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Measurement and Spatial Assessment of Radon Concentration in Ground water Sources in Parts of Oyo and Osun States, Southwestern Nigeria

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ABSTRACT

This study presents the measurement and spatial assessment of radon concentrations in groundwater sources in parts of Oyo and Osun States, Southwestern Nigeria. Groundwater samples (n = 200) were collected from 200 locations, comprising hand-dug wells and boreholes, and analyzed using the RAD7 electronic radon detector. Radon concentrations, ingestion and inhalation doses, and total annual effective doses were determined, and radiological indices, including excess lifetime cancer risk, were estimated. The results show that, Radon concentrations ranged from 0.71 to 25.98 Bq/L in Oyo and 0.12 to 35.9 Bq/L in Osun, with mean total annual effective doses of 3.82 µSv/y and 4.79 µSv/y, respectively. Inhalation consistently contributed more to the total dose than ingestion. Comparative analysis revealed slightly higher radon levels in Osun, likely due to deeper wells and local geological variations. When compared with global data, radon concentrations in southwestern Nigeria fall within low-to-moderate ranges and remain below international recommended limits, indicating minimal health risk. Strong correlations between radon and dose parameters suggest that monitoring inhalation doses can reliably predict total exposure, providing a practical approach for radiological risk assessment and groundwater safety management in the region.

1. INTRODUCION

Groundwater is a vital source of freshwater globally, with its demand increasing due to population growth and rising living standards. Many communities rely on groundwater because of its large storage capacity and relatively low susceptibility to surface contamination. However, groundwater may contain dissolved gases, radioactive substances, and other constituents that pose potential health risks. Water is essential for sustaining life, constituting about 70% of human body weight and supporting numerous physiological functions. Among the major water sources—groundwater, surface water, and rainwater—groundwater is particularly susceptible to radon accumulation, especially in boreholes and deep wells. Elevated radon levels in groundwater are often linked to water–rock

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interactions in geological formations enriched with uranium and radium-226 (Akerblom and Lindgren, 2018). Radon is produced through the alpha decay of radium-226 in the uranium-238 decay series. Once generated, radon can escape from mineral grains and dissolve into groundwater during percolation through fractured and crystalline rocks. Its concentration in groundwater depends largely on the radium content of underlying soils and rocks. Naturally occurring radiation accounts for approximately 85.5% of the average radiation dose received by humans, with radon being the largest contributor (Vesna *et al.*, 2018; Mehra and Badhan, 2012). Radon exposure is a major public health concern, as it is the second leading cause of lung cancer after smoking (Zayn Al-Bakhat, 2008). The World Health Organization attributes thousands of cancer-related deaths annually to radon exposure, including those associated with drinking water (WHO, 2023). Radon released from groundwater during household activities also contributes significantly to indoor air radon levels (EPA, 2003).

Despite these health implications, information on groundwater radon levels in many parts of Southwestern Nigeria remains limited. This study therefore focuses on the measurement and spatial assessment of radon concentration in groundwater sources in selected areas of Oyo and Osun States, Southwestern Nigeria. The findings provide baseline data on radon distribution, support radiological risk assessment, and contribute to improved groundwater quality management and public health protection in the region.

2. MATERIALS AND METHOD

STUDY AREA

The study area was located in Southwestern Nigeria and comprised Oyo State and Osun State. Oyo State lies approximately between latitudes 7°00′N and 9°00′N and longitudes 2°30′E and 4°30′E, while Osun State is situated between latitudes 6°30′N and 8°10′N and longitudes 4°00′E and 5°10′E. Oyo State was bounded by Kwara State to the north, Osun State to the east, Ogun State to the south, and the Republic of Benin to the west, whereas Osun State was bounded by Oyo State to the north, Ondo State to the east, Ogun State to the south, and Ekiti State to the northeast. The study area experiences a tropical climate characterized by distinct wet and dry seasons, which influence groundwater recharge and radon transport. Geologically, the area is predominantly underlain by Precambrian crystalline basement complex rocks, known to host uranium- and radium-bearing minerals that enhance radon generation in groundwater. The spatial distribution of the study area and the GPS coordinates of sampling locations in Oyo and Osun States were presented in Figures 1 and 2, respectively.

2.1 Sample collection

A total of 200 groundwater samples were collected from the selected locations within the study area. The distribution and number of samples obtained from each location are presented in Table 1, with 100 samples collected from each state. For each set of 100 samples, 50 were obtained from hand-dug wells and 50 from boreholes, with the water sources varying in depth across locations. The groundwater samples were collected randomly directly from the source into 1.5 L bottles that had been thoroughly rinsed with distilled water. Immediately after collection, each bottle was tightly sealed and clearly labeled. Special care was taken during sampling to minimize water agitation and prevent air bubbles, thereby reducing the potential loss of dissolved radon. All samples were transported promptly to the Pure and Applied Physics Department laboratory at Ladoke Akintola University of Technology, Ogbomosho, Oyo State, ensuring that radon

measurements were carried out within its effective decay time of 3.8 days.

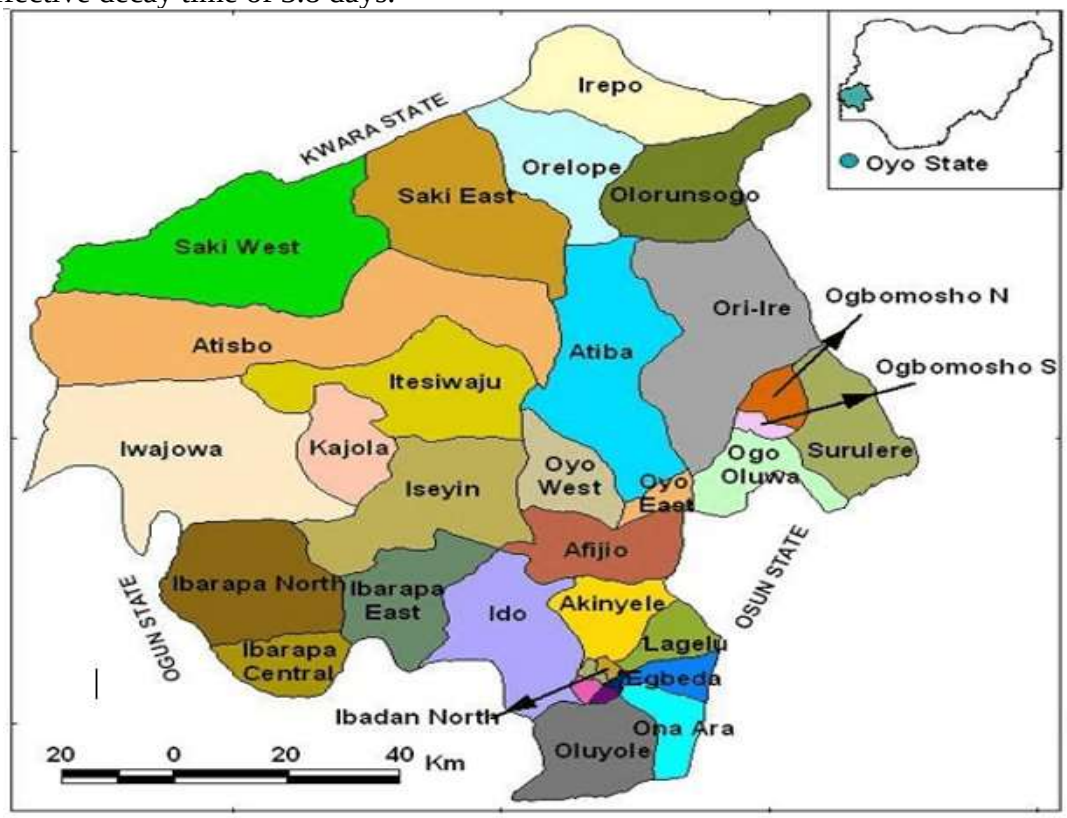


Figure 1: A map showing the GPS location of Oyo State (nigeriagalleria.com)



Figure 2: A map showing the GPS location of Osun State (yourjigsawouzzles.com)

Radon concentration in the groundwater samples was measured using a RAD7 electronic radon detector manufactured by Durridge Inc., USA. The experimental arrangement used for the measurement is illustrated schematically in Figure 3.

Table 1: Sampling locations and number of groundwater samples collected in Oyo and Osun States

S/N	State	Locations	Sample number
1	Oyo	Ibadan	20
		Oggbomos	20
		Oyo	20
		Iseyin	20
		igangan	20
2	Osun	Osogbo	20
		Ede	20
		Ilesha	20
		Ileife	20
		Ejigbo	20

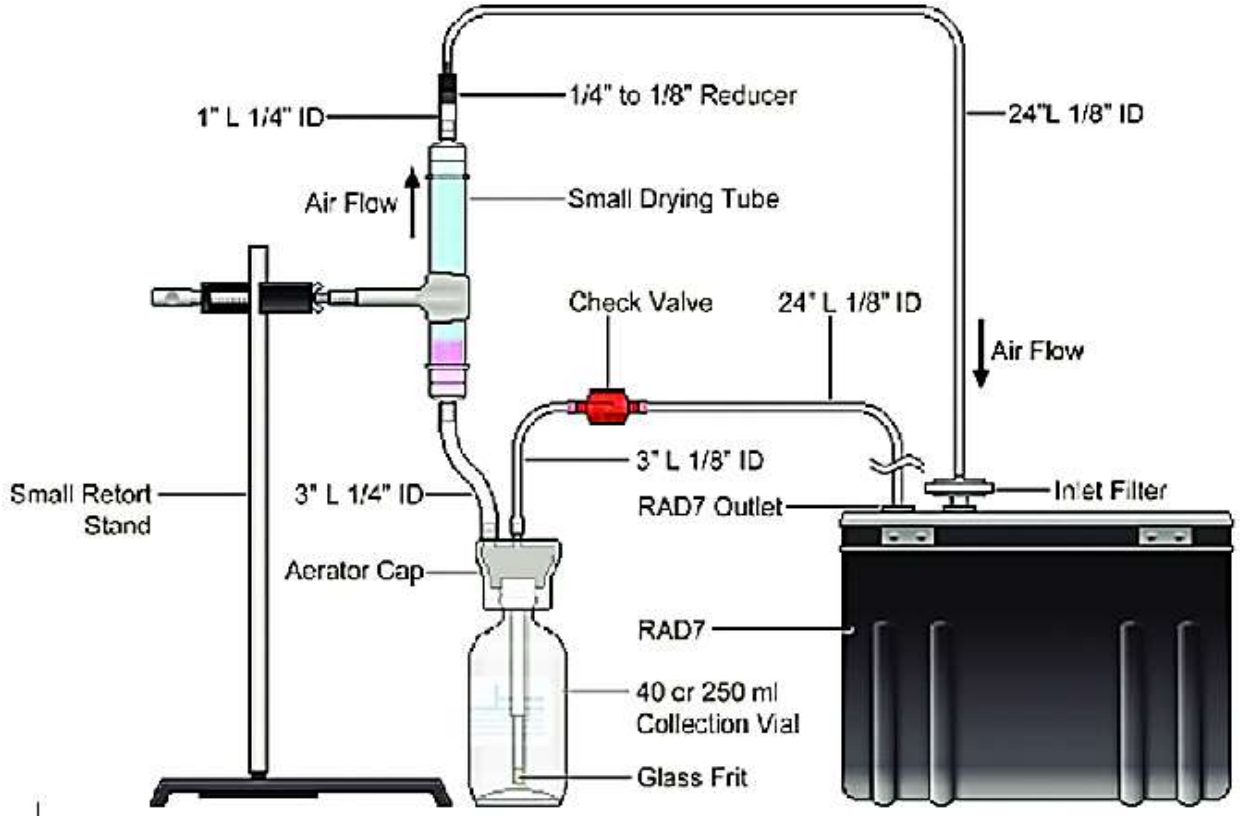


Figure 3: A RAD7 set up for measuring ^{222}Rn water samples

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2.2 Sample Preparation and Measurement

Groundwater samples were collected into 250 mL vials and immediately sealed to prevent contact with air, following the RAD7 RADH2O manual (Durridge, 2012). Each sealed vial was gently shaken for over two minutes to transfer radon-222 from the water into the organic scintillation medium. Radon concentrations were then measured using the RAD7 electronic radon detector (Durridge Co. Inc., USA), a well-calibrated solid-state alpha detector that converts alpha radiation directly into electrical signals using a silicon semiconductor. The internal sample chamber is a 0.7 L hemispherical cell coated with a conductive material, with a lower detection limit of less than 0.37 Bq L^{-1}. Measurements were recorded for 30 minutes, and the radon levels obtained were subsequently used for statistical analysis and the calculation of radiological indices, considering the geological characteristics of the sampling locations. A schematic of the RAD7 detector setup is shown in figure 4.



Figure 4**:** Durridge Rad7 Machine (DURRIDE, 2015)

The RAD 7 is a Sniffer detects the 3-minute alpha decay of a radon daughter, without interference from other radiations. It also detects the instantaneous alpha decay of a thoron daughter for rapid thoron measurements. The radon measurement was translated to the annual effective dose due to inhalation and ingestion.

3. ESTIMATION OF RADIOLOGICAL INDICES OF RADON MEASUREMENT

3.1 Annual Effective Dose due to Ingestion

The annual effective dose corresponding to the groundwater radon concentration was evaluated using Eq. (1)

$$He = C \times F \times I \times D \quad (1)$$

where He is the annual effective dose ($msvy^{-1}$)., C is the radon (^{222}Rn) concentration in (Bqm^{-3})., F is the equilibrium factor (0.5)., T is the indoor occupancy factor inhabitant Spend in rooms out of 24hours which is 3504 hy^{-1}., and D is the dose conversion factor (9 x 10^{-6} $msvh^{-1}/Bqm^{-3}$).

3.2 Annual Committed Dose due to Inhalation

The annual mean committed doses due to inhalation (E) measure in $mSvy^{-1}$ were calculated by using the parameters established in UNSCEAR report 2000, as:

$$E(mSvy^{-1}) = C_{Rnw} \times R_{aw} \times F \times T \times (DCF) \quad (2)$$

Where: C_{Rnw} is the Concentration of radon in water; R_{aw} is the Ratio of radon in air to water (10^{-4}), F is the radon equilibrium factor between radon and its decay products (0.4); (DCF) is the dose Conversion Factor for radon exposure ($9 \times 10^{-6}\ per\ Bq\ m^{-3}$); T is an occupancy factor assumed based on the period inhabitants spend in indoor rooms out of 24 hours which is estimated by $9\ hrs/24\ hrs = 0.375 \approx 0.4 = (0.4 \times 24\ hrs \times 365\ days = 3504\ hy^{-1})$. (Oni *et. al.*, 2014).

3.3 Annual Committed Dose by Ingestion

The estimated annual effective dose by ingestion was assessed based on the usual intake of water by populace of the study area. The annual effective dose was calculated using the equation 3.3 as,

$$E = K \times C \times KM \times t \quad (3)$$

where E is the committed effective dose from ingestion (mSv); K is the ingesting dose conversion factor of ^{222}Rn ($l0^{-8}$ $SvBq^{-l}$ for adult and 2 x $l0^{-8}Sv\ Bq^{-1}$ for Children (UNSCEAR 2000); C = the concentration of ^{222}Rn (Bq 1^{-1}); KM is the water consumption (2 litres day^{-1}); t = the duration of consumption (365 days) (World Health Organization(WHO) 2004).For the dose calculation, a conservative consumption of 2 litres per day for standard adult drinking the same water and directly from the source point was assumed (UNSCEAR, 2008).

3.4 Estimated of Excess Life Cancer Risk

The Excess Lifetime Cancer Risk (ELCR) due to radon exposure is estimated using the expression shown in Eq. (4)

$$ELCR = E \times L \times R \quad (4)$$

where E is theannual effective dose (Svy^{-1}); L is the average life expentancy (typically taken as 70 years); R is the fatal cancer risk facor per unt dose (Sv^{-1}), usually 0.05 Sv^{-1} as recommeded by ICRP/UNSCEAR.

3.5 Data Analysis Technique

Descriptive statistics were applied to assess radon concentrations across different bedrock types in the study area. Analysis of variance (ANOVA) was used to evaluate differences in mean radon levels, while correlation analysis examined the relationship between bedrock and radon concentration. Summary statistics included

minimum, maximum, median, mean, standard deviation, and standard error.

4. RESULTS AND DISCUSSION

The measurements across the 100 locations in Oyo State presented in figure 5 indicate that radon concentrations range from 0.71 to 25.98 Bq/L, ingestion doses from 0.15 to 5.46 µSv/y, inhalation doses from 0.18 to 6.55 µSv/y, and total annual effective doses from 0.33 to 12.00 µSv/y. The data reveal that most locations have low to moderate values, while a few locations form localized hotspots with elevated radon and dose levels. Inhalation contributes more to the total annual effective dose than ingestion, confirming it as the dominant exposure pathway. Statistical analysis shows that radon has a very strong positive correlation with inhalation dose ($R \approx 0.998$, $R^2 \approx 99.6\%$) and total annual effective dose ($R \approx 0.996$, $R^2 \approx 99.2\%$), while the correlation with ingestion dose is slightly lower ($R \approx 0.992$, $R^2 \approx 98.4\%$). Inhalation and ingestion doses are also strongly correlated with each other ($R \approx 0.993$, $R^2 \approx 98.6\%$), reflecting their joint dependence on radon levels. Despite the observed variability and the presence of hotspots, all measured values remain well below international recommended limits for public exposure. This indicates that the health risk to the population from radon exposure via both inhalation and ingestion is minimal. The strong correlations further suggest that monitoring inhalation doses can effectively predict total exposure, simplifying risk assessment in the region.

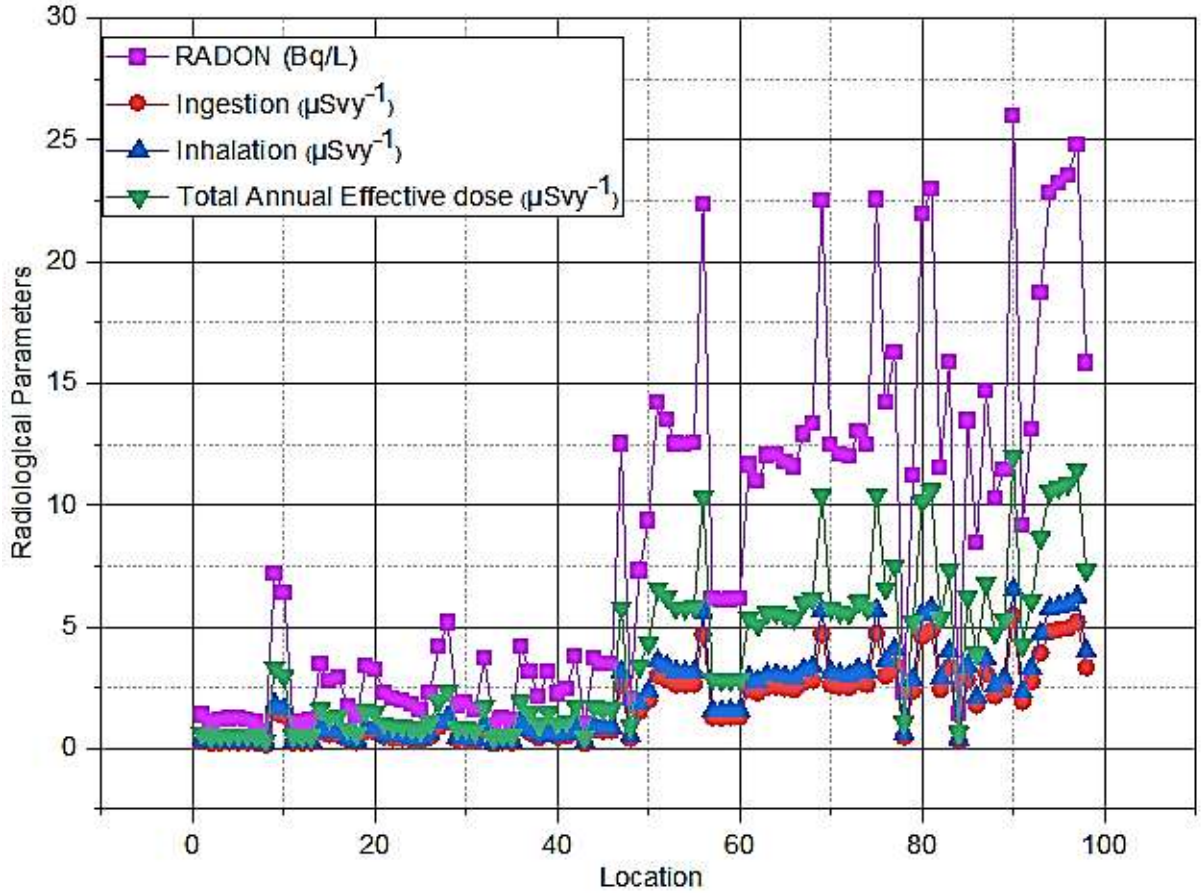


Figure 5:

The descriptive statistics of the radiological parameters measured across the 100 locations in Oyo State are presented in Table 2. The standard deviation, variance, and coefficient of variation (CV) values highlight the degree of variability in the measured radiological parameters across Oyo State. Radon shows a standard deviation of 7.21 Bq/L and a variance of 52.0, reflecting substantial fluctuations across locations, while its CV of 80.3 percent indicates a high relative variability compared to the mean. Similarly, ingestion and inhalation doses have standard deviations of 1.51 µSv/y and 1.82 µSv/y, variances of 2.28 and 3.31, and CVs around 80 percent, demonstrating that both pathways exhibit consistent relative variability. The total annual effective dose follows the same trend, with a standard deviation of 3.33 µSv/y, variance of 11.1, and CV of 80 percent. The high CVs suggest the presence of localized hotspots where exposure is higher, even though the overall mean values are low. Despite these fluctuations, all measured parameters remain far below international exposure limits, confirming that the health risk to the population from radon inhalation and ingestion is minimal under typical exposure conditions

Table 2. Summary of radiological parameters and associated dose statistics in Oyo State.

Parameter	Min	Max	Mean	Std Dev	Variance	CV (%)
Radon (Bq/L)	0.71	25.98	8.98	7.21	52.0	80.3
Ingestion (µSv/y)	0.15	5.46	1.89	1.51	2.28	79.9
Inhalation (µSv/y)	0.18	6.55	2.27	1.82	3.31	80.2
TAED (µSv/y)	0.33	12.00	4.16	3.33	11.1	80.0

Figure 6 depicts the measurements across the 100 locations in Osun State. The radon concentrations ranging from 0.118 to 33.6 Bq/L, ingestion doses from 0.025 to 7.056 µSv/y, inhalation doses from 0.030 to 8.467 µSv/y, and total annual effective doses from 0.054 to 15.523 µSv/y. Most locations exhibit low to moderate values, while some sites form localized hotspots with elevated radon and dose levels. Inhalation is consistently higher than ingestion, confirming it as the dominant exposure pathway. Despite these variations, all values remain below international recommended limits, suggesting minimal health risk to the population under typical exposure conditions.

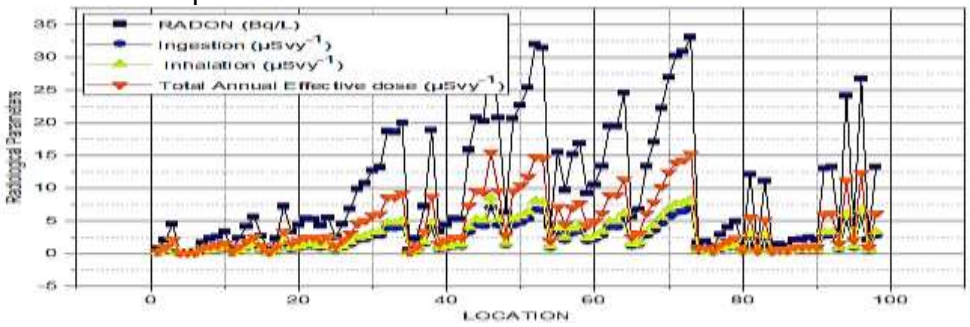


Figure 6: The measurements across the 100 locations in Osun State

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Table 3 shows that radon concentrations range from 0.118 to 27.0 Bq/L, ingestion doses from 0.025 to 5.67 µSv/y, inhalation doses from 0.030 to 6.804 µSv/y, and total annual effective doses from 0.054 to 12.474 µSv/y. Most locations have low to moderate exposure, with inhalation contributing more to total dose than ingestion. The standard deviations and CVs (~95%) indicate moderate variability due to localized hotspots. All values remain below international limits, suggesting minimal health risk to the population.

Table: 3: Radon Concentrations

Parameter	Min	Max	Mean	Std Dev	Variance	CV (%)
Radon (Bq/L)	0.118	27.0	8.76	8.32	69.3	95.0
Ingestion (µSv/y)	0.025	5.67	2.45	2.33	5.44	95.1
Inhalation (µSv/y)	0.030	6.804	2.92	2.77	7.68	94.9
Total annual effective dose (µSv/y)	0.054	12.474	4.59	4.36	19.0	95.0

4.1 Comparison of Radiological parameters between Oyo and Osun States

The mean radon concentration and corresponding doses in groundwater from Oyo and Osun States are summarized in Table 3 and visualized in Figure 7. Oyo State shows a mean radon concentration of 8.27 Bq/L at a mean depth of 42 m, while Osun State has a slightly higher mean radon of 10.37 Bq/L at a mean depth of 49 m. Correspondingly, the mean ingestion, inhalation, and total annual effective doses are higher in Osun (2.178, 2.612, and 4.789 µSv/y) than in Oyo (1.74, 2.08, and 3.820 µSv/y). The bar chart in Figure 7 highlights these differences, showing that Osun consistently records higher values for all parameters. In both states, inhalation contributes more to the total annual effective dose than ingestion, confirming it as the dominant exposure pathway. The slightly higher radon levels and doses in Osun may be attributed to deeper wells and localized geological variations. Despite these differences, the mean doses in both regions remain well below international recommended limits, indicating minimal health risk to the population from groundwater radon exposure.

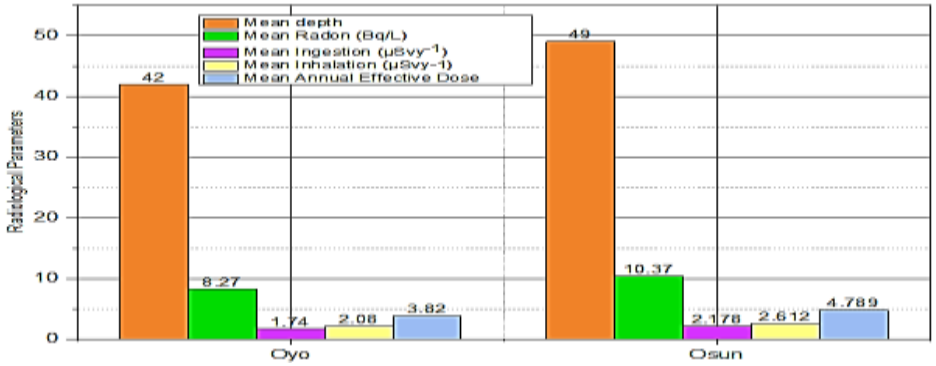


Figure 7: The mean radon concentration and corresponding doses in groundwater from Oyo and Osun States

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4.2 Comparison of Radon Concentration range in groundwater under investigation with those in other countries

The radon concentrations observed in groundwater from Oyo (0.71–25.98 Bq/L) and Osun (0.12–35.9 Bq/L) States fall within the lower to moderate ranges reported globally (Table 7). For example, studies from India report ranges of 0.24–106.17 Bq/L and 12.5–86.2 Bq/L (Shilpa et al., 2017; Duggai et al., 2020), while Strzelin, Poland recorded a wider range of 0.5–119.4 Bq/L (Przylibski et al., 2020). In Pakistan, reported values are 2.0–7.9 Bq/L (Manzoor et al., 2008), which are comparable to some of the lower-radon locations in southwestern Nigeria.

The results from this study indicate that radon levels in Oyo and Osun States are generally lower than many global hotspots but comparable to low-to-moderate regions in India and Pakistan. The Osun State maximum value (35.9 Bq/L) is slightly higher than the maximum in Oyo State, reflecting the influence of localized geological variations and deeper groundwater sources. Overall, the values are well below international recommended limits, suggesting that groundwater in these areas poses minimal radiological health risk to the population.

4.3 Box Plot

The comparative analysis of radon concentration and its annual effective doses via ingestion and inhalation in Oyo and Osun States is presented in figure 8 and Table 4. Radon concentrations in Osun ranged from 0.12 to 25.98 Bq/L, with a median of 3.1 Bq/L and IQR of 1.08–7.18 Bq/L, while in Oyo they ranged from 0.18 to 33.6 Bq/L, with a median of 4.5 Bq/L and IQR of 0.72–9.93 Bq/L. The ingestion dose ranged from 0.0248 to 5.4558 µSv/y in Osun and 0.0379 to 7.056 µSv/y in Oyo, with medians of 0.49 and 0.55 µSv/y, respectively. Inhalation dose ranged from 0.0297 to 6.5469 µSv/y in Osun and 0.0455 to 8.467 µSv/y in Oyo, with medians of 0.52 and 0.60 µSv/y. Consequently, the total annual effective dose ranged from 0.0545 to 12.0 µSv/y in Osun and 0.083 to 15.5 µSv/y in Oyo, with medians of 1.0 and 1.55 µSv/y. Overall, Oyo State showed slightly higher exposure than Osun across all parameters, and inhalation was the dominant pathway. The presence of outliers indicates spatial variability likely due to geological differences and building characteristics. These results provide baseline data for public health assessments and potential mitigation in areas with elevated radon levels.

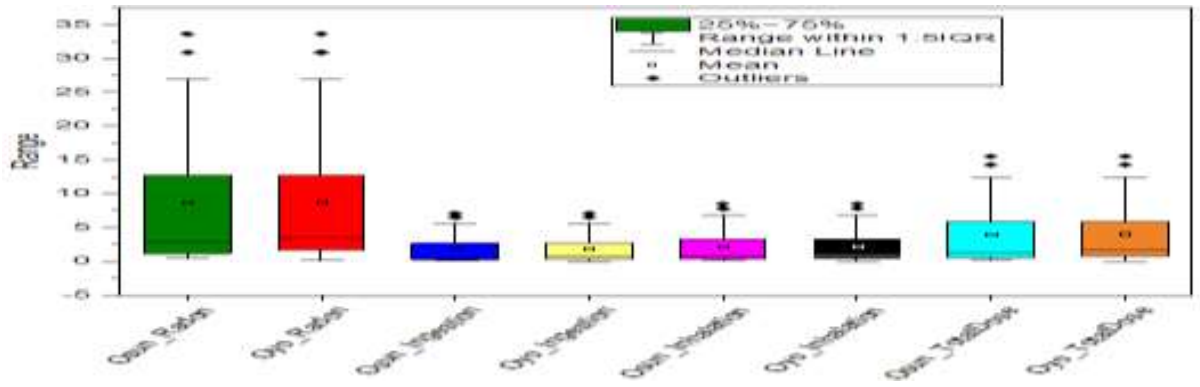


Figure 8: Summary statistics of radon concentration and annual effective dose in Osun and Oyo States

Table 4: Summary statistics of radon concentration and annual effective dose in Osun and Oyo States

Parameter	Osun Min	Osun Max	Osun Median	Osun IQR	Oyo Min	Oyo Max	Oyo Median	Oyo IQR
Radon (Bq/L)	0.12	25.98	3.1	1.08 – 7.18	0.18	33.6	4.5	0.72 – 9.93
Ingestion dose (µSv/y)	0.0248	5.4558	0.49	0.23 – 1.52	0.0379	7.056	0.55	0.18 – 2.67
Inhalation dose (µSv/y)	0.0297	6.5469	0.52	0.27 – 1.83	0.0455	8.467	0.60	0.21 – 3.20
Total annual effective dose (µSv/y)	0.0545	12.0	1.0	0.50 – 3.32	0.083	15.5	1.55	0.38 – 5.87

5. CONCLUSION

This study assessed radon concentrations and associated radiological doses in groundwater from Oyo and Osun States, Southwestern Nigeria, using measurements from 98 locations in each state. Radon levels ranged from 0.71 to 25.98 Bq/L in Oyo and 0.12 to 35.9 Bq/L in Osun, with mean total annual effective doses of 3.82 µSv/y and 4.79 µSv/y, respectively. Inhalation was consistently the dominant exposure pathway, contributing more to the total dose than ingestion. Comparative analysis shows that Osun State exhibits slightly higher radon levels and doses, likely due to deeper wells and local geological variations. When compared with other regions globally, radon levels in southwestern Nigeria fall within low-to-moderate ranges and are well below international recommended limits, indicating minimal health risk to the population. Strong correlations between radon concentration and dose parameters suggest that monitoring inhalation doses can reliably predict total exposure, providing a practical approach for radiological risk assessment and groundwater safety management in the region.

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