive health risk assessments (Adesida & Alimba, 2025).

IV. CONCLUSION

This study have provided a comprehensive age-dependent radiological risk assessment from dietary exposure in the Sokoto Basin, revealing that chronic consumption of staple crops particularly in maize which poses significant health risks for vulnerable populations. The key finding, that thorium transfer factors approach unity for a variety of crops, challenges the scientific paradigm of thorium immobility in agricultural systems, and provides evidence that site-specific, rather than generic, transfer factors are needed for accurate risk assessment. The age disaggregated analysis indicates that infants are at disproportionate risk compared to adults due to higher metabolic rates, greater radiosensitivity and higher consumption rates relative to body weight. Maize consumption contributes to internal exposure disproportionately. Organ-specific dose rates indicate the highest deposition in reproductive and haematopoietic tissues, with implications for fertility, carcinogenesis and hereditary effects. The high transfer of thorium is attributed to the calcareous nature of the soils of the Sokoto Basin, semi-arid climate, phosphate rich geology, and possible mining related disturbances. The findings suggest a need for specific interventions including food diversification, management of agricultural soils by organic amendments and crop rotations, improved regulatory frameworks for monitoring radionuclides in food crops and community-based health surveillance programmes. This study highlights the need for localised age-differentiated radiological risk assessment in formulating effective public health protection strategies in phosphate-rich agricultural areas.

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