# Assessment of Natural Radioactivity and Associated Radiological Indicators in Water and Surface Soils Around Beta Glass Plc and Its Environs, Ughelli, Delta State, Nigeria

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***ABSTRACT***

*A radiometric assessment was conducted around Beta Glass plc using sodium iodide detector (3×3-inch NaI (TI)). The study collected 14 soil and 13 water samples from June to July 2022, analyzing radioactivity concentrations of $^{40}K$, $^{238}U$, and $^{232}Th$. The mean specific activity concentrations of $^{40}K$, $^{238}U$, and $^{232}Th$ were 184.00±29.73 $Bqkg^{-1}$, 14.55±2.50 $Bqkg^{-1}$, and 8.60±1.04 $Bqkg^{-1}$, respectively, in soil samples, but these elements' concentrations in water were 27.429±5.633 $BqL^{-1}$, 6.661±1.421 $BqL^{-1}$, and 2.518±0.361 $BqL^{-1}$, respectively. The average activity concentrations of $^{40}K$, $^{238}U$, and $^{232}Th$ were lower than the safe limit, and the corresponding radiation hazard indices for soil samples were all below the UNSCEAR-recommended acceptable limits. The mean activity concentrations of radionuclides in water samples were higher than the UNSCEAR's recommended international limits for $^{40}K$, $^{238}U$, and $^{232}Th$. Nonetheless, elevated radiological health hazards imply that cumulative dosages may cause cancer, even though these values might not pose an immediate health concern to the local community's people or the workforce.*

## INTRODUCTION

Radiation can originate anywhere, whether in outer space, on the ground, or even inside of our bodies. Radiation can be found in every direction we look and has been here on earth ever since it was formed. The term "background radiation" refers to this particular type of radiation. Background radiation, or what scientists refer to as "ubiquitous background radiation," is emitted from radioactive substances (radionuclides) that are both naturally occurring or manufactured by humans. Some naturally occurring radionuclides can be discovered in the ground beneath our feet, while others are created when radiation from outer space interacts with the atmosphere. Two examples of man-made activities that have contributed to the discharge of radionuclides into the environment are medical procedures that use radionuclides to image the body and power generation that employs radioactive uranium as fuel (Al-Khawlany et al., 2018).
The human population is subjected to persistent radiation exposure, with the radiation coming from a diverse array of different sources. The natural world is responsible for some of these sources,

while human activity is responsible for others. Cosmic radiation, radiation originating from radionuclides in the earth's crust (sometimes referred to as "external radiation"), and radiation originating from radionuclides that are ingested or inhaled and then retained in the human body (frequently referred to as "internal radiation") are examples of radiation that originates from natural sources. The quantity of exposure to natural radiation that one receives is controlled by a number of factors, some of which include location on Earth, geological formations, and even certain acts taken by humans (Karmaker et al., 2021). The research that was conducted in 2001 by Gur et al. indicates that the rate of exposure to cosmic radiation is influenced by the height above sea level. There are radionuclides that occur naturally in the planet's environment. The earth's crust, air, soil, rocks, water, and plants are only a few of the geological formations where these radionuclides can be found. The natural surroundings can become polluted when they are exposed to dangerous substances, which can have negative effects not only on humans but also on other biotic species that are found in the environment (Jankovi´c et al., 2023). Radionuclide sources are a leading contributor to environmental contamination. This pollution can be caused either by naturally occurring radionuclides or by the activities of humans.

Natural radioactivity can be found practically anywhere, including in the seas and oceans, the soil, the rock formations that make up our planet, and the building materials. The welfare of humanity depends critically on the monitoring of natural background radiation. In the realm of radiation and radioactivity concentration research in the environment, studies on radionuclide concentration fluctuations with geological formation, soil type, and depth profiles are relatively new (Sowole et al., 2018).

Irradiation of human beings comes from both within and outside of their bodies on a constant basis. Outside sources include, for instance, radiation from the ground and radiation from space. People can be exposed to radionuclides from both inside and outside sources. Radionuclides can enter the body through the food, water, and air that people ingest (Chaturvedi & Jain, 2019). Radiation can have a variety of sources but can be found everywhere (thus the term "ubiquitous").

Numerous research on the analysis of naturally occurring radionuclides have been conducted, both in industrial contexts, to ascertain the existence and concentration of these radioactive elements, which would assist comprehend their quality and potential pollution of soil and water resources.

Surface soils in the vicinity of the Oluwa Glass Industry in Igbokoda, Ondo State, Nigeria, were investigated for natural radioactivity and associated dose rates using a well-calibrated NaI (TI) that was well shielded and had a detector connected to a computer-resident quantum MCA2100R multichannel analyzer. Make an estimate of the radioactive concentrations of $^{238}U$, $^{232}Th$ and $^{40}K$ in the soil samples. With mean values of 11.49 and 9.94 $Bqkg^{-1}$, respectively, it was found that the range of activity levels in the soil samples was from 153.74 to 228.13 $Bqkg^{-1}$ for $^{40}K$, from 9.40 to 14.07 $Bqkg^{-1}$ for $^{238}U$, and from 8.42 to 12.08 $Bqkg^{-1}$ for $^{232}Th$. The Excess Lifetime Cancer Risk was 0.085, the mean Absorbed Dose Rate was 19.73±18.43 $nGyh^{-1}$, and the Annual Effective Dose was 24.20±8.31 $\mu Svy^{-1}$. The level of activity concentration of $^{40}K$ found in the current experiment was higher still than 58.69 $Bqkg^{-1}$ for $^{40}K$ measured for soil samples acquired from locations in Sagamu, Southwest Nigeria. The mean global values for the mean AED, the mean ELCR, and the mean absorbed dose rate were 54.00 $nGyh^{-1}$, 66.00 $\mu Svy^{-1}$, and 0.29, respectively. As a result, the scientists came to the conclusion that at the time this study was being performed at the chosen site

in Igbokoda, Ondo State, Nigeria, the radionuclides that are naturally occurring $^{238}U$, $^{232}Th$ and $^{40}K$ had already largely decayed to stable nuclei (Ajanaku et al., 2018).

Making use of gamma-ray spectrometer equipped with a NaI (Tl) detector, researchers were able to determine the levels of naturally occurring radioactivity in samples of soil taken from the Agbara Industrial area, Nigeria. The content of $^{238}U$ varied from 10.21±3.50 to 67.41±18.2 $Bqkg^{-1}$, while the concentration of $^{232}Th$ varied from 26.43±10.8 to 96.24±18.81 $Bqkg^{-1}$, and the concentration of $^{40}K$ varied from 298.65±60.70 to 840.52±150.25 $Bqkg^{-1}$. The means of these three quantities were as follows: 28.69±11.00, 45.86±10.25, and 481.22±106.17 $Bqkg^{-1}$. The AED (Annual Effective Dose) range anywhere from 0.08 to 0.16 $mSvy^{-1}$, with a value of 0.11 $mSvy^{-1}$ serving as the average. The average component of contamination for $^{228}Ra$ was 0.87, whereas the factor for $^{232}Th$ was 1.02, and the value for $^{40}K$ was 1.15. The $^{232}Th$ and $^{40}K$ contamination in the ground is of a modest degree. According to the Index of Pollution Levels, there has been a decline in the grade of the soil in approximately half of the regions that have been covered. The fact that the average cancer risk found in this study ($0.4 \times 10^{-3}$) is higher than the threshold set by the World Health Organization indicates that there is a significant risk for residents of this area to develop lung cancer throughout the course of their lifetimes if they spend their entire lives in the location under investigation (Ademola, 2021).

In Ghana's Ketu South region of the Volta Region, tests were conducted to determine the natural radioactivity in soil dust samples collected from busy business locations along roadways. Using high-purity germanium (HPGe) gamma-ray spectroscopy, the materials' amounts of $^{238}U$, $^{232}Th$, and $^{40}K$ specific activity were determined. These measurements were performed on the samples. The radiological impact of the nearby roadway dirt on the outcomes was investigated. The activity content of the samples ranged from 74.62 to 156.3 $Bqkg^{-1}$, with an average value of 112.4 $Bqkg^{-1}$ for $^{238}U$. While the activity concentrations of $^{232}Th$ ranged from 6.5 to 29.0 $Bqkg^{-1}$, those of $^{40}K$ ranged from 83.76 to 224.27 $Bqkg^{-1}$, with 141.02 $Bqkg^{-1}$ being the average. The findings were used to make an estimation of the radiological characteristics of the soils under investigation. They had values for the radium equivalent ($Ra_{eq}$) activity, absorbed dose rate (D), and annual effective dose (AED) that were lower than those suggested as acceptable or safe limits by international organizations like UNSCEAR (2000) and ICRP (1991). The soils in the examined area had the typical amounts of radiation, making them radiologically safe, according to the findings of the Addo et al. study from 2020 (Addo et al., 2020).

In order to investigate the radiometric survey of soil samples collected from specific villages in the Ika North-East local government area of Delta State, Nigeria, gamma-ray [NaI (TI)] spectroscopy was used. While $^{238}U$ and $^{232}Th$ had average activity concentrations of 37.49 ± 2.44 $Bqkg^{-1}$ and 29.46 ± 2.42 $Bqkg^{-1}$, respectively, $^{40}K$'s average activity concentration in soil samples from the chosen areas was 512.43 ± 1.91 $Bqkg^{-1}$. The acquired average findings of $^{40}K$ and $^{238}U$ were found to be higher than the standard value limits of 400 $Bqkg^{-1}$ and 30 $Bqkg^{-1}$, respectively, when compared to the advised safe limit. Comparing this to the normative values allowed for its discovery. The calculated radiological hazard levels were found to be lower than the global average level, with the exception of the annual gonadal dose equivalent, which was found to be higher than the global average value by 33.3%. According to their report's findings, there is little to no harm to the health of these communities' residents who are exposed to the soils in these locations (Eseka et al., 2018).

To provide useful scientific data and statistics regarding the health impacts of radioactive exposure on humans, radioactivity levels in the soil, and water near Beta Glass Plc and its surroundings were monitored and evaluated in this study. Excess lifetime cancer risk (ELCR), activity concentrations, absorbed dose, annual effective dose, radium equivalent, external and internal hazard indices, representative gamma index ($I_\gamma$), and annual gonadal equivalent dose (AGDE), are all evaluated and provided in tabular and graphical form. The results were compared to the global average, the activity concentration, and radium equivalent results from other similar studies.

## MATERIALS AND METHOD

### Study Area

The study was conducted in a few chosen locations near Beta Glass Plc, which includes Ekakpamre, Eruemukohwarie, and Ekrerhavwen, as well as Beta Glass Plc, situated at Kilometer 17 on the Warri-Patani Road in Ughelli. The location of Ughelli is between latitude N5° 30' 0.6732" and longitude E5° 59' 37.8024", about 50 kilometers (31 miles) east of Warri. Among the most important industrial cities in the Niger Delta region of Nigeria is Ughelli, which is also a major agricultural region. Among the industries that are active in the area are the extraction of oil and gas, the production of electricity, the production and processing of bottles, and the supply of mechanical services for vehicles. Around Ughelli, one of the major onshore oil production sites in the Niger Delta of Nigeria, there are more than 0.432 million residents (NPC Bulletin 2006).

Approximately 160 oil and gas wells and five flare stations make up this region, which produces some of the Niger Delta's largest amounts of gas and oil onshore. Fuel for the numerous oil wells is transported to the flow stations via a system of pipelines that cross over them. The landscape is intertwined with these pipelines (Agbalagba, 2016). The principal objectives of Beta Glass plc are the production and distribution of glassware to companies that specialize in the manufacturing of soft drinks, alcoholic beverages, pharmaceuticals, and cosmetics. They also manufacture, supply, and market glass bottles and containers. The corporation runs factories in the Delta region's Ughelli and Ogun State's Agbara. Among its export destinations are Angola, Burkina Faso, Benin, Cameroon, the Democratic Republic of the Congo, Gambia, Ghana, Liberia, Guinea, Mauritius, Rwanda, and Togo. The company's parent company is Frigo Glass Industries Nigeria Limited (Ekpo, 2016). Fig. 1 shows the map with the sampling points and the research areas marked.

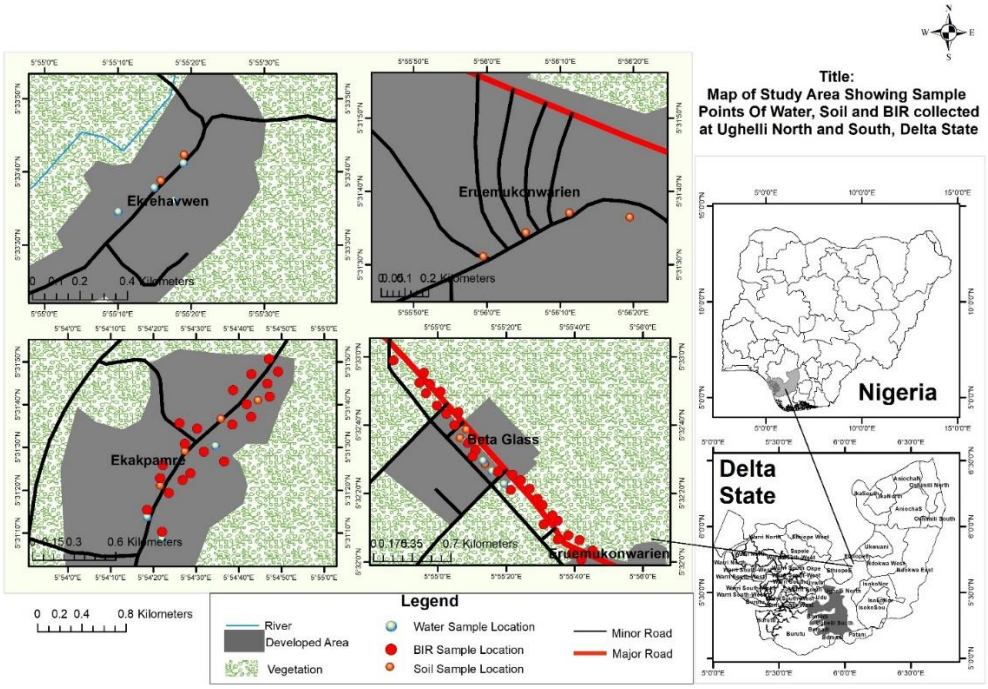


**Fig. 1:** A map depicting the research areas as well as the sampling points

## Methods of Data Collection

The research method of a survey was selected for the purpose of determining the concentration of natural occurring radionuclide level in Beta Glass Plc and its surroundings.

The data samples (soil and water) were manually collected at twenty-seven different points around Beta Glass Plc in Ughelli; water samples were collected at thirteen (13) different places, which include underground water (BW), surface water (SW), treated water (TW), and waste water (WW) from the company. Soil samples were collected at fourteen (14) different points around Beta Glass Plc. in Ughelli. Washed sand and cullet were obtained from the company and included in the soil specimens that were taken from a total of fourteen different points at a distance of twenty meters from each other. A portable handheld geographical positioning system (Germin Oregon 450 GPS) was utilized to determine the exact location of each sampling point.

## Procedures for Measurement

1. First, a random collection of the samples and the GPS location of various data points in the areas under research (each community) were simultaneously gathered. This was done in order to begin the analysis.
2. After that, a gamma ray spectrometer (GRS; NAIS-3″×3″ detector) was used to determine the levels of $^{40}K$, $^{238}U$, and $^{232}Th$ which are all measured in $Bqkg^{-1}$ (for the soil samples) or $BqL^{-1}$ (for the water samples).

### Sample Preparation

The obtained soil samples were air-dried in the laboratory until they reached a constant weight, then crushed to a fine powder and put through a mesh screen with a 0.5-mm opening size. After being collected, the water was immediately acidified at a rate of 10 milliliters per liter with 11 millimeters of hydrochloric acid. This was done to prevent the radionuclide content of the water from being absorbed through the walls of the container (IAEA, 1999). In order to prevent contamination during the preparation process, the water container was cleaned with a diluted solution of tetraoxosulfate (VI) acid and then dried. Before the counting could begin, the samples were first given appropriate labels, then vacuum-sealed, and finally placed inside a cylindrical Marinelli beaker. Before the gamma-ray counting was performed, this step was taken in order to guarantee that the radionuclides and their progeny would reach a condition of secular radioactive equilibrium (Ononugbo et al., 2017).

## RADIOLOGICAL HAZARD INDICATORS

### Natural Radionuclide Activity Concentration

According to Addo et al. (2013), an analytical expression for the specific activity concentration, $A_{E_i}(Bqkg^{-1})$, of a radionuclide $i$ and for a photopeak at energy $E$ can be written as follows:

$$\mathrm{A_{E_i}} = \frac{\gamma_{\mathrm{E_n}}}{\varepsilon_{\mathrm{E_i}} \mathrm{p_i} \mathrm{M_s} \mathrm{T}} \qquad (1)$$

where $\gamma_{E_n}$ represents the sample's net peak count at energy $E$, $\varepsilon_{E_i}$ represents the detector's absolute efficiency at energy $E$, $p_i$ represents the likelihood that the sample would emit gamma rays, $M_s$ represents the sample's mass (dry weight) in kilograms, and $T$ represents the entire counting time in seconds (30000s).

### Radium Equivalent ($Ra_{eq}$) Radioactivity Values

According to the measurements, there is not a consistent pattern of radioactive dispersion across the environment. According to Orosun et al. (2019), the specific activity of chemical substances containing various amounts of $^{238}$U, $^{232}$Th and $^{40}$K has been described using radium equivalents ($Ra_{eq}$) activity in $Bqkg^{-1}$ so that it may be compared with the activity of materials exposed to radiation.

The term “Radium Equivalent," abbreviated "$Ra_{eq}$," refers to the aggregate of the activity concentrations of 10 $BqKg^{-1}$ in relation to the equivalent radioactivity. The concept of radium equivalent is predicated on the premise that the elements 10 $BqKg^{-1}$ of $^{238}$U, 7 $BqKg^{-1}$ of $^{232}$Th, and 130 $BqKg^{-1}$ of $^{40}$K all provide the same amount of beta-ray dosage. In Beretka and Mathew's (1985) and Krieger's (1981) research, an equation was developed to provide a mathematical definition of comparable radioactivity.

$$Ra_{eq}(Bqkg^{-1}) = C_U + 1.43\ C_{Th} + 0.077\ C_K \qquad (2)$$

where $C_U$, $C_{Th}$ and $C_K$ is the activity concentration (measured in $Bqkg^{-1}$) of $^{238}$U, $^{232}$Th and $^{40}$K respectively.

**External Hazard Index ($H_{ex}$)**

Many naturally occurring radioactive isotopes and artificially created ones share the property of radioactive decay. The public is exposed when these radioactive materials decay because an external radiation field is created. Among radionuclides are Uranium ($^{238}U$), Thorium ($^{232}Th$), and Potassium ($^{40}K$), among others, depending on the source and dose. Because of the existence of $^{238}U$ and $^{232}Th$, considerable exposure occurs most frequently. Eqn. 3 contains a mathematical representation of the external hazard index ($H_{ex}$) (Orosun et al., 2019).

$$H_{ex} = \frac{C_U}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \quad (3)$$

where $C_U$, $C_{Th}$ and $C_K$ are as defined in Eqn. 2 above. In order to establish a safe limit and the suitability of the soil and water for various uses, the value of the index must be lower than 1 (a unity). In other words, to determine that the radiation hazard of the water and soil samples in the study area is negligible, the index value must be less than unity.

**Internal Hazard Index ($H_{in}$)**

According to Beogo C, Cisse O, and F (2022), the $H_{in}$ (Internal Hazard Index) is a metric used to evaluate the dangers connected to radioactive contamination of soil and water as a result of internal exposure to radon ($^{222}Rn$) and its daughter progeny by breathing in alpha particles. In Eqn. 4, it is mathematically represented (Orosun et al., 2019).

$$H_{in} = \frac{C_U}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810} \leq 1 \quad (4)$$

The radiation danger must have an index value for this $H_{in}$ that is less than unity in order to be deemed minor. where the definitions of $C_U$, $C_{Th}$, and $C_K$ are the same as in Eqn. 2.

**Absorbed Dose Rate (D)**

The amount of ionizing radiation energy released by radionuclides per unit mass of a material is measured by the absorbed dose rate (D). Its accepted term is gray (Gy), and its unit of measurement is joules per kilogram ($Jkg^{-1}$), where $1Gy = 1Jkg^{-1}$. As demonstrated in Eqn. 5 (Mohanad et al., 2020), the Absorbed Dose Rates (D) owing to gamma radiation at a height of 1meter above ground level for the radionuclides' consistent spread ($^{238}U$, $^{232}Th$, and $^{40}K$) can be expressed.

$$D = 0.462\ C_U + 0.604\ C_{Th} + 0.0417\ C_K \quad (5)$$

where D is the Absorbed Dose Rate ($nGyh^{-1}$). According to Eqn. (2), the $C_U$, $C_{Th}$, and $C_K$ are correspondingly, the uranium, thorium, and potassium activity concentrations.

**Annual Effective Dose Equivalent (for the soil samples)**

In order to determine the outdoor AEDE (Annual Effective Dose Equivalent) caused by gamma ray exposure, Eqn. 6 was used to compute the AEDE for the soil samples (Ogungbemi et al., 2023). The outdoor space's 0.2 occupancy factor and the dose conversion factor of 0.7 $SvGy^{-1}$ (conversion factor for calculating the effective dose adults receive from absorbed radiation in the air) were selected. This means that, an average 20% of the time is spent outside, internationally.

$$AEDE_{outdoor}(\mu Svy^{-1}) = D(nGyh^{-1}) \times 8760h \times 0.7\ (SvGy^{-1}) \times 0.2 \times 10^{-6} \quad (6)$$

where D is the background gamma radiation-induced Absorbed Dose Rate, expressed in $nGyh^{-1}$. On the other hand, AEDE is expressed in $mSvy^{-1}$. There are 365 days in a year, and there are 24 hours in each day. The annual absorbed dose was taken into account while calculating the AEDE (annual effective dose) exposure for both the general population and personnel.

**Annual Effective Dose Equivalent (for the water samples)**

The Annual Effective Dose Equivalent ($AEDE_w$) due to ingesting Uranium, Thorium, and Potassium in water samples was determined using activity concentration and dose conversion factors for $^{238}U$, $^{232}Th$, and $^{40}K$ in order to assess the exposure to radiation in water to the public in the nearby communities around Beta Glass Plc. Eqn. 7 was used to calculate the AEDE (Ogungbemi et al, 2023).

$$AEDE_W = \sum_{i=1}^{3} A_i DCF_i I \quad (7)$$

where $Ai$ stands for activity concentration of radionuclide $i$, $DCFi$ is radionuclide dose conversion factor, and $I$ is the WHO annual water intake for an adult, which is 730l, where $AEDE_W$ is the Annual Effective Dose Equivalent for the water. According to Ogungbemi et al. (2023), the $DCFi$ for $^{238}U$, $^{232}Th$, and $^{40}K$ are $4x10^{-8}SvBq^{-1}$, $2.3x10^{-7}SvBq^{-1}$, and $6.2x10^{-9}SvBq^{-1}$, respectively.

**Excess Lifetime Cancer Risk (ELCR)**

The possible carcinogenic effects of exposure to radionuclides (gamma radiation) by ingestion, inhalation, and contact with external radiation sources are what determine the likelihood of getting cancer over a specific period of time. Even at low doses, ionizing radiation increases the risk of developing cancer over time. According to Avwiri et al. (2014), the excess lifetime cancer (ELCR) probability was determined using the AEDE, as stated in Eqn. 8.

$$ELCR = AEDE \times DL \times RF \quad (8)$$

where RF stands for risk factor ($Sv^{-1}$), which denotes the likelihood of developing lethal cancer per Sievert, and AEDE stands for annual effective dose equivalent. The average life expectancy is determined at 70 years. The International Commission on Radiological Protection (ICRP) uses RF as $0.05Sv^{-1}$ for public effects, claim Taskin et al. (2009) and Avwiri et al. (2014).

**Annual Gonadal Equivalent Dose (AGDE)**

To determine the annual equivalent dosage gotten in the gonads (the reproductive organ), the annual gonadal equivalent dose (AGDE) is utilized. Due to its susceptibility to radiation, the gonad is regarded as an organ of interest along with the active bone marrow and bone surface cells (UNSCEAR (2000, 2008) and ICRP (2012)).

Increased exposure to AGDE is known to have an effect on the bone marrow and also damages red blood cells, which are then replaced by white blood cells. This process is known as the erythropoiesis replacement pathway. This ultimately results in cancer of the blood, sometimes known as leukemia. Using Eqn. 9, the AGDE caused by the activities of $^{238}U$, $^{232}Th$, and $^{40}K$ in the water and top soil of the research region was evaluated (Agbalagba et al., 2014).

$$AGDE\ (\mu Svy^{-1}) = 3.09C_U + 4.18C_{Th} + 0.314C_K \quad (9)$$

where $C_U$, $C_{Th}$, and $C_K$ are the radionuclide activity concentrations ($^{238}U$, $^{232}Th$, and $^{40}K$) in soil and water, respectively.

**Representative Gamma Index (Iγ)**

Estimating the gamma radiation risk posed by radionuclides in a particular sample can be done with the use of the Representative Gamma Index (Iγ). The Iγ can also be used to correlate the Annual Dose Rate (ADR) as a result of the excessive gamma radiation from the outside that is created by surface materials. This is possible since the gamma index can be measured directly.

Since gamma rays may penetrate any material, they have the potential to seriously harm human cells. As a result, a rise in the Iγ (Representative Gamma Index) above the benchmark value of unity may raise the danger of radiation exposure, which could in turn cause cancer by inducing human cells to deform (Avwiri et al., 2013). Another approach for screening materials that could represent a health risk when used for construction and other activities is the Representative Gamma Index (Tufail et al., 2007). According to Agbalagba et al. (2014), the representative gamma index, denoted as Iγ, was calculated using Eqn. 10.

$$I_\gamma = \frac{C_U}{150} + \frac{C_{Th}}{100} + \frac{C_K}{1500} \leq 1 \quad (10)$$

where $C_U$, $C_{Th}$, and $C_K$ are the radionuclide activity concentrations of $^{238}U$, $^{232}Th$, and $^{40}K$ in soil and water, respectively.

**RESULTS AND DISCUSSION**

**Activity Concentration of $^{238}U$, $^{232}Th$ and $^{40}K$ in the Soil**

Table 1 presents the results of the activity concentrations of $^{238}U$, $^{232}Th$, and $^{40}K$ in soil samples from the research territory. Moving on to the graphical representation of the activity concentrations of these radionuclides, Figs. 2–4 showcase their comparison with UNESCEAR standards. The associated radiological indicators for these radionuclides are displayed in Tables 2 through 4 and compared with UNESCEAR standards in Figs. 5–12. Furthermore, in Tables 5–6, the detailed descriptive analysis and the correlations between the activity concentrations of the radionuclides and the radiation hazards indices are presented. Where Figs. 13–15 provide a side-by-side evaluation of the correlation between the concentration activity project's performance. Table 4.8 presents the comparison of the activity concentration and radium equivalent results with other similar studies published in the literature.

**Table 1:** The radiation levels in topsoil samples that were taken at the study sites that were measured

| Location | Geographical location | Sample code | $^{40}$K (Bqkg$^{-1}$) | $^{238}$U (Bqkg$^{-1}$) | $^{232}$Th (Bqkg$^{-1}$) |
|---|---|---|---|---|---|
| **Ekakpamre/ECN** | N05°31′431″ E005°54′227″ | 1A | $127.81 \pm 6.89$ | $BDL$ | $9.24 \pm 0.57$ |
| | N05°31′441″ E005°54′229″ | 1B | $179.26 \pm 9.82$ | $23.88 \pm 3.39$ | $6.38 \pm 0.40$ |
| | N05°31′464″ E005°54′214″ | 1C | $138.94 \pm 7.58$ | $21.48 \pm 3.58$ | $10.01 \pm 0.63$ |
| | N05°31′471″ E005°54′210″ | 1D | $30.93 \pm 1.69$ | $13.03 \pm 2.25$ | $7.83 \pm 0.48$ |
| **Beta Glass Plc** | N05°31′45″ E005°46′039″ | 2A | $117.27 \pm 5.50$ | $23.11 \pm 3.58$ | $18.23 \pm 1.12$ |
| | N05°31′379″ E005°56′128″ | 2B | $390.68 \pm 21.39$ | $16.76 \pm 2.69$ | $10.82 \pm 0.67$ |
| | N05°31′281″ E005°56′089″ | 2C | $192.50 \pm 10.43$ | $14.23 \pm 2.33$ | $10.56 \pm 0.65$ |
| | N05°31′327″ E005°56′061″ | 2D | $212.96 \pm 11.54$ | $31.05 \pm 4.22$ | $9.15 \pm 0.56$ |
| **Eruemukohwarien** | N05°32′541″ E005°55′827″ | 3A | $394.69 \pm 20.96$ | $17.37 \pm 2.51$ | $9.64 \pm 0.60$ |
| | N05°32′569″ E005°55′821″ | 3B | $145.26 \pm 7.97$ | $14.90 \pm 2.48$ | $5.89 \pm 0.37$ |
| | N05°32′598″ E005°55′809″ | 3C | $157.00 \pm 8.59$ | $12.96 \pm 2.55$ | $BDL$ |
| | N05°32′619″ E005°55′970″ | 3D | $296.00 \pm 15.96$ | $BDL$ | $8.72 \pm 0.55$ |
| **Ekrerhavwen** | N05°32′412″ E005°55′107″ | 4A | $165.72 \pm 9.02$ | $14.98 \pm 2.55$ | $7.00 \pm 0.43$ |
| | N05°33′541″ E005°55′148″ | 4B | $27.02 \pm 1.51$ | $BDL$ | $6.97 \pm 0.44$ |
| **Minimum** | | | $\mathbf{27.02 \pm 1.51}$ | $\boldsymbol{BDL}$ | $\boldsymbol{BDL}$ |
| **Maximum** | | | $\mathbf{394.69 \pm 20.96}$ | $\mathbf{31.05 \pm 4.22}$ | $\mathbf{18.23 \pm 1.12}$ |
| **Mean ± SE** | | | $\mathbf{184.00 \pm 29.73}$ | $\mathbf{14.55 \pm 2.50}$ | $\mathbf{8.60 \pm 1.04}$ |
| **World Average (UNSCEAR, 2000)** | | | **420** | **33** | **45** |

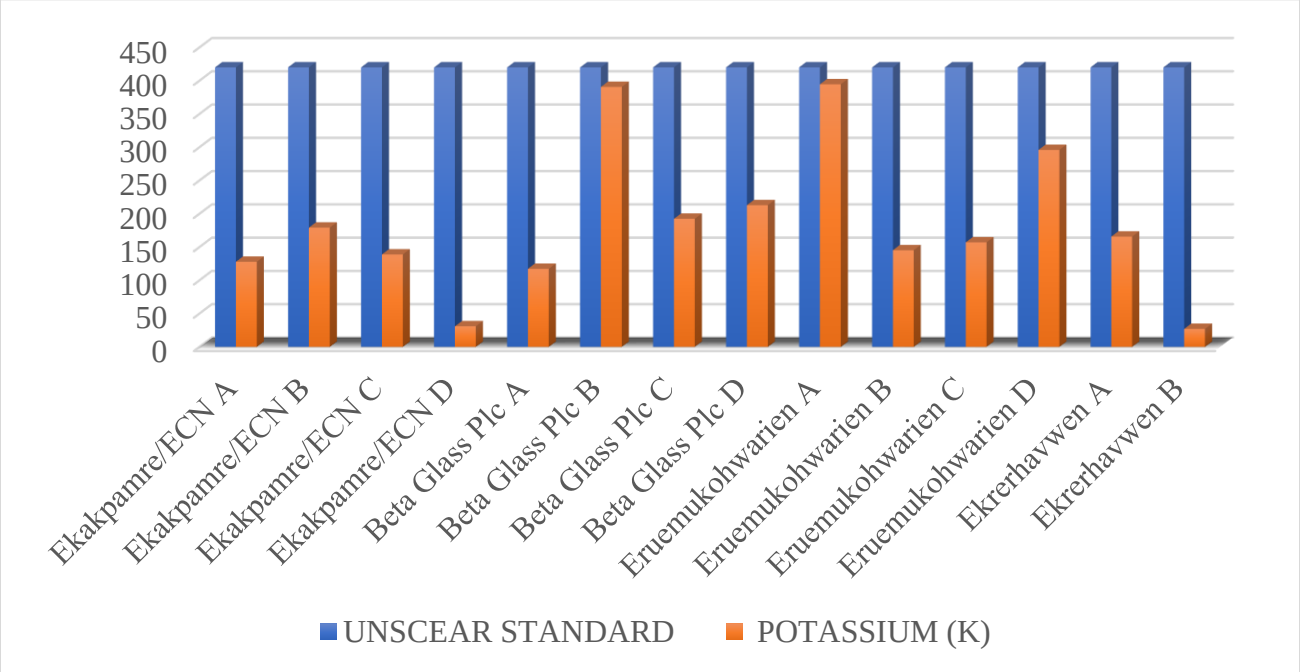


**Fig 2:** The comparison of potassium activity concentration ($^{40}K$ $Bqkg^{-1}$) in soil with UNESCEAR standard in the areas under study

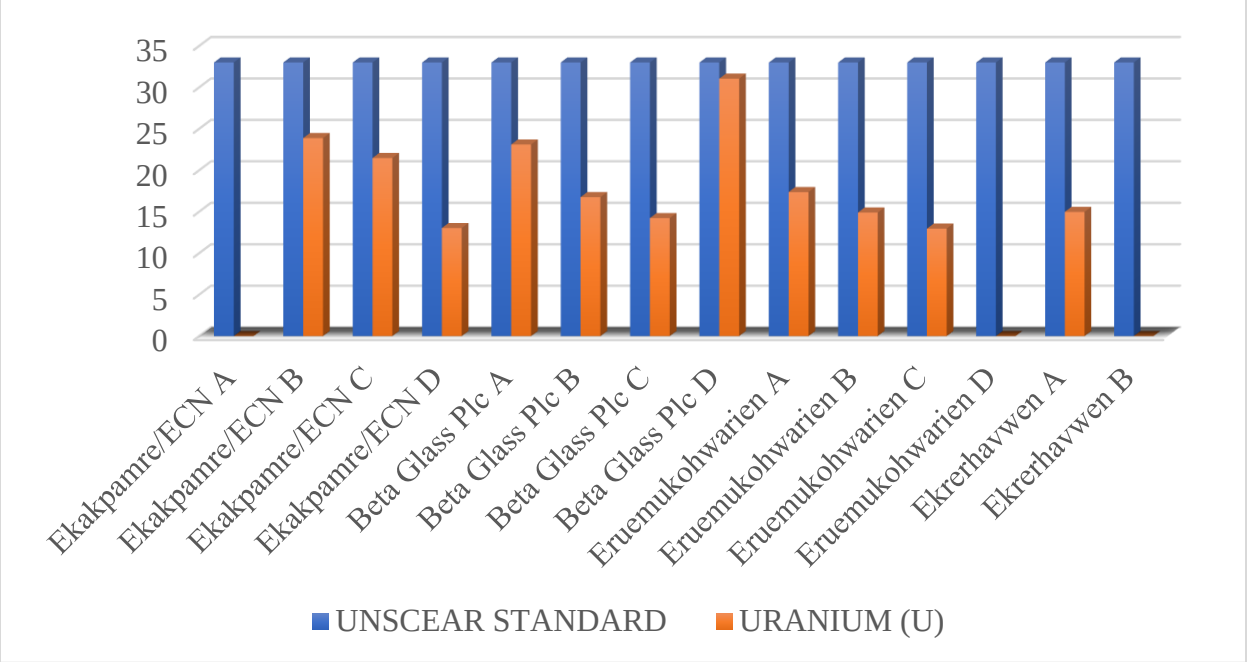


**Fig 3:** The comparison of uranium activity concentration ($^{238}U$ ($Bqkg^{-1}$)) in soil with UNESCEAR standard in the areas under study

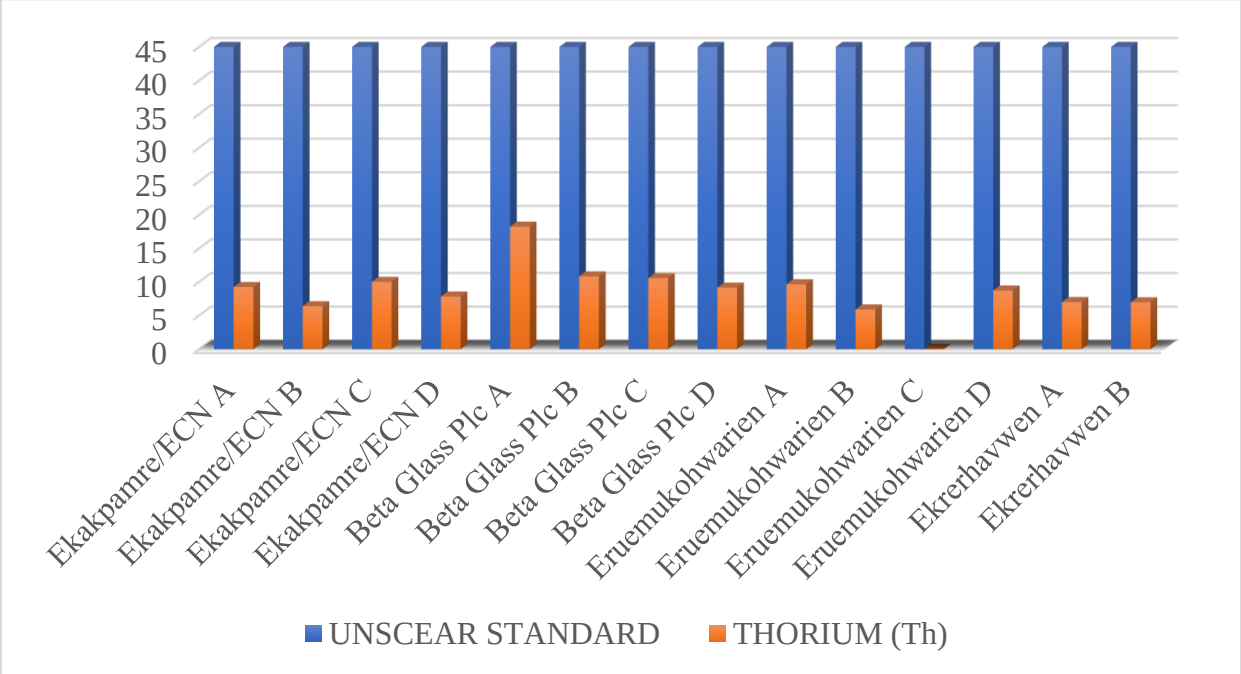


**Fig 4:** The comparison of thorium activity concentration ($^{232}$Th (Bqkg$^{-1}$)) in soil with UNESCEAR standard in the areas under study

**Table 2:** For the soil samples, the radium equivalent, external, and internal hazard indices

| Location | Geographical location | Sample code | $Ra_{eq}(Bqkg^{-1})$ | $H_{ex}$ | $H_{in}$ |
|---|---|---|---|---|---|
| **Ekakpamre/ECN** | N05°31′431″ E005°54′227″ | 1A | 23.055 | 0.062 | 0.062 |
| | N05°31′441″ E005°54′229″ | 1B | 46.806 | 0.126 | 0.191 |
| | N05°31′464″ E005°54′214″ | 1C | 46.493 | 0.126 | 0.184 |
| | N05°31′471″ E005°54′210″ | 1D | 26.609 | 0.072 | 0.107 |
| **Beta Glass Plc** | N05°31′45″ E005°46′039″ | 2A | 58.209 | 0.157 | 0.220 |
| | N05°31′379″ E005°56′128″ | 2B | 62.315 | 0.168 | 0.214 |
| | N05°31′281″ E005°56′089″ | 2C | 44.153 | 0.119 | 0.158 |
| | N05°31′327″ E005°56′061″ | 2D | 60.532 | 0.164 | 0.247 |

| | | | | | |
|---|---|---|---|---|---|
| **Eruemukohwarien** | N05°32′541″ E005°55′827″ | 3A | 61.546 | 0.166 | 0.213 |
| | N05°32′569″ E005°55′821″ | 3B | 34.508 | 0.093 | 0.133 |
| | N05°32′598″ E005°55′809″ | 3C | 25.049 | 0.068 | 0.103 |
| | N05°32′619″ E005°55′970″ | 3D | 35.262 | 0.095 | 0.095 |
| **Ekrerhavwen** | N05°32′412″ E005°55′107″ | 4A | 37.750 | 0.102 | 0.142 |
| | N05°33′541″ E005°55′148″ | 4B | 12.048 | 0.033 | 0.033 |
| **Minimum** | | | **12.048** | **0.033** | **0.033** |
| **Maximum** | | | **62.315** | **0.168** | **0.247** |
| **Main ± SE** | | | **41.024 ± 4.281** | **0.111 ± 0.012** | **0.150 ± 0.017** |
| **World Average (UNSCEAR, 2000)** | | | **89** | **< 1** | **< 1** |

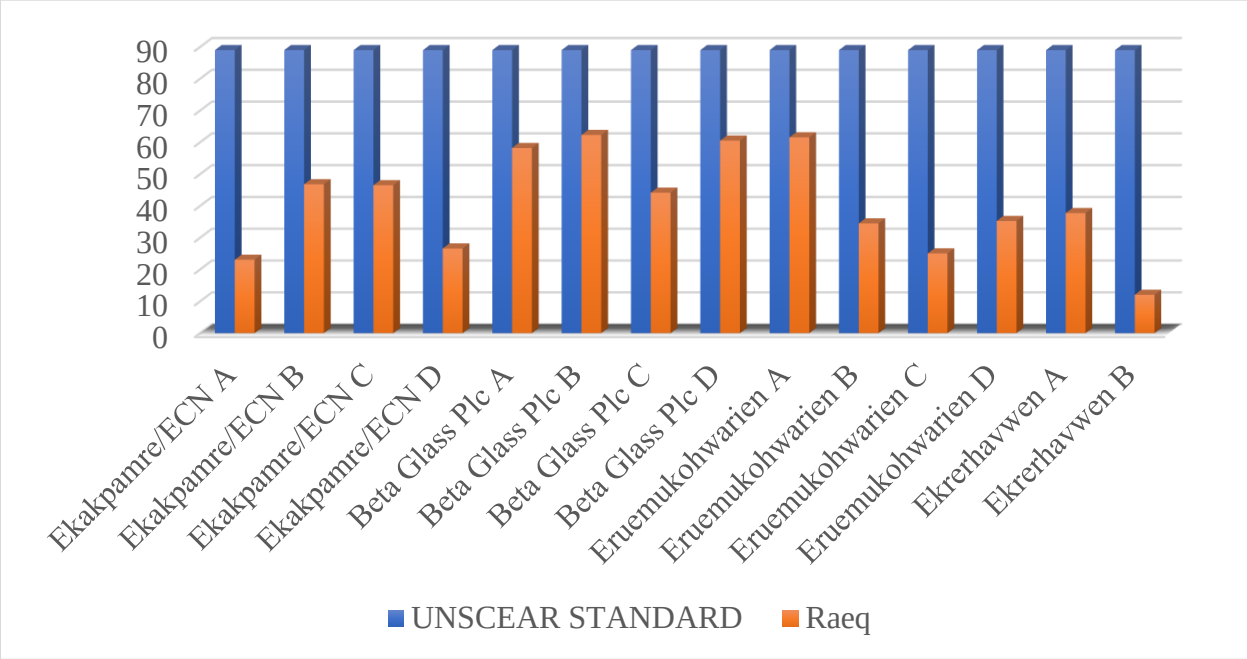


**Fig 5:** The comparison of the concentration of radium equivalent activity ($Ra_{eq}$ ($Bqkg^{-1}$)) in soil with UNESCEAR standard in the areas under study

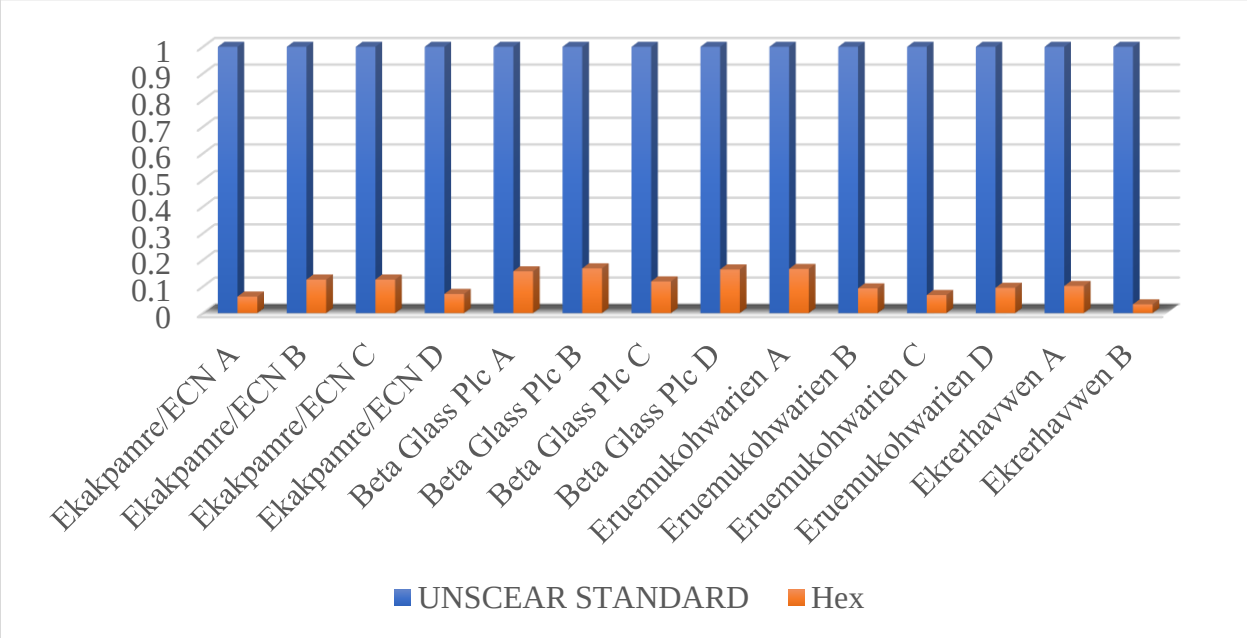


**Fig 6:** The comparison of external hazard index ($H_{ex}$) in soil with UNESCEAR standard in the areas under study

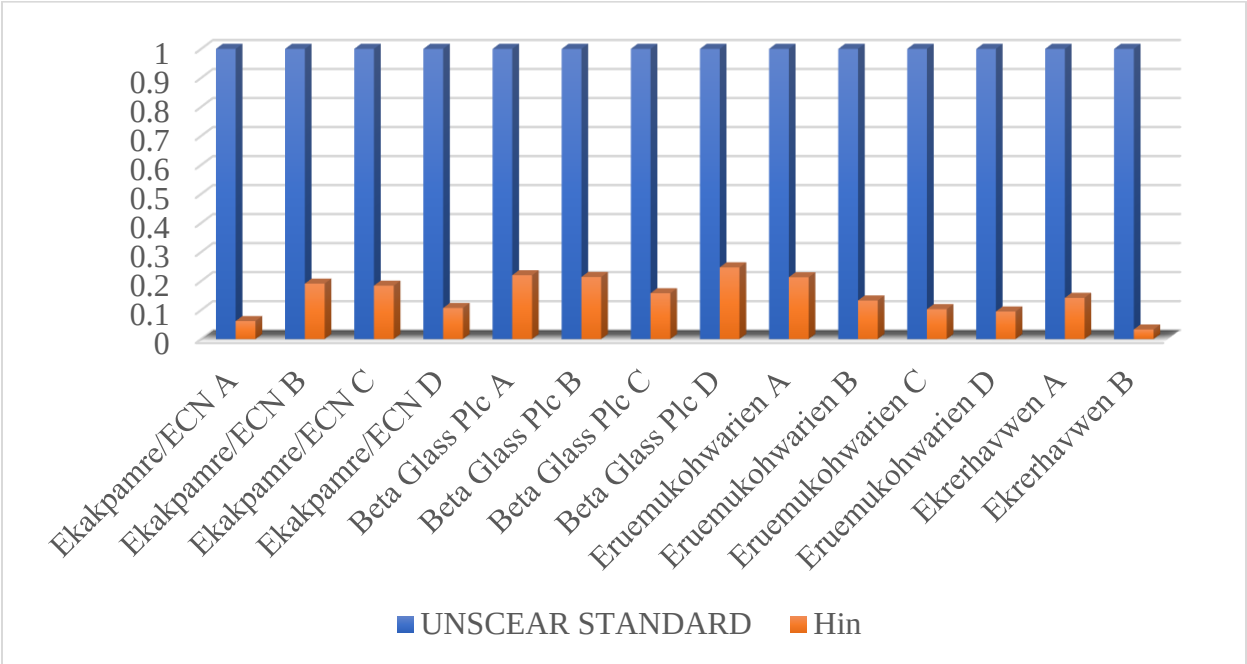


**Fig 7:** The comparison of internal hazard index ($H_{in}$) in soil with UNESCEAR standard in the areas under study

**Table 3:** The soil samples' excess lifetime cancer risk, annual effective dose equivalent, and absorbed dose rate

| Location | Geographical location | Sample code | $D(nGyh^{-1})$ | $AEDE(mSvy^{-1})$ | $ELCR(\times 10^{-3})$ |
|---|---|---|---|---|---|
| **Ekakpamre/ECN** | N05°31′431″ E005°54′227″ | 1A | 10.911 | 0.013 | 0.046 |
| | N05°31′441″ E005°54′229″ | 1B | 22.361 | 0.027 | 0.095 |
| | N05°31′464″ E005°54′214″ | 1C | 21.764 | 0.027 | 0.095 |
| | N05°31′471″ E005°54′210″ | 1D | 12.039 | 0.015 | 0.053 |
| **Beta Glass Plc** | N05°31′45″ E005°46′039″ | 2A | 26.578 | 0.033 | 0.116 |
| | N05°31′379″ E005°56′128″ | 2B | 30.570 | 0.037 | 0.130 |
| | N05°31′281″ E005°56′089″ | 2C | 20.980 | 0.026 | 0.091 |
| | N05°31′327″ E005°56′061″ | 2D | 28.752 | 0.035 | 0.123 |
| **Eruemukohwarien** | N05°32′541″ E005°55′827″ | 3A | 30.307 | 0.037 | 0.130 |
| | N05°32′569″ E005°55′821″ | 3B | 16.499 | 0.020 | 0.070 |
| | N05°32′598″ E005°55′809″ | 3C | 12.534 | 0.015 | 0.053 |
| | N05°32′619″ E005°55′970″ | 3D | 17.610 | 0.022 | 0.077 |
| **Ekrerhavwen** | N05°32′412″ E005°55′107″ | 4A | 18.059 | 0.022 | 0.077 |
| | N05°33′541″ E005°55′148″ | 4B | 5.337 | 0.007 | 0.025 |
| **Minimum** | | | **5.337** | **0.007** | **0.025** |
| **Maximum** | | | **30.570** | **0.037** | **0.130** |
| **Main $\pm$ SE** | | | $\mathbf{19.59 \pm 2.075}$ | $\mathbf{0.024 \pm 0.003}$ | $\mathbf{0.084 \pm 0.009}$ |
| **World Average (UNSCEAR, 2000)** | | | **60** | **0.07** | **0.29** |

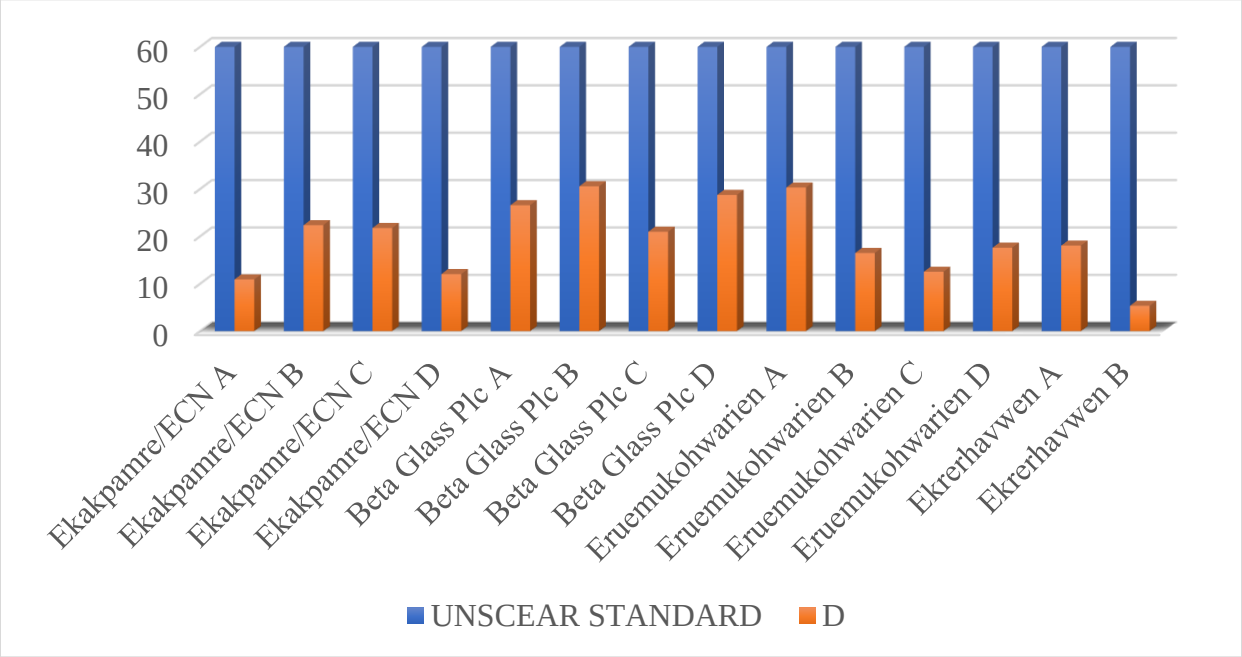


**Fig 8:** The absorbed dose rate (D ($nGyh^{-1}$)) comparison in soil with UNESCEAR standard in the areas under study

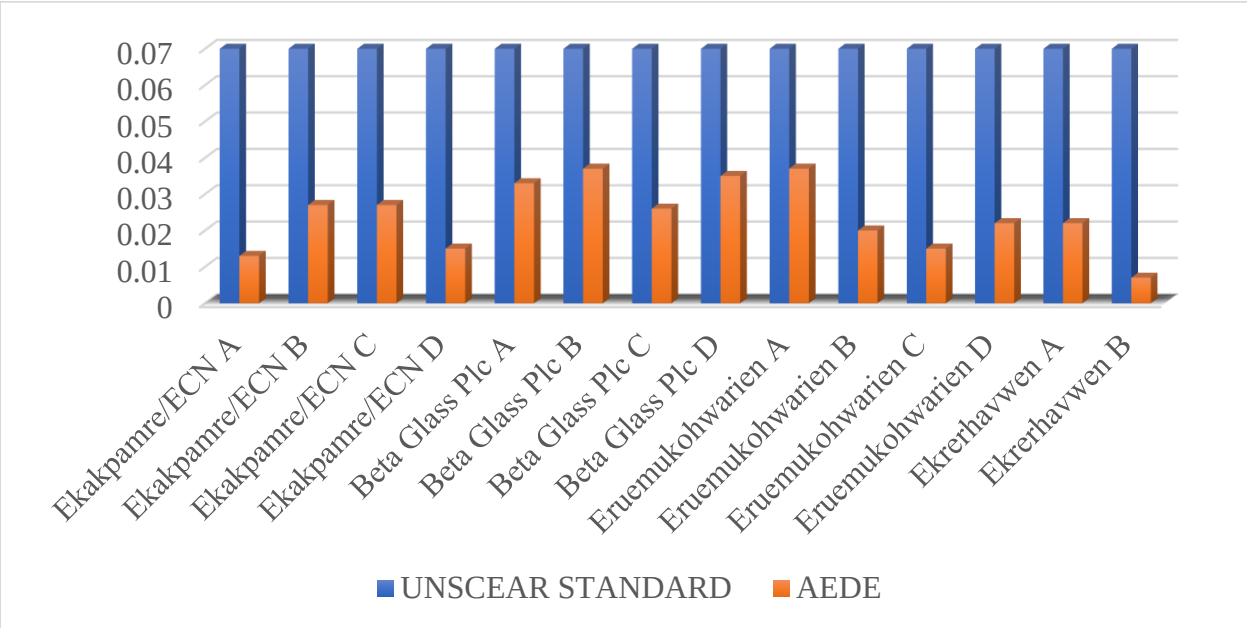


**Fig 9:** The annual effective dose equivalent (AEDE ($mSvy^{-1}$)) comparison in soil with UNESCEAR standard in the areas under study

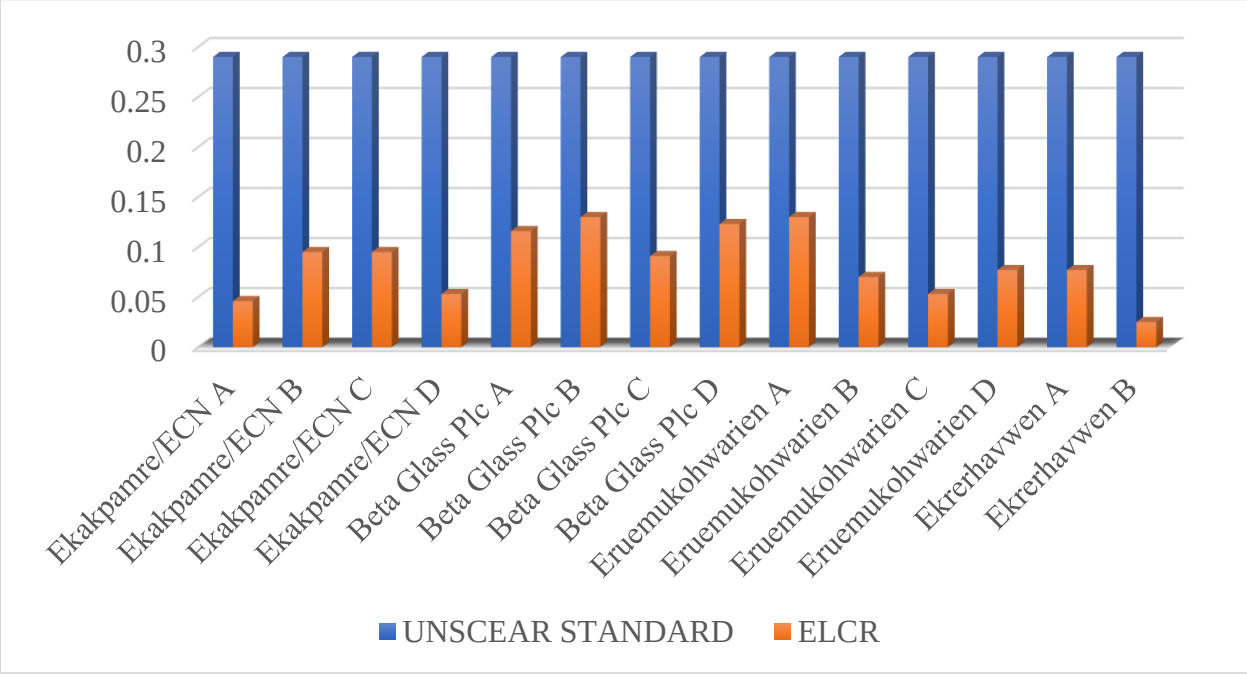


**Fig 10:** The comparison of excess lifetime cancer (ELCR ($\times 10^{-3}$)) in soil with UNESCEAR standard in the areas under study

**Table 4:** Representative Gamma Index and Annual Gonadal Equivalent Dose for Soil Samples

| Location | Geographical location | Sample code | $AGDE(\mu Svy^{-1})$ | $I_\gamma$ |
|---|---|---|---|---|
| **Ekakpamre/ECN** | N05°31′431″ E005°54′227″ | 1A | 78.756 | 0.178 |
| | N05°31′441″ E005°54′229″ | 1B | 156.745 | 0.343 |
| | N05°31′464″ E005°54′214″ | 1C | 151.842 | 0.336 |
| | N05°31′471″ E005°54′210″ | 1D | 82.704 | 0.186 |
| **Beta Glass Plc** | N05°31′45″ E005°46′039″ | 2A | 184.434 | 0.415 |
| | N05°31′379″ E005°56′128″ | 2B | 219.690 | 0.480 |
| | N05°31′281″ E005°56′089″ | 2C | 148.557 | 0.329 |
| | N05°31′327″ E005°56′061″ | 2D | 201.061 | 0.440 |
| **Eruemukohwarien** | N05°32′541″ E005°55′827″ | 3A | 217.901 | 0.475 |
| | N05°32′569″ | 3B | 116.273 | 0.255 |

| | | | | |
|---|---|---|---|---|
| | E005°55′821″ | | | |
| | N05°32′598″ E005°55′809″ | 3C | 89.344 | 0.191 |
| | N05°32′619″ E005°55′970″ | 3D | 129.394 | 0.285 |
| **Ekrerhavwen** | N05°32′412″ E005°55′107″ | 4A | 127.584 | 0.280 |
| | N05°33′541″ E005°55′148″ | 4B | 37.619 | 0.088 |
| **Minimum** | | | **37.619** | **0.088** |
| **Maximum** | | | **219.690** | **0.480** |
| **Mean ± SE** | | | **138.707 ± 14.733** | **0.306 ± 0.032** |
| **World Average (UNSCEAR, 2000)** | | | **300** | **0.50** |

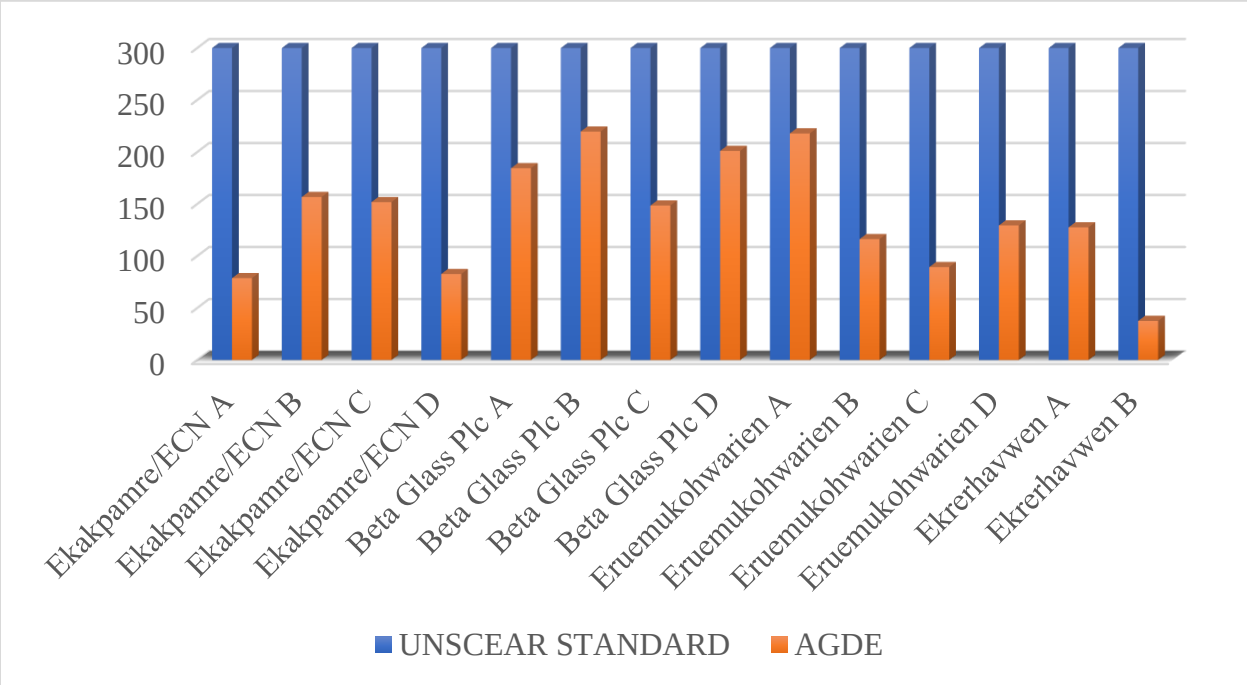


**Fig 11:** The comparison of annual gonadal equivalent (AGDE ($\mu Svy^{-1}$)) in soil with UNESCEAR standard in the areas under study

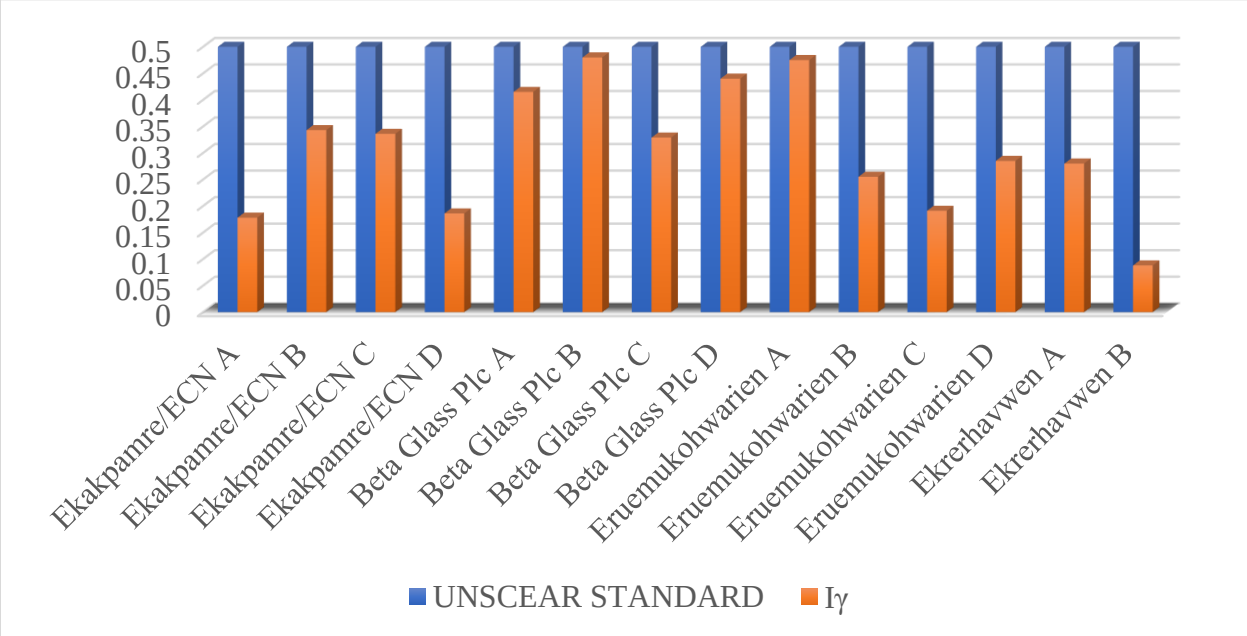


**Fig 12:** The comparison of gamma index (Iγ) in soil with UNESCEAR standard in the areas under study

**Table 5:** For the soil samples taken from the study region, the descriptive analysis of the radionuclide activity concentration and radiation hazard indices are presented below

| Descriptive Statistics | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N Statistic | Minimum Statistic | Maximum Statistic | Sum Statistic | Mean Statistic | Std. Deviation Statistic | Skewness Statistic | Std. Error | Kurtosis Statistic | Std. Error |
| $^{40}K$ | 14 | 27.02 | 394.69 | 2576 | 184 | 111.23848 | 0.75 | 0.597 | 0.272 | 1.154 |
| $^{238}U$ | 14 | 0 | 31.05 | 203.75 | 14.554 | 9.33887 | -0.326 | 0.597 | -0.238 | 1.154 |
| $^{232}Th$ | 14 | 0 | 18.23 | 120.44 | 8.6029 | 3.8962 | 0.362 | 0.597 | 3.702 | 1.154 |
| $Ra_{eq}$ | 14 | 12.05 | 62.32 | 574.34 | 41.024 | 16.01764 | -0.142 | 0.597 | -0.982 | 1.154 |
| $H_{ex}$ | 14 | 0.03 | 0.17 | 1.55 | 0.1108 | 0.04317 | -0.135 | 0.597 | -0.996 | 1.154 |
| $H_{in}$ | 14 | 0.03 | 0.25 | 2.1 | 0.1501 | 0.06454 | -0.262 | 0.597 | -0.916 | 1.154 |
| D | 14 | 5.34 | 30.57 | 274.3 | 19.593 | 7.76393 | -0.13 | 0.597 | -0.809 | 1.154 |
| AEDE | 14 | 0.01 | 0.04 | 0.34 | 0.024 | 0.00944 | -0.135 | 0.597 | -0.909 | 1.154 |
| ELCR | 14 | 0.03 | 0.13 | 1.18 | 0.0844 | 0.03306 | -0.121 | 0.597 | -0.921 | 1.154 |
| AGDE | 14 | 37.62 | 219.69 | 1941.9 | 138.71 | 55.1247 | -0.098 | 0.597 | -0.722 | 1.154 |
| Iγ | 14 | 0.09 | 0.48 | 4.28 | 0.3058 | 0.11985 | -0.097 | 0.597 | -0.807 | 1.154 |
| Valid N (listwise) | 14 | | | | | | | | | |

**Table 6:** For the soil samples taken from the study area, the correlations between the activity concentrations of the radionuclides and the radiation hazards indices are presented below

| | $^{40}$K | $^{238}$U | $^{232}$Th | $Ra_{eq}$ | $H_{ex}$ | $H_{in}$ | D | AEDE | ELCR | AGDE | Iγ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **$^{40}$K** | 1 | | | | | | | | | | |
| **$^{238}$U** | 0.17212 | 1 | | | | | | | | | |
| **$^{232}$Th** | 0.13002 | 0.24025 | 1 | | | | | | | | |
| **$Ra_{eq}$** | 0.68032 | 0.75864 | 0.55745 | 1 | | | | | | | |
| **$H_{ex}$** | 0.67842 | 0.76105 | 0.55623 | 0.99997 | 1 | | | | | | |
| **$H_{in}$** | 0.52277 | 0.89956 | 0.46856 | 0.967 | 0.96793 | 1 | | | | | |
| **D** | 0.73253 | 0.73137 | 0.51432 | 0.99703 | 0.99687 | 0.95426 | 1 | | | | |
| **AEDE** | 0.72436 | 0.72812 | 0.53424 | 0.99768 | 0.99758 | 0.9535 | 0.99934 | 1 | | | |
| **ELCR** | 0.72314 | 0.72932 | 0.5345 | 0.99782 | 0.99773 | 0.95407 | 0.99936 | 0.99998 | 1 | | |
| **AGDE** | 0.76215 | 0.70353 | 0.5036 | 0.9929 | 0.99261 | 0.94058 | 0.99897 | 0.99798 | 0.99791 | 1 | |
| **Iγ** | 0.74912 | 0.70288 | 0.53091 | 0.99506 | 0.99473 | 0.94182 | 0.99911 | 0.99887 | 0.99883 | 0.99947 | 1 |

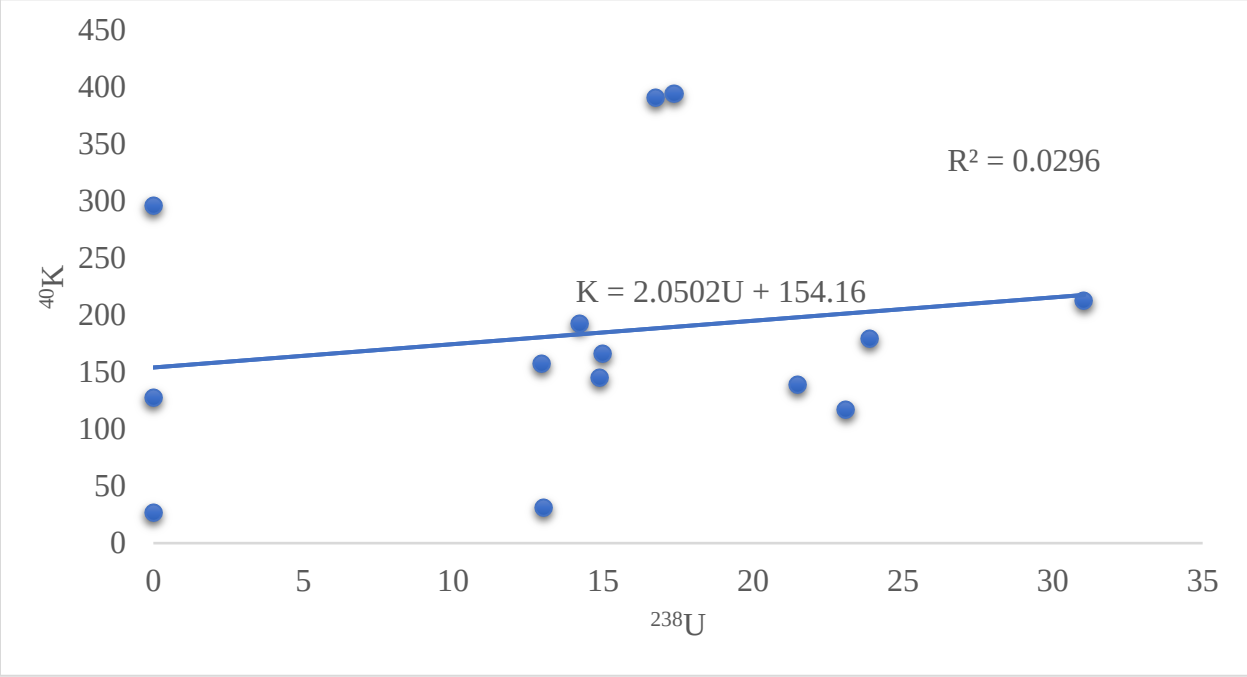


**Fig 13:** Correlation between the concentration activity of $^{40}$K and $^{238}$U

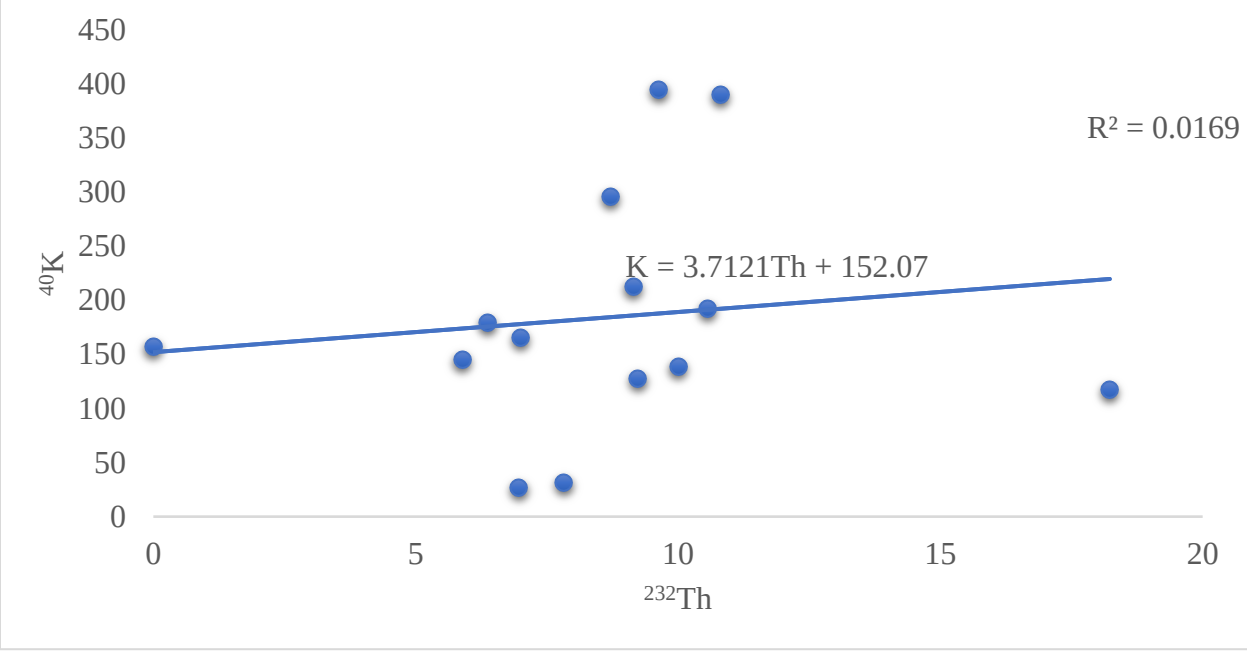


**Fig 14:** Correlation between the concentration activity of $^{40}$K and $^{232}$Th

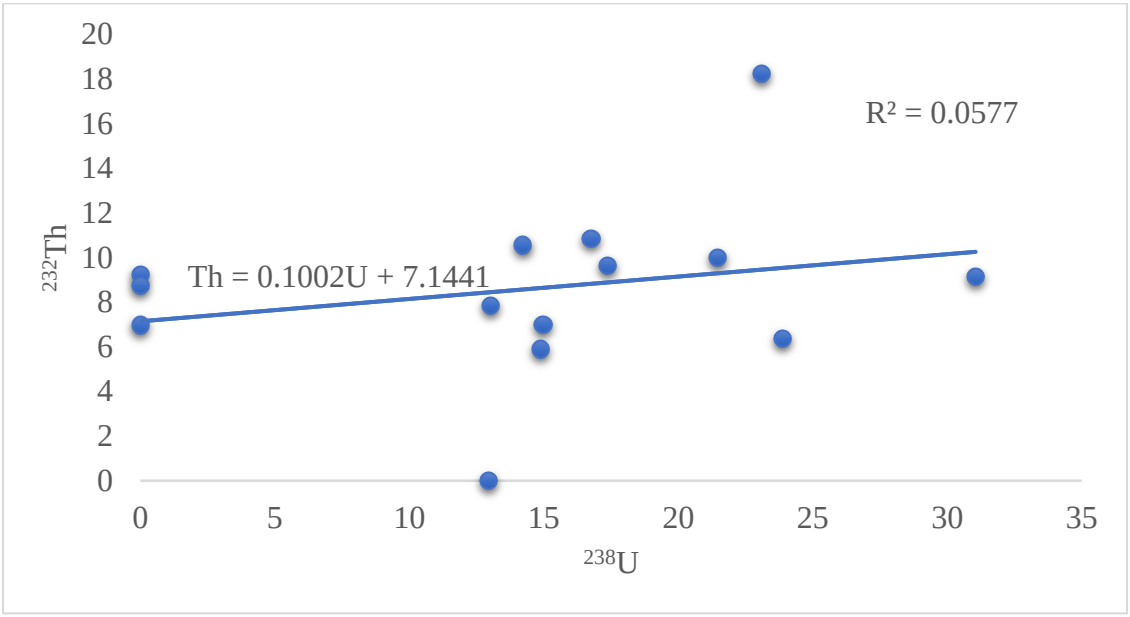


**Fig 15**: Correlation between the concentration activity of $^{232}$Th and $^{238}$U

**Table 7:** Comparison of the activity concentration and radium equivalent results with other similar studies published in the literature

| Country/region | Activity Concentrations (BqKg$^{-1}$) | | | $Ra_{eq}$ | References |
|---|---|---|---|---|---|
| | $^{40}$K | $^{238}$U | $^{232}$Th | | |
| Nigeria (Agbara) | 481.22±106.17 | 28.69±11.00 | 45.86±10.25 | 131.32 | Ademola, (2021) |
| Ghana | 102.69 | 112.39 | 11.73 | 137.061 | Addo *et al,* (2020) |
| Nigeria | 512.73±2.89 | 37.49± 2.44 | 29.46 ± 2.42 | 106.67 | Eseka *et al*, (2018) |
| Nigeria (Agbara) | 103±7.5 | 40.3±7.2 | 26.0±2.2 | 85.5±10 | Gbadamosi *et al.,* (2017) |
| Nigeria | 270.14 ± 61.79 | 12.14 ± 4.17 | 23.23 ± 7.67 | - | Oluyide *et al*, (2018) |
| Kenya | 1086±49 | 143±7 | 95±4 | 362±18 | Kiprono, (2020) |
| Nigeria | 224.26±11.75 | 19.16±2.35 | 21.26±1.41 | - | Avwiri *et al,* (2013) |
| Nigeria (Igbokoda) | 194.69±17.40 | 11.49±2.10 | 9.94±1.05 | - | Ajanaku *et al.,* (2018) |

| | | | | | |
|---|---|---|---|---|---|
| **Nigeria** | **184.00±29.73** | **4.316 ± 3.22** | **14.55±2.50** | **41.024±4.281** | **Present Study** |
| **Worlds Average** | **420.0** | **33.0** | **45.0** | **≤ 370. 0** | **UNSCEAR (2000)** |

### Activity Concentration of $^{238}U$, $^{232}Th$ and $^{40}K$ in the Water

Table 8 presents results of the measurements of the activity concentrations of $^{238}U$, $^{232}Th$, and $^{40}K$ in water samples from the study area. In the bar graphs in Figs. 16–18, the different radionuclides listed in Table 8 are compared to the safe limit set by the WHO in 2011. Understanding is made quick and simple because of the visual portrayal. The associated radiological parameters for these radionuclides are displayed in Tables 9 through 11. and the ELCR was compared with WHO standards in Fig. 19. Furthermore, in Tables 12–13, the detailed descriptive analysis and the correlations between the activity concentrations of the radionuclides and the radiation hazards indices are presented. The relationship between the three radionuclides in water is depicted in scatter plots in Fig 20 to 22. This graph sheds light on whether there is a correlation or not between these factors, as mentioned in Table 8. Table 14 compares the activity concentration and radium equivalent findings to those of other investigations of a similar nature that have been documented in the literature.

**Table 8:** The radioactive concentrations that were measured in the water samples that were taken at the study locations

| Location | Geographical location | Sample code | 40K ($BqL^{-1}$) | 238U ($BqL^{-1}$) | 232Th ($BqL^{-1}$) |
|---|---|---|---|---|---|
| **Beta Glass Plc** | N05°32′657″ E005°55′713″ | TW1 | 38.65±29.04 | 12.37±0.96 | 2.58±0.14 |
| | N05°32′667″ E005°55′644″ | TW2 | 23.40±1.13 | 10.47±0.81 | 3.53±0.20 |
| | N05°32′678″ E005°55′600″ | TW3 | 2.48±0.12 | BDL | 2.99±0.17 |
| | N05°32′367″ E005°55′634″ | WW1 | 50.54±2.44 | 3.88±0.32 | 1.57±0.09 |
| | N05°32′642″ E005°55′751″ | WW2 | 12.71±0.61 | 9.71±0.76 | 0.45±0.03 |
| **Ekakpamre** | N05°32′367″ E005°55′265″ | SW1 | 70.57±3.37 | 0.36±0.03 | 4.03±0.23 |
| | N05°32′353″ E005°55′280″ | SW2 | 12.84±0.62 | 11.91±0.93 | 4.08±0.23 |
| | N05°32′327″ E005°55′206″ | SW3 | 26.41±1.27 | 2.47±0.20 | 2.32±0.13 |
| | N05°32′534″ E005°55′210″ | SW4 | 3.50±0.17 | 5.93±0.47 | 0.34±0.02 |
| **Ekrerhavwen** | N05°32′410″ E005°55′101″ | SW5 | 11.14±0.54 | 11.47±0.92 | 1.09±0.06 |

| | | | | | |
|---|---|---|---|---|---|
| | N05°33′354″ E005°55′145″ | SW6 | 24.63±1.19 | 1.54±0.12 | 3.88±0.21 |
| | N05°32′355″ E005°55′213″ | BW1 | 50.00±2.41 | 2.46±0.20 | 3.22±0.18 |
| | N05°32′561″ E005°55′013″ | BW2 | 29.70±1.43 | 14.02±1.11 | 2.65±0.14 |
| **Minimum** | | | **2.48±0.12** | **BDL** | **0.34±0.02** |
| **Maximum** | | | **70.57±3.37** | **14.02±1.11** | **4.08±0.23** |
| **Mean ± SE** | | | **27.429±5.633** | **6.661±1.421** | **2.518±0.361** |
| **Standard (WHO, 2011)** | | | **10.0** | **10.0** | **1.0** |

**BDL** – below the detectable limits
**TW** - treated water, **WW** - waste water, **SW** - surface water and **BW** - borehole water

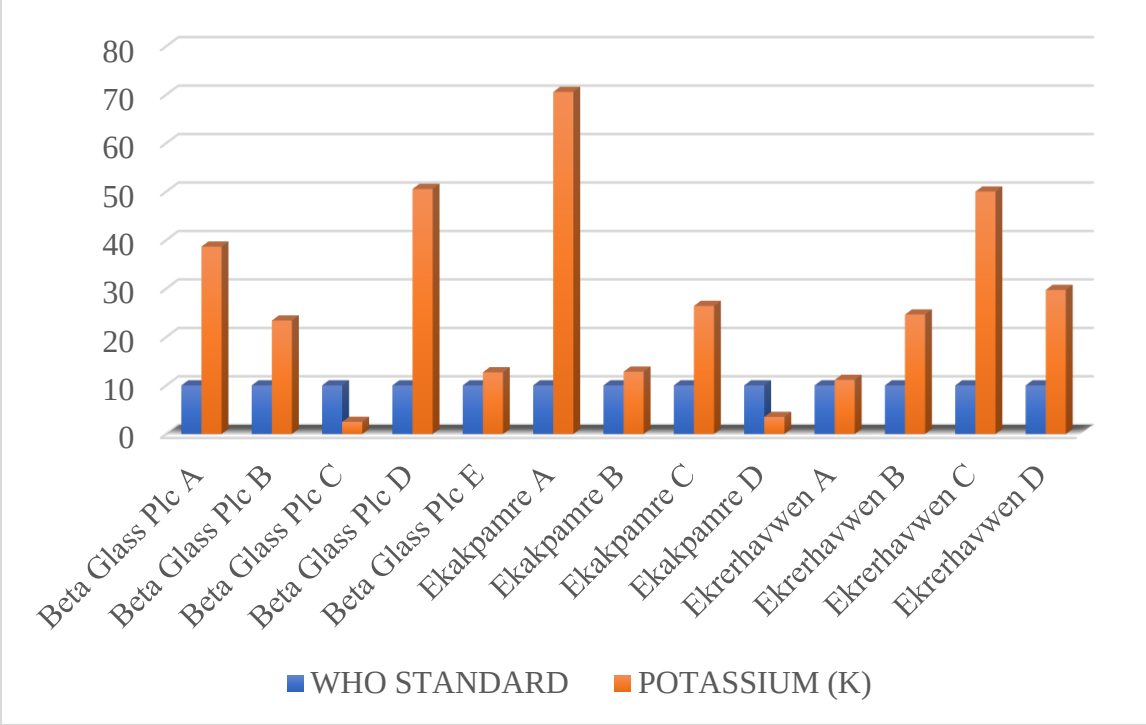


**Fig 16:** The potassium ($^{40}K$ ($BqL^{-1}$)) activity concentration comparison in water with UNESCEAR standard in the areas under study

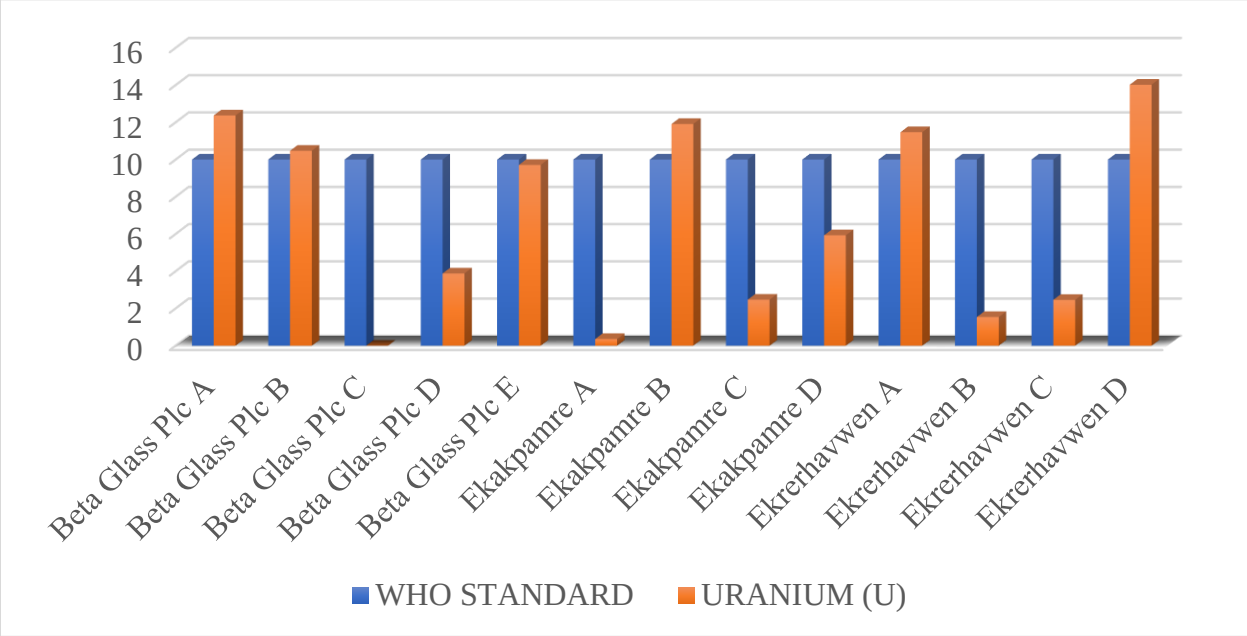


**Fig 17:** The comparison of the activity concentration of uranium ($^{238}U$ ($BqL^{-1}$)) in water with UNESCEAR standard in the areas under study

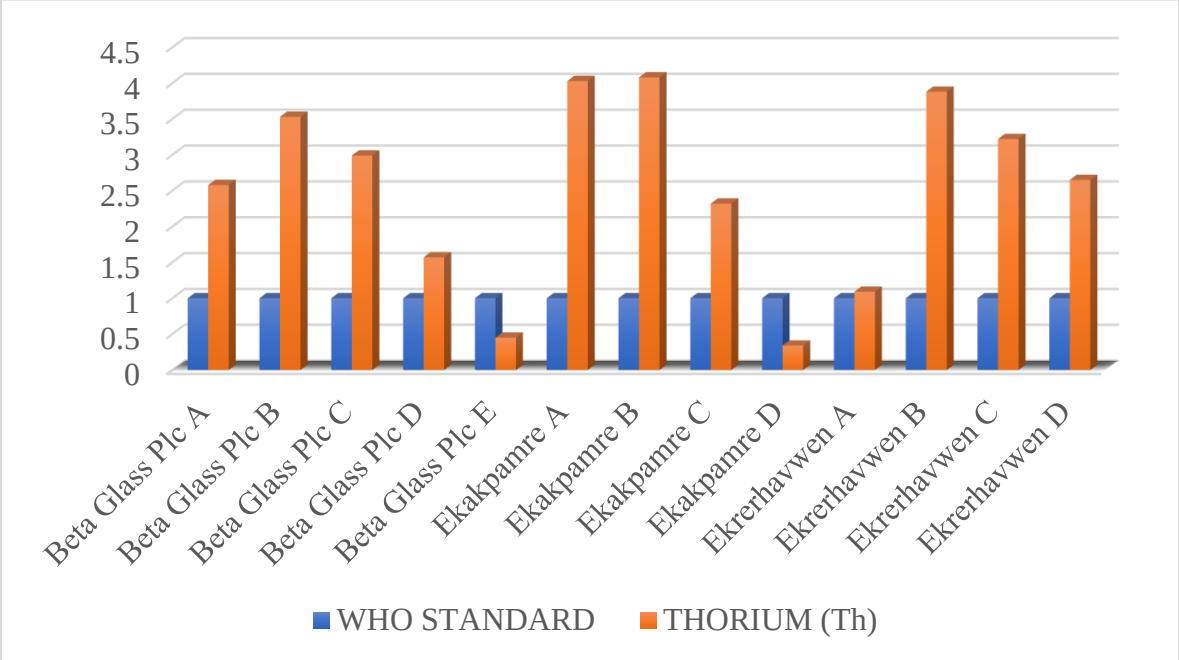


**Fig 18:** The comparison of the activity concentration of Thorium ($^{232}Th$ ($BqL^{-1}$)) in water with UNESCEAR standard in the areas under study

**Table 9:** The water samples' Radium equivalent, external, and internal hazard indexes

| Location | Geographical location | Sample code | $Ra_{eq}(\mathbf{BqL^{-1}})$ | $H_{ex}$ | $H_{in}$ |
|---|---|---|---|---|---|
| **Beta Glass Plc** | N05°32′657″ E005°55′713″ | TW1 | 19.035 | 0.051 | 0.085 |
| | N05°32′667″ E005°55′644″ | TW2 | 17.320 | 0.046 | 0.075 |
| | N05°32′678″ E005°55′600″ | TW3 | 4.467 | 0.012 | 0.012 |
| | N05°32′367″ E005°55′634″ | WW1 | 10.017 | 0.027 | 0.038 |
| | N05°32′642″ E005°55′751″ | WW2 | 11.332 | 0.031 | 0.057 |
| **Ekakpamre** | N05°32′367″ E005°55′265″ | SW1 | 11.557 | 0.031 | 0.032 |
| | N05°32′353″ E005°55′280″ | SW2 | 18.733 | 0.051 | 0.083 |
| | N05°32′327″ E005°55′206″ | SW3 | 7.821 | 0.021 | 0.028 |
| | N05°32′534″ E005°55′210″ | SW4 | 6.686 | 0.018 | 0.034 |
| **Ekrerhavwen** | N05°32′410″ E005°55′101″ | SW5 | 13.886 | 0.038 | 0.069 |
| | N05°33′354″ E005°55′145″ | SW6 | 8.985 | 0.024 | 0.028 |
| | N05°32′355″ E005°55′213″ | BW1 | 10.915 | 0.029 | 0.036 |
| | N05°32′561″ E005°55′013″ | BW2 | 20.096 | 0.054 | 0.092 |
| **Minimum** | | | **4.467** | **0.012** | **0.012** |
| **Maximum** | | | **20.096** | **0.054** | **0.092** |
| **Mean ± SE** | | | **12.373±1.404** | **0.033±0.004** | **0.052±0.007** |

**Table 10:** Annual Effective Dose, Absorbed Dose Rates, and Excess Lifetime Cancer Risk for the Water Samples

| Location | Geographical location | Sample code | $D(nGyh^{-1})$ | $AEDE_w$ ($mSvy^{-1}$) | ELCR ($\times 10^{-3}$) |
|---|---|---|---|---|---|
| **Beta Glass Plc** | N05°32′657″ E005°55′713″ | TW1 | 8.885 | 0.485 | 1.696 |
| | N05°32′667″ E005°55′644″ | TW2 | 7.945 | 0.502 | 1.757 |
| | N05°32′678″ E005°55′600″ | TW3 | 1.909 | 0.257 | 0.898 |
| | N05°32′367″ E005°55′634″ | WW1 | 4.848 | 0.303 | 1.962 |
| | N05°32′642″ E005°55′751″ | WW2 | 5.288 | 0.209 | 0.730 |
| **Ekakpamre** | N05°32′367″ E005°55′265″ | SW1 | 5.543 | 0.503 | 1.762 |
| | N05°32′353″ E005°55′280″ | SW2 | 8.502 | 0.546 | 1.909 |
| | N05°32′327″ E005°55′206″ | SW3 | 3.643 | 0.291 | 1.017 |
| | N05°32′534″ E005°55′210″ | SW4 | 3.091 | 0.123 | 0.431 |
| **Ekrerhavwen** | N05°32′410″ E005°55′101″ | SW5 | 6.422 | 0.284 | 0.994 |
| | N05°33′354″ E005°55′145″ | SW6 | 4.082 | 0.404 | 1.414 |
| | N05°32′355″ E005°55′213″ | BW1 | 5.166 | 0.420 | 1.468 |
| | N05°32′561″ E005°55′013″ | BW2 | 9.316 | 0.495 | 1.731 |
| **Minimum** | | | **1.909** | **0.123** | **0.431** |
| **Maximum** | | | **9.316** | **0.546** | **1.962** |
| **Mean ± SE** | | | **5.742±0.650** | **0.371±0.037** | **1.367±0.138** |

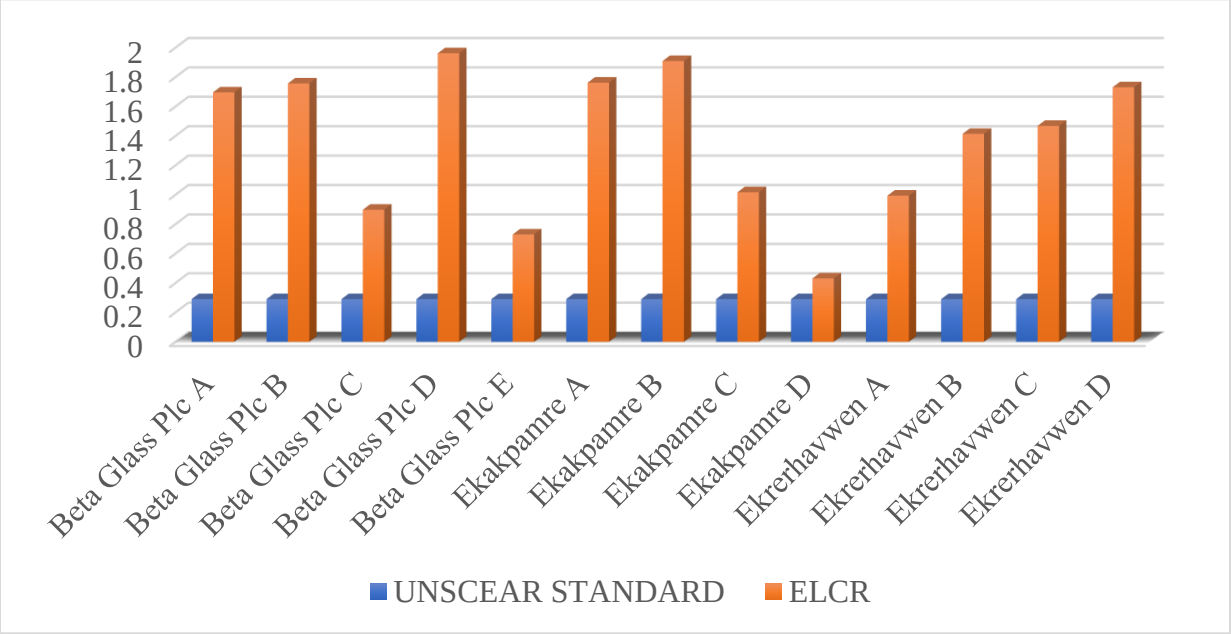


**Fig 19:** The comparison of the activity concentration of excess lifetime cancer (ELCR ($\times 10^{-3}$)) in water with UNESCEAR standard in the areas under study

**Table 11:** Representative Gamma Index and Annual Gonadal Equivalent Dose for Water Samples

| Location | Geographical location | Sample code | $AGDE(\mu Svy^{-1})$ | $I_\gamma$ |
|---|---|---|---|---|
| **Beta Glass Plc** | N05°32′657″ E005°55′713″ | TW1 | 61.144 | 0.134 |
| | N05°32′667″ E005°55′644″ | TW2 | 54.455 | 0.121 |
| | N05°32′678″ E005°55′600″ | TW3 | 13.277 | 0.032 |
| | N05°32′367″ E005°55′634″ | WW1 | 34.421 | 0.075 |
| | N05°32′642″ E005°55′751″ | WW2 | 35.876 | 0.078 |
| **Ekakpamre** | N05°32′367″ E005°55′265″ | SW1 | 40.117 | 0.090 |
| | N05°32′353″ E005°55′280″ | SW2 | 57.888 | 0.129 |
| | N05°32′327″ E005°55′206″ | SW3 | 25.623 | 0.057 |
| | N05°32′534″ E005°55′210″ | SW4 | 20.844 | 0.045 |
| **Ekrerhavwen** | N05°32′410″ | SW5 | 43.496 | 0.095 |

| | | | | |
|---|---|---|---|---|
| | E005°55′101″ | | | |
| | N05°33′354″ | SW6 | 28.711 | 0.065 |
| | E005°55′145″ | | | |
| | N05°32′355″ | BW1 | 36.761 | 0.082 |
| | E005°55′213″ | | | |
| | N05°32′561″ | BW2 | 63.725 | 0.140 |
| | E005°55′013″ | | | |
| **Minimum** | | | **13.277** | **0.032** |
| **Maximum** | | | **63.725** | **0.140** |
| **Mean ± SE** | | | **39.718±4.403** | **0.088±0.010** |

**Table 12:** For the water samples taken from the study region, the descriptive analysis of the radionuclide activity concentration and radiation hazard indices are presented below

**Descriptive Statistics**

| | N Statistic | Minimum Statistic | Maximum Statistic | Sum Statistic | Mean Statistic | Std. Deviation | Skewness Statistic | Std. Error | Kurtosis Statistic | Std. Error |
|---|---|---|---|---|---|---|---|---|---|---|
| $^{40}K$ | 13 | 2.48 | 70.57 | 356.57 | 27.4285 | 20.31165 | 0.771 | 0.616 | 0.044 | 1.191 |
| $^{238}U$ | 13 | 0.00 | 14.02 | 86.59 | 6.6608 | 5.12354 | 0.055 | 0.616 | -1.827 | 1.191 |
| $^{232}Th$ | 13 | 0.34 | 4.08 | 32.73 | 2.5177 | 1.30190 | -0.520 | 0.616 | -0.966 | 1.191 |
| $Ra_{eq}$ | 13 | 4.47 | 20.10 | 160.85 | 12.3731 | 5.06385 | 0.234 | 0.616 | -1.135 | 1.191 |
| $H_{ex}$ | 13 | 0.01 | 0.05 | 0.43 | 0.0333 | 0.01364 | 0.225 | 0.616 | -1.143 | 1.191 |
| $H_{in}$ | 13 | 0.01 | 0.09 | 0.67 | 0.0515 | 0.02648 | 0.256 | 0.616 | -1.485 | 1.191 |
| D | 13 | 1.91 | 9.32 | 74.64 | 5.7415 | 2.34242 | 0.146 | 0.616 | -1.016 | 1.191 |
| AEDE | 13 | 0.12 | 0.55 | 4.82 | 0.3709 | 0.13429 | -0.365 | 0.616 | -1.085 | 1.191 |
| ELCR | 13 | 0.43 | 1.96 | 17.77 | 1.3668 | 0.49770 | -0.559 | 0.616 | -0.999 | 1.191 |
| AGDE | 13 | 13.28 | 63.73 | 516.34 | 39.7183 | 15.87427 | 0.082 | 0.616 | -0.952 | 1.191 |
| Iγ | 13 | 0.03 | 0.14 | 1.14 | 0.0879 | 0.03467 | 0.109 | 0.616 | -1.034 | 1.191 |
| Valid N (listwise) | 13 | | | | | | | | | |

**Table 13:** For the water samples taken from the study area, the correlations between the activity concentrations of the radionuclides and the radiation hazards indices are presented below

| | $^{40}K$ | $^{238}U$ | $^{232}Th$ | $Ra_{eq}$ | $H_{ex}$ | $H_{in}$ | D | AEDE | ELCR | AGDE | Iγ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $^{40}K$ | 1 | | | | | | | | | | |
| $^{238}U$ | -0.290681 | 1 | | | | | | | | | |
| $^{232}Th$ | 0.389901 | -0.216509 | 1 | | | | | | | | |
| $Ra_{eq}$ | 0.158281 | 0.842308 | 0.269039 | 1 | | | | | | | |
| $H_{ex}$ | 0.152217 | 0.855194 | 0.194202 | 0.983640 | 1 | | | | | | |
| $H_{in}$ | -0.039104 | 0.949885 | 0.022107 | 0.957064 | 0.960663 | 1 | | | | | |
| D | 0.198757 | 0.832834 | 0.257673 | 0.998745 | 0.984484 | 0.953292 | 1 | | | | |
| AEDE | 0.489001 | 0.290817 | 0.823543 | 0.748077 | 0.690395 | 0.541106 | 0.747048 | 1 | | | |
| ELCR | 0.641592 | 0.184107 | 0.671339 | 0.631305 | 0.615092 | 0.436153 | 0.643396 | 0.865824 | 1 | | |
| AGDE | 0.245496 | 0.806319 | 0.283558 | 0.995879 | 0.980636 | 0.939209 | 0.998793 | 0.768836 | 0.671521 | 1 | |
| Iγ | 0.235666 | 0.807629 | 0.283049 | 0.993974 | 0.979815 | 0.936568 | 0.996331 | 0.764674 | 0.677179 | 0.997184 | 1 |

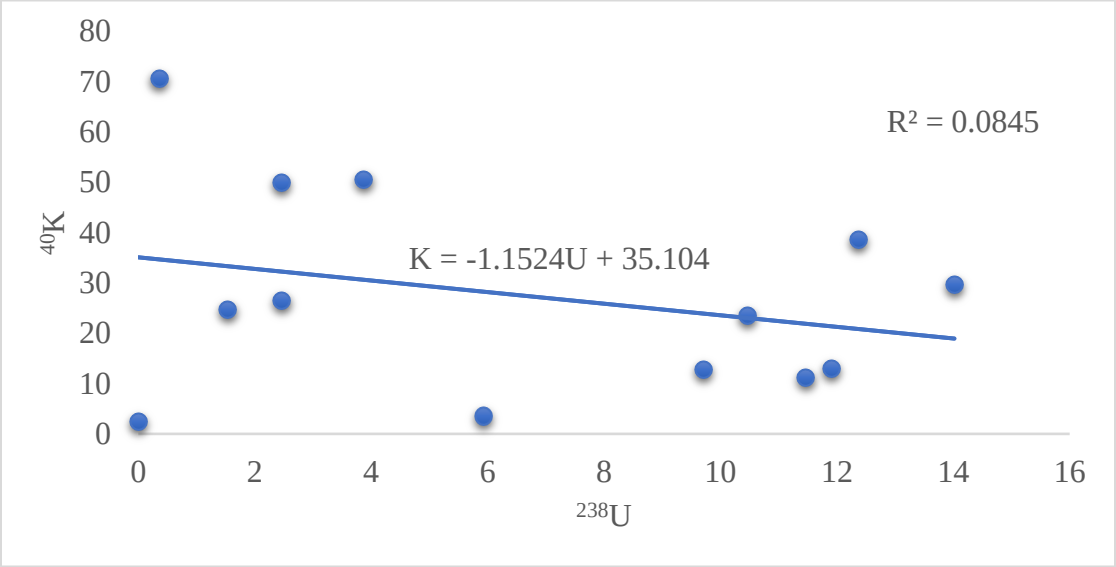


**Fig 20:** Correlation between the concentration activity of $^{40}$K and $^{238}$U for the water samples in the area under study

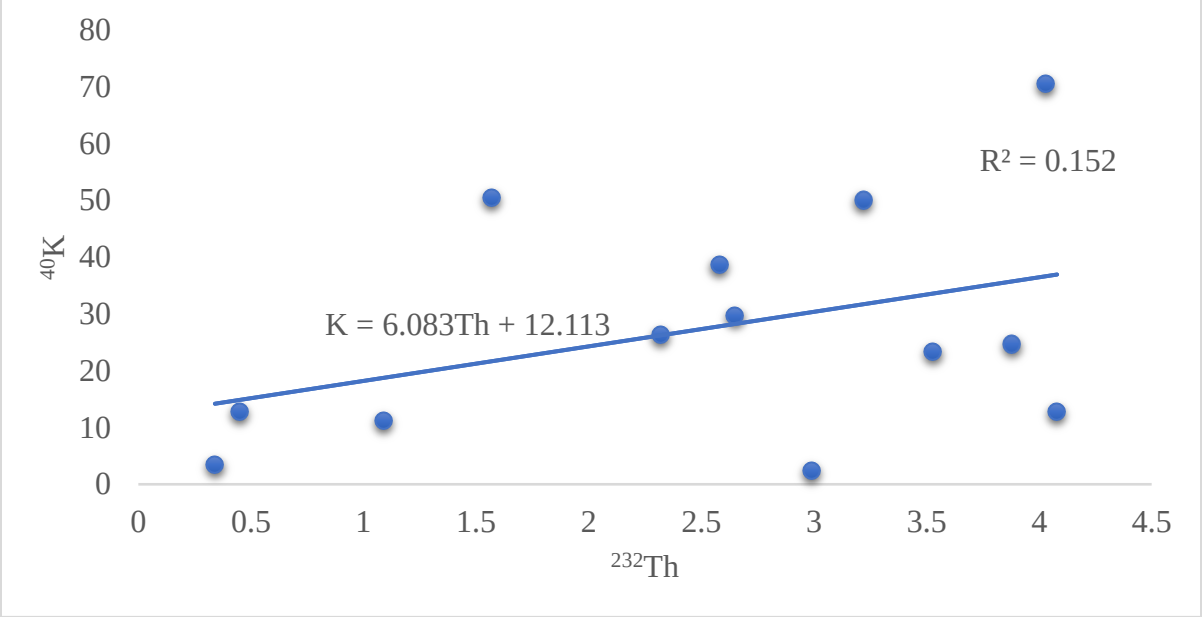


**Fig 21:** Correlation between the concentration activity of $^{40}$K and $^{232}$Th for the water samples in the area under study

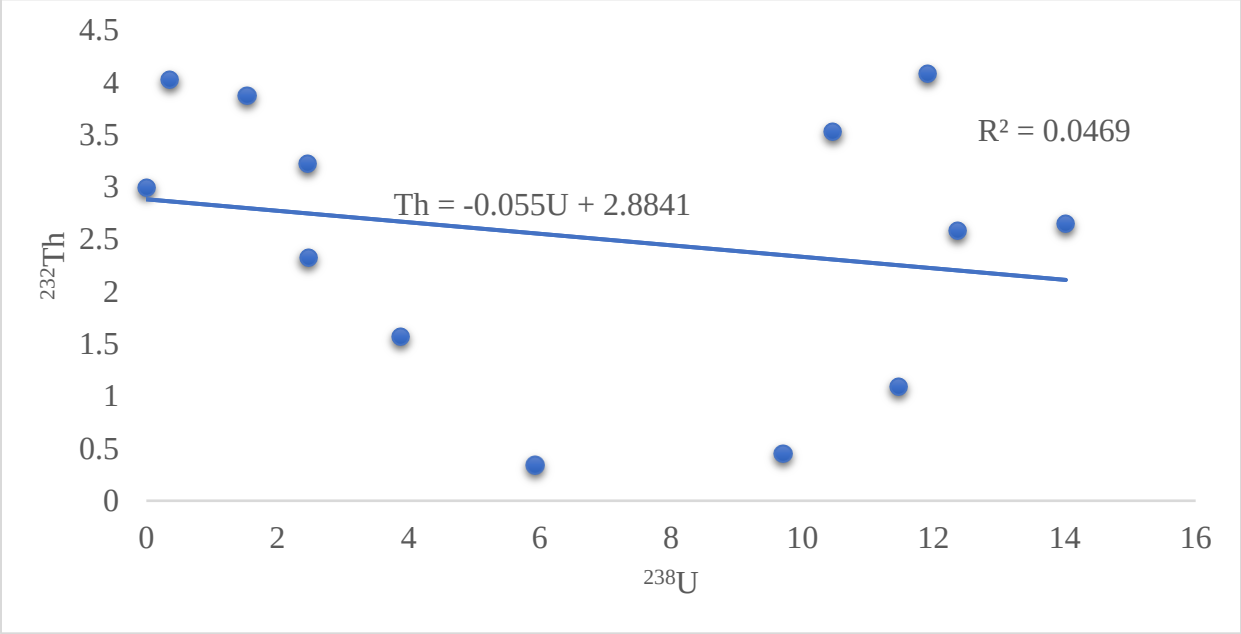


**Fig 22:** Correlation between the concentration activity of $^{232}Th$ and $^{238}U$ for the water samples in the area under study

**Table 14:** Comparison of the activity concentration and radium equivalent results with other similar studies published in the literature

| Country/region | Activity Concentration ($BqL^{-1}$) | | | $Ra_{eq}$ | References |
|---|---|---|---|---|---|
| | $^{40}K$ | $^{238}U$ | $^{232}Th$ | | |
| Nigeria | 69.04 ± 15.29 | 7.64 ± 2.90 | 10.04 ± 3.31 | - | Oluyide *et al.,* (2018) |
| Nigeria | 24.77 ± 8.3 | 7.92 ± 2.7 | 6.96 ± 2.4 | - | Ulakpa *et al,* (2016) |
| Nigeria | 52 + 2.1 | 9.6 + 0.7 | 5.4 + 0.4 | - | Oyebanjo *et al*, (2015) |
| Nigeria | 170.19±55.28 | 10.81± 3.67 | 13.49± 4.60 | 59.70 | Ononugbo *et al.,* (2017) |
| Iraq | 9.07±1.32 | 1.84±0.39 | 1.31±0.33 | 5.21±0.49 | Alaboodi *et al*, (2020) |
| Nigeria | 3.98±0.26 | 17.73±5.04 | 11.00±2.58 | - | Awodugba, (2008) |
| Nigeria | 0.8±0.3 | 0.4±0.4 | 0.8±0.2 | - | Ogungbemi *et al,* (2023) |
| **Nigeria** | **27.429±5.633** | **6.661±1.421** | **2.518±0.361** | **12.373±1.404** | **Present Study** |

| | | | | | |
|---|---|---|---|---|---|
| **Worlds Average** | **10.0** | **10.0** | **1.0** | **≤ 370. 0** | **UNSCEAR (2000)** |

## DISCUSSION

### Activity concentration of Soil samples

As shown in Table 1, the particular activity concentrations of $^{40}K$, $^{238}U$, and $^{232}Th$ for the soil specimens ranged from 27.02±1.51 to 394.69±20.96 $Bqkg^{-1}$ for $^{40}K$, with an average value of 184.00±29.73 $Bqkg^{-1}$ that is lower than the global average of 420 $Bqkg^{-1}$ UNSCEAR (2000). The higher values were obtained in Beta Glass Plc and Eruemukohwarien, while lower values were obtained in Ekakpamre and Ekrerhavwen. $^{238}U$ varies from BDL to 31.05±4.22 $Bqkg^{-1}$ with the average value of 14.55±2.50 $Bqkg^{-1}$, higher value was recorded in Beta Glass Plc and a lower value (BDL) in Ekrerhavwen, while $^{232}Th$ varies from BDL to 18.23±1.12 $Bqkg^{-1}$ with the average value of 8.60±1.04 $Bqkg^{-1}$ with the higher and lower values obtained in Beta Glass Plc and Eruemukohwarien, respectively. The outcomes are within the range of the 420, 33, and 45 $Bqkg^{-1}$ global average values for $^{40}K$, $^{238}U$, and $^{232}Th$, respectively. The results of activity concentration in soil from the research locations are less than those published by Eseka et al. (2018) and Avwiri et al. (2013), respectively.

In Tables 2 to 4, the related radiological indicators are shown. The results range from 12.048 to 62.315 $Bqkg^{-1}$, with an average value of 41.024±4.281 $Bqkg^{-1}$ for $Ra_{eq}$, which is below the global average of 89 $Bqkg^{-1}$ UNSCEAR (2000). The $Ra_{eq}$, $H_{ex}$, and $H_{in}$ indices of $^{40}K$, $^{238}U$, and $^{232}Th$ in the soil samples are provided in Table 2. While Ekakpamre and Ekrerhavwen had lower values, Beta Glass Plc. and Eruemukohwarien had greater values. The average value of the $H_{ex}$ is 0.111±0.012, with values ranging from 0.033 to 0.168. The $H_{in}$ has a range of values from 0.033 to 0.247, with an average value of 0.150 ±0.017. The $H_{ex}$ and $H_{in}$ values that were determined are below the global average for a unit. The results of Table 3's measurements of the D, AEDE, and ELCR of these radionuclides in the soil ranged from 5.337 to 30.57 $nGyh^{-1}$, with an average value of 19.59±2.075 $nGyh^{-1}$ that is lower than the global average of 60 $nGyh^{-1}$ UNSCEAR (2000). The average value of the AEDE ranges from 0.007 to 0.037 $mSvy^{-1}$, with a mean value of 0.024±0.003 $mSvy^{-1}$ and the average value of the ELCR ranges from 0.025 to 0.130 ($\times 10^{-3}$), with a mean value of 0.084±0.009 ($\times 10^{-3}$). The obtained values for the AEDE and ELCR are, respectively, below the 0.07 $mSvy^{-1}$ and 0.29 $\times 10^{-3}$ averages for the world.

The results of the typical Iγ and AGDE, which are shown in Table 4, range from 37.619 to 219.69 $\mu Svy^{-1}$, with a mean value of 138.707±14.733 $\mu Svy^{-1}$ that is lower than the global average of 300 $\mu Svy^{-1}$. The outcome for Iγ ranges from 0.088 to 0.480, with a mean value of 0.306±0.032 below the suggested tolerable limit of 0.50 according to UNSCEAR (2000). It's possible that industrial activity and the use of fertilizers for agricultural purposes are to blame for the difference in activity concentration in the soil at the research locations.

**Activity concentration of Water samples**

Tables 8–11 display the activity concentrations of $^{40}K$, $^{238}U$, and $^{232}Th$ along with the relevant radiological characteristics. These elements had activity concentrations of 27.429±5.633 $BqL^{-1}$, 6.661±1.421 $BqL^{-1}$, and 2.518±0.361 $BqL^{-1}$ in water. The World Health Organization's recommended worldwide limits of 10.0, 10.0, and 1.0 $BqL^{-1}$, were exceeded by the values for $^{40}K$, $^{238}U$, and $^{232}Th$ for the mean activity concentrations of the radionuclides in the water samples. This implies that there is a considerable cancer risk among the people who use the water at the research location.

The surface and ground water samples' ELCR for the research area spans from $0.431\times10^{-3}$ to $1.962\times10^{-3}$, with $(1.367\pm0.138)\times10^{-3}$ as the mean value. The UNSCEAR-recommended $0.29\times10^{-3}$ global average is a little bit higher than these values. The average AED of the water samples is slightly over the WHO (2011) recommended value of = 0.1 $mSvy^{-1}$ for drinking water and below the value of 1.0 $mSvy^{-1}$ for borehole water. The world-permissible threshold of unity is also not reached by Iγ, $H_{in}$, or $H_{ex}$. When compared to earlier research, the activity concentration of the radionuclides obtained in this investigation, as shown in Table 14, demonstrated that, although there were minor variations in the results for different concentrations of $^{40}K$, $^{238}U$, and $^{232}Th$, these values were slightly beyond the permitted limits. According to Ononugbo et al. (2017), all of the water samples had excess lifetime cancer risk levels that were higher than the amount that is generally regarded as safe.

The study demonstrates that there are no immediate adverse radiological health consequences for the workers and general population due to the radiation levels and doses seen in the study region. However, as indicated by the extra lifetime cancer risk values, there is a chance that cancer may occur as a result of accumulated doses.

## CONCLUSION

In the gamma spectrometry examination, radionuclides from the non-series $^{40}K$ and naturally occurring series-decay $^{238}U$ and $^{232}Th$ were found. The activity concentrations of $^{238}U$, $^{232}Th$, and $^{40}K$ in soil, treated water, waste water, surface water, and ground water around Beta Glass Plc (and the surrounding communities) were studied using a well calibrated Sodium Iodide Detector (3×3inch NaI (TI)), and the results show that the activity concentrations of radionuclides found in soil are all below the world average. When compared to the findings from the prescribed world safe limit, the radiological hazard indices are low. While the activity concentration of $^{40}K$ and $^{232}Th$ in the water surpassed the recommended value when compared to the world safe limit, the activity concentration of $^{238}U$ is just marginally above the global safe limit. However, the excess lifetime cancer risk and annual effective dose equivalent calculated from the activity concentration of these radionuclides exceeded the permitted values of 0.07 ($mSvy^{-1}$) and $0.29\times10^{-3}$ in water samples, respectively. The calculated radiological hazard indices for the water samples still fall below the world safe limit.

This could be attributed to farming and industrial activities in the research area. It is thus advised that more study be conducted on the naturally occurring radionuclides within the factory and environment in order to ascertain the rate of exposure.

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