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Radioactivity and Radiological Health Risks Assessment of Branded bottled Water and Sachet Drinking Water

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Abstract

Water is crucial for human survival and development. While there are different levels of available sources, the water quantity and quality are essential factors in choosing a source. Water as a solvent, it can dissolve and accommodate almost all the substances it interacts with and acts as transport agent for dissolved substances within human body. Therefore, water used for drinking purposes contributes immensely to the environmental factors that affect human health; then, a clean water is vital to the welfare of any community. This study evaluates the radiation levels and radiological health impacts in 30 sachets and 10 bottled water brands from six (6) Local Government Areas of Ijesaland, Osun State, Nigeria, using a Thallium-doped Cesium Iodide detector. Activity concentrations in sachet water ranged from 203.2 to 327.8 BqL^{-1} (mean 268.35 BqL^{-1}), 7.4 to 11.1 BqL^{-1} (mean 8.56 BqL^{-1}), and 10.8 to 19.9 BqL^{-1} (mean 16.3 BqL^{-1}). The concentrations in the bottled water ranged from 249.1to 304.8 BqL^{-1} for ^{40}K, 8.1 to 11.5 BqL^{-1} for ^{238}U, and 11.8 to 18.3 BqL^{-1} for ^{232}Th. The estimated age-dependent annual effective doses (AED) for all age groups, exceed the 0.1 mSv/y permissible limit suggested by International Commission on Radiological Protection (ICRP). The results revealed that the lactate babies (0 -1)yr age-group are the group mostly vulnerable to the effect of radiation. Also the corresponding excess lifetime cancer risks obtained in the study exceeds the World Health Organization (WHO)-permissible limit of 10^{-3}. These findings suggest a serious carcinogenic health risk from the intake of both sachet and bottled water in the area considered in the study.

Keywords*: Natural Radionuclides, Gamma Spectrometry, Bottled Drinking Water, Sachet Drinking Water, Activity Concentration Levels, Annual Effective Dose.*

I. INTRODUCTION

Humans are continually exposed to various sources of ionizing radiation (i.e, different energy types released by atoms that can free tightly-bound electrons from atoms, potentially causing damage) through natural processes from cosmic radiation and terrestrial radioisotopes (radioactive isotopes found in the soil and rocks), and anthropogenic sources such as weapons testing and nuclear industrial accidents. The main exposure pathways are inhalation (breathing in radioactive particles) and ingestion (eating or drinking contaminated food and water). It is estimated that the average dose (amount of radiation energy absorbed) from the ingestion of naturally occurring radionuclides (unstable atoms that emit radiation), e.g uranium-238, (^{238}U), thorium-232 (^{232}Th), decay-series radionuclides (radioactive substances produced by the decay of other radioactive elements), and ^{40}K (potassium-40) in the diet and drinking water is about 0.3 mSv/y (millisieverts per year, a unit measuring the health effect of radiation). (UNSCEAR, 2000, Kinahan et al, 2020). Potable water safety remains a high public health concern, with the use of bottled and sachet water increasing worldwide.

Radiological substances can uniquely affect health among drinking water contaminants. Long-term effects of radiological contamination include the potential to cause cancer and mutation. Therefore, measuring radioactive contaminants in drinking water is important. Activity concentration is a critical step in risk assessment and management (WHO, 2011; UNSCEAR, 2000). Providing information about risks and encouraging informed decisions helps prevent the health effects of radioactivity.

Studies of the radioactivity of bottled and sachet water, especially of natural radionuclides (^{238}U, ^{232}Th,^{40}K), show that risk varies in different nations.

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Portuphy et al., (2018), Madzunya et al., (2020), Kinahan et al., (2020), La Verde et al., (2021), Onyutha et al., (2022), Kumar et al. (2023), Sanjay et al. (2024), and Rukundo et al. (2024) showed that radionuclide distribution in aquatic bodies is inhomogeneous. This pattern leans toward the local geology from which waters are transported and is dominated by anthropogenic activities that infiltrate these areas. Consequently, local geology strongly determines the extent of unavoidable human exposure to radiation.

Contaminated water containing naturally occurring radioactive materials may expose people to external and internal radiation, increasing health risks. Strong evidence links waterborne radioisotope overexposure to health effects such as lung cancer, leukemia, and stomach cancer.

A literature review of the scientific studies have shown that various works have examined the radioactivity and radiological health risks associated with bottled and sachet water consumed various locations in Nigeria.

Ajayi & Adesida (2009) conducted radiological assessment in sachet water from Akure, in Ondo State southwestern Nigeria. It was discovered that some uranium activity levels in the samples exceed the safe limit. Nwankwo & Balogun (2014) evaluates natural radionuclides in some sachet water samples produced in Ilorin, North-central Nigeria. The dose calculated from the activity concentration in some samples exceeds the ICRP-1mSv/y safety limit. The study of Aladeniyi & Aladenika (2015) on the sachet water activity concentration values from Owo, Ondo State, showed that the radionuclide activity level exceeded the safety levels recommended by international regulatory bodies. The radiological hazards from natural radionuclides in carefully chosen packaged drinking waters within two cities (Ilorin & Ogbomoso) in Nigeria, were investigated by Ajibola et al., (2021). The results of the NORMs activity concentrations obtained in the study were within the permissible limits recommended by international organization. Also the expected average effective dose for the general population is within acceptable limit of 1 mSv/y, except for infants, in which it exceed limit value in some samples. The study of Olaniyi et al., (2023) on sachet water natural radionuclides produced in Ibadan, Oyo State, Nigeria showed that the total Annual Effective Dose (AED) obtained exceeds the world average of 0.12 mSv reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000). Also, the values were slightly above the recommended levels of 0.1 mSv and 1.0 mSv proposed by WHO and ICRP respectively, thereby indicating a potential radiological risk from consumption of the analyzed sachet waters. Aladeniyi et al., (2022) performed a body of work examining the activity concentration levels and cancer risks associated with the most circulated sachet water brands in Nigeria. Notably, the estimated effective doses and corresponding cancer risks from ^{226}Ra and ^{228}Ra were above the WHO-suggested acceptable limits of 0.1 $mSvy^{-1}$ and 10^{-3} respectively. This suggests a contributory carcinogenic health hazard of not negligible magnitude arising from drinking water consumed by the baby (0–1 y) and teenage (12–17 y) age groups.

Adeojo et al. (2025) also examined radiological risks from certain sachet and bottled water brands. These are among the most popular drinking water sources in two states (Ondo and Ekiti), South West, Nigeria. For 92% of age groups, the estimated AED exceeded the average dose limit of 0.1 mSv^{-1}.

This study aims at evaluating the health risks from naturally occurring radionuclides in sachet and bottled water in Ijesaland, Osun State, Southwest Nigeria. The objectives are to measure radionuclide activity concentrations by gamma-ray spectroscopy, evaluate age-wise annual effective doses from ingestion of both sachet and bottled water, and assess excess lifetime cancer risk (ELCR) from water consumption.

II. MATERIALS AND METHOD

- *The Study Area*

Ijeshaland occupies 8° 55' N latitude and 3° 25' E longitude. It spans the six local government areas of Osun state, boundary Ilesha West, Ilesha East, Atakumosa West, Atakumosa East, Oriade, Obokun Local Government, and a town, Okemesi, in Ekiti State. It is an evergreen, with deep shade in the area. It lies within the migmatite-gneiss quartzite region of the South Western Nigeria basement complex. (Rahaman, 1976; Ojo et al., 2014).

Surface materials mostly have deep soil profiles in the area's low-lying, well-drained parts. This results from humid climatic conditions. In general, lateritic soils are produced from the weathering of low-grade parent rocks, including sedimentary, metamorphic (schists, gneisses, migmatite), and igneous (granites, basalts, gabbros, peridotites) rocks (Tijani & Onoderu, 2009).

Here, lateritic soils come from weathered metamorphic rocks, especially schists, gneisses, and migmatites. These soils are high in insoluble cations like aluminum and iron. This makes lateritic soils aluminum-iron-rich and common in tropical environments, especially in Nigeria's basement complex. Ijeshaland is pre-equatorial and contains one of Nigeria's largest gold deposits, where gold mining is ongoing.

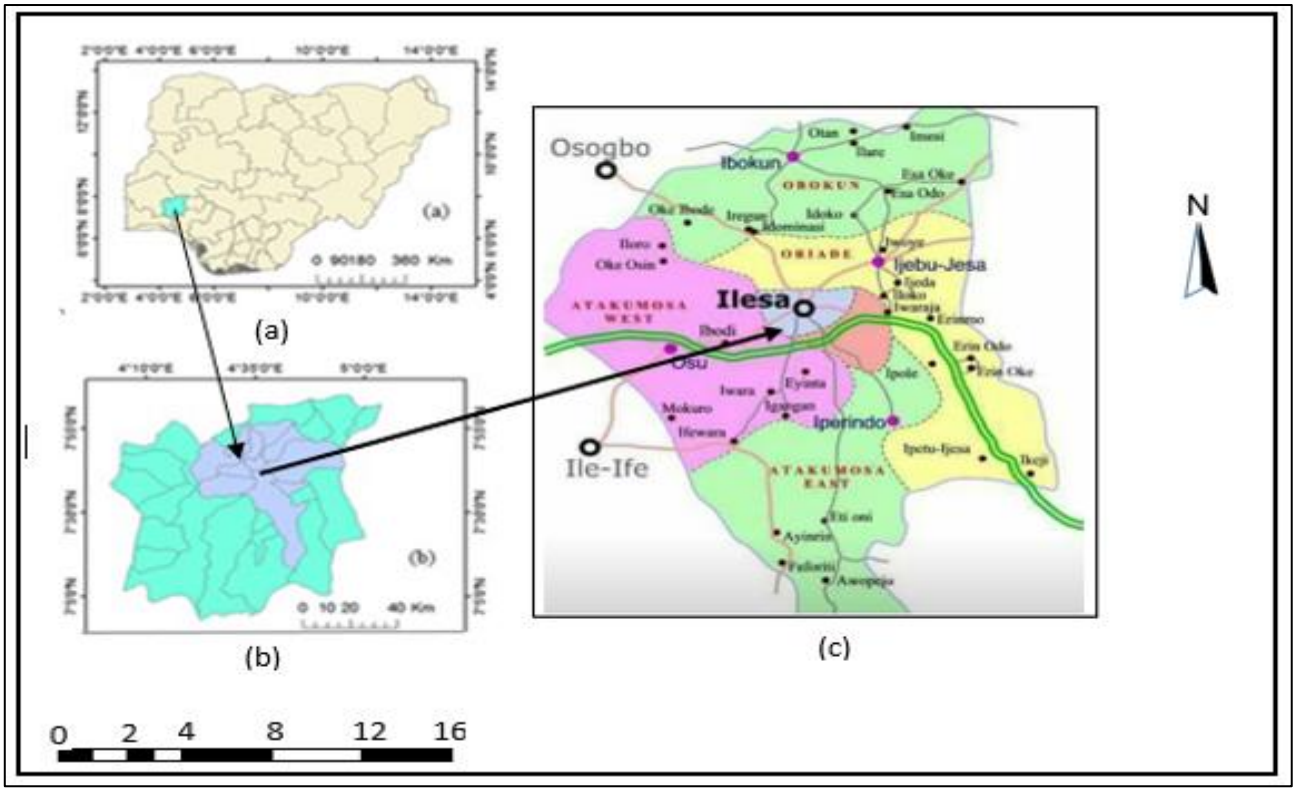


Fig 1 The Map Showing (a) Nigeria (b) Osun State (c) The Study Area

➢ *Sample Collections and Preparation*

Thirty (30) different samples of water, packaged in polythene sachet were randomly collected from 30 popularly consumed sachet water in the studied area, and ten (10) branded bottled water samples were bought from various markets in different towns in Ijeshaland, since few water produced factory produced bottled water in the area. Brands of water samples used in this work were registered and certified by the National Agency for Food and Drug Administration and Control (NAFDAC), the agency that registered and regulate the manufacture and sale of food and drug in Nigeria.

➢ *Activity Concentration Measurement*

To avoid radionuclides from adhering to the container walls, the water samples were acidified with 1 M HCl at a rate of 10 milliliters per liter and put in a plastic container (Orosun et al., 2016). For a period of 28 days, the water samples that were to be examined were sealed. Thallium-doped Cesium Iodide detectors were used in the spectrometric examination of water samples at the Physics and Engineering Physics Department of Obafemi Awolowo University in Ile-Ife, Osun State, Nigeria. A detector, a URSA II Multichannel Analyzer, and a specially designed Pb-shield array make up the spectrometric apparatus utilized in the analysis.

The efficiency and energy calibrations of the detector were performed using a reference water sample with known activity from the International Atomic Energy Agency (IAEA), Vienna, Austria, counted at the same geometry of the samples

All the samples were counted for 10 hours (36,000 seconds) and the peak area corresponding to 609.3 keV (Bi-214) a daughter radionuclide in the decay series of U-238, 936.6 keV (Ac-228) a daughter radionuclide in the decay series of for Th-232 and 1460 keV for K-40, were incorporated in the estimation of samples natural radionuclides.

By comparing the relevant peak area in the sample with the area of a corresponding photo peak in a reference standard with a known activity concentration, this approach determines the sample's activity concentration. Equation (1) was used to determine the activity concentrations of the radionuclides in a sample counted on a detector with a specific efficiency for the gamma line of interest:

$$A(Bqkg^{-1}) = kn_s \quad (1)$$

Where

$$k = (\gamma, \varepsilon, t, M_S)^{-1} \quad (2)$$

Where n_s is the net count rate under the corresponding photo peak, γ is the gamma energy, ε is the detector efficiency at that energy, t is the sample overall counting time (36 000 seconds), and M_S is the sample mass in kg. In comparing the unknown activity of the sample A_S with the known activity of the reference standard sample A_{st} , equation (3) below was employed.

$$A_s = n\frac{A_{st}.M_{st}}{n_{st}M_s} \quad (3)$$

Since the counting geometry and detector efficiency, gamma fractional abundance and the counting time are the same for both the standard and the sample, the subscripts *st* and *s* are referred to standard and sample respectively.

➢ *Statistical Analysis*

Descriptive statistics were used to analyze results from spectrometric analysis and the activity concentrations of radionuclides in the study were subjected to inferential statistics that is independent two-sample *t*-test and Wilcoxon rank sign tests using IBM SPSS (Version 25) software with 0.05 α-level of significance.

➢ *Health Risk Assessment*

- *Annual Effective Dose (AED)*

The annual effective dose (AED) due to ingestion of radionuclides (^{238}U, ^{232}Th and ^{40}K) for various age groups were estimated using equation (4)

$$AED = A_C C_f R_C \quad (4)$$

Where A_c stand for activity concentration (Bql^{-1}) of the radionuclides in water, C_f the age-group dependent dose conversion factors for the radionuclides recommended by ICRP (ICRP, 1996) and the R_C different age-group annual water consumption rate given by World Health Organization (WHO, 2011)

- *Cancer Risks*

The Excess lifetime cancer risks (ELCR) described as probability of the risk of cancer to the population associated with ingestion of a given radionuclide were obtained from equation (5).

$$ELCR = r' I \quad (5)$$

Where *r* stand for the applicable risk coefficient and I = the per capita activity intake.

According to WHO, (2025), the average Nigerian life expectancy is 64.6 years in 2021 and, an individual annual water consumption is about 730 litres. The lifetime intake of water is now equal to 47,158L. .The mortality/morbidity risk coefficients for ^{226}Ra and ^{228}Ra are $7.7\times10^{-9}/1.0\times10^{-8}$Bq^{-1} and $2.00\times10^{-8}/2.88\times10^{-8}$ Bq$^{-1,}$ respectively (USEPA, 1999, UNSCEAR, 2000, Maxwell et al., 2015).

Table 1 Activity Concentration (BqL^{-1}) of the Radionuclides in Sachet Drinking Water

Sample Code	Activity Concentration (Bq L^{-1})		
	^{40}K	^{238}U	^{232}Th
SA1	301.1±31.8	9.8 ± 0.9	12.4 ± 1.8
SA2	278.6 ± 30.2	9.2 ± 0.9	13.4 ± 1.9
SA3	265.5 ± 29.5	8.2 ± 0.9	14.5 ± 2.0
SA4	255.7 ± 28.9	9.4 ± 0.9	19.9 ± 2.3
SA5	249.1 ± 28.6	9.4 ± 0.9	11.8 ± 1.8
SA6	242.6 ± 28.2	8.4 ± 0.8	19.4 ± 2.3
SA7	291.7 ± 30.9	8.6 ± 0.9	13.2 ± 1.9
SA8	272.1± 29.9	9.3 ± 0.9	19.4 ± 2.3
SA9	295.0 ± 11.1	10.4 ± 1.0	16.9 ± 2.1
SA10	249.1 ± 28.6	7.6 ± 0.8	15.1 ± 2.0
SA11	304.8 ± 31.6	8.7 ± 0.9	13.7 ± 1.9
SA12	255.7 ± 28.9	11.1 ± 1.0	14.0 ± 1.9
SA13	255.7 ± 38.9	8.5 ± 0.9	12.1 ± 1.8
SA14	318.0 ± 32.3	9.4 ± 0.9	10.8 ± 1.7
SA15	281.9 ± 30.4	8.3 ± 0.9	15.1 ± 2.0
SA16	226.2 ± 27.2	8.8 ± 0.9	14.2 ± 2.0
SA17	321.2 ± 32.4	7.5 ± 0.8	14.5 ± 2.0
SA18	259.0 ± 29.1	9.7 ± 0.9	16.9 ± 2.1
SA19	275.3 ± 30.0	9.5 ± 0.9	17.7 ± 2.2
SA20	327.8 ± 32.8	8.3 ± 0.9	15.6 ± 2.0
SA21	259.0 ±29.1	10.2±1.0	15.3 ± 2.0
SA22	298.3 ± 31.3	8.1 ± 0.9	17.5 ±2.2
SA23	285.2 ± 30.6	7.4 ± 0.8	16.9 ± 2.1
SA24	262.2 ± 29.3	8.1 ± 0.9	13.2 ± 1.9
SA25	304.8 ± 31.6	8.9 ± 0.9	14.5 ± 2.0
SA26	278.6 ± 30.2	9.8 ± 0.9	18.3 ± 2.2
SA27	291.7 ± 30.9	10.1 ± 1.0	16.9 ± 2.1
SA28	203.2 ± 25.8	10.6 ± 1.0	15.1 ± 2.0
SA29	288.5 ± 30.7	8.0 ± 0.8	12.9 ± 1.9
SA30	321.3 ± 32.4	10.1 ± 1.0	16.4 ± 2.0

III. RESULTS

The radioactive activity concentrations (^{40}K, ^{238}U, and ^{232}Th) in the sachet drinking water are shown in Table 1. As it can be seen, the activity concentrations ranged from 203.2±25.8 to 327.8±32.8 BqL^{-1} with a mean value of 268.35±35.8 BqL^{-1} for potassium-40, 11.1±1.0 to 7.4±0.8 BqL^{-1} with a mean value of 8.56±0.6 BqL^{-1} for uranium-238, and 10.8±1.7 to 19.9±2.3 BqL^{-1} with a mean value of 16.3±3.5 BqL^{-1} for thorium-232.

Table 2 shows that the activity concentration levels for ^{40}K, ^{238}U, and ^{232}Th varied from 249.1±28 to 304.8±31.6 BqL^{-1} with a mean of 272.1±35.2 BqL^{-1}, 8.1±0.9 to 11.5±1.0 BqL^{-1} with a mean of 9.9±2.0 BqL^{-1}, and 11.8 ±1 to 18.3±2.2 BqL^{-1} with a mean of 14.8 ±2.1 BqL^{-1}.

Table 2 Activity Concentration (BqL^{-1}) of Radionuclides in Bottled Water Samples

Sample Code	Activity Concentration in BqL^{-1}		
	^{238}U	^{40}K	^{232}Th
B1	9.6 ± 0.9	285.2 ± 30.6	15.1 ± 2.0
B2	10.2 ± 1.0	262.2 ± 29.3	18.3 ± 2.2
B3	10.2 ± 1.0	259.0 ± 29.1	14.5 ± 2.0
B4	9.2 ± 0.9	288.5 ± 30.7	16.7 ± 2.1
B5	10.6 ± 1.0	265.5 ± 29.5	12.6 ± 1.8
B6	10.3 ± 1.0	265.5 ± 29.5	11.8 ± 1.8
B7	8.9 ± 0.9	249.1 ± 28.6	16.1 ± 2.1
B8	8.1 ± 0.9	281.9 ± 30.4	13.4 ± 1.9
B9	11.5 ± 1.0	304.8 ± 31.6	15.3 ± 2.0
B10	10.3 ± 1.0	259.0 ± 29.1	14.2 ± 2.0

Table 3 displays the annual water consumption rate and dosage conversion factor for various age groups as suggested by the WHO in 2011 and the ICRP in 1996. The specific activity of the radionuclides found in this study was compared with those found in other investigations conducted in various nations of the world in Table 4.

Table 3 Water Consumption Rate Per Year and Conversion Factor ($SvBq^{-1}$)

Age (Years)	Water Consumption Rate Per Year	Conversion Factor (Dose in $SvBq^{-1}$)		
		^{232}Th	^{238}U	^{40}K
0 -1	200	4.6×10^{-6}	4.7×10^{-6}	6.2×10^{-8}
1 – 2	260	4.5×10^{-7}	9.6×10^{-7}	4.2×10^{-8}
2 – 7	300	3.5×10^{-7}	6.2×10^{-7}	2.1×10^{-8}
7 – 12	350	2.9×10^{-7}	8.0×10^{-7}	1.3×10^{-8}
12 – 17	600	2.5×10^{-7}	1.5×10^{-6}	7.6×10^{-9}
>17	730	2.3×10^{-7}	2.8×10^{-7}	6.2×10^{-9}

Based on ICRP recommendations, age-dependent AED in $mSvy^{-1}$ for sachet water and bottled water samples in the surveyed area are shown in Tables 5 and 6 using the various age groups as indicated. The descriptive statistics of radiological risks (lifetime cancer risks), i.e., mortality and morbidity risks associated with adult consumption of ^{226}Ra and ^{228}Ra, are displayed in Table 7.

Table 4 Comparison of Average Activity Concentration of ^{40}K, ^{238}U, ^{232}Th with Other Studies from Different Regions of the World

Location	Source	Activity concentration (BqL^{-1}) ^{40}K,	^{238}U,	^{232}Th	Reference
Pakistan	Bottled water	140.9±30.6 ,	11.3±2.35	5.2±0.9	Fatimah et al.
Uganda	Bottled water	46.3	4.45	1.33	Rukundo et al.
Saudi Arabia	Drinking water	10.96	0.32	0.12	Al-Zahrani
Ghana	Bottled water	4.87	0.14	0.43	Portuphy et al.
South Africa	Bottled water	220.23±22.29	1.76±0.33,	3.68 ±1.37	John et al.
Egypt	Drinking water	8.6±0.75	0.59±0.03	0.36±0.05	Khalil et al.
Nigeria	Sachet water	66.22±54.99	6.88±3.66	9.49±4.98	Aladeniyi et al.
Nigeria	Sachet water	21.10	2.78	3.98	Olaniyi et al.
Nigeria	Sachet water	67.74±18.08	6.61±2.20	12.19±3.67	Omoteji et al.
Nigeria	Sachet water	1.74	0.54	0.87	Adeojo et al.
Nigeria	Bottled water	1.20	0.35	0.76	Adeojo et al.
Present study	Sachet water	268.35±35.8	8.56±0.6	16.3±3.5	Bamidele et al.
Present study	Bottled water	272.1±35.2	11.5±1.0	14.8±2.1	Bamidele et al.

Table 5 Age–Dependent AED ($mSvy^{-1}$) Due to Intake of Radionuclides in Sachet Water Samples

Age (Years)	Radionuclides ($mSvy^{-1}$)								
	^{238}U			^{232}Th			^{40}K		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
0 – 1	6.96	8.04	10.44	9.94	14.99	18.31	2.52	3.32	4.06
1 – 2	1.85	2.14	2.77	1.13	1.91	2.09	2.21	2.93	3.58
2 – 7	1.38	1.59	2.06	1.13	1.71	2.09	1.46	1.81	1.97
7 – 12	2.07	2.39	3.10	1.09	1.65	2.02	0.79	1.22	1.49
12 – 17	6.66	7.70	9.99	1.62	2.45	2.98	0.93	1.22	1.49
> 17	1.51	1.75	2.27	1.81	2.74	3.34	0.92	1.21	1.49

Table 6 Age –Dependent AED ($mSvy^{-1}$) Due to Intake of Radionuclides in Bottled Water Samples

Age (Years)	Radionuclides ($mSvy^{-1}$)								
	^{238}U			^{232}Th			^{40}K		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
0 – 1	7.60	9.30	10.08	10.90	14.10	16.80	3.12	3.32	3.80
1 – 2	2.00	2.40	2.90	1.42	1.70	2.10	1.60	1.70	1.92
2 – 7	1.50	1.82	2.14	1.21	1.64	1.9 2	2.70	3.05	3.42
7 – 12	2.27	2.80	3.30	1.20	1.52	1.92	1.13	1.21	1.42
12 – 17	7.29	8.92	10.35	1.80	2.20	2.72	1.14	1.24	1.39
> 17	1.70	2.05	2.48	2.01	2.56	3.15	1.13	1.23	1.38

Table 7 Radiological Risks of Radium Isotopes ^{226}Ra and ^{228}Ra in the Samples of the Sachet and Bottled Water

Descriptive Statistics	Life-time Cancer Risks (ELCR× 10^{-3}							
	Sachet Water				Bottled Water			
	Mortality	Morbidity	Mortality	Morbidity	Mortality	Morbidity	Mortality	Morbidity
	^{226}Ra		^{228}Ra		^{226}Ra		^{228}Ra	
Min	2.7	3.8	11.7	16.8	2.9	3.8	9.7	13.9
Max	4.0	5.2	18.8	27.0	4.2	5.4	17.3	24.9
Mean	3.3	4.6	14.6	22.2	3.6	4.7	13.6	19.6

IV. DISCUSSION

Table 1 above, indicates that Potassium-40, in the absence of other radionuclides, was the most abundant radionuclide contributing significantly to the total radionuclide activity in sachet water samples in the studied area. On the other hand, activity concentrations average, followed the descending order of ^{40}K,> ^{232}Th, > ^{238}U. Variations in the distribution of the radionuclide activity concentration in the sachet water might be attributable to the geochemical event of parent radionuclides (for radium isotopes) or geological framework of sources of water. These mainly relate to the rocks hosting the aquifers, which at the deep water table, solid-phase interactions with water over long periods may be regarded as root cause that may have led to this variations. Meanwhile, the abundance of ^{40}K in sachet water could be attributed to its natural abundance in the media surrounding it, and its activity depends on the geological constitution of the area in question, as with other radionuclides. Moreover, ^{40}K is one of the most important radiological sources among other radionuclides that may enter the body through contaminated water or food. Also Pottasium-40 is an important element for all systems in the human body and it is controlled homeostatically by the system of the body. However, the determination of a guideline value of ^{40}K for the purpose of control is intake, is highly unnecessary, as its concentration in drinking water is unlikely to reach a level of health concern (WHO 2017; Aladeniyi et al. 2022).

The mean activities of ^{40}K, ^{238}U, and ^{232}Th detected in sachet water samples all exceed the international accepted permissible limits of 10.0 BqL^{-1}, 1.0 BqL^{-1}, and 0.1 BqL^{-1} for ^{40}K, ^{238}U, and ^{232}Th, respectively. (UNSCEAR, 2000; WHO, 2011).

A higher ^{40}K concentration observed in this study agrees with trends reported in several studies on both sachet and bottled water from various regions and countries, as it can be seen in Table 4. An average activity concentration of 140.9 BqL^{-1}, 11.3 BqL^{-1}, and 5.2 BqL^{-1}, for ^{40}K, ^{238}U and ^{232}Th, respectively was recorded from studies of bottled drinking water in Pakistan by Fatimah et al. (2007), the average activity concentration of 94.64 BqL^{-1}, 1.72 BqL^{-1}, and 0.068 BqL^{-1} for ^{40}K, ^{238}U, and ^{232}Th, respectively in Tunisia dam by Younes et al. (2023), and in Nigeria, Aladenyi et al. (2022) reported an average activity concentration of 66.22 BqL^{-1}, 6.88 BqL^{-1}, and 9.49 BqL^{-1} for ^{40}K, ^{238}U, and ^{232}Th, respectively in sachet water. In addition, John et al. (2025) reported average activity concentrations of 220.22 BqL^{-1}, 1.76 BqL^{-1}, and 3.688 BqL^{-1} for ^{40}K, $^{238}U/^{226}Ra$, and ^{232}Th, respectively, in natural mineral bottled water in South Africa. Comparing the average activity concentrations of the radionuclides from other studies with present study, the activity concentrations of natural radionuclides in water samples (sachet and bottled water) were rather similar to those reported in other studies in Nigeria, Pakistan, and South Africa. This finding could be attributed to similarities in the geological substrates of the study areas, which largely determine radionuclide concentrations in water, as well as to the presence of gold deposits in the studied area. In contrast, the gold ore bodies contain traces of naturally occurring radioactive material (NORM), which may be transported into the sources of water used in producing both sachet and bottled water.

Furthermore, it is noticeable that the concentrations of both ^{226}Ra and ^{228}Ra in each of the audited brands of bottled water exceeded the safe limits (set at 10.0 BqL^{-1} for ^{40}k, 1.0 Bq L^{-1} for ^{226}Ra, and 0.1 Bq L^{-1} for $^{228}Ra/^{223}Th$) by the World Health Organization given in the year 2011 as sachet water. Obviously, this means that the water factories of those brands have not been using any means to remove or reduce radionuclide content in water during production, or to monitor the radionuclide content of their end products (bottled/sachet water) as part of their quality control.

The largest contribution to the AED value among the radionuclides came from ^{232}Th across all age groups, followed by ^{238}U, and ^{40}K as shown in Table 5. This outcome may be due to the geological features of the rocks that host the aquifers from which the sachet water was produced. The results for AED showed higher values in infants (0–1 yr) than in the other age groups, and the AED-estimated value exceeded the World Health Organization target of 0.1 mSv. Although the doses for all age groups surpassed the permissible radiation limit, the most vulnerable group that will have maximum internal radiation exposure through sachet water intake is the infant

(0–1 yr) age group, followed by teens (12-17y). Two age groups, i.e., (0–1 y) and (12–17 y), represent important developmental periods in human bone mass (intensive bone growth). Rapid bone growth requires high calcium deposition, yet there are also conditions of ^{238}U bone uptake at similar rates that can ultimately lead to bone and head-sinus cancers (Alomari et al., 2019; Khandaker et al., 2017; WHO, 2017). A similar pattern of vulnerability within these age groups was reported in Asaduzzaman et al. (2016) study of commercially bottled water in Bangladesh, Khandaker et al. (2017) assessment of bottled mineral water in Malaysia, and Aladeniyi et al. (2022) studies of sachet water in Nigeria. The results obtained from AED estimation for bottled water samples in the studied area were the same as those for sachet water in the same area. This might be because the cold sachet and bottled water originate from the same groundwater sources, which rely on the aquifer conditions and local lithology in the surveyed area (Altlkulaç et al., 2022; Bazza et al., 2023; Martinez et al., 2025). The calculated highest dose equivalent for infants (0–1 yr) is distinctly higher than that for other age groups, and the AEDs estimated were higher than the World Health Organization permissible values of 0.1 mSv and 1.0 mSvy-1, as laid down by the International Commission on Radiological Protection (ICRP, 1996). Table 7 shows the ELCR (mortality and morbidity) specified values for ^{226}Ra and ^{228}Ra in adults, which range from $2.7x10^{-3}$ to $4.4x10^{-3}$ (mean $3.3x10^{-3}$) and $3.8x10^{-3}$ to $5.2x10^{-3}$ (mean $4.6x10^{-3}$) for ^{226}Ra respectively. The risks for ^{228}Ra vary from $11.7x10^{-3}$ to $18.8x10^{-3}$, with mean values of $14.6\ x10^{-3}$ and $16.8x10^{-3}$ to $27.0x10^{-3}$, respectively. The mean values obtained in this study are higher than average values of $2.5\times10^{-3}/3.5\times10^{-3}$ for ^{226}Ra and $9.7\times10^{-3}/7.5\times10^{-3}$ for ^{228}Ra (mortality/morbidity risk) reported by Aladeniyi et al. (2022) in the most popular sachet water brands available in Ondo State of Nigerian.. The reported mean mortality/morbidity risk values for bottled water were higher than the $2.1\times10^{-5}/3.0\times10^{-5}$ values for ^{226}Ra and the $5.4\times10^{-5}/7.5\times10^{-5}$ values for ^{228}Ra reported by Asaduzzaman et al. (2016), who studied bottled water sold in Bangladesh. The increased radiological risk observed in this study, compared with the reference values, indicates that the public's intake of both sachet and bottled water may pose a radiological hazard if the manufacturers of the brand do not take active corrective measures.

V. CONCLUSION

The research scrutinized the radiation exposure associated with water brands, with its evaluation focusing on 30 sachet-water brands and 10 bottled water brands, which are produced and consumed in the Ijesa area, Osun State, Southwest Nigeria. Actinides and natural radionuclide content, along with ^{40}K isotopes, were monitored in sachet and bottled water, respectively, using gamma-ray spectroscopy. It turns out that the concentrations exceed the WHO permissible ions for drinking water. An appraisal of the annual effective doses (AEDs) by age group and excess lifetime cancer risks (ELCRs) revealed that the levels exceed the thresholds recognized by international organizations, making the consumed water a radiological threat. Producers must, without delay, introduce associated treatments. It is therefore important that oversight agencies conduct more frequent surveillance of quality issues to ensure the continued well-being of the public from radiological exposure.

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- *Statement of Declaration of Interest*

There is no conflicts of interest

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