



ISSN: 0067-2904

## Assessment of Some Widely Consumed Sachet and Bottled Water Brands; Implications for Radiation Risks in Ondo and Ekiti State, South Western Nigeria.

Taiwo Temitope Adejo<sup>1</sup>, Warith Adewale Adebisi<sup>1\*</sup>, Ifedayo Olukemi Adejo<sup>2</sup>,  
Olumuyiwa Femi Adewumi<sup>1</sup>, Khadijat Kuburat Babalola<sup>1</sup>, Surajudeen Otolowo Azeez<sup>1</sup>

<sup>1</sup>Department of Physical and Chemical Sciences, Faculty of Science, Federal University of Health Sciences, Ila-Orangun, Nigeria

<sup>2</sup> Department of Physics, Federal University of Technology, Akure, Nigeria

Received: 21/11/2023

Accepted: 23/5/2024

Published: 30/7/2025

### Abstract

In recent years, drinking water in bottles or sachets has become increasingly accepted in major towns and cities in Ekiti and Ondo states, southwestern Nigeria. Selected sachet and bottled water based on a wide range of consumer samples were collected from various manufacturers and distributors in both states. Activity concentrations of natural radioactivity, including  $^{40}\text{K}$ ,  $^{226}\text{Ra}$  and  $^{232}\text{Th}$ , were measured using a gamma ray spectrometer with a high-purity germanium detector (HPGe). The activity concentration of  $^{40}\text{K}$ ,  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  ranged from  $0.46 \pm 0.02$  to  $4.74 \pm 0.44 \text{ Bq L}^{-1}$ ,  $0.14 \pm 0.01$  to  $1.62 \pm 0.30 \text{ Bq L}^{-1}$ , and  $0.16 \pm 0.11$  to  $1.42 \pm 0.21 \text{ Bq L}^{-1}$ , respectively in sachet water. Activity concentration values in bottled water for  $^{40}\text{K}$ ,  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  ranged from  $0.72 \pm 0.10$  to  $2.32 \pm 0.14 \text{ Bq L}^{-1}$ ,  $0.15 \pm 0.01$  to  $0.82 \pm 0.03 \text{ Bq L}^{-1}$ , and  $0.19 \pm 0.03$  to  $1.42 \pm 0.10 \text{ Bq L}^{-1}$ , respectively. Determined ingested annual effective dose on the scale of International Commission on Radiological Protection (ICRP) for the age groups of 0-1y, 1-2y, 2-7y, 7-12y, 12-17y and  $> 17\text{y}$  from consumption of the water samples are  $0.831 \text{ mSvy}^{-1}$ ,  $0.258 \text{ mSvy}^{-1}$ ,  $0.204 \text{ mSvy}^{-1}$ ,  $0.245 \text{ mSvy}^{-1}$ ,  $0.620 \text{ mSvy}^{-1}$ ,  $0.261 \text{ mSvy}^{-1}$  respectively for sachet water, it is  $0.613 \text{ mSvy}^{-1}$ ,  $0.118 \text{ mSvy}^{-1}$ ,  $0.156 \text{ mSvy}^{-1}$ ,  $0.175 \text{ mSvy}^{-1}$ ,  $0.428 \text{ mSvy}^{-1}$ ,  $0.203 \text{ mSvy}^{-1}$ , respectively for bottled water. The mean contributions of  $^{40}\text{K}$ ,  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  activities of both water type samples in the study area from an annual volume consumption is higher than the recommended tolerable limit of  $0.1 \text{ mSvy}^{-1}$  or lower as reported by WHO. It is therefore strongly recommended that nursing mothers should guard the lactating populace from the consumption of the surveyed samples to minimize the stochastic risk of radiation hazards in infants.

**Keywords:** Sachet water, Bottled water, Natural radioactivity, Annual Effective Dose, Stochastic, Radiation hazard

### 1. Introduction

Although having access to clean drinking water is a fundamental human right, billions worldwide still do not have it [1, 2]. Due to their perceived safety and convenience, sachet and bottled water have become increasingly popular substitutes for tap and underground water in many developing nations, including Nigeria. However, the purity and safety criteria

\*Email: [warith.adebisi@fuhsi.edu.ng](mailto:warith.adebisi@fuhsi.edu.ng)

for these water sources and brands are frequently under dispute, with many brands falling short [3]. The purity of sachet and bottled water is an important consideration in establishing its safety for consumption. Water contamination takes many forms, physical, chemical, biological and radiological. Radiological contamination of water comes from high levels of radioactive nuclides. The presence of radiation poses a potential concern to public health. The level of radiation is dependent on the vulnerability of each individual and the sort of contact with the people [7]. To protect public health, it is critical to determine the quantity of radiation in various forms of water, including sachet and bottled water brands across states in Nigeria.

Ionizing radiation, which manifests as electromagnetic waves or particles and is capable of causing DNA strand breaks, mutations, and cell death [4], is a problem that affects our environment on a worldwide scale. If not carefully monitored, radiation-contaminated water poses a variety of severe health risks to people and the ecology, including cancer and radiation illness. The exposure can happen via ingestion, inhalation, or even skin contact [5], [6], and it can be challenging to identify because radioactive chemicals are frequently tasteless, odorless, and undetectable at the early stage.

When taken in high quantities over an extended period, radioactive substances present in water do constitute a health concern. These radioactive pollutants can get into the water from various places, including human activities like mining, industrial waste and the discharge of nuclear power plants' effluents, as well as natural sources like the rock and soil that hold the water they are extracted from. Groundwater typically has a bigger problem with radiological elements like  $^{226}\text{U}$ ,  $^{226}\text{Ra}$ ,  $^{228}\text{Th}$ , and  $^{228}\text{Ra}$  than surface water [7]. Additionally, the nylon and plastic used for packaging occasionally include radioactive materials that might contaminate water [8].

According to Kebir [10], Al-Hayani et al. [11], Borrego-Alonso et al. [12], and Muhammad et al. [13], the primary natural radionuclides in drinking water are Uranium-238, Thorium-232, and their decay products such as Radium-226 and Radium-228. Several studies have been undertaken worldwide to assess the amounts of radiation in sachet and bottled water.

In Nigeria, Olaniyi et al. [14] calculated the mean activity content of Radium-226, Thorium-232, and Potassium-40 in sachet water samples, which it was found to be higher than the World Health Organization (WHO) and European Union (EU) recommended limit. Similarly, Usikalu et al. [15] estimated the mean activity concentration of Potassium-40, Uranium-238, and Thorium-232 of the Bell University of Technology to be 442.66 Bq/kg, 41.98 Bq/kg, and 48.35 Bq/kg, respectively, in their investigation in Bells Area and Canaan City, Ota, Nigeria. Aladeniyi et al. [16] studied 35 brands of the most commonly used sachet drinking water in Ondo state to assess the associated health risks to the general public. The determined annual effective dosages were found to surpass the WHO acceptable limits.

The current study seeks to assess the quality of sachet and bottled water of different brands as well as the potential health risks connected with their usage within Ekiti and Ondo states. The study will specifically evaluate the activity concentration of chosen natural radionuclides ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ ), because these elements can pose a health risks if present in high concentrations, in frequently consumed sachet and bottled water brands produced in both states. The study also estimates the annual effective dose (AED) from consumption of selected sachet and bottled water brands.

## 2 Material and Methods

### 2.1 Sample Collection

In this study, a total of thirty-five (35) sachet and bottled water brands were acquired from major towns and cities in the states of Ondo and Ekiti. Fifteen (15) popular sachet drinking water brands were acquired from different markets in four main towns in Ekiti state, and four (4) popular bottled drinking water brands were also purchased from the same four major towns in Ekiti state. Twelve (12) widely consumed sachet water brands were acquired for analysis in Ondo state, whereas four (4) generally consumed brands of bottled water were obtained for examination from four major towns and cities.

### 2.2 Sample Preparation

Marinelli beakers were utilized as measuring containers in this study. The containers were cleansed and rinsed with weak hydrochloric acid and distilled water prior to use. Each beaker was filled to the brim, absolutely devoid of air, and carefully sealed. The samples were then transferred to the laboratory and held for one month to allow the daughter products to reach radioactive equilibrium with their parents [17], which means that the rate of radioactive generation can be equal to the rate of decay (secular equilibrium).

### 2.3 Radioactivity Measurement and Analysis of Spectra

A non-destructive examination using computerized gamma ray spectrometry equipment (Fig. 1) with high-purity germanium (HPGe) detector of relatively high efficiency was used to assess the activity concentration of the water samples. The gamma spectrometer was connected to a multichannel analyzer card (MCA) installed on a desktop computer through standard electronics. MAESTRO-32 software was used to manually collect and evaluate the data, while Microsoft Excel spreadsheet program was utilized to compute the natural radioactivity concentrations in all samples.



**Figure. 1:** The Radioactivity Measuring System

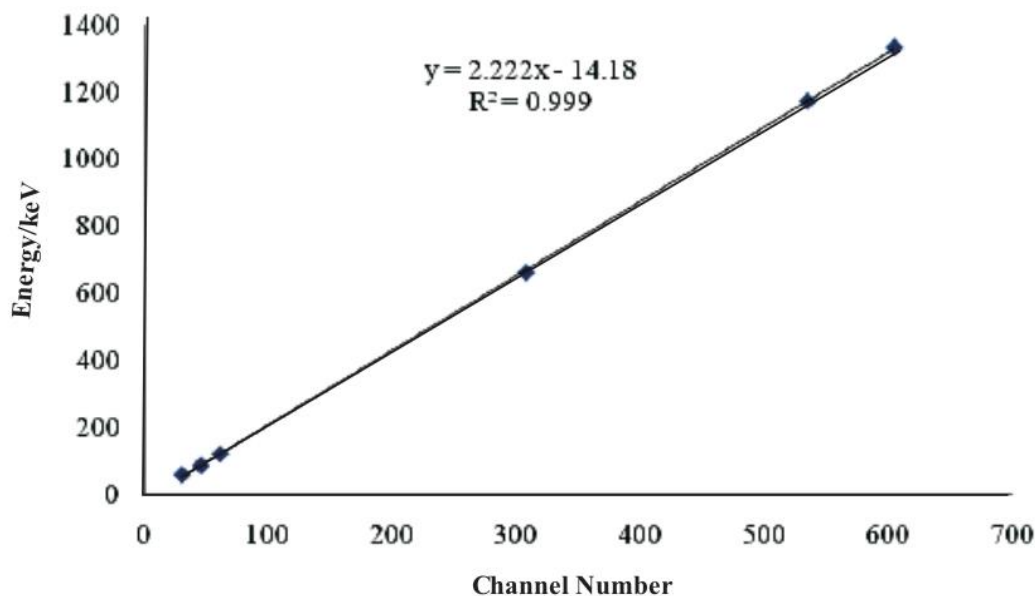
The detector and measuring equipment were calibrated for energy and efficiency before measurements, to enable both qualitative and quantitative analysis of the samples. Energy and efficiency calibrations were carried out using a mixture of calibration radionuclide standards that were uniformly dispersed and had a volume of about 1000 ml and a density of about 1.0

$\text{gcm}^{-3}$  in a 1.0 L Marinelli beaker. Energy calibration was done by comparing the main gamma peaks in the standard's spectra to the channel numbers.

According to 'American National Standard Calibration and Usage of Sodium Iodide Detector Systems' N42.12-1980 [18], the formula between energy and channel number is as follows:

$$E = A_0 + A_1 \cdot \text{CN} \quad (1)$$

Where: E is the energy, CN is the channel number for a given radionuclide,  $A_0$  and  $A_1$  are calibration constants for a given geometry. Figure 2 shows the calibration curve.



**Figure 2:** Energy Calibration Curve

#### 2.4 Activity Measurement

The specific activity concentrations ( $A_{sp}$ ) of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in  $\text{BqL}^{-1}$  for water samples were determined using the following expression [19]:

$$A_{sp} = \frac{N_{sam}}{P_E \cdot \epsilon \cdot T_c \cdot M} \quad (2)$$

Where:

- $N_{sam}$  – Net counts of the radionuclide in the sample
- $P_E$  – Gamma ray emission probability
- $\epsilon$  – Total counting efficiency of the detector
- $T_c$  – Sample counting time
- $M$  – Mass of sample (kg) or volume (L)

#### 2.5 Estimation of Annual Effective Dose

The following relation was used to estimate the annual effective dose,  $E_d$  ( $\text{Sv y}^{-1}$ ), due to ingestion of natural radionuclides found in sachet and bottled water brands [20]:

$$E_d = A_{sp} CR_w D_{cw} \quad (3)$$

Where:  $A_{sp}$  is the activity concentration of radionuclides in the ingested sachet and bottled water ( $\text{BqL}^{-1}$ ),  $CR_w$  is the annual intake of sachet and bottled drinking water ( $\text{L y}^{-1}$ ), and  $D_{cw}$  is the ingested dose conversion factor for the public ( $\text{SvBq}^{-1}$ ).  $D_{cw}$  used in the calculation varies with radionuclides and the age of individuals ingesting the radionuclides.

The total annual effective dose  $D$  ( $\text{Sv y}^{-1}$ ) to an individual was established by summing the contributions from all radionuclides present in the water samples:

$$D = \sum A_{sp} CR_w D_{cw} \quad (4)$$

For the age categories 0 - 1 year, 1 - 2 years, 2 - 7 years, 7 - 12 years, 12 - 17 years, and > 17 years, the annual average intake of sachet and bottled drinking water is determined to be 200, 260, 300, 350, 600, and 730 liters, respectively [21, 22].

### 3 Results and Discussion

#### 3.1 Activity Concentration

Table 1 shows the natural radioactivity activity concentrations of  $^{40}\text{K}$ ,  $^{232}\text{Th}$ , and  $^{226}\text{Ra}$  in different sachet water brands in Ondo and Ekiti. The activity concentrations in sachet drinking water vary from  $0.46 \pm 0.02$  to  $4.74 \pm 0.44 \text{ BqL}^{-1}$  with an average of  $1.74 \text{ BqL}^{-1}$  for  $^{40}\text{K}$ ,  $0.16 \pm 0.11 \text{ BqL}^{-1}$  to  $1.42 \pm 0.21 \text{ BqL}^{-1}$  with an average of  $0.87 \text{ BqL}^{-1}$  for  $^{232}\text{Th}$ , and  $0.14 \pm 0.01 \text{ BqL}^{-1}$  to  $1.62 \pm 0.30 \text{ BqL}^{-1}$  with an average of  $0.54 \text{ BqL}^{-1}$  for  $^{226}\text{Ra}$ . It was found that the J & M brand of sachet water has the highest activity concentration of  $^{40}\text{K}$ , while the Rinmola and the Ogo-Oluwa brands have the lowest activity concentration of  $^{40}\text{K}$ . The highest and lowest activity concentrations of  $^{232}\text{Th}$  were found in the Febyoks and Ogo-Oluwa brands, respectively; the highest activity concentration of  $^{226}\text{Ra}$  was found in the Lokotobi and the Todmok brands, and the Anglican and Wale brands had the lowest activity concentration of  $^{232}\text{Th}$ . Furthermore,  $^{40}\text{K}$  gave the highest activity concentration; this is likely since  $^{40}\text{K}$  is abundant in natural systems and could also be as a consequence of potassium ion-exchange resins used by some treatment facilities.  $^{226}\text{Ra}$  has the lowest activity levels in sachet drinking water samples. The mean value of  $^{232}\text{Th}$  level was approximately twice higher than  $^{226}\text{Ra}$ . This could be because most of the sachet water samples were slightly acidic, and  $^{232}\text{Th}$  is more soluble in groundwater than in surface waters [23]. The average values of  $^{232}\text{Th}$  and  $^{226}\text{Ra}$  are lower than the world value proposed by the World Health Organization maximum content in drinking water of  $1000 \text{ mBqL}^{-1}$  [20].

**Table 1:** Activity Concentration in  $\text{BqL}^{-1}$  for Sachet Water Samples from Ondo and Ekiti States

| S/N | Sample ID | Activity Concentration ( $\text{BqL}^{-1}$ ) |                   |                   |
|-----|-----------|----------------------------------------------|-------------------|-------------------|
|     |           | $^{40}\text{K}$                              | $^{232}\text{Th}$ | $^{226}\text{Ra}$ |
| 1   | Anglican  | $0.92 \pm 0.10$                              | $1.02 \pm 0.03$   | $0.14 \pm 0.01$   |
| 2   | Ayanfe    | $4.54 \pm 0.45$                              | $1.12 \pm 0.15$   | $1.26 \pm 0.15$   |
| 3   | P.K       | $0.90 \pm 0.05$                              | $0.86 \pm 0.02$   | $0.41 \pm 0.04$   |
| 4   | Dele      | $0.55 \pm 0.02$                              | $0.54 \pm 0.14$   | $0.24 \pm 0.03$   |
| 5   | Albest    | $3.03 \pm 0.16$                              | $0.95 \pm 0.02$   | $0.56 \pm 0.02$   |
| 6   | Me & You  | $1.84 \pm 0.03$                              | $1.20 \pm 0.10$   | $1.03 \pm 0.05$   |
| 7   | Lokotobi  | $0.68 \pm 0.02$                              | $1.36 \pm 0.18$   | $1.62 \pm 0.30$   |
| 8   | Lade      | $1.84 \pm 0.05$                              | $1.25 \pm 0.20$   | $1.03 \pm 0.08$   |
| 9   | J & M     | $4.74 \pm 0.52$                              | $1.12 \pm 0.20$   | $1.38 \pm 0.22$   |
| 10  | Eliseg    | $0.78 \pm 0.12$                              | $0.19 \pm 0.02$   | $0.15 \pm 0.01$   |
| 11  | Ewakin    | $2.10 \pm 0.21$                              | $0.81 \pm 0.04$   | $0.58 \pm 0.02$   |
| 12  | Yopeky    | $0.90 \pm 0.08$                              | $0.76 \pm 0.10$   | $0.41 \pm 0.02$   |
| 13  | Tkopas    | $0.92 \pm 0.10$                              | $0.88 \pm 0.12$   | $0.35 \pm 0.02$   |
| 14  | Todmok    | $0.68 \pm 0.02$                              | $1.30 \pm 0.22$   | $1.62 \pm 0.30$   |
| 15  | Sparkleen | $1.02 \pm 0.05$                              | $0.73 \pm 0.11$   | $0.82 \pm 0.03$   |

|    |           |           |           |           |
|----|-----------|-----------|-----------|-----------|
| 16 | Keniks    | 0.55±0.02 | 0.54±0.11 | 0.24±0.06 |
| 17 | Magtos    | 3.85±0.08 | 0.74±0.08 | 0.16±0.01 |
| 18 | Rinmola   | 0.46±0.02 | 0.18±0.01 | 0.21±0.02 |
| 19 | Wale      | 0.92±0.10 | 1.01±0.13 | 0.14±0.01 |
| 20 | Raphilo   | 3.03±0.22 | 0.85±0.02 | 0.56±0.03 |
| 21 | Febyoks   | 2.32±0.14 | 1.42±0.21 | 0.25±0.01 |
| 22 | Love Lead | 0.72±0.06 | 0.64±0.03 | 0.19±0.02 |
| 23 | Ogo-Oluwa | 0.46±0.04 | 0.16±0.11 | 0.21±0.02 |
| 24 | Olamide   | 3.50±0.10 | 0.77±0.22 | 0.36±0.02 |
| 25 | Diamond   | 3.85±0.08 | 0.74±0.05 | 0.16±0.01 |
| 26 | Ige       | 0.84±0.10 | 0.43±0.08 | 0.22±0.02 |
| 27 | Dorcas    | 0.72±0.08 | 0.46±0.02 | 0.19±0.02 |

Table 2 shows the natural radioactivity activity concentrations of  $^{40}\text{K}$ ,  $^{232}\text{Th}$ , and  $^{226}\text{Ra}$  in sampled bottled water brands in Ondo and Ekiti. It has been observed that activity concentrations in bottled drinking water due to  $^{40}\text{K}$  range from  $0.720\pm0.10$  to  $2.32\pm0.14$   $\text{BqL}^{-1}$  with an average of  $1.20$   $\text{BqL}^{-1}$ , due to  $^{232}\text{Th}$  ranges from  $0.19\pm0.03$   $\text{BqL}^{-1}$  to  $1.42\pm0.10$   $\text{BqL}^{-1}$  with an average of  $0.76$   $\text{BqL}^{-1}$  and activity concentration due to  $^{226}\text{Ra}$  ranges from  $0.15\pm0.01$   $\text{BqL}^{-1}$  to  $0.82\pm0.03$   $\text{BqL}^{-1}$  with an average of  $0.35$   $\text{BqL}^{-1}$ . The highest activity concentration of  $^{40}\text{K}$  was found in the Bride brand bottled water, while the lowest activity concentration of  $^{40}\text{K}$  was found in the SkyloAcqua brand. The FUTA brand had the highest activity concentration of  $^{226}\text{Ra}$ , the Olvine brand had the lowest activity concentration of  $^{232}\text{Th}$ , and the Bride and the Olvine brands had the highest and lowest activity concentrations of  $^{232}\text{Th}$ , respectively.  $^{40}\text{K}$  had the highest activity concentration in the bottled water samples, whereas  $^{226}\text{Ra}$  provided the lowest activity concentration. In conclusion, the sequence of activity concentrations was  $^{40}\text{K} > ^{232}\text{Th} > ^{226}\text{Ra}$ .

**Table 2:** Activity Concentration in  $\text{BqL}^{-1}$  for Bottled Water Samples from Ondo and Ekiti States

| S/N | Sample ID  | Activity Concentration ( $\text{BqL}^{-1}$ ) |                   |                   |
|-----|------------|----------------------------------------------|-------------------|-------------------|
|     |            | $^{40}\text{K}$                              | $^{232}\text{Th}$ | $^{226}\text{Ra}$ |
| 1   | Sovic      | 0.84±0.15                                    | 0.44±0.05         | 0.22±0.04         |
| 2   | Yemi       | 0.92±0.06                                    | 0.78±0.02         | 0.19±0.01         |
| 3   | Bride      | 2.32±0.14                                    | 1.42±0.10         | 0.35±0.14         |
| 4   | Olvine     | 0.78±0.10                                    | 0.19±0.03         | 0.15±0.01         |
| 5   | FUTA       | 1.02±0.10                                    | 0.73±0.02         | 0.82±0.03         |
| 6   | SkyloAcqua | 0.72±0.10                                    | 0.85±0.13         | 0.18±0.01         |
| 7   | Michade    | 2.10±0.14                                    | 0.61±0.18         | 0.52±0.06         |
| 8   | Edna       | 0.92±0.08                                    | 0.86±0.12         | 0.35±0.02         |

### 3.2 Annual Effective Dose (AED)

Table 3 illustrates the total annual effective dose ( $E_d$ ) calculated by Eq. (3) for sachet water using the activity concentrations of the indicated radionuclides, the annual water consumption rate, and the relevant ingestion dose conversion coefficients [21]. The different age groups mentioned earlier were also recognized as significant groups in this arena. The recommended effective dose which the individual may ingest is  $0.1$   $\text{mSv y}^{-1}$  or lower [13, 24, 25].

**Table 3:** Total Annual Effective Dose ( $\mu\text{Sv y}^{-1}$ ) of the Different Age Groups from Sachet Water Consumed in Ondo and Ekiti States

| S/N | Sample ID    | 0 – 1 year | 1 – 2 years | 2 – 7 years | 7 – 12 years | 12 – 17 years | >17 years |
|-----|--------------|------------|-------------|-------------|--------------|---------------|-----------|
| 1   | Anglican     | 500        | 170         | 150         | 140          | 280           | 200       |
| 2   | Ayanfe       | 1820       | 490         | 380         | 480          | 1320          | 470       |
| 3   | P.K          | 760        | 210         | 180         | 210          | 500           | 220       |
| 4   | Dele         | 450        | 130         | 110         | 120          | 300           | 140       |
| 5   | Albest       | 970        | 330         | 220         | 270          | 650           | 280       |
| 6   | Me & You     | 1570       | 420         | 330         | 420          | 1120          | 420       |
| 7   | Lokotobi     | 2300       | 570         | 440         | 590          | 1660          | 560       |
| 8   | Lade         | 1570       | 420         | 330         | 420          | 1120          | 420       |
| 9   | J & M        | 1980       | 520         | 410         | 520          | 1430          | 490       |
| 10  | Eliseg       | 560        | 190         | 150         | 160          | 320           | 230       |
| 11  | Ewakin       | 940        | 260         | 210         | 260          | 650           | 270       |
| 12  | Yopeky       | 760        | 210         | 180         | 210          | 500           | 220       |
| 13  | Tkopas       | 690        | 200         | 170         | 190          | 450           | 220       |
| 14  | Todmok       | 2300       | 570         | 440         | 590          | 1660          | 560       |
| 15  | Sparkleen    | 1180       | 310         | 240         | 310          | 860           | 300       |
| 16  | Keniks       | 450        | 130         | 110         | 120          | 300           | 140       |
| 17  | Magtos       | 460        | 170         | 130         | 150          | 270           | 170       |
| 18  | Rinmola      | 310        | 80          | 60          | 80           | 220           | 70        |
| 19  | Wale         | 500        | 170         | 150         | 140          | 280           | 200       |
| 20  | Raphilo      | 970        | 330         | 220         | 270          | 650           | 280       |
| 21  | Febyoks      | 740        | 230         | 210         | 220          | 450           | 300       |
| 22  | Love Lead    | 430        | 130         | 120         | 110          | 270           | 150       |
| 23  | Ogo-Oluwa    | 310        | 80          | 60          | 80           | 220           | 70        |
| 24  | Olamide      | 700        | 220         | 170         | 200          | 460           | 220       |
| 25  | Diamond      | 460        | 170         | 130         | 150          | 270           | 170       |
| 26  | Ige          | 400        | 120         | 100         | 100          | 260           | 120       |
| 27  | Dorcas       | 430        | 130         | 120         | 110          | 270           | 150       |
|     | <b>MEAN</b>  | 831        | 258         | 204         | 245          | 620           | 261       |
|     | <b>RANGE</b> | 310 -2300  | 80 – 570    | 60 – 440    | 80 – 590     | 220 -1660     | 70 – 560  |

Owing to the consumption of sachet drinking water, the annual effective dose received by the collective ingestion has been estimated which varied from 0.31 to 2.30  $\text{mSvy}^{-1}$  with a mean of 0.831  $\text{mSvy}^{-1}$ , 0.08 to 0.57  $\text{mSvy}^{-1}$  with a mean of 0.258  $\text{mSvy}^{-1}$ , 0.06 to 0.44  $\text{mSvy}^{-1}$  with a mean of 0.204  $\text{mSvy}^{-1}$ , 0.08 to 0.59  $\text{mSvy}^{-1}$  with a mean of 0.245  $\text{mSvy}^{-1}$ , 0.22 to 1.66  $\text{mSvy}^{-1}$  with a mean of 0.620  $\text{mSvy}^{-1}$ , 0.07 to 0.56  $\text{mSvy}^{-1}$  with a mean of 0.261  $\text{mSvy}^{-1}$  for the age groups of the living population 0 – 1 year, 2 – 7 years, 7 – 12 years, 12–17 years and >17 years, respectively. Furthermore, comparing the averages of the annual effective doses due to the intake of the different brands of sachet water with the WHO permissible limit, it is evident from Table 3 that the cumulative average annual effective doses due to activities of natural radionuclides,  $^{40}\text{K}$ ,  $^{226}\text{Ra}$ , and  $^{232}\text{Th}$  in sachet drinking water samples for all the six different age groups are higher than the recommended limit of 0.1  $\text{mSvy}^{-1}$  for drinking water due to the ingestion of natural radionuclides.

The total annual effective dose ( $E_d$ ) calculated for bottled drinking water using the activity concentrations of the indicated radionuclides, the annual water consumption rate, and the relevant ingestion dose conversion coefficients [21] is shown in Table 4.

**Table 4:** Total Annual Effective Dose ( $\mu\text{Sv y}^{-1}$ ) of the Different Age Groups from Bottled Water Consumed in Ondo and Ekiti States

| S/N | Sample ID    | 0 – 1 year | 1 – 2 years | 2 – 7 years | 7 – 12 years | 12 – 17 years | >17 years |
|-----|--------------|------------|-------------|-------------|--------------|---------------|-----------|
| 1   | Sovic        | 400        | 120         | 100         | 100          | 260           | 120       |
| 2   | Yemi         | 250        | 150         | 130         | 130          | 290           | 170       |
| 3   | Bride        | 760        | 230         | 210         | 220          | 450           | 300       |
| 4   | Olvine       | 190        | 70          | 60          | 60           | 170           | 60        |
| 5   | FUTA         | 1180       | 310         | 240         | 310          | 860           | 300       |
| 6   | SkyloAcqua   | 490        | 160         | 130         | 140          | 290           | 180       |
| 7   | Michade      | 940        | 260         | 210         | 250          | 650           | 270       |
| 8   | Edna         | 690        | 200         | 170         | 190          | 450           | 220       |
|     | <b>MEAN</b>  | 613        | 188         | 156         | 175          | 428           | 203       |
|     | <b>RANGE</b> | 250 - 1180 | 70 – 310    | 60 – 240    | 60 – 310     | 170 – 860     | 60 – 300  |

Due to the consumption of bottled drinking water, the annual effective dose received by the collective ingestion varied from 0.25 to 1.18  $\text{mSv y}^{-1}$  with a mean of 0.613  $\text{mSv y}^{-1}$ , 0.07 to 0.31  $\text{mSv y}^{-1}$  with a mean of 0.118  $\text{mSv y}^{-1}$ , 0.06 to 0.24  $\text{mSv y}^{-1}$  with a mean of 0.156  $\text{mSv y}^{-1}$ , 0.06 to 0.31  $\text{mSv y}^{-1}$  with a mean of 0.175  $\text{mSv y}^{-1}$ , 0.17 to 0.86  $\text{mSv y}^{-1}$  with a mean of 0.428  $\text{mSv y}^{-1}$ , 0.06 to 0.30  $\text{mSv y}^{-1}$  with a mean of 0.203  $\text{mSv y}^{-1}$  for age groups of the living population of 0 – 1 year, 2 – 7 years, 7 – 12 years, 12 – 17 years and >17 years, respectively. The annual effective dose values were observed to be greater than the permissible value. This could be attributed to either prolonged exposure time or cumulative exposure from other hidden radionuclides.

Furthermore, comparing the averages of the annual effective doses due to the intake of the different brands of bottled water, it is evident from Table 4 that the cumulative annual effective doses due to the activity of natural radionuclides  $^{40}\text{K}$ ,  $^{226}\text{Ra}$ , and  $^{232}\text{Th}$  in bottled drinking water samples for all six different age groups are higher than the recommended limit of 0.1  $\text{mSv y}^{-1}$  for drinking water due to the ingestion of natural radionuclides.

The study shows that it is not radiologically safe to consume most of the sachet and bottled drinking water of the studied brands since their cumulative annual effective doses are higher than the recommended limit. However, the Rinmola and the Ogo-Oluwa sachet water brands are considered safe for the age groups 1 – 2 years, 2 – 7 years, 7 – 12 years and adults >17 years. The Olvine brand of bottled water is also considered safe for 1 – 2 years, 2 – 7 years, 7 – 12 years and adults >17 years. It is scientifically reasonable to assume that the incidence of cancer or hereditary effects rises in direct proportion to an increase in the equivalent dose in the relevant organs or tissues due to consumption of sampled water in Ondo and Ekiti states.

#### 4 Conclusions

A total of 35 brands of sachet and bottled drinking water popularly consumed in Ekiti and Ondo states were analyzed for natural radioactivity in view of implication for radiological hazard using gamma ray spectrometer with high purity germanium detector (HPGe). The

activity concentrations in sachet drinking water varied from  $0.46 \pm 0.02$  to  $4.74 \pm 0.44$  BqL<sup>-1</sup> with an average of 1.74 BqL<sup>-1</sup> for <sup>40</sup>K,  $0.16 \pm 0.11$  to  $1.42 \pm 0.21$  BqL<sup>-1</sup> with an average of 0.87 BqL<sup>-1</sup> for <sup>232</sup>Th, and  $0.14 \pm 0.01$  to  $1.62 \pm 0.30$  BqL<sup>-1</sup> with an average of 0.54 BqL<sup>-1</sup> for <sup>226</sup>Ra. It has also been observed that activity concentrations in bottled drinking water due to <sup>40</sup>K range from  $0.720 \pm 0.10$  to  $2.32 \pm 0.14$  BqL<sup>-1</sup> with an average of 1.20 BqL<sup>-1</sup>, due to <sup>232</sup>Th ranges from  $0.19 \pm 0.03$  to  $1.42 \pm 0.10$  BqL<sup>-1</sup> with an average of 0.76 BqL<sup>-1</sup> and due to <sup>226</sup>Ra ranges from  $0.15 \pm 0.01$  to  $0.82 \pm 0.03$  BqL<sup>-1</sup> with an average of 0.35 BqL<sup>-1</sup>.

As a result, the possible risk of exposure was assessed by calculating the total annual effective doses for six age groups: 0 - 1 year, 1 - 2 years, 2 - 7 years, 7 - 12 years, 12 - 17 years, and > 17 years, resulting from drinking sachet and bottled water. The estimated doses were consistently higher than 0.1 mSv<sup>-1</sup> for 92% of the age groups. To avoid any potential harm, it is advised that consumers limit their water intake to half the recommended volume, or better yet, stop consuming these products altogether. Additionally, manufacturers should take precautions to shield their products at the point of sale from direct sunlight during transport and display for advertisement to prevent radiation contamination and an increase in the levels of NO<sub>2</sub>-TDS and turbidity after plastic packaging because leaching of compounds from plastic bottles can result [23]. It is also recommended that this type of study be conducted regularly on new brands of sachet and bottled water, at least twice a year, to ensure safety.

## 5 Disclosure and conflict of interest

I, the corresponding author on behalf of all contributing authors, declare that there is no known conflict of interest regarding the submission and publication of this paper.

## References

- [1] C. M. D. Oliveira, 'Sustainable access to safe drinking water: fundamental human right in the international and national scene,' *Ambiente E Agua - Interdiscip. J. Appl. Sci.*, vol. 12, no. 6, p. 985, Nov. 2017, doi: 10.4136/ambi-agua.2037.
- [2] M. J. Mimoso, M. R. Anjos, and J. Teixeira, 'The right to water as a fundamental right,' *World J. Environ. Res.*, vol. 8, no. 2, pp. 45–52, Dec. 2018, doi: 10.18844/wjer.v8i2.3833.
- [3] C.F. Ezeama and C. C. Achonye, 'Analysis of Sachet Water, Bottled Water and Borehole Water Consumed in and around Anambra State Polytechnic, Mgbakwu,' *J. Adv. Res. Med. Health Sci.* ISSN 2208-2425, vol. 9, no. 6, pp. 21–26, Jun. 2023, doi: 10.53555/nmhs.v9i6.1716.
- [4] J. A. Jones, R. C. Casey, and F. Karouia, 'Ionizing Radiation as a Carcinogen,' in *Comprehensive Toxicology*, Elsevier, 2010, pp. 181–228. doi: 10.1016/B978-0-08-046884-6.01411-1.
- [5] B. Gouget, 'Uranium: Toxicity to Renal Cells and Osteoblasts,' in *Encyclopedia of Environmental Health*, Elsevier, 2011, pp. 534–540. doi: 10.1016/B978-0-444-52272-6.00611-5.
- [6] M. A. Akpanowo et al., 'Assessment of radioactivity and heavy metals in water sources from Artisanal mining areas of Anka, Northwest Nigeria,' *Sci. Afr.*, vol. 12, p. e00761, Jul. 2021, doi: 10.1016/j.sciaf.2021.e00761.
- [7] S. Sharma and A. Bhattacharya, 'Drinking water contamination and treatment techniques,' *Appl. Water Sci.*, vol. 7, no. 3, pp. 1043–1067, Jun. 2017, doi: 10.1007/s13201-016-0455-7.
- [8] V. Komolprasert and K. M. Morehouse, Eds., *Irradiation of Food and Packaging: Recent Developments*, vol. 875. in ACS Symposium Series, vol. 875. Washington, DC: American Chemical Society, 2004. doi: 10.1021/bk-2004-0875.
- [9] M. K. Hasson, Q. Y. Al-Kubaisi, and K. K. Ali, 'Evaluation of Uranium Concentration and Calculated Doses of Radiation Resulting from the Tap and Bottled Drinking Water in Babylon - middle Iraq,' *Iraqi J. Sci.*, pp. 676–690, Feb. 2023, doi: 10.24996/ij.s.2023.64.2.17.
- [10] H. Kebir, 'Natural radionuclide concentrations in drinking water (well and spring mineral waters) samples from Bordj-Bouarrerdj region, east Algeria,' *J. Radioanal. Nucl. Chem.*, vol. 331, no. 2, pp. 727–737, Feb. 2022, doi: 10.1007/s10967-021-08126-8.

- [11] A. H. Al-Hayani, A. H. Al-Mashhadani, and N. F. Tawfiq, 'Radioactivity Investigation in Water of Tigris River in Salah Al-Din Governorate, Iraq,' *J. Phys. Conf. Ser.*, vol. 1999, no. 1, p. 012057, Sep. 2021, doi: 10.1088/1742-6596/1999/1/012057.
- [12] D. Borrego-Alonso, B. Quintana-Arnés, and J. C. Lozano, 'Natural radionuclides behaviour in drinking groundwaters from Castilla y León (Spain); radiological implications,' *Water Res.*, vol. 245, p. 120616, Oct. 2023, doi: 10.1016/j.watres.2023.120616.
- [13] A. N. Muhammad, A. F. Ismail, and N. N. Garba, 'Annual effective dose associated with radioactivity in drinking water from tin mining areas in North-western Nigeria,' *J. Radiat. Res. Appl. Sci.*, vol. 15, no. 3, pp. 96–102, Sep. 2022, doi: 10.1016/j.jrras.2022.06.008.
- [14] D. Olaniyi, C. Nwankwo, S. M. Oyeyemi, O. O. Akerele, and L. R. Owoade, 'Natural Radioactivity in Sachet Drinking Water Produced in Ibadan, Oyo State, Nigeria,' Mar. 29, 2023, doi: 10.21203/rs.3.rs-2741289/v1.
- [15] M. R. Usikalu, C. A. Enemuwe, R. O. Morakinyo, M. M. Orosun, T. A. Adagunodo, and J. A. Achuka, 'Background Radiation from <sup>238</sup>U, <sup>232</sup>Th, and <sup>40</sup>K in Bells Area and Canaan City, Ota, Nigeria,' *Open Access Maced. J. Med. Sci.*, vol. 8, no. E, pp. 678–684, Dec. 2020, doi: 10.3889/oamjms.2020.5434.
- [16] K. Aladeniyi, C. J. Olowookere, M. U. Khandaker, and S. J. Alsufyani, 'Evaluation of Radiological Health Risks in Popularly Consumed Brands of Sachet Water in Nigeria,' *Front. Public Health*, vol. 10, p. 917422, Jul. 2022, doi: 10.3389/fpubh.2022.917422.
- [17] A. Papadopoulos, G. Christofides, A. Koroneos, S. Stoulos, and C. Papastefanou, 'Radioactive secular equilibrium in <sup>238</sup>U and <sup>232</sup>Th series in granitoids from Greece,' *Appl. Radiat. Isot.*, vol. 75, pp. 95–104, May 2013, doi: 10.1016/j.apradiso.2013.02.006.
- [18] 'American National Standard Calibration and Usage of Sodium Iodide Detector Systems,' IEEE. doi: 10.1109/IEEESTD.1980.79669.
- [19] D. S. Adelana, G. O. Avwiri, and E. O. Agbalagba, 'Natural Radionuclide Concentration in Kaolin Deposits and Dose Assessment Within Delta State, Nigeria,' *Res. J. PURE Sci. Technol.*, vol. 6, no. 2, pp. 25–38, Oct. 2023, doi: 10.56201/rjpst.v6.no2.2023.pg25.38.
- [20] M. Moshir Rahman, 'Assessment of Natural Radioactivity Levels and Radiological Significance of Bottled Drinking Water in Bangladesh,' *Am. J. Phys. Appl.*, vol. 3, no. 6, p. 203, 2015, doi: 10.11648/j.ajpa.20150306.13.
- [21] K. Eckerman, J. Harrison, H.-G. Menzel, and C. H. Clement, 'ICRP Publication 119: Compendium of Dose Coefficients Based on ICRP Publication 60,' *Ann. ICRP*, vol. 42, no. 4, pp. 1–130, Aug. 2013, doi: 10.1016/j.icrp.2013.05.003.
- [22] M. Puncher and J. D. Harrison, *Assessing the reliability of dose coefficients for ingestion and inhalation of radionuclides by members of the public*. London: Health Protection Agency, 2013.
- [23] M. Yehia, A. Baghdady, F. M. Howari, S. Awad, and A. Gad, 'Natural radioactivity and groundwater quality assessment in the northern area of the Western Desert of Egypt,' *J. Hydrol. Reg. Stud.*, vol. 12, pp. 331–344, Aug. 2017, doi: 10.1016/j.ejrh.2017.06.002.
- [24] A. Altıkulaç, A. Kurnaz, Ş. Turhan, and M. Kutucu, 'Natural Radionuclides in Bottled Mineral Waters Consumed in Turkey and Their Contribution to Radiation Dose,' *ACS Omega*, vol. 7, no. 38, pp. 34428–34435, Sep. 2022, doi: 10.1021/acsomega.2c04087.
- [25] H. R. Fadhil, S. K. Al Nasri, and I. T. Al-Alawy, 'Measurement of Radiation Background and Estimation of the Annual Effective Dose for Workers in the Radiochemistry Laboratories at the Al-Tuwaitha Site,' *Iraqi J. Sci.*, pp. 4749–4760, Nov. 2022, doi: 10.24996/ij.s.2022.63.11.14.