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Radon in Drinking Water from Laterite-Dominated Terrains of Yewa, Southwestern Nigeria: An Assessment of Radiological Health Risk

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ABSTRACT
Radon-222 (^{222}Rn) is a naturally occurring radionuclide and a major contributor to radiation exposure via groundwater. Yewa South Local Government Area (LGA), Ogun State, Nigeria, has extensive lateritic weathering that may influence radionuclide occurrence, yet its groundwater radon levels remain insufficiently characterised. This study determined ^{222}Rn concentrations in borehole drinking water, estimated age-specific annual cumulative effective dose (ACED), and evaluated excess lifetime cancer risk (ELCR) for adults. Twenty groundwater samples (10 for each location) were collected, with one control site at Bells University of Technology, Ota, and analysed using a RAD7 radon detector. ACED was computed using age-specific water-ingestion rates and ICRP Publication 158 dose coefficients. Adult ELCR was derived from ACED using a 70-year lifetime and a 5.5×10^{-2} Sv^{-1} risk factor. One-way ANOVA and Tukey's HSD test were used to compare groups. Mean ^{222}Rn concentrations were 480.31 Bq/L (Abule Agbara) and 485.65 Bq/L (Ilobi Town), significantly exceeding the control (161 Bq/L; $p < 0.001$), with no significant difference between sites. Mean ACED was highest in infants (0.491 and 0.496 mSv y^{-1}), while adult ACED was 0.270 and 0.273 mSv y^{-1}, and the maximum ACED was 0.844 mSv y^{-1}. All ACED values remained below 1 mSv y^{-1}, whereas the mean adult ELCR (~9.5×10^{-4}) exceeded the conventional 10^{-4} reference level. These findings indicate elevated radon exposure and increased estimated cancer risk relative to the conventional reference level, despite doses remaining below 1 mSv y^{-1}. Routine surveillance, protection of vulnerable age groups, and pre-consumption mitigation such as aeration are recommended.

Keywords:
Radon-222,
Borehole drinking water,
Annual Cumulative Effective Dose (ACED),
Excess Lifetime Cancer Risk (ELCR),
Lateritic geology,
Radiological health risk.

INTRODUCTION

Radon-222 (^{222}Rn) is a naturally occurring radionuclide in the ^{238}U decay series and an important contributor to environmental radiation exposure. It is a radioactive noble gas with a half-life of about **3.8 days** and can accumulate in groundwater following its generation from radium-bearing minerals in the subsurface. Because radon is relatively mobile in groundwater and its concentration can decrease through radioactive decay and degassing after water leaves the subsurface, groundwater characteristics and geological conditions are important determinants of its occurrence in drinking water (Ajiboye *et al*., 2022; Farai *et al*., 2023; Omeje *et al*., 2016). Groundwater is a major source of drinking water in Nigeria, particularly in communities dependent on wells and boreholes. Yewa South Local Government

Area (LGA), Ogun State, lies within a geological transition between the Basement Complex and the Dahomey Basin and is characterised by extensive lateritic weathering. Lateritisation involves prolonged weathering and redistribution of minerals within the soil and weathered-rock profile. Such processes can influence the distribution and mobility of uranium- and radium-bearing minerals, potentially affecting radon generation and emanation into pore spaces and groundwater. The resulting interaction between weathered materials and groundwater may therefore influence radon transport and its persistence in subsurface water (Adewoyin *et al*., 2018; Oyeyemi *et al*., 2018; Adekiya *et al*., 2024). Although groundwater radon has been investigated in parts of southwestern Nigeria, published data specifically characterising ^{222}Rn in Yewa South LGA are few or essentially unavailable, particularly with respect to age-specific radiological risks (Fatoki and Ademola, 2020; Farai *et al*., 2023). This represents an important knowledge gap because local geological conditions may produce spatially variable radon concentrations and associated exposure levels. Therefore, this study determined the activity concentrations of ^{222}Rn in drinking-water sources in Yewa South LGA, estimated the annual cumulative effective dose across age groups, and evaluated the associated excess lifetime cancer risk for adults.

MATERIALS AND METHODS

Study Area

The study was conducted in Yewa South Local Government, Ogun State, Southwestern Nigeria, where two borehole sampling locations, Abule Agbara (6°45′13.11″ to 6°45′15.56″ N, 3°2′32.4″ to 3°2′31.38″ E) and Ilobi Town (6°44′43.54″ to 6°44′47.74″ N, 3°3′6.88″ to 3°3′9.40″ E), were selected within the study area, which extends approximately from 6°37′46″ to 6°55′42″ N and 2°47′24″ to 3°06′48″ E as shown in Figure 1, while the control sample was collected at Bells University of Technology, Ota **(**6°40′58″ N, 3°11′9″ E**)**. Groundwater samples were collected directly from borehole outlets using clean, pre-labelled, airtight polyethylene bottles with minimal agitation to prevent radon loss through degassing (IAEA, 2022), stored in insulated containers and transported promptly to the laboratory, where ^{222}Rn was measured 2 days after collection using a RAD7 electronic radon detector following the manufacturer's recommended water-analysis protocol, with the instrument calibrated and background-corrected before analysis, each sample measured once for approximately 30 min, and quality control maintained through careful sample handling and decay correction of measured ^{222}Rn activity for the 2-day interval between sampling and measurement, and the RAD7 extracts dissolved radon into a closed air loop, where alpha particles from radon progeny are detected using a solid-state silicon detector, and activity concentrations were expressed in Bq L^{-1} after calibration and background correction.

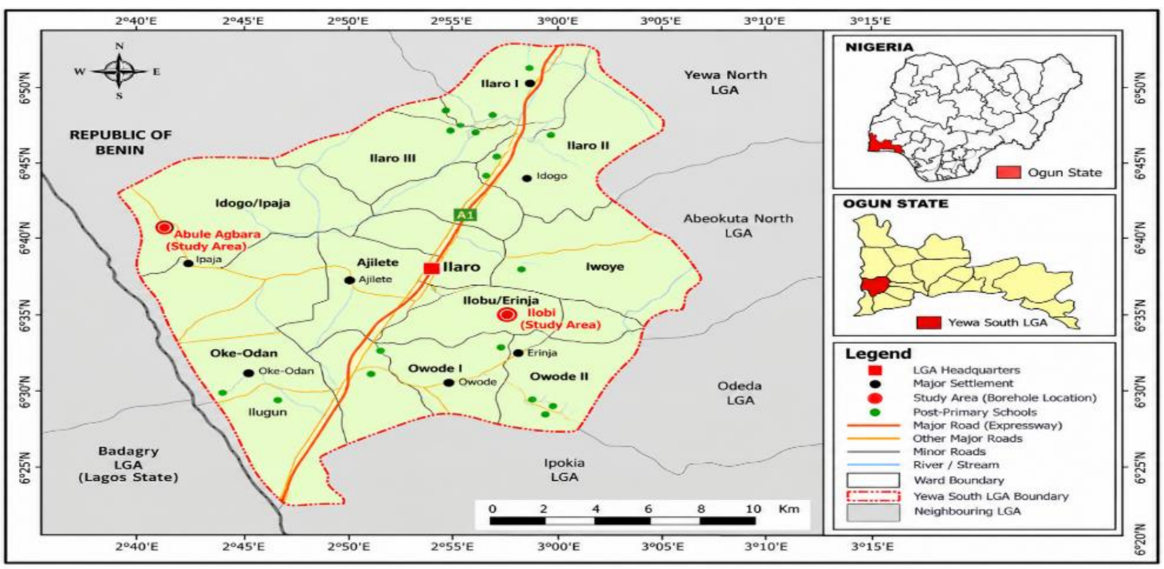

Figure 1: Location map of the study area (Yewa South Local Government Area, Ogun State, Nigeria) (Google map)

Determination of Annual Cumulative Effective Dose (ACED)

The annual cumulative effective dose due to ingestion of radionuclides in drinking water was estimated using the recommended International Commission on Radiological Protection publication 158 and the World Health Organization (ICRP, 2024; WHO, 2022):

$$ACED = C \times IR \times DCF \times 1000 \qquad (1)$$

Where ACED is the Annual Cumulative Effective Dose (mSv y^{-1}), C is the Activity concentration (Bq L^{-1}), IR is the Daily water ingestion rate (Lday^{-1}), DCF is the Age-dependent ingestion dose coefficient (Sv Bq^{-1}), and 1000 converts Sv to mSv.

The annual committed effective dose (ACED) was estimated using age-specific daily drinking-water consumption rates of 0.7, 1.1, 1.3, 1.5, 1.8, and 2.0 L/day for infants aged 3 months (0-12 months), children aged 1 year (1-2 years), 5 years (>2-7 years), 10 years (>7-12 years), 15 years (>12-17 years), and adults (>17 years), respectively, assuming 365 days of exposure per year. The age-specific ingestion dose coefficients prescribed in ICRP Publication 158 were applied to account for the radiological dose associated with ingestion of ^{222}Rn. The corresponding dose coefficients were 4.0×10^{-9} (3 months), 2.1×10^{-9} (1 year), 1.2×10^{-9} (5 years), 8.6×10^{-10} (10 years), 7.5×10^{-10} (15 years), and 7.7×10^{-10} (Adult) Sv/Bq. These age-dependent dose coefficients and water-consumption rates were incorporated into the ACED calculations to evaluate potential radiation exposure from the ingestion of radionuclides in drinking water across the different age groups.

Determination of Excess Lifetime Cancer Risk (ELCR)

The Excess Lifetime Cancer Risk associated with ingestion of radionuclides in drinking water was estimated for the adult group only using (Ahmed, 2025):

$$ELCR = ACED \times DL \times RF \qquad (2)$$

Where ELCR is the Excess Lifetime Cancer Risk, ACED is the Annual Cumulative Effective Dose (mSv y^{-1}), DL is the Duration of life (typically 70 years), and RF is the Fatal cancer risk factor (5.0×10^{-2} Sv^{-1} for members of the public, ICRP). Thus,

Statistical Analysis

Descriptive statistics were used to summarize the measured activity concentration for each sampling group. A one-way ANOVA was performed to assess differences among the Control, Abule Agbara, and Ilobi town groups. Statistical significance was assessed at the 5% level (α=0.05), and Tukey's HSD post hoc test was used to identify significant pairwise differences following a significant ANOVA result.

RESULTS AND DISCUSSION

^{222}Rn Activity Concentration in Borehole Water

The mean ^{222}Rn activity concentration was 480.31 ± 238.26 Bq/L at Abule Agbara and 485.65 ± 188.85 Bq/L at Ilobi Town, as presented in Table 1, based on ten borehole samples per location (mean sampling distances of 916.5 m and 869.50 m, respectively). The two means are statistically comparable (a difference of about 1%), indicating that both locations draw on a hydrogeological setting with a broadly similar radon source term, most plausibly a laterite-bearing basement lithology common to both sites.

Abule Agbara recorded the widest spread, from a minimum of 32.10 Bq/L to a maximum of 826.00 Bq/L (SD = 238.26 Bq/L), whereas Ilobi Town showed a narrower range, from 194.50 Bq/L to 747.00 Bq/L (SD = 188.85 Bq/L). The higher minimum and lower coefficient of variation at Ilobi Town suggest a more spatially homogeneous radon source, while the wider scatter at Abule Agbara points to localised heterogeneity that elevates radon emanation at specific boreholes while leaving others comparatively low.

Both the mean and the full range of concentrations recorded at each location markedly exceed the Control value of 161 Bq/L and the WHO reference limit of 100Bq/L (WHO, 2024). The Control site was sampled at a greater distance from the source area and is used here only to benchmark the degree of local radiological enrichment, it is not treated as an acceptable upper limit. The consistent excess of Location Abule Agbara and Ilobi Town values over the Control (by a factor of roughly three at the mean, and up to about five at the observed maxima) is consistent with proximity-driven enrichment, since both locations lie appreciably closer to the presumed source area (that is, the laterite-concentrated area) than the Control area. Abodunrin and Akinloye (2020) reported 4.45–12.53 Bq/L (mean 7.44 Bq/L) compared with the present study's much higher mean ^{222}Rn concentrations of 480.31 Bq/L (Abule Agbara) and 485.65 Bq/L (Ilobi Town) in Yewa South, indicating substantially greater radon enrichment in the study area. Farai *et al.* (2023), sampling 33 borehole sources in Abeokuta, southwestern Nigeria, reported a much lower mean borehole ^{222}Rn concentration of 18.8 Bq/L (range 10.65–29.5 Bq/L). Similarly, *Shu'aibu et al.* (2021), using RAD7 alpha spectrometry on ten borehole samples in Gadau, Bauchi State, reported a mean concentration of 38.3 Bq/L (range 4.92–82.89 Bq/L). Both of these means are more than an order of magnitude lower than the 480.31 Bq/L and 485.65 Bq/L means recorded at Location Abule Agbara and Ilobi Town in the present study.

Table 1: Assessment of ^{222}Rn Concentration in Borehole Water

Location	^{222}Rn (Bq/L)	N	Mean Distance	Min (Bq/L)	Max (Bq/L)	Sample Type
Abule Agbara	480.31 ± 238.26	10	916.5m	32.10	826.00	Borehole
Ilobi Town	485.65 ± 188.85	10	869.50m	194.50	747.00	Borehole

Annual Cumulative Effective Dose (ACED) from Ingestion of ^{222}Rn

The age-specific annual cumulative effective dose (ACED) from ingestion of ^{222}Rn is presented in Table 2. Across both locations, the ACED follows a broadly consistent, non-monotonic pattern with age, driven by the product of intake rate and dose coefficient. The 3-month infant group received the highest dose at both locations (0.491 mSv/y at Abule Agbara; 0.496 mSv/y at Ilobi Town), while the 10-year age group received the lowest dose at both locations (0.226 mSv/y at Abule Agbara; 0.229 mSv/y at Ilobi Town). Dose values do not otherwise decline monotonically with age: the 1-year group (0.405/0.409 mSv/y) is substantially lower than the infant group but still markedly higher than the 5-, 10- and 15-year groups, while the adult group (0.270/0.273 mSv/y) is marginally lower than the 5-year group (0.273/0.277 mSv/y) and higher than the 10- and 15-year groups.

The minimum, maximum, and control values for each age group in Table 2 track the corresponding range in ^{222}Rn concentration in Table 1. The minimum ACED corresponds to the lowest-radon borehole and the maximum ACED to the highest-radon borehole at each location, while the Control-derived ACED (e.g., 0.165 mSv/y for infants, 0.091 mSv/y for adults) is consistently the lowest value in each row, again reflecting the lower radon content of the more distant, background site rather than any regulatory threshold. None of the mean, minimum, maximum, or Control ACED values calculated for ^{222}Rn ingestion, even the single highest value recorded (0.844 mSv/y, the Abule Agabra infant maximum) approaches the ICRP dose criterion of 1 mSv per year that is conventionally used in this literature as a public-exposure reference point. Isinkaye *et al.* (2021), assessed 68 groundwater sources at a Nigerian university campus, reported ^{222}Rn concentrations of 7.4–23.3 Bq/L with correspondingly low ACED. Kolo *et al.* (2023), in Bosso Community, Minna, similarly reported much lower ACED values. Despite being an order of magnitude higher than these comparators, the present ACED values remain below 1 mSv/y at every age group and location. Although all ^{222}Rn ACED values remain below 1 mSv/y, ingestion dose is only one component of total exposure, alongside background radiation, other radionuclides, and radon inhalation from domestic water use. For infants and one-year-olds, who record the highest doses, this pathway remains a meaningful contribution to cumulative exposure during a developmentally sensitive period.

Table 2: Annual Effective Dose from Ingestion of ^{222}Rn Concentration in Borehole Water

Location	Age Group	ACED (mSv/y)	Min (mSv/y)	Max (mSv/y)	Control (mSv/y)
Abule Agbara	3 months	0.491	0.033	0.844	0.165
	1Y	0.405	0.027	0.696	0.136
	5Y	0.273	0.018	0.470	0.092
	10Y	0.226	0.015	0.389	0.076
	15Y	0.237	0.016	0.407	0.079
	Adults	0.270	0.018	0.464	0.091
Ilobi Town	3 months	0.496	0.199	0.763	0.165
	1Y	0.409	0.164	0.630	0.136
	5Y	0.277	0.111	0.425	0.092
	10Y	0.229	0.092	0.352	0.076
	15Y	0.239	0.096	0.368	0.079
	Adults	0.273	0.109	0.420	0.091
Reference Limit	-	1	1	1	1

Excess Lifetime Cancer Risk (ECLR) from Ingestion of ^{222}Rn (Adults)

The ECLR due to ingestion of ^{222}Rn for adults is presented in Table 3. The mean ECLR was 9.45×10^{-4} at Abule Agbara (range 6.3×10^{-5} to 1.625×10^{-3}) and 9.55×10^{-4} at Ilobi Town (range 3.83×10^{-4} to 1.470×10^{-3}); the corresponding Control value was 3.19×10^{-4} at both locations. The two locations are again very similar at the mean, consistent with their similar mean ^{222}Rn concentrations, while Ilobi Town shows a narrower risk range, mirroring the narrower concentration range already noted for that location in Section 3.1.

The mean ECLR values obtained at both locations ($\approx 9.5 \times 10^{-4}$) lie roughly an order of magnitude above the reference limit (1×10^{-4}), and even the Control-derived ECLR (3.19×10^{-4}) exceeds it. The finding indicates that ingestion-related radon exposure at both locations, and even at the more distant Control site, falls into a probabilistic risk band that would ordinarily warrant closer monitoring and consideration of exposure-reduction measures for borehole water consumers. Kolo *et al.* (2023) computed ECLR alongside ACED for radon ingestion and inhalation in groundwater at Bosso Community, Minna, reporting risk values that scaled with the comparatively lower radon concentrations measured there. Ajiboye and Isinkaye (2023), evaluating cancer risk from ingestion of natural radionuclides in Ekiti State groundwater, likewise reported ECLR values reflecting the radionuclide concentrations measured in that study area. Both studies illustrate the same underlying principle demonstrated by the present results. These findings support prioritising the boreholes for further radiological characterisation and simple, low-cost mitigation (e.g., aeration or storage-based degassing) before consumption.

Table 3: Excess Lifetime Cancer Risk (ECLR) from Ingestion of ^{222}Rn Concentration in Borehole Water for Adults

Location	ECLR	Min	Max	Control
Abule Agbara	0.000945	0.000063	0.001625	0.000319
Ilobi Town	0.000955	0.000383	0.001470	0.000319

One-way ANOVA and Tukey HSD Post-hoc Test Comparison of ^{222}Rn Concentration in Borehole Water

The measured activity concentration showed a clear difference among the three sampling groups as illustrated in Table 4. The control samples recorded the lowest mean value (161.00 Bq/L), while Abule Agbara and Ilobi Town recorded considerably higher mean values of 480.31 and 485.65 Bq/L, respectively. The model R^2 was 0.45384, indicating that approximately 45.38% of the total variation in the measured response was associated with differences among the three groups. The mean value at Abule Agbara was approximately 198.3% higher than the Control, while the Ilobi Town mean was approximately 201.6% higher than the Control. In contrast, the difference between Abule Agbara and Ilobi Town was only about 1.1%, demonstrating their close similarity. The one-way ANOVA confirmed that the observed differences among the three groups were statistically significant, $F(2,27) = 11.21789$, $p < 0.001$. This finding provides evidence that the mean measured activity/concentration was not the same across all sampling groups.

The post-hoc Tukey analysis further showed that the significant overall effect was attributable to the difference between the Control and Abule Agbara groups (mean difference = 319.31 Bq/L, $p = 0.00105$) and between the Control and Ilobi Town groups (mean difference = 324.65 Bq/L, $p = 0.000874$), as illustrated in Table 5. In contrast, no statistically significant difference was detected between Abule Agbara and Ilobi Town (mean difference = 5.34 Bq/L, $p = 0.99745$).

Table 4: One-Way Analysis of Variance (ANOVA) of ^{222}Rn

Sampling Group / Model	N	Mean (Bq/L)	SD (Bq/L)	SE (Bq/L)	DF	F-value	p-value	R^2	Root MSE	CV
Control	10	161.00	0.00	0.00	-	-	-	-	-	-
Abule Agbara	10	480.31	238.26	75.35	-	-	-	-	-	-
Ilobi Town	10	485.65	188.85	59.72	-	-	-	-	-	-
Overall ANOVA/Model	30	375.65	-	-	2, 27	11.2179	<0.001	0.4538	175.53	0.4673

Table 5: Tukey HSD Post-hoc Comparisons of ^{222}Rn

Comparison	Mean Difference (Bq/L)	SEM	q value	p-value	95% CI for Difference (Bq/L)
Abule Agbara − Control	319.31	78.50051	5.75248	0.00105	124.67657 to 513.93433
Ilobi Town − Control	324.65	78.50051	5.84868	0.000874355	130.01657 to 519.28343
Ilobi Town − Abule Agbara	5.34	78.50051	0.09620	0.99745	−189.29343 to 199.97343

CONCLUSION

This study characterised radon-222 (^{222}Rn) in borehole drinking water at two locations in Yewa South Local Government Area (LGA), Ogun State, Nigeria, and assessed the associated radiological exposure and cancer risk to consumers. Groundwater at Abule Agbara and Ilobi Town was markedly enriched in ^{222}Rn relative to the distant background site, consistent with the influence of the local lateritic geology on radionuclide occurrence and distribution. The statistical analysis confirmed significant differences between both study locations and the background site, while no significant difference was observed between Abule Agbara and Ilobi Town. Age-dependent dose assessment showed that infants and young children receive higher ingestion-related doses than older age groups, indicating greater vulnerability during early development. Although all ACED values remained below 1 mSv y^{-1}, the mean adult ELCR at both study locations exceeded the conventional 10^{-4} reference level, indicating an elevated estimated cancer risk that warrants attention alongside dose-based assessment. The study therefore demonstrates a measurable radiological health concern associated with radon-bearing borehole groundwater in this geologically susceptible area. Routine radiological surveillance, protection of vulnerable age groups, pre-consumption mitigation through measures such as aeration or storage-based degassing, and further characterization of boreholes across Yewa South are recommended to support evidence-based water-safety management and public health protection.

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