

Radiological Assessment of Gamma Ray Index and Excessive Lifetime Cancer Risk in Locally Grown Maize and Beans in Bungoma County, Kenya

Stanley C. Tsimbasi¹, John W. Makokha¹, Benjamin O. Odumo²

¹Department of Science, Technology and Engineering, Kibabii University, Bungoma, Kenya

²Faculty of Science and Technology, Department of Physics, University of Nairobi, Nairobi, Kenya

Email: tsimbasi@gmail.com, makokhajw@kibu.ac.ke, benodumoo@uonbi.ac.ke

How to cite this paper: Tsimbasi, S. C., Makokha, J. W., & Odumo, B. O. (2025). Radiological Assessment of Gamma Ray Index and Excessive Lifetime Cancer Risk in Locally Grown Maize and Beans in Bungoma County, Kenya. *Voice of the Publisher*, 11, 307-317.
<https://doi.org/10.4236/vp.2025.112022>

Received: April 5, 2025

Accepted: June 6, 2025

Published: June 9, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

Radionuclides ingested through food consumption may contribute significantly to the average irradiation of different organs in the body. This study focused on radiological hazard indices by consuming maize (*Zea mays*) and beans (*Phaseolus vulgaris*) locally grown in Bungoma County. The activity concentration of ²²⁶Ra, ²³²Th, and ⁴⁰K in eighteen representative samples was determined by gamma-ray spectrometry technique using a Sodium Iodide (NaI (TI)) scintillation detector, and the hazard indices were determined. The average activity concentration of ²²⁶Ra, ²³²Th, and ⁴⁰K in maize and beans were 20.9 ± 7.2 Bq/kg, 54 ± 21.2 Bq/kg, 161.0 ± 76.8 Bq/kg, and 18.4 ± 4.0 Bq/kg, 43.0 ± 15.5 Bq/kg, 195.0 ± 132.5 Bq/kg respectively. Average AEID values for maize and beans were 1.31 mSv/year and 0.26 mSv/year, respectively. For maize, the gamma ray index is 0.7 ± 0.206 , and excessive lifetime cancer risk is 4.89×10^{-8} . For beans, the gamma-ray index is 0.6 ± 0.2 , and excessive lifetime cancer risk is 1.00×10^{-8} . Excessive lifetime cancer risks associated with ²²⁶Ra, ²³²Th, and ⁴⁰K were all within the internationally recommended limits of 10^{-3} . The average gamma representative indices for both maize and beans were below unity, according to International Commission on Radiological Protection ICRP guidelines, indicating that their consumption poses minimal radiological risk to the residents of Bungoma County.

Keywords

Maize, Beans, Gamma Index, Internal Hazard Index, Excessive Lifetime Cancer Risk

1. Introduction

Humans are exposed internally to radiation, mainly through ingesting foods contaminated with radionuclides (Alatise & Adebessin, 2019). Studies have found cereals and pulses like maize and beans to have bio-accumulated radionuclides depending on their concentration in the soil on which they were recently grown (El-gamal et al., 2019; Avwiri et al., 2021; Mohebian & Pourimani, 2020). According to the study carried out by Vila-Real et al. (2022), cereals and pulses account for over 34% of the food intake in Kenyan households, and it has been projected that intake of food causes at least one-eighth of mean yearly radiation dosage derived from natural sources.

Physical and chemical weathering can cause radioactive nuclides from the Earth's crust to accumulate in agricultural land (Sultana et al., 2019). The concentration of radionuclides like ^{226}Ra , ^{232}Th , and ^{40}K in soil can elevate as a result of agricultural practices such as the use of chemical products such as inorganic fertilizers, herbicides, and pesticides that might contain these radionuclides (Sultana et al., 2019). Granitic rocks and volcanic soils are predominant in the areas surrounding Mount Elgon (Butiki et al., 2021) and investigations undertaken in volcanic locations have established a direct relationship between soil composition and radioactivity (Wabomba et al., 2022; Marques et al., 2021). Direct deposition of these radionuclides on the leaves, fruits, and tubers of plants, as well as root absorption from contaminated soil or water, could result in food chain contamination (Alatise & Adebessin, 2019). These radionuclides accumulate in several parts of the plant, including the edible parts, through the xylem and phloem's vascular system (Asaduz-zaman et al., 2015).

Radionuclides ingested through food consumption play a significant role in the average irradiation of various organs in the body and are crucial factors to consider for long-term health (Fathabadi et al., 2017). Therefore, this study aimed to identify the radiation risks to consumers from the consumption of maize and beans in Bungoma County.

2. Materials and Methods

2.1. Area of Study

Bungoma County, situated in western Kenya in the Lake Victoria Basin, encompasses an area of 3032.4 km² and is positioned between latitudes 00°28'N and 10°30'N, and longitudes 34°20'E and 35°5'E. The county has a population of around 1.67 million and borders Uganda to the northwest, Trans-Nzoia to the northeast, Kakamega to the east, and Busia to the west. It is made up of nine sub-counties: Kanduyi, Bumula, Sirisia, Kabuchai, Mt. Elgon, Webuye East, Webuye West, Tongaren, and Kimilili, see **Figure 1**. (Tsimbasi et al., 2024; Bungoma County, 2021)

Its fertile volcanic soils supporting extensive agriculture may contain natural radionuclides like ^{226}Ra , ^{232}Th , and ^{40}K , which could be further concentrated with fertilizers. Bungoma's population primarily depends on locally grown maize and

beans, so it is important to evaluate the radiological risks that may be associated with consuming them. Agriculture is the county's main economic activity, and these crops are essential for both subsistence and trade.

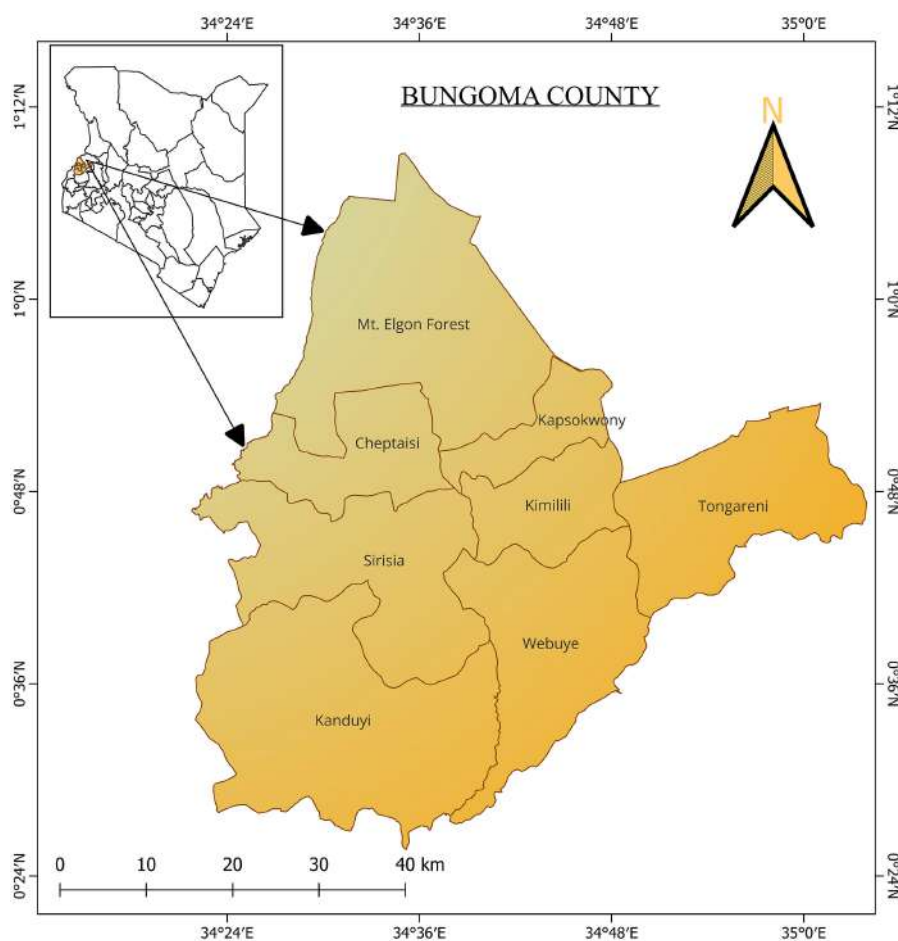


Figure 1. A map showing sub-counties of Bungoma county. (Source: the authors)

2.2. Sample Collection and Preparation

In each of the nine sub-counties, 200 g samples of beans and maize were chosen at random from a subset of households in a single season. To prevent cross-contamination, the samples were placed in tiny, sterile bags, identified with the GPS location, and brought to the lab for processing. To make sure the moisture content was eliminated, the samples were first sun-dried for two days. Nine representative samples were created by mixing 150 g of each of the three maize and bean samples from each sub-county. After the materials were ground into a powder, they were filtered through a 2 μm sieve to create a finely grained sample. The samples were subsequently dried in an oven at 50°C to 60°C until a stable weight was attained. Samples were considered dehumidified when the rate of mass variation went to zero (Lopes et al., 2018). 200 g of representative samples were weighed using an electronic top pan balance, put into cylindrical plastic containers, sealed tightly, and labeled suitably. **Table 1** lists the labels for the maize samples, which were M_1

through M₉. Similarly, bean samples were designated B₁ through B₉ as highlighted in **Table 2**. To allow ²²⁶Ra and ²³²Th to achieve a secular equilibrium with their daughter radionuclides, the samples were stored for a month (El-Gamal et al., 2019).

Table 1. The specific activity concentration, annual effective ingestion dose, gamma index and excessive lifetime cancer risk in maize samples.

Sample code	Specific activity concentration (Bq/kg)			Annual effective ingestion dose (mSv·y ⁻¹)	Gamma index, I (Y _T)	ELCR ×10 ⁻⁸
	²²⁶ Ra	²³² Th	⁴⁰ K			
M ₁	11.50 ± 0.57	23.00 ± 1.16	82.00 ± 4.14	0.5852	0.3 ± 0.01	2.22
M ₂	15.00 ± 0.75	73.00 ± 3.65	46.00 ± 2.34	1.3652	0.8 ± 0.04	6.01
M ₃	20.80 ± 1.04	61.00 ± 3.06	132.00 ± 6.64	1.3311	0.8 ± 0.04	5.41
M ₄	30.10 ± 1.50	23.00 ± 1.16	279.00 ± 13.99	0.9961	0.6 ± 0.03	3.02
M ₅	30.10 ± 1.50	29.00 ± 1.46	170.00 ± 8.52	1.0387	0.6 ± 0.03	3.45
M ₆	12.70 ± 0.63	75.00 ± 3.79	87.00 ± 4.37	1.3829	0.9 ± 0.04	6.13
M ₇	30.10 ± 1.50	64.00 ± 3.21	176.00 ± 8.83	1.5578	0.9 ± 0.04	6.02
M ₈	16.20 ± 0.81	61.00 ± 3.06	206.00 ± 10.31	1.2772	0.8 ± 0.04	5.21
M ₉	22.00 ± 1.10	75.00 ± 3.79	267.00 ± 13.36	1.6206	1.0 ± 0.05	6.53
MEAN ± S.D.	20.90 ± 7.19	54.00 ± 21.15	161.00 ± 76.84	1.24 ± 0.29	0.7 ± 0.206	4.89

Table 2. The specific activity concentration, annual effective ingestion dose, gamma index and excessive lifetime cancer risk in beans samples.

Sample code	Specific activity concentration (Bq/kg)			Annual effective ingestion dose mSv·y ⁻¹	Gamma index (Y _T)	ELCR ×10 ⁻⁸
	²²⁶ Ra	²³² Th	⁴⁰ K			
B ₁	15.00 ± 0.75	23.00 ± 1.16	28.00 ± 1.40	0.156	0.3 ± 0.01	0.59
B ₂	12.70 ± 0.63	67.00 ± 3.35	498.00 ± 24.93	0.354	1.0 ± 0.05	1.37
B ₃	23.10 ± 1.15	23.00 ± 1.16	226.00 ± 11.33	0.212	0.5 ± 0.02	0.68
B ₄	19.60 ± 0.98	58.00 ± 2.92	287.00 ± 14.38	0.332	0.9 ± 0.04	1.28
B ₅	22.00 ± 1.10	32.00 ± 1.60	142.00 ± 7.11	0.231	0.5 ± 0.02	0.83
B ₆	18.50 ± 0.92	40.00 ± 2.04	118.00 ± 5.94	0.245	0.6 ± 0.03	0.95
B ₇	20.80 ± 1.04	40.00 ± 2.04	81.00 ± 4.06	0.252	0.6 ± 0.03	0.98
B ₈	22.00 ± 1.10	64.00 ± 3.21	247.00 ± 12.35	0.360	0.9 ± 0.04	1.42
B ₉	11.50 ± 0.57	43.00 ± 2.19	131.00 ± 6.56	0.226	0.6 ± 0.03	0.93
MEAN ± S.D.	18.40 ± 4.03	43.00 ± 15.51	195.00 ± 132.48	0.263 ± 0.07	0.6 ± 0.22	1.00

2.3. Sample Analysis

International Atomic Energy Agency (IAEA) standard reference materials RG-U, RG-K, and RG-Th were used to acquire the spectrum and estimate the activity concentration of specific radionuclides. The activity concentration of ²³²Th was determined using the ²⁰⁸Tl (2615 keV) gamma energy peak, while the activity con-

centration of ^{226}Ra was estimated using the activity concentration of ^{214}Bi (1765 keV). Because the energy peaks are different from other peaks, they were selected to compensate for the gamma-ray detector's low level of resolution. Its gamma energy peak at 1460 keV was used to determine the activity content of ^{40}K . Each sample's data collection time was 28,800 seconds.

Determining the background radiation was a necessary step in establishing the minimum activity that could be reliably detected (Sultana et al., 2019). This involved measuring counts from distilled water placed in a plastic container over the same time period as the sample measurements. The resulting background counts were deducted from the total counts to yield net counts, which were then utilized to calibrate the energy scale.

2.3.1. The Specific Activity

The decay rate of the radionuclide per unit mass is known as a specific activity. The precise activity linked to every radionuclide in a sample is given by Equation (1) (Wabomba et al., 2022; Yarima et al., 2019).

$$C = \frac{N \times 100}{P_{\gamma} \times \epsilon \times m} \quad (1)$$

where C is the activity of the sample in Bq/kg, ϵ is the counting efficiency of the gamma energy, P_{γ} is the absolute intensity of the gamma-ray and m , net mass of the sample (in kilograms).

2.3.2. Annual Effective Ingestion Dose (AEID)

The whole-body health risk resulting from food consumption is represented by the annual effective ingestion dose (Bilgici Cengiz & Caglar, 2022). Equation (2) can be used to calculate a person's yearly effective ingestion dose based on their dietary intake. According to the Kenya National Bureau of Statistics (2019), maize consumption per capita was an average of 64.1 kg per year, 2014-2018.

$$\text{AEID } (\mu\text{Sv}\cdot\text{y}^{-1}) = C \times A_I \times F_{\text{DC}} \quad (2)$$

where A_I is the annual intake of each food in kilograms per year. F_{DC} is the standard dosage conversion factor, which is equivalent to $0.28 \mu\text{Sv}\cdot\text{Bq}^{-1}$ for ^{226}Ra , $0.23 \mu\text{Sv}\cdot\text{Bq}^{-1}$ for ^{232}Th and $0.0062 \mu\text{Sv}\cdot\text{Bq}^{-1}$ for ^{40}K . The coefficients account for age-related changes in intestinal absorption, body and organ masses, and urinary bladder excretion rates (ICRP, 2012).

2.3.3. The Gamma Ray Index (I_{γ})

The gamma ray index (I_{γ}) is used to calculate the degree of gamma radiation risk connected to naturally occurring radionuclides in particular materials, Equation (3) (Geremew, 2023; Hameed & Fzaa, 2021).

$$I_{\gamma} = \frac{A_{\text{Ra}}}{150} + \frac{A_{\text{Th}}}{100} + \frac{A_{\text{K}}}{1500} \quad (3)$$

2.3.4. Lifetime Cancer Risk (LTCR)

The lifetime cancer risk refers to the likelihood of developing cancer risk arising

from foods taken with the daily diet. Lifetime risk assessment will be estimated by applying the annual ingestion effective dose due to the presence of ^{226}Ra , ^{232}Th , and ^{40}K radionuclides in the foods, from the age of first exposure until the actual life expectancy of 67.47 years, according to the Kenya National Bureau of Statistics (KNBS), Equation (4) (Bilgici Cengiz & Caglar, 2022).

$$\text{LTCR} = \text{AEID} \times L_{\text{span}} \times F_{\text{RC}} \quad (4)$$

where L_{span} is the mean life span (average 67.47 years), F_{RC} is a risk conversion factor and the F_{RC} coefficient is used to convert internal doses to excess cancer risk are 5.02×10^{-3} , 7.38×10^{-1} and $3.58 \times 10^{-1} \mu\text{Sv}^{-1}$ for ^{40}K , ^{232}Th and ^{226}Ra , respectively.

3. Results and Discussion

3.1 The Specific Activity Concentration and Annual Effective Ingestion Dose

The average ^{232}Th , ^{226}Ra and ^{40}K activity in maize were 54.00 ± 21.15 with a range of ($23 \pm 1.1 - 75 \pm 3.79$) Bq/kg, 20.90 ± 7.19 with a range of (11.50 - 30.10) Bq/kg, and 161.00 ± 76.84 with a range of ($46 \pm 2.34 - 279 \pm 13.99$) Bq/kg respectively as seen in **Table 1**. The highest activity was recorded in ^{40}K in sample M₄, while the lowest was recorded from ^{226}Ra in sample M₁.

The average activity level of radionuclide in the nine beans samples for ^{226}Ra , ^{232}Th , and ^{40}K were 18.40 ± 4.03 with a range of ($11.5 \pm 0.57 - 23.1 \pm 1.15$) Bq/kg, 43.00 ± 15.51 with a range of ($23 \pm 1.16 - 67 \pm 3.35$) Bq/kg and 195.00 ± 132.48 with a range of ($28 \pm 1.4 - 498 \pm 24.93$) Bq/kg respectively as seen in **Table 2**. The highest activity concentration in beans was recorded from ^{40}K in B₂, while the lowest was determined from ^{226}Ra in B₉.

Soil composition plays a crucial impact as geological formations, including granitic and volcanic soils, tend to have higher quantities of radionuclides such as ^{226}Ra , ^{232}Th , and ^{40}K (Marques et al., 2021). The usage of phosphate-based fertilizers in the study area, which frequently includes trace levels of radioactive materials, additionally contributes (Kim & Cho, 2022). Environmental factors such as erosion, water runoff, and sediment transport redistribute radionuclides, resulting in uneven concentrations across agricultural fields (UNSCEAR, 2000). Understanding these elements is critical for effectively managing radiological hazards in food and the environment.

The average AEID due to ingestion of maize was found to be 1.239 (0.585 - 1.621) mSv·y⁻¹, **Table 1**, while that of beans was 0.263 (0.156 - 0.36) mSv·y⁻¹, **Table 2** (Tsimbasi et al., 2024). Maize samples recorded higher AEID compared to bean samples, as seen in **Figure 2**. The mean AEID values in maize were above the limit of 1 mSv·y⁻¹ for the general public, as recommended by the International Commission on Radiological Protection (ICRP). This shows that there is an increased health risk for the whole body of an individual due to the intake of maize with higher AEID.

The AEID values found in the current study for Bungoma are significantly

greater than the 0.5 mSv/year noted in Brazil (Lopes et al., 2018), but lower than the 6.13 mSv/year reported in Iran (Changizi et al., 2013). Compared to the current study for Bungoma, studies from Nigeria show AEID values that are much lower, ranging from 1.9 μ Sv/year to 5.12 μ Sv/year (Yarima et al., 2019). Tanzania's maize AEID, on the other hand, was 8.64×10^{-2} mSv/year (Banzi et al., 2017), suggesting a closer exposure level. AEID values in the Bureti region of Kenya were 5.92 mSv/year (Rotich, 2022) which was significantly higher than what was found in the present research. Although consumers may not be immediately in danger of any health problems due to the average concentration of all radioisotopes in maize and beans, there may be a long-term cumulative effect once the current dose is consumed (Tsimbasi et al., 2024; Changizi et al., 2013; Muhammad et al., 2024). Increased radiation exposure to particular organs can affect human health by impairing immunity, which may increase the risk of radiation-related illnesses like cancer and ultimately raise rates of fatalities (Tawalbeh et al., 2011).

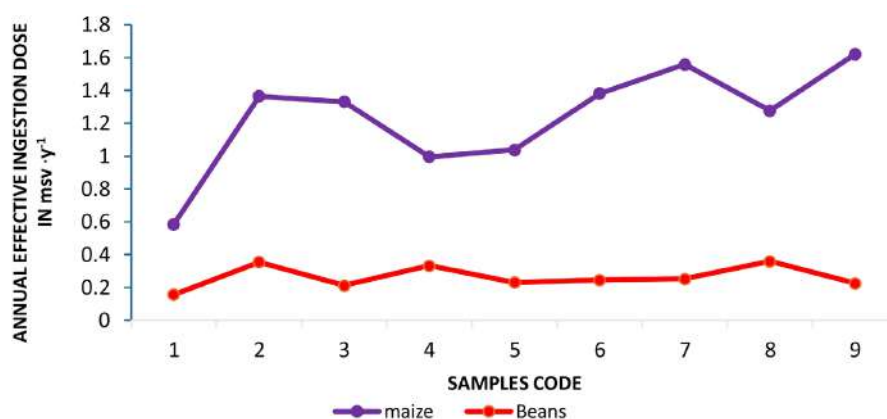


Figure 2. A line graph showing total AEID due to intake of maize and beans mSv.y⁻¹.

3.2. Gamma Index and Excessive Lifetime Cancer Risk

The average gamma index, I_γ , for maize and beans were 0.7 ± 0.03 ($0.3 \pm 0.01 - 1 \pm 0.05$) mSv and 0.6 ± 0.03 ($0.3 \pm 0.01 - 1 \pm 0.05$) mSv respectively. The highest value recorded in maize samples B₂ and M₉ exceeded the threshold value of 1 mSv, as seen in **Figure 3**. The average values indicate that there are minimal risks posed to consumers due to the natural radionuclides present in maize and beans. The mean ELCR was 4.89×10^{-8} , ranging from 2.22×10^{-8} to 6.53×10^{-8} in maize and 1.00×10^{-8} , ranging from 5.9×10^{-9} to 1.42×10^{-8} in beans. Studies in Nigeria (Yarima et al., 2019; Muhammad et al., 2024) revealed maize ELCR values ranging from 1.1×10^{-13} to 1.6×10^{-5} , comparable to the results found in this study. In contrast, Onjefu et al. (2021) documented ELCR values well within internationally permissible limits in Namibia, less than those recorded in Bungoma County, further underscoring the need for regular monitoring.

Samples M₉ and B₂ recorded the highest values of Gamma index which can be related to higher specific activity concentration and AEID, **Figure 2** and **Figure 3**.

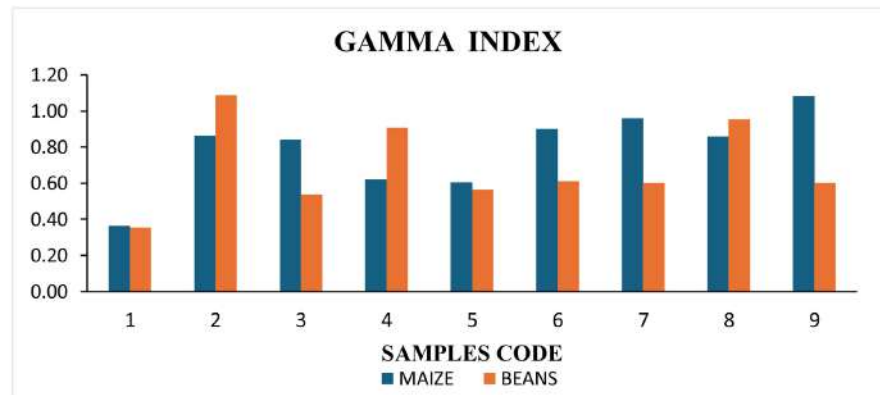


Figure 3. Gamma index in maize and beans samples.

This study suggests that maize consumption presents a slightly greater radiological risk than beans, primarily due to raised AEID and ELCR values, which can be attributed to the higher absorption of ^{232}Th from volcanic soils, differences in plant uptake mechanisms and variations in dietary intake patterns (Tsimbasi et al., 2024). Although the overall radiation levels in both crops are within international safety limits, localized hotspots with higher radiation concentrations indicate potential long-term health risks, especially in maize-consuming populations. The presence of raised ^{232}Th levels in both crops highlights the need for further soil analysis and monitoring to determine the underlying causes of contamination. Since long-term exposure to radionuclides may increase cancer risk, public health interventions should focus on regular monitoring, raising awareness about food safety, and implementing dietary diversification strategies to reduce excessive maize dependency. Conducting a geospatial survey of Bungoma's farmland would help identify high-risk areas and guide mitigation efforts. Furthermore, research into farming practices, including the impact of fertilizers and soil composition, could help in reducing radionuclide uptake in food crops, ultimately ensuring long-term food safety and health security for the local population.

4. Conclusion

Although the overall hazard indices for maize and beans are within ICRP recommended values, maize samples, except M_1 and M_4 , showed AEID values above 1 mSv/year, indicating a possible long-term health risk. The predominant radionuclide contributing to the AEID was ^{232}Th , making up 65% and 61% of the total dose for maize and beans, respectively. Although the ELCR values remained within internationally accepted limits, the study highlights the need for continuous monitoring of radiation levels in locally grown maize and beans to ensure consumer safety. While the immediate health risks are minimal, prolonged exposure to elevated radionuclide concentrations may result in cumulative effects, including increased cancer risks. Therefore, further research and intervention strategies, including soil remediation and dietary diversification, are recommended to mitigate long-term exposure risks and ensure food safety in Bungoma County.

Acknowledgements

The authors would like to convey their heartfelt thanks to the Department of Science, Engineering, and Technology at Kibabii University for their essential assistance and resources during this study. We also acknowledge the National Commission for Science, Technology, and Innovation (NACOSTI) and Bungoma County for issuing the required research licenses. Special thanks go to the local farmers in Bungoma for their collaboration and willingness to share information about their practices.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- Alatise, O. O., & Adebesin, T. C. (2019). Assessment of Radionuclides in Some Nigerian Made Cereals and TEA Products. *Journal of Natural Sciences Engineering and Technology*, 18, 128-142. <https://doi.org/10.51406/jnset.v18i1.2037>
- Asaduzzaman, K., Khandaker, M. U., Amin, Y. M., & Mahat, R. (2015). Uptake and Distribution of Natural Radioactivity in Rice from Soil in North and West Part of Peninsular Malaysia for the Estimation of Ingestion Dose to Man. *Annals of Nuclear Energy*, 76, 85-93. <https://doi.org/10.1016/j.anucene.2014.09.036>
- Avwiri, G. O., Ononugbo, C. P., & Olasoji, J. M. (2021). Radionuclide Transfer Factors of Staple Foods and Its Health Risks in Niger Delta Region of Nigeria. *International Journal of Innovative Environmental Studies Research*, 9, 21-32. <https://doi.org/10.9734/ajr2p/2021/v5i330167>
- Banzi, F., Msaki, P., & Mohammed, N. (2017). Assessment of Radioactivity of ²²⁶Ra, ²³²Th and ⁴⁰K in Soil and Plants for Estimation of Transfer Factors and Effective Dose around Mkuju River Project, Tanzania. *Mining of Mineral Deposits*, 11, 93-100. <https://doi.org/10.15407/mining11.03.093>
- Bilgici Cengiz, G., & Caglar, I. (2022). Evaluation of Lifetime Cancer Risk Arising from Natural Radioactivity in Foods Frequently Consumed by People in Eastern of Turkey. *Journal of Radioanalytical and Nuclear Chemistry*, 331, 1847-1857. <https://doi.org/10.1007/s10967-022-08248-7>
- Bungoma County (2021). *Annual Development Plan 2021*. <https://www.bungoma.go.ke/wp-content/uploads/2023/08/ADP-2021.pdf>
- Butiki, G. W., Makokha, J. W., Masinde, F. W., & Wanyama, C. K. (2021). Annual Effective Dose from Radon-222 Concentration Levels in Underground Water in Bungoma South Sub-County, Kenya. *Journal of Engineering and Technology for Industrial Applications*, 7, 78-82. <https://doi.org/10.5935/jetia.v7i28.736>
- Changizi, V., Shafiei, E., & Zareh, M. R. (2013). Measurement of ²²⁶Ra, ²³²Th, ¹³⁷Cs and ⁴⁰K Activities of Wheat and Corn Products in Ilam Province–Iran and Resultant Annual Ingestion Radiation Dose. *Iranian Journal of Public Health*, 42, Article 903.
- El-Gamal, H., Hussien, M. T., & Saleh, E. E. (2019). Evaluation of Natural Radioactivity Levels in Soil and Various Foodstuffs from Delta Abyan, Yemen. *Journal of Radiation Research and Applied Sciences*, 12, 226-233. <https://doi.org/10.1080/16878507.2019.1646523>
- Fathabadi, N., Salehi, A. A., Naddafi, K., Kardan, M. R., Yunesian, M., Nodehi, R. N. et al.

- (2017). Radioactivity Levels in the Mostly Local Foodstuff Consumed by Residents of the High Level Natural Radiation Areas of Ramsar, Iran. *Journal of Environmental Radioactivity*, 169, 209-213. <https://doi.org/10.1016/j.jenvrad.2016.12.011>
- Geremew, H. (2023). *Activity Concentration of Natural Radionuclides in Agricultural Soil, Fertilizer, Their Transfer to Some Commonly Used Cereal Types, and Associated Health Hazards, Holeta, Ethiopia*. <https://doi.org/10.21203/rs.3.rs-2801551/v1>
- Hameed, B. S., & Fzaa, W. T. (2021). Concentrations and Radiation Hazard Indices of Naturally Radioactive Materials for Flour Samples in Baghdad Markets. *Baghdad Science Journal*, 18, Article 649. <https://doi.org/10.21123/bsj.2021.18.3.0649>
- International Commission on Radiological Protection (2012). ICRP Statement on Tissue Reactions/Early and Late Effects of Radiation in Normal Tissues and Organs—Threshold Doses for Tissue Reactions in a Radiation Protection Context. ICRP Publication 118. *Annals of the ICRP*, 41, 1-322. <https://doi.org/10.1016/j.icrp.2012.02.001>
- Kenya National Bureau of Statistics (2019). *Food Balance Sheets: Kenya 2014-2018 Results*. African Development Bank. <https://www.afdb.org/en/documents/food-balance-sheets-kenya-2014-2018-results>
- Kim, G., & Cho, J. (2022). Radioactive Concentrations in Chemical Fertilizers. *Journal of Radiation Protection and Research*, 47, 195-203. <https://doi.org/10.14407/jrpr.2021.00269>
- Lopes, J. M., Garcêz, R. W. D., Filgueiras, R. A., Silva, A. X., & Braz, D. (2018). Committed Effective Dose Due to the Intake of ^{40}K , ^{226}Ra , ^{228}Ra and ^{228}Th Contained in Foods Included in the Diet of the RIO de Janeiro City Population, Brazil. *Radiation Protection Dosimetry*, 181, 149-155. <https://doi.org/10.1093/rpd/ncx310>
- Marques, R., Prudêncio, M. I., Russo, D., Cardoso, G., Dias, M. I., Rodrigues, A. L. et al. (2021). Evaluation of Naturally Occurring Radionuclides (K, Th and U) in Volcanic Soils from Fogo Island, Cape Verde. *Journal of Radioanalytical and Nuclear Chemistry*, 330, 347-355. <https://doi.org/10.1007/s10967-021-07959-7>
- Mohebian, M., & Pourimani, R. (2020). Specific Activity and Radiation Hazard of Radionuclides in Wheat and Bean Produced Near Shazand, Iran. *Iranian Journal of Medical Physics*, 17, 394-400. <https://doi.org/10.22038/ijmp.2020.44031.1668>
- Muhammad, A. N., Ismail, A. F., & Garba, N. N. (2024). Natural Radioactivity in Food Crops and Soil and Estimation of the Concomitant Dose from Tin Mining Areas in Nigeria. *Journal of Taibah University for Science*, 18, Article 2366507. <https://doi.org/10.1080/16583655.2024.2366507>
- Onjefu, S. A., Kafidi, N. N., Kamunda, C., Uloko, P. I., Hitila, M., Ejembi, E., & Kennedy, J. (2021). Activity Concentrations of ^{226}Ra , ^{232}Th , and ^{40}K in Common Maize Meal Consumed in Namibia and Their Potential Radiation Hazards. *Nigerian Annals of Pure and Applied Sciences*, 4, 131-136. <https://doi.org/10.46912/napas.231>
- Rotich, C. K. (2022). *Effects of Human Exposure and Associated Risks Due to Natural Radioactivity and Heavy Metals in Bureti, Kericho County, Kenya*. Doctoral Dissertation, Kenyatta University.
- Sultana, A., Siraz, M. M., Pervin, S., Rahman, A. M., Das, S. K., & Yeasmin, S. (2019). Assessment of Radioactivity and Radiological Hazard of Different Food Items Collected from Local Market in Bangladesh. *Journal of Bangladesh Academy of Sciences*, 43, 141-148. <https://doi.org/10.3329/jbas.v43i2.45735>
- Tawalbeh, A. A., Abumurad, K. M., Samat, S. B., & Yasir, M. S. (2011). A Study of Natural Radionuclide Activities and Radiation Hazard Index in Some Grains Consumed in Jordan. *Malaysian Journal of Analytical Sciences*, 15, 61-69.

- Tsimbasi, S. C., Makokha, J. W., & Odumo, B. O. (2024). Natural Radioactivity Levels and Radiological Risk Assessment in Locally Grown Maize and Beans from Bungoma County. *Open Access Library, 11*, 1-18. <https://doi.org/10.4236/oalib.1112592>
- UNSCEAR (2000). *United Nations Scientific Committee on the Effects of Atomic Radiation, Sources and Effects of Ionizing Radiation*. United Nations Publication. <https://doi.org/10.18356/49c437f9-en>
- Vila-Real, C. P. D. M., Pimenta-Martins, A. S., Kunyanga, C. N., Mbugua, S. K., Katina, K., Maina, N. H. et al. (2022). Nutritional Intake and Food Sources in an Adult Urban Kenyan Population. *Nutrition Bulletin, 47*, 423-437. <https://doi.org/10.1111/nbu.12582>
- Wabomba, J. S., Waswa, M. N., Khakina, P., & Wanyama, C. K. (2022). Natural Radioactivity Levels in Agricultural Soils in Trans Nzoia County, Kenya. *IRES PUB Journal of Environmental & Material Sciences, 2*, 1-10.
- Yarima, M. H., Khandaker, M. U., Nadhiya, A., & Olatunji, M. A. (2019). Assessment of Natural Radioactivity in Maize and Estimation of Concomitant Dose to Nigerian Via Ingestion Pathway. *Radiation Protection Dosimetry, 184*, 359-362. <https://doi.org/10.1093/rpd/ncz115>