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Full Length Research Article

RADIOMETRIC ASSESSMENT OF RADON-222 CONCENTRATION IN WATER SOURCES AROUND COAL MINING AREAS IN BENUE STATE, NIGERIA

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ABSTRACT
This research evaluated radon-222 levels in water sources around coal mining sites in Benue State, Nigeria. Nineteen water samples were collected and sent for analysis at the Centre for Energy Research and Training, Zaria, Nigeria. The result indicated an average concentration of 1428.416Bq/L, which significantly surpasses the World Health Organization's guideline of 100Bq/L for safe drinking water. The elevated levels are likely due to the area's uranium-rich geological formations. Although the estimated annual effective doses from ingestion (0.001247mSv/y) and inhalation (0.010427mSv/y) are within the International Commission on Radiological Protection's recommended limit of 1mSv/year for the general population, the lung-specific dose (7.535749mSv/y) and lung AEDE (62.85028mSv/y) indicate a notable risk, particularly from radon gas released during routine household activities. The excess lifetime cancer risk (3.6496×10^{-5}), though relatively low, reflects a potential health concern over long-term exposure. In comparison to global findings, such as those from India and other parts of the world where radon levels are generally lower, the results of this study highlight a pressing need for intervention. Measures like water aeration or the use of granular activated carbon (GAC) filters are recommended to reduce radon content and safeguard public health.

Keywords: coal mining areas, radon-222 concentration, Benue State and hazard parameters

INTRODUCTION
Water is a necessity for the sustenance of life. In the region where mineral resources are available and mined for economic growth, water bodies including underground and surface are always contaminated with metals (including radon) through the agents of erosion such as air and run off water during rain Adekoya, 2003; Aliyu *et al.,* 2015*)*. When water containing radon is used for domestic purposes such as drinking, cooking, or bathing, radon may be ingested or released into indoor air, where it can be inhaled, leading to increased radiation exposure of internal organs and the respiratory system (EPA, 2012). Radon-222 (^{222}Rn) is a colorless, odorless, and tasteless radioactive noble gas formed from the radioactive decay of radium-226, a decay product of uranium-238. Naturally present in varying concentrations in rocks, soil and groundwater, radon poses a significant environmental and public health concern due to its radio toxicity. As a noble gas, radon is mobile and can migrate through porous geological media and dissolve into groundwater, especially in areas with uranium-rich geological formations (UNSCEAR, 2000; WHO, 2009; Choubey *et al*., 2008). Long-term exposure to elevated radon levels is recognized as the second leading cause of lung cancer after tobacco smoking (WHO, 2009; Choubey *et al*., 2008; Srinivasa & Sannappa, 2014).

In mining regions, particularly coal mining areas, the disturbance of subsurface geological formations can significantly enhance the release and mobilization of naturally occurring radionuclides, including uranium, thorium, and radium, thus increasing radon exhalation from soil and its dissolution in groundwater (Ajayi & Owolabi, 2008; Srinivasa & Sannappa, 2014). Coal deposits, often associated with organic-rich sedimentary rocks, may contain varying levels of uranium-bearing minerals that contribute to the radiological profile of the surrounding environment. The activities associated with coal extraction such as drilling, blasting, and excavation can amplify the natural release of radon and increase its concentration in nearby water bodies (Ejeh & Elegba, 2010; Gruson, 2014; Friedmann & Keller, 2002).

Benue State, located in North-Central Nigeria, is endowed with significant coal reserves, particularly in areas such as Owukpa and Okaba. These regions have experienced both artisanal and industrial-scale mining operations over the years. However, comprehensive data on the radiological quality of water sources in these mining zones remain limited. With local communities relying heavily on groundwater sources such as wells, boreholes, and streams for drinking and domestic purposes, it becomes imperative to assess the levels of radon-222 in these waters to evaluate potential health risks and ensure that they remain within recommended safety thresholds, such as the 100Bq/L limit set by the World Health Organization (WHO, 2017; UNSCEAR, 2000; USEPA, 2003). Benue State has raining season from April with high humidity and precipitation to October, dry season with harmattan from November to March which ends with heat. Light rains are sometimes seen in January, February and March. The state has vegetation as rain forest with tall grasses and trees, palm oil trees. Land uses in the state are mainly for agricultural purposes such as farming of various crops and planting of economic trees and mining activities (Ikyado, 2024).

This study seeks to conduct a radiometric assessment of radon-222 concentrations in water sources located around coal mining areas in Benue State. By employing reliable and standardized radiometric techniques, the study would provide baseline data on the radiological status of these waters, identify potential hotspots of contamination, and evaluate compliance with international safety standards. The findings would contribute to environmental radiation protection strategies, inform water quality regulations, and guide public health interventions in mining-impacted communities.

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MATERIALS AND METHODS

Study Area

The study area of this research work is Effa Community, Okpokwu Local Government Area, Benue State, Nigeria where coal mining is ongoing. There are two active and one abandoned coal mining sites at the moment, a sizeable water body called river Umabe and streams in the community. Effa community has boundaries with Awo and Okoko villages in Ankpa Local Government Area of Kogi State, North Central Nigeria, Ohimini and Ogbadibo Local Government Areas of Benue State. It is located to the right along Otukpo – Ugbokolo – Okwungaga – Otukpa branch road in Ogbadibo, shortly after Ugbokolo. Okpokwu Local Government is surrounded by Ogbadibo, Ohimini, Otukpo and Ado Local Government Areas of Benue State. The Local Government also has boundaries with Enugu, Ebonyi and Cross River States of Nigeria. Okpokwu has three (3) districts of Edumoga, Ichama and Okpoga. Effa is a community in Edumoga district.

Benue State has land mass of 34,059 square kilometres and is situated on longitude 7° 47' and 10° 0' East. Latitude 6° 25' and 8° 8' North with a population of 4.253,641 people based on 2006 National Population Census. The rainy days are 160.01 annually with temperature as 29.38 °C (84.88 °F). The compositions of soil in the state are loamy, clay, sandy and silk and has agriculture as major occupation with varieties of crops being the "food basket of the nation". Benue state has about thirty four (34) solid minerals with major ones as limestone, coal, granite (Ikyado, 2024). Figure 1 shows the map of Benue State depicting the study area, Okpokwu Local Government Area.

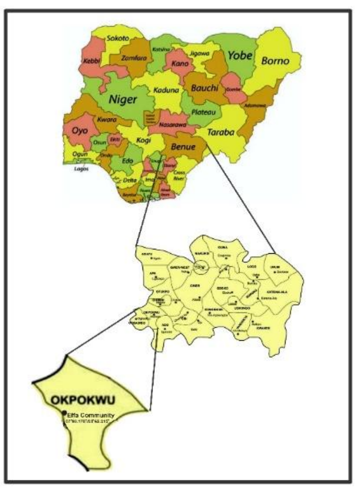

Figure 1: Map of Nigeria and Benue State showing Study Area

Sample Collection and Preparation

Benue State, Nigeria at the moment, has coal mining activities in only Effa, Okpokwu Local Government Area, with three (3) mining sites, one abandoned having exhausted its coal deposit and two (2) active. Run off water from the mining sites flows to all the water bodies in the area. The water bodies include river Umabe, Olumabe and Okolo streams. A total of nineteen water samples were collected from the study area. Eleven from river Umabe, four from Olumabe stream, three from Okolo stream and one as control from the community borehole at Efewu. Geographical positions of the samples were taken.

A well labelled plastic containers for identifications were used to collect water samples from river Umabe, Olumabe and Okolo streams including Efewu community borehole far from the mining sites as controls. The plastic rubbers were rinsed with diluted Nitric Acid (HNO_3) to prevent radioactive absorption by the walls of the containers and tightly covered.

The samples were sent to Energy Research Centre, Zaria, Nigeria for analysis. 10 ml each of the water samples was transferred into a 20 ml glass scintillation vial to which 10 ml of insta-gel scintillation cocktail were added. It was sealed tightly. The vials were shaken for more than two minutes to extract radon-222 in water phase into the organic scintillate, and the samples collected were then counted for 60 minutes in a liquid scintillation counter using energy discrimination for alpha particles.

Method of Water Sample Analysis for Radon- 222

Liquid Scintillation Counter (LSC) was used for the analysis of radon-222 in the water samples. The technique involves collecting a water sample and transferring a known volume into a vial containing a liquid scintillation cocktail. This cocktail is a mixture of solvents and fluorophores designed to detect the alpha and beta particles emitted during the decay of radon-222 and its progeny. The vial was placed in a liquid scintillation detector, which measures the light pulses produced when radiation interacts with the scintillation cocktail. The detector counts and quantifies these pulses to determine the radon-222 concentration in the sample..

Calculation of Hazard Parameters for Radon Concentration

The analysis for this study include calculation of Radon 222 concentration in Bq/l, Annual effective dose to stomach and lungs, Excess lifetime cancer risk and Comparison of findings with standard and other researchers.

i. **Radon-222 Concentration in Bq/l:** The activity concentration of Radon-222 was calculated from the samples and background results obtained using the formula below:

$$C_{Rn-222}(BqL^{-1}) = \frac{C-C_b}{CF\ x\ DE}.e^{\lambda t} \quad (1)$$

where; C_{Rn-222} is the radon-222 activity concentration in water (BqL^{-1}), C is the measured count rate (cps) from the scintillation counter, C_b is the background count rate (cps), CF is the calibration factor (0.2 cps per Bq/L), DE is the efficiency of the detector (0.08), t is the elapsed time (in days) between sample collection and measurement, and λ is the decay constant of radon-222 (1.26×10^{-4} min^{-1}) (USEPA, 2003).

ii. **Annual Effective Dose by Ingestion:** The corresponding annual effective doses (mSv/y) due to ingestion of Radon-222 in water samples from the study area were also calculated taking into account the dose coefficient in (Sv/Bq), the annual water consumption (L/Y) and the activity concentration of Radon-222 obtained from equation 3.1 using equation 2 (Ryan et al., 2003).

$$E = C_{RnW}\ x\ D\ x\ L \quad (2)$$

where: $CRnw$ is the concentration of Radon-222, D is the dose coefficient ($10^{-8}\ Sv/Bq$, $2\times10^{-8}\ Sv/Bq$, $7\times10^{-8} Sv/Bq$) for adults, children and infants respectively (UNSCEAR, 2000). L is the annual water consumption by an adult of 2 litres per day that is $730 L/Y$ (UNSCEAR, 1993).

According to United Nation Scientific Committee on the Effect of Atomic Radiation (UNSCEAR, 2000) doses due to ingestion of radon in water for similar consumption rates could be factor of 2 and 7 higher for children and infants respectively.

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iii. **Dose Contribution to the Stomach due to Ingestion:** It is product of the stomach tissue weighted factor (0.1196) with corresponding ingestion dose using Equation (3) below

$$Dose\ to\ the\ Stomach\ (D_{stomach}) = E_{ing} \times 0.1196 \quad (3)$$

iv. **Annual Effective Dose by Inhalation:** The annual effective dose of Radon by inhalation was estimated using equation (4) as:

$$He = C \times F \times T \times D \quad (4)$$

Where He is the annual effective dose ($mSvy^{-1}$), C is the radon concentration (Bql^{-1}), F is the equilibrium factor (0.5), T is the indoor occupancy time (8000 hy^{-1}), and D is the dose conversion factor (1.1×10^{-5} $mSvh^{-1}/Bql^{-1}$).

v. **Dose Contribution to the Lung due to Inhalation:** It is the product of the lung tissue weighted factor (0.1199) and corresponding inhalation dose using Equation (5)

$$Dose\ to\ the\ Lung\ (D_{lung}) = He \times 0.1199 \quad (5)$$

vi. **Excess Lifetime Cancer Risk Estimation Method:** The excess lifetime cancer risk was evaluated using equation (6) as:

$$ELCR = AEDE \times DL \times RF \times 10^{-3} \quad (6)$$

Where ELCR is the excess lifetime cancer risk, AEDE is the annual effective dose equivalent, DL is the average duration of life (estimated to 70 years), and RF is the Risk Factor (Sv^{-1}), i.e. fatal cancer risk per Sievert. For stochastic effects, ICRP uses RF as 0.05 for public.

RESULTS AND DISCUSSION

The results of radon-222 concentration in water samples collected from the study area are presented in table 1 and figure 2.

Table 1: Raw result of radon-222 concentration (in cpmc) of water samples collected from the study area

S/N	Sample Location Code (N/E)	CPMA/K	CPMB/K	CPMC	SIS	Date of Counting
1.	RUM1 07⁰95.503'/03⁰61.563'	40.58	27.28	87.67	63.792	11/11/2024
2.	RUM2 07⁰95.499'/03⁰61.562'	47.38	49.70	100.70	66.816	11/11/2024
3.	RUM 07⁰95.499'/03⁰61.561'	47.78	42.13	91.68	64.683	11/11/2024
4.	RUM4 07⁰95.501'/03⁰61.560'	51.12	36.13	89.58	60.776	11/11/2024
5.	RUM5 07⁰95.506'/03⁰61.559'	47.20	40.73	91.35	66.810	11/11/2024
6.	RUM6 07⁰95.507'/03⁰61.557'	46.53	41.20	90.67	66.099	11/11/2024
7.	RUM7 07⁰95.512'/03⁰61.556'	43.23	34.18	79.48	66.008	12/11/2024
8.	RUM8 07⁰95.513'/03⁰61.559'	49.93	44.40	97.62	66.003	12/11/2024
9.	RUM9 07⁰95.513'/03⁰61.555'	49.20	40.37	92.27	63.515	12/11/2024
10.	RUM10 07⁰95.498'/03⁰61.561'	48.60	37.32	87.47	62.362	12/11/2024
11.	RUM11 07⁰95.494'/03⁰61.558'	40.45	35.38	77.78	70.129	12/11/2024
12.	Oko1 07⁰94.726'/03⁰61.736'	41.37	37.17	81.07	69.428	12/11/2024
13.	Oko2 07⁰94.722'/03⁰61.740'	50.32	38.67	90.77	63.113	12/11/2024
14.	Oko3 07⁰94.724'/03⁰61.744'	43.37	38.00	84.72	66.924	13/11/2024
15.	Olu1 07⁰95.497'/03⁰61.460'	43.88	35.57	81.72	65.920	13/11/2024
16.	Olu2 07⁰95.503'/03⁰61.460'	46.80	38.87	80.80	65.999	13/11/2024
17.	Olu3 07⁰95.504'/03⁰61.457'	43.35	33.22	77.17	66.536	13/11/2024
18.	Olu4 07⁰95.501'/03⁰61.455'	48.43	39.38	90.02	67.855	13/11/2024
19.	CWS 07⁰94.469'/03⁰62.060'	38.87	32.60	73.43	67.709	13/11/2024
	Mean	**45.704**	**38.01**	**86.63**	**65.814**	
	Background Sample	16.23	16.18	63.83	40.626	17/02/204
	IAEA 423	43.52	15.12	58.75	41.672	17/02/204
	IAEA 427	47.72	16.03	63.85	41.014	17/02/204
	IAEA 427	42.02	16.63	57.73	43.693	17/02/204

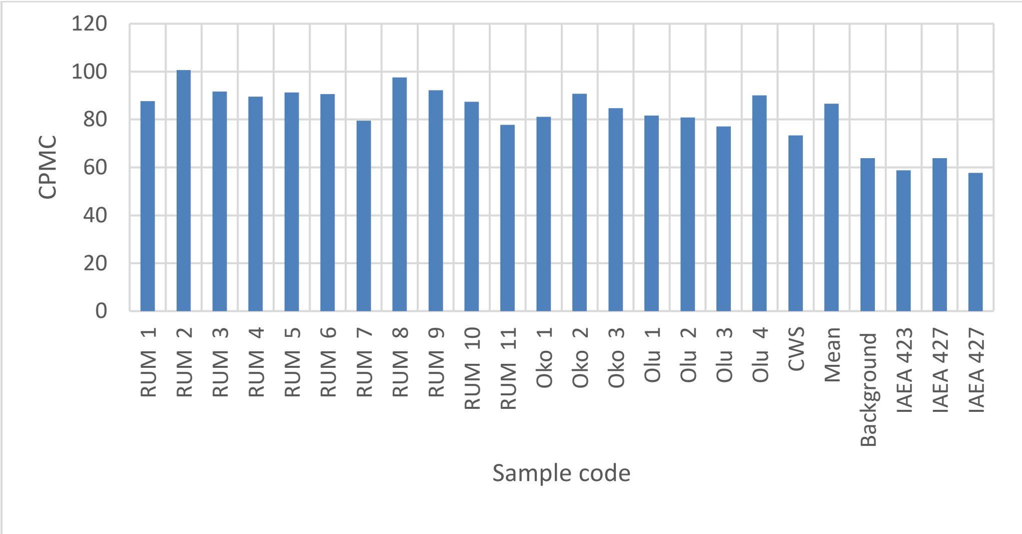

Figure 2: Raw result of radon-222 concentration (in cpmc) of water samples collected from the study area

Table 1 and figure 2 present the raw result of radon-222 concentration (in cpmc) of water samples collected from the study area. The mean radon-222 concentration in the studied water samples was determined to be **86.63 Bq/L**, a moderate level when compared to global standards. Radon in water is influenced by geological formations, as it leaches into groundwater from uranium-bearing rocks. The measured mean value is significant because it approaches the World Health Organization (WHO) reference level of 100 Bq/L for radon in drinking water, beyond which remedial actions are recommended. Although the concentration does not exceed this limit, long-term exposure through drinking or inhalation of radon released during water use could still pose health risks, particularly in radon-prone areas.

The calculated hazard parameters such as radon-222 concentration in Bq/L, annual effective dose equivalent for ingestion and inhalation, organ doses for stomach and lungs, and excess lifetime cancer risk are presented in table 1.

Table 2: Calculated value of the radiological hazards parameters

Sample code	$C_{Rn\text{-}222}$ (Bq/kg)	E_{Ing} (mSv/y)	$D_{Stomach}$ (mSv/y)	E_{Inh} (mSv/y)	D_{Lung} (mSv/y)	ELCR
RUM 1 **07^{0}95.503’/03^{0}61.563’**	1493.571	0.010903	0.001304	65.71714	7.879485	3.81E-05
RUM 2 **07^{0}95.499’/03^{0}61.562’**	2309.898	0.016862	0.002017	101.6355	12.1861	5.90E-05
RUM 3 **07^{0}95.499’/03^{0}61.561’**	1744.797	0.012737	0.001523	76.77107	9.204851	4.45E-05
RUM 4 **07^{0}95.501’/03^{0}61.560’**	1613.232	0.011777	0.001408	70.98223	8.510769	4.12E-05
RUM 5 **07^{0}95.506’/03^{0}61.559’**	1724.123	0.012586	0.001505	75.86139	9.095781	4.40E-05
RUM 6 **07^{0}95.507’/03^{0}61.557’**	1681.521	0.012275	0.001468	73.98691	8.871031	4.29E-05
RUM 7 **07^{0}95.512’/03^{0}61.556’**	980.4694	0.007157	0.000856	43.14066	5.172565	2.51E-05
RUM 8 **07^{0}95.513’/03^{0}61.559’**	2116.937	0.015454	0.001848	93.14522	11.16811	5.41E-05
RUM 9 **07^{0}95.513’/03^{0}61.555’**	1781.76	0.013007	0.001556	78.39746	9.399855	4.55E-05
RUM 10 **07^{0}95.498’/03^{0}61.561’**	1481.041	0.010812	0.001293	65.16582	7.813382	3.78E-05
RUM 11 **07^{0}95.494’/03^{0}61.558’**	873.9648	0.00638	0.000763	38.45445	4.610689	2.23E-05
OKO 1 **07^{0}94.726’/03^{0}61.736’**	1080.083	0.007885	0.000943	47.52364	5.698084	2.75E-05
OKO 2 **07^{0}94.722’/03^{0}61.740’**	1687.786	0.012321	0.001474	74.26257	8.904082	4.31E-05
OKO 3 **07^{0}94.724’/03^{0}61.744’**	1308.754	0.009554	0.001143	57.58519	6.904465	3.34E-05
OLU 1 **07^{0}95.497’/03^{0}61.460’**	1120.805	0.008182	0.000979	49.31542	5.912919	2.86E-05
OLU 2 **07^{0}95.503’/03^{0}61.460’**	1063.167	0.007761	0.000928	46.77936	5.608845	2.71E-05
OLU 3 **07^{0}95.504’/03^{0}61.457’**	835.7484	0.006101	0.00073	36.77293	4.409074	2.13E-05

OLU 4 **07⁰95.501'/03⁰61.455'**	1640.798	0.011978	0.001433	72.19513	8.656196	4.19E-05
CWS **07⁰94.469'/03⁰62.060'**	601.4381	0.00439	0.000525	26.46328	3.172947	1.53E-05
Mean	**1428.416**	**0.010427**	**0.001247**	**62.85028**	**7.535749**	**3.65E-05**
Maximum	**2309.898**	**0.016862**	**0.002017**	**101.6355**	**12.1861**	**5.90E-05**
Minimum	**601.4381**	**0.00439**	**0.000525**	**26.46328**	**3.172947**	**1.53E-05**

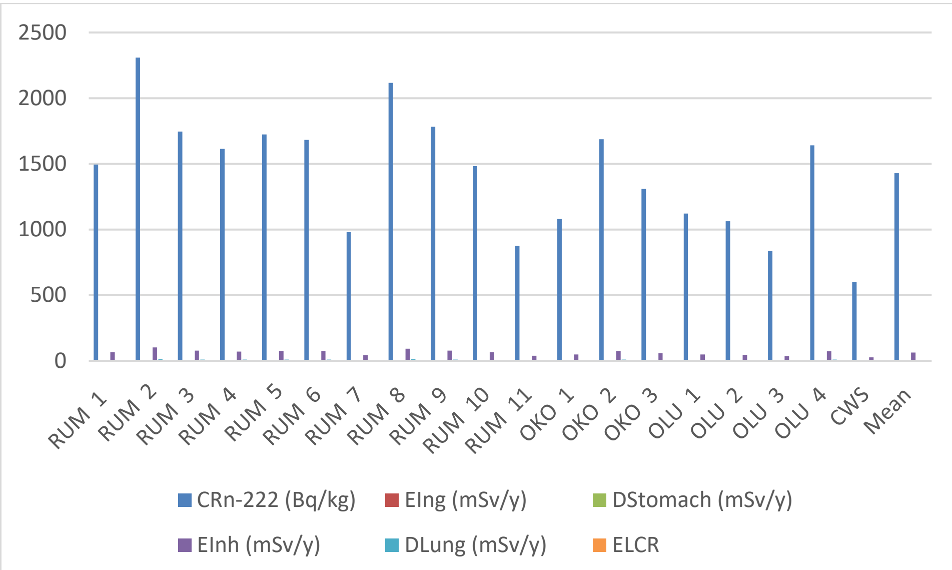

Figure 3: Calculated value of the radiological hazards parameters

Table 2 and figure 3 present the calculated value of radon-222 concentration, annual effective dose for ingestion, dose to stomach, annual effective dose for inhalation, dose to the lung, and excess life cancer risk. The calculated mean radon-222 concentration in the water sample was 1428.416 Bq/L, significantly exceeding the World Health Organization's (WHO, 2011) recommended reference level of 100 Bq/L for radon in drinking water. This high concentration suggests a substantial radon presence, likely due to the local geology, such as uranium-rich or radon-prone formations. Such elevated levels necessitate immediate mitigation measures, as prolonged exposure to radon from water can result in significant radiological health risks.

The calculated annual effective dose equivalent (AEDE) for inhalation was 0.010427 mSv/y, while the dose to the stomach due to ingestion was 0.001247 mSv/y. These values are relatively low when compared to the International Commission on Radiological Protection's (ICRP, 2012) annual dose limit of 1 mSv for the general public. However, the annual effective dose equivalent to the lung was 62.85028 mSv/y, and the dose to the lung was 7.535749 mSv/y, indicating a considerable risk from inhalation exposure during domestic water use (e.g., showers, cooking). Such high doses highlight the critical role of radon released into indoor air, which significantly increases lung cancer risk.

The excess lifetime cancer risk (ELCR) was calculated at 3.6496E-05, which, while small, indicates a non-negligible risk over a lifetime. When compared with other studies, these results reveal much higher radon concentrations and associated risks. For instance, Kumar *et al.* (2016) reported radon concentrations in Northern India averaging around 80–350 Bq/L, with lower doses and ELCR values. Similarly, Papastefanou (2002) documented mean radon concentrations in drinking water worldwide generally below 500 Bq/L. The markedly higher values in the current study suggest the need for immediate public health interventions, such as aeration or granular activated carbon (GAC) treatment systems, to reduce radon concentrations and mitigate associated health risks. Table 2 shows the comparison of the present study with published studies.

Table 3: Comparison of radon-222 concentration in water sample in the present study and published studies

Study Location	**^{222}Rn Concentration (Bq/L)**	**Reference**
Current Study	1428.416	-
Idah and Environs	12.28 (Borehole), 10.23 (Well), 3.05 (Surface Water)	Daniel *et al.* (2017)
Nassarawa LGA, Kano State	Majority exceeded USEPA limits	Umar & Nasir (2023)
Nigerian University Campus Area	34 ± 3.7	Akhter & Erees (2021)
Southwestern Nigeria	45.6 ± 12.3	Adewuyi *et al.* (2020)
Jos Plateau	78.2 ± 15.6	Jibiri & Fasunwon (2018)

The mean radon concentration in the study (1428.416 Bq/L) is exceptionally high compared to other studies in Nigeria. The highest previously reported mean concentration was 78.2 Bq/L from Jos Plateau, an area known for its uranium-rich geology. In contrast, regions like Idah, Kano, and university groundwater sources show much lower values, typically below 50 Bq/L. This suggests that the studied area has a significantly elevated radon level, likely due to geological formations rich in uranium and radium. Given that the WHO and USEPA recommend a safe limit of 100-300 Bq/L, the results highlight a potential health risk that requires urgent attention, including radon mitigation measures and public health monitoring.

Conclusion

The findings of this study reveal alarmingly high levels of radon-222 in water sources around coal mining areas in Benue State, Nigeria, with concentrations significantly exceeding the WHO's safety threshold for drinking water. While the calculated annual effective doses from ingestion and inhalation remain within internationally accepted safety limits, the markedly elevated lung-specific dose and AEDE underscore a significant radiological health risk, particularly from inhalation of radon gas released during daily water use. The associated excess lifetime cancer risk, though modest, further emphasizes the need for proactive public health interventions. Given the geogenic origin of the radon linked to uranium-rich formations and in light of lower levels reported globally, this study highlights the urgent necessity for mitigation strategies such as water aeration and GAC filtration to reduce radon exposure and protect the local population from long-term health effects.

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