Open Access Library Journal
2024, Volume 11, e12592
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Natural Radioactivity Levels and Radiological Risk Assessment in Locally Grown Maize and Beans from Bungoma County

Stanley C. Tsimbasi[1], John W. Makokha[1], Benjamin O. Odumo[2]

[1]Department of Science, Technology and Engineering, Kibabii University, Bungoma, Kenya
[2]Department of Physics, University of Nairobi, Nairobi, Kenya
Email: tsimbasi@gmail.com

How to cite this paper: Tsimbasi, S.C., Makokha, J.W. and Odumo, B.O. (2024) Natural Radioactivity Levels and Radiological Risk Assessment in Locally Grown Maize and Beans from Bungoma County. *Open Access Library Journal*, **11**: e12592.
https://doi.org/10.4236/oalib.1112592

Received: November 8, 2024
Accepted: December 27, 2024
Published: December 30, 2024

Abstract

This study investigated the concentration of ^{226}Ra, ^{232}Th, and ^{40}K in maize (Zea mays) and beans (Phaseolus vulgaris), the common cereals and pulses available in Bungoma County. Eighteen representative samples were collected from the study area and analyzed using a Thallium-activated Sodium Iodide NaI (TI) scintillation detector. The average activity concentration of ^{226}Ra, ^{232}Th, and ^{40}K in maize were found to be 20.9 ± 7.19 Bq/kg, 54 ± 21.15 Bq/kg, and 161 ± 76.84 Bq/kg, while in beans, these values were 18.4 ± 4.03 Bq/kg, 43 ± 15.51 Bq/kg and 195 ± 132.48 Bq/kg respectively. The mean absorbed dose rates were 49 ± 2.45 nGy/h and 43 ± 2.15 nGy/h for maize and beans respectively which were lower than the admissible dose standard of 1500 nGy/h. The average annual effective ingestion dose (AEID) in maize and beans were 1.240 mSv/y and 0. 263 mSv/y respectively. The average AEID values in maize were above the limit of 1mSv/y for the general public, as the International Commission on Radiological Protection (ICRP) recommended. 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. While the AEID in maize suggests an elevated health risk for consumers due to whole-body radiation exposure, the overall radiological risk posed by beans and other consumption in the region remains minimal and within international safety limits hence poses no significant risk to the consumers and the general populace of Bungoma County.

Subject Areas

Nuclear Physics

Keywords

Radionuclides, Radiological Risk Assessment, Absorbed Dose Rate, Annual

Effective Dose, Cereals, Pulses

1. Introduction

Food is an essential source of nutrients for human subsistence. However, its consumption is among the most important routes by which natural and artificial radionuclides get into the human body [1]. It has been projected that the intake of food causes at least one-eighth of the mean yearly dosage derived from natural sources [2]. According to the study carried out by Vila-Real *et al.* [3], cereals and pulses account for over 34% of the food intake in Kenyan households. It is important to understand the rate at which radiation is received [4]. Determining the radiation levels of cereal samples is essential to identifying the expected radiation doses and preventing consumers from being susceptible to low-energy radiation due to the intake of maize and beans.

Natural sources of radiation include high-energy cosmic rays and radioactive nuclides from the Earth's crust, which accumulate in agricultural fields through physical and chemical weathering [5] [6]. Artificial radiation arises mainly from nuclear weapons tests, reactor accidents, and airborne emissions from nuclear facilities, leading to radioactive dust settling on fertile land [7]. Agricultural activities such as the use of inorganic fertilizers, herbicides, and pesticides that may contain radionuclides like ^{226}Ra, ^{232}Th, and ^{40}K may increase the concentration of these radionuclides in soil [8]. Olatunji *et al.* [9] also noted that chemical and fertilizer applications modify the chemical and physical properties of radionuclides in soil, potentially increasing radionuclide uptake. According to ICRP [10], it was estimated that the usage of phosphate fertilizer has at least increased the continued exposure of humans through food consumption. Thus, contamination of the food chain might emerge as an outcome of direct deposition of these radionuclides on plants' leaves, fruits, and tubers, as well as via root absorption from contaminated soil or water, which are primarily the edible components of a plant [1].

According to Fathabadi *et al.* [11], radionuclides that are ingested through food consumption contribute significantly to the average irradiation of different organs in the body and are among the most vital aspects to consider for long-term health. Consumption of contaminated cereals and pulses by these radionuclides can cause health problems like; Immunological defenses, intrauterine growth retardation, poor psychosocial behavior, and malnutrition-related impairments [12]. Lopes *et al.* [13] outlined that the internal dosage owing to natural radionuclides is not harmful, provided that the receiving of such elements is not above the recommended.

Therefore, studying radionuclide levels in food crops is crucial to ensure their concentrations do not exceed the limits recommended by the International Commission on Radiological Protection (ICRP), as elevated levels can pose health risks to consumers. This study aimed to establish baseline information on the natural radioactivity levels in maize and beans consumed in Bungoma County. It focused on measuring the specific activity concentrations of naturally occurring radionuclides, including ^{226}Ra, ^{232}Th, and ^{40}K, in locally grown samples using a Thallium-activated Sodium Iodide NaI (TI) scintillation detector. Additionally, the study assessed the radium equivalent dose, absorbed dose rate, annual effective dose, and annual effective ingestion dose, providing essential data on the radiological hazards associated with the consumption of these foods. By providing specific information on the activity concentration levels of natural radionuclides and the associated health risks, this research contributes to the development of guidelines to protect public health from radiation exposure through food.

2. Materials and Methods

2.1. Area of Study

Bungoma County, located in western Kenya within the Lake Victoria Basin, covers 3032.4 km² and lies between latitudes 00˚28'N and 10˚30'N, and longitudes 34˚20'E and 35˚5'E. The county borders Uganda to the northwest, Trans-Nzoia to the northeast, Kakamega to the east, and Busia to the west, with a population of approximately 1.67 million. It consists of nine sub-counties: Kanduyi, Bumula, Sirisia, Kabuchai, Mt. Elgon, Webuye East, Webuye West, Tongaren, and Kimilili [14] [15].

Figure 1 shows a map of Bungoma County's location within Kenya and the nine sub-counties.

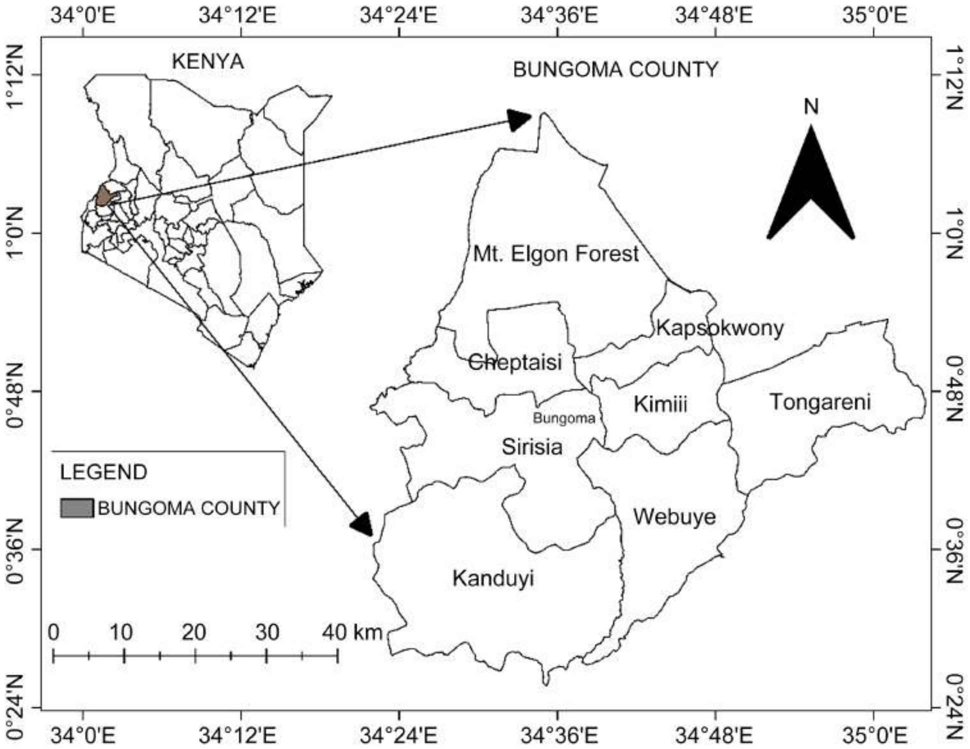

Figure 1. Map of Bungoma county, Kenya.

The region has a tropical climate, with two rainy seasons and an average annual rainfall of 1200mm to 1800mm. Its fertile volcanic soils support extensive agriculture, primarily growing maize and beans, the region's staple foods. Agriculture is the county's primary economic activity, and these crops are crucial for both subsistence and trade. Bungoma's population relies heavily on locally grown crops, making it essential to assess the radiological risks of consuming maize and beans. The region's soils may contain natural radionuclides such as ^{226}Ra, ^{232}Th, and ^{40}K, which could be further concentrated by the use of fertilizers.

The county's proximity to Mount Elgon and its varied topography also pose environmental concerns, such as the accumulation of radionuclides in soil, which could potentially affect food safety. This study focused on measuring radionuclide levels in maize and beans, and seeks to establish a baseline for radiation exposure through food consumption. The findings will provide vital information for protecting public health and informing sustainable agricultural practices in Bungoma County.

This map shows Bungoma County's location within Kenya and the nine sub-counties.

2.2. Sample Collection and Preparation

Approximately 200g of maize and beans samples were collected randomly from 3 different households in each of the nine sub-counties except Mount Elgon where five samples were collected due to its large coverage area. The samples were labeled with the GPS location (latitude and longitude), properly packed in small bags to avoid cross-contamination, and transported to the laboratory for preparation. The samples were first sundried for 2 days to ensure the moisture content was eliminated. 150g of each of the three samples from each sub-county (for maize and beans) were mixed to obtain a representative sample. The samples were then blended into powder using a multifunctional grinder rated at 2300 W, 240 V with a motor speed of 25000 r/min, for 5 minutes each to achieve a homogeneous state. A fine aperture mesh screen with a mesh size of 2 μm was used to filter the powdered samples in order to eliminate any unnecessary particles and produce a finely grained sample that provided a homogeneous matrix to the detector. The samples were then dried in an oven at 50˚C to 60˚C until a steady weight was reached and to make sure that all noticeable moisture has been eliminated from the samples. [8] [16] [17]. Samples were considered dehumidified when the rate of mass variation tends to zero [13]. 200g of samples were weighed using an electronic top pan balance and subsequently moved into 8.5 cm in diameter and 7 cm in height cylindrical containers made of plastic and labeled appropriately [18]. For the maize samples, they were labeled M_1 through M_9 (**Table 1**). Likewise, samples of beans were labeled B_1 through B_9, where B stands for beans and 1 for the region (**Table 2**). The samples were kept for one month to enable the daughter products to enter secular equilibrium with their parents ^{226}Ra and ^{232}Th [6] [19].

2.3. Instrument Calibration

In this work, IAEA standard reference materials RG-U, RG-K, and RG-Th are used to acquire the spectrum and estimate the activity concentration of specific radionuclides. The activity concentration of ^{214}Bi (1765 keV) was used to estimate the activity concentration of ^{226}Ra, while the activity concentration of ^{232}Th was determined using the ^{208}Tl (2615 keV) gamma energy peak [8]. Due to the limited resolution of the gamma-ray detector, the energy peaks were chosen because they differ from other peaks. The activity concentration of ^{40}K was obtained using its 1460 keV gamma energy peak [13]. The net peak count rate (cps) for each radionuclide was calculated by subtracting its net peak count rate from that of the sample. The data acquisition period for each sample was 28800 seconds.

Table 1. The specific activity concentration, radium equivalent, absorbed dose rate and annual effective ingestion dose in maize samples.

Sample	Specific Activity Concentration (Bq/kg)			Radium Equivalent (Bq/kg)	Absorbed Dose Rate (nGy/h)	Annual Effective Ingestion Dose ($mSvy^{-1}$)
	^{226}Ra	^{232}Th	^{40}K			
M_1	11.50 ± 0.57	23.00 ± 1.16	82.00 ± 4.14	51.00 ± 2.56	22.00 ± 1.14	0.5852
M_2	15.00 ± 0.75	73.00 ± 3.65	46.00 ± 2.34	122.00 ± 6.14	53.00 ± 2.65	1.3652
M_3	20.80 ± 1.04	61.00 ± 3.06	132.00 ± 6.64	118.00 ± 5.93	52.00 ± 2.61	1.3311
M_4	30.10 ± 1.50	23.00 ± 1.16	279.00 ± 13.99	85.00 ± 4.25	39.00 ± 1.98	0.9961
M_5	30.10 ± 1.50	29.00 ± 1.46	170.00 ± 8.52	84.00 ± 4.24	38.00 ± 1.93	1.0387
M_6	12.70 ± 0.63	75.00 ± 3.79	87.00 ± 4.37	127.00 ± 6.39	55.00 ± 2.76	1.3829
M_7	30.10 ± 1.50	64.00 ± 3.21	176.00 ± 8.83	135.00 ± 6.77	60.00 ± 3.00	1.5578
M_8	16.20 ± 0.81	61.00 ± 3.06	206.00 ± 10.31	119.00 ± 5.98	53.00 ± 2.65	1.2772
M_9	22.00 ± 1.10	75.00 ± 3.79	267.00 ± 13.36	151.00 ± 7.55	67.00 ± 3.35	1.6206
MEAN ± S.D	**20.90 ± 7.19**	**54.00 ± 21.15**	**161.00 ± 76.84**	**110.00 ± 29.22**	**49.00 ± 12.52**	**1.24 ± 0.29**

Table 2. The specific activity concentration, radium equivalent, absorbed dose rate and annual effective ingestion dose in beans samples.

Samples	Specific Activity Concentration (Bq/kg)			Radium Equivalent (Bq/kg)	Absorbed Dose Rate (nGy/h)	Annual Effective Ingestion Dose $mSvy^{-1}$
	^{226}Ra	^{232}Th	^{40}K			
B_1	15.00 ± 0.75	23.00 ± 1.16	28.00 ± 1.40	50.00 ± 2.52	22.00 ± 1.11	0.156
B_2	12.70 ± 0.63	67.00 ± 3.35	498.00 ± 24.93	147.00 ± 7.35	67.00 ± 3.36	0.354
B_3	23.10 ± 1.15	23.00 ± 1.16	226.00 ± 11.33	73.00 ± 3.69	34.00 ± 1.71	0.212
B_4	19.60 ± 0.98	58.00 ± 2.92	287.00 ± 14.38	125.00 ± 6.26	56.00 ± 2.81	0.332
B_5	22.00 ± 1.10	32.00 ± 1.60	142.00 ± 7.11	78.00 ± 3.94	35.00 ± 1.77	0.231
B_6	18.50 ± 0.92	40.00 ± 2.04	118.00 ± 5.94	86.00 ± 4.3	38.00 ± 1.91	0.245
B_7	20.80 ± 1.04	40.00 ± 2.04	81.00 ± 4.06	85.00 ± 4.27	37.00 ± 1.88	0.252
B_8	22.00 ± 1.10	64.00 ± 3.21	247.00 ± 12.35	132.00 ± 6.63	59.00 ± 2.96	0.360
B_9	11.50 ± 0.57	43.00 ± 2.19	131.00 ± 6.56	84.00 ± 4.21	37.00 ± 1.86	0.226
MEAN ± S.D	**18.40 ± 4.03**	**43.00 ± 15.51**	**195.00 ± 132.48**	**96.04 ± 29.82**	**43.00 ± 13.66**	**0.263 ± 0.07**

SD-Standard deviation.

2.4. Sample Analysis

2.4.1. The Specific Activity

Specific activity is the radionuclide's decay rate per unit mass. This equation provides the specific activity associated with each radionuclide in a sample [8] [20].

$$A = \frac{N \times 100 \times 1000}{P\gamma \times \varepsilon \times W} \tag{1}$$

where A is the activity of the sample in Bq/kg, ε is the counting efficiency of the gamma energy, $P\gamma$ is the absolute intensity of the gamma-ray, and W net weight of the sample (in grams).

2.4.2. Radium Equivalent Activity (Ra_{eq})

Radium equivalent activity is a comparable concentration value of the radium element, denoted Ra_{eq}, used to calculate the risk concentration brought on by ^{226}Ra, ^{232}Th, and ^{40}K (Bq/kg). It was determined by Equation (2) [21].

$$Ra_{eq} = C_{(Ra)} + 1.43C_{(Th)} + 0.077C_{(K)} \tag{2}$$

where $C_{(Ra)}$, $C_{(Th)}$, and $C_{(K)}$ represented radioactivity concentration in (Bq/kg) for ^{226}Ra, ^{232}Th, and ^{40}K, respectively, the maximum amount of radium equivalent activity that is allowed is 370 Bq/kg.

2.4.3. Absorbed Dose Rate

Absorbed dose rate is the quantity of energy that a tissue absorbs per unit mass. It is also known as the direct correlation between natural radionuclide exposure in the air at one meter above the ground and their radioactivity concentrations. The samples' absorbed dose rate is determined using the mean activity concentrations of ^{232}Th, ^{226}Ra, and ^{40}K (Bq/kg) in the samples, Equation (3) [22].

$$D = 0.462C_{Ra} + 0.604C_{Th} + 0.0417C_{K} \tag{3}$$

where D is the absorbed dose rate in $nGyh^{-1}$. Where, C_{Ra}, C_{Th}, and C_K are the specific activities of ^{226}Ra, ^{232}Th, and ^{40}K, respectively in Bq/kg.

2.4.4. Annual Effective Ingestion Dose (AEID)

The Annual Effective Ingestion Dose represents the health risk for the whole body due to the intake of foods [23]. It can be used to estimate an individual's annual effective ingestion dose from radionuclide dietary intake, Equation (4),

$$\text{AEID}\ (\mu Sv\ y^{-1}) = C \times A_I \times F_{DC} \tag{4}$$

where C is the concentration of each radionuclide in units of $Bq \cdot kg^{-1}$, AI is the annual intake of each food in kilograms per year and F_{DC} is the standard dosage conversion factor, which is equivalent to 0.28 $\mu Sv \cdot Bq^{-1}$ for ^{226}Ra, 0.23 $\mu Sv \cdot Bq^{-1}$ for ^{232}Th and 0.0062 $\mu Sv \cdot Bq^{-1}$ for ^{40}K coefficients take account of age-related changes in intestinal absorption, body and organ masses, and excretion rates from the urinary bladder [24].

3. Results and Discussion

3.1. Radiological Assessment of Maize Samples

Table 1 presents the specific activity concentrations of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K, along with the radium equivalent (Raeq), absorbed dose rate (nGy/h), and annual effective ingestion dose (AEID) in maize samples (M_1 to M_9) from the study area. The results provide valuable insights into the radiological safety of maize consumed in Bungoma County.

3.1.1. Specific Activity Concentrations

The specific activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K vary significantly across the maize samples. The concentration of ^{226}Ra ranges from 11.50 ± 0.57 Bq/kg (M_1) to 30.10 ± 1.50 Bq/kg (M_4, M_5, and M_7). The mean value of 20.90 ± 7.19 Bq/kg indicates relatively moderate variation, but M_4, M_5, and M_7 exhibit higher concentrations as seen in Figure 2, suggesting potential local variations in soil or environmental factors influencing ^{226}Ra uptake.

For ^{232}Th, the concentration shows wider variation, ranging from 23.00 ± 1.16 Bq/kg (M_1, M_4) to 75.00 ± 3.79 Bq/kg (M_6, M_9). The mean value is 54.00 ± 21.15 Bq/kg, indicating that some samples have relatively higher concentrations, particularly M_6, M_7, and M_9, see Figure 2 which could reflect localized differences in soil composition or fertilizer use.

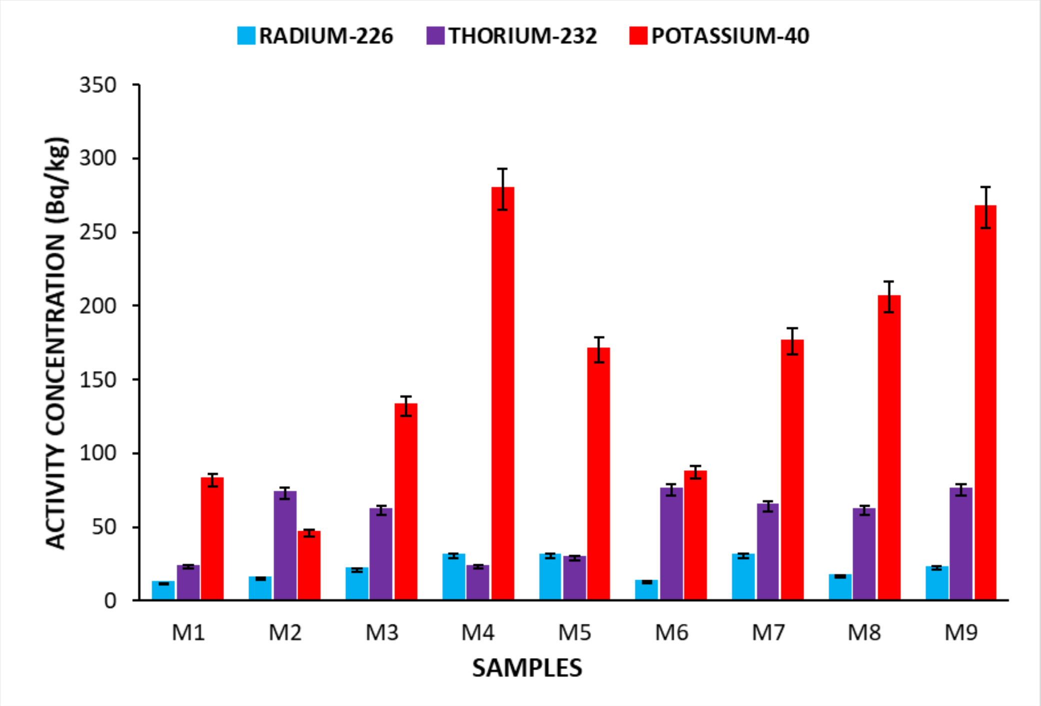

Figure 2. Activity concentration in maize.

^{40}K exhibits the highest concentration among the three radionuclides, with values ranging from 46.00 ± 2.34 Bq/kg (M_2) to 279.00 ± 13.99 Bq/kg (M_4). The mean value of 161.00 ± 76.84 Bq/kg suggests substantial variability. ^{40}K is a common radionuclide in soils and plants due to its abundance in nature, and the variations seen here could be linked to differences in the potassium content of soils in various locations.

Bungoma showed higher ^{226}Ra and ^{232}Th levels compared to Rio, Brazil, which recorded 5.40 ± 1.3 Bq/kg for ^{226}Ra and 1.09 ± 0.17 Bq/kg for ^{232}Th, but ^{40}K was significantly lower in Bungoma than in Rio (489.36 ± 23.70 Bq/kg) [13]. Compared to Bureti, Kenya, Bungoma had much lower levels for all radionuclides, as Bureti recorded 68 ± 4 Bq/kg for ^{226}Ra, 77 ± 5 Bq/kg for ^{232}Th, and 651 ± 33 Bq/kg for ^{40}K [25]. This highlights the moderate levels of radioactivity in Bungoma relative to regions with higher and lower radionuclide concentrations.

3.1.2. Radium Equivalent (Ra_{eq})

The radium equivalent activity (Ra_{eq}) is a standard measure used to compare the combined activity of ^{226}Ra, ^{232}Th, and ^{40}K to a single value that reflects their potential radiological hazard. In the samples, Ra_{eq} values range from 51.00 ± 2.56 Bq/kg (M_1) to 151.00 ± 7.55 Bq/kg (M_9) (see **Figure 3**).

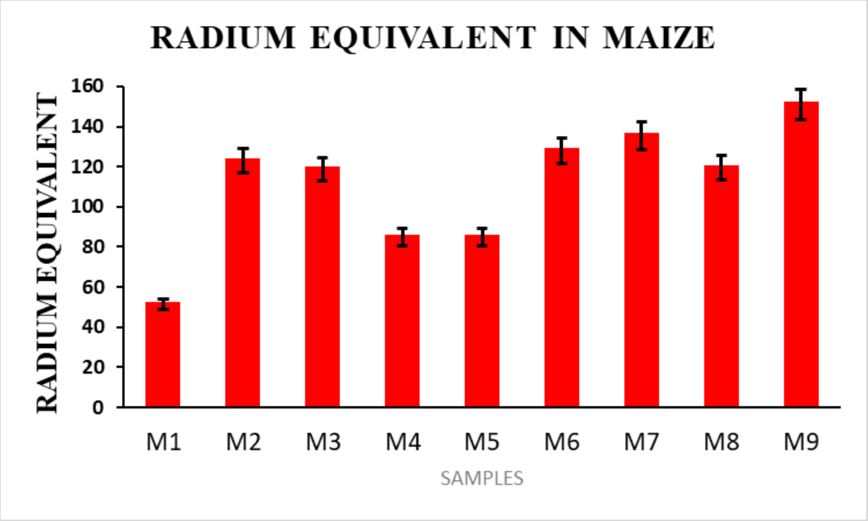

Figure 3. Radium equivalent in maize (NB: The value of ^{40}K in this figure was reduced by a scale factor of 5 since it had higher values compared to ^{226}Ra and ^{232}Th. This aided in interpreting activity concentration at lower values accurately).

The mean value is 110.00 ± 29.22 Bq/kg, which is well below the safety limit of 370 Bq/kg. These values can be attributed to higher levels of ^{232}Th and ^{40}K in examined maize samples. This implies that the maize samples from Bungoma County pose no significant radiation hazard based on their.

In the current study, Ra_{eq} values varied significantly across the regions studied reflecting differences in environmental and agricultural factors. Soil composition plays a key role, as geological formations like granitic and volcanic soils tend to have higher levels of radionuclides such as ^{226}Ra, ^{232}Th, and ^{40}K [26]. The use of phosphate-based fertilizers further contributes, as these often contain trace amounts of radioactive elements [27]. Environmental processes like erosion, water runoff, and sediment transport also redistribute radionuclides, creating uneven concentrations across agricultural fields [5]. Understanding these factors is crucial for managing radiological risks in food and the environment. Dhaka, Bangladesh, was reported to have a Ra_{eq} of 113.78 Bq/kg, slightly higher than some other areas [8]. Skopje, North Macedonia, recorded a notably low Ra_{eq} of 7.64 Bq/kg [28], while Penang, Malaysia, showed a significantly higher value of 211.646 Bq/kg [2]. In the Niger Delta, Nigeria, a moderate Ra_{eq} of 48.4 Bq/kg was observed [29]. These variations illustrated the impact of regional geological conditions and agricultural practices on radionuclide concentrations.

3.1.3. Absorbed Dose Rate

The absorbed dose rate (ADR) indicates the rate at which radiation energy is absorbed by human tissue from exposure to the radionuclides. In the maize samples, the dose rate ranges from 22.00 ± 1.14 nGy/h (M_1) to 67.00 ± 3.35 nGy/h (M_9) as seen in **Figure 4**, with a mean of 49.00 ± 12.52 nGy/h. These values are significantly lower than the global average outdoor absorbed dose rate of 59 nGy/h, as reported by United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR [5].

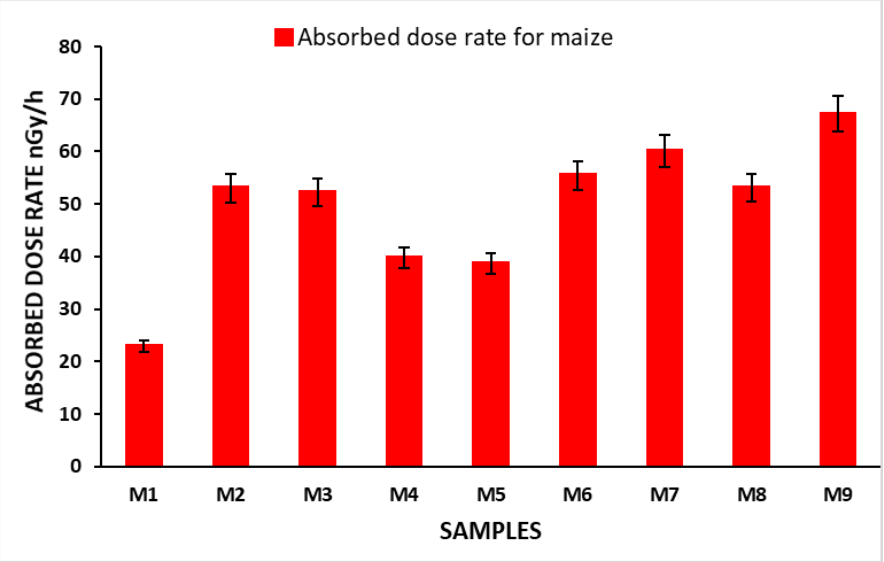

Figure 4. Absorbed dose rate in maize.

Elevated values of ADR in maize may lead to an increase in the annual effective ingestion dose which in turn translates to increased irradiation risk of internal organs of the body. From this study the radiation exposure from maize consumption in this region remains within acceptable limits and does not present an immediate radiological threat to the population.

3.1.4. Annual Effective Ingestion Dose (AEID)

The annual effective ingestion dose (AEID) is a critical parameter for assessing the potential health risks associated with consuming radionuclides through food. In the study, AEID values range from 0.5852 mSv/y (M_1) to 1.6206 mSv/y (M_9). ^{232}Th had the highest contribution of 65% of the total AEID compared to ^{40}K and ^{226}Ra, as seen in **Figure 5**. The average AEID is 1.24 ± 0.29 mSv/y, which slightly exceeds the recommended safety limit of 1 mSv/y set by the International Commission on Radiological Protection (ICRP) for the general public.

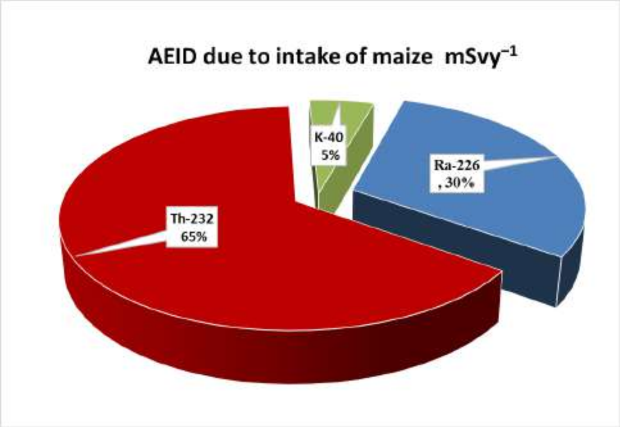

Figure 5. Annual effective ingestion dose in maize.

Although the mean AEID suggests an elevated health risk from maize consumption, it is important to note that not all samples exceed the limit. Samples such as M_1 and M_4 show relatively lower doses, while M_9 and M_7 present higher risks, see **Table 1**. Elevated radiation doses to specific organs can impact human health by weakening the immune system, causing a variety of diseases, and ultimately raising mortality rates [30].

The elevated AEID values, particularly in M_9, highlight a potential concern for consumers in regions where these maize samples were grown, and measures to mitigate exposure, such as monitoring fertilizer use or soil quality, may be necessary.

3.2. Radiological Assessment of Beans Samples

Table 2 presents the specific activity concentrations of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in beans (samples B_1 to B_9), alongside the corresponding radium equivalent (Ra_{eq}), absorbed dose rate (nGy/h), and annual effective ingestion dose (AEID) for consumers. The results offer key insights into the radiological safety of beans consumed in Bungoma County, providing data essential for assessing potential health risks.by the International Commission on Radiological Protection (ICRP) for the general public.

3.2.1. Specific Activity Concentrations in Beans

The specific activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K vary significantly across the nine samples: ^{226}Ra concentrations range from 11.50 ± 0.57 Bq/kg (B_9) to 23.10 ± 1.15 Bq/kg (B_3), with a mean of 18.40 ± 4.03 Bq/kg. ^{232}Th shows wider variability, with concentrations ranging from 23.00 ± 1.16 Bq/kg (B_1, B_3) to 67.00 ± 3.35 Bq/kg (B_2), with a mean of 43.00 ± 15.51 Bq/kg. ^{40}K exhibits the highest variation, with concentrations ranging from 28.00 ± 1.40 Bq/kg (B_1) to 498.00 ± 24.93 Bq/kg (B_2) (See **Figure 6**).

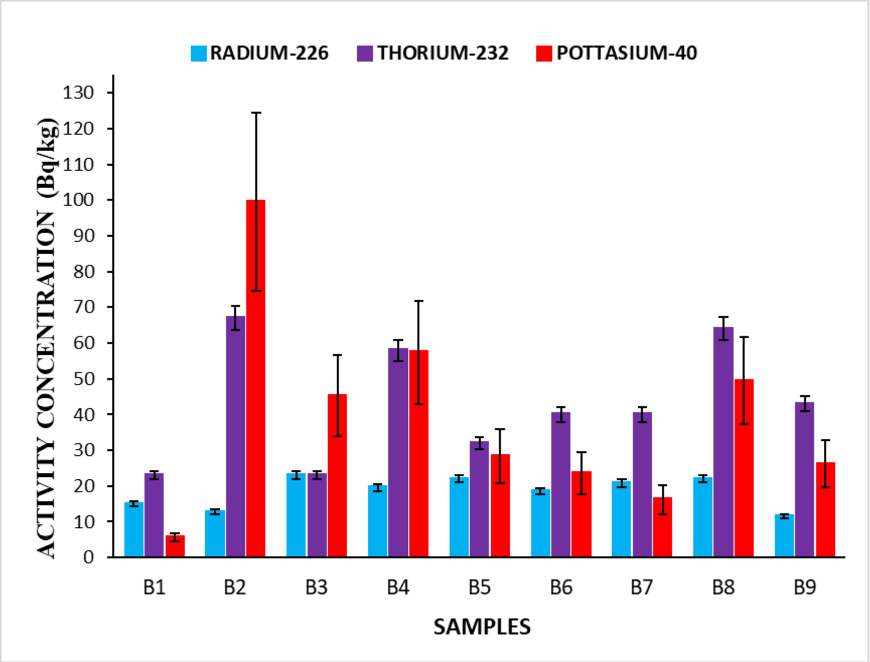

Figure 6. Activity concentration in beans (*NB: The value of* ^{40}K *in* **Figure 6** *was reduced by a scale factor of* 5 *since it had higher values compared to* ^{226}Ra *and* ^{232}Th. *This aided in interpreting activity concentration at lower values accurately*).

The mean value of 195.00 ± 132.48 Bq/kg indicates significant variability. ^{40}K is a naturally occurring radionuclide that tends to vary based on soil and crop type, and its relatively high levels in beans are typical due to potassium's essential role in plant growth.

When comparing radionuclide activity concentrations in beans, several regions report higher levels than the current study. In Bangladesh, ^{226}Ra and ^{40}K concentrations are notably higher, while ^{232}Th is lower [8]. Similarly, in Tanzania, both ^{232}Th and ^{40}K are much higher than in the current study, while ^{226}Ra levels are comparable [31]. In the Niger Delta, Nigeria, ^{232}Th and ^{40}K are also higher, while ^{226}Ra is slightly lower than in the current study [29]. In Bureti, Kenya, all radionuclides are significantly higher compared to the current study [13]. These comparisons reveal how regional geological and agricultural factors influence radionuclide concentrations in different areas.

Since ^{40}K's particles are diminutive than those of ^{232}Th and ^{226}Ra, they diffuse more from the substrate to the plants than do the latter two. This explains why ^{40}K has a higher concentration of ^{40}K in maize and bean samples [32]. It may also be connected to farmers' extensive use of nitrogenous fertilizers to increase yields, which the crops may subsequently take along with minerals and other nutrients [33]. The elevated values of ^{40}K and ^{232}Th in samples M_8 and B_8, **Table 1** and **Table 2**, correspond to the earlier research done on the assessment of human exposure to natural sources of radiation on the soil in the Tongaren constituency which recorded high values at 85.0 ± 4.3 Bq/kg and 981.5 ± 49.1 Bq/kg for ^{232}Th and ^{40}K respectively. This suggests there is a strong correlation between radionuclides available in the soil and those transferred to plants for instance cereals [34]. This broad range highlights the potential influence of soil composition, agricultural practices, and environmental factors on thorium concentrations in beans.

3.2.2. Radium Equivalent (Ra_{eq})

The radium equivalent (Ra_{eq}) combines the activity of ^{226}Ra, ^{232}Th, and ^{40}K into a single metric to assess the overall radiological hazard of the samples. Ra_{eq} values in beans range from 50.00 ± 2.52 Bq/kg (B_1) to 147.00 ± 7.35 Bq/kg (B_2), with a mean of 96.04 ± 29.82 Bq/kg (See **Figure 7**).

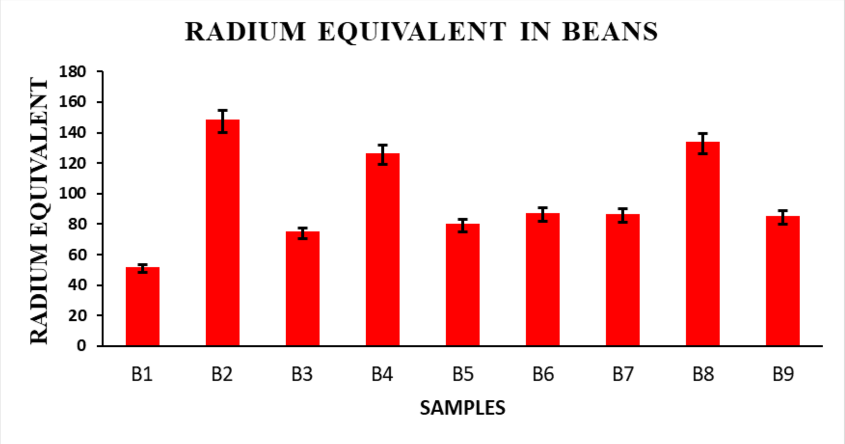

Figure 7. Radium equivalent in beans.

The Ra_{eq} in this study is much higher compared to other regions. For instance, the Niger Delta, Nigeria, and Shazand, Iran, have moderate values of 63.41 Bq/kg and 41.28 Bq/kg [29] [35], while Skopje, North Macedonia, has the lowest at just 6.46 Bq/kg. This study higher Ra_{eq} could be due to its volcanic soils, which are rich in granitic rocks, and the use of inorganic fertilizers that might introduce additional radionuclides. These geological and farming practices likely explain the elevated levels observed in the area.

These values are well below the internationally accepted safety threshold of 370 Bq/kg, indicating that the combined activity of the radionuclides does not pose significant radiological risks to consumers. Even the highest value in sample B_2 is far below this limit, suggesting that the beans are safe in terms of overall radionuclide content.

3.2.3. Absorbed Dose Rate

The absorbed dose rate represents the amount of radiation energy absorbed by human tissue from exposure to these radionuclides. In the samples, absorbed dose rates range from 22.00 ± 1.11 nGy/h (B_1) to 67.00 ± 3.36 nGy/h (B_2), with a mean of 43.00 ± 13.66 nGy/h (See **Figure 8**).

The values are generally lower than the global average absorbed dose rate of 59 nGy/h [5]. This indicates that radiation exposure due to bean consumption in Bungoma County does not pose a substantial health risk.

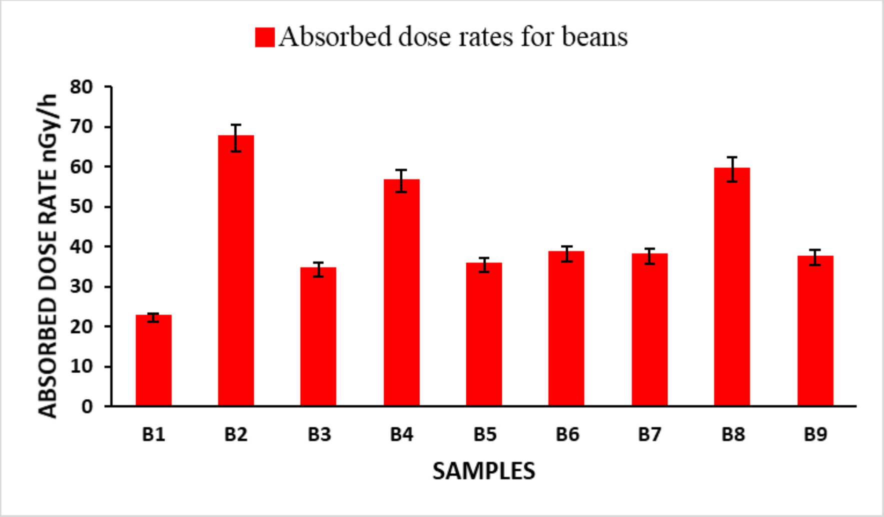

Figure 8. Absorbed dose rate in beans.

3.2.4. Annual Effective Ingestion Dose (AEID)

The annual effective ingestion dose (AEID) is a key metric for assessing the potential health risks from consuming radionuclide-contaminated food. The AEID values range from 0.156 mSv/y (B_1) to 0.360 mSv/y (B_8), with a mean of 0.263 ± 0.07 mSv/y (See Table 2).

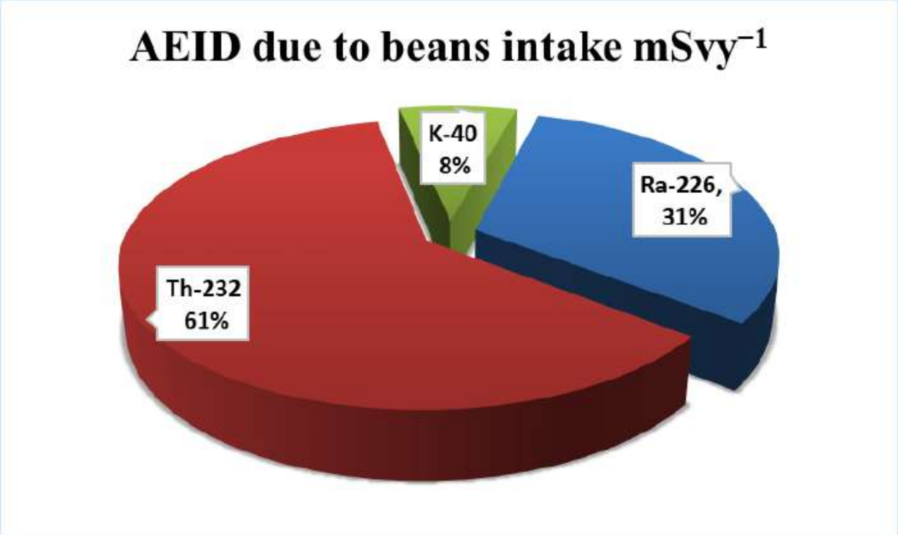

Figure 9. Annual effective ıngestion dose beans.

All AEID values are well below the 1 mSv/y safety threshold set by the International Commission on Radiological Protection (ICRP) for the general public. This implies that based on the current consumption levels of beans in Bungoma County, the radiation dose received by individuals from this food source is within acceptable limits. As shown in Figure 9, ^{232}Th accounted for the highest contribution, with 61% of the total AEID, surpassing both ^{226}Ra and ^{40}K.

The average concentration of all radioisotopes might not present any immediate health risk to consumers, but there may be a long-term cumulative effect following the current dose ingestion [30] [36] [37].

3.3. Comparison of Maize and Beans

While both maize and beans from Bungoma County are largely within safety limits for most radiological parameters, maize poses a slightly higher potential radiological risk due to its elevated AEID. This difference emphasizes the need for targeted mitigation measures for maize, such as soil testing and regulated fertilizer use, to ensure consumer safety. Beans, on the other hand, are safer but still warrant monitoring for consistency over time.

3.4. Implications and Health Risk Assessment

The results show that while the radium equivalent and absorbed dose rates for maize and beans remain within global safety limits, certain maize samples exceed the annual effective ingestion dose (AEID) threshold of 1 mSv/y, posing a potential health risk for consumers heavily reliant on maize. Exceeding the annual effective ingestion dose (AEID) threshold of 1 mSv/year in maize consumption poses significant health risks. Radionuclides such as ^{226}Ra, ^{232}Th, and ^{40}K accumulate in tissues over time, with ^{226}Ra linked to bone cancer and leukemia (ICRP). Similarly, ^{232}Th and ^{40}K can affect soft tissues, increasing organ-specific cancer risks [35]. Vulnerable groups, including children and pregnant women [8], face heightened risks due to tissue sensitivity and potential impacts on fetal development [5]. Prolonged exposure to these elevated radiation levels could increase cancer risk, warranting further epidemiological studies. In contrast, beans are safer, with all parameters, including AEID, below recommended thresholds. However, samples like B_2 and B_8, with slightly higher radium equivalent and absorbed dose rates, require monitoring to ensure long-term safety. The variability in radionuclide concentrations, particularly for ^{40}K, highlights the need for continuous monitoring to account for environmental and agricultural changes.

4. Conclusions

The average activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were 20.90 ± 7.19 Bq/kg, 54.00 ± 21.15 Bq/kg, 161.00 ± 76.84 Bq/kg, and 18.40 ± 4.03 Bq/kg, 43.00 ± 15.51 Bq/kg, 195.00 ± 132.48 Bq/kg in maize and beans respectively. The mean absorbed dose rates were 49.00 ± 2.45 nGy/h and 43.00 ± 2.15 nGy/h for maize and beans respectively which were lower than the world average of 57 nGy/h [5]. The AEID had an average of 1.312 $mSvy^{-1}$ and 0. 263 $mSvy^{-1}$ in maize and beans respectively.

These findings suggest that the overall radiation exposure from maize consumption in Bungoma County is not alarmingly high, except AEID in maize was slightly above 1 $mSvy^{-1}$ as discussed. There is no immediate radiological concern for consumers, as the radium equivalent, absorbed dose rate, and annual effective ingestion dose from maize and beans are all below internationally recognized safety thresholds. Continuous monitoring and mitigation strategies, including soil testing and improved agricultural practices, are recommended. High use of phosphate fertilizers and other chemical-based farm inputs for the augmentation of the crops should be regulated as they can elevate and stimulate the presence of ^{226}Ra, ^{232}Th, and ^{40}K in cereals and pulses. This is to ensure the safety of the local population of radionuclide levels, particularly as agricultural practices evolve and environmental conditions change.

Acknowledgement

The authors would like to express their sincere gratitude to the staff of the Department of Science, Engineering, and Technology at Kibabii University for their invaluable support and resources throughout this research. We also extend our appreciation to the National Commission for Science, Technology and Innovation (NACOSTI) and Bungoma County for granting the necessary 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

[1] Alatise, O.O. and Adebesin, T.C. (2020) 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

[2] Salih, N. (2018) Determination of Natural Radioactivity and Radiological Hazards of 226Ra, 232Th, and 40K in the Grains Available at Penang Markets, Malaysia, Using High-Purity Germanium Detector. *ARO—The Scientific Journal of Koya University*, **6**, 71-77. https://doi.org/10.14500/aro.10327

[3] 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

[4] Solehah, A.R., Yasir, M.S. and Samat, S.B. (2016). Activity Concentration, Transfer Factors and Resultant Radiological Risk of 226Ra, 232Th, and 40K in Soil and Some Vegetables Consumed in Selangor, Malaysia. *AIP Conference Proceedings*, **1784**, Article ID: 040016. https://doi.org/10.1063/1.4966802

[5] 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

[6] El-Gamal, H., Hussien, M.T. and 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

[7] Abbasi, A., Kurnaz, A., Turhan, Ş. and Mirekhtiary, F. (2020) Radiation Hazards and Natural Radioactivity Levels in Surface Soil Samples from Dwelling Areas of North Cyprus. *Journal of Radioanalytical and Nuclear Chemistry*, **324**, 203-210.

https://doi.org/10.1007/s10967-020-07069-w

[8] Sultana, A., Siraz, M.M., Pervin, S., Rahman, A.M., Das, S.K. and Yeasmin, S. (2020) 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

[9] Olatunji, M.A., Uwatse, O.B., Khandaker, M.U., Amin, Y.M. and Faruq, G. (2014) Radiological Study on Newly Developed Composite Corn Advance Lines in Malaysia. *Physica Scripta*, **89**, Article ID: 125002. https://doi.org/10.1088/0031-8949/89/12/125002

[10] ICRP (1999) ICRP Publication 82: Protection of the Public in Situations of Prolonged Radiation Exposure (Vol. 82). Elsevier Health Sciences. https://doi.org/10.1016/s0146-6453(00)00009-9

[11] 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

[12] Yachiso, G.T., Chaubey, A.K. and Turi, B. (2023) Transfer Factor of Radionuclides from Soil to Cereal Crops around Gold Mining and Evaluation of Corresponding Radiological Hazard Levels Oromia, Ethiopia. *International Journal of Environmental Analytical Chemistry*, **104**, 6947-6963. https://doi.org/10.1080/03067319.2022.2158737

[13] Lopes, J.M., Garcêz, R.W.D., Filgueiras, R.A., Silva, A.X. and Braz, D. (2018) Committed Effective Dose Due to the Intake of 40K, 226Ra, 228ra and 228Th 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

[14] Bungoma County Government (2021) Annual Development Plan 2021. https://www.bungoma.go.ke/wp-content/uploads/2023/08/ADP-2021.pdf

[15] Butiki, G.W., Makokha, J.W., Masinde, F.W. and Wanyama, C.K. (2021) Annual Effective Dose from Radon-222 Concentration Levels in Underground Water in Bungoma South Sub-County, Kenya. *ITEGAM—Journal of Engineering and Technology for Industrial Applications*, **7**, 78-82. https://doi.org/10.5935/jetia.v7i28.736

[16] Wanyama, C.K., Makokha, J.W. and Masinde, F.W. (2020) A Radiological Survey in Tailings: A Case Study of Rosterman Gold Mine, Western Kenya. *OALib*, **7**, e6293. https://doi.org/10.4236/oalib.1106293

[17] Wanyama, C.K., Masinde, F.W., Makokha, J.W. and Matsitsi, S.M. (2020) Estimation of Radiological Hazards Due to Natural Radionuclides from the Rosterman Gold Mine Tailings, Lurambi, Kakamega, Kenya. *Radiation Protection Dosimetry*, **190**, 324-330. https://doi.org/10.1093/rpd/ncaa113

[18] Wanyama, C.K., Makokha, J.W., Masinde, F.W. and Waswa, M.N. (2020) Natural Radioactivity and External Dose Rates in Tailing Samples from Rosterman Gold Mine, Kakamega County, Kenya. *ITEGAM—Journal of Engineering and Technology for Industrial Applications*, **6**, 73-77. https://doi.org/10.5935/jetia.v6i26.718

[19] Wanyama, C.K., Makokha, J.W. and Masinde, F.W. (2020) Assessment of Natural Radioactivity Levels in Tailings from Lurambi-Rosterman Gold Mine, Kakamega County Kenya. *Global Scientific Journal*, **8**, 2456-2468.

[20] Wanyama, C.K., Makokha, J.W., Masinde, F.W. and Matsitsi, S.M. (2020) Radiological Assessment of the Activity Concentrations of 40K, 232Th, 238U and Exposure Levels in the Rosterman Gold Mine of Lurambi Area, Western, Kenya. *International Journal of Research and Scientific Innovation*, **7**, 209-212.

[21] Amana, M.S. (2017) Radiation Hazard Index of Common Imported Ceramic Using for Building Materials in Iraq. *Australian Journal of Basic and Applied Sciences*, **11**, 94-102.

[22] Belivermis, M., Kılıç, O., Çotuk, Y. and Topcuoğlu, S. (2009) The Effects of Physicochemical Properties on Gamma Emitting Natural Radionuclide Levels in the Soil Profile of Istanbul. *Environmental Monitoring and Assessment*, **163**, 15-26. https://doi.org/10.1007/s10661-009-0812-1

[23] Ahmed, F., Daif, M.M., El-Masry, N.M. and Abo-Elmagd, M. (2010) External and Internal Radiation Exposure of Herbal Plants Used in Egypt. *Radiation Effects and Defects in Solids*, **165**, 65-71. https://doi.org/10.1080/10420150903428054

[24] Stewart, F.A., Akleyev, A.V., Hauer-Jensen, M., Hendry, J.H., Kleiman, N.J., MacVittie, T.J., *et al.* (2012) ICRP PUBLICATION 118: ICRP Statement on Tissue Reactions and Early and Late Effects of Radiation in Normal Tissues and Organs—Threshold Doses for Tissue Reactions in a Radiation Protection Context. *Annals of the ICRP*, **41**, 1-322. https://doi.org/10.1016/j.icrp.2012.02.001

[25] 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.

[26] 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

[27] Kim, G. and 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

[28] Angeleska, A., Dimitrieska Stojkovik, E., Hajrulai Musliu, Z., Stojanovska Dimzoska, B., Esmerov, I. and Angelovska, A. (2022) Assessment of Radiological Hazard for Various Food Commonly Used in Republic of North Macedonia. *Journal of Agriculture and Plant Sciences*, **20**, 9-14. https://doi.org/10.46763/japs22202009a

[29] Avwiri, G.O., Ononugbo, C.P. and 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

[30] Tawalbeh, A.A., Abumurad, K.M., Samat, S.B. and 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.

[31] Banzi, F., Msaki, P. and 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

[32] Awudu, A.R., Faanu, A., Darko, E.O., Emi-Reynolds, G., Adukpo, O.K., Kpeglo, D.O., *et al.* (2011) Preliminary Studies on 226Ra, 228Ra, 228Th and 40K Concentrations in Foodstuffs Consumed by Inhabitants of Accra Metropolitan Area, Ghana. *Journal of Radioanalytical and Nuclear Chemistry*, **291**, 635-641. https://doi.org/10.1007/s10967-011-1444-9

[33] Alharbi, A. and El-Taher, A. (2013) A Study on Transfer Factors of Radionuclides from Soil to Plant. *Life Science Journal*, **10**, 532-539.

[34] Wanjala, E.M. (2016) Assessment of Human Exposure to Natural Source of Radiation on the Soil in Tongaren Constituency of Bungoma County, Kenya. Master's Thesis, Kenyatta University.

[35] Mohebian, M. and 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.

[36] Rilwan, U., Jafar, M., Musa, M., Idris, M.M. and Waida, J. (2022) Transfer of Natural Radionuclides from Soil to Plants in Nasarawa, Nasarawa State, Nigeria. *Journal of Radiation and Nuclear Applications*: *An International Journal*, **7**, 81-86. https://doi.org/10.18576/jrna/070209

[37] Muhammad, A.N., Ismail, A.F. and 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 ID: 2366507. https://doi.org/10.1080/16583655.2024.2366507