Journal of Radiation and Nuclear Applications
An International Journal

http://dx.doi.org/10.18576/jrna/080112

Estimation of Radiological Effects from Consumption of milk from Volcanic areas of Kisoro, South-western Uganda.

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Received: 9 Oct. 2022, Revised: 3 Nov. 2022, Accepted: 11 Dec. 2022
Published online: 1 Jan. 2023.

Abstract: Determination of activity concentrations of Naturally Occurring Radionuclides in foodstuffs and Radiological Effects from consumption such foodstuffs is very important in assessing internal radiation hazards like cancer to population. The concentration of Naturally Occurring Radionuclides depends on geological formations of specific areas. The aim of this study was to estimate the Radiological effects from consumption of milk from volcanic areas of Kisoro, South-western Uganda. The Radiological Effects that were determined in this study were Radium Equivalent, Annual Effective Dose Equivalent, and Excess Lifetime Cancer Risk. Seventy nine (79) samples of milk were collected from cattle farms in seven sub counties where geological formation was volcanic eruption. Radiological Effects due to Naturally Occurring Radionuclides U-238, Th-232, and K-40 in milk samples were determined. The average activity concentrations were determined using NaI(Tl) detector. The activity concentrations were used to determine the Radiological Effects. The average activity concentrations in milk for U-238, Th-232, and K-40 were; 1.058 Bq l^{-1}, 1.369 Bq l^{-1}, and 19.679 Bq l^{-1}, respectively. Average Radium Equivalent was 4.531 Bq l^{-1}, the annual Effective Dose Equivalent was 0.014 mSv y^{-1} and the Excess Lifetime Cancer Risk was 0.041×10^{-3}. Samples that were collected from cattle farms that were relatively flat and at lower altitudes had relatively higher activity concentrations hence higher Radiological Effects. The Radium Equivalent, annual Effective Dose Equivalent and, ELCR were all lower than the safe value from consumption of milk by 0.099 Bq l^{-1}, 0.0019 mSv y^{-1}, and 0.005×10^{-3}, respectively hence from the results, it is concluded that the milk is safe for human consumption. Since the differences from the safe values are very small, the quantity of milk to be consumed was estimated to be 0.105 litres per day (0.74 litres per week) in order to keep the Radiological Effects low.

Keywords: Milk, Activity Concentration, Radiological Effects, Radium Equivalent, Effective Dose, Excess Life time cancer Risk , Volcanic.

1 Introduction

Exposure to natural radiation energy (ionizing radiation) has been identified as one of the primary causes of radiation ailments for many people living in areas where the underlying bed rock is crystalline rock or sedimentary rocks [1]. Radioactivity is widely spread in the earth's environment and it exists in various geological formations in soils, rocks, plants, water, air, and in building materials [2].

According to Jack in 1913 [3], Mufumbiro ranges is a set of eight volcanic mountains consisting of Mt. Muhavura, and Mgahinga along Uganda-Rwanda border; Sabyinyo found along Uganda-Democratic Republic of Congo (DRC) border; Nyiragongo, Nyamuragira, and Mikemo that are found in the Democratic Republic of Congo; and Karisimbi and Bisoke that are found along Rwanda and DRC border. Mt. Muhavura, Mgahinga, Sabyinyo, Karisimbi, Bisoke and Mikemo are dormant volcanoes, while Mt. Nyiragongo and Mt. Nyamuragira are active.

Mt. Nyiragongo erupted in 2002 and recently in 2021 and magma spewed in Lake Kivu and cultivation land [4] and [5].

Volcanic eruptions enhance the concentrations of naturally occurring radionuclides in the environment, hence increasing the radiation exposure to humans [6]. The exposure to the ionising radiation is directly from inhalation of radon (external exposure) or ingestion of radionuclides through food and water (internal exposure). Internal exposure is more harmful than external exposure [7] . Reference concentration values of radionuclides in food and water were set by International Bureau of Standards as shown in Table 1 [8] and [9]. The notation ND is for no published data available.

The district is made up of fourteen sub counties. These sub Counties are Nyakabande, Nyarusiza, Chahi, Murora, Muramba, Nyakinama, Kanaba, Nyarubuye, Busanza,

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Nyabwishenyi, Kirundo, Bukimbiri, Nyundo and Kisoro municipality

Nyarubuye, Busanza, Nyabwishenyi, Kirundo, Bukimbiri, Nyundo and Kisoro municipality [10]. This research was conducted in the sub Counties of Nyakabande, Nyarusiza, Chahi, Murora, Muramba, Nyakinama, Nyarubuye, and Kisoro municipality. These sub Counties were purposely selected because they have volcanic soils where farming is practiced. The geographical locations of the sub counties in shown in Figure 2.

Fig.1: Map of South-Western Uganda showing the location of Kisoro District.

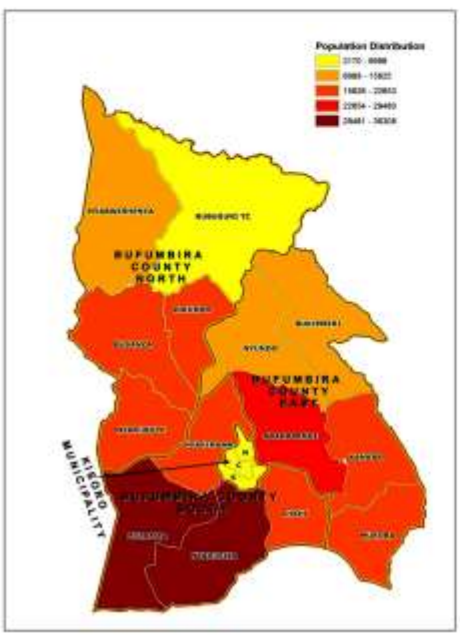

Fig. 2: Map of Kisoro district showing Sub Counties.

2 Materials

The following materials were used.

i. 0.5 litre plastic bottles to keep milk samples.
ii. Formalin to preserve milk samples.
iii. Marinelli beakers in which the samples were put in order to be mounted on the NaI detector for gamma spectrography.

2.1 Sample Collection

Seventy nine (79) milk samples were collected from cattle farms in the sub Counties of Nyakabande, Nyarusiza, Murora, Muramba , Nyakinama, Nyarubuye and Chahi and Kisoro Municipality. Milk samples from each sub county were coded as;

1. Nyakabande: NDEMn;
2. Chahi and Kisoro Municipality: CHIMn;
3. Nyarusiza: NZAMn;
4. Murora: MRAMn;
5. Muramba: MBAMn;
6. Nyarubuye: NYEMn;
7. Nyakinama : NMAMn.

Where n = 1, 2, 3,... is the farm (village) where the sample was collected

2.2 Sample Preparation

Milk samples were preserved using formalin 0.2 ml per 0.5 l and then packed in plastic bottles.

All the samples were left for 30 days in order for the radionuclides to attain secular equilibrium with their daughters [12] and [13]. The samples were prepared in Mutolere SS laboratory and the experimentation was done in Makerere University Department of Physics Radioisotope laboratory using NaI detector and Maestro II software program.

2.3 Determination of Activity Concentrations in Samples

The samples were put in Marinelli beakers and weighed. The Marinelli beakers were mounted on the NaI detector for gamma spectrography one after the other. The acquisition time of spectrum, which is graph of Counts against energy of gamma radiation in each sample, for each sample was between 7000 and 8000 s and this was initiated using Autodas software until a defined spectra were obtained for easy analysis. Background radiation was recorded for almost the same acquisition time as the samples and saved as 'rsp bkg220`. Energy and efficiency calibration of the NaI detector was done using Eu-152. Before analysing any spectrum, the spectrum for the background radiation was subtracted using the command 'rsp bkg220` subtracted to correct for the contribution from the background radiation. The spectrum has peaks corresponding to particular radionuclides in the sample that are centred on the energy of gamma radiation in the sample as shown in Table 3. Using \l" and \u" commands, and arrow keys, markers were placed on the lower and upper sides of each peak.

Command \cen" determines the; centroid (used to identify the energy of gamma radiation in the peak), the area N under the peak, standard deviation in energy, and the count rate. The area under each peak (N) was used to calculate the activity concentrations using Equation 1 for milk samples [14].

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$$C = \frac{N}{vTc} \text{ Bq l}^{-1}, \qquad (1)$$

where N is the net area under the peak, v is the volume of the milk sample, T is the life time, and c= ηk is correction coefficient for each radionuclide that was used to calculate the specific activity where k is branching ratio of the radionuclides [11] and η is the efficiency of the detector.

The average specific activity for the radionuclides of the same series was calculated to get C_{Ra} or C_U and C_{Th}. The concentrations in milk were used to calculate the radiological effects due to the radionuclides present in the milk.

Following from [13] and [15] radiological effects are defined and calculated as shown in the sections that follow.

1. **Radium Equivalent Activity (Raeq)**

The Raeq represents a weighted sum of activities of Ra-226, Th-232, and K-40. It is based on the estimation that 1 Bq kg^{-1} of Ra-226, 0.7 Bq kg^{-1} of Th-232 and 13 Bq kg^{-1} of K-40 produce the same radiation dose. It provides a useful guideline in regulating safety standards for dwellings [15].

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_K, \qquad (2)$$

where C_{Ra}, C_{Th}, and C_K are average activities of Ra-226 or (U-238), Th-232, and K-40, respectively. The activity concentrations were calculated using Equation 1. The coefficients; 1, 1.43, and 0.077 in Equation 2 are conversion factors of the radionuclides. [13].

2. **Absorbed Dose Rate (Dr) and Annual Effective Dose Equivalent (AEDE)**

Dose Rate (Dr) is the radiation dose absorbed per hour by a material. It is calculated as;

$$Dr = 0.427 \times C_{Ra} + 0.662 \times C_{Th} + 0.043 \times C_K \quad (3)$$

where 0.427, 0.662, and 0.043 are Dose Conversion Factors for the radionuclides of

Ra, Th and K, respectively in nSv/hr/Bq l^{-1} [13] .

Annual Effective Dose Equivalent (AEDE) is the dose absorbed by a material in a year. It is calculated in mSv y^{-1} using Equation 4 [8].

$$AEDE = Dr \times 24 \times 365.25 \times 0.7 \times 10^{-6} \qquad (4)$$

where 0.7 × 10^{-6} is a conversion factor.

3. **Excess Lifetime Cancer Risk (ELCR)**

The excess Lifetime cancer risk is a measure of the probability of developing cancer over a Lifetime at a given exposure to ionizing radiation. It represents the number of extra cancer cases expected in a given population of people when exposed to ionizing radiation.

It is calculated using equation 5 [13].

ELCR = AEDE × Average lifetime × Risk factor**;** (5)

where AEDE is the Annual Effective Dose Equivalent in mSv y^{-1}.

The cancer Risk factor is 0.05 Sv^{-1} [13]. Tables 1 and 2 were used as control values for this study. Since Excess Lifetime Cancer Risk (ELCR) depends on quantity (mass or volume) of radionuclides one ingests, in this study, the quantity of milk one should consume per day was estimated using Equation 6 in order to mitigate the risk of developing cancer in one's lifetime from consumption of milk from volcanic areas of Kisoro district.

(ELCRn) = k (Qn); (6)

where (ELCRn) is n ×1 matrix for average Excess Lifetime Cancer Risks for the sub counties and (Qn) is average quantity of milk that was used to calculate the dose rate.

3 Results and Discussion

3.1 Results

Activity concentrations and corresponding Radiological Effects in milk samples in each sub county are shown in Tables 3 to 10. Activity concentrations in Tables 3 to 10 are shown in Figures 3 to 10.

Nyakabande Sub County

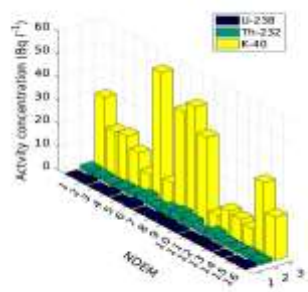

Fig.3: Activity concentrations in milk samples from Nyakabande Sub County.

In Nyakabande, the lowest activity concentration of U-238 in milk samples was 0.265 Bq l^{-1} from a farm in sample NDEM5. The highest was 1.481 Bq l^{-1} in sample NDEM6 with an average of 0.664 Bq l^{-1}. For Th-232, the lowest was 0.513 Bq l^{-1} in sample NDEM11 and highest was 3.845 Bq l^{-1} in sample NDEM6 with average of 1.881 Bq l^{-1} , while for K-40, the lowest was 6.141 Bq l^{-1} in NDEM11 and the highest was 54.544 Bq l^{-1} in NDEM6 with average of 24.300 Bq l^{-1}. The Ra_{eq} varied from 1.592 Bq l^{-1} in NDEM11 to 10.235 Bq l^{-1} in NDEM6 with average of 5.225 Bq l^{-1}. AEDE varied from 0.008 mSv y^{-1} in NDEM14 to 0.031 mSv y^{-1} in NDEM6 with average of 0.016 mSv y^{-1}. The ELCR varied from 0.014 $\times 10^{-3}$ in NDEM11 to 0.094 $\times 10^{-3}$ also NDEM6 village with average of 0.047 $\times 10^{-3}$. NDEM6 was collected near wolfram mine at Mutolere and this may be the reason why the concentrations are high.

Chahi and Kisoro Municipality

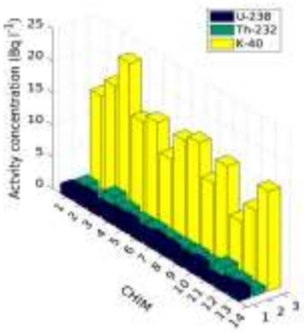

Fig.4: Activity concentrations in milk samples from Chahi Sub County and Kisoro Municipality.

In Chahi and Kisoro Municipality, the activity concentrations of U-238, Th-232, and K-40 in milk varied from; 0.687 Bq l^{-1} in CHIM11 to 1.786 Bq l^{-1} in CHIM10 with an average of 1.494 Bq l^{-1}; 0.419 Bq l^{-1} in CHIM2 to 2.320 Bq l^{-1} in CHIM3 with an average of 1.197 Bq l^{-1} ; and 8.201 Bq l^{-1} in CHIM11 to 22.378 Bq l^{-1} in CHIM3 with an average of 14.632 Bq l^{-1}, respectively. The lowest Radium Equivalent was 3.685 Bq l^{-1} in CHIM11 and the highest was 6.333 Bq l^{-1} in CHIM3 with an average of 4.333 Bq l^{-1}. AEDE varied from 0.011 mSv y^{-1} in CHIM2, CHIM6, CHIM9, and CHIM12 to 0.019 mSv y^{-1} in CHIM3 with an average of 0.013 mSv y^{-1}. ELCR varied from 0.032×10^{-3} in CHIM6 and CHIM12 to 0.056×10^{-3} in CHIM3. Samples that were collected from relatively flat areas and at lower altitude have higher values and this could be due to deposition of the radionuclides due to soil erosion like CHIM3.

Nyarusiza Sub County

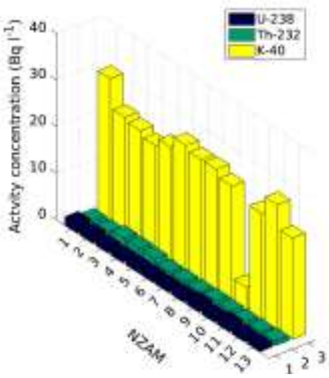

Fig.5: Activity concentrations in milk samples from Nyarusiza Sub County.

In Nyarusiza Sub County, activity concentrations of U-238, Th-232, and K-40 varied from;
0.966 Bq l^{-1} in NZAM13 to 1.882 Bq l^{-1} in NZAM1 with an average of 1.235 Bq l^{-1}; 0.797 Bq l^{-1} in NZAM12 to 1.692 Bq l^{-1} in NZAM4 with an average of 1.147 Bq l^{-1}; and 21.915 Bq l^{-1} in NZA13 to 30.538 Bq l^{-1} in NZAM1 with an average of 24.915 Bq l^{-1}, respectively. The Radium Equivalent varied from 4.042 Bq l^{-1} in NZAM13 and NZAM12 to 6.054 Bq l^{-1} in NZAM1 with an average of 4.793 Bq l^{-1}. AEDE varied from 0.012 mSv y^{-1} in NZAM12 to 0.018 mSv y^{-1} in NDEM1 with an average of 0.014 mSv y^{-1}. ELCR varied from 0.037×10^{-3} in NZAM13 to 0.054×10^{-3} in NZAM1 with an average of 0.043×10^{-3}. Like in Chahi and Kisoro Municipality, samples that were collected from relatively flat areas and at lower altitude have higher values and this could be due to deposition of the radionuclides due to soil erosion like NZAM1.

Muroran Sub County

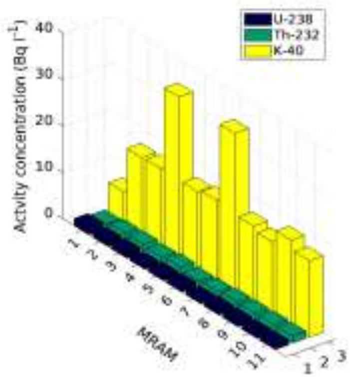

Fig.6: Activity concentrations in Milk samples from Murora Sub County.

In Murora Sub County, activity concentrations of U-238, Th-232, and K-40 varied from 0.803 Bq l^{-1} in MRAM4 to 1.550 Bq l^{-1} in MRAM1 with an average of 1.060 Bq l^{-1}; 1.052 Bq l^{-1} in MRAM1 to 1.584 Bq l^{-1} in MRAM5 with an average of 1.422 Bq l^{-1}; and 15.554 Bq l^{-1} in MRAM9 to 33.996 Bq l^{-1} in MRAM4 with an average of 19.875 Bq l^{-1}, respectively. Radium Equivalent varied from 3.931 Bq l^{-1} in MRAM6 to 5.389 Bq l^{-1} in MRAM4 with an average of 4.624 Bq l^{-1}. AEDE varied from 0.012 mSv y^{-1} in MRAM6 to 0.017 mSv y^{-1} in MRAM4 with an average of 0.014 mSv y^{-1}. ELCR varied from 0.035×10^{-3} in MRAM6 to 0.050×10^{-3} in MRAM4 with an average of 0.041×10^{-3}. Like in the previous sub counties, samples that were collected from relatively flat areas and at lower altitude have higher values and this could be due to deposition of the radionuclides due to soil erosion like MRAM4.

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Muramba Sub County

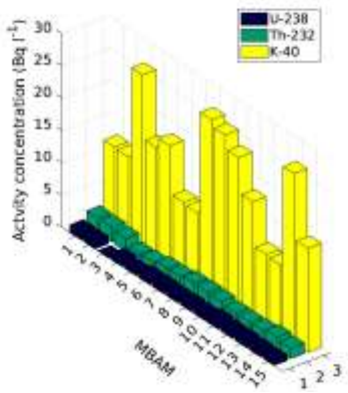

Fig.7: Activity concentrations in milk samples from Muramba Sub County.

In Muramba Sub County, the activity concentrations of U-238, Th-232, and K-40 varied from; Non detectable (SV) value in MBAM3 to 1.332 Bq l^{-1} in MBAM11 with average of 0.947 Bq l^{-1}; 0.957 Bq l^{-1} in MBAM4 to 2.392 Bq l^{-1} in MBAM1 with an average of 1.735 Bq l^{-1}; and 10.720 Bq l^{-1} in MBAM13 to 26.286 Bq l^{-1} in MBAM8 with average 17.558 Bq l^{-1}, respectively. Raeq varied from 3.492 Bq l^{-1} in MBAM5 to 5.813 Bq l^{-1} in MBAM8 with average of 4.779 Bq l^{-1}, respectively. AEDE varied from 0.011 mSv y^{-1} in MBAM4 and MBAM5 to 0.017 mSv y^{-1} in MBAM8 and MBAM9 with an average of 0.014 mSv y^{-1}. ELCR varied from 0.032×10^{-3} in MBAM5 to 0.052×10^{-3} in MBAM8, MBAM9, and MBAM14 with an average of 0.042×10^{-3}. Like in the previous sub counties, samples that were collected from relatively flat areas and at lower altitudes have higher values and this could be due to deposition of the radionuclides due to soil erosion like MBAM9.

Nyarubuye Sub County

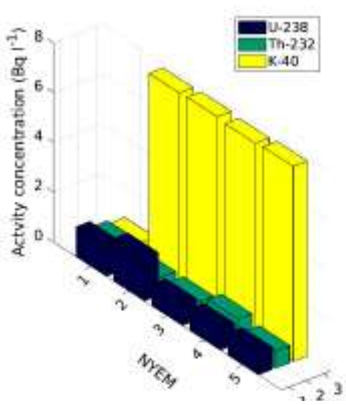

Fig.8: Activity concentrations in milk samples from Nyarubuye Sub County.

In Nyarubuye Sub County, the activity concentrations of U-238, Th-232, and K-40 in milk samples varied from; 0.864 Bq l^{-1} in NYEM4 to 1.720 Bq l^{-1} in NYEM2 with an average of 1.108 Bq l^{-1}; 0.687 Bq l^{-1} in NYEM2 to 0.978 Bq l^{-1} in NYEM4 with an average of 0.800 Bq l^{-1}; and 7.765 Bq l^{-1} in NYEM4 to 10.818 Bq l^{-1} in NYEM1 with an average of 8.410 Bq l^{-1} , respectively. Raeq, AEDE, and ELCR varied from; 2.455 Bq l^{-1} in NYEM2 to 3.390 Bq l^{-1} in NYEM1 with an average of 2.899 Bq l^{-1}; 0.007 mSv y^{-1} in NYEM3 and NYEM5 to 0.01 mSv y^{-1} in NYEM1 with an average of 0.008 mSv y^{-1}; and 0.021×10^{-3} in NYEM3 to 0.030×10^{-3} in NYEM1 with average of 0.025×10^{-3}, respectively. Like in the previous sub counties, samples that were collected from relatively flat areas and at lower altitudes have higher values and this could be due to deposition of the radionuclides due to soil erosion like NYEM1.

Nyakinama Sub County

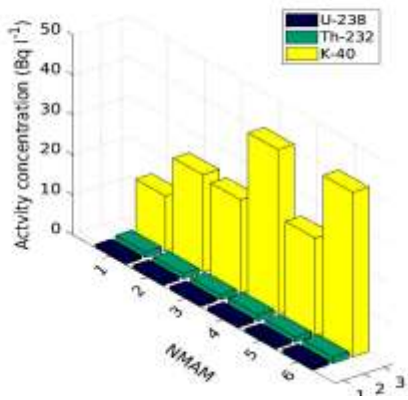

Figure 9: Activity concentrations in milk samples from Nyakinama Sub County.

In Nyakinama Sub County, the activity concentrations of U-238, Th-232, and K-40 in milk samples varied from; 0.803 Bq l^{-1} in NMAM1 to 0.996 Bq l^{-1} in NMAM6 with an average of 0.897 Bq $l^{-1;}$ 1.308 Bq l^{-1} in NMAM2 to 1.573 Bq l^{-1} in NMAM4 with an average of 1.402 Bq l^{-1}; and 13.791 Bq l^{-1} in NMAM1 to 41.251 Bq l^{-1} in NMAM4 with an average of 28.062 Bq l^{-1}, respectively. Raeq, AEDE, and ELCR varied from; 3.780 Bq l^{-1} in NMAM1 to 6.639 Bq l^{-1} in NMAM5 with an average of 5.062 Bq l^{-1}; 0.011 mSv y^{-1} in NMAM1 to 0.020 mSv y^{-1} in NMAM4 and NMAM with an average of 0.015 mSv y^{-1}; and 0.034×10^{-3} in NMAM1 to 0.060×10^{-3} in NMAM4 with average of 0.046×10^{-3}, respectively. Like in the previous sub counties, samples that were collected from relatively flat areas and at lower altitudes have higher values and this could be due to deposition of the radionuclides due to soil erosion like NMAM4.

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The whole volcanic area of Kisoro District

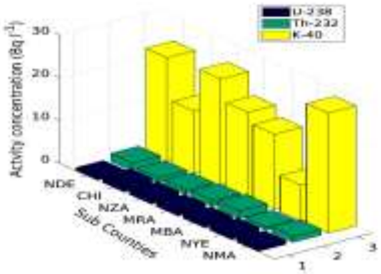

Fig. 10: Average activity concentrations in milk samples from the whole of volcanic area of Kisoro District.

In the volcanic areas of Kisoro district, the average activity concentrations of U-238, Th-232, and K-40 in milk samples were; 1.058 Bq l^{-1}, 1.369 Bq l^{-1}, and 19.679 Bq l^{-1}, respectively. Average Radium Equivalent was 4.531 Bq l^{-1}. Annual effective Dose Equivalent was 0.014 mSv y^{-1}. Excess Lifetime Cancer Risk was 0.041×10^{-3}. Using Table 1 and the maximum safe concentration of K-40 in food of 60 Bq l^{-1} [9], the safe contribution to Radiological Effects due to radionuclides in milk were calculated as follows; Radium Equivalent was 4.630 Bq l^{-1} Annual Effective Dose Equivalent was 0.0159 mSv y^{-1}, and Excess lifetime cancer risk was 0.0476×10^{-3} . Table 2 gives the safe AEDE for only uranium and thorium. Uranium and thorium were the only ones considered since K-40 is essential for human growth and metabolism. The Radium Equivalent, annual Effective Dose Equivalent, and ELCR were all lower than the safe value from consumption of milk by 0.099 Bq l^{-1}, 0.0019 mSv y^{-1}, and 0.005×10^{-3}, respectively. Since the differences from the safe values are small, the, the quantity of milk one should consume should be regulated to keep the Radiological Effects low. This estimation was done in the next subsection. Nyakabande Sub County is relatively flat and at lower altitude compared to the other sub counties. This could be the reason why the activity concentrations of the radionuclides in samples from Nyakabande hence radiological effects are relatively higher due to deposition of the radionuclides due to soil erosion.

3.2Estimation of safe milk consumption rate

In order to determine the relationship between the average Excess Lifetime Cancer Risks in Table 11 and volume of milk used to calculate the activity concentrations of 0.5 l for all samples (Qn), linear regression was used to solve Equation 6 as follows;

$$\begin{pmatrix} 0.000047 \\ 0.000038 \\ 0.000043 \\ 0.000041 \\ 0.000042 \\ 0.000025 \\ 0.000046 \end{pmatrix} = k \begin{pmatrix} 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \\ 0.5 \end{pmatrix},$$

The value of k is k = 7.4457×10^{-5}. The respective Excess Lifetime Cancer Risk-volume relation is shown by Equation 7 in life time of 60 years.

$$ELCRm = 7.4457 \times 10^{-5} v; \quad (7)$$

The contribution to the Excess Lifetime Cancer Risk by milk that was calculated using Table 1 and 60 Bq kg^{-1} reference values of U-238, Th-232, and k-40, the quantity of milk one should consume to be safe in litres in a year is v such that;

$$0.0476 \times 10^{-3} = \frac{7.4457 \times 10^{-5}}{60} v$$

$$v = 38.38.$$

In one day,

$$v = \frac{38.38}{365.25} = 0.105$$

Or 0.74 litres per week.

4 Conclusions

The average activity concentrations in milk form U-238, Th-232, and K-40 were; 1.058 Bq l^{-1}, 1.369 Bq l^{-1}, and 19.679 Bq l^{-1}, respectively. Average Radium Equivalent was 4.531 Bq l^{-1}, Annual Effective Dose Equivalent was 0.014 mSv y^{-1} and Excess Lifetime Cancer Risk was 0.041×10^{-3}. Samples that were collected from cattle farms that were relatively flat and at lower altitudes had relatively higher activity concentrations hence higher Radiological Effects. The safe values from consumption of milk for Ra_{eq}, annual Effective Dose equivalent and Excess Lifetime Cancer Risk were determined as 4.630 Bq l^{-1}, 0.0159 mSv y^{-1}, and 0.046×10^{-3}. The values of the Radiological Effects for this study were lower than the safe values by 0.009 Bq l^{-1}, 0.0019 mSv y^{-1}, and 0.005×10^{-3} respectively. The results therefore, show that the milk is safe but the differences are small hence the consumption rate was estimated to 0.105 litres per day (0.74 litres per week) in order to keep the radiological effects low.

Acknowledgement

We acknowledge University Staff Development Committee of Kabale University for funding this study. We are highly indebted to the Radioisotope Laboratory of Makerere University for analysing our samples. We highly thank the Physics laboratory of St. Paul's Mutolere Secondary School where the samples were prepared and stored.

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Table 1: Reference concentration values of radionuclides of uranium and thorium series in food and drinking water.

Products	**Concentrations (Bq kg $^{-1}$ or Bq l $^{-1}$) $\times 10^{-3}$**								
	U-238	Th-230	Ra-226	Pb-210	Po-210	Th-232	Ra-228	Th-228	U-235
Milk	1	0.5	5	15	15	0.3	5	0.3	0.05
Meat	2	2	15	80	60	1	10	1	0.05
Grain	20	10	80	50	60	3	60	3	1
Vegetables	20	20	50	80	100	15	40	15	1
Rootsand fruits	3	0.5	30	40	30	0.5	20	0.5	0.1
Fish	30	10	100	200	2000	10	ND	100	ND
Water	1	0.1	0.5	10	5	0.05	0.5	0.05	0.04

Table 2: Reference "Annual Effective" doses from radionuclides of uranium and thorium series.

	Committed Annual Effective Dose (mSv)			
	Infants	Children	Adults	Age-weighted
Total Diet (ED_{fdw})	0.26	0.2	0.11	0.14
Drinking water (ED_{dw})	0.012	0.012	0.007	0.009
$\frac{ED_{dw}}{ED_{fdw}}$	4.8%	6.1%	6.1%	6%

Table 3: Activity Concentrations in Milk samples from Nyakabande.

Sample	**Average Activity Concentration (Bq l^{-1})**			**Radiological Effects**		
	U-238	Th-232	K-40	Ra_{eq} (Bq l^{-1})	AEDE (mSv y^{-1})	ELCR $\times 10^{-3}$
NDEM1	0.266	1.7886	30.863	5.196	0.016	0.048
NDEM2	0.929	1.345	18.546	4.280	0.013	0.038
NDEM3	0.293	0.856	19.479	3.017	0.009	0.028
NDEM4	0.973	1.559	14.856	4.346	0.013	0.038
NDEM5	0.396	1.747	28.187	5.065	0.016	0.047
NDEM6	1.481	3.185	54.544	10.235	0.031	0.094
NDEM7	0.406	1.206	9.871	2.891	0.009	0.026
NDEM8	0.944	2.780	43.041	8.234	0.025	0.075
NDEM9	0.870	3.845	47.754	10.045	0.030	0.091
NDEM10	0.666	2.771	37.239	7.496	0.023	0.068
NDEM11	0.386	0.513	6.141	1.592	0.005	0.014
NDEM12	0.798	2.765	10.736	5.579	0.016	0.048
NDEM13	0.675	1.394	9.839	3.426	0.010	0.030
NDEM14	0.342	1.177	8.313	2.665	0.008	0.024
NDEM15	0.265	1.821	30.784	5.239	0.016	0.049
NDEM16	0.932	1.345	18.601	4.288	0.013	0.038
Average	0.664	1.881	24.300	5.225	0.016	0.047

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Table 4: Activity Concentrations in Milk samples from Nyakabande.

Sample	Average Activity Concentration ($Bq\ l^{-1}$)			Radiological Effects		
	U-238	Th-232	K-40	Ra_{eq} ($Bq\ l^{-1}$)	AEDE ($mSv\ y^{-1}$)	ELCR $\times 10^{-3}$
CHIM1	1.577	1.428	14.554	4.740	0.014	0.041
CHIM2	1.773	0.419	17.427	3.714	0.011	0.033
CHIM3	1.292	2.320	22.378	6.333	0.019	0.056
CHIM4	1.573	1.424	14.517	4.727	0.014	0.041
CHIM5	1.785	0.931	15.785	4.332	0.013	0.038
CHIM6	1.228	1.112	11.339	3.691	0.011	0.032
CHIM7	1.783	0.933	15.529	4.313	0.013	0.038
CHIM8	1.683	0.989	16.541	4.371	0.013	0.038
CHIM9	1.249	1.131	11.532	3.754	0.011	0.033
CHIM10	1.786	0.932	15.551	4.316	0.013	0.038
CHIM11	0.687	1.903	8.201	4.040	0.012	0.035
CHIM12	1.226	1.110	11.320	3.685	0.011	0.032
CHIM13	1.785	0.931	15.542	4.313	0.013	0.038
Average	1.494	1.197	14.632	4.333	0.013	0.038

Table 5: Activity Concentrations in Milk samples from Nyarusiza.

Sample	Average Activity Concentration ($Bq\ l^{-1}$)			Radiological Effects		
	U-238	Th-232	K-40	Ra_{eq} ($Bq\ l^{-1}$)	AEDE ($mSv\ y^{-1}$)	ELCR $\times 10^{-3}$
NZAM1	1.882	1.273	30.538	6.054	0.018	0.054
NZAM2	1.510	1.080	24.314	4.927	0.015	0.044
NZAM3	1.106	1.797	23.574	5.491	0.016	0.049
NZAM4	1.062	1.692	22.474	5.212	0.016	0.047
NZAM5	1.080	1.567	24.314	5.193	0.016	0.047
NZAM6	1.074	0.987	26.789	4.477	0.041	0.041
NZAM7	1.038	0.987	25.782	4.435	0.014	0.041
NZAM8	1.141	0.927	25.792	4.453	0.014	0.041
NZAM9	1.516	1.079	24.345	4.934	0.015	0.044
NZAM10	1.027	0.973	24.792	4.327	0.013	0.040
NZAM11	1.611	0.839	22.779	4.565	0.014	0.041
NZAM12	1.009	0.797	26.721	4.042	0.013	0.039
NZAM13	0.996	0.963	21.676	4.042	0.012	0.037
Average	1.235	1.147	24.915	4.793	0.014	0.043

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Table 6: Activity Concentrations in Milk samples from Murora.

Sample	Average Activity Concentration ($Bq\ l^{-1}$)			Radiological Effects		
	U-238	Th-232	K-40	Ra_{eq} ($Bq\ l^{-1}$)	AEDE ($mSv\ y^{-1}$)	ELCR $\times 10^{-3}$
MRAM1	1.550	1.052	16.563	4.330	0.013	0.038
MRAM2	1.048	1.554	16.497	4.540	0.013	0.040
MRAM3	1.152	1.549	16.553	4.642	0.014	0.041
MRAM4	0.803	1.353	34.437	5.389	0.017	0.050
MRAM5	1.054	1.584	16.543	4.593	0.014	0.041
MRAM6	1.101	1.061	17.045	3.931	0.012	0.035
MRAM7	0.816	1.275	33.996	5.257	0.016	0.049
MRAM8	1.041	1.544	16.497	4.519	0.013	0.040
MRAM9	1.052	1.549	15.554	4.465	0.013	0.039
MRAM10	0.992	1.582	18.458	4.676	0.014	0.042
MRAM11	1.047	1.543	16.487	4.523	0.013	0.040
AVERAGE	1.060	1.422	19.875	4.624	0.014	0.041

Table 7: Activity Concentrations in Milk samples from Muramba.

Sample	Average Activity Concentration ($Bq\ l^{-1}$)			Radiological Effects		
	U-238	Th-232	K-40	Ra_{eq} ($Bq\ l^{-1}$)	AEDE ($mSv\ y^{-1}$)	ELCR $\times 10^{-3}$
MBAM1	1.204	2.392	12.349	5.575	0.016	0.048
MBAM2	1.182	2.327	12.167	5.446	0.016	0.047
MBAM3	SV	1.987	26.270	4.864	0.015	0.045
MBAM4	1.018	0.957	16.450	3.653	0.011	0.033
MBAM5	0.621	1.031	18.143	3.492	0.011	0.032
MBAM6	1.048	1.522	10.748	4.052	0.012	0.035
MBAM7	1.074	1.596	10.472	4.163	0.012	0.036
MBAM8	0.941	1.990	26.312	5.813	0.017	0.052
MBAM9	1.001	1.989	25.301	5.793	0.017	0.052
MBAM10	0.916	1.921	23.254	5.454	0.016	0.049
MBAM11	1.332	1.543	17.762	4.906	0.014	0.043
MBAM12	1.071	1.507	10.986	4.072	0.012	0.035
MBAM13	1.045	1.592	10.720	4.147	0.012	0.036
MBAM14	0.941	1.988	26.286	5.808	0.017	0.052
MBAM15	0.811	1.677	16.148	4.454	0.013	0.040
Average	0.947	1.735	17.558	4.779	0.014	0.042

SV stands for ‘Small Value’ that could not be detected.

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Table 8: Activity Concentrations in Milk samples from Nyarubuye.

Sample	Average Activity Concentration ($Bq\ l^{-1}$)			Radiological Effects		
	U-238	Th-232	K-40	Ra_{eq} ($Bq\ l^{-1}$)	AEDE ($mSv\ y^{-1}$)	ELCR $\times 10^{-3}$
NYEM1	1.193	0.954	10.818	3.390	0.010	0.030
NYEM2	1.720	0.687	7.805	3.303	0.009	0.028
NYEM3	0.864	0.690	7.839	2.454	0.007	0.021
NYEM4	0.874	0.978	7.765	2.870	0.008	0.025
NYEM5	0.887	0.689	7.825	2.475	0.007	0.022
Average	1.108	0.800	8.410	2.899	0.008	0.025

Table 9: Activity Concentrations in Milk samples from Nyakinama.

Sample	Average Activity Concentration ($Bq\ l^{-1}$)			Radiological Effects		
	U-238	Th-232	K-40	Ra_{eq} ($Bq\ l^{-1}$)	AEDE ($mSv\ y^{-1}$)	ELCR $\times 10^{-3}$
NMAM1	0.803	1.339	13.791	3.780	0.011	0.034
NMAM2	0.891	1.308	24.374	4.638	0.014	0.042
NMAM3	0.893	1.311	23.418	4.571	0.014	0.042
NMAM4	0.907	1.572	41.251	6.331	0.020	0.059
NMAM5	0.891	1.308	24.379	4.639	0.014	0.042
NMAM6	0.996	1.573	41.159	6.415	0.020	0.060
Average	0.897	1.402	28.062	5.062	0.015	0.046

Table 10: Average activity Radiological Effects in milks samples from all volcanic areas.

Sample	Average Activity Concentration ($Bq\ l^{-1}$)			Radiological Effects		
	U-238	Th-232	K-40	Ra_{eq} ($Bq\ l^{-1}$)	AEDE ($mSv\ y^{-1}$)	ELCR $\times 10^{-3}$
NYAKABANDE	0.664	1.881	24.300	5.225	0.016	0.047
CHAHI + KM	1.494	1.197	14.632	4.333	0.013	0.038
NYARUSIZA	1.235	1.147	24.915	4.793	0.014	0.043
MURORA	1.060	1.422	19.875	4.624	0.014	0.041
MURAMBA	0.947	1.735	17.558	4.779	0.014	0.042
NYARUYE	1.108	0.800	8.410	2.899	0.008	0.025
NYAKINAMA	0.897	1.402	28.062	5.062	0.015	0.046
AVERAGE	1.058	1.369	19.679	4.531	0.014	0.041

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