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

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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 ^{226}Ra, ^{232}Th, and ^{40}K 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 ^{226}Ra, ^{232}Th, and ^{40}K 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 ^{226}Ra, ^{232}Th, and ^{40}K 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 & Adebesin, 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 (Elgamal 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 & Adebesin, 2019). These radionuclides accumulate in several parts of the plant, including the edible parts, through the xylem and phloem's vascular system (Asaduzzaman 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 km^2 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 subcounties: 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.

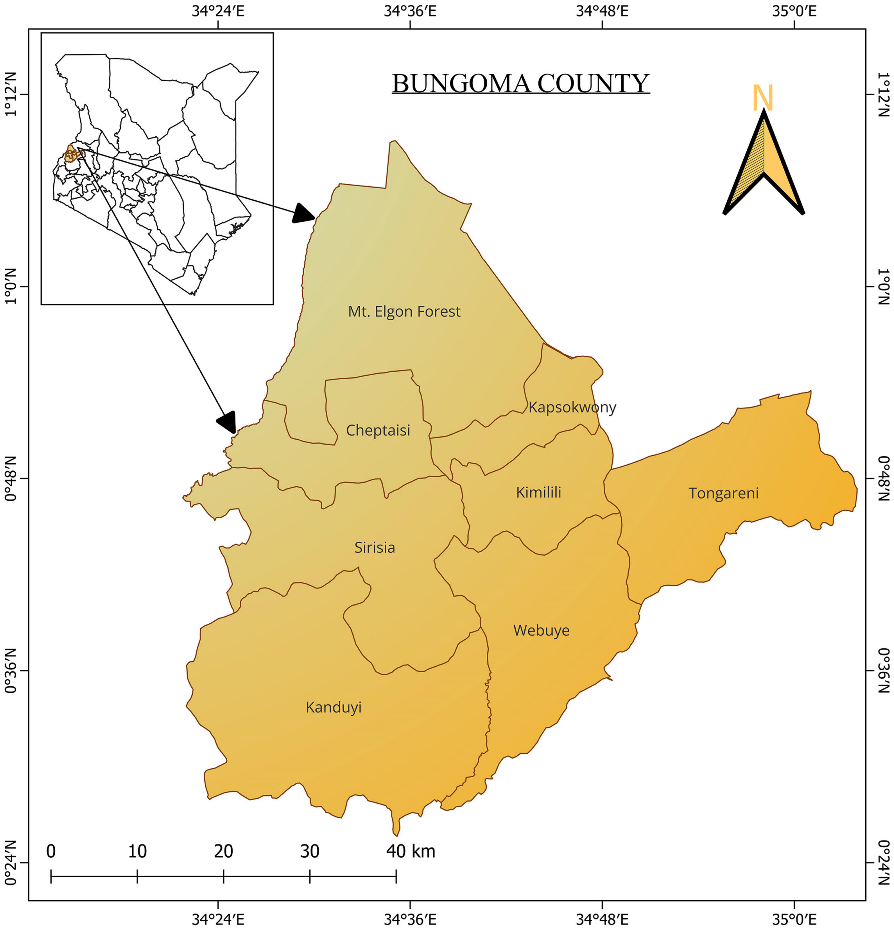

Figure 1. A map showing sub-counties of Bungoma county. (Source: the authors)

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 M_9. Similarly, bean samples were designated B_1 through B_9 as highlighted in Table 2. To allow ^{226}Ra and ^{232}Th 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 (Υ_r)	ELCR $\times 10^{-8}$
	^{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 (Υ_r)	ELCR $\times 10^{-8}$
	^{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 ^{232}Th was determined using the ^{208}Tl (2615 keV) gamma energy peak, while the activity concentration 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).

$$C = \frac{N \times 100}{P_\gamma \times \varepsilon \times m} \tag{1}$$

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.

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

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 μSv·Bq^{-1} for ^{226}Ra, 0.23 μSv·Bq^{-1} for ^{232}Th and 0.0062 μSv·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).

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

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).

$$\text{LTCR} = \text{AEID} \times L_{\text{span}} \times F_{RC} \tag{4}$$

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 3.58×10^{-1} μSv^{-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 ± 1.1 - 75 ± 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 ± 2.34 - 279 ± 13.99) Bq/kg respectively as seen in **Table 1**. The highest activity was recorded in ^{40}K in sample M_4, while the lowest was recorded from ^{226}Ra in sample M_1.

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 ± 0.57 - 23.1 ± 1.15) Bq/kg, 43.00 ± 15.51 with a range of (23 ± 1.16- 67 ± 3.35) Bq/kg and 195.00 ± 132.48 with a range of (28 ± 1.4 - 498 ± 24.93) Bq/kg respectively as seen in **Table 2**. The highest activity concentration in beans was recorded from ^{40}K in B_2, while the lowest was determined from ^{226}Ra in B_9.

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 μSv/year to 5.12 μSv/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).

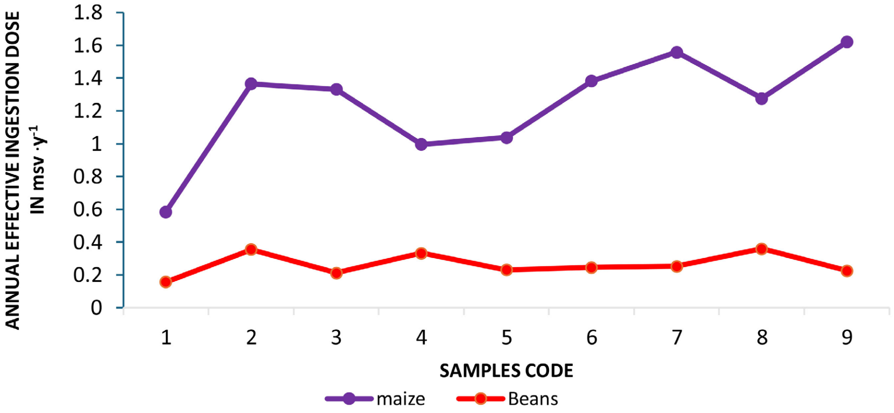

Figure 2. A line graph showing total AEID due to intake of maize and beans mSv·y^{-1}.

3.2. Gamma Index and Excessive Lifetime Cancer Risk

The average gamma index, $I_{\gamma r}$ for maize and beans were 0.7 ± 0.03 (0.3 ± 0.01 - 1 ± 0.05) mSv and 0.6 ± 0.03 (0.3 ± 0.01 - 1 ± 0.05) mSv respectively. The highest value recorded in maize samples B_2 and M_9 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 M_9 and B_2 recorded the highest values of Gamma index which can be related to higher specific activity concentration and AEID, **Figure 2** and **Figure 3**.

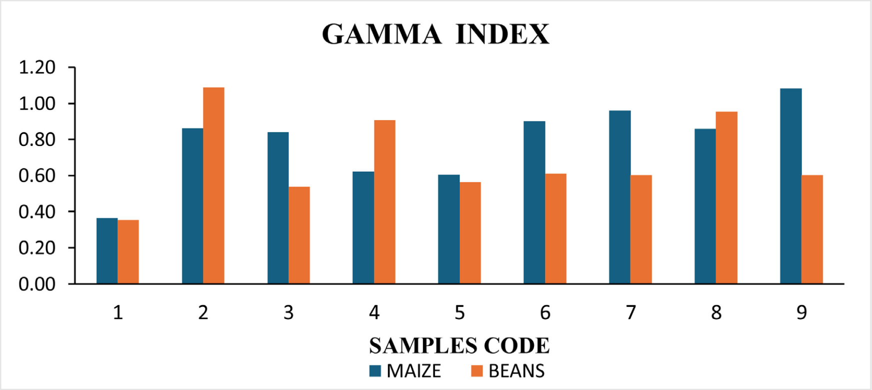

Figure 3. Gamma index in maize and beans samples.

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.

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Conflicts of Interest

The authors declare no conflicts of interest.

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