



Recent Challenges on Cancer Health Risks Determinants from Quality Drinking Water Samples in Some Selected Areas in Birnin Kudu, Jigawa State, Nigeria



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ABSTRACT

Radon (²²²Rn) is a naturally occurring radioactive gas that constitutes one of the major contributors to natural background radiation exposure and poses significant health risks to humans. Although alpha particles emitted by radon cannot penetrate the skin, inhalation of radon released from water during domestic activities and ingestion of radon-contaminated drinking water may increase the risks of lung and gastrointestinal cancers. This study assessed the concentration of ²²²Rn and the associated radiological health risks in drinking water obtained from selected communities in Birnin Kudu Local Government Area, Jigawa State, Nigeria. Eight water samples, comprising four borehole and four hand-dug well samples, were collected from four locations and analyzed using a Liquid Scintillation Counter (Tri-Carb LSA-1000) at the Centre for Energy Research and Training, Ahmadu Bello University, Zaria. The mean radon concentrations were 16.48 Bq/L for hand-dug well water and 16.23 Bq/L for borehole water. These values exceed the guideline limits of 10 Bq/L recommended by the World Health Organization (WHO) and 11.1 Bq/L recommended by the United States Environmental Protection Agency (USEPA). The estimated annual effective doses due to inhalation remained below the recommended safety limits for all age groups, whereas the annual effective doses due to ingestion and the corresponding excess lifetime cancer risks exceeded the recommended values. These findings indicate that the investigated water sources may pose potential health risks if consumed without treatment. Therefore, appropriate water treatment and routine radiological monitoring are recommended to minimize radon exposure and protect public health.

Keywords:

Radon (²²²Rn);
 Drinking water;
 Borehole water;
 Hand-dug well;
 Annual effective dose;
 Excess lifetime
 Cancer risk;
 Radiological
 Assessment.

INTRODUCTION

Water is one of the most essential natural resources for sustaining life and supporting socioeconomic development. It covers approximately 71% of the Earth's surface and constitutes a significant proportion of the human body (Musa et al., 2014). Beyond its biological importance, water plays a critical role in agriculture, industry, transportation, hydroelectric power generation, and domestic activities. Consequently, ensuring access to safe and high-quality drinking water remains a global public health priority (Abdullahi and Garba, 2015; Abdulrasheed et al., 2025; Dankawu et al., 2022). However, the availability of potable water that satisfies microbiological,

chemical, and radiological quality standards continues to be a major challenge, particularly in developing countries. Among the various contaminants affecting drinking water quality, naturally occurring radioactive materials (NORMs) have received increasing scientific attention due to their potential adverse health effects. Radon (²²²Rn), a naturally occurring radioactive noble gas, is one of the most significant contributors to natural background radiation exposure. It is produced through the radioactive decay of uranium (²³⁸U) present in rocks, soils, and groundwater aquifers (Shuaibu et al., 2024). Because radon is colorless, odorless, and chemically inert, its presence in drinking water cannot be detected without specialized analytical techniques.

Radon has an atomic number of 86 and exists in several isotopic forms, among which ^{222}Rn and ^{220}Rn (thoron) are the most radiologically important. The isotope ^{222}Rn , with a half-life of approximately 3.82 days, is the most stable and abundant naturally occurring isotope. It decays by emitting alpha particles, producing a series of radioactive progeny capable of delivering significant radiation doses to human tissues following inhalation or ingestion (UNSCEAR, 1993).

Natural background radiation contributes the largest proportion of the annual radiation dose received by humans worldwide. Although artificial radiation sources are extensively utilized in medicine, industry, agriculture, and scientific research, exposure from natural sources—particularly radon and its decay products remains substantially higher for the general population. Numerous epidemiological studies have established radon as the second leading cause of lung cancer after cigarette smoking and the leading cause among non-smokers (Jidele et al., 2021).

Groundwater sources, including boreholes and hand-dug wells, constitute the primary source of drinking water for millions of people globally, especially in rural communities where piped water supplies are limited (Abdullahi, and Toriman, 2015; Daniela et al., 2023; Zarma et al., 2023). During domestic activities such as cooking, bathing, washing, and showering, dissolved radon escapes from water into indoor air, thereby increasing inhalation exposure. Although drinking water contributes only a relatively small fraction of indoor airborne radon, prolonged exposure through both inhalation and ingestion may increase the risk of lung and gastrointestinal cancers (Dankawu et al., 2024). The United States Environmental Protection Agency (USEPA, 1999) estimated that radon in drinking water contributes to approximately 168 cancer-related deaths annually in the United States, with nearly 89% resulting from inhalation of radon released into indoor air and approximately 11% associated with ingestion-related stomach cancer (USEPA, 2008).

In addition to its health implications, radon has several important environmental applications. Owing to its radioactive properties and relatively short half-life, ^{222}Rn is widely used as a natural tracer in hydrogeological investigations, groundwater movement studies, air–water exchange processes, earthquake prediction research, volcanic monitoring, and environmental assessment (Garba et al., 2017; Yashaswini et al., 2020). These applications highlight the dual significance of radon as both an environmental tracer and a public health concern. In Nigeria, inadequate access to safe drinking water remains a significant public health challenge, particularly

in many rural and semi-urban communities. Residents frequently depend on groundwater sources such as boreholes and hand-dug wells for drinking and domestic purposes. Previous investigations conducted in several parts of the country have reported elevated concentrations of radon in groundwater exceeding the guideline values recommended by international regulatory agencies (Dankawu et al., 2021; Ajiboye et al., 2022; Shuaibu et al., 2024). Despite these findings, limited information is available regarding the radiological quality of drinking water in Birnin Kudu Local Government Area of Jigawa State.

Therefore, this study was undertaken to determine the concentration of ^{222}Rn in borehole and hand-dug well water collected from selected communities in Birnin Kudu, Jigawa State, Nigeria. In addition, the study evaluated the associated annual effective dose resulting from inhalation and ingestion as well as the excess lifetime cancer risk for different age groups. The findings are expected to provide baseline radiological data that will support environmental monitoring, public health protection, and evidence-based water resource management in the study area.

MATERIALS AND METHODS

Study Area

This study was conducted in Birnin Kudu Local Government Area, Jigawa State, and northwestern Nigeria. Birnin Kudu is geographically located between latitude $11^{\circ}26'60''\text{N}$ and longitude $9^{\circ}28'30''\text{E}$. The study area occupies approximately 127 km² and has a predominantly Sudan Savannah vegetation characterized by distinct wet and dry seasons.

The area is underlain by geological formations that are rich in crystalline basement rocks, which may contain naturally occurring radionuclides capable of releasing radon into groundwater. The dominant soil types include sandy, clayey, and loamy soils, whose permeability and mineralogical characteristics influence groundwater movement and radon migration (A. G. Abdullahi et al., 2022; A. G. Abdullahi et al., 2024).

Residents of the study area depend largely on groundwater obtained from boreholes and hand-dug wells for drinking and domestic purposes because of limited access to treated municipal water supplies. The sampling locations were carefully selected to provide representative groundwater sources across the study area. The geographical coordinates and descriptions of the sampling sites are presented in **Table 1**, while the location map is shown in **Figure 1**.

Table 1. The geographical coordinates and descriptions of the sampling sites

S/No	Description of sites	Sample soil	Latitude (N)	Longitude (E)	Distance in meters
1	Kakar Dan Sarki	KSK	11°27'28.262N	9°28'14.01E	500m
2	Zarenawa	ZNW	11°27'22'500.N	9°28'30.060''E	350m
3	Tudun Mahauta	TMH	11°21'0.372''	9°28'43.56''E	430m
4	Gangare	GGR	11°27'33.816N	9°28'61.428E	500m

Map of Jigawa state and Birnin kudu local government area illustrating study area



Figure 1. Illustration (a) the map of Jigawa state (b) map of Birnin kudu local government area as a study area comprehensive sample preparation and analytical analysis.

Sample Collection

A comprehensive sampling campaign yielded twenty two (22) water specimens obtained from four (4) distinct geographical locations situated within the Birnin Kudu metropolitan region of Jigawa State, Nigeria. The sampling protocol included collection of four manually-excavated well water samples and four borehole water samples distributed across the designated study sites. Water samples were collected in high-density polyethylene containers that had undergone rigorous cleaning and rinsing procedures utilizing distilled water to prevent extraneous radon contamination. Hand-dug well samples were acquired utilizing bailer equipment, with preliminary purging procedures executed by repeatedly extracting and allowing the wells to replenish, thereby guaranteeing acquisition of representative samples from fresh water sources. Borehole water samples were procured following a minimum operational duration of four minutes preceding collection to ensure sample authenticity. Collection bottles were filled to maximum capacity to minimize atmospheric gas entrapment, then immediately sealed to prevent radon loss through volatilization during laboratory transport. To maintain radionuclide solubility and prevent adsorption onto container surfaces, 20 milliliters of concentrated nitric acid (HNO_3) was introduced to each sample. Subsequent to fieldwork completion, all specimens were expedited to the Center for Energy Research and Training (CERT) at Ahmadu Bello University, Zaria, for

Sample Preparation

About 15 mL of each sample was added into a scintillation vial containing 10 mL of insta-gel scintillation cocktail. The vials were tightly sealed and then shaken thoroughly for three minutes to extract ^{222}Rn in the water phase into the organic scintillator.

Sample Analysis

A well calibrated Liquid Scintillation Counter (Tri-Carb-LSA1000) located at the Center for Energy Research and Training (CERT), Ahmadu Bello University, Zaria – Nigeria. Were used to analyze the prepared samples. The samples were analyzed three hours after preparation, to allow for radioactive equilibrium between ^{222}Rn and its daughter progeny to be established. Equation 1, 2, 3, 4, 5 & 6 was used to determined ^{222}Rn concentration, Annual Effective dose due to inhalation and ingestion for different age categories (adult, children and infant), excess life cancer risk inhalation and ingestion for different age groups (adult, children and infant) for boreholes and local hand dug-wells water sample as determine by (Dankawu et al., 2021; Madaki et al., 2024; UNSCEAR, 1993; UNSCEAR, 2000).

$$R(\text{Bq/L}) = 100 - (SC - BC)e(\lambda t) \quad (i)$$

$$AED_{inh} = CRn \times RW \times F \times T \times DF \times 1000 \quad (ii)$$

$$AED_{ing} = K \times G \times CR_n \times 1000$$

$$ELCR_{inh} = AED_{inh} \times LE \times RF$$

$$ELCR_{ing} = AED_{ing} \times LE \times RF$$

Where:

Rn = Concentration of radon in Bq/L, SC = Count rate of the sample (counts/min), BC = Count rate of the background (counts/min), t = Time elapsed between sample collection and analysis, in minutes, 0.964 = Fraction of ^{222}Rn in the cocktail in a 22 mL total capacity vial, consisting of 12 mL of the sample, 12 mL of cocktail, and 2 mL of air, 5 = Number of emission per count, CR_n = Concentration of ^{222}Rn in water (Bq/L), T = Average residence time of an individual indoors (7000 hours per year), F = Equilibrium factor between radon and its decay products (0.4), RW = Ratio of radon released to air from water use to radon concentration in water (10^{-4}), G = Water ingestion rate (547.5 L/year for children, 182.5 L/year for infants, and 730 L/year for adults), K = Dose coefficient (2×10^{-8} for children, 7×10^{-8} for infants, and 1×10^{-8} for adults), 1000 = Conversion factor from Sv to mSv DF = Conversion dose factor 9nSv (Bqhm-3)⁻¹; AED_{inh} and AED_{ing} denote the annual effective dose in mSv per year due to the inhalation and ingestion of radon emitted from water, respectively, ELCR_{inh} and ELCR_{ing} are the excess life cancer risk for inhalation and ingestion, AED_{inh} and AED_{ing} correspond to the annual effective doses from inhalation and ingestion for various age

- (iii) groups, LE indicates a life expectancy of 70 years, and
 (iv) RF represents the fatal risk factor of 0.05 per Sievert
 (v) (S/v).

Radiological Risk Assessment

The radiological health risks associated with radon in drinking water were evaluated by calculating:

- Radon concentration (Bq L⁻¹)
- Annual effective dose due to inhalation
- Annual effective dose due to ingestion
- Excess lifetime cancer risk (ELCR)

For three population groups:

- Adults
- Children
- Infants

The calculations were performed using internationally accepted dose conversion factors and water consumption rates recommended by UNSCEAR and the World Health Organization (WHO).

The mathematical expressions employed in this study are presented below.

Parameters Used in the Calculations

The symbols used in the equations represent the following quantities:

Symbol	Description
Rn	Radon concentration in water (Bq L ⁻¹)
SC	Sample count rate (counts min ⁻¹)
BC	Background count rate (counts min ⁻¹)
T	Time elapsed between sampling and analysis (minutes)
CR _n	Measured radon concentration (Bq L ⁻¹)
RW	Transfer coefficient of radon from water to indoor air (10^{-4})
F	Radon equilibrium factor (0.4)
T	Indoor occupancy time (7000 h year ⁻¹)
DF	Dose conversion factor (9 nSv h ⁻¹ per Bq m ⁻³)
G	Annual water ingestion rate for adults, children, and infants
K	Age-dependent ingestion dose conversion coefficient

RESULTS AND DISCUSSION

Radon Concentration and Annual Effective Dose in Hand-Dug Well Water

Table 2. ^{222}Rn concentration in BqL-1 and annual Effective dose due to inhalation and ingestion in mSv/y for well water sample

S/N	Samples ID	Rn (Bq l ⁻¹)	AED _{inh} (mSvy ⁻¹)	AED _{ing(A)} (mSvy ⁻¹)	AED _{ing(c)} (mSvy ⁻¹)	AED _{ing(I)} (mSvy ⁻¹)
1	ZNW1	18.59	0.05	0.12	0.21	0.24
2	ZNW2	14.42	0.04	0.14	0.18	0.17
3	KSK 3	19.06	0.05	0.13	0.22	0.26
4	KSK 4	17.19	0.04	0.10	0.16	0.21
5	GGR 6	16.56	0.03	0.11	0.17	0.18
6	GGR 7	17.84	0.04	0.12	0.14	0.19
7	MEAN	16.48	0.05	0.11	0.19	0.20

The radon concentration ranged from 14.42 Bq/L to 19.06 Bq/L, with a reported mean value of 16.48 Bq/L. The highest concentration was recorded at KSK 3, whereas the lowest concentration was observed at ZNW 2.

The estimated annual effective dose due to inhalation ranged from 0.03 to 0.05 mSv y^{-1} , which is below the recommended guideline values for public exposure. In contrast, the annual effective doses due to ingestion were considerably higher across all age groups, with infants receiving the highest dose, followed by children and adults. This trend reflects the greater dose conversion coefficients and physiological sensitivity associated with younger age groups. The observed radon concentrations

exceed the guideline values of 10 Bq/L recommended by the World Health Organization (WHO) and 11.1 Bq/L recommended by the United States Environmental Protection Agency (USEPA), suggesting that prolonged consumption of untreated water from these sources may present potential radiological health risks.

Excess Lifetime Cancer Risk in Hand-Dug Well Water

The excess lifetime cancer risk (ELCR) values estimated from inhalation and ingestion pathways for the hand-dug well water samples are presented in Table 3.

Table 3. Result for excess life cancer risk due to inhalation and ingestion for different age categories (Adult, child and infant) for well water samples

S/N	SAMPLE ID	ELCR _(INH)	ELCR _{(ING)A}	ELCR _{(ING)C}	ELCR _{(ING)I}
1	ZNW1	2.15 E-3	6.18 E-3	9.26 E-3	1.02 E-3
2	ZNW2	1.45 E-3	5.02 E-3	7.37 E-3	8.65 E-3
3	KSK 3	2.16 E-3	6.20 E-3	9.30 E-3	1.04 E-3
4	KSK 4	1.78 E-3	5.45 E-3	8.33 E-3	1.01 E-3
5	GGR 6	1.65 E-3	5.13 E-3	7.54 E-3	9.07 E-3
6	GGR 7	1.57 E-3	5.34 E-3	8.07 E-3	9.21 E-3
7	MEAN	1.76 E-3	5.10 E-3	8.28 E-3	5.04 E-3

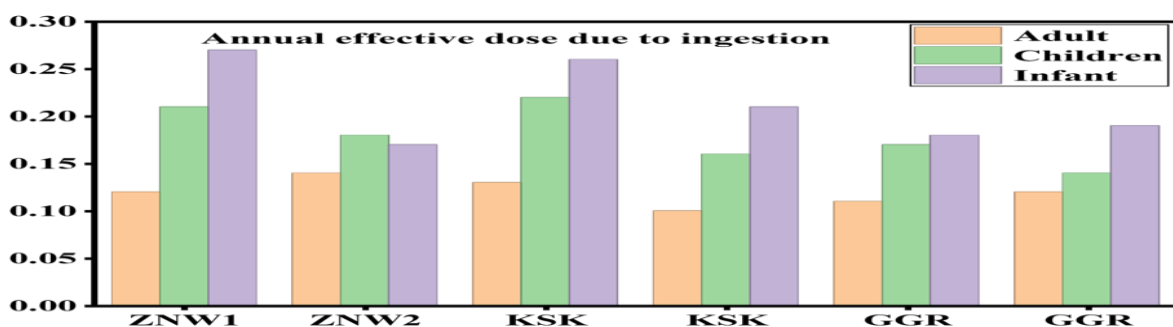
The ELCR due to inhalation remained relatively low for all sampling locations. However, the ingestion pathway produced higher cancer risk estimates, particularly for infants and children. The highest ELCR values were observed at **KSK 3**, corresponding to the location with the highest measured radon concentration, whereas the lowest values were recorded at **ZNW 2**. These findings

indicate a strong positive relationship between radon concentration and estimated lifetime cancer risk, demonstrating that increased radon activity in groundwater results in proportionally higher radiation doses and associated health risks.

Radon Concentration and Annual Effective Dose in Borehole Water

Table 4. The measured radon concentrations and annual effective doses for borehole water samples.

S/N	SAMPLE ID	Rn (Bq ⁻¹)	ID AED _{inh} (mSvy ⁻¹)	AED _{ing(A)} (mSvy ⁻¹)	AED _{ing(C)} (mSvy ⁻¹)	AED _{ing(I)} (mSvy ⁻¹)
1	AGB 25	19.74	0.05	0.09	0.18	0.21
2	AGB26	16.48	0.07	0.18	0.26	0.22
3	UDD 23	16.80	0.07	0.15	0.21	0.20
4	UDD 24	16.23	0.05	0.11	0.15	0.17
	MEAN	16.48	0.05	0.14	0.19	0.20



Among the sampled boreholes, **AGB 25** recorded the highest radon concentration, while **UDD 24** exhibited the lowest concentration.

The annual effective dose due to inhalation remained below internationally accepted safety limits. Nevertheless, the ingestion doses for adults, children, and infants exceeded the recommended values, indicating that

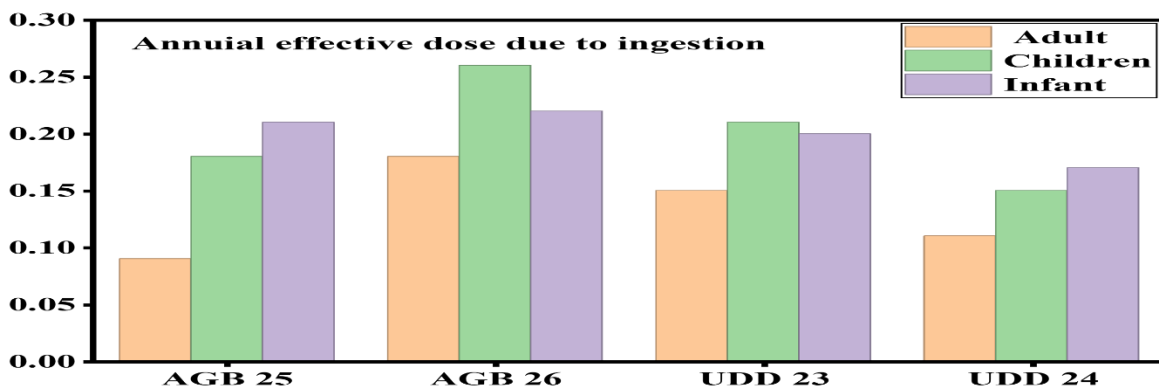
ingestion represents the dominant exposure pathway associated with groundwater consumption in the study area.

Excess Lifetime Cancer Risk in Borehole Water

The calculated excess lifetime cancer risk values for borehole water samples are presented in the Table 5.

Table 5. Result for excess life cancer risk due to inhalation and ingestion for different age categories (Adult, child and infant) for well water samples

S/N	SAMPLE ID	ELCR _(ING)	ELCR _{(ING)A}	ELCR _{(ING)C}	ELCR _{(ING)I}
1	AGB 25	1.42 E-3	4.82 E-3	7.11 E-3	8.32 E-3
2	AGB 26	2.34 E-3	7.28 E-3	0.84 E-3	1.02 E-3
3	UDD 23	1.74 E-3	5.36 E-3	7.21 E-3	0.87 E-3
4	UDD24	1.16 E-3	4.14 E-3	5.71 E-3	7.14 E-3
	MEAN	1.23 E-3	5.24 E-3	5.68 E-3	4.05 E-3



The ELCR resulting from inhalation remained relatively low across all sampling locations, whereas ingestion produced substantially higher risk estimates for all age groups. Infants exhibited the highest estimated lifetime cancer risk because of their greater radiation sensitivity and higher ingestion dose coefficients. The highest ELCR values were observed at AGB 26, while the lowest values occurred at UDD 24, reflecting the corresponding variation in measured radon concentrations. Overall, the results indicate that ingestion of untreated groundwater constitutes the principal radiological health concern in the study area.

The present study evaluated the concentration of ^{222}Rn in borehole and hand-dug well water collected from selected communities in Birnin Kudu Local Government Area, Jigawa State, Nigeria. The results demonstrate that radon is present in all investigated groundwater sources at concentrations exceeding the guideline values recommended by both the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA). The elevated radon concentrations observed in the study area are likely associated with the local geological characteristics. Groundwater flowing through uranium-bearing rocks and mineralized soils

dissolves radon generated from the radioactive decay of uranium and transports it into aquifers. Similar geological influences have been reported in previous studies conducted in northern Nigeria and other regions with crystalline basement formations (Madaki et al., 2025). Comparison with previous Nigerian studies (Table 6) indicates that the measured concentrations are lower than those reported for Dutse, Sokoto, Damaturu, and Ondo but higher than values reported for Kaduna and Ogun States. International comparison (Table 8) similarly shows that the concentrations obtained in the present study exceed those reported in Bangladesh, Pakistan, Iran, and Malaysia, although they remain well below the WHO reference level of 100 Bq/L for drinking water.

The estimated annual effective doses due to inhalation remained below the recommended safety limits, suggesting that radon released into indoor air during normal household water use contributes only a relatively small proportion of the total radiation dose received by the population. Conversely, the estimated annual effective doses due to ingestion exceeded the recommended guideline values for adults, children, and infants. This finding indicates that ingestion represents the dominant exposure pathway and may increase the

probability of developing gastrointestinal cancers following long-term consumption of untreated groundwater. The calculated excess lifetime cancer risk followed the same trend as the annual effective dose, with ingestion producing substantially higher risk estimates than inhalation. Infants consistently exhibited the highest estimated risk because of their greater radiosensitivity and age-dependent dose conversion factors. These findings are consistent with previous investigations conducted in Dutse, Sokoto, and other parts of northern Nigeria, where ingestion was identified as the principal pathway contributing to radiological health risks associated with groundwater consumption. Overall, the findings demonstrate that although the inhalation

pathway poses minimal risk, prolonged consumption of untreated groundwater from the investigated locations may constitute a significant public health concern. Regular radiological monitoring, together with appropriate water treatment technologies such as aeration, storage before consumption, or activated carbon filtration, is therefore recommended to reduce radon concentrations and protect public health.

2024; Dankawu et al., 2022), the findings are consistent with investigations by Abdurashid et al. (2024), Shuaibu et al. (2024), Madaki et al. (2024), and Dankawu et al. (2022), demonstrating that risk estimates exceed the WHO acceptable baseline of $2.9E^{-4}$.

Table 6. Comparison of ^{222}Rn Concentration obtained with previous Nigerian study

Locations	^{222}Rn Conc. (Bq l^{-1})	Reference
Kaduna	10.69	(Garba and Hussaini, 2018).
Zaria	12.43	(Garba et al, 2017).
Lagos	18.8	(Mostafa et al., 2022)
Sokoto	34.00	(Abba et al, 2020).
Jos	17.00	(Aminu, 2020).
Dutse	83.77	(Dankawu et al., 2021)
FUD	21.77	(Madaki et al., 2025)
Ogun	7.7	(Jidele et al., 2021)
Damaturu	64.66	(Adams, 2017).
Abeokuta	14.3	Farai et al., 2023
Ondo	35.9	(Ajiboye et al., 2022)
Niger	17.3	(Kolo et al., 2023)
Birnin kudu	16.48	Current Study 2026

Table 7. Comparison of ^{222}Rn Concentration obtained with world Standard

^{222}Rn Conc. (Bq l^{-1})	Standards
10	UNSCEAR,1993; WHO, 2004
11.1	(USEPA, 2003)
11.1	SON
4.0-40.0	UNSCEAR, 1993
100	(Current study, 2024)
16.48	Current study 2026

Table 8. Comparison of ^{222}Rn Concentration obtained with Other Countries

Countries	^{222}Rn Conc. (Bq l^{-1})	Reference
Bangladesh	4.42	(Sudhir, et al, 2016).
Pakistan	2.4	(Tabar and Yakut, 2014)
Iran	1.2	(Malakootian, et al, 2017)
Malaysia	14.7	(Nasar, et al, 2015).
Birnin kudu	16.48	Current study, 2026

Table 9. Comparison of annual effective doses due to inhalation and ingestion from Dutse with others related research

Locations	$E_{inh}(mSvy^{-1})$	$EA_{ing}(mSvy^{-1})$	$EC_{ing}(mSvy^{-1})$	$EI_{ing}(mSvy^{-1})$	References
Sokoto	0.04	2.48	3.72	4.34	Abba et al.,2020
Daura	-	0.47	0.944	3.304	Adams 2017
FUD	0.06	0.161	0.237	0.278	Madaki et al., 2024
Dutse	0.24	0.69	1.030	1.202	Dankawu et al., 2021
Jos	-	0.12	-	-	(Aminu et al., 2020)
Birnin kudu	0.05	0.11	0.19	0.20	Current study 2026

CONCLUSION

This study assessed the concentration of radon (^{222}Rn) and its associated radiological health risks in drinking water obtained from selected communities in Birnin Kudu Local Government Area, Jigawa State, Nigeria. A total of eight (8) groundwater samples, comprising four hand-dug well water samples and four borehole water samples, were collected and analyzed using a Tri-Carb LSA-1000 Liquid Scintillation Counter at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria. The analysis revealed that the mean radon concentration in the investigated water sources exceeded the guideline limits recommended by the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA). Although the estimated annual effective doses due to inhalation remained below the recommended public exposure limits, the annual effective doses resulting from ingestion and the corresponding excess lifetime cancer risks exceeded the recommended safety levels, particularly among infants and children. The elevated radon concentrations observed in the groundwater are most likely associated with the geological characteristics of the study area, where uranium-bearing rocks and mineralized soils contribute to radon generation and dissolution into groundwater. Consequently, prolonged consumption of untreated groundwater from the investigated locations may increase the probability of developing gastrointestinal cancers.

Based on these findings, the study concludes that the investigated groundwater sources require appropriate treatment before being used for drinking and domestic purposes. Routine radiological monitoring of groundwater, public awareness programmes, and the implementation of suitable radon mitigation techniques such as aeration, storage prior to consumption, or activated carbon filtration are strongly recommended to reduce potential health risks. Finally, the results of this

study provide valuable baseline radiological data for groundwater quality assessment and will assist environmental protection agencies, public health authorities, and water resource managers in developing appropriate strategies for safeguarding drinking water quality in Birnin Kudu and similar geological environments.

ACKNOWLEDGMENT

The authors sincerely appreciate the technical support provided by the staff of the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, during the laboratory analysis of the water samples. The authors also acknowledge the cooperation of the residents of the selected communities in Birnin Kudu Local Government Area during sample collection.

The authors are equally grateful to the Department of Public Health, School of Public Health, University of Port Harcourt, Nigeria, for their encouragement and academic support throughout the course of this research.

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