

Issues lists available at [UMKB journals](#)

Journal of Applied Engineering Science & Technology

Journal home page: <https://journals.univ-biskra.dz/index.php/jaest><https://doi.org/10.69717/jaest.v6.i1.150>

Evaluation of Radon-222 concentration and its associated risks in groundwater sources of communities around selected mining sites in Sierra Leone

Mohamed Mustapha Abu^a, Muteeu Abayomi Olopade^{b,c,*}^aDepartment of Physics, School of Basic Sciences, Njala University, Sierra Leone^bDepartment of Physics, University of Lagos, Akoka, Lagos, Nigeria^cDepartment of Physics, Fourah Bay College, University of Sierra Leone, Freetown, Sierra Leone

ABSTRACT

Radon-222 in groundwater poses significant health risks through ingestion and inhalation, being the second leading cause of lung cancer deaths in the U.S., with 21,000 fatalities annually. This study evaluated radon-222 levels and associated risks in groundwater near mining sites in Sierra Leone during the rainy season. Fifteen samples from each site – Koidu, Yengema and Marampa, were analyzed using a calibrated DURRIDGE RAD-7 detector. Risks were calculated for infants, children and adults, including annual effective doses, Excess lifetime cancer risks and Lung Cancer Cases per million people per year. The results showed that Radon-222 concentrations in the groundwater samples ranged from 5.07 to 41.63 Bq/l with an average value of 19.10 Bq/l. The total annual effective doses varied from 65.53 to 590.49 ($\mu\text{Sv/y}$), highest in infants. Excess lifetime cancer risks ranged from 0.0002 to 0.0021, with infants at the greatest risk. Lung cancer incidence was approximately 0.0009 per million people per year. Importantly, all samples remained below WHO and EU limits of 100 Bq/l, indicating compliance with international safety guidelines and no immediate health risk. However, 87.5% of samples exceeded USEPA's more stringent maximum contaminant level of 11.1 Bq/l. This discrepancy reflects differing regulatory philosophies: USEPA's precautionary approach versus WHO/EU's risk-based thresholds. While the water meets international standards for safe consumption, the exceedance of USEPA standards suggests potential long-term health concerns warranting continued monitoring, particularly for vulnerable populations such as infants and children. Simple, low-cost mitigation measures such as aeration, storage (allowing radon to decay/escape) and ventilation during water use are recommended where concentrations approach upper limits.

KEYWORDS

Radon-222
Groundwater Contamination
Mining
Health Hazards
RAD7

ARTICLE HISTORY

Received	Revised	Accepted	Published
29 Dec 2025	01 Mar 2026	26 Mar 2026	09 Apr 2026

1 Introduction

Environmental radioactivity from both natural and human-made sources is an unavoidable aspect of human exposure to ionizing radiation. Among natural radionuclides, radon-222 (^{222}Rn), a colorless, odorless, and tasteless radioactive noble gas produced from the decay of uranium-238 and radium in geological formations, is a significant contributor to natural background radiation exposure worldwide [1, 2, 3, 4]. It is the most stable isotope of radon, with a half-life of 3.8215 days [5]. Due to its chemical inertness and high solubility in water, it easily migrates through geological layers and can accumulate in groundwater, posing health risks, such as lung cancer through both inhalation and ingestion pathways [6, 7].

The International Agency for Research on Cancer (IARC) and the World Health Organization (WHO) have classified radon as a Group 1 carcinogen, with extensive epidemiological evidence linking prolonged radon exposure to increased lung cancer risk

[8, 6, 9]. Radon is the primary cause of lung cancer among non-smokers and the second leading cause among smokers [10, 11]. Among the 18.1 million new cases and 9.8 million total cancer deaths worldwide, lung cancer accounts for approximately 1.8 million deaths while stomach cancer causes around 783,000 deaths [6]. The primary health hazard from radon arises from alpha particles emitted during decay of radon-222 isotopes, which, when inhaled, deposits in the bronchi and alveoli, damaging lung tissues [12, 13]. Besides inhalation of radon gas, ingestion of radon contaminated water significantly contributes to internal radiation exposure and can increase indoor air contamination through degassing during domestic water use [14].

Due to the hazards posed by radon-222 and its decay products, various international organizations have established guideline values to safeguard public health. WHO and the United State Environmental Protection Agency (USEPA) recommended maximum contamination levels (MCL) of 10 and 11.1 Bq/L, respectively, for radon-222 in water, based on the Safe Drinking Water Act [15, 16]. The European Union has set an

* Corresponding author. Muteeu Abayomi Olopade (M.A. Olopade)
E-mail : muteeu.olopade@usl.edu.sl

MCL of 100 Bq/l, with a higher upper limit of 1000 Bq/l indicating the need for remedial measures [17]. Additionally, both WHO and European Committee report that the total indicative dose (TID) from radioactive substances including radon-222, should not exceed 0.1 mSv/y [15, 18]. Consequently, the International Commission on Radiological Protection (ICRP) (2012) recommends that all countries conduct radon surveys to identify radon-prone areas, emphasizing the importance of measuring radon-222 levels in groundwater to monitor public exposure to ionizing radiation [9].

Anthropogenic activities such as mining significantly influence radon mobilization and accumulation in groundwater by altering hydrogeological conditions, increasing weathering of uranium-rich minerals, creating pathways for radon migration and elevating radionuclide activities [19, 20]. Sierra Leone, notable for its mineral wealth and active mining - both legal and illegal serves as a pertinent case study for assessing radon-related health risks in affected communities.

Numerous studies globally have investigated natural radioactivity and radon-222 levels in water, evaluating potential radiation risks [10, 21-25]. In sub-Saharan Africa, especially Sierra Leone, research on groundwater radon levels in mining regions like Koidu, Yengema and Marampa is crucial due to the health threats posed by radon exposure through water consumption and inhalation [26]. Despite extensive mining and dependence on groundwater for drinking, there is a notable lack of comprehensive data on radon-222 concentrations and related health risks in Sierra Leone's mining communities. This gap raises concerns, particularly for vulnerable groups such as infants and children, who are more susceptible to radiation.

This study aims to fill this critical knowledge gap by providing the first detailed assessment of radon-222 levels and associated health risks in groundwater sources near mining sites in Sierra Leone during the rainy season, when radon mobilization is maximized. The findings will establish baseline data for evaluating radiation exposure risks, highlight differences across age groups for targeted interventions, inform national policies on radon in drinking water, and contribute to the limited knowledge of radon occurrence in West African mining regions.

2 Methodology

2.1 Study area description

This study was conducted in three mining communities in Sierra Leone: Koidu (Latitude: 8.64387, longitude: -10.9714) and Yengema (latitude: 8.71441, longitude: -

11.17057) in the Kono District (Eastern Province), and Marampa in the Port Loko District (Northern Province) (Figure 1). These sites were selected due to their long history of intensive mining activities, primarily for diamonds (Koidu and Yengema) and iron ore (Marampa), and the potential for elevated radon levels in groundwater due to mining-induced geological disturbances.

Koidu and Yengema are both situated within the Kono greenstone belt, which comprises archaic to proterozoic metamorphic rocks including schists, gneisses, and amphibolites. The region is underlain by kimberlite intrusions, which are the primary host rocks for diamonds. These kimberlite pipes are rich in uranium-bearing minerals such as zircon, monazite, and apatite, which serve as primary sources of radon-222 through the uranium-238 decay series. The geological structure is characterized by extensive fracturing and faulting associated with kimberlite emplacement, creating preferential pathways for radon migration from deep geological formations into shallow aquifers. Marampa area is located within the Marampa Itabirite Formation, characterized by Precambrian banded iron formations (BIF) interbedded with schists and phyllites. The iron ore deposits are associated with hematite and magnetite mineralization. While iron ore itself is not a significant source of uranium, the surrounding metasedimentary rocks, particularly black shales and phosphatic units, contain elevated concentrations of uranium and thorium. These rocks, when subjected to weathering and mining-induced fracturing, release radon into the groundwater system.

Sierra Leone experiences a tropical climate with distinct wet and dry seasons: Rainy Season (May to October) is characterized by intense precipitation events, high relative humidity (>80%), and temperatures ranging from 24-28°C. The mean annual rainfall ranges from 2,500 mm in Koidu/Yengema to 3,000 mm in Marampa. Dry Season (November to April) is characterized by reduced rainfall (<50 mm/month), lower humidity (60-70%), and higher temperatures (28-32°C). Groundwater levels decline, potentially concentrating dissolved radon.

2.2 Measurements of radon-222 in the groundwater samples

Measurements of radon-222 concentrations in all groundwater samples were performed using a calibrated digital RAD-7 detector (Durrige Company, USA), a state-of-the-art electronic radon detector that is appropriate for radon measurements in water [27, 14]. Figure 2 illustrates the experimental setup of the RAD-7 with RAD H2O accessories designed for the measurements of ²²²Rn in water.



Fig.1. Map showing sampling locations.

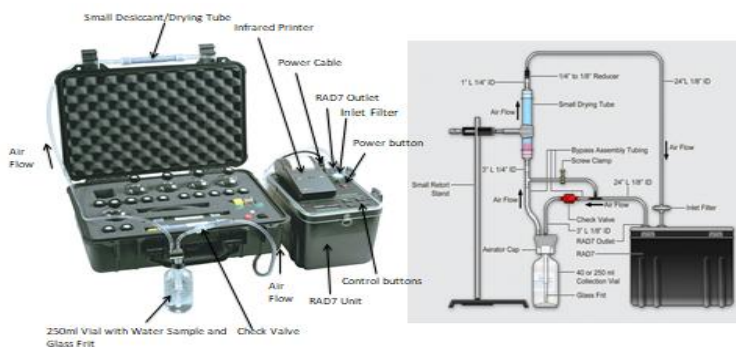


Fig.2. Durrige RAD7 setup for the analysis of Radon-222 in the groundwater

During the rainy season (from June-September 2025), a total of 45 groundwater samples – 15 from each of the three mining locations, were collected from randomly selected, actively used hand-dug wells (W) and boreholes (B). To ensure measurement precision and account for any potential short-term variability, three replicate measurements were taken at each sampling point during different times of the day: morning (6:00 am - 11:00 am), afternoon (12:00 pm - 4:00 pm), and evening (5:00 pm - 7:00 pm), with specific codes for each sampling point: KW1 to KW15 for Koidu, YW1 to YW15 for Yengema, and MW1 to MW15 for Marampa.

Groundwater radon concentrations are generally stable in the short term due to the relatively constant rate of radon emanation from geological formations and the buffering capacity of aquifers. However, minor temporal variations can occur due to factors such as changes in atmospheric pressure, groundwater pumping, and temperature fluctuations. Our observations indicated that radon levels remained relatively consistent across the three sampling times, with coefficients of variation typically below 10%, confirming the stability of groundwater radon concentrations in the study area. The three measurements were therefore treated as technical replicates to improve the precision and reliability of the mean radon concentration for each sampling location, rather than to investigate diurnal variations.

Water samples were collected directly into clean 250 ml bottles that were previously rinsed with the water that was to be analyzed. Prior to measuring, the RAD-7 was connected to its accessories and purged with fresh dry air for 15 minutes in order to remove any residual radon from the system, ensuring accurate readings. Then, using the RAD-7's internal pump, the water sample was aerated in a closed loop to transfer the dissolved radon into the measurement chamber and reading taken over a 30-minute measurement cycle.

2.3 Annual effective dose due to Radon-222 ingestion (RAEDE_{Ing})

The annual effective dose equivalent due to radon-222 ingestion (RAEDE_{ing}) in (μSv/y), was calculated using the equation from [3, 14, 20]:

$$RAEDE_{Ing} = C_{Rn} \times K \times C_w \times T \tag{1}$$

where C_{Rn} represents the measured concentration of ²²²Rn in water (Bq/L); K is the age-specific dose conversion factor (Sv/Bq), with values of 7×10^{-8} Sv/Bq for infants (0–2 years), 2×10^{-8} Sv/Bq for children (3–12 years), and 1×10^{-8} Sv/Bq for adults (> 12 years); C_w denotes the age-specific daily water intake rate (L/day), which is 0.5 L/day for infants, 1.5 L/day for children, and 2 L/day for adults; and T is the duration of water consumption per year, set at 365 days/year.

These age-specific parameters are derived from ICRP guidelines and consider variations in radio-sensitivity, metabolic rates, and water consumption patterns across different age groups [28, 29]. Consequently, RAEDE_{ing} in μSv/y for infants, children and adults are calculated using the following equations (1a), (1b), and (1c), respectively:

$$RAEDE_{Ing}(Infants) = 12.775 \times C_{Rn} \tag{1a}$$

$$RAEDE_{Ing}(Children) = 10.95 \times C_{Rn} \tag{1b}$$

$$RAEDE_{Ing}(Adults) = 7.3 \times C_{Rn} \tag{1c}$$

2.4 Annual effective dose equivalent due to Radon-222 inhalation (RAEDE_{Inh})

The annual effective dose equivalent due to radon-222 inhalation from degassing during domestic water use was estimated using UNSCEAR methodology as given by equation 2 [3]:

$$RAEDE_{Inh} (\mu \frac{Sv}{y}) = C_{Rn} \times R_{AW} \times E_F \times O_F \times DCF \tag{2}$$

where R_{AW} represents the ratio of radon in air to radon in water, valued at 10^{-4} ; E_F denotes the global average equilibrium factor for radon and its decay products, which is 0.4; O_F is the worldwide average indoor occupancy factor of 7000 hy^{-1} ; and DCF is the dose conversion factor, set at $9 \text{ nSv h}^{-1}(\text{Bq m}^{-3})^{-1}$ for radon and its progeny.

2.5 Total annual effective dose equivalent (RAEDE_{Total})

The total annual effective dose equivalent (RAEDE_{Total}) was calculated as the sum of ingestion and inhalation doses [3]:

$$RAEDE_{Total} = RAEDE_{Ing} + RAEDE_{Inh} \tag{3}$$

2.6 Excess lifetime cancer risk assessment

Excess lifetime cancer risks (ELCR) represent the probability of developing cancer over a lifetime due to radon exposure and were calculated using ICRP methodology [30, 31]:

$$ELCR = RAEDE_{Total} \times LD \times RF \tag{4}$$

where LD is the mean life duration = 70 years, RF is the stochastic risk factor = 0.05 Sv^{-1} .

2.7 Determination of lung cancer cases per million people per year

Lung cancer cases per million people per year (LCC) were determined using equation 5 [32]:

$$LCC = RAEDE_{Inh} \times 18 \times 10^{-6} \tag{5}$$

where 18×10^{-6} is the risk factor for inducing lung cancer (μSv^{-1}).

3 Results and discussions

3.1 Measured radon – 222 concentrations in groundwater

Radon-222 concentrations in groundwater samples from the three mining communities exhibited considerable variability, ranging from 7.12 to 41.63 Bq/l with an average value of 20.71 Bq/l, 5.07 to 41.10 Bq/l with an average value of 18.32 Bq/l, and 7.21 to 40.02 Bq/l with an average value of 18.28 in the morning, afternoon and evening, respectively. The average daily concentration in this study, varied from 6.67 to 38.61 Bq/l with an average value of 19.10 Bq/l. Table 1 presents the measured radon-222

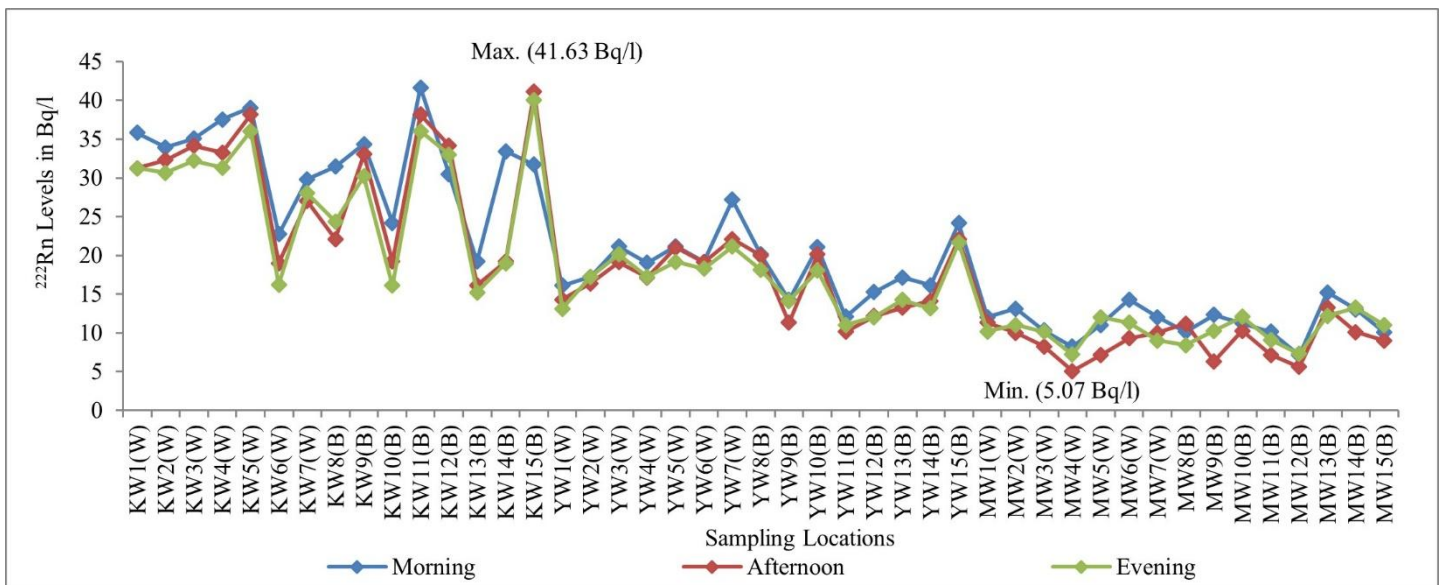


Fig.3. Measured Radon-222 concentrations during the morning, afternoon and evening hours against the sample location.

Table 1. Measured Radon-222 Concentrations, $RAEDE_{ing}$ and $RAEDE_{inh}$, ELCR for all age groups, and LCC across the sampling locations.

Location Code	Radon-222 Concentration (C_{Rn}) in Bq/l				Annual Effective Dose due to Ingestion and Inhalation in $\mu Sv/y$						Excess Lifetime Cancer Risk			LCC	
					$RAEDE_{ing}$			$RAEDE_{inh}$	$RAEDE_{Total}$		Infants	Children	Adults		Infants
	Morning	Afternoon	Evening	Mean	Infants	Children	Adults	Infants	Children	Adults	Infants	Children	Adults		
KW1(W)	35.83	31.22	31.24	32.76	418.55	358.76	239.17	82.56	501.12	441.32	321.74	0.0018	0.0015	0.0011	0.0015
KW2(W)	33.92	32.3	30.64	32.29	412.46	353.54	235.69	81.36	493.82	434.90	317.06	0.0017	0.0015	0.0011	0.0015
KW3(W)	35.07	34.12	32.21	33.80	431.80	370.11	246.74	85.18	516.97	455.29	331.92	0.0018	0.0016	0.0012	0.0015
KW4(W)	37.54	33.24	31.31	34.03	434.73	372.63	248.42	85.76	520.49	458.38	334.17	0.0018	0.0016	0.0012	0.0015
KW5(W)	39.05	38.18	36.01	37.75	482.21	413.33	275.55	95.12	577.34	508.45	370.67	0.0020	0.0018	0.0013	0.0017
KW6(W)	22.73	19.01	16.23	19.32	246.86	211.59	141.06	48.69	295.55	260.29	189.76	0.0010	0.0009	0.0007	0.0009
KW7(W)	29.81	27.01	28.01	28.28	361.23	309.63	206.42	71.26	432.49	380.89	277.68	0.0015	0.0013	0.0010	0.0013
KW8(B)	31.43	22.11	24.34	25.96	331.64	284.26	189.51	65.42	397.06	349.68	254.93	0.0014	0.0012	0.0009	0.0012
KW9(B)	34.36	33.04	30.18	32.53	415.53	356.17	237.44	81.97	497.50	438.13	319.41	0.0017	0.0015	0.0011	0.0015
KW10(B)	24.19	19.18	16.11	19.83	253.29	217.10	144.73	49.96	303.25	267.07	194.70	0.0011	0.0009	0.0007	0.0009
KW11(B)	41.63	38.18	36.01	38.61	493.20	422.74	281.83	97.29	590.49	520.03	379.12	0.0021	0.0018	0.0013	0.0018
KW12(B)	30.48	34.18	33.01	32.56	415.91	356.50	237.66	82.04	497.95	438.54	319.71	0.0017	0.0015	0.0011	0.0015
KW13(B)	19.21	16.12	15.21	16.85	215.22	184.47	122.98	42.45	257.67	226.92	165.43	0.0009	0.0008	0.0006	0.0008
KW14(B)	33.43	19.18	19.01	23.87	304.98	261.41	174.28	60.16	365.14	321.57	234.44	0.0013	0.0011	0.0008	0.0011
KW15(B)	31.68	41.1	40.02	37.60	480.34	411.72	274.48	94.75	575.09	506.47	369.23	0.0020	0.0018	0.0013	0.0017
YW1(W)	16.11	14.31	13.11	14.51	185.37	158.88	105.92	36.57	221.93	195.45	142.49	0.0008	0.0007	0.0005	0.0007
YW2(W)	17.23	16.41	17.22	16.95	216.58	185.64	123.76	42.72	259.30	228.36	166.48	0.0009	0.0008	0.0006	0.0008
YW3(W)	21.13	19.13	20.11	20.12	257.08	220.35	146.90	50.71	307.79	271.06	197.61	0.0011	0.0009	0.0007	0.0009
YW4(W)	19.03	17.16	17.23	17.81	227.48	194.98	129.99	44.87	272.35	239.86	174.86	0.0010	0.0008	0.0006	0.0008
YW5(W)	21.15	21.01	19.15	20.44	261.08	223.78	149.19	51.50	312.58	275.28	200.69	0.0011	0.0010	0.0007	0.0009
YW6(W)	19.17	19.12	18.27	18.85	240.85	206.44	137.63	47.51	288.36	253.95	185.14	0.0010	0.0009	0.0006	0.0009
YW7(W)	27.16	22.11	21.13	23.47	299.79	256.96	171.31	59.14	358.92	316.10	230.44	0.0013	0.0011	0.0008	0.0011
YW8(B)	20.17	20.01	18.16	19.45	248.43	212.94	141.96	49.01	297.44	261.95	190.97	0.0010	0.0009	0.0007	0.0009
YW9(B)	14.24	11.32	14.13	13.23	169.01	144.87	96.58	33.34	202.35	178.21	129.92	0.0007	0.0006	0.0005	0.0006
YW10(B)	21.04	20.14	18.01	19.73	252.05	216.04	144.03	49.72	301.77	265.76	193.75	0.0011	0.0009	0.0007	0.0009
YW11(B)	12.07	10.14	11.01	11.07	141.46	121.25	80.84	27.90	169.37	149.16	108.74	0.0006	0.0005	0.0004	0.0005
YW12(B)	15.24	12.14	12.01	13.13	167.74	143.77	95.85	33.09	200.82	176.86	128.94	0.0007	0.0006	0.0005	0.0006
YW13(B)	17.15	13.24	14.23	14.87	190.01	162.86	108.58	37.48	227.49	200.34	146.06	0.0008	0.0007	0.0005	0.0007
YW14(B)	16.13	14.11	13.16	14.47	184.81	158.41	105.61	36.46	221.27	194.87	142.06	0.0008	0.0007	0.0005	0.0007
YW15(B)	24.14	22.1	21.63	22.62	289.01	247.73	165.15	57.01	346.02	304.74	222.16	0.0012	0.0011	0.0008	0.0010
MW1(W)	12.02	11.32	10.17	11.17	142.70	122.31	81.54	28.15	170.85	150.46	109.69	0.0006	0.0005	0.0004	0.0005
MW2(W)	13.13	10.03	11.03	11.40	145.59	124.79	83.20	28.72	174.31	153.51	111.92	0.0006	0.0005	0.0004	0.0005
MW3(W)	10.32	8.25	10.12	9.56	122.17	104.72	69.81	24.10	146.27	128.82	93.91	0.0005	0.0005	0.0003	0.0004
MW4(W)	8.22	5.07	7.21	6.83	87.30	74.83	49.88	17.22	104.52	92.05	67.10	0.0004	0.0003	0.0002	0.0003
MW5(W)	11.04	7.11	12.04	10.06	128.56	110.19	73.46	25.36	153.92	135.55	98.82	0.0005	0.0005	0.0003	0.0005
MW6(W)	14.31	9.31	11.31	11.64	148.74	127.49	85.00	29.34	178.08	156.84	114.34	0.0006	0.0005	0.0004	0.0005
MW7(W)	12.01	10.01	9.01	10.34	132.14	113.26	75.51	26.07	158.20	139.32	101.57	0.0006	0.0005	0.0004	0.0005
MW8(B)	10.12	11.18	8.44	9.91	126.64	108.55	72.37	24.98	151.62	133.53	97.35	0.0005	0.0005	0.0003	0.0004
MW9(B)	12.32	6.32	10.25	9.63	123.02	105.45	70.30	24.27	147.29	129.72	94.57	0.0005	0.0005	0.0003	0.0004
MW10(B)	11.22	10.26	12.06	11.18	142.82	122.42	81.61	28.17	171.00	150.59	109.79	0.0006	0.0005	0.0004	0.0005
MW11(B)	10.13	7.17	9.07	8.79	112.29	96.25	64.17	22.15	134.44	118.40	86.32	0.0005	0.0004	0.0003	0.0004
MW12(B)	7.12	5.62	7.28	6.67	85.25	73.07	48.72	16.82	102.07	89.89	65.53	0.0004	0.0003	0.0002	0.0003
MW13(B)	15.2	13.24	12.19	13.54	173.02	148.30	98.87	34.13	207.15	182.43	133.00	0.0007	0.0006	0.0005	0.0006
MW14(B)	13.02	10.08	13.23	12.11	154.71	132.60	88.40	30.52	185.22	163.12	118.92	0.0006	0.0006	0.0004	0.0005
MW15(B)	10.11	9.01	11.03	10.05	128.39	110.05	73.37	25.33	153.71	135.37	98.69	0.0005	0.0005	0.0003	0.0005
Max.	41.63	41.1	40.02	38.61	493.20	422.74	281.83	97.29	590.49	520.03	379.12	0.0021	0.0018	0.0013	0.0018
Min.	7.12	5.07	7.21	6.67	85.25	73.07	48.72	16.82	102.07	89.89	65.53	0.0004	0.0003	0.0002	0.0003
Average	20.71	18.32	18.28	19.10	244.05	209.18	139.45	48.14	292.19	257.32	187.59	0.0010	0.0009	0.0007	0.0009

concentration levels in the sampled groundwater sources, annual effective dose equivalents and excess lifetime cancer risks for all age groups and Lung Cancer Cases per Million per people per year across all sampling locations. Figure 3 presents a plot of the measured radon-222 concentrations in groundwater across the location during the sampling periods.

Comparison of the average concentrations of radon-222 in the groundwater samples with international standards shows that 87.5% of groundwater samples exceeded

the USEPA recommended limit (11.1 Bq/L), while all samples (100%) remained below the EU/WHO limit (100 Bq/L). This is illustrated in Figure 4 below. The divergence between these standards reflects different regulatory philosophies: USEPA's lower threshold (11.1 Bq/L) represents a more precautionary approach aimed at minimizing any potential risk, while WHO and EU standards (100 Bq/L) are based on comprehensive risk assessments balancing health protection with practical implementation considerations [15,

17]. Compliance with WHO/EU guidelines indicates that the groundwater does not pose an immediate health risk under internationally accepted standards. However, the exceedance of USEPA limits suggests that long-term exposure may warrant attention, particularly for high-consumption populations and vulnerable groups such as infants and children. This dual perspective emphasizes the importance of context-specific risk assessment rather than absolute classification of water as 'safe' or 'unsafe'.

The spatial distribution of radon concentrations varied across the three mining communities, with Koidu Kimberlite showing the highest overall average concentration (29.73 Bq/L), followed by Yengema (17.38 Bq/L) and Marampa (10.19 Bq/L), as presented in Table 2. Also, the maxima radon-222 concentrations across Koidu Kimberlite, Yengema and Marampa mining communities are 38.61, 23.47 and 13.54 Bq/L, respectively. The minima radon-222 concentrations across Koidu Kimberlite,

Yengema and Marampa mining communities are 16.85, 11.07 and 6.67 Bq/L, respectively.

The elevated radon concentrations in Koidu can be attributed to the presence of kimberlite intrusions, which are enriched in uranium-bearing accessory minerals (zircon, apatite, monazite) that serve as primary radon sources through the uranium-238 decay chain. Additionally, extensive diamond mining activities in Koidu have created numerous fractures and excavations that enhance radon migration from deep geological formations into shallow aquifers. The relatively lower concentrations in Marampa, despite active iron ore mining, reflect the lower uranium content of banded iron formations compared to kimberlite rocks. However, the presence of uranium-enriched black shales and phosphatic units in the surrounding meta-sedimentary rocks still contributes to measurable radon levels.

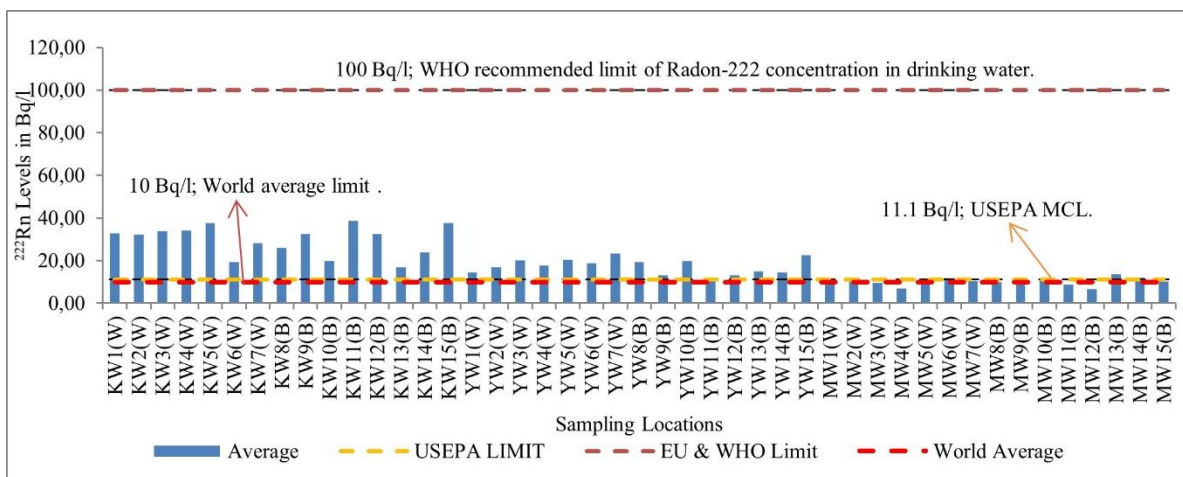


Fig.4. A plot of the averaged daily Radon-222 Concentration of well and borehole water samples in Bq/l against Study location.

Table 2. Summary of Radon-222 concentrations in groundwater across the study locations.

Study Location	Number of Samples	Max. (Bq/l)	Min. (Bq/l)	Average (Bq/l)	SD	Median	Range
Koidu	15	38.61	16.85	29.73	7.04	32.53	21.76
Yengema	15	23.47	11.07	17.38	3.70	17.81	12.39
Marampa	15	13.54	6.67	10.19	1.83	10.06	6.87

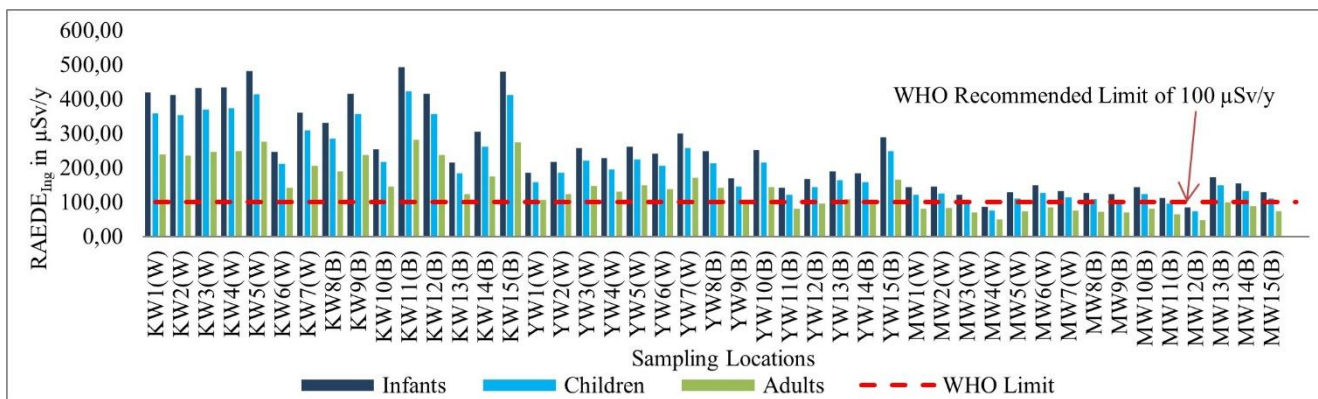


Fig.5. Annual Effective Dose Equivalents due to Radon-222 Ingestion for infants, children and adults.

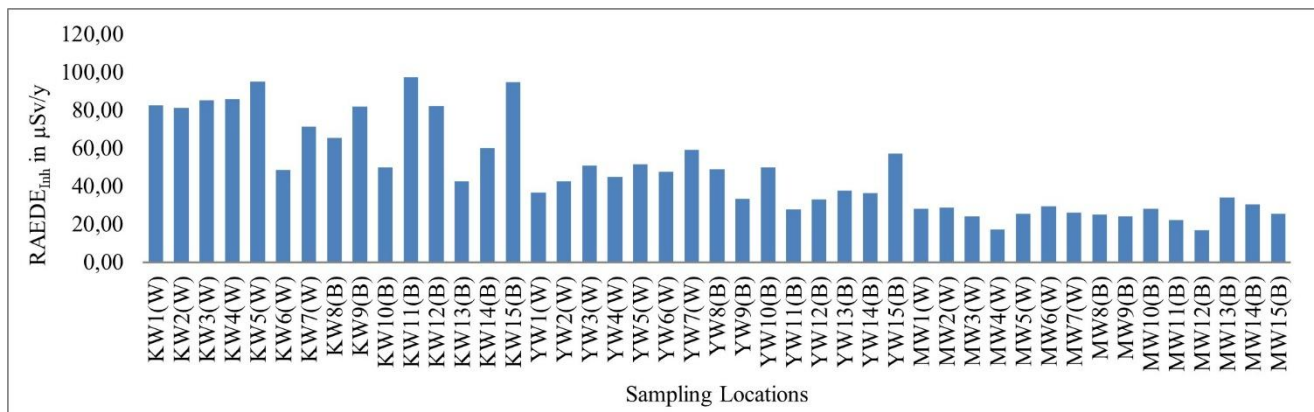


Fig.6. Annual Effective Dose Equivalents due to Radon-222 Inhalation.

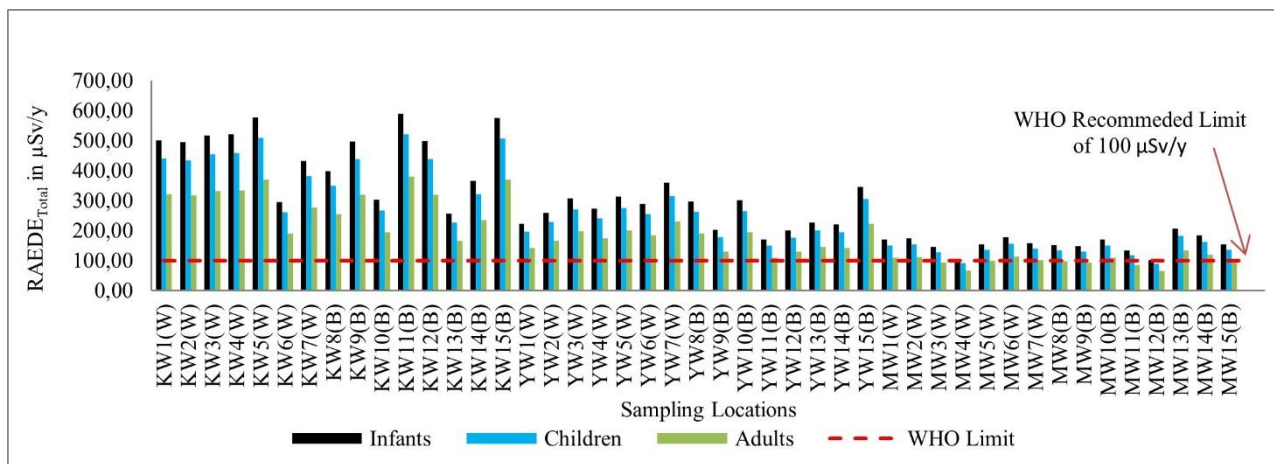


Fig.7. A plot of the Total Annual Effective Dose Equivalents for Infants, Children and Adults against the sampling locations.

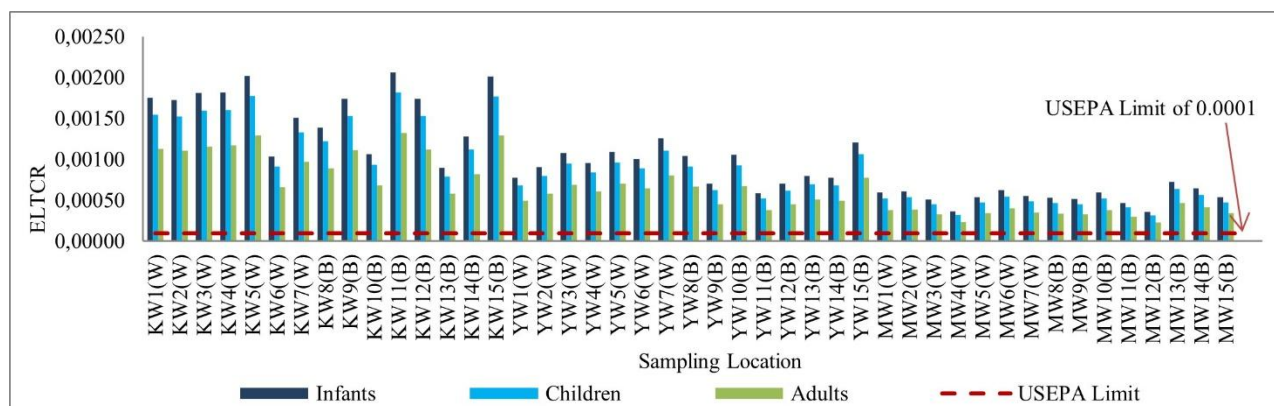


Fig.8. A plot of the estimated Excess Lifetime Cancer Risk for infants, children and Adults against the sample area.

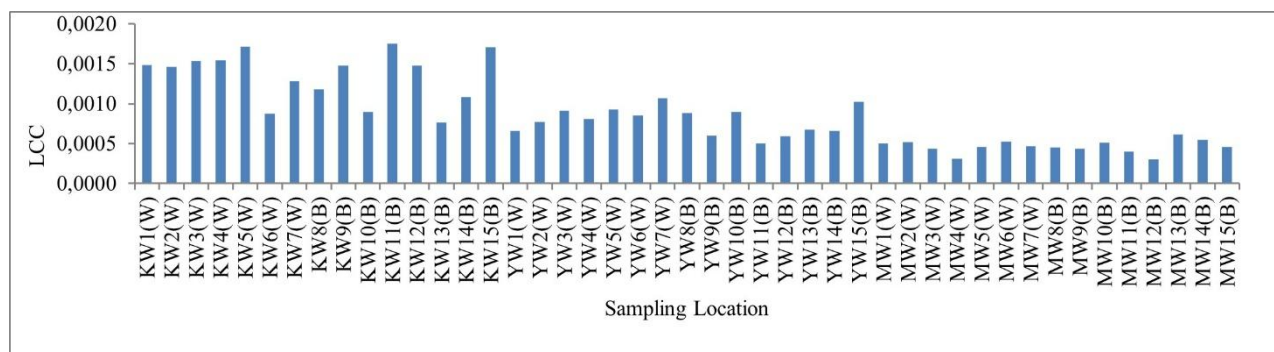


Fig.9. The Lung Cancer Cases per Million per people per year across the study area.

3.2 Estimated annual effective dose equivalent (RAEDE)

The annual effective dose equivalents attributable to radon-222 ingestion (RAEDE_{Ing}) from groundwater sources varies among age groups, with infants receiving doses ranging from 85.25 to 493.20 µSv/y (mean: 244.05 µSv/y), children from 73.07 to 422.74 µSv/y (mean: 209.18 µSv/y), and adults from 48.72 to 281.83 (mean: 139.45 µSv/y). Additionally, the annual effective dose equivalents resulting from 222Rn inhalation (RAEDE_{Inh}) spans from 16.82 to 97.29 µSv/y (mean: 48.14 µSv/y) across all sampled sources. Figures 5 and 6 illustrate the spatial distribution of these dose values in relation to sampling locations. The combined total annual effective dose equivalents (RAEDE_{Total}), accounting for both ingestion and inhalation pathways, ranges from 102.07 to 590.49 µSv/y for infants (mean: 292.19 µSv/y), 89.89 to 520.03 µSv/y for children (mean: 257.32 µSv/y), and 65.53 to 379.12 µSv/y for adult (mean: 187.59 µSv/y). A comparison with the WHO’s recommended limit of 100 µSv/y, indicates that a significant proportion of samples exceeded this threshold - 97.78% for infants, 95.56% for children, and 82.22% for adults (Figure 7). All average dose values surpass this permissible limit, highlighting considerable radiological health risks across all age groups.

3.3 Estimated excess lifetime cancer risk

The excess lifetime cancer risk (ELCR) for infants, children and adults was plotted against the sampling locations in Figure 8 below. The estimated ELCR values ranged from

0.0004 to 0.0021 µSv/y with an average of 0.0010 µSv/y for infants. For children, the range was from 0.0003 to 0.0018 µSv/y averaging 0.0009 µSv/y. For adults, the values ranged from 0.0002 to 0.0013 µSv/y with an average of 0.0007 µSv/y. Notably, all these ELCR exceeded the USEPA limit of 0.0001 [16], indicating a significant long-term risk of developing cancer from exposure to the groundwater in these areas.

3.4 Lung cancer cases per million per people per year

LCC due to Radon-222 in the sampled groundwater ranged from 0.0003 to 0.0018 with an average of 0.0009 per million people per year. The maximum and minimum LCC values were observed in KW11(B) and MW4(W) respectively, as shown in Figure 9.

4 Conclusion

This study provides the first comprehensive assessment of radon-222 concentrations and associated radiological health risks in groundwater from mining communities in Sierra Leone, using a calibrated Durridge RAD-7 electronic device. The results of this study show that while all sampled groundwater sources complied with WHO and EU standards (100 Bq/L), indicating no immediate health risk, 87.5% of samples exceeded the more conservative USEPA limit (11.1 Bq/L). This dual finding reflects the ongoing international debate on appropriate radon safety thresholds and different risk management approaches. Although compliance with WHO/EU guidelines suggests the

water is safe for consumption under international standards, the exceedance of USEPA limits indicates potential long-term health concerns that warrant continued monitoring and risk mitigation. Moreover, with majority of the $RAEDE_{Total}$ for infants (97.78%), children (95.56%), and adults (82.22%) exceeding the WHO limit of $100 \mu Sv/y$, and considering the cumulative nature of radiation exposure, precautionary measures are advisable to minimize long-term risks, particularly for vulnerable populations including infants and children. Therefore, it's recommended that all groundwater from sources in these communities undergo simple, low-cost radon mitigation techniques suitable for rural communities, such as aeration systems, open storage tanks allowing radon degassing, or agitation methods that promote radon release before water use.

With appropriate public health interventions, the already low radiological risks can be further minimized, ensuring the safety and well-being of communities dependent on groundwater resources in mining-affected areas.

Ethical considerations

This study received approval from the School of Postgraduate, University of Sierra Leone. Community consent was obtained from local leaders and they were informed about the study objectives before sample collection. Preliminary results were communicated to community stakeholders to facilitate awareness, potential risks and mitigation actions.

Acknowledgements

The authors appreciate Mr. Derrick Ivan Dunn and the Sierra Leone's Nuclear Safety and Radiation Protection Authority for providing the RAD-7 and its accessories that were used during this study. In addition, we remain thankful to the University of Sierra Leone especially, its school of postgraduate studies, for the guidance and support to undertake this research. We are also grateful to the community leaders and stakeholders in Koidu, Yengema and Marampa for the support they accorded me throughout the data collection phase.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

References

- [1] M.S. Alam, M.M. Siraz, A.M. Jubair, S.C. Das, D.A. Bradley, M.U. Khandaker et al., A study on measuring the ^{222}Rn in the Buriganga River and tap water of the megacity Dhaka, PLOS ONE 18(5) (2023) e0286267. <https://doi.org/10.1371/journal.pone.0286267>.
- [2] E.G. Vogianis, D. Nikolopoulos, Radon sources and associated risk in terms of exposure and dose, Frontiers in Public Health 2 (2015) 207. <https://doi.org/10.3389/fpubh.2014.00207>.
- [3] UNSCEAR, Sources and Effects of Ionizing Radiation, United Nations, New York, 2000.
- [4] H. Keramati, R. Ghorbani, Y. Fakhri, A.M. Khaneghah, G.O. Conti, M. Ferrante et al., Radon 222 in drinking water resources of Iran: A systematic review, meta-analysis and probabilistic risk assessment, Food and Chemical Toxicology 115 (2018) 460–469. <https://doi.org/10.1016/j.fct.2018.03.042>.
- [5] F.G. Kondev, M. Wang, W.J. Huang, S. Naimi, G. Audi, The NUBASE2020 evaluation of nuclear properties, Chinese Physics C 45(3) (2021) 030001. <https://doi.org/10.1088/1674-1137/abddae>.
- [6] WHO, World Health Organization latest global cancer data, World Health Organization, Geneva, 2018.
- [7] V. Duggal, V. Rani, R. Mehra, K. Saini, B.S. Bajawa, Assessment of age-dependent radiation dose and toxicity risk due to uranium ingestion through groundwater, India, Toxicological & Environmental Chemistry (2016). <https://doi.org/10.1080/02772248.2016.1196210>.
- [8] IARC, IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 43, Lyon, 1988.
- [9] ICRP, Compendium of Dose Coefficients based on ICRP Publication 60, Annals of the ICRP 41(Suppl.) (2012) 1–130.
- [10] S. Bello, R. Nasiru, N.N. Garba, D.J. Adeyemo, Annual effective dose associated with radon, gross alpha and gross beta radioactivity in drinking water from gold mining areas of Shanono and Bagwai, Kano

- state, Nigeria, Microchemical Journal 154 (2020) 104551. <https://doi.org/10.1016/j.microc.2019.104551>.
- [11] A. Ruano-Ravina, K.T. Kelsey, A. Fernandez-Villar, J.M. Barros-Dio, Action levels for indoor radon: different risks for the same lung carcinogen? European respiratory journal, 50(5) (2017) 1701609. <https://doi.org/10.1183/13993003.01609-2017>.
- [12] A.R. Mathloom, M.H. Alkhafaji, A.A. Al-Hachami, The study of determining the levels of radon gas concentrations (soil, water and plants) in the areas exposed to military operations in Suq Al-Shuyoukh district, South of Thi-Qar province, Iraq, Journal of Physics: Conference Series, 1804 (2021) 012146. <https://doi.org/10.1088/1742-6596/1804/1/012146>.
- [13] A.A. Sahar, M.D. Saudi, H.M. Muwafaq, Radon Concentrations Assessment and Effective Dose Estimation in the Buildings of University of Technology/Baghdad, Eng. And Tech. Journal, 32(13) (2014) 3216-3227. <https://doi.org/10.30684/etj.32.13A.13>.
- [14] S.K. Ezzulddin, H.H. Mansour, Assessment of Radon Exposure in Erbil Drinking Water Resources, ZANCO Journal of Pure and Applied Sciences, 29(4) (2017) 184–194. <https://doi.org/10.21271/zjpas.29.s4.22>.
- [15] WHO, Guidelines for Drinking-water Quality: Fourth edition incorporating the first and second addenda, World Health Organization, Geneva, 2022.
- [16] USEPA, Radon in Drinking Water: Health Risk Reduction and Cost Analysis, Federal Register 64, Washington, 1999.
- [17] A. Aruwa, A.A. Kassimu, P.M. Gyuk, B. Ahmadu, J.O. Aniegbu, Studies on radon concentration in underground water of Idah, International Journal of Research Granthaalayah, 5(9) (2017) 266–275. <https://doi.org/10.29121/granthaalayah.v5.i9.2017.2242>.
- [18] N. Todorovic, J. Nikolov, S. Forkapic, I. Bikit, D. Mrdja, M. Krmar et al., Public exposure to radon in drinking water in SERBIA, Applied Radiation and Isotopes, 70 (2012) 543–549. <https://doi.org/10.1016/j.apradiso.2011.11.045>.
- [19] F.Z. Darabi, M. Rahimi, M. Malakootian, N. Javid, Studying radon concentration in drinking water resources in Zarand city (Iran) and its villages, Journal of Radioanalytical and Nuclear Chemistry, 326 (2020) 33–39. <https://doi.org/10.1007/s10967-020-07349-5>.
- [20] M.M. Orosun, T.B. Ajibola, O.E. Ehinlafa, A.I. Kolawole, B.N. Salawu, S.D. Ishaya et al., Annual Effective Dose Assessment of Radon in Drinking Water from Abandoned Tin and Cassiterite Mining Site in Oyun, Kwara State, Nigeria, Pollution, 8(1) (2022) 181–192. <https://doi.org/10.22059/poll.2021.326962.1136>.
- [21] E.H. El-Araby, H.A. Soliman, M. Ebo-Elmagd, Measurement of radon levels in water and the associated health hazards in Jazan, Saudi Arabia. Journal of radiation research and applied sciences, 12(1) (2019) 31–36. <https://doi.org/10.1080/16878507.2019.1594134>.
- [22] H. Nuhu, S. Hashim, M.S. Sanusi, M.A. Saleh, Radon activity concentration measurements in water sources from Perak State, Malaysia, Journal of radiation research and applied sciences, 13(1) (2020) 665–671. <https://doi.org/10.1080/16878507.2020.1820270>.
- [23] H.K. Shu'aibu, M.U. Khandaker, A. Baballe, S. Tata, M.A. Adamu, Determination of radon concentration in groundwater of Gadau Bauchi State, Nigeria and estimation of effective dose. Radiation Physics and Chemistry, 178 (2021) 108934. <https://doi.org/10.1016/j.radphyschem.2020.108934>.
- [24] S. Suresh, D.R. Rangaswamy, E. Srinivasa, J. Sannappa, Measurement of radon concentration in drinking water and natural radioactivity in soil and their radiological hazards. Journal of Radiation Research and Applied Science, 13(1) (2020) 12–26. <https://doi.org/10.1080/16878507.2019.1693175>.
- [25] A.M. Kamba, I.O. Okunade, Radon measurement in commercial borehole water from some selected areas in Kaduna metropolis using Liquid Scintillation Counter, International Journal of Mathematics and Physics Research, 3(2) (2016) 71–81.
- [26] I.M. Kareem, A. Ahmed, R.S. Mohammed, H.R. Abdo, W.Y. Shlaimoon, N.A. Karim, Radiological Risk Assessment of 222 Radon Concentration And Annual Effective Dose Calculation in Ground water From Zakho, Iraq, Journal of Advanced Zoology, 45(2) (2024) 1326–1334. <https://doi.org/10.53555/jaz.v45i2.4082>.

- [27] United Nations, Sources and Effects of Ionizing Radiation, United Nations, New York, 2001.
- [28] H. Bem, U. Plota, M. Staniszewska, E.M. Bem, D. Mazurek, Radon (^{222}Rn) in underground drinking water supplies of the Southern Greater Poland Region, *Journal of Radioanalytical and Nuclear Chemistry*, 299(3) (2014) 1307-1312. <https://doi.org/10.1007/s10967-013-2912-1>.
- [29] V. Duggal, R. Mehra, A. Rani, Analysis of radon concentration in drinking water in Hanumangarh district of Rajasthan, India, *Radiation Protection and Environment*, 36(2) (2013) 65-70. <https://doi.org/10.4103/0972-0464.128870>.
- [30] G.O. Awiri, C.P. Ononugbo, I.E. Nwokeoji, Radiation hazard indices and excess lifetime cancer risk in soil, sediment, and water around Mini-Okoro/Oginigba creek, PortHarcourt, Rivers State, Nigeria, *Comprehensive Journal of Environment and Earth Sciences*, 3(1) (2014) 38-50.
- [31] D. Spasic, L. Gulan, B. Vuckovic, Indoor radon testing, effective dose and mitigation measures in a residential house of mining area. *Atmosphere*, 15(7) (2024) 745. <https://doi.org/10.3390/atmos15070745>.
- [32] A. Azhdarpoor, M. Hoseini, S. Shahsavani, N. Shamsedini, E. Gharehchahi, Assessment of excess lifetime cancer risk and risk of lung cancer due to exposure to radon in a middle eastern city in Iran. *Radiation Medicine and Protection*, 2, (2021) 112-116. <https://doi.org/10.1016/j.radmp.2021.07.002>.