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Radiological assessment of commonly food crops in Southwestern Nigeria

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Keywords: natural radionuclides, food crops, annual effective dose, gamma spectrometry

Abstract

Natural radionuclides are present in food items at different levels and are influenced by factors like background radiation, climate, and agricultural practices. These radionuclides play a crucial role in humans' internal radiation exposure. Notably, radionuclides within the decay series ^{238}U and ^{232}Th as well as ^{40}K are significant concerns in radiation protection due to their prevalence and potential health risks. The activity concentrations of radionuclides ^{238}U, ^{232}Th, and ^{40}K in several food crops consumed within Lagos city in Nigeria were measured using gamma spectrometry. The concentrations of ^{238}U, ^{232}Th, and ^{40}K ranged from 0.90 to 55.30, BDL (Below Detection Limit) to 161.60 and 10.30 to 1075.20 Bqkg^{-1}, respectively. The average radionuclide activity concentrations are below the acceptable global level, or the worldwide average values set by the United Nations Scientific Committee on the Effects of Atomic Radiation in 2000 (UNSCEAR, 2000), which are 35, 30, and 400 Bqkg^{-1} for ^{238}U, ^{232}Th, and ^{40}K, respectively. The study calculated the annual effective dose for individuals consuming the studied food items, and the annual internal dose from ingesting was found to be 8.95×10^{-04} μSvy^{-1}. It's noteworthy that this computed value is below the worldwide value of 0.32 mSv y^{-1} set for the public. Additionally, the excess lifetime cancer risk (ELCR) value was 3.13×10^{-3} μSvy^{-1}, which is within the world safe limit value (2.9×10^{-4} μSvy^{-1}). Therefore, there is no potential radiological risk associated with the measured data.

1. Introduction

The Earth naturally contains radionuclides like thorium, uranium, and radium, distributed across geological formations such as soil, water, and plants [1–4]. The radioactivity in our environment results from a combination of natural processes and human activities, including industrial mining and farming. Different regions exhibit varying levels of radioactivity due to their geological characteristics. The degree of natural exposure exhibits global variability, typically differing by a factor of approximately [5]. The rates of radionuclide accumulation in vegetables and fruits are contingent upon the type of soil and rock in which they grow [6–10]. Radionuclides enter food crops through various pathways: direct deposition on leaves or exposed plant parts, uptake from soil into roots, re-suspension as dust from soil or other surfaces, and washing into water sources used for irrigation by rain. The absorption of radionuclides from soil into plant roots is akin to the process of non-radioactive element uptake. Factors influencing this absorption include soil type, climate, plant species, and the chemical form of radionuclides. The distribution of radionuclides within the plant decreases from the roots to the leaves [11, 12].

Human exposure to environmental radionuclides can lead to the accumulation of these substances in organs such as the lungs, kidneys, liver, skeletal tissues, and muscles [13–16]. The retention of radionuclides in bodily organs can have diverse effects on human health. Human tissues are sensitive to ionizing radiation which implies that these tissues can be affected by primordial radionuclides, namely ^{238}U, ^{232}Th, and ^{40}K, which can be transported to humans through water, plants, leaves, etc The fundamental radiological data is established through radiation studies to investigate the levels and distribution patterns of radionuclides within the environment. This essential information is core for human exposure estimation from sources of radiation either natural or man-made. In addition, it is substantial in rules establishment and radiation protection regulations [1, 17].

Human ingestion of radioactive materials often occurs through the consumption of contaminated food and water in the environment [18]. The ingestion of food crops represents one of the most common pathways for transferring radionuclides to the human body. When these harmful components are consumed, either directly or as supplements, they are transported into the body, posing potential risks to human health [19–23]. Understanding and monitoring these pathways are essential for assessing and mitigating the impact of radionuclides on human health. There is increasing concern among humans regarding pollution in the environment and potentially harmful health effects related to radionuclides, particularly driven by advancements in the science of nuclear energy. This heightened concern may be attributed to the potential for pollution of radiation arising from nuclear accidents or nuclear weapons uses. Radiation exposure and radionuclide distributions in the environment studies, including the present study, provide crucial data for assessing radiological safety following a potential radiation fallout in the future. This data serves as an important source for futurity comparative analyses, particularly when evaluating high levels of activity concentrations resulting from human activity in residential and professional settings [24–26]. By understanding the environmental impact of radionuclides, researchers and policymakers can develop strategies and regulations to mitigate potential risks and ensure the safety of both the environment and human populations in the aftermath of nuclear incidents [27].

In Southwestern Nigeria, high soil radioactivity levels have been reported by several researchers, with little or no information on the radioactivity level of food crops. Thus, this study seeks to investigate the radioactivity level in selected food crop samples within the Southwestern Nigeria Region, and its radiological hazards. The study aims to assess radiological hazards by calculating various data points, including annual effective dose (AED), radiological indices, and excess lifetime cancer risk (ELCR).

2. Materials and methods

2.1. Study area

The study focuses on Lagos, the second most populous city in Africa and the largest city in Nigeria, figure 1. Lagos spans a latitude range of 6.4510 to 6.6080N and a longitude range of 3.39470 to 3.62180E. The city covers an extensive land area of about 3577 km^2 in the southwestern geopolitical region of Nigeria. The investigation involved the collection of food crops from various sources, including farms located at LASU farms and markets in Ikotun and Oyingbo within the Lagos region. This geographical scope provides a comprehensive overview of the radiological assessment of food crops in a highly populated and diverse urban setting.

2.2. Sample collection and preparation

In this research, edible plant parts were systematically collected from farms and markets for a radiological assessment. The collected samples underwent a thorough cleaning process to remove dirt and contaminants, followed by peeling, slicing, and oven drying at 100 °C for 48 h to eliminate moisture content. Subsequently, the dried samples were pulverized to achieve a fine-grained homogeneous texture. To prevent the escape of radon isotopes (^{220}Rn and ^{222}Rn), the pulverized samples were carefully packed and sealed in well-labeled airtight containers. These sealed samples were then stored for 28 days, allowing for the establishment of secular equilibrium. Following this period, gamma spectrometry measurements were conducted using a NaI (Tl) crystal multichannel spectroscopic analyzer. The analysis took place at the Centre for Energy Research and Development, Obafemi Awolowo University, Ile-Ife, as outlined by Olagbaju *et al* in 2021. This systematic procedure ensures the reliability and accuracy of the radiological assessment of the edible plant parts under investigation.

2.3. Samples analysis and activity measurements

The research employed a NaI (Tl) crystal measuring 7.6 × 7.6 cm^2 (Model no 802 Series) coupled with the Canberra 10 Plus series Multi-Channel Analyzer (MCA). This setup, encased in a lead (Pb) shield and connected to the electronic system via a 50 Ω coaxial cable, was utilized for counting the activity of radionuclides in the

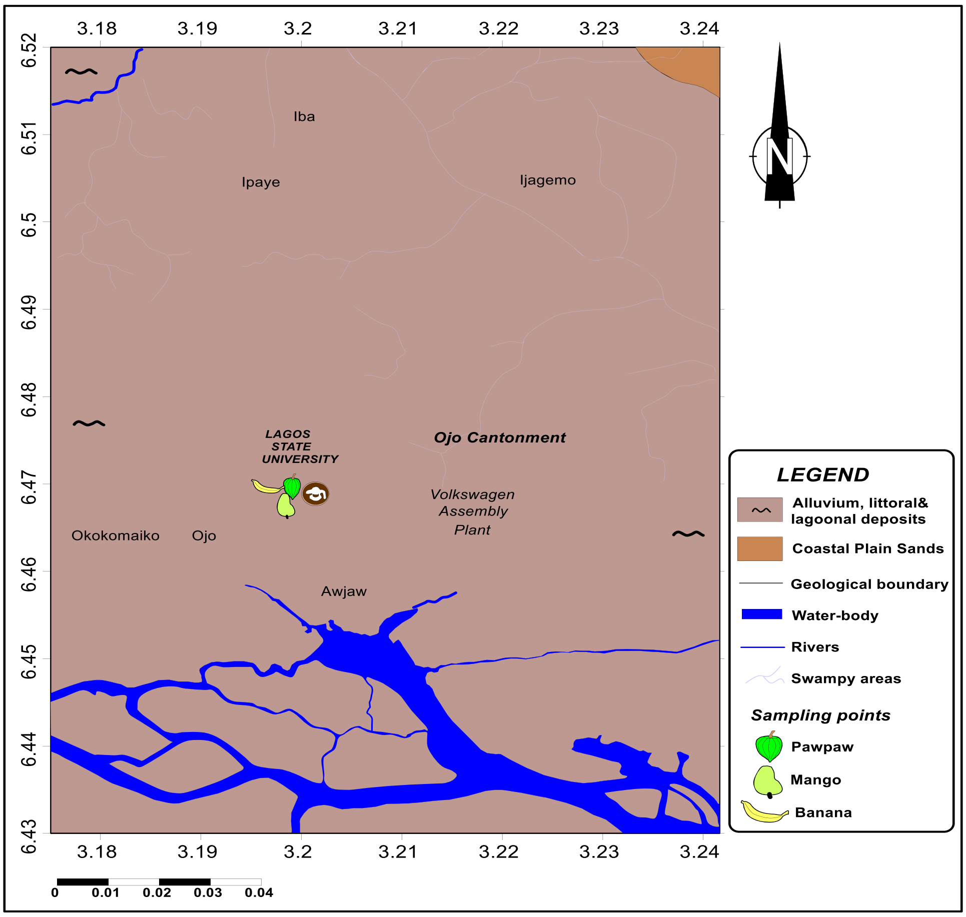

Figure 1. Geographic map of the study area.

samples. Each sample underwent a counting duration of 216,000 s (60 h). The activity concentrations of $^{238}U/^{226}Ra$ and ^{232}Th were determined using the γ-lines of their decay products: ^{214}Bi (1764.5 keV) and ^{208}Tl (2614.5 keV), respectively. The activity concentration of ^{40}K was determined using its 1460 keV γ-line. To calculate the activity concentrations (C, in Bq/kg) of the radionuclides, equation (1) was employed. The equation involves parameters such as count rate (Cn) under the corresponding peak, the efficiency of the detector (K) at the specific gamma-ray energy, the absolute transition probability of the specific gamma-ray ($\rho\gamma$), and the sample mass (Ms). The methodology ensures a rigorous approach to quantifying the radionuclide activity concentrations in the studied samples.

$$C(Bqkg^{-1}) = K\ x\ C_n \tag{1}$$

The lower limit of detection (LLD) at a 95% confidence level based on the characteristics of the measured spectrum is determined by the following equations, [28]:

$$LLD = \frac{C_{\min}}{\varepsilon\rho_\gamma M_s T} \tag{2}$$

where $C_{\min}$ represents the minimum net area of the measured spectrum.

$$C_{\min} = 4.66(S_b)^{1/2} \tag{3}$$

where S_b represents the calculated standard error of the net count because of Compton scattering and other effects. The Minimum Detectable Activity Concentration (MDA) is calculated using the following formula:

$$MDA = \frac{4.66\ (S_b)^{1/2}}{\varepsilon\rho_\gamma M_s T} \tag{4}$$

where M_s is the sample mass.

2.4. Calculation of absorbed dose and annual effective dose

The calculation of absorbed and annual effective dose involves converting radionuclide activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in food crops samples into doses. This process includes multiplication by specific factors for each radionuclide to account for the absorbed gamma dose.

For ^{238}U: Multiply the activity concentration by a factor of 0.462 (nGy h^{-1} per Bq kg^{-1}).

For ^{232}Th: Multiply the activity concentration by a factor of 0.604 (nGy h^{-1} per Bq kg^{-1}).

For ^{40}K: Multiply the activity concentration by a factor of 0.0417 (nGy h^{-1} per Bq kg^{-1}).

Mathematically, the absorbed gamma dose (D) can be represented as follows [5]:

$$D(nGyh^{-1}) = 0.462C_U + 0.604C_{Th} + 0.0417C_K \tag{5}$$

2.5. Computing of radium equivalent

The radium equivalent activity (Ra_{eq}) is a radiation hazard index used to represent the equivalent activity of natural radionuclides, considering their respective contributions to the gamma-ray dose rate. It is calculated using the equation, [29, 30]:

$$Ra_{eq} = C_U + 1.43C_{Th} + 0.077C_K \tag{6}$$

where C_U is the activity concentration ^{238}U, C_{Th} is the activity concentration of ^{232}Th *and* C_K is the activity concentration ^{40}K (in Bq kg^{-1}), respectively. The coefficients (1.43 and 0.077) are used to weight the contributions of ^{232}Th and ^{40}K relative to ^{238}U in terms of gamma-ray dose rate.

2.6. Identification of radiological hazards

The radiological hazards associated with radionuclides such as ^{226}Ra (^{238}U), ^{232}Th, and ^{40}K are often expressed using hazard indices. The hazard indices help assess the potential radiological risks from external (H_{ex}) and internal exposure (H_{in}), gamma radiation (I_γ), and alpha radiation ($I\alpha$). The indices mentioned are calculated as follows [26, 29, 30]:

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \tag{7}$$

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \tag{8}$$

$$I_\gamma = \frac{C_{Ra}}{300} + \frac{C_{Th}}{200} + \frac{C_K}{300} \tag{9}$$

$$I_\alpha = \frac{C_{Ra}}{370} \tag{10}$$

where C_{Ra}, C_{Th}, and C_K are the ^{226}Ra (^{238}U), ^{232}Th, and ^{40}K activity concentrations in Bq/kg, respectively, in the fruit and vegetable samples. The requirement $H_{ex} \leqslant 1$ ensures compliance with the recommended safety limit for external gamma radiation exposure, restricting the external gamma radiation dose from materials to be below 1.5 mGy per year. This criterion helps maintain radiation exposure levels within acceptable limits to safeguard human health and minimize potential adverse effects associated with external gamma radiation.

2.7. Annual ingestion dose

The calculation of the annual ingestion radiation dose involves assessing the amount of radiation exposure resulting from the consumption of food items. This calculation considers both the concentration of relevant radionuclides in the food and the annual consumption rate of that food [31]. The annual effective dose $E_{ing}\left(\frac{mSv}{yr}\right)$ from ingestion of ^{238}U, ^{232}Th and ^{40}K radionuclides through food crops and water samples was estimated by the equation, [5]:

$$E_{ing}\left(\frac{mSv}{yr}\right) = C_\tau I_{ing} \sum_{j=1}^{3} DCF_{ing} \tag{11}$$

where, C_τ is the radionuclides activity concentration in the sample, I_{ing} is the consumption rate per year, DCF_{ing} is the coefficient of effective dose in Sv/Bq for the natural radionuclides ingestion. For ^{238}U, ^{232}Th, and ^{40}K, the coefficient of effective dose is 4.50×10^{-8} Sv/Bq, 2.30×10^{-7} Sv Bq^{-1} and 6.20×10^{-9} Sv Bq^{-1} respectively (ICRP, 2012). The average consumption rate of 179.9 kg yr^{-1} and 79.8 kg/yr for cereals and vegetables, is applied to estimate the food crop's annual effective doses and 600 l/yr for water [32, 33].

Table 1. Activity concentrations and radium equivalent of natural radionuclides in food crops in $Bqkg^{-1}$.

Samples	^{238}U	^{232}Th	^{40}K	Ra_{eq}
Banana fruit	1.78	1.16	22.76	5.19
Mango fruit	7.82	0.53	25.96	10.58
Basmati Rice	24.80	19.00	118.00	61.06
Foreign Long Rice	24.00	43.90	140.20	97.57
Foreign short Rice	13.60	6.20	10.30	23.26
Local rice	8.80	29.30	117.90	59.78
Wheat	1.60	26.40	51.10	43.29
Ofada rice	9.90	42.60	53.60	74.95
Sweet potato	12.80	4.70	184.90	33.76
Yellow yam	5.10	51.00	197.70	93.25
Irish potato	34.70	50.90	277.30	128.84
Water yam	0.90	9.00	152.10	25.48
Water yam sin	26.00	56.70	169.60	120.14
Yellow yam skin	34.40	BDL	200.40	49.38
Sweet potato	18.50	47.20	360.20	113.73
Irish potato	55.30	161.60	1075.20	369.18
Minimum	**0.90**	**0.00**	**10.30**	**5.19**
Maximum	**55.30**	**161.60**	**1075.20**	**369.18**
Average	**17.50**	**34.39**	**197.33**	**187.19**

*BDL: Below Detection Limit.

2.8. Excess lifetime cancer risk (ELCR)

The potential lifetime excess cancer risk serves as a valuable metric for summarizing population risks and enabling comparisons between pollutants and exposure routes, the excess lifetime cancer risk (ELCR) is determined using the formula:

$$ELCR = E_{ing} \times LE \times RF \tag{12}$$

where E_{ing} is the ingestion annual effective dose (Sv/yr) of ^{238}U, ^{232}Th and ^{40}K through food, LE is life expectancy (70 years), and RF is the factor risk (Sv^{-1}). For risk assessment, the coefficient nominal probability recommended by [34] for stochastic health effects induced radiation is 7.3×10^{-2} Sv^{-1}.

3. Results and discussion

The activity concentration of naturally occurring radionuclides (^{238}U, ^{232}Th, and ^{40}K) varies across different food items with calculated Ra_{eq} are presented in table 1, and frequency distributions are shown in figure 2.

The observed range is from 0.90 $Bqkg^{-1}$in Water yam to 55.30 $Bqkg^{-1}$in Irish potato, with an average value of 17.50 $Bqkg^{-1}$ for ^{238}U. For ^{232}Th, the range is from below the limit of detection (BDL) in Yellow yam skin to 161.60 $Bqkg^{-1}$in Irish potato, with an average value of 34.39 $Bqkg^{-1}$. As for ^{40}K, the range extends from 10.30 $Bqkg^{-1}$in Foreign short Rice to 1075.20 $Bqkg^{-1}$in Irish potato, with an average value of 197.33 $Bqkg^{-1}$. The average activity concentrations of ^{238}U, ^{232}Th, and ^{40}K in vegetables and fruits reported by UNSCEAR (2000) are given as 35, 30, and 400 $Bqkg^{-1}$, respectively. Therefore, the average activity concentrations of ^{238}U, ^{232}Th, and ^{40}K calculated in the studied food crops are observed to be below the recommended values. It is observed that Potassium-40 is the most abundant naturally occurring radionuclide in all sampled food crops. This prevalence can be attributed to its significance in plant growth [35, 36]. The observed variations in the activity concentration of naturally occurring radionuclides among different sampled food crops suggest that the uptake of radionuclides by plants depends on their similarity to the nutrient requirements for various plant growth [37]. As seen from table 1, the radium equivalent activity values range from 5.19 to 369.18 $Bqkg^{-1}$ with an average value of 187.19 $Bqkg^{-1}$. It is noticed that the values of radium equivalent evaluated in vegetables are greater than those evaluated in fruit samples.

The calculated radiological hazards, including hazard index external (H_{ex}), internal (H_{in}), gamma, and alpha indices (I_γ, I_α) in food crops samples, are presented in table 2, and the box bar for each parameter is shown in figure 3. The external hazard index (H_{ex}) ranged from 0.08 in the Foreign short Rice sample to 4.38 in the Irish potato with an average value of 0.83. The internal hazard index (H_{in}) varied from 0.02 in Banana fruit to 1.15 in Irish potatoes with an average value of 0.27. The gamma index (I_γ) ranged from 0.09 in Banana fruit to 4.58 in Irish potatoes with an average value of 0.89 and the alpha index (I_α) ranged from 0.002 in Water yam to 0.15 in

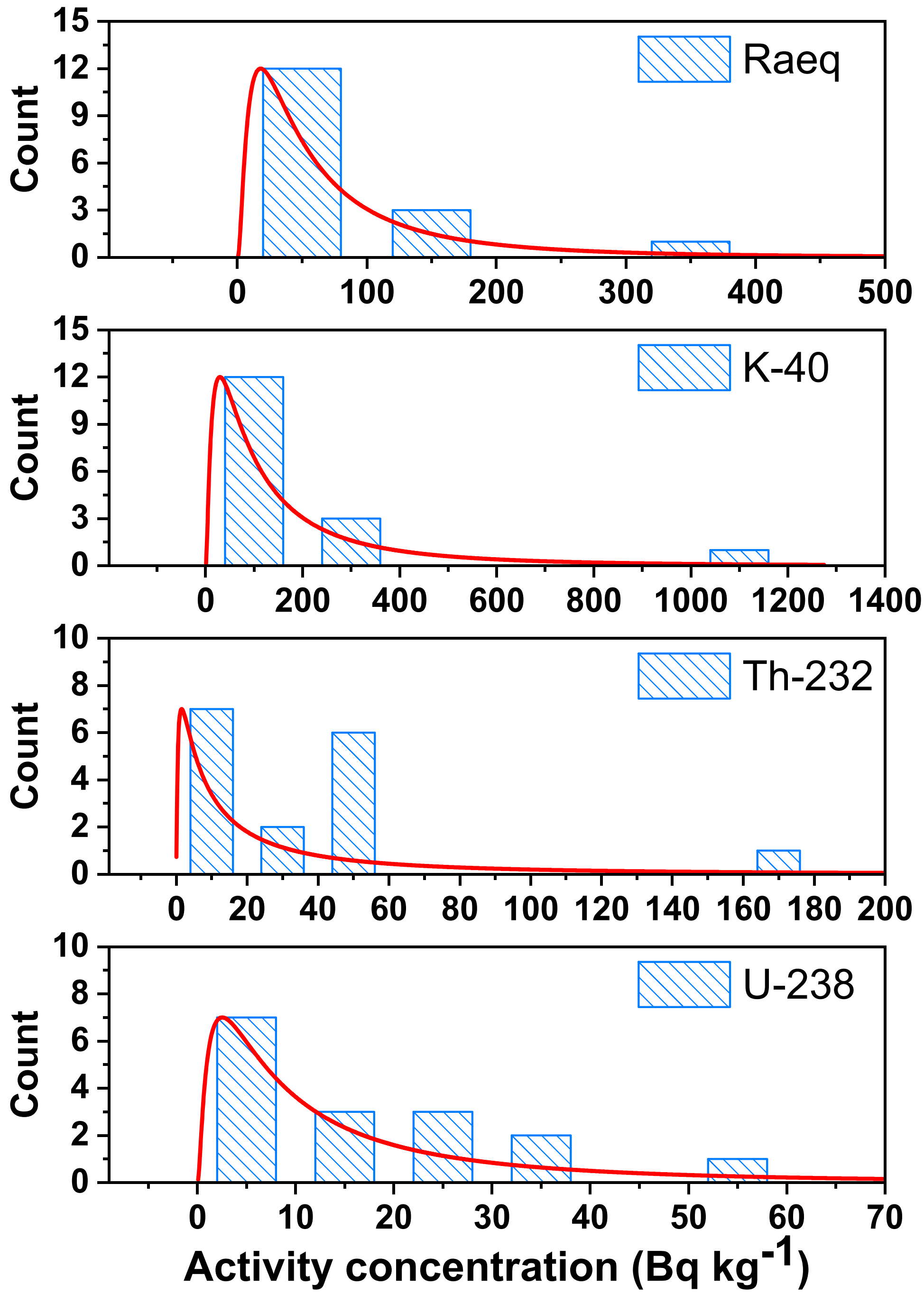

Figure 2. Frequency distributions of naturally occurring radionuclides (^{238}U, ^{232}Th, and ^{40}K) and calculated Ra_{eq} in different food items under study.

Irish potatoes with an average value of 0.05. These values are generally considered safe since they are less than unity, indicating that the radioactivity levels in these samples are within acceptable limits.

The study presents the calculated absorbed in table 3, it ranged from 2.47 $nGyh^{-1}$ in Banana fruit to 58.34 $nGyh^{-1}$ in Irish potato with an average value of 37.083 $nGyh^{-1}$. These values were lower when compared to the world average value of 55 nGy/h [32]. The ^{40}K presence in the body contributes to an annual effective dose of approximately 165 μSvy^{-1} *for* adults and 185 μSvy^{-1} for children, based on UNSCEAR data. However, when considering the ingestion of ^{40}K through food, the annual effective dose is slightly higher at 170 μSvy^{-1}. Additionally, the annual effective doses from the ingestion of ^{232}Th and ^{238}U are 120 *each*. Consequently, the total annual effective dose from these natural sources is estimated to be 290 μSvy^{-1}, [35, 39].

In the current study, the average committed effective dose resulting from the presence of ^{40}K and consumed through food crops (vegetables and fruits) ranged from 9.23×10^{-5} μSvy^{-1} in banana fruit to 4.64×10^{-3} μSvy^{-1} in Irish potatoes, with an average value of 8.95×10^{-4} μSvy^{-1}. It is noteworthy that ^{40}K contributes the most to the average value of the annual ingestion radiation dose, as indicated in table 4. This suggests that the

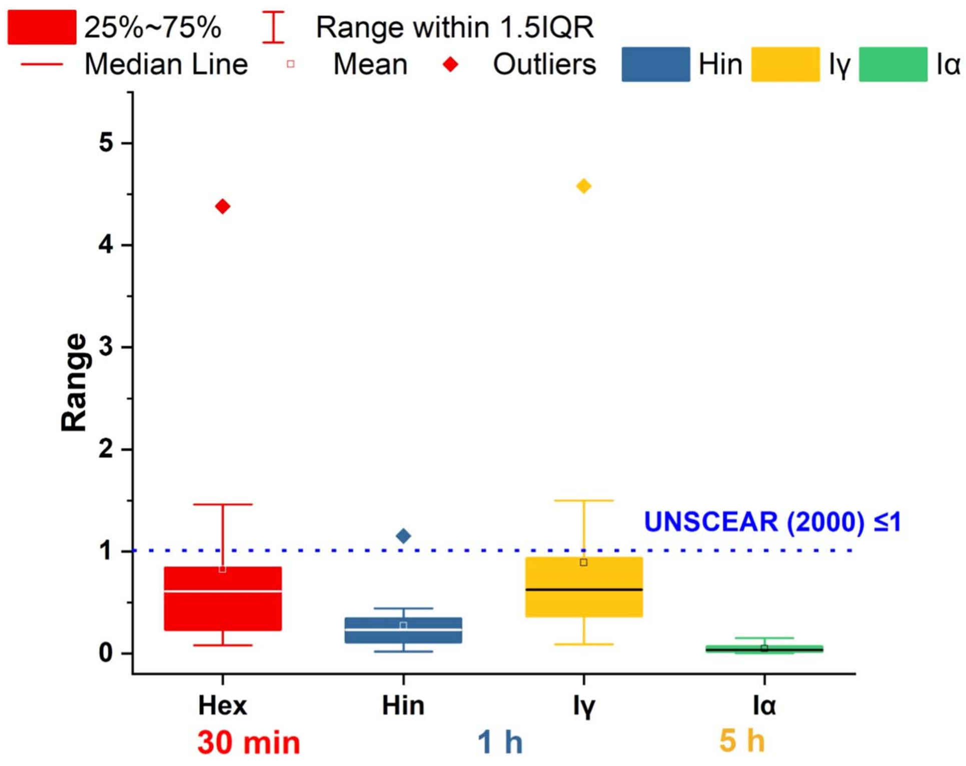

Figure 3 External and internal hazard indices (H_{ex}, H_{in}), gamma and alpha indices (I_γ, I_α) in different food items under study.

Table 2. External and internal hazard indices (H_{ex}, H_{in}), gamma and alpha indices (I_γ, I_α) in different food items under study.

Samples	H_{ex} (mSvy^{-1})	H_{in} (mSvy^{-1})	I_γ	I_α
Banana fruit	0.09	0.02	0.09	0.005
Mango fruit	0.12	0.05	0.12	0.02
Basmati Rice	0.54	0.23	0.57	0.07
Foreign Long Rice	0.63	0.33	0.77	0.06
Foreign short Rice	0.08	0.1	0.11	0.04
Local rice	0.49	0.19	0.57	0.02
Wheat	0.21	0.12	0.31	0.004
Ofada rice	0.25	0.23	0.42	0.03
Sweet potato	0.76	0.13	0.68	0.03
Yellow yam	0.80	0.27	0.93	0.01
Irish potato	1.19	0.44	1.29	0.09
Water yam	0.59	0.07	0.56	0.002
Water yam sin	0.75	0.39	0.94	0.07
Yellow yam skin	0.88	0.23	0.78	0.09
Sweet potato	1.46	0.36	1.50	0.05
Irish potato	4.38	1.15	4.58	0.15
Mean	**0.83**	**0.27**	**0.89**	**0.05**
UNSCEAR (2000)	$\leqslant 1$			

radiation exposure from the ingestion of these radionuclides in the studied food crops is within acceptable safety levels. However, the radiation risk associated with the consumption of individual crops might not be negligible, as they form a fraction of the human diet, though cooking can also reduce the level of radionuclides in food crops [40]. The probability of lifetime cancer risk due to the consumption of naturally occurring radionuclides in investigated food crops is also presented in table 4. The average carcinogenic risk via the consumption of sampled food crops is 3.13×10^{-3}, which is within the ICRP limit for cancer risk of 2.5×10^{-3}, based on an

Table 3. Absorbed ($nGyh^{-1}$) dose in samples.

Samples	Absorbed dose rate ($nGyh^{-1}$)
Banana fruit	2.47
Mango fruit	5.02
Basmati Rice	27.85
Foreign Long Rice	43.45
Foreign short Rice	10.46
Local rice	26.68
Wheat	18.82
Ofada rice	32.54
Sweet potato	16.46
Yellow yam	41.40
Irish potato	58.34
Water yam	12.19
Water yam sin	53.33
Yellow yam skin	24.25
Sweet potato	52.08
Irish potato	167.99
Mean	**37.083**
World safety limits	**59** [38]

Table 4. Radiological assessment of food crops.

Samples	D_{ing} (μSvy^{-1})				ELCR	TCR
	^{238}U	^{232}Th	^{40}K	Total		
Banana fruit	6.39×10^{-06}	4.17×10^{-06}	8.17×10^{-05}	9.23×10^{-05}	3.23×10^{-04}	$3.24 \times 10^{+08}$
Mango fruit	2.81×10^{-05}	1.90×10^{-06}	9.32×10^{-05}	1.23×10^{-04}	4.31×10^{-04}	$1.18 \times 10^{+08}$
Basmati Rice	8.91×10^{-05}	6.82×10^{-05}	4.24×10^{-04}	5.81×10^{-04}	2.03×10^{-03}	$2.45 \times 10^{+07}$
Foreign Long Rice	8.62×10^{-05}	1.58×10^{-04}	5.03×10^{-04}	7.47×10^{-04}	2.62×10^{-03}	$1.68 \times 10^{+07}$
Foreign short Rice	4.88×10^{-05}	2.23×10^{-05}	3.70×10^{-05}	1.08×10^{-04}	3.78×10^{-04}	$5.54 \times 10^{+07}$
Local rice	3.16×10^{-05}	1.05×10^{-04}	4.23×10^{-04}	5.60×10^{-04}	1.96×10^{-03}	$3.01 \times 10^{+07}$
Wheat	5.75×10^{-06}	9.48×10^{-05}	1.84×10^{-04}	2.84×10^{-04}	9.94×10^{-04}	$4.41 \times 10^{+07}$
Ofada rice	3.56×10^{-05}	1.53×10^{-04}	1.92×10^{-04}	3.81×10^{-04}	1.33×10^{-03}	$2.32 \times 10^{+07}$
Sweet potato	4.60×10^{-05}	1.69×10^{-05}	6.64×10^{-04}	7.27×10^{-04}	2.54×10^{-03}	$5.03 \times 10^{+07}$
Yellow yam	1.83×10^{-05}	1.83×10^{-04}	7.10×10^{-04}	9.11×10^{-04}	3.19×10^{-03}	$2.09 \times 10^{+07}$
Irish potato	1.25×10^{-04}	1.83×10^{-04}	9.96×10^{-04}	1.30×10^{-03}	4.56×10^{-03}	$1.28 \times 10^{+07}$
Water yam	3.23×10^{-06}	3.23×10^{-05}	5.46×10^{-04}	5.82×10^{-04}	2.04×10^{-03}	$9.13 \times 10^{+07}$
Water yam sin	9.34×10^{-05}	2.04×10^{-04}	6.09×10^{-04}	9.06×10^{-04}	3.17×10^{-03}	$1.39 \times 10^{+07}$
Yellow yam skin	1.24×10^{-04}	$0.00 \times 10^{+00}$	7.20×10^{-04}	8.43×10^{-04}	2.95×10^{-03}	$2.67 \times 10^{+07}$
Sweet potato	6.64×10^{-05}	1.69×10^{-04}	1.29×10^{-03}	1.53×10^{-03}	5.35×10^{-03}	$1.63 \times 10^{+07}$
Irish potato	1.99×10^{-04}	5.80×10^{-04}	3.86×10^{-03}	4.64×10^{-03}	1.62×10^{-02}	$5.03 \times 10^{+06}$
Maximum	$\mathbf{3.23 \times 10^{-06}}$	$\mathbf{0.00 \times 10^{+00}}$	$\mathbf{3.70 \times 10^{-05}}$	$\mathbf{9.23 \times 10^{-05}}$	$\mathbf{3.23 \times 10^{-04}}$	$\mathbf{5.03 \times 10^{+06}}$
Minimum	$\mathbf{1.99 \times 10^{-04}}$	$\mathbf{5.80 \times 10^{-04}}$	$\mathbf{3.86 \times 10^{-03}}$	$\mathbf{4.64 \times 10^{-03}}$	$\mathbf{1.62 \times 10^{-02}}$	$\mathbf{3.24 \times 10^{+08}}$
Average	$\mathbf{6.28 \times 10^{-05}}$	$\mathbf{1.23 \times 10^{-04}}$	$\mathbf{7.09 \times 10^{-04}}$	$\mathbf{8.95 \times 10^{-04}}$	$\mathbf{3.13 \times 10^{-03}}$	$\mathbf{5.46 \times 10^{+07}}$

annual effective dose limit of 1 mSv for the general population [35, 41, 42]. This indicates negligible or no potential carcinogenic risk in the exposed population. Table 5 compares the computed annual effective dose and Excess Lifetime Cancer Risk (ELCR) for different samples of food crops in this study with those of related investigations carried out both inside and outside of Nigeria. It appears that the committed effective dose and ELCR in the study are significantly lower compared to references [3, 23, 26].

The study utilized Pearson's correlation coefficient analysis to explore the relationship between D_{ing} and the measured activity of radionuclides. The results illustrated in figures 4(a)–(c), indicated a positive correlation between D_{ing} and the radionuclides ^{40}K, ^{238}U, and ^{232}Th. This suggests that all the nuclides contributed proportionally to D_{ing}, influencing the Excess Lifetime Cancer Risk (ELCR).

4. Conclusion

In this work, the three primordial radionuclides ^{238}U, ^{232}Th, and ^{40}K in samples of food crops consumed within Lagos city in Nigeria were measured using gamma spectrometry. The study also encompassed the calculation of

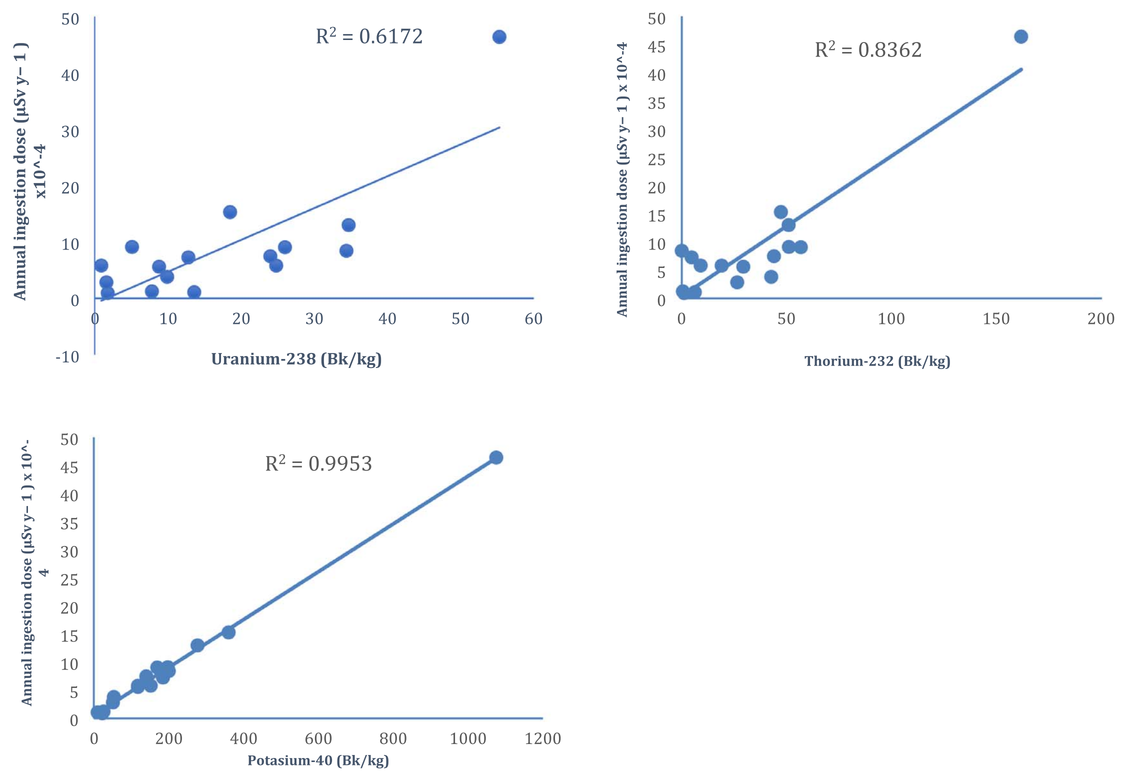

Figure 4. Correlation of D_{ing} with ^{238}U, ^{232}Th, and ^{40}K.

Table 5. Comparing the annual effective dose and ELCR of the tested samples to those of prior research conducted globally.

Country	D_{ing} (μSvy^{-1})			ELCR (μSvy^{-1})	References
	^{238}U	^{232}Th	^{40}K		
Lagos, Nigeria	6.28×10^{-05}	1.23×10^{-04}	7.09×10^{-04}	3.13×10^{-03}	Present Work
Anatolia, Turkey (Fruits)	31.40	11.15	142.37	0.07	[26]
Anatolia, Turkey (Vegetables)	0.81	0.50	5.30	0.14	[26]
Iraq (Turkish foodstuff)	0.13	0.06	0.09	0.96	[3]
EKITI STATE, NIGERIA	0.404	0.474	0.490	1.064	[23]
Mali	Mean Value 326.0 (~0.33 mSvy^{-1})			9.28×10^{-04}	[17]
Malaysia (Vegetables)	0.023×10^{-03}	0.019×10^{-03}	0.191×10^{-03}	8.13×10^{-04}	[38]
Malaysia (Fruits)	0.047×10^{-03}	0.024×10^{-03}	0.124×10^{-03}	6.83×10^{-04}	[38]
World safety limits	120	120	170	0.29	[5, 37]

various radiological parameters based on the collected data. The obtained results include the absorbed and the annual effective dose, radium activity equivalent, gamma and alpha indices, excess lifetime cancer risk, and ingestion annual dose. These results contribute to a comprehensive evaluation of the radiological impact associated with the consumption of the analyzed foodstuffs. The average activity concentrations of ^{238}U, ^{232}Th, and ^{40}K measured in food crops are observed to be below the recommended values. The calculated radiological hazards, including external hazard index (H_{ex}), internal hazard index (H_{in}), gamma index (I_γ), and alpha index (I_α) in food crops, are generally considered safe. This conclusion is drawn from the fact that these hazard indexes are all less than unity, indicating that the radioactivity levels in the analyzed vegetable and fruit samples are within acceptable limits, posing no significant radiological risk. The average annual committed effective dose of the natural radionuclides to the consumers was calculated and found to be below 0.3 mSvy^{-1} recommended by the United National Scientific Committee on the Effect of Atomic Radiation. Also, lifetime cancer risk in soil due to exposure to naturally occurring radionuclides was found to be within the threshold level of 2.90×10^{-04}, indicating negligible or no potential carcinogenic risk in the exposed population. However, it is recommended that soil and food crop radioactivity levels in the Southwestern region of Nigeria, be simultaneously investigated, to establish the natural radionuclides transfer factor from soil to the various food crops investigated.

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Data availability

All data that support this study is included in the submitted manuscript.

Conflict of interest

The authors declare no conflicts of interest.

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Ethical statement

Not applicable.

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