Nigerian Journal of Physics (NJP)
ISSN online: 3027-0936
ISSN print: 1595-0611
DOI: https://doi.org/10.62292/njp.v35i3.2026.597
Volume 35(3), September 2026

Geological Determinants of Indoor Radon-222 Levels in Residential Buildings: A Case Study of Cross River State, Southeastern Nigeria

Egor, A. Obeten; Abong, A. Agwul and *Ushie, A. Joseph

Department of Physics, University of Cross River State, P.M.B 1123, Calabar, Cross-River State, Nigeria.

*Corresponding Author's Email: ushieutsu@gmail.com

ABSTRACT

Indoor Radon-222 concentration levels display variability due to geological and building related factors, but the pattern of variability remains understudied in Nigeria's tropical South-South region. This study observed indoor Radon-222 in 216 residential buildings in Cross River State, Nigeria using Airthings Corentium Home Radon detector system. The observed mean concentrations of Radon-222 gas varied from 48.22±6.01 Bq/m^3 in Akpabuyo to 319.88±6.62 Bq/m^3 in Obudu. Result of impact of geology on concentration level of indoor radon gas using Kruskal-Wallis statistics produced a mean rank in the order; Precambrian rocks (135.49 Bq/m^3) > Cretaceous sediments (111.32 Bq/m^3) > Tertiary-Quaternary sediments (21.89 Bq/m^3). Medium-large effective size (r = 0.41) was observed. Result of one-way ANOVA test produced the same order; Precambrian rocks (223.46Bq/m^3) > Cretaceous sediments (176.22 Bq/m^3) > Tertiary-Quaternary sediments (49.44 Bq/m^3). Furthermore, the mean radon concentrations for buildings of age 0-5 *years*, 6-10 *years*, 11-15 *years* and > 16 *years* were 132.12± 99.81 Bq/m^3, 132.64±14.53 Bq/m^3, 173.69±18.69 Bq/m^3 and 211.06±12.36 Bq/m^3 respectively. Result of Kruskal-Wallis test yields a mean rank in the order; > 16 *years* (126.77 Bq/m^3) >11-15*years* (104.74 Bq/m^3) > 6-10 *years* (84.58 Bq/m^3) > 0-5 *years* (81.42 Bq/m^3). The effect size was small, r = 0.1. Based on World Health Organization recommendation, it is concluded that Cross River State is characterized by low and high radon potential zone with substantial proportion of the region belonging to high risk zone. It is therefore recommended that occupants should ensure adequate ventilation of their living rooms to keep radon gas accumulation in check.

Keywords:
Buildings,
Cross River State,
Geological,
Radon-222,
Nigeria.

INTRODUCTION

Air quality accounts for individuals' health condition. Recently, the presence of radioactive contaminant in air gained tremendous attention globally. Radon-222 is the most prevalent radionuclide readily found in air. Radon-222 is a naturally radioactive gas formed from alpha decay of Radium-226 in both Uranium-238 and Thorium-234 decay series. It occurs everywhere including caves, crevices of rocks, basements of apartments, soils and groundwater (Olowookere et *al*., 2022). As a geogenic gaseous pollutant, it diffuses from soils and rocks containing primordial radionuclides particularly those of Uranium-238 and Thorium-234 into indoor space where it accumulates to levels that culminates in significant radiogenic risk. Radon-222 has been classified as class-1 carcinogen for nonsmoker and the second leading cause of lung cancer on a global scale (Guo *et al*., 2012; EPA, 2016; CRCPD, 2018; WHO, 2018).It accounts for 3-14 % of lung cancer mortality cases across the globe. Truly speaking, radon poses a lower risk to human health due to its longer half-life (3.8 days) than its short-lived by-products such as Polonium-218(3 minutes half-life) and Polonium-214 (0.16 *ms* half-life). When radon is inhaled, the daughter radionuclides generated combined with aerosol, dust and smoke particles in the inhaled air to form massive aggregates. The aggregates become deposited in the respiratory track and then emit alpha radiation that permeate bronchi cells, mucous membrane, alveoli and other pulmonary tissues ((EPA, 2016; Field, 2018; Olowookere *et al*., 2022). Consequently, the bronchial epithelial cells become ionized leading to alteration or destruction of deoxyribonucleic acid. If the alteration is not repaired, it culminates in the increased chance of carcinogenesis. In a report by Maryam *et al.* (2016), they stated that long term contact with radon is responsible for all histological type of lung cancer including adenocarcinoma, carcinoma and squamous cell carcinoma. According to WHO (2023) and UNSCEAR (2019), inhalation and ingestion of Radon-222 gas accounts for 11*%* deaths from lung cancer among smokers and 25 *%* of lung cancer deaths among nonsmokers. Radon-222 activity level is controlled by source-pathway-receptor model. The fundamental source is the geological material containing significant levels of primordial radioisotopes of Uranium-238 and Thorium-234 respectively. The pathway is governed by building structural design and characteristics such as building aggregates, type of foundation, fissure on the floor and walls and degree of ventilation. The receptor is the indoor dwellers whose exposure is contingent on the amount of time spent indoor and the rate of ventilation. Among these factors, geology is the most basic determinant (Usikalu *et al.,* 2020; Samaila *et al.,* 2023). Buildings underlain by phosphate rich sediments, granite, shales, potassic evaporite, phosphate and clay have been reported to record high indoor radon levels worldwide Review of studies conducted by Oni *et al*. (2012), Mark *et al.* (2013), Obed *et al*. (2010), Ademola *et al*., 2015, Afolabi *et al.* (2015), Amin *et al*. (2015), Ojo *et al*. (2015), Olusegun *et al*. (2015), Ademola and Ojeniran, (2017), Ademola and Oyeleke, (2017), Adegun *et al*. (2019), Gregory *et al.* (2020), Usikalu *et al*., (2017), Usikalu *et al*., (2018), Usikalu *et al.* (2020), Lawal *et al*. (2023), Kelechi *et al*. (2023) among others gives a mean indoor radon value of 104 Bq/m^3 in Nigeria. The geologic environment of Cross River State comprised three major terrains: Precambrian basement (Obudu basement complex and Oban Massif) of granites and gneisses, Cretaceous sediments and Tertiary-Quaternary alluvium along coastal plains. Basement terrains with dominant granitic rocks and Cretaceous sediments have been reported as high radon emitting materials (Olowookere *et al.,* 2022; Samaila *et al.,* 2023). More so, most residential buildings in cross River State are constructed using quarry products such as gravel, rock dust and sand derived directly from granitic formation. This may increase indoor radon ingress. Despite the geological risk profile, no empirical study has been conducted to ascertained indoor Radon-222 activity levels in Cross River State or correlate radon activity levels with specific geological units. This knowledge gap hinders assessment of geogenic radon potential profile of Cross River State, Southeastern Nigeria, prevents risk based land use planning and limits health authorities to identify areas that need priority intervention. Therefore this study aims to assess the spatial distribution of indoor Radon-222 concentration in Cross River State, Southeastern Nigeria. The specific objectives of this study includes measurement of indoor Radon-222 concentrations in residential buildings, assessment of the impact of geology on indoor Radon-222 concentration and investigation of the impact of building age on indoor radon activity levels. The results of this study will provide the first indoor measurement and geological risk investigation for radon gas in the Cross River State and contribute to Nigeria's national radon database.

Study area

Cross River State (Figure 1) is located in Southeastern arm of Nigeria between the latitude 4° 28'N and 6° 55'N and longitude 7° 50'E and 9° 28'E. The state has an area expand of 20,156 km^2. Obianwu *et al*. (2015) reported that Cross River State exhibits dendritic drainage style. The main drainage system comprises Great Kwa River and Cross River. Other tributaries such as Afi River, Munaya River, Ovarr, Okwo, Usee, Nde, Atimaka, Okpon, Okang, Abep, Besun, Udip, Ujidam among others drain the area. Physiographically, the terrain of Cross River State is undulating with extreme southern axis of Cross River State characterized by low topography having elevation in the range of 32-50 *m* above sea. The elevation increases northward to a value of 150 *m* above sea level in western part of Oban and 350 *m* in other places. Within Oban axis, few relief features have peaks of 1200 *m* above sea level (Essoka & Oku, 2015; Ekwueme & Okoro, 2019). In the northern arm of the Cross River State, Ajadi and Yakubu (2017) reported that topographic elevation reaches 350-400 *m* above sea level in Obudu with some hills having altitudes ranging between 2000-2064 *m*. The climatic characteristics of the study area belong to that of humid tropical rain forest type with alternate rainy and dry seasons. Average precipitation is 207.11 *mm* per annum. Temperature varies between 22.5-36.8 *°C* (Essoka & Oku, 2015).

Geology of cross River State (Figure 2) is diverse: Oban Massif and Tertiary-Quaternary sediments in the South, Obudu Massif in the North, Cretaceous sediments in the central zone. For the purpose of this study, the geological framework of Cross River State is stratified into 3 geologic zones:

Zone A: Basement complex- granites, gneisses, tonalite, charnokite, schist, diorite, dolerite, granodiorite and migmatite (Asinya *et al*., 2016; Ekwueme & Okoro, 2019; Edem *et al*., 2023).

Zone B*:* Cretaceous sediments- shales, sandstone, limestone and marl (Eseme *et al*., 2002; Oden, 2012; Obianwu *et al*., 2015.

Zone C: Tertiary-Quaternary sediments-silt, coastal sand and coastal alluvium (Odumodu, 2009; Ayodele *et al*., 2017).

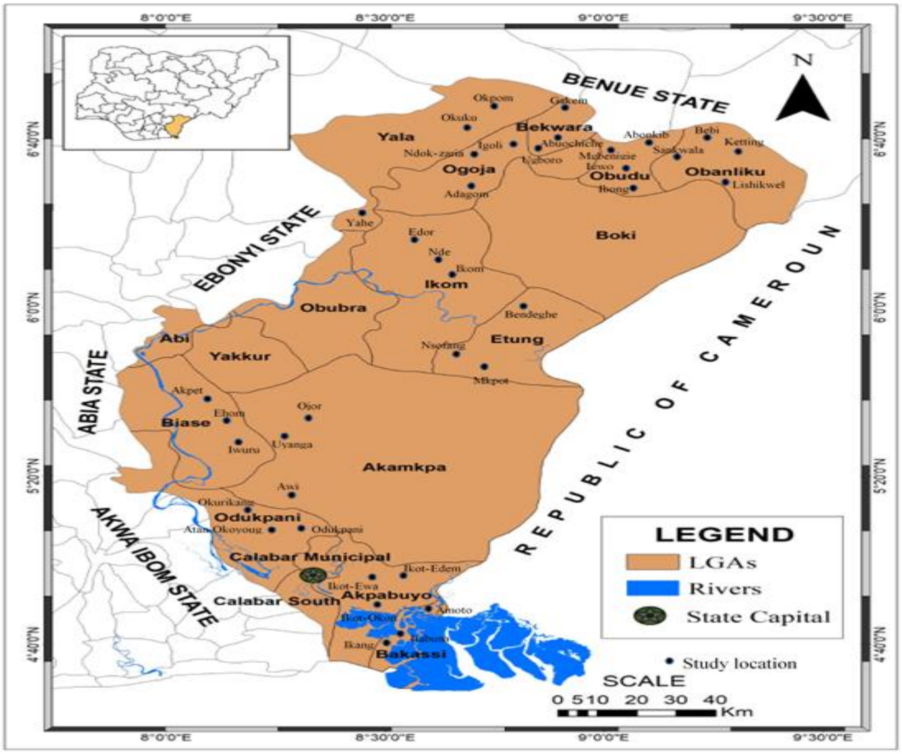

Figure 1: Map of Cross River State showing study locations (Adapted from Cross River State Survey Agency, 1997)

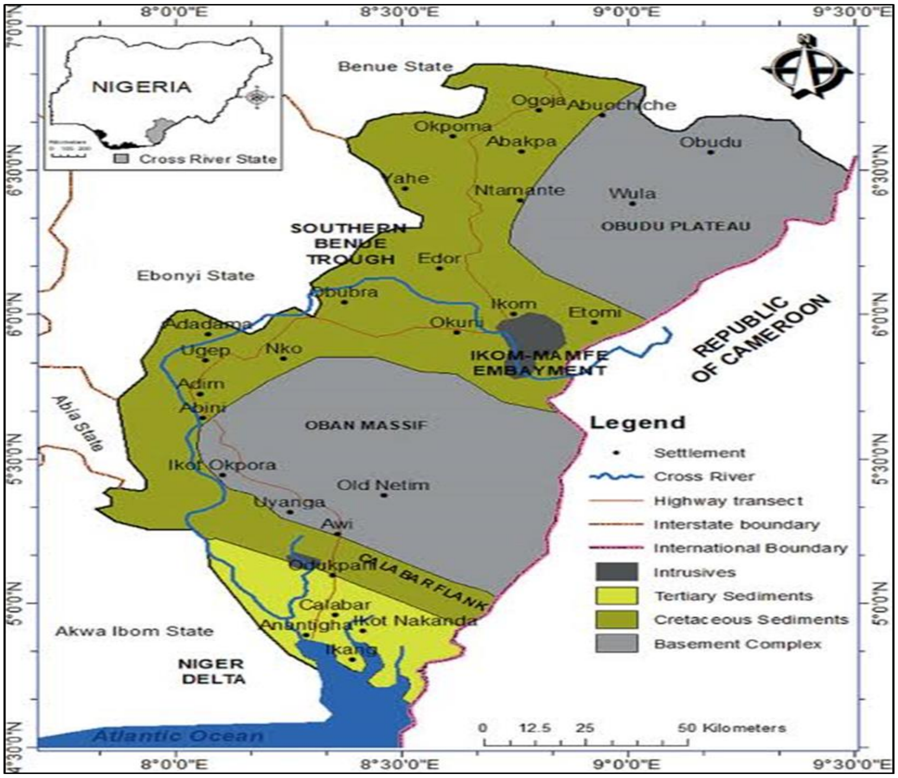

Figure 2: Geologic map of Cross River State (Adapted from Department of Geology, University of Calabar drawing unit, 2025

MATERIALS AND METHODS

Radon-222 activity levels were observed using Airthings Corentium Home Radon Detector System modelled CR-39. Two detectors were deployed for the study. Prior to testing, the detector systems were reset to short term average measurement mode and placed 100 *cm* above the floor, 150 *cm* from windows and doors and 50 *cm* from the walls of bedrooms to prevent thoron interference. Detectors were exposure for a period of 24 hours after which they were retrieved and readings were recorded in unit of Picocurie. At the same time, the location coordinates were obtained using Garmin Ground Positioning System to georeference the sampled stations. For each sampling point, geological and building data were collected through physical inspection, geological map and structured questionnaire. The measured data were subjected to statistical analysis. Analysis of data started with conversion of observed radon values in picocurie per litre (*PC/L*) to Becquerel per cubic metre (Bq/m^3) using the conversion factor; 1 *PC/l* = 37 Bq/m^3.The spatial distribution of indoor Radon-222 gas with respect to study locations was presented in map. Statistical analysis of observed indoor radon levels started with normality test using Kolmogorov-Smimov and Shapiro-Wilk tests. One-way analysis of variance (ANOVA) with Games-Howell post-hoc test was used to determine the impact of geology and building age on indoor radon levels. The results were validated using Kruskal-Wallis H test. Statistical significance was set at $P < 0.05$. All statistical analyses were performed using SPSS version-20.0.

RESULTS AND DISCUSSION

The result of tests of normality (Table 1) using Kolmogorov-Smimov and Shapiro-Wilk tests indicates that the data were normally distributed, $P > 0.05$.The mean of the measured indoor Radon-222 concentration levels for each study location were found to be 319.8±6.62 Bq/m^3, 175.55±8.35 Bq/m^3, 233.38±3.01 Bq/m^3, 162.50±6.09 Bq/m^3, 164.05±8.97 Bq/m^3, 118.88±2.84 Bq/m^3, 181.77±6.86 Bq/m^3, 210.16±5.25 Bq/m^3, 22.00±1.35 Bq/m^3, 259.44±2.70 Bq/m^3, 48.22±6.01 Bq/m^3 and 50.66±8.59 Bq/m^3 in Obudu, Obanliku, Bekwara, Ogoja, Yala, Ikom, Etung, Akamkpa, Biase, Odukpani, Akpabuyo and Bakassi respectively. Minimum, maximum, mean and standard deviation of the measured indoor Radon-222 levels are presented in Table 2. The result reveals that mean Radon-222 concentration has a minimum level of 48.22±6.01 Bq/m^3in Akpabuyo and a maximum level of 319.88 ±6.62 Bq/m^3 in Obudu. Again, the result indicates that while the mean radon concentration levels in Akpabuyo and Bakassi were below the reference limit of 100 Bq/m^3 recommended by WHO (2018), the mean radon levels in Obudu, Obanliku, Bekwara, Ogoja, Yala, Ikom, Akamkpa, Biase and Odukpani exceed the WHO reference limit. Figure 3 shows high indoor radon exposure levels in Obudu, Obanliku, Bekwara, Ogoja, Yala, Ikom, Etung, Akamkpa, Biase and Odukpani, thus, the locations are considered high risk or high radon potential area. This anomaly is attributed to high concentration of uranium and thorium minerals in rocks that make up the geology of the sampled locations. Other predisposing factors are poor ventilation, building design, age of the buildings, fissures on the building walls and climatic factors. Again, Bakassi and Akpabuyo show substantially low radon levels, hence the region is considered low radon potential zone. The findings of this study have been found to be comparatively higher than the findings reported by Obed *et al*., (2010), Afolabi *et al.,* (2015), Ingrid and Jiri, (2017), Abood (2018), Rejah (2018), Adegun *et al*., (2019), Hashim and Nayif (2019) and Abdullah *et al.* (2024) but relative agree with the results of Olusugun *et al*. (2015) and Ahmed *et al*. (2019). Furthermore, it was noticed that the results of this study are lower compared to the findings of Christiana *et al*. (2024) and Yerlan *et al*. (2024).

Table 1: Tests of Normality

Variable	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	P-value	Statistic	df	P-value
Radon concentration	0.129	216	0.050	0.902	216	0.051

Table 2: Minimum, Maximum, Mean, Standard Error and Standard Deviation of Measured Indoor Radon-222 Concentration Level

Locations	N	Minimum (Bq/m^3)	Maximum (Bq/m^3)	Mean (Bq/m^3)	Std. Error (Bq/m^3)	Std. Deviation (Bq/m^3)
Obudu	18	96.00	632.00	319.88	1.91	6.62
Obanliku	18	67.00	352.00	175.55	1.97	8.35
Bekwara	18	98.00	462.00	233.38	0.68	3.01
Ogoja	18	67.00	281.00	162.50	0.03	6.09
Yala	18	58.00	320.00	164.05	0.44	8.97
Ikom	18	62.00	212.00	118.88	1.50	2.84
Etung	18	75.00	379.00	181.77	1.66	6.86

Akamkpa	18	84.00	373.00	210.16	2.08	5.25
Biase	18	104.00	401.00	220.00	0.01	1.35
Odukpani	18	51.00	452.00	259.44	3.985	2.70
Akpabuyo	18	14.00	98.00	48.22	0.90	6.01
Bakassi	18	27.00	98.00	50.66	0.784	8.59
WHO (2018)				100.00		

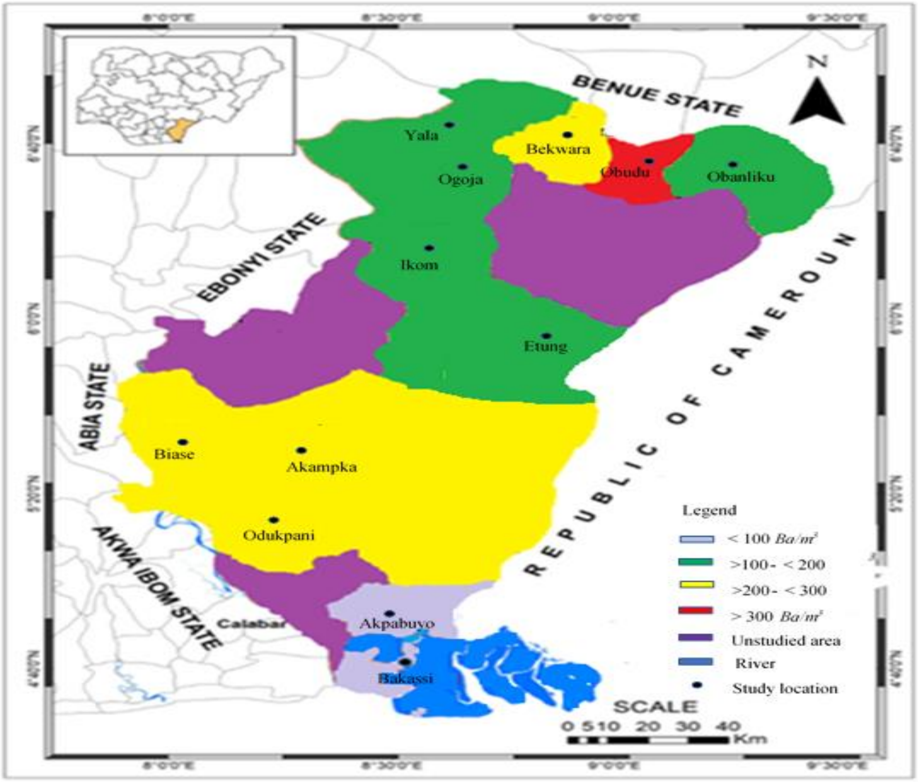

Figure 3: Geogenic Radon-222 potential map of Cross River State

The result of Kruskal-Wallis test presented in Table 3 shows a statistically significant difference among the three geologic zones, H(2) = 89.436, P = 0.000. The mean rank gave an order; Precambrian rocks (135.49 *Bq/m³*) > Cretaceous sediments (111.32 *Bq/m³*) > Tertiary-Quaternary sediments (21.89 *Bq/m³*).This implies that buildings sited on Precambrian rocks record the highest radon level while buildings sited on Tertiary-Quaternary sediments record the least radon levels. Medium-large effective size (r = 0.41) was observed. This signifies that the geologic materials significantly differ and that 41 % of the variance in indoor radon level is due to geology of the study area. Also, The ANOVA result (Table 4) shows a significant mean variance in indoor radon level with geology of the study locations, F(2, 213) = 37.289, P = 0.000. Computed means of indoor radon level were also in the order; Precambrian rocks (223.46 *Bq/m³*) > Cretaceous sediments (176.22 *Bq/m³*) > Tertiary-Quaternary sediments (49.44 *Bq/m³*). Both results of Kruskal-Wallis H test and ANOVA test produced the same pattern and both results demonstrate that residential buildings sited on basement and Cretaceous sedimentary rocks recorded the highest mean radon level with substantial proportion exceeding World Health Organization (WHO) reference limit of 100 *Bq/m³*. On the contrary, mean radon level recorded by residential buildings located on Tertiary-Quaternary sediments were lower than World Health Organization reference limit. More so, the result of pairwise Games-Howell post-hoc multiple comparisons (Table 5) shows that the variance in indoor radon gas accumulation between buildings sited on Precambrian rocks and Cretaceous sediments, Precambrian rocks and Tertiary-Quaternary sediments, Cretaceous sediments and Precambrian rocks, Cretaceous sediments and Tertiary-Quaternary sediments, Tertiary-Quaternary sediments and Precambrian rocks and Tertiary-Quaternary sediments and Cretaceous sediments were significant, P = 0.014, , P = 0.000, P = 0.014, , P = 0.000,, P = 0.000 and , P = 0.000. The findings of this study show that the geology of the study location influences the concentration level of the indoor radon gas. The variance in indoor radon level with geology as observed in this study is accounted for by the amount of primordial radionuclides (Uranium and Thorium) present in a given rock type which decay spontaneously to emit radon gas that migrates into the indoor space via diverse migration channels. The findings demonstrate that occupants of buildings underlain by Precambrian and Cretaceous sedimentary rocks are more vulnerable to indoor radon exposure than occupants of building underlain by Tertiary-Quaternary sediments. The findings supported the reports of Ibrahim, *et al.* (2014),Olukunle *et al.* (2021), Preethi and Jeyanthi (2022), Samaila *et al*. (2023) and Yerlan *et al*. (2024) that indoor radon level depends on the geology of the study area.

Table 3: Result of Kruskal-Wallis Test of Variability of Indoor Radon-222 with Geology

Geology	N	Mean Rank	H-value	df	P-value	r-value
Precambrian rock	108	135.49	89.436	2	0.000	0.410
cretaceous sediment	72	111.32				
Tertiary sediment	36	21.89				
Total	216					

Table 4: Analysis Of Variance Model Summary of Variability of Indoor Geogenic Radon-222 with Geology

Geology	N	Mean Radon ((Bq/m^3)	Std. Deviation	Std. Error	Subset for α = 0.05		
					1	2	3
Precambrian rock	108	223.46	123.00	11.83	223.46	176.22	49.44
cretaceous sediment	72	176.22	99.34	11.70			
Tertiary sediment	36	49.44	22.31	3.71			
Total	216	178.71	121.14	8.24			
Source of variation	Sum of squares	df	Mean square	F-Value	P-value		
Between group	818296.0	2	409148.0	37.289	0.000		
Within group	2337084.1	213	10972.2				
Total	3155380.2	215					

Table 5: Games-Howell post hoc multiple Comparisons

(I) geology	(J) geology	Mean Difference (I-J)	Std. Error	P-value	95% Confidence Interval	
					Lower Bound	Upper Bound
Precambrian rock	Cretaceous sediments	47.24	16.64	0.014	7.87	86.60
	Tertiary-Quaternary sediments	174.01	12.40	0.000	144.59	203.44
Cretaceous sediments	Precambrian rock	-47.24	16.64	0.014	-86.60	-7.87
	Tertiary-Quaternary sediments	126.77	12.28	0.000	97.46	156.08
Tertiary-Quaternary sediments	Precambrian rock	-174.01	12.40	0.000	-203.44	-144.59
	Cretaceous sediments	-126.77	12.28	0.000	-156.08	-97.46

*. The mean difference is significant at the 0.05 level.

Furthermore, the result of the impact of the age of a building on indoor Radon-222 concentration level presented in Table 6 reveals that the age of a building significantly impacts the concentration level of indoor radon, F(3, 212) = 6.071, P = 0.001. The result equally shows that the mean radon concentrations associated with buildings of age group 0-5 *years*, 6-10 *years*, 11-15 *years* and > 16 *years* are 132.12± 99.81 Bq/m^3, 132.64±14.53 Bq/m^3, 173.69±18.69 Bq/m^3 and 211.06±12.36 Bq/m^3respectively. Pairwise comparisons using Games-Howell post hoc multiple comparisons test (Table 7) reveals that the pair between 0-5 and 6-10 *years* and 6-10 and 0-5*years* do not differ significantly, P = 1.000 and P = 1.000 respectively. But, the pair between 0-5 and 11-15 *years*, 0-5 and >16 *years*, 6-10 and 11-15 *years*, 6-10 and >16 *years*, 11-15 and 6-10 *years*, 11-15 and ≥ 16 *years*, 11-15 and 0-5 *years*, ≥ 16 and 0-5 *years*, ≥ 16 and 6-10 *years* and ≥16 and 11-15 *years* differ significantly, P = 0.009. P = 0.002, P = 0.013, P = 0.001, P =0.059, P = 0.013, P = 0.007, P = 0.002 and P = 0.001 and 0.047 respectively. Figure 4 demonstrates that buildings of age 0-5*years* and 6-10 *years* maintained fairly constant radon levels while buildings of age greater than 10 *years* showed increasing accumulation of indoor radon gas. The increase in indoor radon level with increasing age as obtained from the result is correlated with development of crevices, joints and other forms of discontinuities as the building gets older. Jelena *et al.* (2024) reported that structural features create pathways for radon gas to seep or migrate from the soil into the indoor space. The result of Kruskal-Wallis test statistics (Table 8) reveals that building age significantly impact indoor Radon-222 concentration levels, H(3) = 19.921, P = 0.001.The mean rank gave an order; > 16 *years* (126.77Bq/m^3) >11-15 *years* (104.74 Bq/m^3) > 6-10 *years* (84.58 Bq/m^3) > 0-5 *years* (81.42). The effect size was small, r = 0.1. This implies that 10 % of the variance in indoor radon level is due to the age of the building. This result validates the result of one-way ANOVA with Games-Howell post hoc test. The finding of this study agreed well with the result reported by Jelena *et al*. (2024).

Table 6: Analysis of Variance Model Summary of the Impact of Building Age on Indoor Radon-222 Concentration Level

Building age (*y*)	**N**	**Mean Radon (Bq/m^3)**	**Std. Deviation**	**Std. Error**	**Subset for α = 0.05**	
					1	**2**
0 -5	33	132.12	99.8	17.38	132.12	
6 -10	33	132.64	83.4	14.53	132.64	
11-15	48	173.69	129.5	18.69	173.69	173.69
16 and above	102	211.06	124.8	12.36		211.06
Total	216	178.71	121.1	8.24		
Source of variation	Sum of squares	df	Mean square	F-Value	P-value	
Between group	249627.0	3	83209.0	6.071	0.001	
Within group	2905753.2	212	13706.3			
Total	3155380.2	215				

Significant at $P < 0.05$

Table 7: Games-Howell Post Hoc Multiple Comparisons

(I) Building age (*year*)	**(J) Building age (*year*)**	**Mean Difference (I-J)**	**Std. Error**	**P-value**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
0-5	6-10	-.515	22.663	1.000	-60.35	59.32
	11-15	-41.566	25.530	0.009	-108.59	25.46
	16 and above	-78.938*	21.337	0.002	-135.15	-22.72
6-10	0-5	.515	22.663	1.000	-59.32	60.35
	11-15	-41.051	23.677	0.013	-103.20	21.10
	16 and above	-78.422*	19.082	0.001	-128.47	-28.37
11-15	0-5	41.566	25.530	0.059	-25.46	108.59
	6-10	41.051	23.677	0.013	-21.10	103.20
	16 and above	-37.371	22.412	0.007	-96.05	21.31
16 and above	0-5	78.938*	21.337	0.002	22.72	135.15
	6-10	78.422*	19.082	0.001	28.37	128.47
	11-15	37.371	22.412	0.047	-21.31	96.05

*. The mean difference is significant at the 0.05 level.

Figure 4: Impact of Building Age on Indoor Radon-222 Concentration

Table 8: Kruskal-Wallis Test Model Summary of the Impact of Building Age on Indoor Radon-222 Concentration Level

Building's age (*y*)	N	Mean Rank	H-value	df	P-value	r-value
0-5	33	81.42	19.921	3	0.001	0.10
6-10	33	84.58				
11-15	48	104.74				
16 and above	102	126.77				
Total	216					

CONCLUSION

Airthings Corentium Home Radon Detector System Model CR-39 has proven its efficiency for mapping of indoor geogenic radon activity level in 216 dwellings in Cross River State, Southeastern Nigeria. The study showed that buildings sited on basement and Cretaceous sedimentary rocks record mean radon level above World Health Organization (WHO) reference limit of 100 Bq/m^3. Hence, indoor radon level is correlated with basement and Cretaceous sedimentary rocks. On the contrary, mean radon level recorded by residential buildings located on Tertiary-Quaternary sediments were lower than World Health Organization reference limit. Statistical analysis confirmed that geology of an area and age of a buildings are significant predictors of indoor radon level. Based on WHO reference limit, Cross River State is characterized by high and low risk regions and warrant priority attention and mitigations.

REFERENCES

Abood, H. N. (2018) Indoor radon levels and the associated effective dose rate determination at AlElaf distinguish secondary school for girls in the Basrah governorate, Iraq. *Advance and Applied Science Resource*, *9*(2), 75-78.

Abdullah, S. M., Wisam, T. A., & Wisam, B. A. (2024). Calculation the excess lifetime lung cancer risk and human health risk assessment by inhalation of radon gas in the health centers of Al-Hay City in Wasit, Iraq using LR-115 detectors. *Cross Current International Journal of Medical and Biosciences,* 6, 84-91.

Adegun, I. K., Anyaegbuna, B. E., & Olayemi, O. A. (2019). Indoor radon concentration survey in bank basements in three Nigeria Cities. *Journal of Physics*, *4*(3), 75-128.

Adeleye, D. R., & Fayose, E. A. (1973). Stratigraphy of the type section of Awi formation, Odukpani area; Southeastern Nigeria. *Nigeria Journal of Mining and Geology*, 15, 33-37.

Ademola, JA; Oyeleke, OA (2017). Radon- 222 in ground water and effective dose due to ingestion and inhalation in the city of Ibadan, Nigeria. *Journal of Radiological Protection, 37*(1), 189-2000.

Ademola, J. A., Ojeniran, O. R (2017). Radon-222 from different sources of water and the assessment of health hazard. *Journal of Water Health*, *15*(11): 97-102

Ademola, JA; Oyeleke, OA (2017). Radon- 222 in ground water and effective dose due to ingestion and inhalation in the city of Ibadan. *Nigeria Journal of Radiological Protection, 37*(1):189-2000

Afolabi, O. T., Esan, D. T., Banjoko, B. Faewonyomi, B. A. Tobih, J. E., & Olubudun, B. B. (2015). Radon level in a Nigerian university campus. *BMC Research Note*, *8*(1), 677-682.

Ahmed, F. H., Mhana, W. J., Hassan, S. F., & Mansour, H. L. (2019). Indoor radon concentrations measurements for selected dwellings in some Baghdad Districts Iraq. *Ядерна фізика та енергетика*, 5, 7-10.

Ajadi J., & Yakubu S. (2017). Preliminary studies of the litho-structural evolution of areas around Obudu Northeast, Sheet 291, Southeastern Nigeria. *International Journal of Research in Engineering and Science,* 5, 15-31.

Ajayi, O. S. (2009). Measurement of activity concentrations of 40-k, 226-Ra and 232
Th for assessment of radiation hazards from soils of the Southwestern Region of Nigeria. *Journal of Radiation Environmental Biophysics, 48*(3), 323-332.

Ahmed, F. H., Mhana, W. J., Hassan, S. F., & Mansour, H. L. (2019). Indoor radon concentrations measurements for selected dwellings in some Baghdad Districts Iraq. *Ядерна фізика та енергетика*, 5, 7-10.

Ajadi J., & Yakubu S. (2017). Preliminary studies of the litho-structural evolution of areas around Obudu Northeast, Sheet 291, Southeastern Nigeria. *International Journal of Research in Engineering and Science,* 5, 15-31.

Amin, S., Forough, S., Ali, R., & Hasn, R. (2015). Health risk assessment of household exposure to indoor radon in association with the dwelling's age. *Journal of Radiation Protection and Research, 40*(2), 155-161.

Christiana O. H., Michael, K. M., Charles, A. O., Keren, A. Delali, T., Ruth, S. A., Denis, K. A., & Irene, O. N (2024). Indoor radon monitoring in building types of a Periurbanarea in Cape Coast Metropolis, Southern Ghana. Retrieved from https://www.scribbr.com/methodology

CRCPD (2018). *Conference of Radiation Control Program Directors. Reducing the risk from radon: Information and intervention*. A guide for health care providers http://www.radonleaders.org/sites/default/files/HealthCareProfessionalsGuide

Edem G.O., Ekwueme, B.N., & Ephraim, B. E., (2023). Global petrology of intrusive rocks of Oban Massif, Southeastern Nigeria. *Journal of Geological Sciences*, 21,167-182.

Ekwueme, B. N., & Okoro A. U., (2019). Geology of the Oban Massif: Explanation of 1:250,000 sheet 80 (Oban). *Nigerian geological survey agency. Bulletin*, 55, 187.

Eseme, E., Ayying, C. M., & Foba-Tendo, J. (2002). Geochem and genesis of brine emanation from Cretaceous strata of the Mamfe basin, Cameroon. *Journal of African Earth Sciences,* 35, 407-477.

Essoka, A. N., & Oku, E., (2015). Physical properties and management of forested steep land being converted to farm lands: The case study of Oban Hills, Cross River State, Nigeria.

Ekwueme, B. N. (2003). *Precambrian geology and evolution of southern Nigerianbasement complex.* Calabar: University of Calabar press, 135

Ekwueme, B. N., & Okoro A. U., (2019). Geology of the Oban Massif: Explanationof 1:250,000 sheet 80 (Oban). Nigerian geological survey agency. *Bulletin*, (55), 187.

EPA (2016). US Environmental Protection Agency (2016). *A citizen's guide to radon*: guide to protecting yourself and your family from radon. https://www.epa.gov/sites/production/files201612/documents/2016_a_citizens_guide_to_radon.pdf. Accessed June 28, 2018.

Ephraim, B. E. (2012). Granitoids of older granite suites in southeastern Nigeria. *Advances in Applied Science Research*, *3*(2), 994-1007.

Field, R. W (2018). *Radon: A leading environmental cause of lung cancer*. Editorial Radon. American Family Physician 98 (5):281-282.

Gregory, O.A., Emmanuel, E., & Isreal, I. (2020). Evaluation of radon gas concentration in some selected basement buildings in Port Harcourt, River State. *Journal of Innovative Environmental Studies Research*, *8*(3), 1-9.

Guo, Q; Zhang, L; Guo, L (2012). Assessment of the unattached fraction of indoor radon progeny and its contribution to dose: a pilot study in China. *Journal of Radiological Protection,* 32, 447-454.

Hashim, A. K., & Nayif, S. S. (2019). Assessment of internal exposure to radon in schools in Karbala, Iraq. *Journal of Radiation and Nuclear Applications*, *4*(1), 25-34.

Ingrid, G.S., & Jiri, S. (2017). Indoor radon concentration related to different radon areas and indoor radon prediction. IOP conference series. *Earth and Environmental Science*, 95, 1-9.

Jelena, R., Nadına, R., Andris, R., Žanna, M., Inese-Martin, S., & Ivars, V. (2024). Assessment of Indoor Radon Gas Concentration in Latvian Households. *Atmosphere*, https://www.mdpi.com/journal/atmosphere

Lawal, M.K., Ayanlola, P.S. Aremu, A.A., Oladapo, O.O., Isola, G.A., Oni, O.M., & Adeoje, E.A. (2023). Assessment of occupational exposure to radon-222 in water treatment and production plants in Ogbomoso, Southwestern Nigeria. *International Journal Radiation Research*, *21*(2), 255-260.

Maryam, Y., Abbas, S., Mohammad, H., Narges, S., Noushin, R., & Majid, K. (2016). Estimation of the residential radon levels and the annual effective dose in dwellings of Shiraz, Iran. *Journal of Electronic Physician*, *8*(6), 2497-2505.

Obed, RI; Ademola, AK; Ogundare, F. O. (2012). Radon measurement by nuclear track detection in dwellings in Oke-Ogun area, Southwestern Nigeria. *Radiation Protection Dosimetry, 148*(4): 475-481.

Obianwu, V. I., Egor, A. O., Okiwelu, A. A., & Ebong, E. D. (2015). Integrated geophysical studies over parts of central Cross River State for the determination of groundwater potential and foundation properties of rocks. *Journal of Applied Geology and Geophysics, 3*(4), 49-64.

Oden, M. I., Okpamu, T. A., & Amah, E. A. (2012). Comparative analysis of fracture linearments in Oban and

Obudu areas, southeastern Nigeria. *Journal of Geography and Geology*, *4*(2), 36-47.

Odumodu, C. F. R. (2000). Subsidence and thermal history of Calaba Flank.Implications for petroleum exploration. *Global Journal of Geological Sciences*, *7*(1), 36-46.

Olowookere, C. J., Aladeniyi, K., Abu, G. A., & Erimona, J. (2022). Evaluation of cancer risk associated with radon concentration measured in the Science Faculty Building Complex Basement of a tertiary institution I Southwestern Nigeria. *Journal of Applied Science and Environmental management*, *26*(5), 837-843.

Olukunle, O. O., Olatunde, M. O., Emmanuel, A. O., Adetola, O. O., & Abraham, A. A (2021). Assessment of Annual Tracheobronchial Effective Dose from Indoor Radon Inhalation in Selected Residential Buildings in Southwestern Nigeria. *International Journal of Health Sciences and Research*, *11*(6), 58-68.

Olusegun, T. A., Esan, D. T., Bosun, B., Benjamin, A., & Tobih, J. E. (2015). Radon level in Nigerian University Campus. *BMC Research Notes*, 8, 677.

Oni, M. O., Isola, G. A., Oladapo, O. O., & Oni, E. A. (2012). Estimation of lifetimerisk from indoor radon in some offices in Nigeria University. *Research journal of environmental and earth sciences, 4*(1), 131-133.

Preethi, G., & Jeyanthi, J. (2022). Importance of radon assessment in indoorenvironment-a review. *Materials today: Processings*, *56*(3), 1495-1500.

Rejah B. K. (2018). Radon and thoron concentrations and resultingdose in air ofSoutheastern Baghdad regions. *International Journal of Engineering and Technology*, *7*(3), 1540-1543.

Samaila, B., Bello, A., Wali, S.U., Yahaya, M. N., & Abubakar, N. (2023). Radiological implication of radon levels on human health: Systematic review in Nigeria. *Journal of Scientific and technical Research,6*(2), 4396-43986.

Usikalu, M. R., Olatinwo, V., Akpochafor, M., Aweda, M. A., Giannini, G.m., & Massimo, V. (2017). Measurement of radon concentration in selected houses in Ibadan, Nigeria. IOP Conference Series: *Journal of Physics:* Conference Series 852 (2017) 012028 https://doi.org/10.1088/1742-6596/852/1/012028.

Usikalu, M. R., Onumejor, C. A., Akinpelu, A., & Ayara, W.A. (2018). Improvement on indoor radon accumulation rate in CST Laboratories at Covenant University, Ota, Nigeria. *International Journal of Mechanical Engineering and Technology (IJMET)*, *9*(10), 135-148.

Usikalu, M. R., Onumejor, C. A., Achuka, J. A., Akinpelu, A., Omeje, M., Adagunodo, T. A. (2020). Monitoring of radon concentration for different building types in Covenant University, Nigeria. *Cogent Engineering*, 7, 1759396 https://doi.org/10.1080/23311916.2020.1759396

WHO (2018). World Health Organization. *WHO handbook on indoor radon*: a public health perspective. http://apps.who.int/iris/bitsstream/10665/44149/1/9789241547673_eng.pdf. Accessed June 28, 2018

WHO (2023). World Health Organization. Nigeria data, *Https://data.who.int/countries/566.* Accessed June, 2025