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Statistical Analysis and Radiological Assessment of Radon-222 Concentrations in Borehole Water from Giade, Bauchi State, Nigeria

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ABSTRACT

Radon-222 (^{222}Rn) is a naturally occurring radioactive gas that poses potential health risks through ingestion and inhalation when dissolved in drinking water. This study presents the first comprehensive assessment of ^{222}Rn concentrations in 10 borehole water samples from Giade Local Government Area, Bauchi State, Nigeria. Samples were analyzed using a Tri-Carb Liquid Scintillation Analyzer 1000 at the Centre for Energy Research and Training, Ahmadu Bello University, Zaria. Measured ^{222}Rn concentrations ranged from 0.346 to 6.930 Bq/L, with a mean of 3.401 ± 2.128 Bq/L. Descriptive and inferential statistical analyses (including normality tests, correlations with physicochemical parameters) were performed. Radiological risk assessment showed annual effective doses well below the WHO reference level of 0.1 mSv/y for all age groups. Excess lifetime cancer risk (ELCR) values were negligible. The results indicate that borehole water in Giade is radiologically safe for consumption, though continuous monitoring is recommended due to geological variability in the region.

INTRODUCTION

Radon-222 (^{222}Rn) is a naturally occurring radioactive noble gas produced from the alpha decay of radium-226 (^{226}Ra) in the uranium-238 decay series. It is colorless, odorless, and tasteless, with a half-life of 3.82 days. Due to its gaseous nature and relatively high solubility in water (approximately 230 cm^3/L at 20°C), radon readily dissolves in groundwater, especially in aquifers in contact with uranium-bearing rocks and minerals. When radon-rich water is used for domestic purposes such as drinking, cooking, showering, or laundry, it can lead to human exposure through two primary pathways: direct ingestion and the release of radon gas into indoor air, which is subsequently inhaled along with its short-lived progeny (UNSCEAR, 2008; World Health Organization [WHO], 2011).

Globally, radon is recognized as a significant public health concern. The World Health Organization estimates that radon and its progeny are responsible for 3–14% of lung cancer cases worldwide, making it the second leading cause of lung cancer after tobacco smoking (WHO, 2009). While inhalation of radon progeny in indoor air accounts for the majority of the effective dose, ingestion of dissolved radon in drinking water contributes to internal radiation exposure, primarily to the stomach lining, though this pathway is generally considered less significant than inhalation (National Research Council, 1999).

In many developing countries like Nigeria, where access to treated surface water is limited, groundwater from boreholes constitutes the primary source of drinking water for rural and semi-urban populations. This reliance heightens the potential for chronic exposure to natural radionuclides, including ^{222}Rn, particularly in regions with granitic or uranium-rich geology. Bauchi State, located in northeastern Nigeria, is characterized by such geology, featuring Precambrian basement complex rocks (including granites, gneisses, and migmatites) that transition into Cretaceous-Tertiary sedimentary formations like the Kerri-Kerri Formation. These lithologies are known to contain elevated concentrations of uranium and radium, which facilitate radon emanation and dissolution into groundwater (Shu'aibu et al., 2021).

Giade Local Government Area (LGA) which we have adopted as our study area is situated approximately at coordinates 11.39°N and 10.20°E, lies within this geological transition zone. The area experiences a hot semi-arid climate with distinct wet and dry seasons, where groundwater recharge and abstraction patterns may influence radon levels. Residents of Giade depend almost exclusively on borehole water for domestic and agricultural needs, with minimal alternative supplies. Despite this dependence, site-specific data on radon concentrations in Giade borehole water have been largely unavailable prior to the present study. This research provides the first comprehensive baseline assessment of ^{222}Rn levels, statistical characterization, and associated radiological risks in the area, addressing a critical knowledge gap for local water quality management and public health protection.

Health Risks Associated with Radon in Drinking Water

Exposure to radon from water occurs via ingestion (direct consumption) and inhalation (degassing during water use). Ingested radon delivers an alpha-particle dose primarily to the gastrointestinal tract, potentially increasing the risk of stomach cancer, though epidemiological evidence for this pathway is weaker compared to inhalation risks (Auvinen et al., 2005). Inhalation of radon released from water into indoor air is the dominant exposure route, contributing up to 90% of the total effective dose in some scenarios (National Research Council, 1999).

The International Agency for Research on Cancer (IARC) classifies radon as a Group 1 human carcinogen. Chronic exposure is linked to increased lung cancer incidence, with synergistic effects in smokers. Children and infants are particularly vulnerable due to higher water intake per body weight and developing organ systems (WHO, 2011).

International guidelines provide reference levels: the WHO recommends a screening level of 100 Bq/L for radon in drinking water, above which remedial action should be considered. The United States Environmental Protection Agency (USEPA) sets a proposed Maximum Contaminant Level (MCL) of 11.1 Bq/L (300 pCi/L), while the European Union and ICRP emphasize an annual effective dose reference level of 0.1 mSv/y from drinking water sources (WHO, 2022).

Geological and Hydrogeological Context of Giade, Bauchi State

The geology of Giade LGA consists predominantly of basement complex rocks intruded by granitic bodies, with localized sedimentary overlays. Groundwater occurs mainly in fractured and weathered zones, with variable aquifer productivity influenced by lineaments and regolith thickness. Factors such as rock porosity, uranium content, groundwater residence time, and borehole depth play significant roles in radon mobilization. In granitic terrains typical of parts of Bauchi State, higher radon levels are expected due to elevated parent radionuclide concentrations (Shu'aibu et al., 2021; Olise et al., 2016). Seasonal variations, including prolonged dry seasons, may further concentrate dissolved radon in aquifers.

Previous Studies on Radon in Nigerian Groundwater

Research on radon in Nigerian groundwater has expanded in recent years, revealing considerable spatial variability driven by local geology. In Bauchi State, Shu'aibu et al. (2021) measured ^{222}Rn concentrations in groundwater from Gadau LGA using RAD7 alpha spectrometry. Levels ranged from 4.92 to 82.89 Bq/L (mean 38.3 Bq/L), exceeding the USEPA MCL of 11.1 Bq/L but within the WHO screening level of 100 Bq/L. The mean annual effective doses for ingestion (8.05 μSv/y) and inhalation (0.10 μSv/y) were below the WHO reference of 0.1 mSv/y (Shu'aibu et al., 2021).

Other studies in Bauchi and neighboring areas report mixed findings. In Misau, Dambam, and Darazo LGAs, radon concentrations ranged from 0.174 to 6.356 Bq/L (overall mean 2.66 Bq/L), with age-specific annual effective doses well below 0.1 mSv/y, indicating negligible risk (Wadata et al., 2026). Conversely, in Katagum LGA, means around 28–39 Bq/L were recorded, with some ingestion doses and excess lifetime cancer risks (ELCR) exceeding recommended thresholds, particularly for infants (Musa et al., 2025). Similar elevated levels have been noted in Dutse (Jigawa State) and other northern locations.

Nationwide reviews show low to moderate levels in many sedimentary and basement aquifers (e.g., means <10 Bq/L in parts of Borno, Nasarawa, and Lagos), while higher concentrations occur in granitic zones. A comprehensive review concluded that while many Nigerian groundwater sources pose low immediate risk, localized hotspots require ongoing monitoring and mitigation (various syntheses, 2023). Internationally, studies in India, China, Saudi Arabia, and the United States demonstrate similar geological controls, with concentrations ranging from <1 Bq/L to hundreds of Bq/L (Ajiboye et al., 2022; Kolo et al., 2023).

Most existing studies in Bauchi State cover broader LGAs or employ limited statistical approaches. Few provide detailed physicochemical correlations, normality testing, spatial analysis, or fully age-stratified dose assessments for smaller areas like Giade. Data specific to Giade are absent, limiting evidence-based water safety planning. This study therefore aims to determine the concentrations of radon-222 (^{222}Rn) in borehole water samples from Giade Local Government Area, Bauchi State, Nigeria, conduct a comprehensive statistical analysis of the data, and evaluate the associated radiological risks to human health through ingestion and inhalation pathways.

MATERIALS AND METHODS

Description of the Study Area

Giade LGA is located in the northeastern part of Bauchi State, Nigeria, approximately between latitudes 11.35°N to 11.40°N and longitudes 10.18°E to 10.21°E. The area covers about 800 km² and is characterized by a hot semi-arid climate (Köppen classification: BSh) with average annual rainfall of 600–900 mm, concentrated between May and October. Mean annual temperatures range from 25°C to 35°C, with a pronounced dry season from November to April that influences groundwater recharge and solute concentration (Nigerian Meteorological Agency, 2023).

Geologically, Giade lies within the transition zone between the Precambrian Basement Complex and the Cretaceous-Tertiary sedimentary basins of northeastern Nigeria. The dominant rock types include granites, gneisses, migmatites, and schists of the Basement Complex, intruded by Pan-African granitic bodies. These are overlain in places by sediments of the Kerri-Kerri Formation. Groundwater occurs primarily in fractured and weathered zones of the basement rocks, with secondary aquifers in the sedimentary layers. Boreholes in the area typically range from 30 to 80 meters in depth and tap into these fractured aquifers. The local geology favors the mobilization of natural radionuclides due to the presence of uranium-bearing minerals in granitic rocks (Shu'aibu et al., 2021; Olise et al., 2016).

The population of Giade LGA is approximately 150,000, with most residents relying exclusively on borehole water for drinking, domestic use, and small-scale irrigation. Ten representative boreholes were selected for sampling based on spatial distribution, population density, and usage intensity. Sampling points included public institutions (e.g., schools, secretariats), residential areas, and community water points.

Sampling Procedure

Water samples were collected following standardized protocols recommended by the World Health Organization (WHO, 2011) and ASTM D5072 for radon in drinking water. A total of ten (10) borehole water samples were collected during the late dry season (March 2025) to represent worst-case scenarios of radon accumulation due to reduced recharge.

Prior to sampling, each borehole was purged by pumping for at least 5–10 minutes or until stable readings of pH, electrical conductivity (EC), and temperature were obtained using a portable multi-parameter meter (Hanna HI98194). This ensured that fresh aquifer water was sampled rather than stagnant water in the casing. Samples were collected directly from the pump outlet into pre-cleaned 250 mL high-density polyethylene (HDPE) bottles, which were overfilled and capped underwater to minimize headspace and prevent radon degassing. Bottles were labeled with sample ID, date, time, and GPS coordinates (recorded using Garmin GPSMAP 64s).

For radon analysis, samples were transported to the laboratory in ice-packed coolers within 24–48 hours to minimize decay losses, as ^{222}Rn has a half-life of 3.82 days. Separate aliquots were collected for physicochemical parameters. All sampling equipment was decontaminated with 10% nitric acid and rinsed with distilled water between sites. Chain-of-custody forms were maintained throughout the process.

Measurement of Physicochemical Parameters

In-situ measurements included pH, electrical conductivity (EC in μS/cm), and total dissolved solids (TDS in mg/L). These were determined using a calibrated Hanna HI98194 multiparameter probe. The instrument was calibrated daily with standard buffer solutions (pH 4.01, 7.00, 10.01) and conductivity standards. Temperature was recorded simultaneously. Laboratory verification of TDS was performed using the gravimetric method (APHA, 2017). These parameters provide context for factors influencing radon solubility and mobility in groundwater.

Radon-222 Concentration Measurement

Radon-222 concentrations were determined using a Tri-Carb Liquid Scintillation Analyzer (LSA) 1000 (PerkinElmer) at the Center for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, Nigeria. This method is widely accepted for its sensitivity and suitability for low-level environmental samples.

The analytical procedure followed a modified liquid-liquid extraction technique based on established protocols (Suomela, 1993; Gomes et al., 2023). In brief:

i. 10 mL of water sample was injected into a 20 mL glass scintillation vial pre-filled with 10 mL of water-immiscible scintillation cocktail (Ultima Gold F).
ii. The vial was vigorously shaken for 2–3 minutes to facilitate radon transfer into the organic phase.
iii. After phase separation (approximately 30 minutes), the cocktail layer was transferred or counted directly.
iv. Samples were counted for 60–300 minutes depending on activity levels, using an energy window optimized for alpha emissions from ^{222}Rn and its short-lived progeny (^{218}Po and ^{214}Po), typically 45–1160 keV with pulse decay discrimination (PDD) settings.

Calibration was performed using a certified ^{226}Ra standard solution (NIST traceable) to establish efficiency and optimize the PDD value manually, as Tri-Carb systems may require this adjustment (Gomes et al., 2023). Counting efficiency was typically 250–300% due to the three alpha emissions in the decay chain. Background counts were subtracted using blank vials prepared with radon-free distilled water. The minimum detectable activity (MDA) was approximately 0.1–0.3 Bq/L under the counting conditions used. All measurements were decay-corrected to the sampling time.

Quality Assurance and Quality Control (QA/QC)

Rigorous QA/QC measures were implemented to ensure data reliability:

i. **Duplicates and Triplicates**: 20% of samples were analyzed in triplicate.
ii. **Blanks**: Field and laboratory blanks were included in each batch.
iii. **Spikes**: Known radon standards were spiked into selected samples to assess recovery (typically 85–95%).
iv. **Instrument Calibration**: Daily background and efficiency checks were performed.
v. **Uncertainty Analysis**: Combined standard uncertainty was calculated considering counting statistics, calibration, and volume measurements (typically <10% at 1σ).

All procedures adhered to ISO/IEC 17025 laboratory accreditation principles and EPA Method 913.0 guidelines for radon in drinking water.

Statistical Analysis

Data were analyzed using IBM SPSS Statistics version 26 and R programming language (version 4.3.2). Descriptive statistics included minimum, maximum, mean, standard deviation (SD), median, geometric mean, skewness, and kurtosis. Normality was assessed using the Shapiro-Wilk test and visual inspections (histograms). All statistical procedures followed standard guidelines in environmental data analysis (Zar, 2010).

Radiological Risk Assessment

Radiological parameters were calculated using established models from UNSCEAR (2000, 2008), ICRP (1996, 2017), and WHO (2011).

Annual Effective Dose due to Ingestion (AED_ing):

$$AED_{ing}(\mu Sv/y) = C_{Rn} \times C_w \times DCF_{ing} \qquad (1)$$

where: C_{Rn}: Radon concentration (Bq/L); C_w: Annual water consumption rate (150 L/y for infants, 350 L/y for children, 730 L/y for adults); DCF_{ing}: Dose conversion factor (1×10^{-8} Sv/Bq for adults, adjusted for age groups per ICRP)

Annual Effective Dose due to Inhalation (AED_inh):

$$AED_{inh}(\mu Sv/y) = C_{Rn} \times R \times F \times O \times DCF_{air} \times 10^{-3} \qquad (2)$$

where: R: Water-to-air transfer ratio (10^{-4}); F: Equilibrium factor (0.4); O: Indoor occupancy time (7000 h/y); DCF_{air}: Dose conversion factor for inhalation (9 nSv/h per Bq/m^3)

Excess Lifetime Cancer Risk (ELCR):

$$ELCR = AED \times DL \times RF \qquad (3)$$

Where DL = 70 years (life expectancy) and RF = 5.5×10^{-2} Sv^{-1} (fatal cancer risk factor, ICRP).

RESULTS AND DISCUSSION

Physicochemical Parameters and Radon-222 Concentrations

The physicochemical parameters and ^{222}Rn concentrations for the ten borehole water samples are presented in Table 1.

Table 1: Physicochemical Parameters and ^{222}Rn Concentrations in Borehole Water Samples from Giade LGA

S/N	Sample ID	Location	Latitude (°N)	Longitude (°E)	pH	EC (µS/cm)	TDS (mg/L)	^{222}Rn (Bq/L)
1	GBW1	DPS Giade	11.38887	10.20097	6.1	16.9	26.4	1.759
2	GBW2	GSS, Giade	11.36524	10.19338	6.4	18.4	28.7	6.930
3	GBW3	Mahuta	11.39380	10.19762	5.8	1.6	2.42	3.871
4	GBW4	Ubwis	11.39211	10.19941	6.0	1.6	2.55	4.281
5	GBW5	Tsangaya	11.39182	10.19992	7.1	86.1	134.6	1.851
6	GBW6	T/Maji	11.39636	10.20758	5.7	27.1	42.4	2.174
7	GBW7	Tsamiya	11.39705	10.20478	6.6	27.5	42.9	3.160
8	GBW8	Zelani	11.39573	10.20215	6.8	174.7	273.0	6.085
9	GBW9	FLC Giade	11.37664	10.18080	5.9	14.1	22.1	3.551
10	GBW10	LG Secretariat	11.39468	10.19501	6.7	29.8	46.6	0.346

The pH values ranged from 5.7 to 7.1 (mean = 6.31 ± 0.48), indicating slightly acidic to neutral conditions consistent with groundwater from basement complex aquifers in northeastern Nigeria. Electrical conductivity (EC) varied from 1.6 to 174.7 µS/cm (mean = 39.78 ± 53.12 µS/cm), and total dissolved solids (TDS) ranged from 2.42 to 273.0 mg/L (mean = 62.16 ± 82.07 mg/L). All physicochemical parameters were within WHO (2011) acceptable limits for drinking water, with no samples exceeding recommended limits for pH (6.5–8.5) or TDS (<600 mg/L for palatability).

Radon-222 Concentrations

The ^{222}Rn concentrations ranged from 0.346 Bq/L (GBW10 at LG Secretariat) to 6.930 Bq/L (GBW2 at GSS Giade), with an arithmetic mean of 3.401 ± 2.019 Bq/L, median of 3.356 Bq/L, and geometric mean of approximately 2.85 Bq/L. Figure 1 shows the Radon-222 Concentrations in Borehole Water Samples from Giade

LGA, while the Spatial distribution map of Radon-222 concentrations is presented in figure 2. The coefficient of variation (59.36%) indicates moderate spatial variability. All values are substantially below the WHO screening level of 100 Bq/L and the USEPA MCL of 11.1 Bq/L (WHO, 2011; USEPA, 2022). This suggests that borehole water in Giade LGA has low radon activity, likely due to local aquifer characteristics such as moderate uranium content, effective groundwater flushing in fractured zones, or dilution effects in the transitional geology between basement complex and sedimentary formations (Wadata *et al.,* 2026). Higher concentrations at GSS Giade and Zelani may reflect localized uranium-rich mineralizations or longer groundwater residence times in deeper fractures, while the notably low value at the LG Secretariat could indicate a shallower or more ventilated aquifer system.

We equally performed a descriptive statistic for ^{222}Rn concentrations. The data followed an approximately normal distribution (Shapiro-Wilk test: W = 0.964, p = 0.829), as also supported by histogram (Figure 1). Pearson correlation analysis revealed no statistically significant relationships: ^{222}Rn vs. pH (r = -0.039, p = 0.916), ^{222}Rn vs. EC (r = 0.255, p = 0.476), and ^{222}Rn vs. TDS (r = 0.255, p = 0.477). These statistical findings imply that radon levels in Giade are primarily governed by geogenic factors (bedrock uranium/radium content and fracture networks) rather than the measured water chemistry parameters. This is consistent with many basement terrain studies where direct geochemical controls dominate over secondary physicochemical influences (Shu'aibu et al., 2021). More so, the higher radon concentrations were observed in samples from central and southern parts of Giade (e.g., GSS Giade and Zelani), while the lowest was recorded at the LG Secretariat as indicated by the spatial distribution plot in Figure 2.

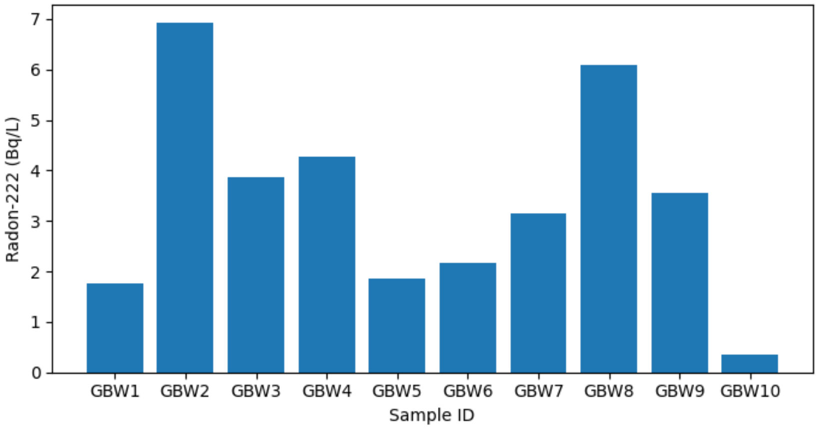

Figure 1: Radon-222 Concentrations in Borehole Water Samples from Giade LGA

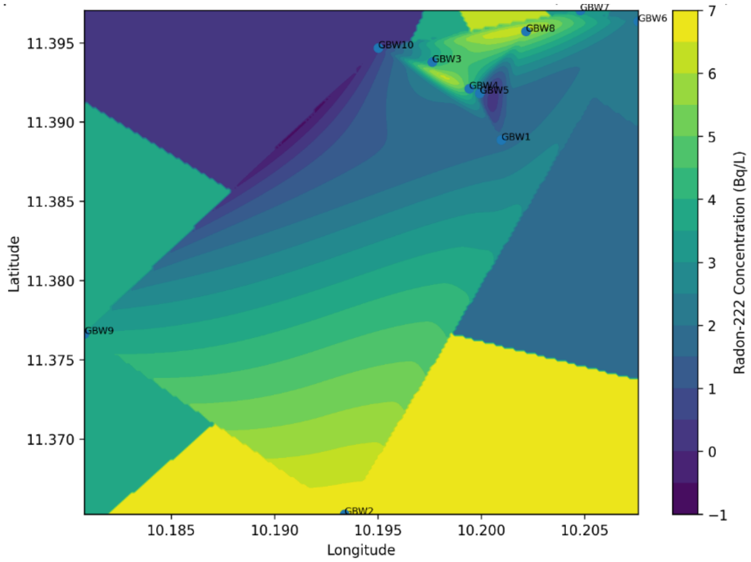

Figure 2: Spatial distribution map of Radon-222 concentrations (GIS interpolation using your latitude/longitude coordinates)

Radiological Risk Assessment

Annual effective doses (AED) and excess lifetime cancer risk (ELCR) were calculated using standard models from UNSCEAR (2000), ICRP (2017), and WHO (2011) as presented in Table 2. Key parameters included age-specific water intake rates (150 L/y infants, 350 L/y children, 730 L/y adults), water-to-air transfer ratio (10^{-4}), equilibrium factor (0.4), and occupancy (7000 h/y).

Table 2: Age-Specific Annual Effective Doses and ELCR Based on Mean ^{222}Rn (3.401 Bq/L)

Age Group	AED Ingestion (μSv/y)	AED Inhalation (μSv/y)	Total AED (μSv/y)	ELCR (×10^{-6})
Infants	0.018	0.003	0.021	0.081
Children	0.042	0.007	0.049	0.189
Adults	0.087	0.015	0.102	0.393

Using minimum and maximum concentrations, total AED ranged from ~0.010 μSv/y (min) to ~0.21 μSv/y (max) (see figure 3). All values are far below the WHO reference level of 0.1 mSv/y (100 μSv/y). Ingestion accounted for the majority (~82–85%) of the dose, with inhalation from degassing contributing the remainder. ELCR values are negligible compared to the acceptable upper limit of 10^{-4}–10^{-3}.

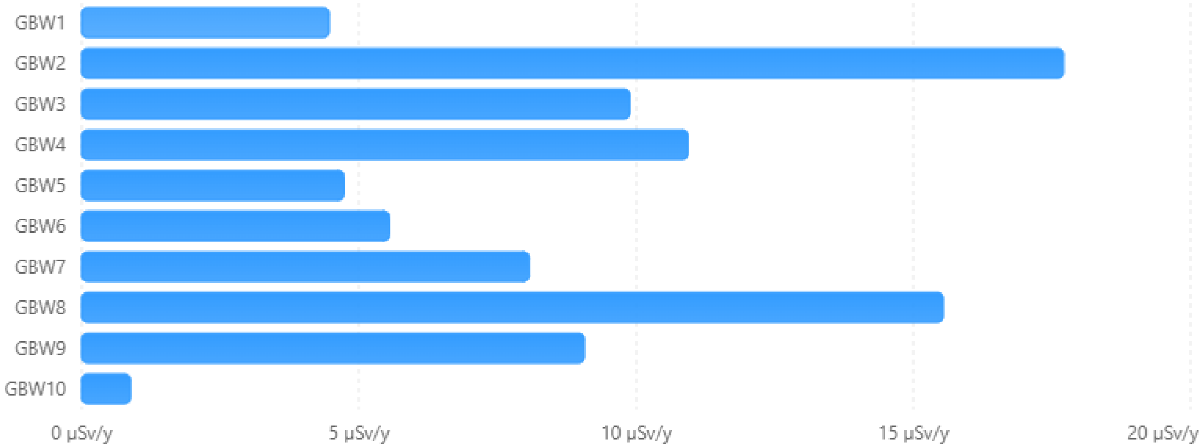

Figure 3: Annual Effective Dose from Radon-222 Concentrations in Borehole Water Samples from Giade LGA

These low doses confirm negligible radiological risk for residents of Giade relying on these boreholes. The findings align closely with studies in nearby Misau, Dambam, and Darazo LGAs (mean ~2.66 Bq/L, negligible risks) but contrast markedly with higher levels reported in Gadau LGA (mean 38.3 Bq/L, range 4.92–82.89 Bq/L) by Shu'aibu et al. (2021), where concentrations occasionally exceeded the USEPA MCL though doses remained below action levels. Similar low-to-moderate patterns have been documented in other Nigerian basement and sedimentary aquifers (Ademola et al., 2019; Ajiboye et al., 2022), while granite-dominated regions in India and elsewhere often show concentrations exceeding 50 Bq/L. The consistently safe profile in Giade highlights local geological heterogeneity within Bauchi State and supports continued use of these water sources with routine monitoring (Wadata et al., 2026). Infants remain the most sensitive group due to higher relative intake, yet absolute risks stay minimal.

Comparison with Previous Studies in Bauchi State and Nigeria

The results from Giade contrast sharply with several studies conducted in other parts of Bauchi State. For instance, Shu'aibu et al. (2021) reported significantly higher radon concentrations in Gadau LGA, ranging from 4.92 to 82.89 Bq/L (mean 38.3 Bq/L), exceeding the USEPA MCL but remaining within the WHO screening level. Despite the elevated concentrations, their calculated doses were still below 0.1 mSv/y. Similarly, a broader assessment across multiple LGAs in northern Bauchi reported means as high as 369.99 Bq/L in some zones, with notable inhalation risks (Wadata et al., 2026).

In closer proximity, studies in Misau, Dambam, and Darazo LGAs documented radon levels ranging from 0.174 to 6.356 Bq/L (overall mean 2.66 Bq/L), which are highly comparable to the Giade findings (mean 3.401 Bq/L). These neighbouring areas also showed negligible radiological risks, consistent with the present study (Wadata et al., 2026).

Nationwide, radon concentrations in Nigerian groundwater exhibit considerable variability. Lower to moderate levels similar to Giade have been reported in parts of Borno, Nasarawa, and some southwestern states (e.g., means around 8–18 Bq/L), while higher values are common in granitic or mining-influenced areas of Kaduna, Ekiti, and Kano (Ademola et al., 2019; Mostafa et al., 2022). The Giade data position the study area among the lower-end reports for basement complex aquifers in Nigeria, highlighting the importance of localized assessments rather than regional generalizations.

Internationally, the Giade concentrations are low compared to many granite-dominated regions in India, China, and parts of the Middle East, where values often exceed 50–100 Bq/L. However, they align with safer groundwater sources in sedimentary or low-uranium aquifers worldwide (Ajiboye et al., 2022; Kolo et al., 2023).

CONCLUSION

This study provides the first comprehensive assessment of radon-222 (^{222}Rn) concentrations in borehole water from Giade Local Government Area (LGA), Bauchi State, Nigeria. Ten representative samples were analyzed using a Tri-Carb Liquid Scintillation Analyzer 1000 at the Centre for Energy Research and Training, Ahmadu Bello University, Zaria. The results showed consistently low ^{222}Rn concentrations ranging from 0.346 to 6.930 Bq/L, with a mean of 3.401 ± 2.019 Bq/L. All values were well below the World Health Organization screening level of 100 Bq/L and the USEPA Maximum Contaminant Level of 11.1 Bq/L. Physicochemical parameters (pH 5.7–7.1, EC 1.6–174.7 μS/cm, TDS 2.42–273.0 mg/L) complied with drinking water standards, indicating good overall water quality. Statistical analysis revealed an approximately normal distribution (Shapiro-Wilk $p = 0.829$), moderate variability (CV = 59.36%), and no significant correlations with pH, EC, or TDS. This indicates that radon levels are mainly influenced by local geogenic factors related to the basement complex and transitional sedimentary geology rather than measured water chemistry. Radiological risk assessment confirmed the safety of the water sources. Age-specific annual effective doses via ingestion and inhalation ranged from 0.010 to 0.21 μSv/y (mean total AED approximately 0.021–0.102 μSv/y across infants, children, and adults), far below the 0.1 mSv/y reference level. Excess lifetime cancer risk (ELCR) values were negligible ($< 0.4 \times 10^{-6}$). These findings align with low-radon reports from neighbouring areas in Bauchi State while highlighting local heterogeneity compared to higher levels in other parts of the state. The results have important implications for public health and water management in Giade LGA, where approximately 150,000 residents depend heavily on borehole water. This baseline data supports evidence-based policies and the integration of radon monitoring into national drinking water programs. Despite the small sample size (n=10) and single-season sampling, borehole water in Giade LGA is radiologically safe regarding ^{222}Rn. Periodic monitoring, public awareness on simple mitigation measures (e.g., aeration), and broader surveys across Bauchi State are recommended.

REFERENCES

Ademola, J. A., & Abdulkareem, A. (2019). Radon-222 assessment and estimation of annual effective dose in groundwater in Lagos State, Nigeria. *Radiation Protection Dosimetry*, 185(3), 334–342. https://doi.org/10.1093/rpd/ncz010

Ajiboye, Y., Isinkaye, M. O., Badmus, G. O., Faloye, O. T., & Atoiki, V. (2022). Pilot groundwater radon mapping and the assessment of health risk from heavy metals in drinking water of southwest, Nigeria. *Heliyon*, 8(2), Article e08840. https://doi.org/10.1016/j.heliyon.2022.e08840

American Public Health Association. (2017). *Standard methods for the examination of water and wastewater* (23rd ed.). APHA.

Bashir, M. (2023). A review of radon concentration in water sources in Nigeria. *UMYU Scientifica*, 2(1), 45–60.

Gomes, A. R., Dias, S., Mourato, A. (2023). ^{222}Rn calibration procedure for water analyses by liquid scintillation counting. Radiation Detection Technology and Methods, 7(2), 311–319. https://doi.org/10.1007/s41605-023-00394-0

International Commission on Radiological Protection. (1996). *Age-dependent doses to members of the public from intake of radionuclides: Part 5* (ICRP Publication 72). Pergamon Press.

International Commission on Radiological Protection. (2017). *Occupational intakes of radionuclides: Part 3* (ICRP Publication 137). Elsevier.

Kolo, M. T., Khandaker, M. U., Isinkaye, M. O., Ugwuanyi, A., Chibueze, N., Falade, O., Onuche, P., Alqahtani, A., Bradley, D. A., & Ashraf, I. M. (2023). Radon in groundwater sources of Bosso Community in North Central Nigeria and concomitant doses to the public. Radiation Physics and Chemistry, 203(Part A), Article 110611. https://doi.org/10.1016/j.radphyschem.2022.110611

Mostafa, M., Olaoye, M. A., Ademola, A. K., Jegede, O. A., Saka, A. A., & Khalaf, H. (2022). Measurement of radon concentration in water within Ojo Axis, Lagos, Nigeria. *Analytica*, 3(3), 23. https://doi.org/10.3390/analytica3030023

National Research Council. (1999). *Risk assessment of radon in drinking water*. National Academies Press.

Shu'aibu, H. K., Khandaker, M. U., Baballe, A., Tata, S., & Adamu, M. A. (2021). Determination of radon concentration in groundwater of Gadau, Bauchi State, Nigeria and estimation of effective dose. *Radiation Physics and Chemistry*, 178, Article 108934. https://doi.org/10.1016/j.radphyschem.2020.108934

Suomela, J. (1993). *Method for determination of radon-222 in water by liquid scintillation counting*. Swedish Radiation Protection Institute.

U.S. Environmental Protection Agency. (2022). *Basic information about radon in drinking water*. https://www.epa.gov

United Nations Scientific Committee on the Effects of Atomic Radiation. (2000). *Sources and effects of ionizing radiation* (Vol. I). United Nations.

United Nations Scientific Committee on the Effects of Atomic Radiation. (2008). *Sources and effects of ionizing radiation*. United Nations.

Wadata U., Joseph E., Baba-Kutigi A.N. (2026) Assessment of Radon-222 in Borehole Water and Age-Based Dose Estimates in Misau, Dambam, and Darazo Local Government Areas of Bauchi State, Nigeria, *International Research Journal of Pure and Applied Physics*, 13 (1),14-24, https://doi.org/10.37745/irjpap.13vol13n11424

World Health Organization. (2009). *WHO handbook on indoor radon: A public health perspective*. WHO.

World Health Organization. (2011). *Guidelines for drinking-water quality* (4th ed.). WHO. https://www.who.int/publications/i/item/9789241548151

World Health Organization. (2022). *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda*. WHO.

Zar, J. H. (2010). *Biostatistical analysis* (5th ed.). Pearson.