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ORIGINAL RESEARCH ARTICLE

Determination of Radon-222 (^{222}Rn) in Well and Borehole Water at Nasarawa LG, Kano State, Nigeria

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ABSTRACT
Nassarawa LG is one of Kano's most densely populated local government areas and depends solely on groundwater (well and borehole) for drinking and other domestic purposes. Radon, one of the most important radioactive elements, is abundant due to the presence of uranium and radium. It can dissolve in underground water, leading to internal exposure if ingested. Therefore, there is a need for a radiological assessment of Radon-222 in the water and an evaluation of the health hazards associated with the level (high or low) of radon and background radioactivity. A total of one hundred (100) water samples were collected from the study area. The samples were analysed using a liquid scintillation counter from the Center for Energy Research (CERT), Ahmadu Bello University, Zaria. The mean radon activity concentration in the water was found to be 12.78±0.04 Bq/L, which is higher than the maximum permissible limits of 11.1 Bq/L and 10 Bq/L set by the USEPA and WHO, respectively (WHO, 2004; USEPA, 2003). The mean radon activity concentration in well and borehole water was 11.946±0.04Bq/L and 13.612±0.04Bq/L, respectively, with a range from 3.634±0.04Bq/L to 44.952±0.04Bq/L. The highest recorded radon activity concentration was 44.952±0.04Bq/L in borehole water from Giginyu, and the lowest was recorded in well water from Kawo. 70% of the total samples had a high radon concentration, exceeding the maximum contaminant levels of 11.1 Bq/L set by USEPA and 10 Bq/L set by WHO, as also reported by UNSCEAR. The concentration level was found to be higher in borehole water compared to well water. In conclusion, many of the samples from the study area exceeded the maximum contaminant levels of 11.1 Bq/L (USEPA) and 10 Bq/L (WHO), indicating a significant public health concern that warrants further investigation and mitigation measures. It recommended that continuous monitoring and assessment of Radon-222 levels in drinking water should be implemented to protect public health.

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Radon-222, Environmental Radiation, Radon Concentration, effective dose, Liquid scintillation.

INTRODUCTION
Humans are always exposed to various forms of radiation from natural and artificial sources. The natural sources usually come from either cosmic or terrestrial radionuclides. These radionuclides often exist in the air humans breathe, the food they eat, water they drink, and pose a serious health effect to individuals and even offspring (Martin, 2013; Abdullahi *et al.,* 2017). Primordial radionuclides exist independently or in one of the naturally occurring series of radionuclides. These series have existed since the solar system's formation and have a half-life of over billion years except for Neptunium, which has already decayed due to its short half-life compared to the solar system's age (Ishimori *et al.*, 2013). There are three series still in existence, namely: Uranium series (U-238), Thorium series (Th-232) and Actinium series (U-235). The series is named according to the radionuclide that serves as the parent nuclide (Ishimori *et al.*, 2013). Radionuclides (unstable nuclides) attain stability through the emission of radiation, which can be alpha, beta, or gamma, producing nuclides (daughters) of lesser mass number. The parent decays via several transformations and produces daughters like Radium, Polonium, Radon, and others that affect humans because of their alpha emission properties, while Radon is an inert gas in three (3) different forms: Radon, Thoron, and Actinon. Radon-222 can diffuse in air or dissolve in water (Garba *et al.,*

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2011). The radiation released when it interacts with the biological system leads to abnormal cell transformation, leading to cancer inhaled or ingested into the biological system (Gyuk, 2017; Abdallah *et al.*, 2007). When used for domestic purposes, water containing radionuclides acts as an external or internal exposure if ingested or inhaled and can be of serious health concern (Onoja *et al.*, 2004). Radionuclides such as Radium-226 and polonium-218 pose a serious health problem due to their alpha-emission property, while Radon-222 (^{222}Rn), which is an inert gas, is more prone to inhalation and ingestion due to its ability to emanate into the air or dissolve in water used for other domestic purposes by human beings (Garba *et al.*, 2011). Many researchers have tried using various techniques to measure radon concentration in ground waters of various places around the world. Most of the techniques used (Solid State Nuclear Track detector SSNTD-CR9, continuous Radon monitor) (Ahmad *et al.*, 2017) are unavailable or inaccessible in this part of the world. During the past years, many efforts were made to measure parameters related to groundwater (Physio-chemical properties and groundwater potential, Groundwater Quality Assessment and its Suitability for Drinking Purposes, and Suitability of groundwater quality for drinking using water quality index in Kano metropolis) in the study area (Adamu, 2018; Hassan & Iliyasu, 2021; Simon and Arhyel, 2024), neglecting the radon concentration level in the waters which is of utmost importance because it might lead to health effect in individuals and offspring within the study area. Against these backdrops, this work assessed ^{222}Rn concentration in well and borehole water samples due to the high dependence of the populace on groundwater for drinking, cooking, and other domestic purposes.

METHODOLOGY

Study Area

The study area, Nassarawa LGA, is located within the latitude 11°58'20" - 12°1'40"N and longitude 8°31'40" - 8°36'40"E with a population of 596,669 and area of 34 $km2$. Bounded by Fagge and Ungoggo LGAs to the North, Tarauni and Kumbotso LGAs to the South, Gezawa to the East, and Kano Municipal to the West. The basement complex of the metamorphic and granite rocks underlies Nassarawa LGA. The granitic rocks have been classified as older granites and younger granites. The older granites include pink granite and undifferentiated granites. They are 15 dated back to Precambrian time and form the largest group (about 95%) of the granitic areas. The older granites have been subjected to many tectonic movements and pressures through geologic history, such that the older rocks often have several sets of fracture lines, and in some locations, the mafic minerals show evidence of these stresses (KNARDA, 1989). The pink granite is characterized by pink, orange, or red feldspars, very coarse grains, and low white and mafic minerals content. The rocky outcrops of Bompai and Magwan of the study area are pink and predominantly massive, forming smaller hills, and are all rooted to the basement (KNARDA, 1989).

Sample Collection

Ten (10) water samples (5 well and 5 boreholes) each were collected from each ward, making a total of 100 samples. The water samples from wells were collected after the stagnant water had been purged out and allowed to refill to ensure fresh samples were obtained, while samples from boreholes were collected after the borehole had been operated for a few minutes to ensure the samples were fresh (KNARDA, 1989; Garba *et al.,* 2011; Gyuk *et al.*, 2017).

The samples were collected in clean plastic sampling bottles which were cleaned and rinsed with distilled water to avoid the samples from being contaminated. The samples were transported immediately for analysis (Gyuk *et al.*, 2017).

Sample Preparation

The sample preparation procedures reported by Garba *et al.* (2011) and Gyuk *et al.* (2017) were followed to prepare the samples. 10 ml of each sample was added into a 20 ml glass scintillation vial to which 10 ml of insta-gel scintillation cocktail was added. The vial was shaken vigorously for the ^{222}Rn to be extracted from the water phase to the organic scintillant solution due to its greater solubility in organic liquids. The vials were left for more than 3 hours to allow for in growth of the short-lived decay products of ^{222}Rn and the attainment of secular equilibrium. The background samples were prepared by dissolving 10 ml of the scintillation solution in 10 ml of distilled water.

Calibration Procedure for LSA for ^{222}Rn in Water

For calibration, a secondary calibration material was created. 1ml of the 226Ra was dissolved in distilled water to create a secondary calibration material. The solution was kept in storage for one month to allow for equilibrium. After mixing 10 mL of the solution with 10 mL of install-gel scintillation cocktail, 60 minutes of counting with a window setting of 25-900 were performed in region C of the LSA. Equation 3.2 was used to determine the calibration factor (ASTM, 1999; Garba *et al.*, 2018).

$$Calibration\ Factor\ (CF) = \frac{SC - BC}{C - V} \qquad (1)$$

Where

SC = Standard ^{226}Ra Count (count/min)
BC = Background Count rate (count/min)
C = Standard ^{226}Ra concentration (Bq/L)
V = Volume of Standard ^{226}Ra used (L)

Sample Analysis

The Samples were analyzed using a Liquid scintillation counter (Parkard Tri-carb LSA 1000TR) at the Center for Energy Research and Training (CERT), Ahmadu Bello University Zaria, for 60mins each. The radon concentration was then calculated using equation 3.1 (ASTM, 1999; Garba et al., 2011):

$$R_n(BqL^{-1}) = \frac{100(CS - CB)e^{\lambda t}}{60 \times DF \times CF} \quad (2)$$

Where
R_n = Radon concentration,
CS = sample count per second
CB = Background count per second,
100 = conversion factor from per 10 mL to per L
λ = decay factor ($1.26 \times 10^{-4} min^{-1}$)
t = time elapsed between sample collection and counting (4320 min(3days))
CF = Calibration Factor (0.964, which represents the Fraction of Radon in a vial of 22 mL capacity)
DF = Decay Factor Number of emissions per disintegration of Radon (Given as 5)
60 = conversion factor from minute to seconds

The annual effective doses due to ^{222}Rn ingestion and inhalation were calculated using equations 3.2 and 3.3 (Ravikumar *et al*., 2012; Khattak *et al.,* 2011; Tabar and Yakut, 2014; Binesh *et al*., 2010; Shahbazi and Saeb, 2008):

$$E_{ing} = CF_{ing} \times R_n \times T_w \quad (3)$$

$$E_{inh} = R_n \times R_w \times F \times t_R \times CF_{inh} \quad (4)$$

Where

E_{ing}= Annual Effective dose due to Radon Ingestion
CF_{ing} = Ingestion dose Conversion factor (conversion factor of Rn-222 ($SvBq^{-1}$), for adults, children, and infants were taken as $10^{-8}SvBq^{-1}$, $2 \times 10^{-8}SvBq^{-1}$ and $7 \times 10^{-8}SvBq^{-1}$ respectively) (Todorovic et al., 2012, Duggal et al., 2013, Asadi and Rahimi, 2013, Bem et al., 2014).
R_n= Radon concentration
T_w = Annual water consumption (for adults, children, and infants; these values are 2, 1.5, and 0.5 liters per day, Equal to 730, 547.5, and 182.5litres per yr) as suggested by ICRP
E_{inh}= Annual Effective dose due to Radon Inhalation
R_w = Ratio of Radon released in air when water is used to Radon in water (10^{-4})
F = Equilibrium factor between Radon and its daughters (0.4)
t_R = Average Residence time of individual in the interior (7000h/year)
CF_{inh}= Dose conversion factor due to inhalation ($9nSv(Bqhm^{-3})^{-1}$

RESULT AND DISCUSSION

Well Water

The mean ^{222}Rn concentration of each sampling location is presented in Table 1. The mean concentration of all well water samples within the study area was $11.9\ Bq/L$. The highest ^{222}Rn mean concentration from the well water sample locations was recorded from Dakata with a concentration of $22.5 Bq/L$ which is seen to be higher than the maximum permissible limit of $11.1 Bq/L$ and $10 Bq/L$ given by USEPA and WHO (WHO, 2004; USEPA, 2003) and the lowest was recorded from Kawo with a concentration of $4.4 Bq/L$ which is lower than the recommended limit. The mean concentration ranges from $4.4\ Bq/L$ to $23.0 Bq/L$. The mean annual effective dose (AED) due to inhalation was found to be $30.1 \mu Sv/yr$, while those of ingestion of ^{222}Rn in well water (for Adults, Children, and Infants) were found to be 87.7 $\mu Sv/yr$, 130.8 $\mu Sv/yr$, and 152.6 $\mu Sv/yr$ respectively. The highest AED for the inhalation of ^{222}Rn was $56.8\ \mu Sv/yr$. For the consumption of well water, the mean AED were found to be $87.205\ \mu Sv/yr$, $130.807\ \mu Sv/yr$, and $152.609\ \mu Sv/yr$ for adult, children, and infants respectively. These values are less than the WHO permissible limit of $100 \mu Sv/yr$ and $200 \mu Sv/yr$ for adults and children, respectively (WHO, 2004). This high ^{222}Rn concentration can be associated with the ^{222}Rn sources in the aquifer within the study area (KNARDA, 1989; Garba *et al.,* 2011; Gyuk *et al.,* 2017). Other factors related to this can also include human activities (e.g., quarrying) and the rocky nature of the collected samples, which seem to be predominantly granite.

Borehole water

The mean ^{222}Rn concentrations are presented in Table 2. The mean concentration of all borehole water samples was $13.6\ Bq/L$. The location with the highest mean, ^{222}Rn, was found to be Tudun Wada, with a value of $24.2 Bq/L$, and the lowest is Hotoro North, with $7.2 Bq/L$. The highest ^{222}Rn mean concentration from the borehole water sample locations was recorded from Tudun Wada with concentration of $23.3 Bq/L$ which is seen to be higher than the maximum permissible limit of $11.1 Bq/L$ and $10 Bq/L$ given by USEPA and WHO (WHO, 2004; USEPA, 2003) and the lowest was recorded from Hotoro North with concentration of $7.2 Bq/L$ which is lower than the recommended limit. The mean concentration ranges from $7.0\ Bq/L$ to $24.0 Bq/L$. The highest AED for the inhalation of Radon was found to be $58.4\ \mu Sv/yr$, for ingestion $177.0\ \mu Sv/yr$, $256.6\ \mu Sv/yr$ and $309.8\ \mu Sv/yr$. The mean annual effective dose(AED) due to inhalation and ingestion (for Adults, Children, and Infants) of ^{222}Rn concentration in well water was found to be $34.0 \mu Sv/year$, 99.4 $\mu Sv/year$, 149.0 $\mu Sv/year$, and 173.9 $\mu Sv/year$. For the consumption of borehole water, the mean AED for adults, children, and infants was found to be $99.364\ \mu Sv/yr$, $149.00\ \mu Sv/yr$, and $174.00\ \mu Sv/yr$ respectively. These values are less than the WHO permissible limit of $100 \mu Sv/yr$ and $200 \mu Sv/yr$ for adults and children, respectively (WHO, 2004). Although all the water samples were from the same study area, the borehole water samples showed a greater increase in ^{222}Rn concentration. This could result from the boreholes' depth within the sample locations, which made them closer to the entrapped parent nuclide of ^{222}Rn.

From the result, we can see that most ^{222}Rn concentrations are higher than the world mean concentration of $11.1 Bq/L$ and $10 Bq/L$ given by USEPA and WHO (WHO, 2004; USEPA, 2003).

Table 1: Mean ^{222}Rn Concentration and annual effective dose in well water

Location	Mean Conc. (Bq/L)	Annual Effective Dose $(\mu Sv/year)$			
		Inhalation (All Ages)	Ingestion (Adult)	Ingestion (Children)	Ingestion (Infant)
Kawo	4.4	11.08	32.0	48.0	56.0
Giginyu	10.6	26.6	77.0	115.6	134.8
Hotoro north	4.8	12.0	34.8	52.2	60.9
Hotoro south	13.7	34.6	100.2	150.5	175.3
Badawa	10.0	25.2	90.5	109.6	127.8
Dakata	22.5	56.8	151.0	246.8	287.8
Kawaji	20.4	51.4	149.0	223.4	260.6
Tokarawa	13.9	35.1	101.6	152.2	177.6
Gama	8.4	21.1	61.1	91.6	106.9
Tudun wada	10.8	27.3	79.0	118.5	138.3
Mean	**11.95**	**30.12**	**87.62**	**130.84**	**152.60**

Table 2: Mean ^{222}Rn Concentration and annual effective dose in borehole water

Location	Mean Conc. (Bq/L)	Annual Effective Dose $(\mu Sv/year)$				
		Inhalation (All Ages)	Ingestion (Adult)	Ingestion (Children)	Ingestion (Children)	Ingestion (Infant)
Kawo	10.7	26.9	77.9	116.8	116.8	136.3
Giginyu	20.4	51.5	149.1	223.5	223.5	260.9
Hotoro north	7.2	18.1	52.5	78.7	78.7	91.8
Hotoro south	8.1	20.5	59.3	89.0	89.0	103.7
Badawa	10.8	27.2	78.9	118.4	118.4	138.0
Dakata	16.0	40.4	117.0	175.6	175.6	204.8
Kawaji	14.7	37.0	107.0	160.6	160.6	187.4
Tokarawa	13.7	34.4	99.7	149.5	149.6	174.3
Gama	10.3	26.0	75.2	112.7	112.7	131.9
Tudun wada	24.2	58.4	177.0	265.6	265.6	309.8
Mean	**13.61**	**34.04**	**99.36**	**149.04**	**149.05**	**173.89**

Radon-222 is a significant concern in the context of radiological health hazards, especially when present in water sources (Martin, 2013; Abdullahi *et al.,* 2017; Garba *et al.*, 2011). Various studies have investigated the concentration of Radon-222 in different regions and water sources, revealing notable variations and potential health risks.

Oluwaseun et al. (2022) conducted a study to measure the concentration of Radon-222 and estimate the excess lifetime cancer risk in water well samples along the Iwaraja-Ifewara faults in Southwestern Nigeria. The Radon-222 concentration ranged from 5.0 to 400.1 Bq/L, with a mean value of 45.78 Bq/L. This study found that the Radon-222 concentration exceeded most samples' USEPA recommended limit of 11.1 Bq/L. The mean annual effective dose was 59.4 μSv/y, below the USEPA recommended 100 μSv/y. The excess lifetime cancer risk (ECLR) due to inhalation from the water samples ranged from 75.6 to 6053.5, with a mean of 692.9. The highest Radon-222 activity concentration was found in the Akesan well and borehole, with 32 ± 1.8 Bq/L and 31.1 ± 1.8 Bq/L, respectively. The mean value for all samples was 18.8 ± 7.4 Bq/L. The maximum average was at the Akesan site (30.4 ± 2.04 Bq/L), nearly three times the recommended level of 11.1 Bq/L, while the minimum value was at the Ipaye site (10.8 ± 5.18 Bq/L), which is close to the recommended level.

Bello et al. (2019) determined the Radon-222 concentration in Bagwai and Shanono mining sites. The overall mean Radon-222 activity concentration in drinking water was 36.101 Bq/L, more than three times the maximum permissible limits set by USEPA and WHO. The average annual effective dose (AED) due to the inhalation of surface and groundwater was 73.134 μSv/y and 108.818 μSv/y, respectively. The average AED for water ingestion by adults, children, and infants were 263.53, 395.304, and 461.188 μSv/y, respectively, exceeding the WHO permissible limits of 100 μSv/y for adults and 200 μSv/y for children.

Isinkaye et al. (2017) investigated the annual effective dose due to Radon-222 in deep and shallow wells in Ekiti state, Nigeria, using a Durrige RAD7 electronic Radon detector. For deep wells (boreholes), the Radon-222 concentration ranged from 13.4 to 105.8 Bq/L, with a mean value of 30.9 Bq/L. Hand-dug wells with removable covers had Radon-222 concentrations ranging from 2.1 to 43.7 Bq/L, with a mean value of 19.5 Bq/L. Hand-dug wells with manual pumps had Radon-222 concentrations ranging from 2.5 to 206.1 Bq/L, with a mean of 81.2 Bq/L. The total annual effective dose incurred through groundwater consumption in the study area was within the guideline value of 0.1 mSv recommended by the European Union and WHO.

Halim et al. (2018) measured indoor and tap water Radon-222 at various campuses of Giresun University using CR-9 detectors. Indoor Radon-222 levels ranged from 76 Bq/L to 504 Bq/L, with a mean of 193.7 Bq/L, which exceeds the recommended limit. The mean Radon-222 concentration for tap water was found to be 6.73 Bq/L, below the recommended limit.

Rabi'u et al. (2017) measured the radiation dose from consuming well water in the Abeokuta metropolis by measuring Radon-222 and Radon-220 concentrations using CR-39 and LR-115 detectors. Radon-222 concentrations ranged from 3.1 to 90.8 kBq/L. Statistical analysis showed that 94% of wells had Radon-222 concentrations above the USEPA's maximum contaminant level of 11.1 kBq/L, though none exceeded the 1000 kBq/L threshold for remedial action recommended by the European Union. The annual effective doses from water consumption ranged from 44.5 to 1325.7 μSv/y for children and 22.3 to 66.8 μSv/y for adults, with means of 484.7 μSv/y and 242.3 μSv/y, respectively.

Gyuk et al. (2017) used a liquid scintillation counter to determine the effective dose in male adults due to Radon-222 in well water samples from Idah, Nigeria. The range was 3.0 to 18.24 Bq/L, with a mean of 10.23 Bq/L, and an annual effective dose range of 0.0198 to 0.1198 mSv/y, with a mean of 0.0721 mSv/y, which is below the WHO limit of 0.1 mSv/y.

Comparing these findings with the results from Nassarawa LG, Kano, where the mean Radon-222 activity concentration in water was 12.78 Bq/L, higher than the permissible limits set by USEPA and WHO, it is evident that Radon-222 levels can vary significantly depending on geological and environmental factors. In Nassarawa LG, the Radon-222 concentration in borehole water (mean: 13.612 Bq/L) was higher than in well water (mean: 11.946 Bq/L), with ranges from 3.634 Bq/L to 44.952 Bq/L.

Overall, many of the samples from Nassarawa LG exceeded the maximum contaminant levels of 11.1 Bq/L (USEPA) and 10 Bq/L (WHO), indicating a significant public health concern that warrants further investigation and mitigation measures. This comparison underscores the importance of continuously monitoring and assessing Radon-222 levels in drinking water to protect public health.

CONCLUSION

A Liquid Scintillation Counter determined the Radon-222 concentration in groundwater sources (Well and borehole) of Nasarawa LGA in Kano State. The mean radon activity concentration in the water is higher than the maximum permissible limit of $11.1\ Bq/L$ and $10\ Bq/L$ given by USEPA and WHO (WHO, 2004; USEPA, 2003) with the highest Radon-222 concentration recorded in the borehole from Tudun Wada and the least was recorded in well from Kawo. 75% of the total samples have a high concentration of Radon higher than the maximum contaminant level. The AED due to inhalation of Radon is less than the permissible limit, but the mean AED due to ingestion of Radon by adults, children, and infants was greater than the WHO permissible limit. From the results, it was observed that the water samples in some of the study area locations are unsafe for drinking, and therefore, there is a need for remediation within the study area.

REFERENCES

Abdallah, S. M., Habib, R. R., Nuwayhid, R. Y., Chatila, M., & Katul, G. (2007). Radon measurements in well and spring water in Lebanon. Radiation Measurements, 42(2), 298–303. **[Crossref]**

Abdullahi, A. S., Mathew, J. S., & Ndikilar, C. E. (2017). An assessment of gross beta radioactivity concentration in underground water in Nassarawa town of Nassarawa state, Nigeria. *International Journal of Latest Research in Science and Technology*.

Acar, O., Kalfa, O. M., Inkaya, O. Y., & Turker, A. R. (2013). Determination and evaluation of gross alpha and beta activity concentrations and metal levels in thermal waters from Ankara, Turkey. *Turkish Journal of Chemistry*, 37, 805-811. **[Crossref]**

Adamu, M. D. (2018). An assessment of ground water potential in Nassarawa Local Government, Kano state, Nigeria. *International Journal of Social Science*, 11(3), 29–30.

Agbalagba, O. E. (2017). Assessment of excess lifetime cancer risk from gamma radiation levels in Effurun and Warri city of Delta state, Nigeria. *Journal of Taibah University for Science*, 11(3), 367-380. **[Crossref]**

Ahmad, N., et al. (2017). An overview of radon concentration in Malaysia. *Journal of Radiation Research and Applied Sciences*. **[Crossref]**

ARPANSA. (2015). Radon exposure & health. Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) Fact Sheet.

Aruwa, A., Kassimu, A. A., Gyuk, P., Ahmadu, B., & Aniegbu, J. (2017). Studies on radon concentration in underground water of Idah, Nigeria. *International Journal of Research Granthaalayah,* 5(9). **[Crossref]**

Asadi, A., & Rahimi, M. (2013). Determination of the annual effective dose absorbed by the people of Rafsanjan city and surrounding areas with measurement of radon gas concentration in drinking water using active method. *Physics Conference of Iran*, Birjand University.

ASTM. (1999). American society for testing and measurements. Standard test method for Radon in drinking water. ASTM Designation: D5072-98.

Atsor, A. J., Akpa, T. C., & Akombor, A. A. (2015). Determination of gross alpha and beta radioactivity in underground water at Gboko and its environs. Research *Journal of Physical Sciences*, 3(6), 1-9.

Baba-Kutugi, A. N., Sa'idu, A., Basiru, Y. A., Sanusi, R. K., & Sanusi, A. (2012). Analysis of gross alpha and gross beta radioactivity in sachet water hawked in Birnin Kebbi, Kebbi State.

Bello, S., Nasiru, N., Garba, N. N., & Adeyemo, D. J. (2019). Annual effective dose associated with Radon, gross alpha and gross beta radioactivity in drinking water from gold mining areas of Shanono and Bagwai, Kano state, Nigeria. *Microchemical Journal*, 154, 104551. **[Crossref]**

Bem, H., Plota, U., Staniszewska, M., Bem, E. M., & Mazurek, D. (2014). Radon (222Rn) in underground drinking water supplies of the Southern Greater Poland Region. *Journal of Radioanalytical and Nuclear Chemistry*, 299, 1307-1312. **[Crossref]**

Benson, I. D., & Ugbede, F. O. (2018). Measurement of background ionizing radiation and evaluation of lifetime cancer risk in highly populated motor parks in Enugu city, Nigeria. IOSR *Journal of Applied Physics*, 10(3), 77-82.

Binesh, A., Mohammadi, S., Mowlavi, A., Parvaresh, P., & Arabshahi, H. (2010). Evaluation of the radiation dose from radon ingestion and inhalation in drinking water sources of Mashhad. *Research Journal of Applied Science*, 5, 221-225. **[Crossref]**

Canadian Nuclear Safety Commission. (2010). Radon in Canada's uranium industry. Retrieved 30th September 2010, from http://www.nuclearsafety.gc.ca/eng/readingroom/fact-uranium.cmf.

Cember, H. (2009). Introduction to health physics (4th ed.). McGraw Hill.

Clapham, C., & Horan, N. J. (1996). Radon in private water supplies: The unknown risk. *Water Environment Journal*, 10, 211–214. **[Crossref]**

Duggal, V., Mehra, R., & Rani, A. (2013). Determination of 222Rn level in groundwater using a RAD7 detector in the Bathinda district of Punjab, India. Radiation Protection Dosimetry, 156, 239-245. **[Crossref]**

Fasae, K. P., Ibikunle, K. S., & Akinkuade, S. T. (2015). Gross alpha and beta activity concentrations in portable drinking water in Ado - Ekiti metropolis and the committed effective dose. *International Journal of Advanced Research in Physical Science* (IJARPS), 2(1), 1-6.

Ferdous, M. J., Rahman, M. M., & Begum, A. (2012). Gross alpha and gross beta activities of tap water samples from different locations of Dhaka City. *Sri Lankan Journal of Physics*, 13(1), 1-8. **[Crossref]**

Frengstad, B., Skrede, A. K., Krog, J. R., Strand, T., Lind, B., & Banks, D. (2003). Radon in potable groundwater: Examples from Norway. In: Natural Ionizing Radiation and Health, Proceedings from a Symposium held at the Norwegian Academy of Science and Letters, Det Norske Videnskaps-Akademi, Oslo, Norway, 27–38.

Gado, A. A., Muthukumar, M., Gwani, M., Jonathan, L. A., Kazuga, S., Umar, A. B., Jafar, A. B., & Anbazhagi, M. (2018). Determination of gross alpha, beta radioactivity in sachet drinking water. *Research Journal of Physical Sciences*, 6(3), 1-7.

Garba, N. N., Rabiu, N., Dewu, B. B. M., Sadiq, U., & Yamusa, Y. A. (2011). Radon assessment in groundwater sources from Zaria and environs, Nigeria. *International Journal of Physical Sciences*, 8(42), 1983–1987.

Garba, Z. N., & Hussain, A. R. (2018). Assessment of radon concentration in underground well water from selected parts of Kaduna metropolis. *ChemSearch Journal*, 9(2), 8–12.

Gyuk, M. P., Ahmadu, B., Kassimu, A. A., Aruwa, A., Ali, H., & Hyuk, I. D. (2017). Survey of alpha and beta radioactivity concentration and estimated committed effective dose to the general public due to intake of groundwater in some parts of Chikun and Kaduna South LGAs of Kaduna state, Nigeria. *International Journal of Research - Granthaalayah*, 5(9), 124-131. **[Crossref]**

Gyuk, P. M., Aruwa, A., Dogara, M. D., & Daniel, I. H. (2017). Annual effective dose of radon-222 in well water samples in male adults: Idah, Nigeria.

American Journal of Optics and Photonics, 5(4), 45-49. **[Crossref]**

Halim, B., F., Banu Ö., Tuba, Ö., Ö., and Halil G, 2018. INDOOR and TAP WATER RADON (222Rn) CONCENTRATION MEASUREMENTS AT GIRESUN UNIVERSITY CAMPUS AREAS, *Applied Radiation and Isotopes*. **[Crossref]**

Hassan, M., & Iliyasu, S. (2021). Groundwater quality assessment and its suitability for drinking purposes in Nasarawa Area, Kano State, Nigeria. *International Journal of Science for Global Sustainability: A Publication of Faculty of Science, Federal University Gusau*, 7(2).

International Commission on Radiological Protection (ICRP). (2007). The 2007 recommendations of the International Commission on Radiological Protection: Annuals of the ICRP Publication. Elsevier, 103(2-4).

Ishimori, Y., Lange, K., Martin, P., Mayya, Y. S., & Phaneuf, M. (2013). Technical reports series No. 474. Measurement and calculation of radon releases from NORM residues. Vienna, Austria.

Isinkaye, M. O., & Ajiboye, Y. (2017). Assessment of annual effective dose due to radon concentrations in deep and shallow wells within Ekiti State, Nigeria. Radioprotection, 52(3), 167–175. **[Crossref]**

ISO. (1992). Water quality measurement of gross alpha activity in non-saline water. International Standard Organization (ISO 9696).

Job, C. C., & Ifegwem, G. (2006). Radionuclide concentrations in well water from oil-producing area of Nigeria and their radiological impact. *Journal of Environmental Radioactivity*, 94, 123–130.

Kaça, P., Matolin, M., & Havlova, V. (2000). The occurrence of 222Rn in ground waters and its implications to geology and health hazard (The Krkonose-Jizera Mts. region, Czech Republic). *Environmental Geology,* 39, 571-579.

Kano State Agricultural and Rural Development Authority (KNARDA).(1989). Rural water supply project, Vol. II, Summary of Hydrogeological Data. *Final Report, WARDROP Engineering Inc.* 24 p. plus Appendices.

Khan, H. M., et al. (2015). Measurement of gross alpha and beta activity in well water of Tarbela, Pakistan. Radiation Protection Dosimetry, 164, 259-265.

Khattak, N., Khan, M., Shah, M., Javed, M (2011). Radon concentration in drinking water sources of the Main Campus of the University of Peshawar and surrounding areas, Khyber Pakhtunkhwa, Pakistan. *Journal of Radioanalytical and Nuclear Chemistry*. 290:493-505. **[Crossref]**

Lawal, T. A., Aliyu, S., & Ayuba, A. U. (2015). Gross alpha and beta radioactivity in drinking water in Karu, Nigeria. *International Journal of Environmental Monitoring and Analysis,* 3(3), 150-155.

MacDonell, M. (2017). Risk assessment information system (RAIS). Argonne National Laboratory.

Marcovecchio, J. E., Ferrer, L., Beltrame, M. O., & Andrade, S. (2007). Heavy metals, major metals, trace elements. In: Nollet, L. M. L. (Ed.), Handbook of water analysis (2nd ed.). CRC Press, Boca Raton, FL, USA. **[Crossref]**

Martin J. E., (2013). *Physics for radiation protection. Third edition*. Pg-214. **[Crossref]**

Martínez-Ruiz, T., Navarro-Ortega, A., & Gutiérrez-Serpa, A. (2007). Determination of the 222Rn activity concentration in underground drinking water in the province of Salamanca (Spain) and the committed effective dose. Radiation Protection Dosimetry, 123, 68-74.

Michael, E., Agbalagba, E., Avwiri, G. O., & Enyinna, P. I. (2012). Evaluation of radon concentration in groundwater of a part of Southern Nigeria. *International Journal of Research and Reviews in Applied Sciences*, 13(3), 672–682.

Mousa, H. E. (2005). Natural radioactivity levels of some water supplies in Egypt. *Journal of Water Supply: Research and Technology*, 54(1), 1-11.

Muammer, A., & Bouguerra, N. (2015). Natural radioactivity measurements in groundwater and associated dose assessments from radon ingestion and inhalation in Tunisia. *Journal of Environmental Radioactivity*, 148, 156-163.

Olatunbosun, O. A., Oladapo, O. S., & Agbede, O. O. (2015). Determination of gross alpha and beta activity concentration in ground water from Owo, Ondo state, Nigeria. *Journal of Environment and Earth Science*, 5(14), 119-125.

Olatunji, M. A., Obadunwo, A. A., Oladapo, M. A., & Arogunjo, A. M. (2015). Measurements of gross alpha and beta radioactivity in groundwater and estimate of adults and infants dose intake in Akure city, Southwestern Nigeria. *International Journal of Research in Earth and Environmental Sciences*, 2(1), 39-46.

Olatunji, M. A., Shittu, H. O., Adekitan, O. A., & Oladapo, O. S. (2020). Determination of the levels of gross alpha and beta activities in well water from Akure and its environs. *Journal of Radiation Research and Applied Sciences*, 13(1), 123-133. **[Crossref]**

Oluwaseun G D, Augustine K A, Pauline A. J, Kayode F. A, Inioluwa O O, (2022). Measurements of radon and estimation of excess lifetime cancer risk in water-well samples along Iwaraja[1]Ifewara faults Southwestern, Nigeria. *International Research Journal of Public and Environmental Health* Vol.9 (4), pp. 120-124 August 2022 ISSN: 2360-8803(e) ISSN: 2814-3817(p). **[Crossref]**

Onoja, R.A. (2004). *Survey of Gross Alpha and Beta Radioactivity in Wells from Zaria.* (Unpublished M.Sc. thesis) A.B.U.Zaria.

Ononugbo, C. P., Avwiri, G. O., & Agbalagba, E. O. (2017). Health risk assessment of drinking water due to gross alpha and beta activity in Rivers State, Nigeria. Radiation Protection Dosimetry, 174(2), 276-283. **[Crossref]**

Pintilie, I., Savin, C., Anton, I., Simionov, V., Stefanescu, M., & Necula, R. (2007). Study of gross alpha and gross beta contamination in water of East of Romania, Eighth Symposium on the Natural Radiation Environment (NRE-VIII), Rio de Janeiro, Brazil.

Pravica, D., & Bikit, I. (2014). Natural radionuclides and radiation risk in drinking water: Results from 2010 to 2013 in Serbia. Radiation Protection Dosimetry, 160, 351-354.

Rabi, R., Mohammed, A. U., Ali, A. A., Ahmad, B., & Gado, A. (2017). Radioactivity concentrations of 40K, 232Th, 226Ra in water samples from Hadejia Emirate, Jigawa State, Nigeria. *International Journal of Innovative Research and Development*, 6(10), 248-254. **[Crossref]**

Raude, J. M., Mboya, C. R., Yalwala, S., & Simiyu, G. M. (2016). Measurement of gross alpha and beta activity concentrations in water samples from the Shores of Lake Victoria, Kenya. *International Journal of Applied Chemistry*, 12(1), 21-26. **[Crossref]**

Ravikumar, P., Somashekar, R. K., 2012. Estimates of the dose of radon and its progeny inhaled inside buildings. *European Journal of Environmental Sciences*, Vol. 3, No. 2, pp. 88–95. **[Crossref]**

Reguigui, N., Abdellatif, A., Khelifi, M. S., & Baccouche, S. (2001). Measurements of alpha and beta activities in drinking water from wells and springs in Tunisia. *Proceedings of the 6th International Symposium on Environmental Geochemistry*.

Risma, R. (2020). Estimation of annual effective dose due to radon concentration in groundwater sources from selected areas of Abuja, Nigeria. *Global Journal of Pure and Applied Sciences*, 26(1).

Sadeghi, M., Mesdaghinia, A. R., & Talebi, A. (2011). Determination of gross alpha and gross beta activity in water samples using low-level proportional counter. *Journal of Environmental Health Science & Engineering*, 8, 191-198.

Shahbazi-Gahrouei and Saeb, M (2008). Dose assessment and radioactivity of the mineral water resources of Dimeh springs in the Chaharmahal and Bakhari province, Iran. *Nukleonika*, 53:31-34.

Shevchenko, V. N., & Zhitkova, E. S. (2003). Environmental problems and health effects of Radon (pp. 200). Moscow: Institute of Medical and Biological Problems.

Simon, S. M., Arhyel, Y. M., 2024. Suitability of groundwater quality for drinking using water quality index in Kano metropolis. *FUDMA Journal of Sciences (FJS).* Vol 8. 1 February pp 69-77 ISSN print: 2645 – 2944. **[Crossref]**

Singh, B., Kumar, V., & Kumar, A. (2016). Measurement of radon concentration in drinking water and associated health risks in Hamirpur district of Himachal Pradesh, India. Radiation Protection Dosimetry, 168(2), 328-332. **[Crossref]**

Skwarzec, B., Borylo, A., & Kosobudzki, P. (2001). Annual effective dose due to 222Rn ingestion with potable water. *Journal of Environmental Radioactivity*, 55, 285-288. **[Crossref]**

Tabar, E and Yakut, H (2014). Radon measurements in water samples from the thermal springs of Yalova basin, Turkey. *Journal of Radioanalytical and Nuclear Chemistry.* 299(1): 311- 319. 18. **[Crossref]**

Todorovic, N., Nikolov, J., Stojkovic, I., & Jovic, M. (2012). Gross alpha and beta activity in well water from Southern Serbia. Radiation Protection Dosimetry, 152(1-3), 228-232.

United Nations Scientific Committee on the Effects of Atomic Radiation. (2000). Exposures from natural radiation sources. Annex B. UN, New York.

United States Environmental Protection Agency (USEPA). (1991). National primary drinking water regulations; radionuclides; proposed rule. Federal Register, 56(138), 33050–33127.

United States Environmental Protection Agency (USEPA). (2000). National primary drinking water regulations; radon-222; proposed rule. Federal Register.

United States Environmental Protection Agency (USEPA). (2001). National primary drinking water regulations; radon-222; final rule. Federal Register.

United States Environmental Protection Agency (USEPA). (2004). EPA Map of Radon Zones: US EPA Map of Radon Zones. Retrieved 30th September 2010, from www.epa.gov

United States Environmental Protection Agency (USEPA). (2013). National primary drinking water regulations: EPA 816-F-09-004. Federal Register.

United States Environmental Protection Agency (USEPA). (2019). Basic information about radionuclides in drinking water. Retrieved 30th September 2010, from water.epa.gov

UNSCEAR. (2000). United Nations Scientific Committee on the Effects of Atomic Radiation: Sources and effects of ionizing radiation. Report to the General Assembly with scientific annexes, Vol. 1: Annex A: Dose assessment methodologies.

USEPA (2003). Assessment of risks from radon in homes: Indoor air division (EPA 402R03003).

WHO (2004). Guidelines for drinking water quality (3rd ed., Vol. 1). Geneva

World Health Organization. (2017). Guidelines for drinking-water quality (4th ed.). WHO, Geneva, Switzerland.