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Radiological Impact Assessment of Radon Levels in Drinking Water and its Associated Health Risks in Aniocha North, Delta State, Nigeria

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ABSTRACT

Groundwater is a major source of natural water for domestic, industrial and agricultural use; however, its contamination by ^{222}Rn has become a major source of human health concern globally. To assess the associated health risks of radon exposure to various age groups within Aniocha North Local Government Area (LGA) of Delta State, Nigeria, twenty water samples from 12 surface reservoirs and eight boreholes were collected from five communities within the local government and analyzed using RAD7. The measured concentrations of ^{222}Rn in the sampled water, ranges from 0.278 Bq/L in OBIOR 5 to 9.281 Bq/L in ISSELE-AZAGBA 3 with mean concentration of 3.808Bq/L , found to be lower than the recommended threshold by the United States Environmental Protection Agency. The estimated radiological indices revealed that the average annual effective doses due to ingestion of radon are 8.82714×10^{-6}, 3.9998×10^{-6}, and 2.79296×10^{-6}($\mu Sv/y$) for adults, children and infants respectively. Inhalation dose ranged from 0.0004158 to 0.02338812 ($\mu Sv/y$)with a mean of 0.008689212 ($\mu Sv/y$)all of which are below 0.1 ($\mu Sv/y$), radiogenic cancer risk (RCR) are 0.001937832, 0.000875817, 0.000610314, for adults, children and infants while for excess lifetime cancer risk (ELCR) are 3.39845×10^{-5}, 1.53992×10^{-5}, 1.07529×10^{-5} for adults, children and infants. Results reveal that there is no significant public health risk from ^{222}Rn ingested and inhaled from sampled water within study area.

Keywords:
Radon,
Borehole,
Surface reservoir,
Delta State,
Effective dose,
ELCR,
Nigeria.

INTRODUCTION

Humans continuously receive radiation from naturally occurring radioactivity in soil, air and water. The largest fraction of the natural radiation received, comes from a radioactive gas, radon, World Health Organization (WHO) (WHO, 2004). Radon, a naturally occurring and radioactive gas having no colour, odour or taste Mokobia et al., (2020); Nwabuoku et al., (2026) exists in three main isotopes; ^{219}Rn, ^{220}Rn and ^{222}Rn of which only ^{222}Rn with half-life of 3.82 days Mugahed et al., (2025) is of most interest, as the others are very short-lived Khattak et al., (2011); Isinkaye et al., (2023) resulting from the natural decay of Uranium-238 (^{238}U), Thorium-232 (^{232}Th), and Uranium-235 (^{235}U), respectively (Ijaboe et al., 2024; Muhammad et al., 2024; Mugahed et al., 2025).

^{222}Rn has been classified as carcinogenic and also described by the WHO as the second leading cause of lung cancer after tobacco smoking (WHO, 2009). In Europe, approximately 9-15% of the annual lung cancer related cases is attributed to ^{222}Rn exposures (Darby et al., 2005; Krewski et al., 2006). In most countries, ^{222}Rn have been projected to cause about 3–14% of lung cancers (WHO, 2021) Continuous exposure to indoor radon at levels above 100 Bq/m^3 is considered a serious environmental issue, while exposure to radon drinking water above 100 Bq/L is considered a radiological risk (WHO, 2008). In long exposures, WHO recommended an accumulated effective dose rate of not more than 100 µSv/y through ingestion.

The presence of radon in ground water is as a result of Uranium and Radium bearing mineral in rock and soil (Idris et al., 2011; Sethy et al., 2015; Srilatha et al., 2014). Among the radionuclides detected in water, ^{222}Rn is by far the most frequent in water sources, especially groundwater, due to its easy passage through porous and fractured rocks by gaseous diffusion allowing this gas to easily dissolve in groundwater (Shilpa et al., 2017). Owing to its radiotoxic effect and as a leading cause of lung cancer, it is of special interest all over the world (UNSCEAR, 2000). Groundwater as a major source of natural water resources plays a vital role for drinking purposes, industrial usage and agricultural practices (Bewick et al., 2003). However, groundwater contamination by ^{222}Rn has become one of the most critical environmental issues in developed as well as in developing nations. Apart from natural processes, human activities such as using fertilizer in agriculture, ore processing and mining, industrial activities, tends to release radionuclides into the environment. There have been a growing concerns among the general public, researchers and governments over risks of exposure to radiation and what potential harm this exposure may pose to human health which has lead to the study of natural radioactivity in recent years Mehnati et al., (2022) and Hassan et al., (2024) as high levels of naturally occurring radioactive materials (NORMs) in the environment can significantly threaten human health (Duggal et al., 2017a; Ijabor et al., 2022). ^{222}Rn and its progenies cause severe damage to lungs and other respiratory organs when inhaled. Intake of radon laden water is a major pathway of exposure to radon. High level of radon in water presents a serious health treat due to exposure through inhalation on basis of exhalation of radon from water into indoor air and through ingestion on the basis of drinking (Duggal et al., 2017a). The United Nations Scientific Committee on the Effects of Atomic Radiations UNSCEAR, (2000) estimated that, over 80%, of the dose from radon in water comes from inhalation rather than ingestion. Health effects of radon in drinking water include direct radiation exposure to intestinal tissues and its impact on the lungs when inhaled resulting in molecular changes (arising from alpha particles released during radon decay) that are associated with carcinogenesis (Das, 2021; Ullah et al., 2022). Although exposure route through inhalation contribute to significant radiation dose, the ingestion route is still prominent. ^{222}Rn is highly soluble in water making daily drinking of water a significant pathway of radon and its progenies to stomach and intestine resulting in gastrointestinal cancer (Ullah et al., 2020; Khutia et al., 2023). There are reports of radon monitoring in water and air with indication of positive correlation between radon ingestion and certain types of malignant diseases (Mamun & Alazmi, 2022). Local communities like those sampled within the LGA that depend on groundwater (borehole) and surface reservoir as their main source of drinking water may be exposed to higher risk of stomach cancer and lung cancer through inhalation of exhaled radon in water (Hassan et al., 2024; El-Taher, & Al-Turki, 2016; Pourimani & Nemati, 2016; Saidu and Bala, 2018; Abojassim, 2019; Hassan & Almatani, 2022).

A number of studies have been conducted in Asia and elsewhere around the world. For instance, Muhammad et al. (2024) analyzed ^{222}Rn in groundwater of three northern districts and reported 30 % of samples in Lower Dir exceeding 11.1 Bq/L, highlighting geological controls on radon release as the cause (Muhammad et al., 2024). Similar study by Haroon and Muhammad (2022) also reported average radon levels in groundwater of Mirpur exceeding USEPA limit. Ullah et al., (2022) also reported radon levels above USEPA limit for hot-spring water in Gilgit-Chitral. These studies from Asia have shown that radon levels and effective doses vary with respect to depth, geology, and seismic activity of the sampled water source.

As a basic requirement for all life form, drinking water must therefore meet certain desirable quality in regards to radon in order to minimize human exposure and reduce risk. In this regard, the United States Environmental Protection Agency (USEPA) (USEPA, 1999) recommended a permissible radon of 100 Bq/L and 11.1 Bq/L respectively for ^{222}Rn in drinking water. Efforts have been put in by scientists and researchers from different parts of Nigeria to measure radon levels in drinking water sources in order to minimize impact on human health, identify regions of hot spots and establish baseline data for future assessment of contamination (Duggal et al., 2020; Isinkaye & Ajiboye, 2017; Ajiboye et al., 2018; Fatoki et al., 2021; Orosun et al., 2021; Michael et al., 2022). Certain industrial activity like crude oil exploration is responsible for the radiotoxic waste scattered on the surrounding soil and the environment which can also find its way into underground water source (Olagbaju et al., 2025).

In line with ongoing research on radon in water in Nigeria and elsewhere around the world, it is necessary to examine ^{222}Rn levels and health risks assessment in all drinking water sources from granitic geological areas like the study area. In Aniocha North LGA and elsewhere in the South Eastern and South Southern, Nigeria, no similar study has been reported. Among the different sources of drinking water available in the study area, borehole and surface reservoir water is common. The present study therefore aims to measure ^{222}Rn levels in borehole and reservoir water in the study area and to evaluate the health risks posed to different age groups in the area.

MATERIALS AND METHODS

Sample Collection

Water samples were collected from boreholes and surface reservoirs into sealed containers from within four communities from Aniocha North of Delta State, Nigeria. Standard methods were used to collect and process the water samples for ^{222}Rn activity concentration measurement. At the collection points for borehole water, the taps was left running for 3 min in order to eliminate the excess radon (^{222}Rn), which might have accumulated on the cavity on top of the water level in the borehole (Isinkaye & Ajiboye, 2017). This was done to get representative samples for analysis. For surface reservoirs, water was collected directly into the containers using a prewashed bailer. The samples were initially collected into 1.5 L plastic bottles and sealed immediately at the collection points before being transported to the laboratory. Analysis was done within 3–4 days after the samples were collected. Further details on sampling methods have been published elsewhere (Al–Alawy and Hassan, 2018; Ajiboye et al., 2022; Kolo et al., 2023). Figure 1 shows the sampling points of the sampling location.

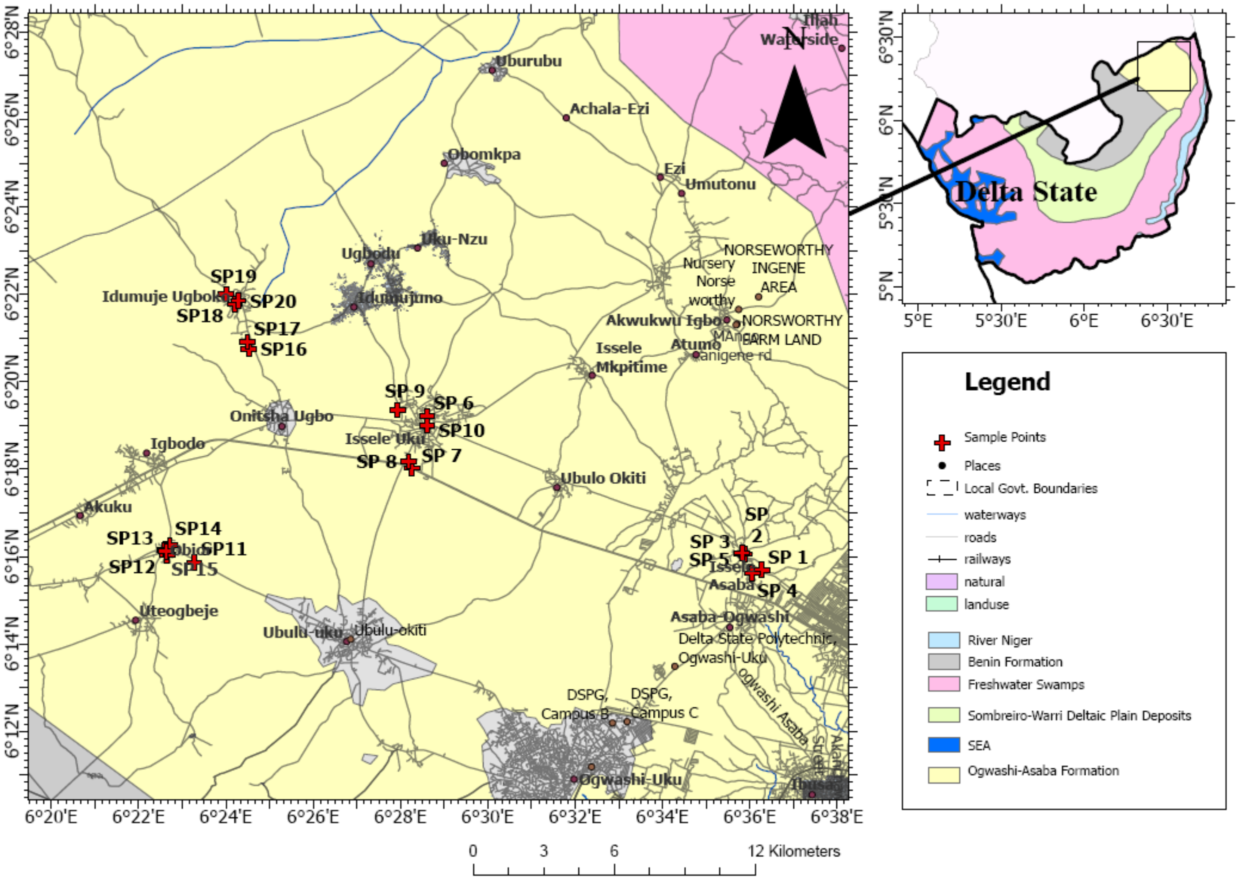

Figure 1: Map showing sampling points in Aniocha North LGA

Sample measurements for ^{222}Rn activity concentration

Measurement of ^{222}Rn concentrations in the water samples will be carried out using a factory calibrated DURRIDGE RAD7 detector with Big Bottle System that uses a closed loop aeration process. RAD7 is a solid-state alpha detector used for both short-term and long-term measurement of radon concentration that accumulate on the detector surface using sniffing technique. The set up of the detector employed is shown in Figure 2.2. The measurement procedures will be conducted following the procedures stated in the user's manual (Durridge, 2015), as well as in previous studies (Inacio et al., 2017; Ismail et al., 2021). The Big Bottle System was implemented owing its capability to analyze large water samples up to 2.5 L. In this study, a 1.5 L bottle will be adopted in a closed loop aeration process, which allows constant water and air volumes to be maintained with independent flow rate. The aeration process allows air to recirculates through the water thereby extracting radon from the water into the air loop until a state of equilibrium is reached. It takes about 10 minutes to attain the equilibrium state, after which further extraction of radon from the water becomes impossible and the pump stops automatically. The process is repeated thrice; thus, it takes 30 minutes to complete a sample measurement. Prior to each measurement, the RAD7 detector was purged to get rid of entrapped radon and dry air in the chamber. Each 1.5 L bottle containing the collected water sample will be fixed to the detector and made to operate in a sniff mode to measure the radon concentration extracted into the air loop. The Big Bottle System conversion factor (by substituting 1.5 L for 2.5 L) and water temperature during aeration will be employed to automatically compute the concentration of ^{222}Rn in each water sample (Durridge, 2018). To prevent silt and sediment from getting into the RAD7 air pump and distorting the detector sensitivity, a pre treatment involving the use of an in-line filter to capture silts and particulates before the air flow into the instrument.

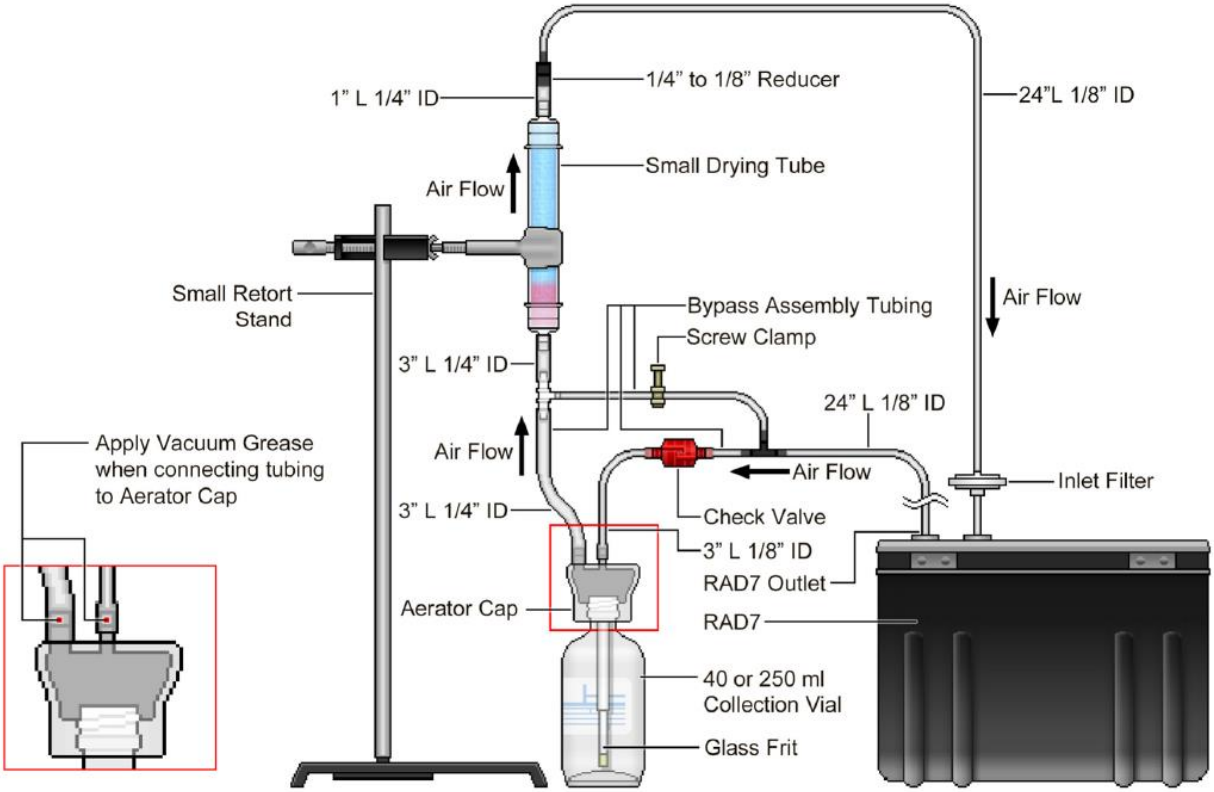

Figure 2: RAD7 electronic Rn detector (Durridge, 2022).

Annual effective dose to assess the effective dose due to ingestion of any radionuclides in water, dose coefficient expressed as Sv/Bq is utilized taking into account the ingestion rate and the concentration of such radionuclide. The American National Research Council's (NRC) Commission on Life Sciences recommended using the dose coefficient of 3.5×10^{-9} Sv/Bq for this purpose (NRC, 1999; Tan et al., 2019; Mamun and Alazmi, 2022). Recently, more realistic values of 1 ×10^{-8} Sv/Bq, 2 ×10^{-8} Bq/Sv and 7 ×10^{-8} Bq/Sv, have been recommended to be used as the ingestion dose coefficient for adults, children and infants, respectively (UNSCEAR, 2000; Jibril et al, 2021; Kumar et al., 2022; Mugahed et al., 2025). The ingestion dose (E_{ing}) is given as:

$$E_{ing}(\mu Sv/y) = C_{Rn} \times DCC_{ing} \times V_A \qquad (1)$$

where, C_{Rn} is the radon concentration is drinking water, DCC_{ing} is the dose conversion coefficient given as 3.5×10^{-9} Sv/Bq and VA is the estimated volume of drinking water consumed directly from tap annually. The annual water consumption volume is taken as 730 L/y for adult, children for 330 L/y and 230 L/y for infant based on the assumption that adults and will take 2 L of water per day, children will take 1 L of water per day and infants will take 0.6 L of water per day (NRC, 1999; Isinkaye & Ajiboye, 2017).

Also, the dose from inhalation (E_{inh}) of dissolved radon released into air during water usage is given as in equation 2 (USEPA, 1991; Tan et al., 2019):

$$E_{inh}(\mu Sv/y) = C_{Rn} \times DCC_{inh} \times EF \times T \times f \qquad (2)$$

where, C_{Rn} is the radon concentration in Bq/L, EF is the average annual indoor occupancy factor estimated as 7000 h/y, T is the radon transfer factor from water to air given as 0.1 L/m^3, f *is* the radon and its daughters equilibrium factor recommended to be 0.4 and DCC_{inh} is the dose conversion coefficient given as 9×10^{-6} (mSv/Bq/h/m3) as recommended by NRC and UNSCEAR (NRC, 1999; USEPA, 2000).

Radiogenic-cancer risk Assessment

Radiogenic-Cancer Risk (*RCR*) accompanying the intake of certain concentrations of ^{222}Rn in the chosen water source was used to assess the radiation risk in this study. LS is average lifetime expectancy and RC represents the radon cancer risk coefficients $(1.1 \times 10^{-8} Bq^{-1})$ (USEPA, 1991) and CR stands for annual consumption rate (730 L/y for adult, 330 L/y for children, and 230 L/y for infants), as given in Equation

$$RCR = CRn \times CR \times LS \times RC \quad (3)$$

For evaluating the annual effective dose for lungs (Dlungs) and stomach (Dstomach), the following formula is used:

$$D_{stomach,lungs}(\mu Sv^{-1}) = W_T \times D_{ing.,inh} \quad (4)$$

where WT (0.12) is the tissue weighting factor for lungs and stomach.

Excess life cancer risk (ELCR)

$$ELCR = AED \times DL \times RF \quad (5)$$

Where *AED* is the annual effective dose, *DL* is the lifetime exposure duration (70 years), *RF* is the risk factor (EPA's cancer risk factor is 0.055 in Sv).

RESULTS AND DISCUSSION

The concentration of radon measured in the two sampled water source in this LGA ranges from 0.165 to 9.281 Bq/L with a mean value of 3.807 Bq/L. The highest radon concentrations for all water sample is 9.281 Bq/L recorded for Issele-Azagba 3 and lowest value of 0.165 Bq/L recorded for Obior 4. This is as depicted in Figure 3. However for Surface Reservoir samples, Issele-Azagba 2 has the highest value of 2.710 Bq/L. The high radon value recorded in borehole water sample can be attributed to the geology of the LGA but these values are lower than USEPA value of 11 Bq/L.

Table 1: Details of Sampling Points in Aniocha North LGA

S/N	Community	Rn Conc. (Bq/L)	Coordinates		Water Source	Age of Water Source (yrs)
			Latitude	Longitude		
1	Issele Azagba 1	1.167	6.2616	6.6045	Surface Reservoir	9
2	Issele Azagba 2	2.710	6.2676	6.598	Surface Reservoir	17
3	Issele Azagba 3	9.281	6.268	6.597	Borehole	5
4	Issele Azagba 4	1.064	6.2604	6.6009	Surface Reservoir	10
5	Issele Azagba 5	4.362	6.2681	6.597	Borehole	4
6	Issele Uku 1	8.633	6.3202	6.4768	Borehole	2
7	Issele Uku 2	1.512	6.3005	6.471	Surface Reservoir	23
8	Issele Uku 3	1.301	6.303	6.4697	Surface Reservoir	18
9	Issele Uku 4	5.877	6.3226	6.4655	Borehole	30
10	Issele Uku 5	9.064	6.3166	6.4768	Borehole	28
11	Obior 1	5.126	6.2645	6.3879	Borehole	12
12	Obior 2	2.332	6.2673	6.3775	Surface Reservoir	25
13	Obior 3	1.614	6.2694	6.3767	Surface Reservoir	28
14	Obior 4	0.165	6.2709	6.3786	Surface Reservoir	31
15	Obior 5	0.278	6.2687	6.3772	Surface Reservoir	8
16	Idumuje Ugboko 1	6.346	6.3459	6.4088	Borehole	10
17	Idumuje Ugboko 2	5.429	6.3486	6.4082	Borehole	4
18	Idumuje Ugboko 3	0.787	6.3629	6.4034	Surface Reservoir	32
19	Idumuje Ugboko 4	0.871	6.3668	6.4001	Surface Reservoir	16
20	Idumuje Ugboko 5	1.043	6.3643	6.4048	Surface Reservoir	29

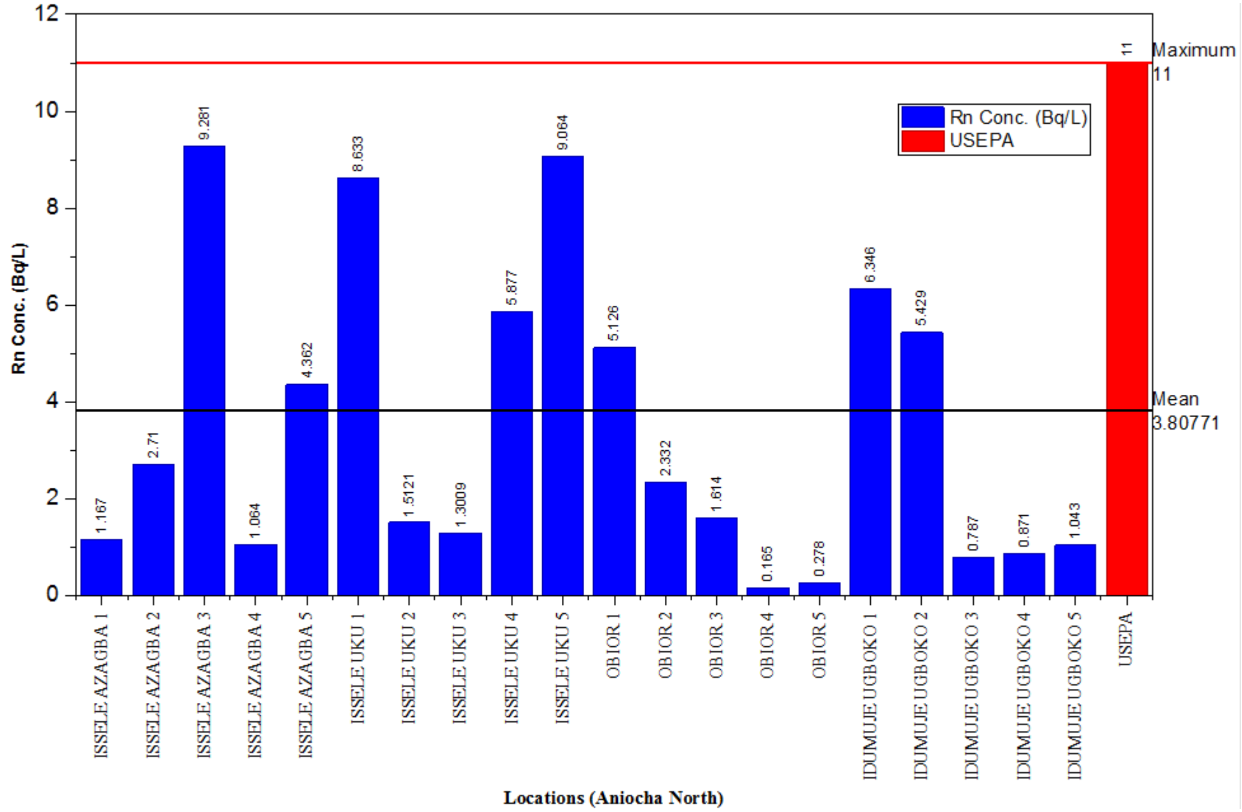

Figure 3: Radon Concentration as measured in two water source in Aniocha North LGA

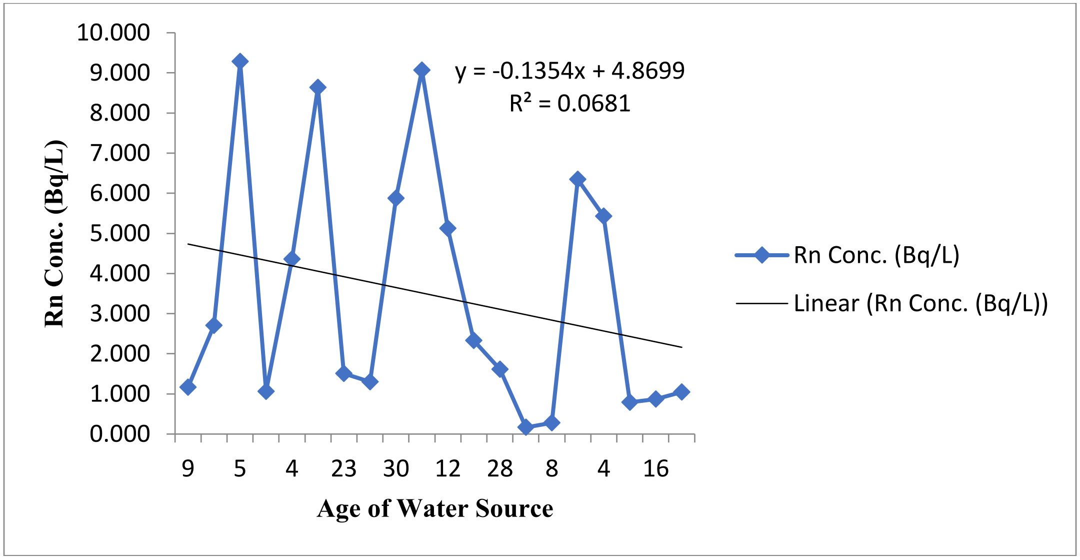

Figure 4: Graph showing the relationship between Rn Conc. (Bq/L) and age of water source in Aniocha North

To predict the relationship between radon concentration in the sampled water and the age of the water source, A scatter plot in Figure 4 was done where a negative slope (-0.135) was observed. This indicates a very slight possibility for radon concentration to decrease as the age of the water sources increases. The extremely low R^2 value of 0.068 explains that only 6.8% of the total variation observed in radon concentration data. Conversely, 93.2% of factors responsible for high radon level in water is not the age of the water sources.

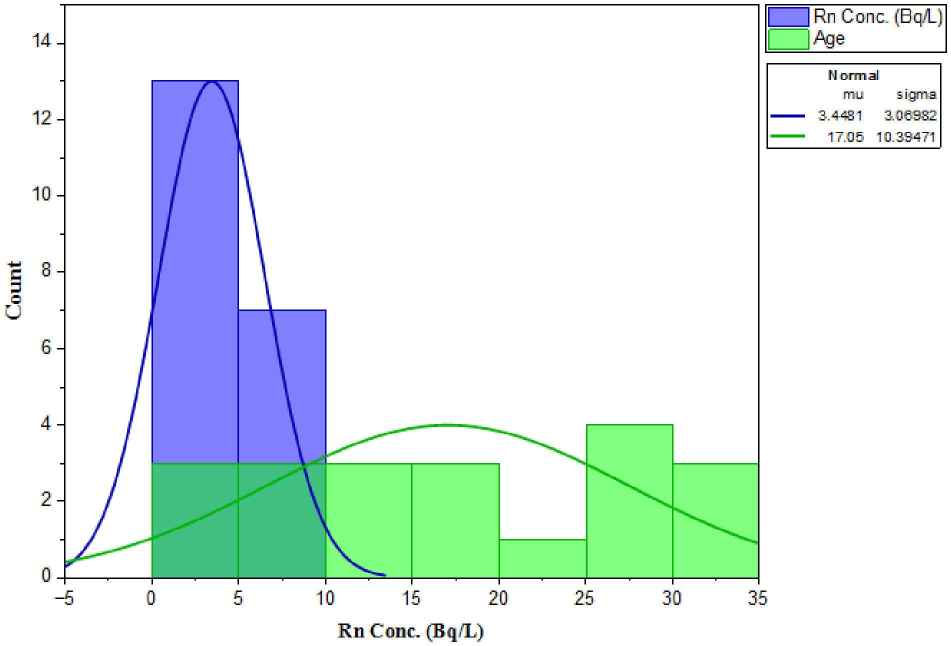

Figure 5: Distribution Curve for Rn Conc. and age of water source in Aniocha North LGA

The graph presented in Figure 5 depicts the frequency distribution for Rn Conc. in the sampled water sources from the study area overlaid with a normal distribution curve for both borehole and surface reservoir water sources. The bimodal histogram is an indication that radon concentration is clustered around 0-10 Bq/L.

Table 2 shows the comparison of the results of this study with those obtained in other studies from Nigeria and elsewhere around the world. The average radon concentration for surface reservoir and borehole obtained within the study area are 1.192 Bq/L and 6.769 Bq/L respectively. The average value obtained for borehole in this study is lower than those reported by Cadungog et al., (2025) in Taal, Phillipines; Akindipe et al., (2025) in Ede, Osun, Nigeria; Omirou et al., (2024) in Arnea, Greece; Isinkaye & Ajiboye, (2017) in Ekiti State, Nigeria; Jibril et al., (2021) in Sabon Gari, Kaduna, Nigeria; and Shuaibu et al., (2021) in Gadau, Bauchi, Nigeria, and Ismail et al., (2021) all for groundwater. These differences may be due to variations in local geology of the respective sampling areas and depth of borehole which was not considered in this study while the low mean value obtained for surface reservoir can be as a result duration of reservoir cover opening time.

Table 2: Comparison of radon concentrations obtained in this study with other locations

Location	**Radon Conc. (Bq/L)**	**Water Source**	**References**
Jazan, Saudi Arabia	3.30	Groundwater	El-Araby, 2025
Aqsu, Zavodskoy, and Saumalkol. Kazakhstan	5 ± 1 to 1185 ± 355	Groundwater	Ibrayeva and Bakhtin, 2025
Gujarat, India	2.19	Groundwater	Sahoo et al., 2025
Taal, Phillipines	16.84	Groundwater	Cadungog et al., 2025
Ede, Osun, Nigeria	15.35 ± 9.73	Borehole	Akindipe et al., 2025
Arnea, Greece	9.1	Borehole	Omirou et al., 2024
Ekiti State, Nigeria	30.9	Borehole	Isinkaye and Ajiboye, 2017
Sabon Gari, Kaduna, Nigeria	14.9	Borehole	Jibril et al., 2021
Gadau, Bauchi, Nigeria	38	Groundwater	Shuaibu et al., 2021
Malaysian Peninsular, Malaysia	32.36 ±1.8	Groundwater	Ismail et al., 2021
Aniocha North, Delta State, Nigeria	1.192, 6.769	Surface Reservoir, Borehole	This Study

Table 3: Annual Effective Dose $(\mu Sv/y)$Due to Ingestion of Radon for Three Age Groups in Aniocha North

S/N	E_{ing} for Adults	E_{ing} for Children	E_{ing} for Infants
	2.98752×10^{-6}	1.35372×10^{-6}	9.4527×10^{-7}
	6.9376×10^{-6}	3.1436×10^{-6}	2.1951×10^{-6}
	2.37594×10^{-5}	1.0766×10^{-5}	7.51761×10^{-6}
	2.72384×10^{-6}	1.23424×10^{-6}	8.6184×10^{-7}
	1.11667×10^{-5}	5.05992×10^{-6}	3.53322×10^{-6}
	2.21005×10^{-5}	1.00143×10^{-5}	6.99273×10^{-6}
	3.87098×10^{-6}	1.75404×10^{-6}	1.2248×10^{-6}
	3.3303×10^{-6}	1.50904×10^{-6}	1.05373×10^{-6}
	1.50451×10^{-5}	6.81732×10^{-6}	4.76037×10^{-6}
	2.32038×10^{-5}	1.05142×10^{-5}	7.34184×10^{-6}
	1.31226×10^{-5}	5.94616×10^{-6}	4.15206×10^{-6}
	5.96992×10^{-6}	2.70512×10^{-6}	1.88892×10^{-6}
	4.13184×10^{-6}	1.87224×10^{-6}	1.30734×10^{-6}
	4.224×10^{-7}	1.914×10^{-7}	1.3365×10^{-7}
	7.1168×10^{-7}	3.2248×10^{-7}	2.2518×10^{-7}
	1.62458×10^{-5}	7.36136×10^{-6}	5.14026×10^{-6}
	1.38982×10^{-5}	6.29764×10^{-6}	4.39749×10^{-6}
	2.01472×10^{-6}	9.1292×10^{-7}	6.3747×10^{-7}
	2.22976×10^{-6}	1.01036×10^{-6}	7.0551×10^{-7}
	2.67008×10^{-6}	1.20988×10^{-6}	8.4483×10^{-7}
Average	8.82714×10^{-6}	3.9998×10^{-6}	2.79296E-06

The Principal Component Analysis (PCA) plot is a multivariate statistics technique used to reduce the dimension of large datasets while most of the variation. In this work we performed the PCA to ascertain any link between the variables analyzed.

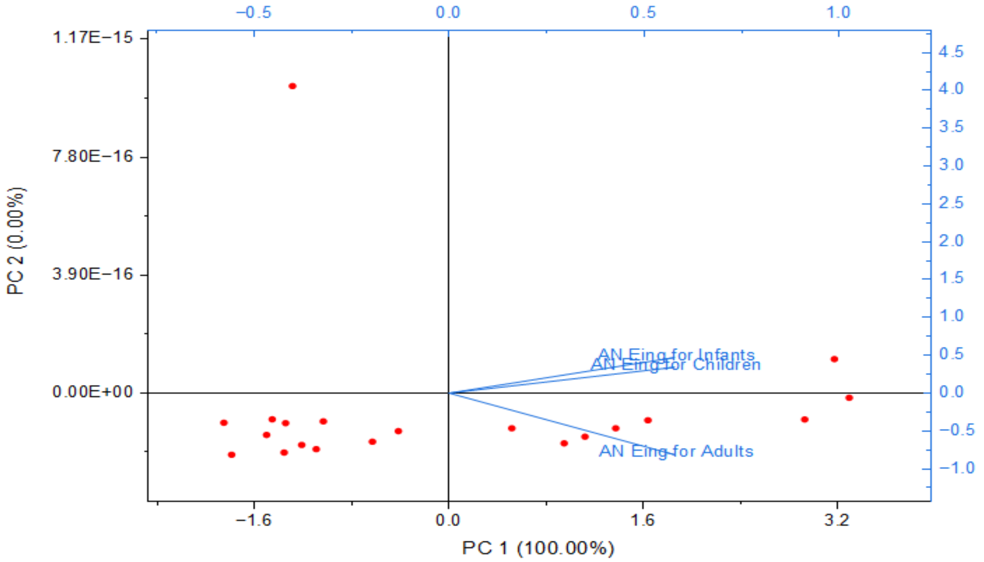

Figure 6: Principal Component Analysis (PCA) showing relationship and distribution of three age groups in Aniocha North

The graph in Figure 6 also captures two principal components, (PC 1) for the majority of the variance in the data and (PC 2) for the second most significant variation (PC 2). The plot reveals that annual effective dose to three different age groups for Aniocha North (AN) LGA as a result of ingestion of radon in the sampled water sources is separated along PC 1 and PC 2 indicating difference in radon contribution to these age groups. As revealed in the figure, $E_{ing}$for infants and children is skewed toward the positive values of PC 1 and PC 2 while $E_{ing}$for adults is positioned toward the negative PC 1 values. Variability between age groups can also be seen in the data spread across PC 1 and PC 2.

The estimated annual effective dose to the general public due to inhalation of radon from the two sampled water sources within the selected communities of Aniocha North LGA are presented in Table 4. The calculated inhalation dose ranged from 0.0004158 to 0.02338812 $(\mu Sv/y)$with a mean of 0.008689212$(\mu Sv/y)$for AN. The result for the ANOVA test is shown in Table 5. For variations to occur in the ANOVA result, F-value must be greater than 1 and p-value < α-value (Adagunodo et al., 2023). As shown in Table 5, both F-value and p-value is greater than α-value 1 and 0.05.

Table 4: Annual Effective Dose and Effective Dose to Lung $(\mu Sv/y)$Due to Inhalation of Radon for AN LGA

S/N	E_{inh} AN	D_{lung}AN
	0.00294084	0.000352901
	0.0068292	0.000819504
	0.02338812	0.002806574
	0.00268128	0.000321754
	0.01099224	0.001319069
	0.02175516	0.002610619
	0.003810492	0.000457259
	0.003278268	0.000393392
	0.01481004	0.001777205
	0.02284128	0.002740954
	0.01291752	0.001550102
	0.00587664	0.000705197
	0.00406728	0.000488074
	0.0004158	0.000049896
	0.00070056	8.40672E-05
	0.01599192	0.00191903
	0.01368108	0.00164173
	0.00198324	0.000237989
	0.00219492	0.00026339
	0.00262836	0.000315403

AN: Aniocha North,

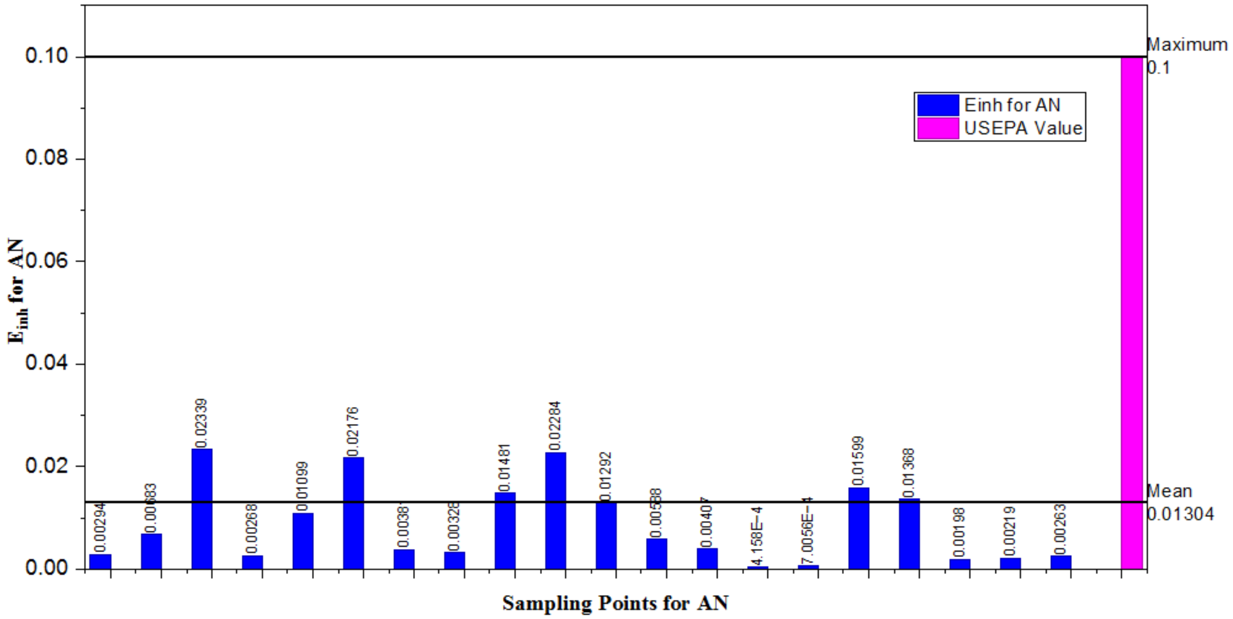

Figure 7: Annual effective dose $(\mu Sv/y)$due to inhalation of Radon through water for AN

Table 5: Result for ANOVA Test

	Cluster DF	Cluster SS	Error DF	Error SS	F Value	Prob>F
D_{lung} for AN	1	2.72098×10^{-6}	16	7.74386×10^{-7}	3.51373	0.07924

Table 6 is the calculated annual effective dose to stomach due to ingestion of radon from the water samples of borehole and surface reservoirs within the local government.

Table 6: Annual Effective Dose to Stomach($\mu Sv/y$)Due to Ingestion of Radon through Water for AN

S/N	D_{st} for Adult	D_{st} for Children	D_{st} for Infants
	3.58502×10^{-7}	1.62446×10^{-7}	1.13432×10^{-7}
	8.32512×10^{-7}	3.77232×10^{-7}	2.63412×10^{-7}
	2.85112×10^{-6}	1.29192×10^{-6}	9.02113×10^{-7}
	3.26861×10^{-7}	1.48109×10^{-7}	1.03421×10^{-7}
	1.34001×10^{-6}	6.0719×10^{-7}	4.23986×10^{-7}
	2.65206×10^{-6}	1.20171×10^{-6}	8.39128×10^{-7}
	4.64517×10^{-7}	2.10484×10^{-7}	1.46976×10^{-7}
	3.99636×10^{-7}	1.81085×10^{-7}	1.26447×10^{-7}
	1.80541×10^{-6}	8.18078×10^{-7}	5.71244×10^{-7}
	2.78446×10^{-6}	1.26171×10^{-6}	8.81021×10^{-7}
	1.57471×10^{-6}	7.13539×10^{-7}	4.98247×10^{-7}
	7.1639×10^{-7}	3.24614×10^{-7}	2.2667×10^{-7}
	4.95821×10^{-7}	2.24669×10^{-7}	1.56881×10^{-7}
	5.0688×10^{-8}	2.2968×10^{-8}	1.6038×10^{-8}
	8.54016×10^{-8}	3.86976×10^{-8}	2.70216×10^{-8}
	1.94949×10^{-6}	8.83363×10^{-7}	6.16831×10^{-7}
	1.66779×10^{-6}	7.55717×10^{-7}	5.27699×10^{-7}
	2.41766×10^{-7}	1.0955×10^{-7}	7.64964×10^{-8}
	2.67571×10^{-7}	1.21243×10^{-7}	8.46612×10^{-8}
	3.2041×10^{-7}	1.45186×10^{-7}	1.0138×10^{-7}
Average	1.05926×10^{-6}	4.79976×10^{-7}	3.35155×10^{-7}

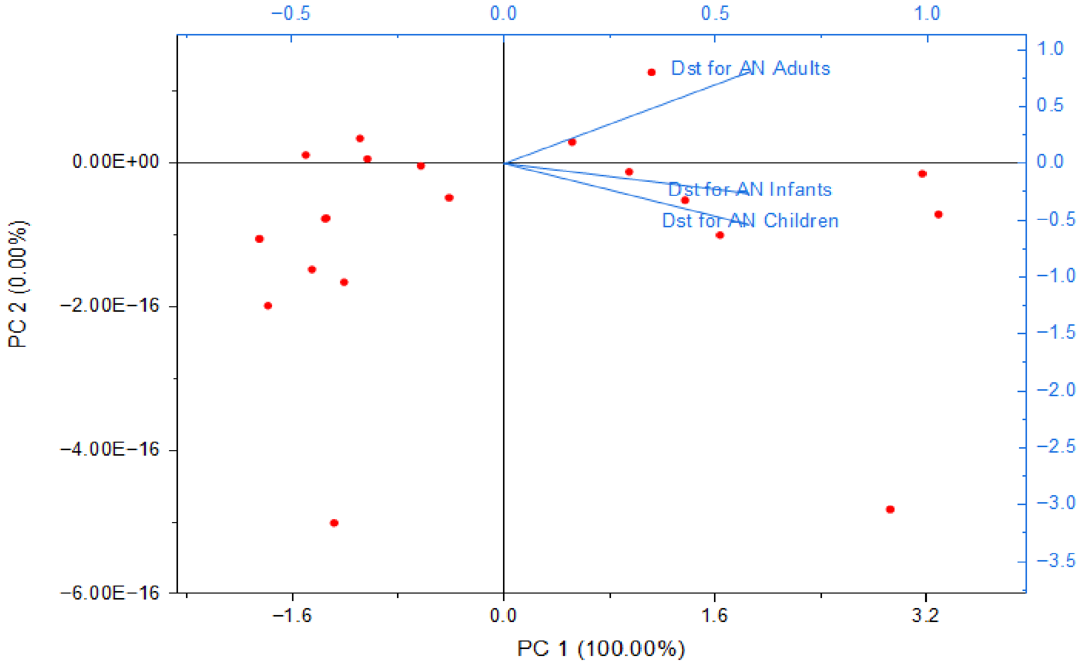

Figure 8: Principal Component Analysis (PCA) for effective dose to stomach due to ingestion of radon in AN

In AN, two principal components was captured for effective dose to stomach of three distinct age groups. As seen in the figure, one PC is the majority of the variance in the data, indicated as PC 2, while the other PC is the second most significant variation indicated as PC 1. There is separation of these age groups along the positive and negative PC 1 and PC 2 indicating that dose to stomach contributing to these age groups differs. The figure also reveals that D_{st} for adults in this LGA are more exposed to radon dose (positioned towards the positive side of PC 1 values) as compared to D_{st} to infants and children is skewed towards the negative PC 1 The data spread across PC 1 and PC 2 also indicates the variability between the age groups. The plot also reveals that children in this LGA are least exposed followed by infants.

Table 7 shows result for radiogenic cancer risk (RCR) from ingestion of radon through Water for AN LGA. Figures 9 and 10 are results for a K-Means Cluster Analysis and PCA for radiogenic cancer risk (RCR) for three age groups in AN LGA. The initial cluster shows two clusters as starting point for the RCR values across the age groups. For initial cluster, cluster 1 has a lower initial RCR value of 9.273×10^{-5}, 4.191×10^{-5} and 2.9205×10^{-5} for adults, children and infants while cluster 2 has a higher initial RCR value of 0.00522, 0.00236 and 0.00164 for adults, children and infants respectively. The final cluster shows that cluster 2 maintaining a high RCR value for adults, children and infants while cluster 2 keeps a low RCR value for adults, children and infants. There is a distance of 0.00335 between clusters which implies a separation exists amongst the clusters. There are 12 observations in cluster 1 and 8 observations in cluster 2. ANOVA test revealed a statistical significance in the clusters with difference in the RCR values across clusters. The three test supports the statistical findings of clear separation between cluster 1 (low risk) and cluster 2 (high risk).

Table 7: Radiogenic Cancer Risk (RCR) Due to Ingestion of Radon through Water for AN

S/N	RCR for AN Adults	RCR for AN Children	RCR for AN Infants
	0.000655854	0.000296418	0.000206559
	0.00152302	0.00068834	0.00047967
	0.005215922	0.002357374	0.001642737
	0.000597968	0.000270256	0.000188328
	0.002451444	0.001107948	0.000772074
	0.004851746	0.002192782	0.001528041
	0.0008498	0.000384073	0.000267642
	0.000731106	0.000330429	0.000230259
	0.003302874	0.001492758	0.001040229
	0.005093968	0.002302256	0.001604328
	0.002880812	0.001302004	0.000907302
	0.001310584	0.000592328	0.000412764
	0.000907068	0.000409956	0.000285678
	0.00009273	0.00004191	0.000029205
	0.000156236	0.000070612	0.000049206
	0.003566452	0.001611884	0.001123242
	0.003051098	0.001378966	0.000960933
	0.000442294	0.000199898	0.000139299
	0.000489502	0.000221234	0.000154167
	0.000586166	0.000264922	0.000184611
Average	0.001937832	0.000875817	0.000610314

Table 8: K-Means Cluster Analysis for Radiogenic Cancer Risk for AN LGA

	RCR for AN Adults	RCR for AN Children	RCR for AN Infants
Cluster1	9.273×10^{-5}	4.191×10^{-5}	2.9205×10^{-5}
Cluster2	0.00522	0.00236	0.00164

Final Cluster Center

	RCR for AN Adults	RCR for AN Children	RCR for AN Infants
Cluster1	6.95194×10^{-4}	3.14198×10^{-4}	2.18949×10^{-4}
Cluster2	0.0038	0.00172	0.0012

Cluster Summary

	Number of Observations	Within Cluster Sum of Square	Average Distance	Maximum Distance
Cluster1	12	2.49831×10^{-6}	3.51185×10^{-4}	9.45121×10^{-4}
Cluster2	8	1.08335×10^{-5}	0.00107	0.00161

Distance between Final Cluster Centers

	Cluster1	Cluster2
Cluster1	0	0.00355
Cluster2	0.00355	0

ANOVA

	Cluster DF	Cluster SS	Error DF	Error SS	F Value	Prob>F
RCR for AN Adults	1	4.63245×10^{-5}	18	5.68225×10^{-7}	81.52488	<0.0001
RCR for AN Children	1	9.46249×10^{-6}	18	1.16069×10^{-7}	81.52488	<0.0001
RCR for AN Infants	1	4.59499×10^{-6}	18	5.6363×10^{-8}	81.52488	<0.0001

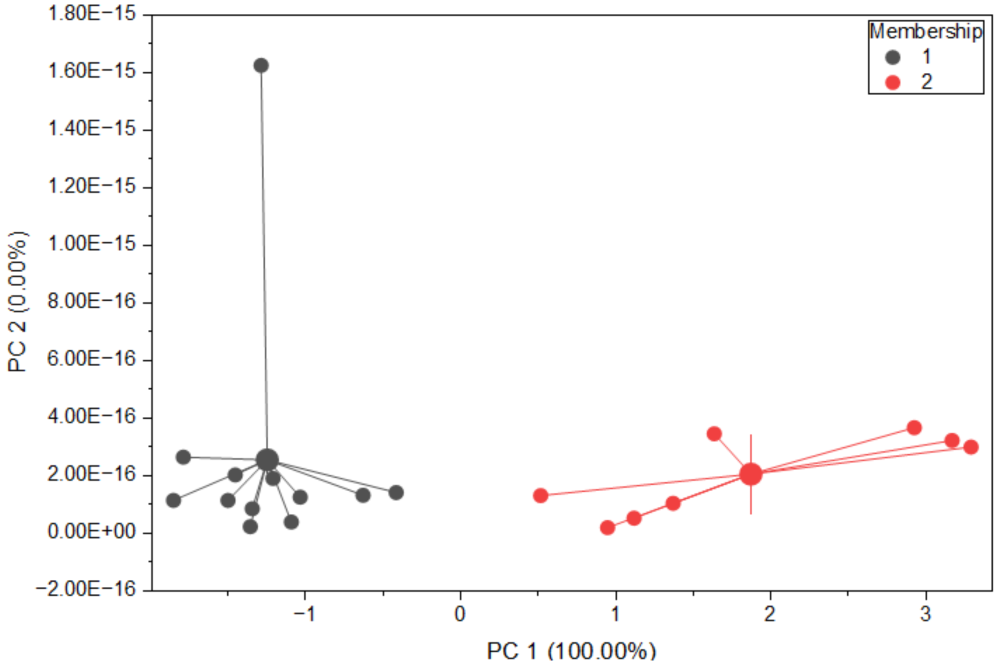

Figure 9: K-Means Cluster Analysis for radiogenic cancer risk for AN LGA

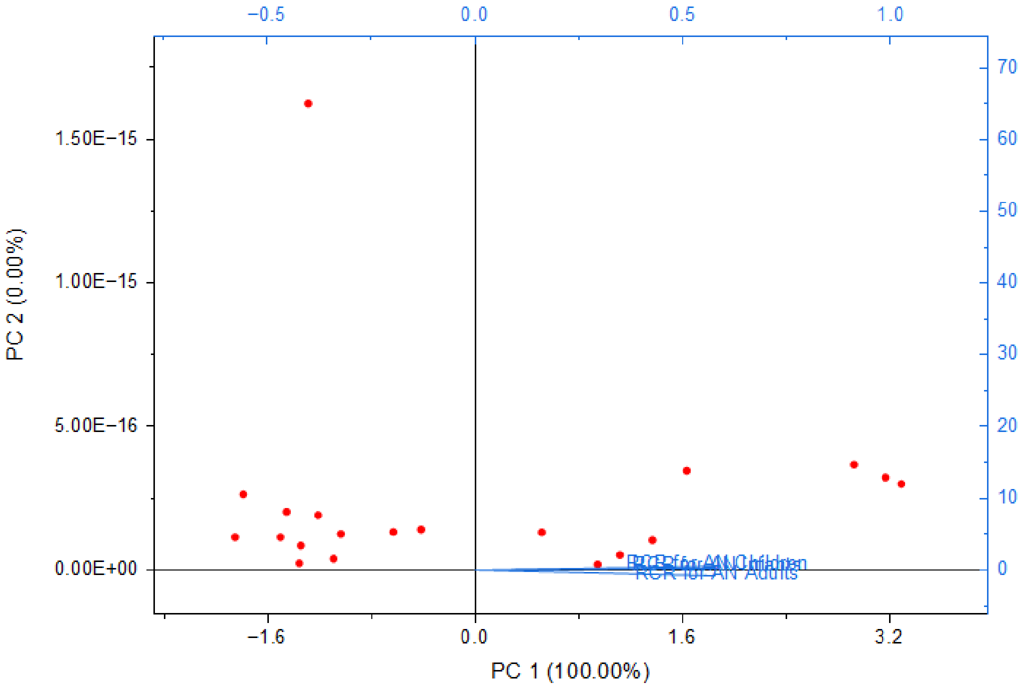

Figure 10: Principal Component Analysis (PCA) for radiogenic cancer risk for AN LGA

Table 9, present results for ELCR due to ingestion of radon in the water source for AN LGA. The average value recorded for adults, children and infants are 3.39845×10^{-5}, 1.53992×10^{-5}, and 1.07529×10^{-5} respectively. A histogram plot for Excess Lifetime Cancer Risk (ELCR) across three distinct age groups (adults, children and infants) is seen in Figure 10. The values as revealed in the histogram plot are very small, ranging from 0 to 0.00020 for the three age groups, indicating risk in terms of per ten thousand. Distribution for adults peaks around 0 to 0.00002 with a significant number of observations in this range, fluctuating as risk increases beyond 0.00002. This is an indication that adults face moderate ELCR in this LGA even though there are fewer cases at higher risks. For children and infants, the distribution peaks at around 0 to 0.00001 and 0 to 0.000005 respectively, indicating slight lower risk for children and even lower risk for infants as against those for adults. The box plot in Figure 11 illustrates distribution of ELCR across the age groups and results show that adults face the most ELCR compared to children and infants.

Table 9: Excess Lifetime Cancer Risk [(ELCR)$\times$ 10^3] Due to Ingestion of Radon through Water for AN

S/N	ELCR for Adults	ELCR for Children	ELCR for Infants
	1.1502×10^{-5}	5.21182×10^{-6}	3.63929×10^{-6}
	2.67098×10^{-5}	1.21029×10^{-5}	8.45114×10^{-6}
	9.14735×10^{-5}	4.14489×10^{-5}	2.89428×10^{-6}
	1.04868×10^{-5}	4.75182×10^{-6}	3.31808×10^{-6}
	4.29919×10^{-5}	1.94807×10^{-5}	1.36029×10^{-6}
	8.50868×10^{-5}	3.8555×10^{-5}	2.6922×10^{-5}
	1.49033×10^{-5}	6.75304×10^{-6}	4.71548×10^{-6}
	1.28217×10^{-5}	5.80982×10^{-6}	4.05686×10^{-6}
	5.79237×10^{-5}	2.62467×10^{-5}	1.83274×10^{-5}
	8.93348×10^{-5}	4.04798×10^{-5}	2.82661×10^{-5}
	5.05219×10^{-5}	2.28927×10^{-5}	1.59854×10^{-5}
	2.29842×10^{-5}	1.04147×10^{-5}	7.27234×10^{-6}
	1.59076×10^{-5}	7.20812×10^{-6}	5.03326×10^{-6}
	1.62624×10^{-6}	7.3689×10^{-7}	5.14553×10^{-7}
	2.73997×10^{-6}	1.24155×10^{-6}	8.66943×10^{-7}
	6.25462×10^{-5}	2.83412×10^{-5}	1.979×10^{-5}
	5.35082×10^{-5}	2.42459×10^{-5}	1.69303×10^{-5}

	7.75667×10^{-6}	3.51474×10^{-6}	2.45426×10^{-6}
	8.58458×10^{-6}	3.88989×10^{-6}	2.71621×10^{-6}
	1.02798×10^{-5}	4.65804×10^{-6}	3.2526×10^{-6}
Average	3.39845×10^{-5}	1.53992×10^{-5}	1.07529×10^{-5}

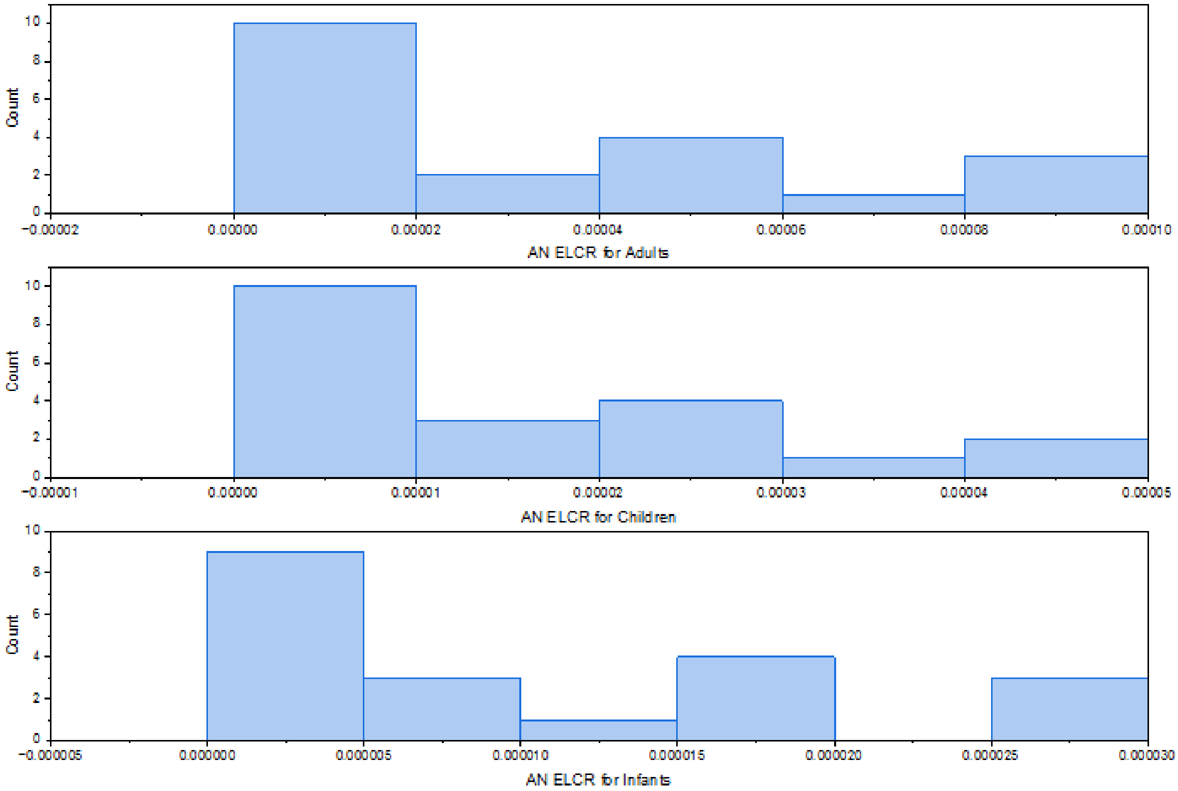

Figure 11: Histogram Plot for ELCR for three age group in AN LGA

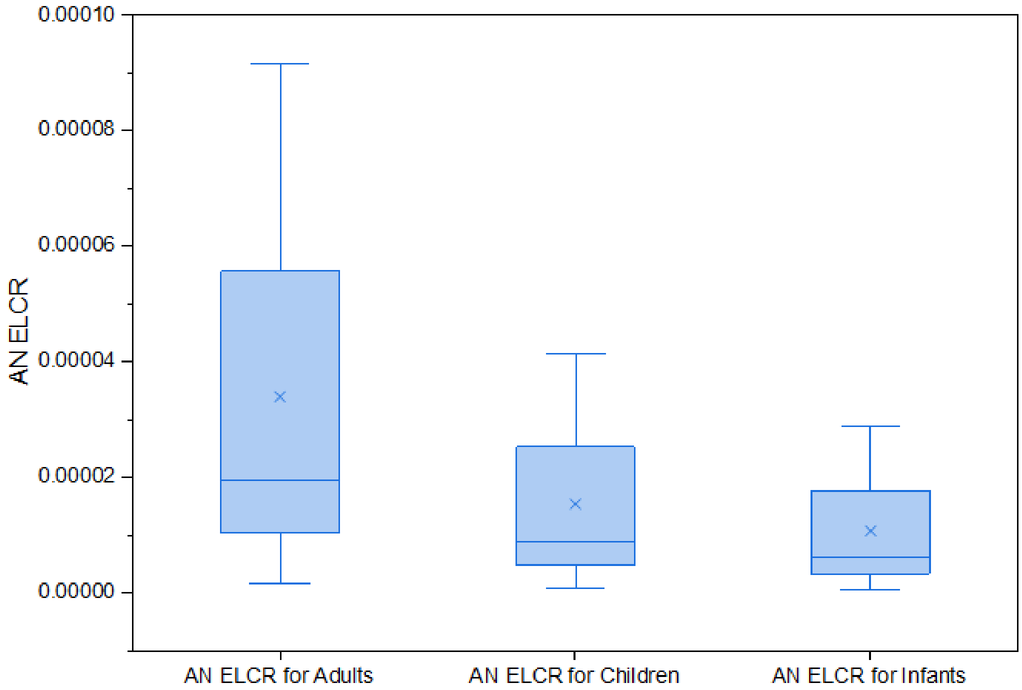

Figure 12: Box Plot for ELCR for three age groups in AN LGA

Table 10: Descriptive Statistics on Columns for ELCR for AN LGA

	Mean	**Standard Deviation**	**Variance**	**Skewness**	**Kurtosis**	**Geometric Mean**	**Geometric SD**	**Minimum**	**Median**	**Maximum**
AN ELCR for Adults	3.3984×10^{-5}	3.0256×10^{-5}	9.15435×10^{-10}	0.80701	-0.72717	2.06614×10^{-5}	3.14443	1.6262×10^{-6}	1.94459×10^{-5}	9.14735×10^{-5}
AN ELCR for Children	1.5399×10^{-5}	1.3709×10^{-5}	1.87959×10^{-10}	0.80701	-0.72717	9.36217×10^{-6}	3.14443	7.368×10^{-7}	8.81142×10^{-6}	4.14489×10^{-5}
AN ELCR for Infants	1.0752×10^{-5}	9.5732×10^{-6}	9.16468×10^{-11}	0.80701	-0.72717	6.53738×10^{-6}	3.14443	5.1455×10^{-7}	6.1528×10^{-6}	2.89428×10^{-5}

CONCLUSION

Water samples collected from borehole and surface reservoir sources from Aniocha North LGA of Delta State, Nigeria have been analyzed for ^{222}Rn activity concentration in this study. Radiogenic health risks have been estimated using statistical approaches. The results show that all analyzed water sample contain ^{222}Rn concentrations below the recommended safe level of 11.1 Bq/L for drinking water. The results from box plot shows distribution of Excess Lifetime Cancer Risk (ELCR) across the age groups and that adult face the most ELCR compared to children and infants. Remediation approaches may not be needed; however periodic assessment of the water sources is advised for the safe use of water in the LGA. Also there is need for a broader Niger Delta study to adequately determine and map areas prone to high radon in different water sources.

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