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Analysis of radionuclide concentrations in fish and radioactivity levels in water from Lake Edward, Rukungiri District, Uganda

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Abstract
The presence of radioactive elements in aquatic ecosystems poses environmental and public health risks, particularly in communities dependent on water bodies for drinking, agriculture, and fishing. This study analyzed the concentration of selected radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) in the fish samples and the gross alpha and gross beta radioactivity in the water samples of Lake Edward, Rukungiri District, Uganda, to assess potential radiological impacts on the local population. Fish samples were collected from the lake and analyzed using gamma spectroscopy. Water samples were collected from different zones of the lake and analyzed using liquid scintillation counting techniques. The study measured radionuclide activity concentrations, calculated absorbed dose rates and effective doses, evaluated hazard indices for fish, and assessed gross alpha and beta radioactivity in water samples. The activity concentrations in fish ranged from 12.76 to 18.73 Bq/kg for ^{226}Ra, 2.28–4.83 Bq/kg for ^{232}Th, and 165.33–209.06 Bq/kg for ^{40}K. The mean absorbed dose rate (41.00 nGy/h) and effective dose (0.59 mSv/y) were below global safety limits. Hazard indices for external (0.27) and internal (0.31) exposure were well below the recommended threshold of 1. Water activity concentrations also met WHO safety standards, though the farming zone exhibited higher beta activity, likely due to agricultural runoff. The results indicate that the radionuclide levels in Lake Edward's water and fish pose no significant radiological risk. However, agricultural practices, particularly fertilizer use, may contribute to elevated radionuclide concentrations. Regular monitoring is recommended to ensure long-term environmental and public health safety, with further studies focusing on agricultural runoff and its potential impact.

Keywords Radioactive element · Radionuclides · Water analysis · Fish contamination · Environmental radioactivity

1 Introduction

The presence of radionuclides in water bodies can originate from various sources, including natural processes such as cosmic ray interactions with the atmosphere and radioactive elements present in the Earth's crust [4, 11]. Fish, being a primary food source for many communities around Lake Edward, can bioaccumulate radioactive substances, posing a direct risk to those who consume them [8]. Additionally, anthropogenic activities such as nuclear power generation, mining, and industrial processes contribute to increased radionuclide pollution [13, 33].

In the context of Uganda, where Lake Edward in Rukungiri District is a vital water resource, understanding the sources and impacts of radionuclide pollution is paramount. Potential sources of radionuclide pollutants in Uganda include mining activities [18], industrial discharge, and agricultural runoff containing radioactive elements [35]. Areas with higher levels of radionuclide pollution often coincide with regions of intense anthropogenic activity [31]. These pollutants can

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be both natural, originating from geological processes, and anthropogenic, resulting from human activities [19, 28]. Understanding the distribution and sources of these pollutants is essential for effective management and remediation strategies [3, 36]. Anthropogenic-driven radionuclide pollutants eventually find their way into water bodies, where they become sedimented and integrated into the aquatic environment [23].

This research investigated radioactivity concentration in the water and fish samples of Lake Edward, Rukungiri District, Uganda, shedding light on the sources, distribution, and potential impacts of radionuclide pollution in this crucial ecosystem. The specific objectives of the study were to determine the concentration of the radionuclides in the fish samples, estimate the radiation dose in the fish samples, and evaluate the gross alpha and gross beta radioactivity in the water samples.

Research on this lake has covered various aspects, including its ecological health, water quality, biodiversity, and contamination from natural and anthropogenic sources. A study by Borges et al. [9] and Musinguzi et al. [20] documented the diversity of fish species in the lake, noting a decline in certain native species due to overfishing and habitat degradation. The health of the aquatic ecosystem, including the presence of invasive species and the impact of human activities, has been studied by researchers like Mwebaze et al. [22]. They highlighted the need for conservation efforts to protect the lake's biodiversity and maintain its ecological balance.

Studies have also considered the potential impact of human activities, such as mining and industrial processes, on radioactivity levels [8, 21, 30]. However, these studies have often been limited in scope and have not extensively covered the accumulation of radioactive elements in biota like fish. This gap needs to be addressed to develop appropriate guidelines and interventions for the local population.

Addressing these gaps, this research on the "Analysis on Distribution of Selected Radioactive Element Concentration in Water and Fish of Lake Edward, Rukungiri District, Uganda," can provide valuable contributions. By focusing on the detection, quantification, and correlation of radioactive elements in water and fish, the study will enhance understanding of radiological risks in the region and inform both conservation efforts and public health policies.

2 Methodology

2.1 The study area

Lake Edward is situated in the western part of Uganda, within the Rukungiri District. Figure 1 shows map of the study area. This lake, one of the smaller African Great Lakes, is located at the coordinates approximately 0°20′ to 0°40′ South latitude and 29°30′ to 29°72′ East longitude [14]. It lies at the border between Uganda and the Democratic Republic of Congo, forming part of the greater Albertine Rift Valley system [8]. The lake covers an area of about 2,325 square kilometers, with a maximum depth of approximately 112 m [8].

Fig. 1 Map of Lake Edward Rukungiri District Uganda

Lake Edward is characterized by a tropical climate with two distinct rainy seasons, typically occurring from March to May and September to November [8]. The lake's waters are relatively shallow compared to other Great Lakes in the region, with extensive littoral zones that provide habitats for various aquatic plants and animals [8]. The surrounding landscape includes a mixture of wetlands, savannahs, and forested areas, which contribute to the lake's rich biodiversity [8]. The lake supports a wide range of flora and fauna, including numerous fish species, some of which are endemic to the region. Notable fish species include Nile tilapia (Oreochromisniloticus), catfish (Clarias spp.), and various cichlids [21]. The lake and its environs are part of the Queen Elizabeth National Park, a UNESCO World Heritage Site, known for its diverse wildlife and significant conservation value [8].

The communities around Lake Edward primarily engage in fishing, agriculture, and livestock rearing [8, 10]. Fishing is a major economic activity, with many local residents depending on the lake's fish for their livelihood and food security. Agriculture in the region includes the cultivation of crops such as maize, beans, bananas, and coffee, which are often grown using water from the lake and surrounding wetlands. Additionally, there are small-scale mining activities and potential oil exploration endeavors in the broader Albertine Graben region [10], which pose potential environmental risks to the lake. Human settlements around the lake have grown over the years, leading to increased pressure on the lake's resources and potential pollution from domestic and agricultural runoff.

Lake Edward faces several environmental challenges, including pollution, overfishing, habitat destruction, and potential radiation contamination. The latter is of particular concern due to its long-term health implications for both aquatic life and human populations. Sources of radiation could include natural geological formations, agricultural runoff containing phosphate fertilizers, and anthropogenic activities such as mining and industrial processes.

2.2 Sampling and samples preparations

Water samples were collected from sixteen locations, grouped into four zones based on land use and potential pollution sources:

- Zone A: Rubirizi community near the lake's shoreline at coordinates 0.3336° S, 29.6953° E. This fishing community was sampled to evaluate how fishing activities affect the lake.
- Zone B: Rukungiri community near the lake's shoreline at coordinate 0.3532° S, 29.6941° E. This farming community was sampled to assess the impact of farming on the lake.
- Zone C: Kanungu community near the lake's shoreline at coordinates 0.3989° S, 29.6922° E. This area is influenced by domestic and livestock activities. Sampling here aimed to examine how household waste and livestock effluents affect the lake's water quality.
- Zone D: Rubirizi community near the lake's shoreline at coordinates 0.4598° N, 33.1734° E. This zone, with minimal human activity, was chosen as a control. It provides a baseline to compare natural conditions with the environmental impacts observed in other zones.

Four samples were collected from each of Zones A, B, C, and D using pre-sterilized polyethylene containers to avoid contamination. Before final sample collection, the containers were rinsed thoroughly with lake water to remove any residues from prior contents or sterilization agents.

To ensure accurate radioactivity measurements, the water samples were immediately filtered after collection to remove suspended particles. This process used 0.45-micron (μm) membrane filters, known for effectively removing particulates, microorganisms, and fine sediment [1, 2, 6]. These filters were chosen to focus on the dissolved fraction of radionuclides, offering better insights into radionuclide mobility and bioavailability.

Filtration was done immediately to prevent chemical changes, such as radionuclide adsorption onto particulates [25, 26]. After filtration, the water samples were stored in airtight containers at controlled temperatures to maintain their stability and integrity until laboratory analysis [25, 26].

Samples of four different fish species were collected using traps to catch the fish in collaboration with local fishermen:

Sample A: Nile tilapia (*Oreochromis niloticus*).
Sample B: Nile perch (*Lates* **niloticus**).
Sample C: African catfish (*Clarias gariepinus*).
Sample D: Semutundu (Bagrus docmak).

Ten samples each of the four different fish species were collected.

2.3 Analytical techniques

To assess radiological concerns related to fish consumption, only the edible fish flesh was analyzed [27]. Skin and bones were separated from the flesh before the drying process began.

First, the fish samples were air-dried at room temperature for 48 h to remove most of the moisture without altering their composition, as excessive heat could affect the samples. After air drying, the samples were placed in a laboratory oven at approximately 110 °C for 24 h to remove any remaining moisture. This temperature and duration ensured complete drying without affecting the radionuclides. A Memmert UFE 500 oven was used, known for its precise temperature control and uniform heat distribution.

Once dried, the samples were homogenized by grinding them into a fine powder using an agate mortar and pestle. This method minimized contamination and ensured uniformity for accurate analysis. Each sample was processed to a weight of 300 g, measured with high precision (to the nearest milligram) using a Sartorius Cubis II analytical balance.

The powdered samples were transferred to uniform plastic containers, sealed to prevent contamination and moisture, and stored for 30 days. This storage period allowed secular equilibrium to be established between radium-226 (^{226}Ra), thorium-232 (^{232}Th), and their daughter radionuclides [32], ensuring accurate radioactivity measurements.

Radioactivity levels in the samples were measured using a NaI(Tl) gamma-ray spectrometer equipped with a 7.26 cm × 7.26 cm NaI(Tl) crystal detector and a high-voltage photomultiplier tube (PMT). This system included an Oxford PCAP Multichannel Analyzer (MCA) card and specialized software for data collection and analysis. The minimum detectable level (MDL) were: ^{226}Ra**:** ≈ 0.12 Bq/kg; $^{\mathbf{232}}$Th**:** ≈ 0.10 Bq/kg; ^{40}K: ≈ 1.5 Bq/kg. Figure 2 shows the efficiency curve of the NaI(Tl) detector.

2.4 Quality control measures

To ensure the accuracy, reliability, and reproducibility of the radioanalytical measurements performed on fish and water samples from Lake Edward, several quality control (QC) measures were implemented in the laboratory:

Calibration of Equipment: The NaI(Tl) gamma spectrometer was energy-calibrated using certified reference materials (RGU-1, RGTh-1, RGK-1) to ensure proper identification of radionuclides. Efficiency calibration was conducted using standard sources with known activity concentrations to establish detection limits and correct for instrumental variations.

Use of Certified Reference Materials (CRMs): CRMs with well-documented radionuclide activity concentrations were analyzed alongside samples to validate the accuracy of the measurements. For quality assurance, regular cross-checks with external laboratories were performed.

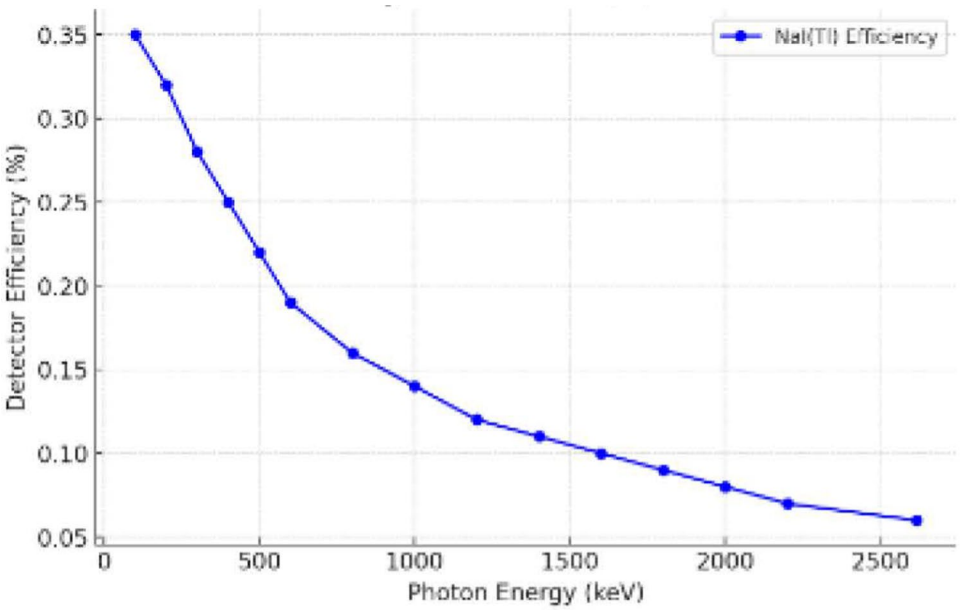

Fig. 2 Efficiency curve of the NaI(Tl) detector used in this study

*Background Radiation Correction***:** A background measurement was conducted using an inert sample (distilled water in a sealed polyethene container) for 30,000 s. The background spectrum was subtracted from each sample spectrum to eliminate contributions from environmental or instrumental background radiation.

*Detection Limit Assessment***:** The Minimum Detectable Activity (MDA**)** for each radionuclide was determined to ensure that reported concentrations were above instrument detection capabilities. The MDA was computed using standard methods that account for background count rates, detector efficiency, and sample measurement time.

*Reproducibility and Precision Checks***:** Each sample was analyzed in triplicate to verify consistency and minimize errors. The relative standard deviation (RSD) of repeated measurements was kept below an acceptable threshold (typically ≤ 5%) to confirm precision.

*Quality Assurance (QA) Procedures***:** Routine performance checks were conducted to ensure the stability of the detector and electronics. Strict adherence to laboratory Standard Operating Procedures (SOPs) was maintained.

*Data Verification and Uncertainty Analysis***:** Measured activity concentrations were corrected for sample weight, detector efficiency, and decay corrections. Uncertainty calculations, including statistical and systematic uncertainties, were performed and reported for each measurement.

By implementing these rigorous quality control measures, the laboratory ensured that the reported radioactivity levels in Lake Edward water and fish were reliable and scientifically valid.

2.5 Calculation of annual effective dose

The estimation of the annual effective dose rates, depended on conversion coefficient from absorbed dose to effective dose, 0.7 SvG/y and outdoor occupancy factor of 0.2 [24]. The effective dose rate in units of mSv/y was calculated by the following formula in Eq. (1) [24]:

$$\text{Effective dose rate (mSv/y)} = \text{D(nGy/h)} \times 8760\text{h} \times 0.2 \times 0.7\text{SvG/y}\ 10^{-6} \tag{1}$$

2.6 External hazard index (Hex)

Radiation exposure due to ^{226}Ra, ^{232}Th and ^{40} K may be external. This hazard, defined in terms of external hazard index and denoted by H_{ex}, was calculated using the Eq. (2) [26]:

$$\boldsymbol{H_{ex}} = \frac{\boldsymbol{C_{Ra}}}{370} + \frac{\boldsymbol{C_{Th}}}{259} + \frac{\boldsymbol{c_K}}{4810} \tag{2}$$

where C_{Ra}, C_{Th} and C_K are the activity concentrations (Bq/kg) of radium, thorium and potassium, respectively as were obtained in the analyzed samples. The value of this index should be less or equal to 1 mSv/y in order for the radiation hazard to be considered acceptable to the public [26].

2.7 Internal hazard index (H_{in})

The internal hazard index (H_{in}) gives the internal exposure to carcinogenic radon and is given by Eq. (3), [26]:

$$\boldsymbol{H_{in}} = \frac{\boldsymbol{C_{Ra}}}{185} + \frac{\boldsymbol{C_{Th}}}{259} + \frac{\boldsymbol{c_K}}{4810} \tag{3}$$

The value of this index should be less or equal to 1 mSv/y in order for the radiation hazard to have negligible hazardous effects to the respiratory organs of the public [26]:

Assessment of Radiological Impact: The estimated absorbed dose rates were compared to established dose criteria and guidelines, such as those recommended by the International Commission on Radiological Protection (ICRP) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). This assessment allowed for the evaluation of potential radiological impacts on both the local populace and the environment.

2.8 Evaluation of gross alpha and gross beta radioactivity in water samples

The gross alpha and gross beta radioactivity in the water samples were measured using liquid scintillation counting techniques. The samples was prepared by adding appropriate scintillation cocktails and then subjected to counting using a liquid scintillation counter [25, 29]. The measured radioactivity levels were then corrected for background radiation and expressed in becquerels per liter (Bq/L).

2.9 Alpha-activity

The alpha activity was expressed as activity concentration C in Becquerel per litre (Bq/l), using the formula [25, 34] as follows:

$$C = \frac{R_n \times a_s \times m \times 1.02}{R_b - R_0 \times 1000 \times V} \tag{4}$$

where.

R_n is the count rate per second corrected for background counts.

Thus, $R_n = R_b - R_0$

R_b is the observed sample count rate in count per second.

R_0 is the background count rate in counts per second.

α_s is the specific activity of the alpha standard.

V is the volume of the sample evaporated in liter.

m is Mass in mg of the residue from volume v and 1.02 is included to correct for 20 ml of nitric acid added per litre as a stabilizer.

Beta-Activity: The gross beta activity was expressed as activity Concentration C in (Bq/1) using the equation [15, 26] as:

$$C = \frac{R_n \times \beta_s \times m \times 1.02}{R_b - R_0 \times 1000 \times V} \tag{5}$$

where: β_s represent the specific activity of Beta standard, all other terms have their usual meanings.

Statistical analysis was performed using SPSS 28 to evaluate the radionuclide concentrations in water and fish samples. Four water samples were analyzed from each of Zones A, B, C, and D, along with ten fish samples from each zone.

3 Results

3.1 Activity concentration of ^{226}Ra, ^{232}Th, and ^{40} K in fish samples

Table 1 summarized the specific activity of ^{226}Ra, ^{232}Th, and ^{40} K in the fish samples in Bq/kg. The activity ^{40} K is distinctly higher than the ^{226}Ra and ^{232}Th.

3.2 Absorbed dose rate, annual effective dose equivalent, external and internal hazard indices for fish

Table 2 presents the dose rate, effective dose equivalent, external and internal hazard indexes for the fish samples.

3.3 Alpha and beta activity concentration in water sample

Gross alpha and beta activity concentration analysis for the collected water samples is presented in Table 3. Figure 3 shows the mean alpha/beta activity distribution in the zones.

Table 1 Specific Activity of ^{226}Ra, ^{232}Th, and ^{40} K Radionuclides in Fish Samples

S/N	Activity Concentration (Bq/kg)											
	^{226}Ra				^{232}Th				^{40} K			
	F-A	F-B	F–C	F-D	F-A	F-B	F–C	F-D	F-A	F-B	F–C	F-D
1	14.00 ± 0.15	18.33 ± 0.12	14.82 ± 0.15	13.56 ± 0.13	3.21 ± 0.18	4.30 ± 0.12	2.79 ± 0.19	2.86 ± 0.18	169.06 ± 0.15	201.53 ± 0.16	198.27 ± 0.12	165.33 ± 0.17
2	18.39 ± 0.18	17.27 ± 0.15	14.19 ± 0.16	14.32 ± 0.17	4.72 ± 0.18	4.83 ± 0.15	3.36 ± 0.14	2.64 ± 0.15	203.73 ± 0.16	203.64 ± 0.13	198.54 ± 0.14	165.78 ± 0.16
3	13.32 ± 0.16	16.42 ± 0.15	14.27 ± 0.13	13.13 ± 0.14	2.28 ± 0.14	4.14 ± 0.19	3.53 ± 0.18	2.71 ± 0.16	178.31 ± 0.14	201.30 ± 0.15	209.06 ± 0.13	169.03 ± 0.15
4	12.79 ± 0.15	17.61 ± 0.17	13.62 ± 0.18	13.74 ± 0.22	3.92 ± 0.17	4.54 ± 0.17	3.46 ± 0.16	3.05 ± 0.21	172.55 ± 0.14	197.94 ± 0.17	199.34 ± 0.15	165.42 ± 0.17
5	14.88 ± 0.17	18.72 ± 0.15	14.29 ± 0.15	13.56 ± 0.18	3.83 ± 0.19	4.32 ± 0.17	3.57 ± 0.16	2.66 ± 0.17	168.74 ± 0.16	203.56 ± 0.18	198.62 ± 0.14	165.33 ± 0.17
6	13.11 ± 0.17	17.19 ± 0.16	14.41 ± 0.15	14.21 ± 0.14	3.86 ± 0.14	3.73 ± 0.15	2.62 ± 0.13	3.14 ± 0.15	173.62 ± 0.18	201.76 ± 0.16	198.75 ± 0.17	165.52 ± 0.16
7	12.76 ± 0.15	17.32 ± 0.13	13.16 ± 0.13	13.68 ± 0.14	2.96 ± 0.16	4.10 ± 0.12	3.24 ± 0.15	2.58 ± 0.13	173.34 ± 0.13	202.55 ± 0.14	201.47 ± 0.15	166.09 ± 0.16
8	12.98 ± 0.21	17.65 ± 0.15	14.74 ± 0.19	13.51 ± 0.21	3.01 ± 0.15	3.86 ± 0.15	3.51 ± 0.22	2.76 ± 0.18	173.56 ± 0.18	201.92 ± 0.17	199.72 ± 0.15	165.48 ± 0.19
9	13.55 ± 0.15	18.21 ± 0.16	14.83 ± 0.14	13.84 ± 0.16	3.92 ± 0.14	3.75 ± 0.17	3.12 ± 0.13	2.53 ± 0.15	169.33 ± 0.16	201.43 ± 0.17	201.53 ± 0.15	165.62 ± 0.16
10	14.32 ± 0.16	17.45 ± 0.15	13.15 ± 0.13	13.73 ± 0.16	2.85 ± 0.15	4.23 ± 0.18	2.68 ± 0.12	3.25 ± 0.15	172.49 ± 0.14	203.07 ± 0.15	199.06 ± 0.16	169.11 ± 0.15
Min	12.76 ± 0.15	17.19 ± 0.16	13.15 ± 0.13	13.13 ± 0.14	2.28 ± 0.14	3.73 ± 0.15	2.62 ± 0.13	2.53 ± 0.15	168.74 ± 0.16	197.94 ± 0.17	198.27 ± 0.12	165.33 ± 0.17
Max	18.39 ± 0.18	18.72 ± 0.15	14.83 ± 0.14	14.32 ± 0.17	4.72 ± 0.18	4.83 ± 0.15	3.57 ± 0.16	3.25 ± 0.15	203.73 ± 0.16	203.64 ± 0.13	209.06 ± 0.13	169.11 ± 0.15
Mean	14.01 ± 0.17	17.62 ± 0.15	14.15 ± 0.15	13.73 ± 0.17	3.46 ± 0.16	4.18 ± 0.16	3.19 ± 0.16	2.82 ± 0.16	175.44 ± 0.15	201.87 ± 0.16	200.44 ± 0.15	166.27 ± 0.16

F = Fish, A = Nile tilapia (Oreochromis niloticus), B = Nile perch (Lates niloticus), C = African catfish (Clarias gariepinus), D = Semutundu (Bagrus docmak)

Table 2 Absorbed dose, effective dose and hazard index for fish samples

Sample number	Sample code	Absorbed dose Rate (nGy/h)	Effective dose Rate (mSv/y)	External hazard Index (H_{ex})	Internal hazard Index (H_{in})
1	A	39.96	0.51	0.24	0.26
2	B	40.35	0.59	0.27	0.32
3	C	41.41	0.56	0.26	0.32
4	D	42.27	0.69	0.29	0.32
	Min	39.96	0.51	0.24	0.26
	Max	42.27	0.69	0.29	0.32
	Mean	41.00	0.59	0.27	0.31

Table 3 Alpha and Beta Activity Concentration in Water Sample collected

S/N	SAMPL ID	Alpha Activity in Bq/L	Beta Activity in Bq/L
1	W-A1	0.20 ± 0.09	0.20 ± 0.03
2	W-A2	0.14 ± 0.03	BDL
3	W-A3	0.09 ± 0.05	0.21 ± 0.03
4	W-A4	0.19 ± 0.09	0.58 ± 0.02
5	W-B1	0.63 ± 0.04	0.72 ± 0.04
6	W-B2	0.79 ± 0.03	0.90 ± 0.05
7	W-B3	0.46 ± 0.02	0.59 ± 0.04
8	W-B4	0.75 ± 0.09	0.78 ± 0.09
9	W-C1	0.40 ± 0.03	0.61 ± 0.03
10	W-C2	0.02 ± 0.02	0.35 ± 0.03
11	W-C3	0.38 ± 0.09	0.58 ± 0.02
12	W-C4	0.03 ± 0.01	0.06 ± 0.04
13	W-D1	0.19 ± 0.01	0.24 ± 0.02
14	W-D2	0.26 ± 0.02	0.28 ± 0.02
15	W-D3	BDL	BDL
16	W-D4	0.22 ± 0.06	0.34 ± 0.09
Mean		0.30 ± 0.05	0.41 ± 0.04
Max		0.79 ± 0.03	0.90 ± 0.05
Min		0.02 ± 0.02	0.06 ± 0.04

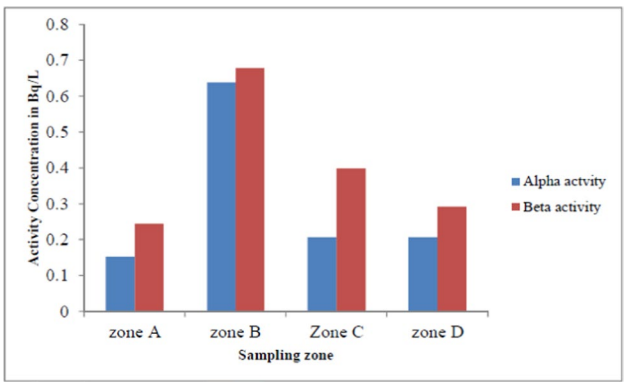

Fig. 3 Mean alpha/beta activity distribution in the zones

Table 4 ANOVA analysis of radionuclides

Radionuclide	Source	Sum of Squares	df	Mean Square	F	Sig. (P-values)
^{226}Ra	Between groups	101.11	3	33.70	35.42	< 0.001
	Within groups	34.26	36	0.95		
^{232}Th	Between groups	9.95	3	3.32	16.03	< 0.001
	Within groups	7.45	36	0.21		
^{40} k	Between groups	9603.06	3	3201.02	104.90	< 0.001
	Within groups	1098.50	36	30.51		

Between Groups: Variance caused by differences between the fish types. Within Groups: Variance within each fish type. F: The test statistic comparing the variances. Sig. (p-value): P-value < 0.005 indicate statistical significant. This confirms significant differences in radionuclide activity concentrations among fish types for all radionuclides

Table 5 ^{226}Ra Tukey's HSD Test

Group 1	Group 2	Mean difference	p-value	Confidence interval (lower, upper)
F-A	F-B	– 3.61	0.001	(– 4.65, – 2.58)
F-A	F-C	– 0.14	0.900	(– 1.19, 0.92)
F-A	F-D	0.28	0.800	(– 0.78, 1.33)
F-B	F-C	3.47	0.001	(2.43, 4.52)
F-B	F-D	3.89	0.001	(2.85, 4.93)
F-C	F-D	0.42	0.700	(– 0.62, 1.47)

Table 6 ^{232}Th Tukey's HSD Test

Group 1	Group 2	Mean Difference	p-value	Confidence interval (lower, upper)
F-A	F-B	-0.72	0.020	(– 1.34, – 0.10)
F-A	F-C	0.28	0.700	(– 0.35, 0.91)
F-A	F-D	0.63	0.070	(– 0.00, 1.26)
F-B	F-C	1.00	0.001	(0.37, 1.63)
F-B	F-D	1.35	0.001	(0.73, 1.98)
F-C	F-D	0.35	0.500	(– 0.27, 0.98)

Table 7 ^{40} K Tukey's HSD Test

Group 1	Group 2	Mean Difference	p-value	Confidence Interval (Lower, Upper)
F-A	F-B	– 26.43	0.001	(– 32.69, – 20.17)
F-A	F-C	– 25.00	0.001	(– 31.26, – 18.74)
F-A	F-D	8.87	0.001	(2.61, 15.13)
F-B	F-C	1.43	0.900	(– 4.83, 7.69)
F-B	F-D	35.30	0.001	(29.04, 41.56)
F-C	F-D	33.87	0.001	(27.61, 40.13)

Table 8 ANOVA Results for Alpha and Beta Activity

Activity	Source	Sum of Squares	df	Mean Square	F	Sig. (P-values)
Alpha	Between Groups	0.8332	3	0.2777	15.30	< 0.001
	Within Groups	0.2181	12	0.0182		
	Total	1.0513	15			
Beta	Between Groups	1.2758	3	0.4253	30.32	< 0.001
	Within Groups	0.1682	12	0.0140		
	Total	1.4440	15			

3.4 ANOVA and Tukey's HSD test for the radionuclides

Table 4 shows the result of the ANOVA analysis of the radionuclides.

Tables 5, 6, 7 show the Tukey's HSD test for the radionuclides. Post-hoc tests identify specific group pairs with significant differences in mean activity concentrations.

3.5 ANOVA and Tukey's HSD test for the alpha (α) and beta (β) activity concentrations

Table 8 shows the ANOVA result for the alpha and beta activity concentrations. The F-value for Alpha activity is 15.30 with a p-value of < 0.001, indicating statistically significant differences in alpha activity between the groups. The F-value for Beta activity is 30.32 with a p-value of < 0.001, indicating statistically significant differences in beta activity between the groups.

Table 9 shows Tukey's HSD test for the Alpha and Beta activity.

Table 9 Tukey's HSD Test for Alpha and Beta Activity

Comparison	Mean Difference	Std. Error	P-Value	95% Confidence Interval (Lower, Upper)
Alpha Activity				
A vs B	– 0.43	0.07	0.001	(-0.57, -0.29)
A vs C	– 0.01	0.07	0.900	(-0.15, 0.13)
A vs D	0.02	0.07	0.800	(-0.12, 0.16)
B vs C	0.42	0.07	0.001	(0.28, 0.56)
B vs D	0.45	0.07	0.001	(0.31, 0.59)
C vs D	0.03	0.07	0.800	(-0.11, 0.17)
Beta Activity				
A vs B	– 0.52	0.08	0.001	(– 0.68, – 0.36)
A vs C	– 0.11	0.08	0.400	(– 0.27, 0.05)
A vs D	– 0.07	0.08	0.500	(– 0.23, 0.09)
B vs C	0.41	0.08	0.001	(0.25, 0.57)
B vs D	0.45	0.08	0.001	(0.29, 0.61)
C vs D	0.04	0.08	0.800	(– 0.12, 0.20)

For Alpha Activity: There is a significant difference between Group A and Group B ($p < 0.05$). There is no significant difference between Group A and Group C or Group A and Group D. For Beta Activity: There is a significant difference between Group A and Group B ($p < 0.05$). No significant difference between Group A and Group C or Group A and Group D

Table 10 Comparison of Radionuclide Activity in Fish and Water from Various Studies

Study location	Radionuclides measured	Activity concentrations (Bq/kg or Bq/L)	Absorbed dose rate (nGy/h)	Effective dose (mSv/y)	Key findings
Lake Edward, Uganda (This Study)	^{22}Ra, ^{232}Th, ^{40} K, Gross α, Gross β	^{22}Ra: 12.76–18.73 Bq/kg, ^{232}Th: 2.28–4.83 Bq/kg, ^{40} K: 165.33–209.06 Bq/kg	41.00	0.59	Safe for fish consumption; water in farming zones showed elevated gross beta activity due to agricultural runoff
Mediterranean Sea [12]	^{22}Ra, ^{232}Th, ^{40} K	^{22}Ra: 9.45–15.80 Bq/kg, ^{232}Th: 1.95–3.87 Bq/kg, ^{40} K: 150.20–200.30 Bq/kg	38.5	0.55	Similar trend of higher ^{40}K concentrations in fish; overall low risk
Singida Municipality, Tanzania [17]	^{22}Ra, ^{232}Th, ^{40} K	^{22}Ra: 13.10–19.22 Bq/kg, ^{232}Th: 2.50–4.96 Bq/kg, ^{40} K: 170.11–215.09 Bq/kg	42.2	0.63	Comparable radionuclide distribution; ^{40}K levels highest, no major health risks
India [7]	^{22}Ra, ^{232}Th, ^{40} K	^{22}Ra: 20.12–30.44 Bq/kg, ^{232}Th: 5.20–8.33 Bq/kg, ^{40} K: 220.45–280.11 Bq/kg	55.8	0.89	Higher activity due to phosphate fertilizers and industrial discharge
China [16]	^{22}Ra, ^{232}Th, ^{40} K, Gross α, Gross β	^{22}Ra: 22.60–35.00 Bq/kg, ^{232}Th: 4.85–9.30 Bq/kg, ^{40} K: 190.55–260.78 Bq/kg	58.3	1.10	Increased levels in agricultural regions; higher internal hazard index
River Niger, Nigeria [5]	^{22}Ra, ^{232}Th, ^{40} K	^{22}Ra: 11.50–16.90 Bq/kg, ^{232}Th: 2.10–4.20 Bq/kg, ^{40} K: 160.50–210.30 Bq/kg	40.2	0.57	Safe levels, similar to Uganda study; natural background radiation dominates

4 Discussion

Lake Edward's radionuclide levels are consistent with global patterns in natural freshwater systems, posing minimal health risks. Table 10 presents a comparison of the present study and other related studies. Across all studies, ^{40}K had the highest activity concentrations in fish, confirming its widespread natural presence in the environment. Studies from India and China reported higher concentrations due to intensive fertilizer use and industrial discharges. The effective doses in Lake Edward fish (0.59 mSv/y) are similar to findings from Tanzania (0.63 mSv/y) and Nigeria (0.57 mSv/y), all well below the 1 mSv/y safety limit. While most studies confirmed safe water levels, China and India reported higher hazard indices**,** likely from human activities. Similarly, in Lake Edward, the farming zone showed elevated beta activity, highlighting the need for agricultural runoff control.

5 Conclusion

This study found that the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in Lake Edward's water and fish were within internationally accepted safety limits. The absorbed dose rate and effective dose were below global averages, indicating minimal radiological risk from fish consumption. Water was generally safe for drinking, except in farming zones where agricultural runoff increased gross beta activity. Fertilizers contributed to elevated radionuclide levels, necessitating better runoff management. Regular monitoring is recommended to ensure continued safety amid ongoing agricultural activities, with further studies focusing on agricultural runoff and its potential impact.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate Kampala International University Research Ethics Committee granted the study ethical approval under reference number: KIU-2024–302, in accordance with the Uganda research guidelines and regulations.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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