

Study of Radon Concentration in Well Water in the Districts of Kirkuk Governorate

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Abstract

This study evaluates the radon ^{222}Rn concentrations in well water from seven districts (Qara Hanjir, Yaychi, Taza, Laylan, Altun Kupri, Dibis and Hawija) of Kirkuk Governorate, Northern Iraq, using the RAD7-H₂O dosimeter. A total of 21 samples were collected (three from each district): Qara Hanjir, Yaychi, Taza, Laylan, Altun Kupri, Dibis, and Hawija. This study is motivated by the fact that radon in groundwater is a significant source of natural radiation exposure, with potential health effects such as lung and stomach cancer if concentrations exceed the international safety limits. The measured radon concentrations ranged from 7.93 Bq/l in Altun Kupri to 18.7 Bq/l in Dibis District. According to the United States Environmental Protection Agency (USEPA) guideline of 11 Bq.l⁻¹, only Taza and Altun Kupri were within the permissible limit, while the other districts exceeded it. The annual effective dose of inhalation ranged from 0.020 mSv.y⁻¹ in Altun Kupri to 0.047 mSv.y⁻¹ in Dibis, whereas the ingestion dose varied from 1.67 mSv.y⁻¹ in Altun Kupri to 3.92 mSv.y⁻¹ in Dibis. Compared with the international standards, inhalation doses remained well below the permissible limits, while ingestion doses in some districts (Dibis and Laylan) slightly exceeded the ICRP lower threshold (3 mSv.y⁻¹), just above the UNSCEAR global average (1.15 mSv.y⁻¹). The calculated excess lifetime cancer risk (ELCR) values are within acceptable ranges, indicating a limited long-term risk from inhalation exposure, but ingestion exposure requires continuous monitoring.

Keywords:

RAD7, Radon concentrations, Pollution; Groundwater.

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1. Introduction

Radioactive pollution is the most common and dangerous kind of pollution. This is a result of the nuclear industry's growth, the use of nuclear energy, the amount of radioactive waste produced by the industry, the use of nuclear energy to generate electricity, and the use of radioisotopes in industry, research, medicine, and agriculture. Radionuclides can arise in two ways: either organically and spontaneously as a result of natural radioactivity, or artificially through man-made intervention in the form of radioactive nuclides (Mdekil et al., 2024). Naturally radioactive elements in the earth's crust, energy

streams entering the atmosphere, and the byproducts of radioactive decay are the main causes of natural radiation. Hawas et al. (2024) said that "These radionuclides can be present in both surface water and groundwater, as they originate from rocks and soils that contain naturally occurring radioactive materials". Sabbarese et al. (2021) declared that Radium, uranium, and radon isotopes are among the common radionuclides found in sources of drinking water. Another source is fission products resulting from human action.

Taher et al. (2024) explained that Radon is considered a colorless, odorless, tasteless, and radioactive noble gas, naturally formed as a byproduct of uranium decay, and it is the main source of more than 50% of the natural radiation humans are exposed to. The concentrations of radon in groundwater are determined by the level of radium in the rocks that make up the aquifers (Makolli et al., 2025), where dissolved radon is produced by the presence of natural uranium in the soil and rocks that interact with water (Caridi et al., 2016).

In Iraq, in recent years, wars have exacerbated radioactive contamination due to the use of depleted uranium and the looting of nuclear facilities, causing significant damage to public life, including water pollution. Therefore, water systems exposed to this type of contamination require careful monitoring to ensure that drinking water is free from any radioactive contamination (Shlioh and Saleh (2018); Abad Ibrahim et al. (2017); Ahmed et al. (2019); Abojassim (2020); Hawas et al. (2024b)).

Recent years have seen a growing focus on the study of natural radioactivity in water. In Dhi-Qar Marzaali et al.(2021) used the RAD7–H₂O dosimeter and reported radon concentrations between 0.032 and 0.78 Bq.l⁻¹, all within acceptable limits based on international standards. In Haditha City, radon concentrations in 22 water samples collected from three districts and the Euphrates River varied from 0.0091 to 0.031 Bq.l⁻¹, with corresponding annual effective doses of 0.033–0.113 μSv.y⁻¹, also well below the WHO and USEPA standards (Al-Paruany et al., 2022). In Baghdad (Al-Bayaa region), another study measured radon in both tap and well water, with concentrations ranging from 2.30 to 5.60 Bq/land annual effective doses of 8.40–20.4 μSv.y⁻¹, which were all below the WHO limits (Jameel, 2023). More recently, a study conducted in Baghdad by Abdulkhaleq et al. (2024) showed that radon levels in 15 bottled drinking water samples varied widely from 3.5 to 74 Bq.m⁻³, as measured by the RAD7 technique. Collectively, these studies indicate that radon concentrations in Iraqi drinking water sources are generally within international safety limits, although local variations are evident depending on geological and hydrological conditions. The present study aims to determine the concentrations of radon (²²²Rn) in well water from seven districts of Kirkuk Governorate using the RAD7–H₂O dosimeter. It

further seeks to evaluate the annual effective doses from ingestion and inhalation of radon and to estimate the excess lifetime cancer risk (ELCR). The results are compared with international safety standards set by USEPA, ICRP, and UNSCEAR to assess the potential radiological health risks associated with groundwater consumption in the study area.

2. Study Area

Kirkuk is one of the major cities in Iraq due to its extensive oil fields and ancient geological formations rich in naturally occurring radioactive materials (NORM), such as uranium and thorium. These elements decay into ²²⁶Ra and ²²²Rn, which may be released into groundwater. Previous studies (e.g., Zaidan, 2010) have shown that formation water and oil-associated sludge can contain high concentrations of these radionuclides. Therefore, Kirkuk provides an ideal environment for monitoring and evaluating natural radiation associated with oil industry activities. In this study, water samples were collected from seven districts across the governorate. Qara Hanjir District, located northeast of Kirkuk, is one of the province's main agricultural regions. Yaychi District, situated to the southwest, is known for its cultivation of grains and vegetables. Taza District, positioned south of Kirkuk, is characterized by its fertile soil and diverse agricultural production. Laylan District, in the east, relies heavily on well water for irrigation, making it a significant agricultural area. Altun Kupri District, found in the northwest, is notable for growing various crops. Dibis District, located west of Kirkuk, is considered a vital agricultural zone. Lastly, Hawija District, in the southwest, is known for its extensive agricultural lands. The geographical distribution of these districts in relation to the administrative divisions of Kirkuk is illustrated in Fig. 1.

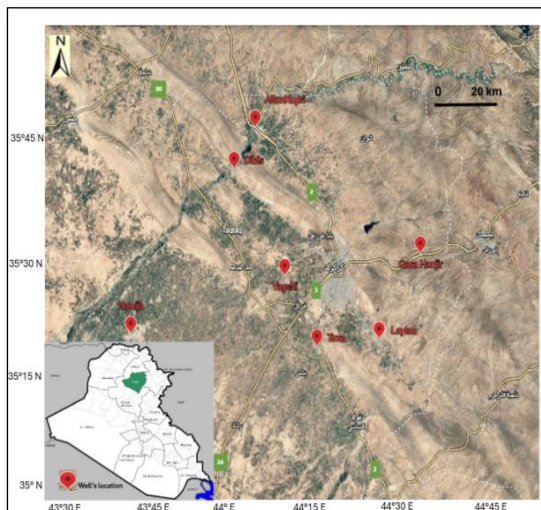


Fig. 1: The Map of Iraq and the locations of samples of well water from Kirkuk Governorate.

3. Methodology

In this research, we measured the concentration of radon gas in water using the RAD7 system. An electronic radon monitor (Rad7–H₂O, DurrIDGE Co., USA) is what makes RAD7 a reliable method for radon detection (Salih, 2021; Hawas et al., 2024a). This device is specially made to determine with high precision the amount of radon gas present in water. It operates based on a solid-state ion-implanted silicon detector that converts alpha radiation into electrical signals. The key feature of the RAD7 system is its ability to electronically determine the energy of each alpha particle emitted by radon progeny (²¹⁸Po and ²¹⁴Po), thereby allowing accurate identification of the isotopes involved and quantification of radon concentration in the sample. Measurements are performed using the RAD-H₂O dosimeter, which is connected to the RAD7 unit. Prior to analysis, the system is dried by circulating air through a desiccant in a closed loop for 10 minutes until humidity drops below 6%. Once the system is ready, the measurement begins by transferring radon from the water sample into the air loop via a five-minute aeration process. This process ensures that approximately 94% of radon is extracted from the water, depending slightly on ambient temperature, and generally remains above 90% efficiency. The RAD7 system then performs four five-minute measurement cycles, during which radon decay products are detected and analyzed. The RAD7 is capable of distinguishing newly captured radon from residual radon left from prior analyses (Subberet and Ali, 2012). The system records output average radon concentration, standard deviation,

time and date of measurement, procedure type, and number of cycles after each test.

Standard deviation (*SD*) is a measure of how dispersed data are around the mean. That is, it shows how far values vary from the mean. The use of Standard Deviation in analyzing radon concentration data measures the variability of radon concentrations in different areas; the standard deviation helps determine the stability or fluctuation of radon concentration in water. Kareem et al. (2020) state that if the standard deviation is low, this means that the radon concentration in all samples is similar, and therefore there is consistency in the data; but if the standard deviation is high, this indicates significant variations between samples, which may indicate the presence of variable sources of radon leakage into the water. We use the equation (1) from Abojassim (2020)

$$SD = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N-1}} \quad (1)$$

Where *SD* is the standard deviation, x_i , $\bar{x}$ and *N* are the count, average, and number of samples, respectively.

Radon is introduced into the human body via ingestion and inhalation, as it is released from water into the air. Radon in water contributes to radiation exposure in the stomach and lungs. For ingestion, the annual effective dose is calculated using the formula (2) (Kandari et al., 2016):

$$E_{ing} \left(\frac{mSv}{y} \right) = C_w \times C_{Rn} \times EDC \quad (2)$$

where E_{ing} is the effective dose from ingestion (Sv), *EDC* is the ingesting dose conversion factor of ²²²Rn 3.5 nSv/Bq (for adults); C_{Rn} is the radon concentration in Becquerels per liter, C_w is the water consumption (60 liters per year).

To calculate the annual effective dose resulting from inhaling radon gas from drinking water, we use the following equation (3): Duggal et al. (2013)

$$E_{inh} = C_{Rn} \times R_{aw} \times F \times O \times DC \quad (3)$$

Where E_{inh} is Effective dose from inhaling radon in unit of Sv, C_{Rn} is the radon concentration in the water, R_{aw} = 10-4 l/m³ Radon transfer rate from water to air, *F*- is Equilibrium coefficient between radon and its radioactive decay products was equal to 0.4; *O*- is average time spent indoors = 7000 h/y; *DCF*- is Radon dose conversion factor = 9 nSv (Bqhm-3)⁻¹. Excess lifetime cancer risk (ELCR) is determined using the following equation (4) based on calculated values of annual effective dose (AED) (Aswood et al., 2022)

$$ELCR = AED \left(\frac{mSv}{y} \right) \times DL (y) \times RF \left(\frac{1}{Sv} \right) \quad (4)$$

Where DL is life expectancy (=70 y); is RF: risk factor (=0.055 Sv⁻¹)

We have collected seven water samples (each with a volume of 450 ml) from different districts within Kirkuk Governorate, located in northern Iraq. From each selected well, three water samples were obtained using either hand pumps, tube wells, deep dug wells exceeding 50 meters, or domestic water taps connected to groundwater sources at similar depths, after allowing water to run for 10 minutes to ensure sample freshness. All samples were stored in filled, tightly sealed containers to minimize air gaps and prevent radon gas loss. Subsequently, the samples were analyzed using the RAD7 device to determine radon gas concentrations. The water sampling followed a purposive sampling approach, targeting wells located in districts surrounding Kirkuk Governorate. These areas were deliberately chosen due to their geological features, including the presence of sedimentary rocks and oil-bearing formations known to contain natural radionuclides such as uranium and thorium, which may lead to elevated levels of radon in groundwater. This strategy ensured a representative evaluation of radon distribution across the studied region.

The RAD-7 dosimeter consists of a semiconductor material (Diab, 2019). It fundamentally comprises a periodic-fill cell. This cell is filled with air through a small opening.

A pump draws air into the cell once at each pre-selected interval for the decay of radon or ²¹⁸Po, allowing for counting, after which the cycle is repeated. The RAD-7 device operates on the basis of a solid-state detector. This device is a silicon ion-implanted Dosimeter that utilizes semiconductor material to convert radiation into an electrical signal. One advantage of solid-state Dosimeters for radon or its progeny is their ability to electronically discriminate the energy associated with incoming alpha radiation, as shown in Fig. 2.

In this context, specific radionuclides can be identified, such as ²¹⁸Po, which has an alpha energy of 6.00 MeV, and ²¹⁴Po, with an energy of 7.69 MeV. The RAD7 device (commonly used with the RAD H₂O accessory) measures radon in water samples over a range of concentrations from less

than 10 pCi.l⁻¹ up to greater than 400 pCi · L⁻¹ (Abdulkhaleq et al., 2024). The equipment is both portable and battery-operated, facilitating rapid measurements. An accurate radon measurement in water can be obtained within one hour of sampling. The RAD H₂O provides results following a 30-minute analysis, demonstrating sensitivity that is comparable to or surpasses that of liquid scintillation methods. In a 5-minute aeration process, the available radon is eliminated from the water (Kareem et al., 2020).

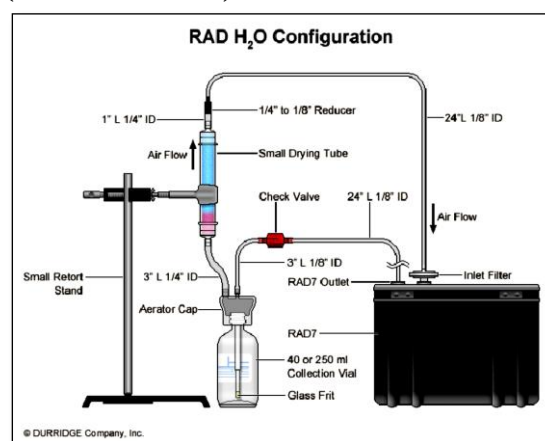


Fig. 2: RAD7 H₂O device and measurement system of radon gas in water.

4. Results and Discussion

A. Radon concentration

The findings about radon concentration in 21 groundwater samples obtained from 7 wells across the districts and sub-districts of Kirkuk Governorate, Iraq, are presented in Table 1. The radon concentration ranges from 7.93 Bq/L in Altun Kupri District to 18.70 Bq/L in Dibis District; see Fig. 3. The permissible maximum concentration level for ²²²Rn in water is 11 Bq/L recommended by the US Environmental Protection Agency (USEPA) and Al-Hamadwi et al. (2012). In this study, all values found were higher than international standards except in Taza and Altun Kupri Districts. The fluctuations in radon concentration may be attributed to the geological structure of the region, the depth of the water source, and variations in climate (Duggal et al., 2013)

Table 1: The Radon concentrations and the locations of well water samples in some districts in Kirkuk

No	Location	Mean Concentration (Bq/l)	Standard Deviation	SD % of Mean
1	Qara Hanjir District	10.83	0.35	3.2
2	Yaychi District	13.03	0.32	2.4

3	Taza District	9.2	0.30	3.2
4	Laylan District	15.87	0.31	1.9
5	Altun Kupri District	7.93	0.15	1.8
6	Dibis District	18.7	0.40	2.1
7	Hawija District	12.13	0.25	2.0

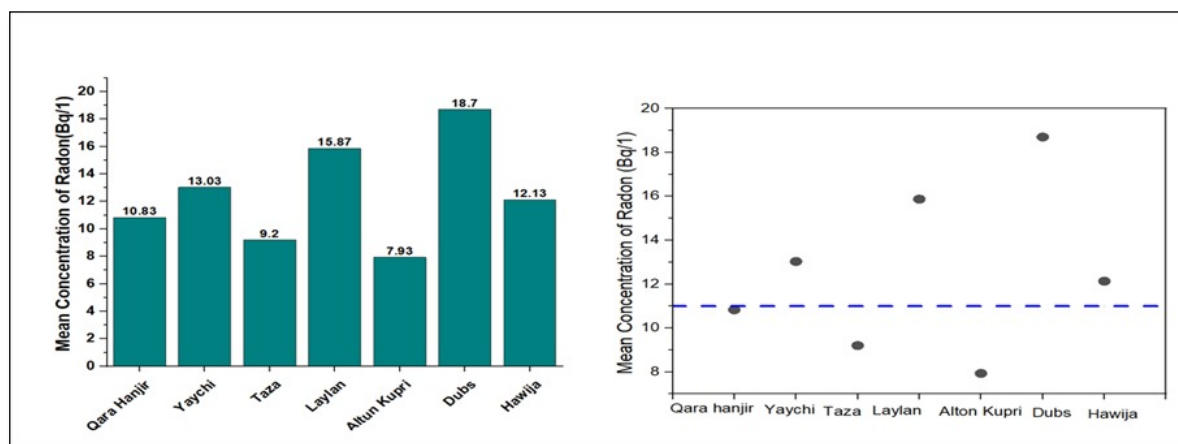


Fig. 3: Radon Concentration in the well water samples; the blue dashed line represents the maximum permissible concentration level for 222Rn in water by (USEPA).

Table 2 presents the variation in radon concentrations in different districts by calculating the standard deviation (Fig. 4). The results show that the standard deviation values, expressed as a

percentage of the mean, are generally low, with a range of (1.8%–3.2%), suggesting good consistency among the measurements across the study area.

Table 2: The Standard Deviation and the locations of the well water samples.

No	Location	Coordinates (Lat, Long)	Elevation (m)	Radon Concentration Bq/l			MEAN
1	Qara Hanjir	35°29'35"N, 44°38'20"E	762.35	10.5	11.2	10.8	10.83
2	Yaychi	35°26'47"N, 44°13'50"E	260.19	12.8	13.4	12.9	13.03
3	Taza	35°17'58"N, 44°19'42"E	239.18	8.9	9.5	9.2	9.2
4	Laylan	35°18'53"N, 44°30'54"E	336.98	15.6	16.2	15.8	15.87
5	Altun Kupri	35°45'24"N, 44°08'31"E	257.48	7.8	8.1	7.9	7.93
6	Dibis	35°40'12"N, 44°04'40"E	248.78	18.3	19.1	18.7	18.7
7	Hawija	35°19'29"N, 43°46'00"E	191	11.9	12.4	12.1	12.13

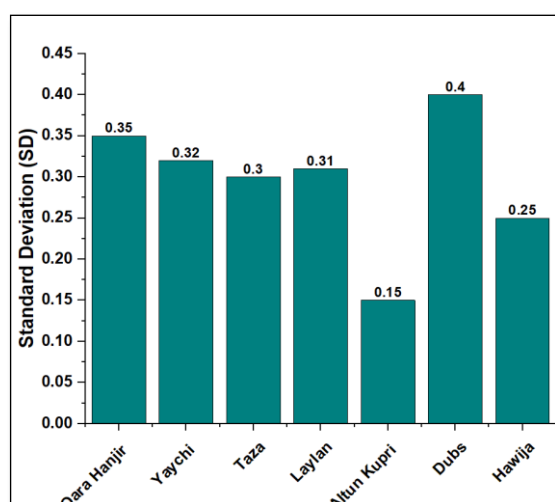


Fig. 4: Standard deviation and the locations of the well water samples.

B. The annual effective dose

The annual effective doses resulting from the ingestion and inhalation of radon in groundwater across different districts were assessed and compared to the international standards established by the International Commission on Radiological Protection (ICRP) and the United Nations Scientific

Committee on the Effects of Atomic Radiation (UNSCEAR). The ICRP recommends a yearly effective dose from natural radiation exposure between 3 and 10 mSv/year, whereas UNSCEAR estimates the global average annual effective dose from natural radionuclide intake to be around 1.15 mSv/year (Kandari et al., 2016)

The annual effective doses for inhalation and ingestion are presented in Table 3. The annual dose for ingestion ranges from 1.67 mSv/y in Altun Kupri District to 3.92 mSv/y in Dibis District. It was found that the Dibis and Laylan Districts slightly exceed the minimal ICRP action level threshold of 3 mSv/y,

while all districts exceed the UNSCEAR limits. The calculated inhalation doses were significantly below the thresholds established by ICRP and UNSCEAR,

with values ranging from 0.020 to 0.047 mSv/y. (Figs. 5 and 6).

Table 3: mean Radon concentrations and Ingestion doses with Inhalation doses of the well water samples in the Kirkuk Governorate

No	Location	Mean Concentration (Bq/l)	Ingestion Dose (mSv/y)	Inhalation Dose (mSv/y)
1	Qara Hanjir	10.83	2.27	0.027
2	Yaychi	13.03	2.74	0.033
3	Taza	9.2	1.93	0.023
4	Laylan	15.87	3.33	0.040
5	Altun Kupri	7.93	1.67	0.020
6	Dibis	18.7	3.92	0.047
7	Hawija	12.13	2.55	0.030

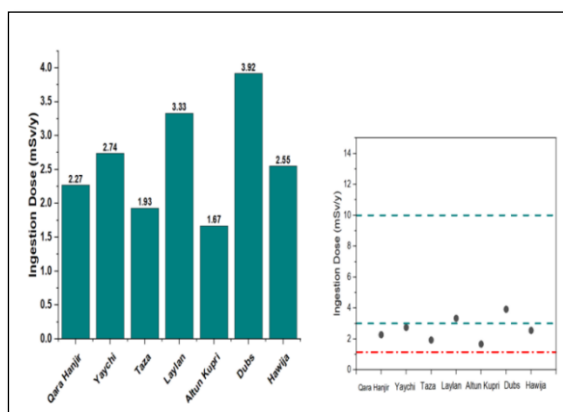


Fig. 5: Ingestion Doses of Radon gas in well water samples and the locations in some districts in Kirkuk Governorate; the green dashed line is the recommended effective dose by ICRP, and the red dashed line is for UNSCEAR.

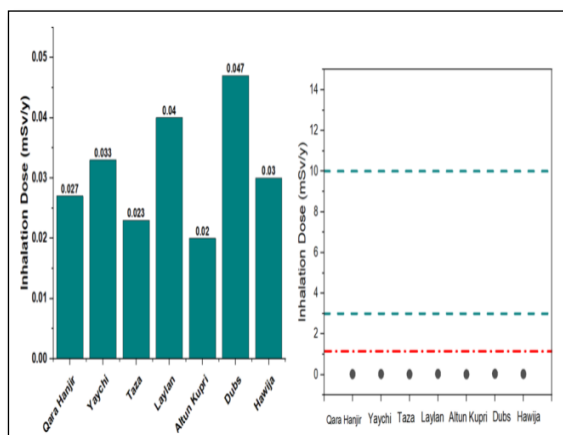


Fig. 6: Inhalation Doses of Radon gas in well water samples in the locations of the districts in Kirkuk Governorate; the green dashed line is the recommended effective dose by ICRP and the red dashed line is for UNSCEAR.

The data characteristics presented in Table (4) show how the radon gas (^{222}Rn) concentrations, annual effective inhalation dose, and excess lifetime cancer risk (ELCR) are identified across the studied districts to be very diverse. The excess lifetime

cancer risk and the annual inhalation dose are found to be directly correlated based on Eq. (4). The ELCR results are within the safe range because the inhalation dose is less than the permissible limit (Cousins et al., 2010)

The presence of radon gas (^{222}Rn) in groundwater samples from the studied districts of Kirkuk can be primarily attributed to the region's geological structure. Kirkuk is known for its oil-bearing formations and sedimentary rocks, which often contain uranium (^{238}U) and thorium (^{232}Th), the parent isotopes of ^{226}Ra and ^{222}Rn . As these radionuclides undergo natural radioactive decay, radon gas is released and can migrate through fractures and pores into surrounding aquifers.

Moreover, studies have shown that radon concentrations in groundwater are positively correlated with the uranium content of local rocks and soils. According to the UNSCEAR (2000) report (Charles, 2001), the sedimentary formations, especially those rich in organic matter, phosphate, or clay, are more likely to contain uranium and therefore generate radon over time. This geological context explains the spatial variability of radon levels across the sampled areas.

Given that some districts in Kirkuk exceed the international safety limit for radon in drinking water (11 Bq/L as recommended by the USEPA), periodic monitoring of radon levels is essential. Regular assessment helps track variations caused by geological factors or industrial activities and supports health risk evaluations related to chronic radon exposure through ingestion or inhalation, ultimately contributing to public safety in at-risk regions.

Table 4: Results of annual effective dose and excess lifetime cancer risk

No.	Location	Mean Concentration (Bq/l)	Inhalation Dose (mSv/y)	Excess lifetime cancer risk (ELCR $\times 10^{-3}$)
1	Qara Hanjir District	10.83	0.027	0.105
2	Yaychi District	13.03	0.033	0.126
3	Taza District	9.2	0.023	0.089
4	Laylan District	15.87	0.040	0.153
5	Altun Kupri District	7.93	0.020	0.076
6	Dibis	18.7	0.047	0.181
7	Hawija	12.13	0.030	0.117

5. Conclusion

Radon concentration measurement results in 21 groundwater samples collected from seven wells in different regions of Kirkuk Governorate, Iraq, showed a radon concentration range from 7.93 Bq/L in the Altun Kupri region to 18.70 Bq/L in Dibis region. Radon concentration in drinking water is not recommended to exceed 11 Bq/L (USEPA). Only the samples from Taza and Altun Kupri regions were within the USEPA's permissible limit, while the remaining measured values exceeded this level. The variability in radon concentration is attributed to the geological conditions, variation in depth for water sources, and climate variation across the study regions. Annual effective doses due to inhalation and ingestion of radon gas across regions of Kirkuk from groundwater are assessed and then compared with set international limits of ICRP and UNSCEAR. Ingestion doses in the Dibis and Laylan regions exceeded the ICRP recommended lower limit (3 mSv.y⁻¹), with all regions exceeding the UNSCEAR limit (1.15 mSv.y⁻¹). However, inhalation doses between the study regions are considerably lower and below the internationally recommended risk limits. The data demonstrated a direct relationship between radon gas concentration (²²²Rn), annual effective dose from inhalation, and estimated lifetime cancer risk (ELCR) in the study regions is due to soil contamination in the region leading to an increase in radon levels contaminating the water. However, ELCR values for lung cancer are still safely within the acceptable range, as the annual inhalation doses are below the ICRP permissible limit (ICRP, 2011).

6. Acknowledgements

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7. Conflict Of Interest

We declare that there is no conflict of interest regarding the conduct or publication of this research.

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دراسة تركيز غاز الرادون في مياه الآبار في أفضية مدينة كركوك

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المخلص

تهدف هذه الدراسة إلى تقييم تراكيز غاز الرادون Rn 222 في مياه الآبار ضمن سبعة أفضية تابعة لمحافظة كركوك (قرية هنجير، يابجي، تازة، ليلان، آلتون كوبري، الدبس، والحويجة)، شمالي العراق، باستخدام كاشف RAD7-H₂O. تم جمع 21 عينة ماء (ثلاث عينات من كل قضاء). وقد استندت هذه الدراسة إلى حقيقة أن الرادون الموجود في المياه الجوفية يُعد أحد المصادر الرئيسية للتعرض الطبيعي للإشعاع، والذي قد يؤدي إلى آثار صحية خطيرة مثل سرطان الرئة والمعدة في حال تجاوز تركيزه الحدود المسموح بها دوليًا. تراوحت تراكيز الرادون المقاسة بين 7.93 بيكريل/لتر في قضاء آلتون كوبري و18.7 بيكريل/لتر في قضاء الدبس. ووفقًا لإرشادات وكالة حماية البيئة الأمريكية (USEPA)، التي تحدد الحد الأقصى المسموح به بـ 11 بيكريل/لتر، فإن منطقتي تازة وآلتون كوبري فقط كانتا ضمن هذا الحد، بينما تجاوزت بقية الأفضية الحد المسموح به. تراوحت الجرعة الفعالة السنوية الناتجة عن الاستنشاق بين 0.020 مللي سيفرت/سنة في آلتون كوبري و0.047 مللي سيفرت/سنة في الدبس، في حين تراوحت جرعة الابتلاع بين 1.67 مللي سيفرت/سنة في آلتون كوبري و3.92 مللي سيفرت/سنة في الدبس. وبالمقارنة مع المعايير الدولية، فإن جرعات الاستنشاق كانت دون الحدود المسموح بها، بينما تجاوزت جرعات الابتلاع في بعض المناطق (الديس وليلان) الحد الأدنى الذي حددته اللجنة الدولية للحماية من الإشعاع (ICRP) البالغ 3 مللي سيفرت/سنة، وكانت أيضًا أعلى من المتوسط العالمي الذي حددته لجنة الأمم المتحدة العلمية المعنية بآثار الإشعاع الذري (UNSCEAR) البالغ 1.15 مللي سيفرت/سنة. كانت قيم خطر الإصابة بالسرطان على مدى الحياة (ELCR) المحسوبة ضمن الحدود المقبولة، مما يشير إلى أن خطر التعرض طويل الأمد عبر الاستنشاق محدود، إلا أن التعرض عبر الابتلاع يتطلب مراقبة مستمرة.

الكلمات المفتاحية:

RAD7، تركيزات الرادون، التلوث، المياه الجوفية.

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