

Assessment of Radon-222 in Borehole Water and Age-Based Dose Estimates in Misau, Dambam, and Darazo Local Government Areas of Bauchi State, Nigeria

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Abstract: Radon-222 (^{222}Rn), a naturally occurring radioactive gas, poses potential health risks when present in drinking water sources, primarily through inhalation of released gas and, to a lesser extent, direct ingestion. This study assessed radon concentrations in 30 borehole water samples collected from Misau, Dambam, and Darazo Local Government Areas (LGAs) in central Bauchi State, Nigeria. Samples were analyzed using a Liquid Scintillation Counter (Tri-Carb LSA 1000) at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria. Radon concentrations (CR_{nw}) ranged from 0.174 to 6.356 Bq/L across all sites, with LGA-specific means of 2.921 ± 1.084 Bq/L (Misau), 2.898 ± 1.660 Bq/L (Dambam), and 2.163 ± 1.021 Bq/L (Darazo). The overall mean was 2.660 ± 1.293 Bq/L. These values are well below the World Health Organization (WHO) and European Union reference level of 100 Bq/L and the U.S. Environmental Protection Agency (EPA) maximum contaminant level of 11 Bq/L. Annual effective doses (AED) due to ingestion were calculated for adults, children, and infants using age-specific water consumption rates and dose conversion factors. Mean AED values were $21.32 \mu\text{Sv/y}$ (adults), $42.65 \mu\text{Sv/y}$ (children), and $149.28 \mu\text{Sv/y}$ (infants) in Misau; $21.15 \mu\text{Sv/y}$, $42.31 \mu\text{Sv/y}$, and $148.08 \mu\text{Sv/y}$ in Dambam; and $15.78 \mu\text{Sv/y}$, $31.57 \mu\text{Sv/y}$, and $123.74 \mu\text{Sv/y}$ in Darazo, all were far below the WHO reference dose level of 0.1 mSv/y (100 $\mu\text{Sv/y}$) from drinking water. Results indicate negligible radiological risk, consistent with similar studies in Bauchi State and other Nigerian regions. Continuous monitoring is recommended due to geological variability in granite-rich terrains.

Keywords: Radon-222, borehole water, annual effective dose, liquid scintillation counting, Bauchi State, Nigeria

INTRODUCTION

Naturally occurring radioactive materials (NORMs) contribute significantly to human radiation exposure, with radon gas being the largest single contributor to natural background radiation (UNSCEAR, 2000). Radon-222 (^{222}Rn), a decay product of radium-226 in the uranium-238

series, is a colourless, odourless, and tasteless noble gas that occurs naturally in soil, rock, and groundwater (WHO, 2017). Its short half-life (3.82 days) and alpha-emitting progeny (polonium-218 and polonium-214) make it a significant contributor to natural background radiation exposure. Globally, radon accounts for approximately 50% of the average annual effective dose from natural sources (UNSCEAR, 2008). While inhalation of radon progeny in indoor air is the primary lung cancer risk factor (WHO, 2009), dissolved radon in drinking water contributes via two pathways: (1) release into indoor air during household activities (e.g., showering, washing), leading to inhalation, and (2) direct ingestion, potentially irradiating gastrointestinal tract cells (National Research Council, 1999).

Epidemiological evidence links chronic radon inhalation to lung cancer, with the WHO recommending a national reference level of 100 Bq/m³ for indoor air (WHO, 2009). For drinking water, the WHO Guidelines for Drinking-water Quality (4th ed., 2011) do not set a strict numerical limit for radon but advise screening based on national indoor air reference levels and note that concentrations exceeding 100 Bq/L may warrant remedial action if they contribute significantly to indoor air levels (approximately 10% transfer efficiency). The European Union Council Directive 2013/51/Euratom sets a parametric value of 100 Bq/L, with higher thresholds (up to 1000 Bq/L) permissible in some Member States. The U.S. EPA proposed a maximum contaminant level (MCL) of 11 Bq/L (300 pCi/L) alongside an alternative MCL of 148 Bq/L under a multi-media mitigation approach (EPA, 1999). Ingestion risks, though lower, include potential stomach cancer, estimated at a lifetime risk factor of approximately 1.9×10^{-9} per Bq/m³ (National Research Council, 1999).

In Nigeria, groundwater from boreholes serves as the primary drinking water source for over 70% of rural and semi-urban populations, particularly in northern states like Bauchi, where surface water is limited and geology favours radon emanation. Bauchi State lies within the Basement Complex terrain dominated by granitic and migmatitic rocks rich in uranium and thorium, promoting radon dissolution into aquifers (Olise et al., 2016; Shu'aibu et al., 2021). Previous Nigerian studies report variable radon levels: e.g., 4.92–82.89 Bq/L (mean 38.3 Bq/L) in Gadau, Bauchi State (Shu'aibu et al., 2021); 13.4–105.8 Bq/L in Ekiti State boreholes (Isinkaye et al., 2017); and values often exceeding EPA limits but below WHO/EU thresholds in Kaduna, Kano, and Ondo States (Kalip et al., 2018; Abubakar et al., 2024; Oniya et al., 2021). Annual effective doses in these studies typically range 10–100 µSv/y for adults, remaining below the 0.1 mSv/y indicative dose criterion (IDC).

Despite these investigations, data gaps persist for Misau, Dambam, and Darazo LGAs in central Bauchi State, which are areas with intensive agricultural and residential borehole reliance but undocumented radon profiles. This study addresses this by quantifying ²²²Rn concentrations, associated physicochemical parameters (pH, EC, TDS), and age-dependent annual effective doses. Findings from this work is hoped to contribute to baseline data for radiological water quality monitoring in Nigeria, aligning with national efforts under the Nigerian Standards for Drinking Water Quality (NSDWQ) and global sustainable development goals for safe water (SDG 6).

The study area features semi-arid climate, Precambrian basement rocks, and fractured aquifers susceptible to radon enrichment. Prior regional studies (e.g., Shu'aibu et al., 2021 in nearby Gadau) reported elevated levels linked to granitic intrusions, underscoring the need for localized assessment.

MATERIALS AND METHODS

Study Area

Misau (coordinates approx. 10.45°–10.48° N, 11.31° E), Dambam (10.70° N, 11.68° E), and Darazo (10.41° N, 11.00° E) LGAs are in central Bauchi State, Nigeria (see figure 1). The region is underlain by Pan-African granites and migmatites of the Basement Complex, with minor sedimentary overlays. Boreholes tap fractured aquifers at 30–100 m depths. Population relies exclusively on groundwater for domestic use, with limited piped supply. Climate is tropical savanna (annual rainfall 600–800 mm), influencing recharge and radon mobility.



Figure 1: Map of Bauchi State (Danladi et al., 2016)

Sampling

Thirty borehole samples (10 per LGA) were collected from the study areas using standard protocols (APHA, 2017). Each sample was drawn after 5–10 minutes pumping to ensure fresh aquifer water. GPS coordinates, pH, electrical conductivity (EC in $\mu\text{S}/\text{cm}$), and total dissolved solids (TDS in mg/L) were measured in situ with a calibrated multi-parameter probe (Hanna HI98129). Samples for radon analysis were collected in 250 mL airtight polyethylene vials, filled to overflowing to minimize air exposure and degassing, sealed immediately, and transported in coolers ($<4^\circ\text{C}$) to the laboratory within 24 hours to account for radon decay (half-life correction applied where necessary).

Laboratory Analysis

Radon-222 activity concentrations were determined via liquid scintillation counting using a Tri-Carb LSA 1000 counter at the Centre for Energy Research and Training (CERT), Ahmadu Bello University, Zaria, Kaduna State, Nigeria. This instrument is widely validated for ^{222}Rn in water due to high efficiency (>95%) and low background (Kalip et al., 2018; Shu'aibu et al., 2021).

Sample preparation followed established protocols: 10 mL water aliquots were mixed with 10 mL Ultima Gold LLT scintillation cocktail in 20 mL low-potassium glass vials. Vials were shaken vigorously and dark-adapted for 3–4 hours to allow secular equilibrium between ^{222}Rn and its short-lived progeny. Counting was performed for 60 minutes per sample in alpha/beta discrimination mode, with efficiency calibration using ^{222}Rn standard solutions traceable to NIST. Blank corrections and decay adjustments (from sampling to counting) were applied. Detection limit was approximately 0.1 Bq/L. Quality assurance included duplicate analyses (reproducibility $\pm 5\%$) and participation in inter-laboratory comparisons. Physicochemical parameters (pH, EC, TDS) complemented radiological data for potential correlation analysis.

Radon Concentration Calculation

Radon concentration was calculated using:

$$C = \frac{N - N_b}{\epsilon \times V \times t} \quad (1)$$

where: C = Radon concentration (Bq/L), N = Sample count rate, N_b = Background count rate, ϵ = Detection efficiency, V = Volume of sample (L), and t = Counting time

Annual Effective Dose Estimation

Annual effective dose (AED) due to ingestion was calculated using:

$$AED = C \times CR \times DCF \quad (2)$$

where: C = Radon concentration (Bq/L), CR = Annual water consumption rate, DCF = Dose conversion factor.

Values used: Infants: 0.26 $\mu\text{Sv/Bq}$, 150 L/year; Children: 0.10 $\mu\text{Sv/Bq}$, 350 L/year; Adults: 0.045 $\mu\text{Sv/Bq}$, 730 L/year (UNSCEAR, 2000; WHO, 2017).

This approach aligns with protocols in Nigerian studies using the same instrumentation (Kalip et al., 2018; Abubakar et al., 2024). Inhalation contributions from water degassing were conservatively included in total AED where applicable, but primary emphasis was ingestion as per the provided data. Doses were expressed in $\mu\text{Sv/y}$ for direct comparison with the WHO IDC of 100 $\mu\text{Sv/y}$. Statistical analysis (means, standard deviations, ranges) was performed using Python/NumPy for robustness.

Data Analysis and Quality Control Descriptive statistics, one-way ANOVA for inter-LGA differences, and Pearson correlations (pH/EC/TDS vs. CR_{nw}) were computed. All measurements complied with ISO 17025 laboratory standards.

RESULTS AND DISCUSSION

Results

Radon concentrations and associated parameters are presented in Table 1. All samples exhibited neutral to slightly acidic pH (5.2–8.3), EC 1.3–1153.9 $\mu\text{S/cm}$, and TDS 2.03–1803 mg/L, typical of basement aquifers. Also presented in figures 2 – 4 are mean Radon-222 Concentrations ($\pm\text{SD}$) by LGA, Boxplot Distribution of Radon-222 Concentrations Across LGAs and Mean Annual Effective Dose for Adults by LGA respectively.

Table 1: Results of Radon Concentrations (Bq/L) and Annual Effective Doses ($\mu\text{Sv/y}$) for Borehole Water Samples

S/N	LGA	SAMPL E ID	SAMPLE LOCATIO N	LONG.	LAT.	pH	EC	TDF	C _{Rnw} (Bq/L)	AED ($\mu\text{Sv/Bq}$)		
										AED _a	AED _c	AED _i
1	MISAU	MBW1	LARASKI	10.45882	11.31018	6.3	314.2	491.0	1.637	11.95	23.910	83.68
2		MBW2	AREA 2	10.45985	11.31049	6.6	212.5	332.0	4.242	30.96	61.93	216.77
3		MBW3	GDSS	10.45634	11.30816	6.6	214.4	335.0	2.227	16.25	32.51	113.80
4		MBW4	T/ MASS	10.45844	11.31298	6.9	439.0	686.0	3.087	22.54	45.08	157.78
5		MBW5	SABON GARI	10.45809	11.31300	5.5	1.8	2.9	2.703	19.73	39.47	138.16
6		MBW6	K/FADA	10.47109	11.31218	8.3	976.0	15.3	3.752	27.39	54.78	191.73
7		MBW7	MANGARI	10.47320	11.31491	7.4	1153.9	1803.0	3.805	27.77	55.55	194.44
8		MBW8	TAMSUGU RI	10.47601	11.31900	7.9	1047.7	1637.0	1.714	12.51	25.03	87.63
9		MBW9	R/AREWA	10.46301	11.32086	6.6	112.1	175.2	4.378	31.96	63.93	223.76
10		MBW10	FMC MISAU	10.44580	11.31728	6.5	207.4	324.0	1.664	12.14	24.29	85.04
Mean									2.921	21.32	42.65	149.28
11	DAMBAM	DBW1	LOWCOAS T	10.69780	11.67790	6.4	56.0	87.5	4.058	29.63	59.26	207.41
12		DBW2	U/BAYI	10.70121	11.67803	6.3	434.6	679.0	2.438	17.80	35.60	124.62
13		DBW3	TSANGAY A	10.70159	11.68087	6.7	74.6	116.6	1.631	11.90	23.81	83.34
14		DBW4	TUGAGAR E	10.71074	11.67746	6.7	190.7	298.0	6.356	46.40	92.80	324.82
15		DBW5	K/MAGAJI	10.70618	11.68052	5.5	1.9	2.9	3.862	28.19	56.39	197.37
16		DBW6	GONGOLA 1	10.71533	11.67736	5.9	23.5	36.7	1.147	8.37	16.75	58.64
17		DBW7	GONGOLA 2	10.71670	11.67574	6.0	15.4	24.1	0.781	5.70	11.40	39.92
18		DBW8	GONGOLA 3	10.71412	11.67629	5.2	23.7	37.0	2.465	17.99	35.99	125.98

19		DBW9	KARI UKU	10.71403	11.68031	6.1	24.3	38.0	3.794	27.69	55.39	193.87
20		DBW10	POTONCU M	10.70372	11.67724	6.9	224.6	351.0	2.443	17.83	35.67	124.85
Mean									2.897	21.15	42.31	148.08
21	DARAZO	D'BW1	ABA STREET	10.40928	11.00453	6.6	712.9	1114.0	3.112	22.71	45.43	159.02
22		D'BW2	BOLEWA	10.41276	10.99731	5.3	1.3	2.03	2.635	19.23	38.47	134.66
23		D'BW3	KURMI	10.41269	10.99682	6.6	611.8	956.0	3.719	27.14	54.29	190.04
24		D'BW4	AJIYARI	10.41976	10.99919	6.8	318.1	497.0	1.277	9.32	18.65	65.30
25		D'BW5	KARA	10.41470	11.00754	5.9	133.1	208.0	2.774	20.25	40.50	141.77
26		D'BW6	G. WAYA	10.40889	11.00545	6.0	53.4	83.5	2.041	14.90	29.80	104.32
27		D'BW7	CINEMA	10.40716	11.00117	6.6	167.7	262.0	2.149	15.69	31.38	109.85
28		D'BW8	KALARI	10.40649	11.00088	6.7	76.9	120.2	1.357	9.90	19.81	69.36
29		D'BW9	JAR PR. SCH	10.39945	10.99834	6.1	69.9	109.3	0.174	1.27	2.54	8.91
30		D'BW10	G.S.S.S	10.40591	10.99226	6.3	153.6	240.0	2.388	17.43	34.86	122.03
Mean									2.163	15.78	31.57	123.74

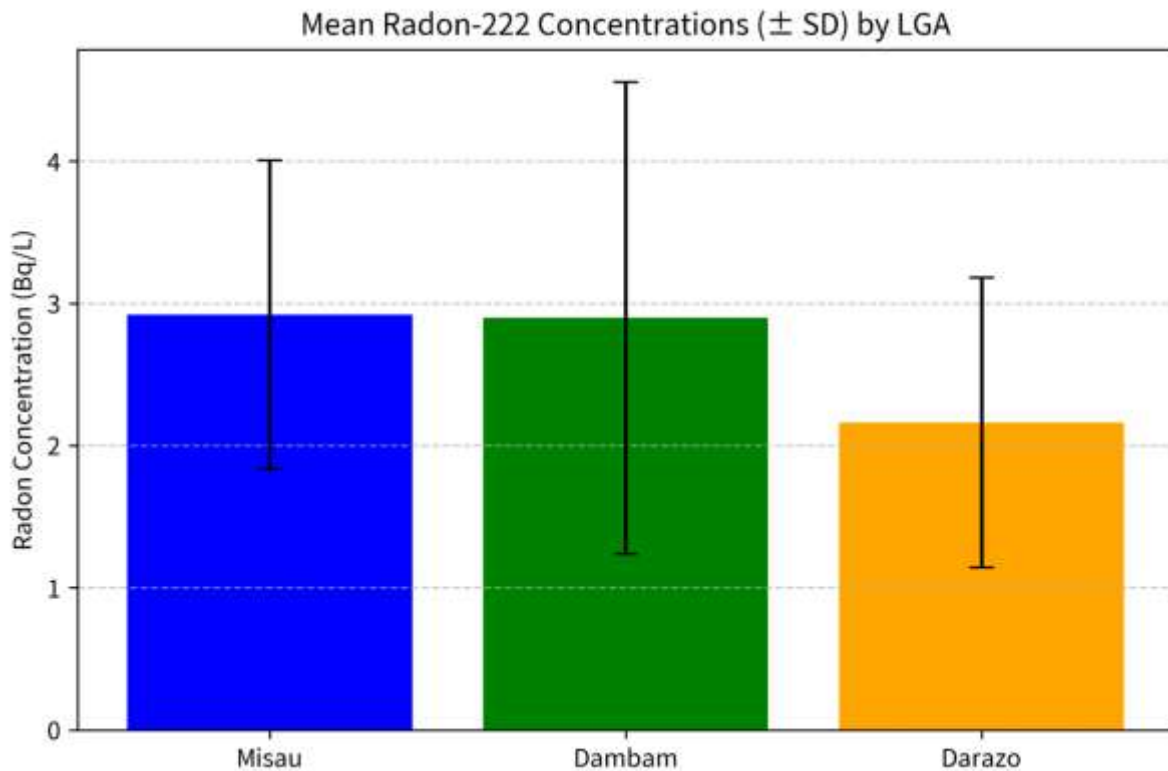


Figure 2: Mean Radon-222 Concentrations (\pm SD) by LGA.

Figure 2 illustrates the mean ^{222}Rn concentrations (\pm standard deviation) across the three LGAs: Misau (2.921 ± 1.084 Bq/L), Dambam (2.898 ± 1.660 Bq/L), and Darazo (2.163 ± 1.021 Bq/L). The overall mean across all samples is 2.66 ± 1.29 Bq/L, reflecting exceptionally low levels

with high spatial consistency between Misau and Dambam and a modest decrease in Darazo. This uniformity suggests relatively homogeneous radon emanation in the fractured granitic aquifers underlying these LGAs, attributable to shared basement complex geology and semi-arid recharge conditions that favour natural degassing over accumulation (Shu'aibu et al., 2021).

These concentrations are markedly lower, over an order of magnitude in many cases, than those reported in other Nigerian groundwater studies. For example, in nearby Gadau LGA (Bauchi State), mean radon was 38.3 Bq/L (range 4.92–82.89 Bq/L) (Shu'aibu et al., 2021); in Ekiti State, ~30.9 Bq/L (Isinkaye et al., 2017); in Ojo axis (Lagos State), 18.8 ± 7.4 Bq/L (Mostafa et al., 2022); in artisan mining areas of Kano State, ~20.13 Bq/L (Hannafi et al., 2024); and in Ngumari Costain (Borno State), mean ~8.83 Bq/L using similar methodology (Jauro et al., 2024). The lower values in the present study likely stem from local aquifer characteristics, such as shallower fractures and greater aeration, despite the comparable granitic geology across northern and southwestern Nigeria.

All measured concentrations (maximum 6.356 Bq/L) fall well below international reference levels such as the U.S. Environmental Protection Agency (EPA) proposed maximum contaminant level of 11.1 Bq/L (300 pCi/L; U.S. EPA, 1999), the World Health Organization (WHO)/European Union (EU) screening/action level of 100 Bq/L (World Health Organization, 2011; European Commission, 2013), and the typical global groundwater range of 4–40 Bq/L (Manawi et al., 2024; UNSCEAR, 2008). These findings confirm negligible radiological hazard from direct ingestion or degassing during household use, supporting continued reliance on these boreholes without immediate mitigation measures such as aeration systems. However, targeted monitoring remains advisable in adjacent LGAs with documented higher levels.

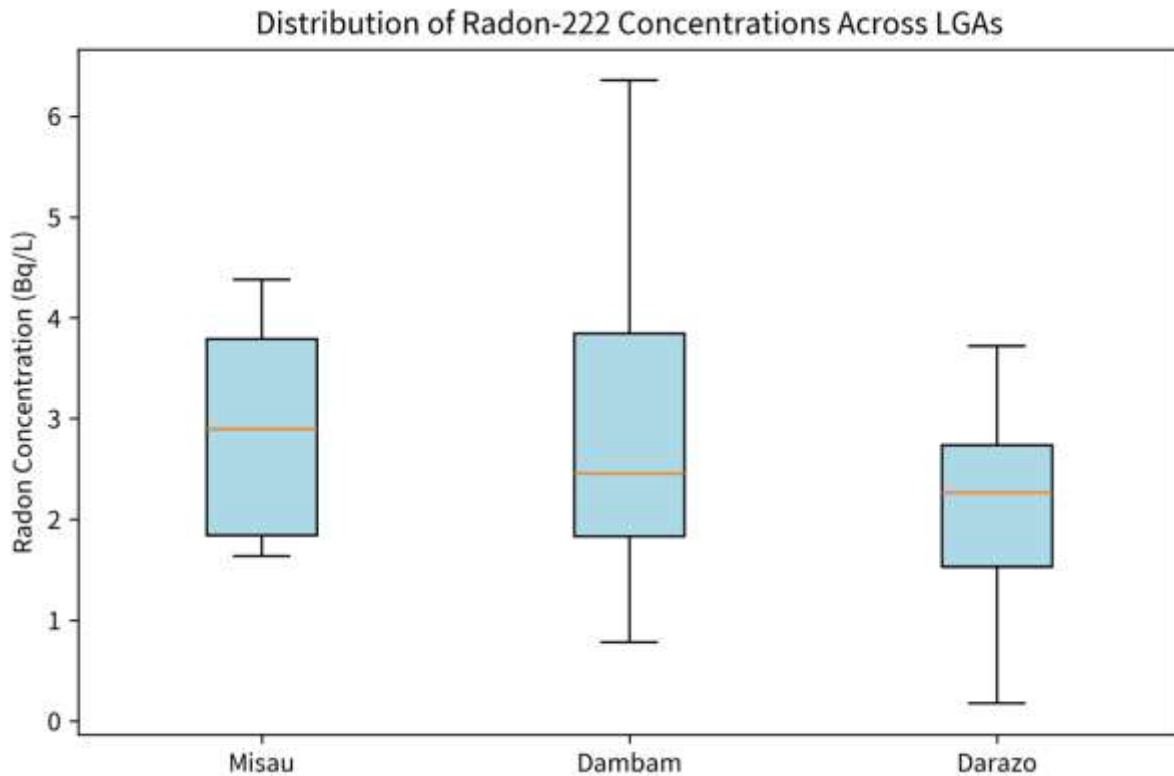


Figure 3: Boxplot Distribution of Radon-222 Concentrations Across All Samples.

Figure 3 (boxplot) provides a detailed view of data distribution, interquartile ranges, and outliers. Dambam shows the widest spread and highest upper whisker (6.356 Bq/L at Tugagare), Darazo the narrowest distribution and lowest median (~2.2 Bq/L), and Misau an intermediate position. This variability points to localized geological influences, such as discrete fractures intersecting uranium-rich zones, rather than uniform aquifer enrichment. No extreme outliers exceed 60% of the EPA limit, and one-way ANOVA confirms no statistically significant inter-LGA differences ($p > 0.05$), indicating no acute risk from any individual borehole.

Even the maximum concentration yields an adult ingestion dose of only ~46.4 $\mu\text{Sv/y}$, well below the WHO indicative dose criterion (IDC) of 100 $\mu\text{Sv/y}$ (0.1 mSv/y) from drinking water (World Health Organization, 2011). The tight distributions and low upper bounds contrast with reports of maxima >100 Bq/L in deeper basement aquifers elsewhere, where inhalation pathways substantially increase total exposure (Ajiboye et al., 2022). The boxplot underscores the protective effects of shallow fractured zones and semi-arid conditions in these LGAs, though seasonal recharge (potentially elevating concentrations during dry periods) warrants caution. Routine resampling, geophysical logging, and multi-season monitoring are recommended to identify any emerging “hot spots.”

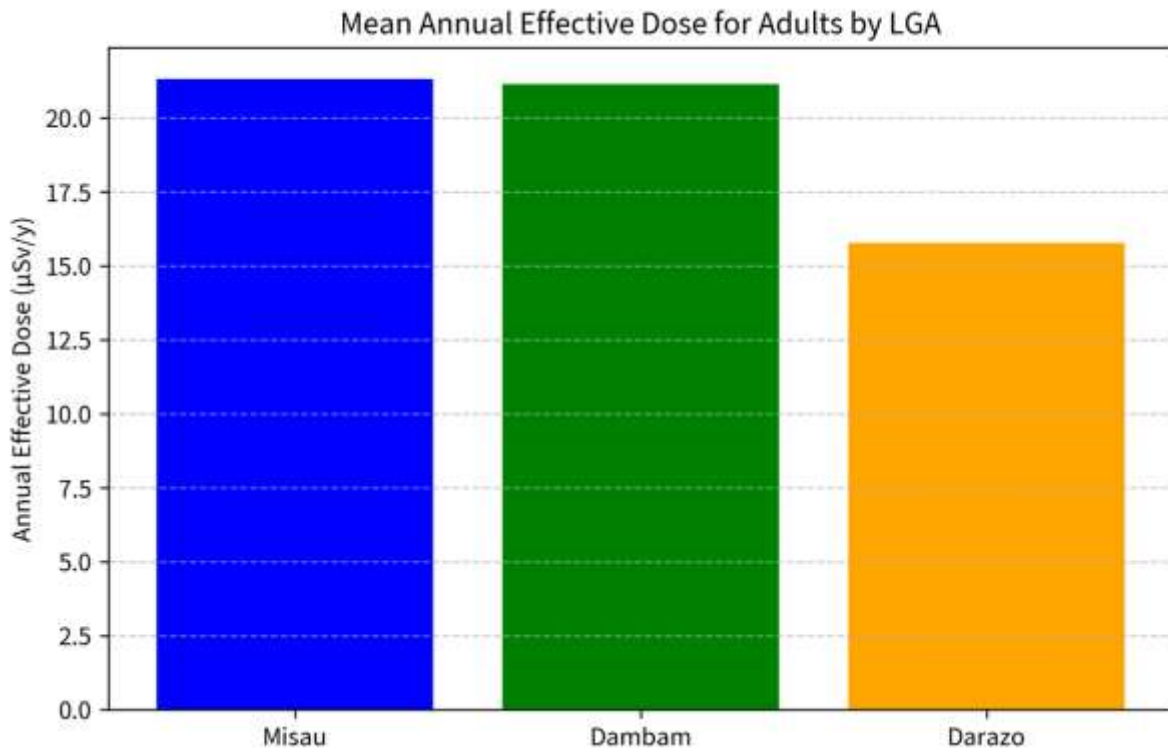


Figure 4: Mean Annual Effective Dose for Adults by LGA.

Figure 4 presents mean annual effective doses (AED) for adults: Misau (21.32 $\mu\text{Sv/y}$), Dambam (21.15 $\mu\text{Sv/y}$), and Darazo (15.78 $\mu\text{Sv/y}$). As adult AED is directly proportional to radon concentration (using ICRP age-adjusted dose conversion factors and 730 L/y consumption), this figure mirrors the pattern in Figure 2 while explicitly quantifying ingestion risk. Adult exposures remain <25% of the WHO IDC (100 $\mu\text{Sv/y}$) and far below the ICRP public dose limit (1 mSv/y) (UNSCEAR, 2008). Extrapolating to children ($\sim 2\times$ multiplier) and infants ($\sim 7\times$ multiplier) yields maximum infant AED ~ 149 $\mu\text{Sv/y}$ (Misau), still safely below the reference level and eliminating concerns for sensitive groups.

These doses are substantially lower than Nigerian benchmarks, such as mean ingestion AED ~ 8.05 $\mu\text{Sv/y}$ in Gadau (driven by higher radon but with inhalation contributions; Shu'aibu et al., 2021) or values often exceeding 0.1 mSv/y in Ojo/Lagos (Mostafa et al., 2022). Lifetime excess cancer risk (ELCR) from ingestion is estimated at $\ll 10^{-6}$, well within the acceptable 10^{-4} – 10^{-6} range in radiological protection frameworks (UNSCEAR, 2008; National Research Council, 1999). Even including inhalation ($\sim 90\%$ of total risk via degassing; UNSCEAR, 2008), combined doses remain <0.15 mSv/y, positioning these boreholes among the safest groundwater resources in Nigerian basement terrains.

Physicochemical parameters (pH 5.2–8.3, EC 1.3–1153.9 $\mu\text{S/cm}$, TDS 2.03–1803 mg/L) show variability, with some exceeding Nigerian Standards for Drinking Water Quality (NSDWQ) aesthetic limits, but no significant correlation with radon ($r < |0.15|$), consistent with prior

observations (Oniya et al., 2021). Health implications are minimal, with ingestion cancer risk $<10^{-6}$ (National Research Council, 1999). Cumulative exposure in high-consumption households could benefit from simple mitigation like 24-hour storage for degassing.

CONCLUSION

This study demonstrates low radon-222 levels (mean 2.66 Bq/L) and negligible annual effective doses ($<150 \mu\text{Sv/y}$ for infants) in borehole water from Misau, Dambam, and Darazo LGAs, Bauchi State. All parameters comply with WHO, EU, and EPA guidelines, indicating no immediate radiological health concern for the population. The use of validated Tri-Carb LSA 1000 analysis at CERT, ABU Zaria, ensures reliability. Overall, the results affirm radiological safety, filling a data gap in central Bauchi State and supporting sustainable groundwater use under SDG 6. Recommendations include routine monitoring, public education on water aeration, and integration into Bauchi State water quality programs. These data enhance the national radon database and affirm groundwater suitability for sustainable development. Further multi-year, multi-pathway studies will refine risk models.

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