Assessment of Radon Gas Concentration in khat Leaves and its Radiological Exposure Effects in Utmah Region, Yemen

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Abstract
This study evaluated the radon concentration in Khat (Catha edulis) leaves collected from Utmah area,Yemen using CR-39 detectors through closed-can technique. The findings indicated that radon concentrations varied from 234.77 to 704.3 Bq/m³, with a mean concentration of 453.215 ± 117.621 Bq/m³. The study calculated the annual radiation dosage associated with Khat consumption, which ranged from 575 to 1732 µSv/y, with a mean value of 1114.051 ± 290.755 µSv/y. This radiation dose violates the standards set by the International Commission on Radiological Protection (ICRP), which recommends a maximum exposure limit of 1 mSv per year for the general population.
Key words: *Radon Gas; CR-39 detectors; khat Leaves; Radiological Exposure; annual radiation dosage.*

تقييم تركيز غاز الرادون في أوراق القات وآثار التعرُّض الإشعاعي الناتج عنها في منطقة عتمة باليمن

صقر الجهمي، مراد المجاهد، فاهم يحيى

الملخص
هدفت هذه الدراسة إلى قياس تركيز غاز الرادون في أوراق نبات القات (Catha edulis) المجمعة من منطقة عتمة في اليمن، باستخدام كاشفات CR-39 وتقنية العلبة المختومة. أظهرت النتائج تفاوت تركيز غاز الرادون بين 234.77 و704.3 بيكريل/م³، بمتوسط قيمته 453.215 ± 117.621 بيكريل/م³. كما تم حساب الجرعة الإشعاعية السنوية الناجمة عن استهلاك القات، والتي تراوحت بين 575 و1732 ميكروسيفرت/عام، بمتوسط 1114.051 ± 290.755 ميكروسيفرت/عام. تجاوزت هذه الجرعة الإشعاعية الحدود المسموح بها من قِبَل اللجنة الدولية للوقاية الإشعاعية(ICRP) ، التي تُوصي بألا يتعدى التعرض الإشعاعي 1 ملي سيفرت سنوياً للأفراد من العامة.
الكلمات المفتاحية: *غاز الرادون ؛ كاشفات CR-39 ؛ أوراق القات ؛ التعرُّض الإشعاعي ؛ الجرعة الإشعاعية السنوية.*

1. Introduction

Understanding the effects of natural radiation exposure is crucial for scientists and health professionals due to its potential impact on public health (Njagi et al., 2022). Recent research indicates that certain plants, such as khat (*Catha edulis*), may contain varying levels of natural radioactive elements, prompting concerns about the health effects associated with the regular consumption of khat (Kassie et al., 2001; Njagi et al., 2022). The khat plant (*Catha edulis*) plays an important role in daily life in Yemen, where it is frequently consumed for its stimulating effects. People chew khat to experience feelings of euphoria and to enhance social interactions. However, the consumption of khat poses health risks due to its content of compounds like cathinone, which is similar to ephedrine and has effects comparable to amphetamines (Al-jalali & Shaltout, 2014; Al-Motarreb et al., 2002; Luqman & Danowski, 1976; Nutt et al., 2007). Khat has been classified as a mildly addictive substance since 1980. However, long-term use, particularly when combined with smoking, has been associated with a higher risk of chronic diseases, including cancers of the mouth and lungs (Al-Hadrani, 2000; Al-Motarreb et al., 2002). Another concern is the natural radioactivity of radon. Radon is a naturally occurring radioactive element found in the environment, and it poses significant health risks, especially in relation to lung cancer (Al-Zoughool & Krewski, 2009; Services, 2002). Numerous studies have explored the environmental and health effects of radon, particularly concerning plants such as *Catha edulis*. These studies examined various aspects, including how radon moves through plants and the health risks associated with consuming them. Nunes et al. (2023) highlighted the relationship between radon and geology, emphasizing importance of understanding radon's impact on human health and the need to develop strategies to reduce radon exposure (Nunes et al., 2023). Additionally, a study by Jayaratne et al. (2011) demonstrated that radon can enter the atmosphere through plants, as they absorb groundwater containing radon and release it during transpiration. It was found that plants can contribute up to 37% of the radon released from soil during the day (Jayaratne et al., 2011; Tavera et al., 2002). A third study by Jalali and Shaltout (2014) measured natural radioactivity in (*Catha edulis*) and tobacco plants using spectroscopy. They found that radioactivity was present in leaves that had not been treated with pesticides (Al-jalali & Shaltout, 2014). A more recent study by Eliod et al. (2024) investigated factors influencing the radon movement from soil to khat plants using a gamma-ray detector, establishingthat radiation levels were within safe limits (Eliud et al., 2024). Furthermore, Njagi et al. conducted a thorough assessment of radiation exposure from natural sources in khat-growing regions, measuring radioactivity in both khat leaves and soil to guarantee consumer safety (Njagi et al., 2022). Lastly, a comprehensive review by Al-Qadhi et al. (2021) underscored the harmful effects of khat on oral cells, demonstrating that its consumption can lead to cell death and toxicity (Al-Qadhi et al., 2021). These studies emphasized the importance of investigating natural radioactivity in plants such as khat, particularly due to the significant variations in radon levels across different regions. The health risks associated with long-term radon exposure underline the necessity for further research aimed at developing effective preventive measures. The primary objective of this study is to measure the levels of radon and radium gas in khat plants cultivated in the

Al-Azraa and Tahayjer areas of Utmah, Yemen. To accurately assess radon concentration, the study utilized a CR-39 nuclear track detector combined with a sealed canister method, analyzing a total of 24 khat plant samples. This study offers insights into the potential environmental and health effects of natural radioactivity in khat plants, which are consumed daily over long periods. The study enhances our understanding of how natural radioactivity impacts the health among the Yemeni population, who regularly consume khat. Additionally, it addresses a gap in the scientific literature regarding natural radiation in the region. The findings support the development of effective environmental and public health strategies aimed at protecting public health and promoting sustainable development in Yemen.

2. The experiment and methods

2.1 Study area

The study aims to measure radon levels in Utmah Reserve, an area known for its seismic activity, which can influence ground-level radon emissions. Understanding the radon levels in this region helps explore the relationship between geological conditions and radon behavior. A total of 24 samples of Khat leaves were collected from two locations: Al-Azraa and Tahayjer (see **Table 1**). Utmah Reserve, located in Dhamar Governorate of Yemen, lies within the Sarawat Mountains, situated between longitudes 43.50° - 44.50° and latitudes 14.21° - 14.35°. It is approximately 55 km west of Dhamar city and 155 km south of Sana'a (refer to **Figure 1**) (*Tourism in Yemen*, n.d.). This region was designated as a nature reserve in 2000 to promote biodiversity and sustainable development (*Otma Reserve*, n.d.).

Figure 1. *Map of Utmah Reserve showing the studied areas.*

Dhamar Governorate, which includes Utmah, has a history of seismic activity, highlighted by significant events such as the 1982 North Yemen Earthquake (Dabbeek et al., 2020). Recent records show a continuous occurrence of seismic events in the region (Alrubaidi et al., 2021), which may influence radon emissions. A total of 24 samples of Khat leaves were collected directly from the plants in both Al-Azraaa and Tahayjer, as shown in **Table 1**.

Table 1. Khat samples from different regions

Region		**Sample Code**	**Region**		**Sample Code**
Al-Azraa	*Taloh*	*Q01 - Q02*	**Tahayjer**	*Al-ssihy*	*Q18*
	Karash	*Q03 - Q07*		*Al-Rretli*	*Q18 - Q19*
	Al-Waqf	*Q08 - Q09*		*Al-Quhli*	*Q20 - Q21*

	Al-Mihriba	*Q10 - Q11*		*Al-Mindary*	*Q22 - Q23*
	Makarish	*Q12 - Q13*		*Sahlat Tahyjer*	*Q24*
	Al-Ddubaysh	*Q14 - Q16*			
	Al-Khizaj	*Q17*			

2.2 CR-39 Nuclear Track Detectors

The technique for detecting radon in this study utilizes CR-39 nuclear track detectors, which are 500 µm thick and composed of poly allyl diglycol carbonate ($C_{12}H_{18}O_7$). These detectors were supplied by Pershore Molding Ltd., UK.

2.3 Sample Preparation and Measurement Procedure

The khat leaf samples were initially dried in a sunny location, with each sample being handled separately. After drying, the samples were ground into a fine powder using an electric mixer. To remove any remaining moisture, the powdered samples were placed in an oven at a temperature of 50-70°C for 4-5 hours. Once completely dried, 70 grams of each sample were weighed and prepared for an equilibrium period by sealing them in airtight boxes measuring 7×10 cm^2, as shown in **Figure 2**. These boxes were kept sealed for 30 days to achieve radioactive equilibrium. After this period, the radon concentrations were measured using CR-39 nuclear track detectors, which record the paths of emitted alpha particles. The CR-39 detector was cut into 1×1 cm^2 pieces and attached to the center of a new lid using double-sided adhesive tape. To maintain equilibrium, the lid containing the detector was quickly swapped in after removing the previous lid that did not have a detector (El-araby et al., 2024; Kheder, 2023). A sponge layer, less than 0.5 cm thick, was placed between the sample and detector to shield it from thoron radiation. The detector was positioned to face radon emissions from the sample, allowing it to capture alpha particles from radon decay. Each container was securely sealed with silicone glue around the lid and left undisturbed with the detectors for 90 days. After the exposure, the detectors were retrieved and chemically etched in a 6.25 M sodium hydroxide solution at 70°C for 6 hours. They were then rinsed with distilled water and air-dried. A light microscope, set to 400x magnification and connected to a digital screen, was used to capture clear images of the tracks. The tracks were analyzed using IMAGEJ software, enabling us to determine the average track density. This data were subsequently used to calculate the radiation intensity per square centimeter for each detector (Al Mugahed & Bentayeb, 2019; El-araby et al., 2024).

2.4 Theoretical Calculations

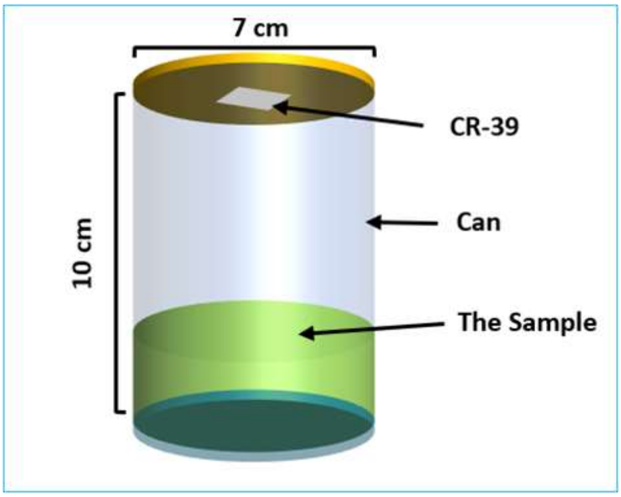

Figure 2. *Plastic can for radon measurement*

2.4.1 The radon equivalent concentration

To determine the concentration of radon, the density of tracks in the detector must be measured, for khat samples.We can use the following equation (El-araby et al., 2024; Syuryavin et al., 2020):

$$\rho = N/A \qquad (1)$$

Where, ρ is the density of tracks (Track/cm^2), N represents the total average number of tracks, and A is the area of the field width (cm^2). The concentration of ^{222}Rn in the samples is calculated in units of Bq/m^3 using the following relationship (Lee et al., 2004):

$$C_{Rn} = \rho / K \ T_{eff} \quad (2)$$

Where C_{Rn} is the activity concentration of ^{222}Rn in the air sample, K is the calibration factor of the SSNTDs detector ($K = 0.05916 \, Traks.cm^{-2}.day^{-1}/Bq.m^{-3}$) (Kheder, 2023). T_{eff} is the effective exposure time in hours. This time reflects the period during which the radon effect is calculated from the sample and is related to the actual exposure time t, by equation (3) (El-araby et al., 2024; Kheder, 2023), This clarification should help in understanding how to analyze the concentration of radon effectively:

$$T_{eff} = t - \frac{1}{\lambda_{Rn}} (1 - e^{-\lambda_{Rn} t}) \quad (3)$$

Where λ_{Rn} is the decay constant of radon equal to ($7.56 \times 10^{-3} h^{-1}$), t is the actual exposure time of 90 days (El-araby et al., 2024).

2.4.2 Radium concentration calculations

The concentration of radium (C_{Ra}) in the samples is calculated using the following formula (EL-Araby & Shabaan, 2023):

$$C_{Ra} = \rho \, h \, A \, / \, M \, T_{eff} \quad (4)$$

Where ρ is the density of the tracks, h is the distance between the top of the sample and the detector, which is equal to 7 cm, A is the surface area from which radon emitted (in cm^2), M is the mass of the sample (in kg). Radium concentrations can be compared against the internationally permissible radium concentration limit of 370 Bq/kg (Eliud et al., 2024; Kheder, 2023).

2.4.3 The annual effective dose

The annual effective dose ($AED_{ing} \left(\frac{\mu Sv}{y}\right)$) from ingesting radionuclides due to khat chewing can be calculated using the following equation (Eliud et al., 2024; Kumar et al., 2022):

$$AED_{ing} \left(\frac{\mu Sv}{y}\right) = A_{Rn} \times (0.5 \frac{kg}{day} \times \frac{365 day}{y}) \times 3.5 \, nSv/Bq \quad (5)$$

Where $A_{Rn} = (C_{Rn} \times V/M)$. This equation represents the specific activity (Pookamnerd et al., 2023; Salih, 2021), here, C_{Rn} refers to the concentration of radon, V is the volume of the exposure tube, and M is the mass of the sample. The consumption rate is assumed to be 0.5 kg per day per adult (Ngari, 2022), while the dose factor for adults is noted as $3.5 \, nSv/Bq$ (Eliud et al., 2024; UNSCEAR, 2000). Additionally, public exposure to indoor radon dose rates is influenced by khat consumption.

3. Result and dissecution

Table 2. Radon concentrations, radium concentration rates and annual effective dose from khat samples.

Sample code	Sample location		Radon concentrations	Radium concentration	Annual effective dose
	Latitude	Longitude	C_{Rn} (Bq/m^3)	C_{Ra} (Bq/kg)	AED (μSv/y)
Q01	14.47333513	44.00145421	391.22	1.50	959
Q02	14.47238747	44.00290065	469.54	1.81	1157
Q03	14.47247957	44.0006486	391.22	1.50	959
Q04	14.47383638	43.99950563	469.54	1.81	1157
Q05	14.47367744	43.99766822	391.22	1.50	959
Q06	14.47241653	43.99869368	391.22	1.50	959
Q07	14.46951064	43.99845546	625.99	2.41	1540
Q08	14.46630589	43.99980191	469.54	1.81	1157

Q09	14.46668107	43.99579367	625.99	2.41	1540
Q10	14.4638484	43.99933102	391.22	1.50	959
Q11	14.46269575	43.9992014	391.22	1.50	959
Q12	14.47023821	43.99849312	704.30	2.71	1732
Q13	14.46842405	43.99874038	469.54	1.81	1157
Q14	14.46103931	43.99649231	625.99	2.41	1540
Q15	14.4619725	43.99532471	547.86	2.11	1349
Q16	14.46054158	43.99496115	234.77	0.90	575
Q17	14.47181359	43.99584361	469.54	1.81	1157
Q18	14.46855126	44.0126284	547.86	2.11	1349
Q19	14.47091834	44.01367829	469.54	1.81	1157
Q20	14.47199351	44.01502642	234.77	0.90	575
Q21	14.47281422	44.01439659	469.54	1.81	1157
Q22	14.4741963	44.01623719	391.22	1.50	959
Q23	14.46282981	44.01169068	391.22	1.50	959
Q24	14.4695442	44.0083035	313.09	1.20	767
		Average ± S. D	***453.215 ± 117.621***	***1.743 ± 0.455***	***1114.051 ± 290.755***
		Max	***704.30***	***2.71***	***1732.2***
		Min	***234.77***	***0.90***	***575.27***

Determination of Radon Concentration

Table 2 presents the results from twenty-four khat samples collected from various locations in the Al-Azraa and Tahayjer areas within the Utmah Reserve in Yemen. The highest radon concentration is detected in sample Q12 (Makaresh), measuring 704.3 Bq/m³, while the lowest concentration is found in sample Q16, which measured 234.77 Bq/m³. The average radon concentration across all samples is 453.215 ± 117.621 Bq/m³. Several samples exceede the internationally recommended radon limit of 200-600 Bq/m³) (ICRP, 2009, 2007), as reported by the International Commission on Radiological Protection (see **Figure 3**). The elevated radon levels in some khat samples are likely attributed to the use of fertilizers and pesticides. The agricultural soil and the geological characteristics of the region may contribute to the presence of radioactive nuclei in the khat plant. However, some samples reveal radon concentrations below the recommended limit. The variation in radon levels among these samples could be attributed to differences in fertilizer and pesticide usage, soil composition, or the radon content in groundwater used for irrigation. Intensive khat cultivation in Utmah Reserve, particularly with heavy use of chemical fertilizers, may increase the presence of radioactive nuclei in the plants. Additionally, factors such as frequent irrigation and the region's seismic activity could also lead to higher concentrations of radioactive elements in the khat plant (El-araby et al., 2024).

Table 2 illustrates the radium activity in khat samples collected from the two study areas, showing levels ranging from 0.9 to 2.71 Bq/kg, with an average of 1.743 ± 0.455 Bq/kg. All recorded radium values are well within the safe limit of 370 Bq/kg, as established by the Organization for Economic Co-operation and Development (EL-Araby & Shabaan, 2023). The variations in radium levels are likely linked to differences in the radioactive content of the soil.

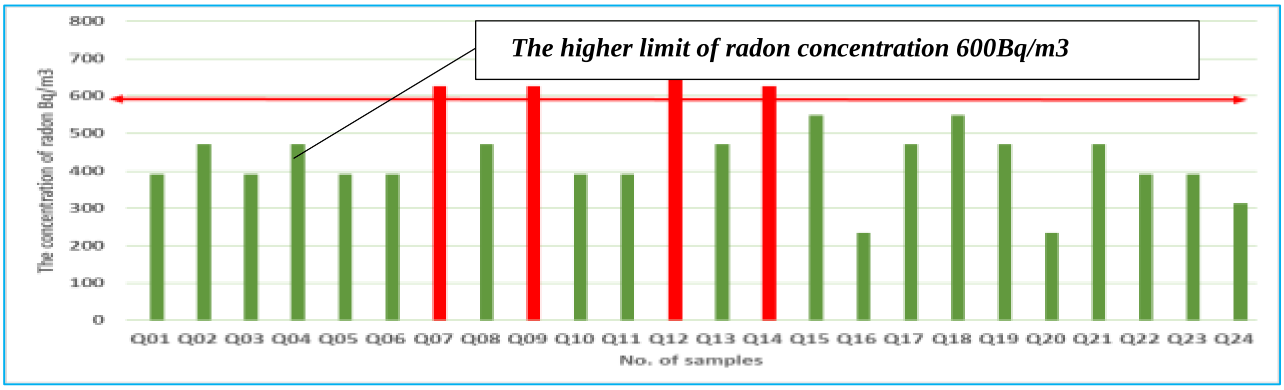

Figure 3. *Measurement of radon gas concentration in Khat plants in Al-Azraa and Tahayjer areas in the Utmah Reserve in Yemen*

Additionally, **Table 2** presents the annual radiation dose values for the Al-Azraa and Tahayjer areas, which ranged from 575 µSv/y to 1732 µSv/y, with an average of 1114.051 ± 290.755 µSv/y (see **Figure 4**). Notably, over 50% of the samples have annual effective dose values that exceeded the international limit of 1 mSv/y (ICRP, 2007), raising concerns about the highest recorded dose value.

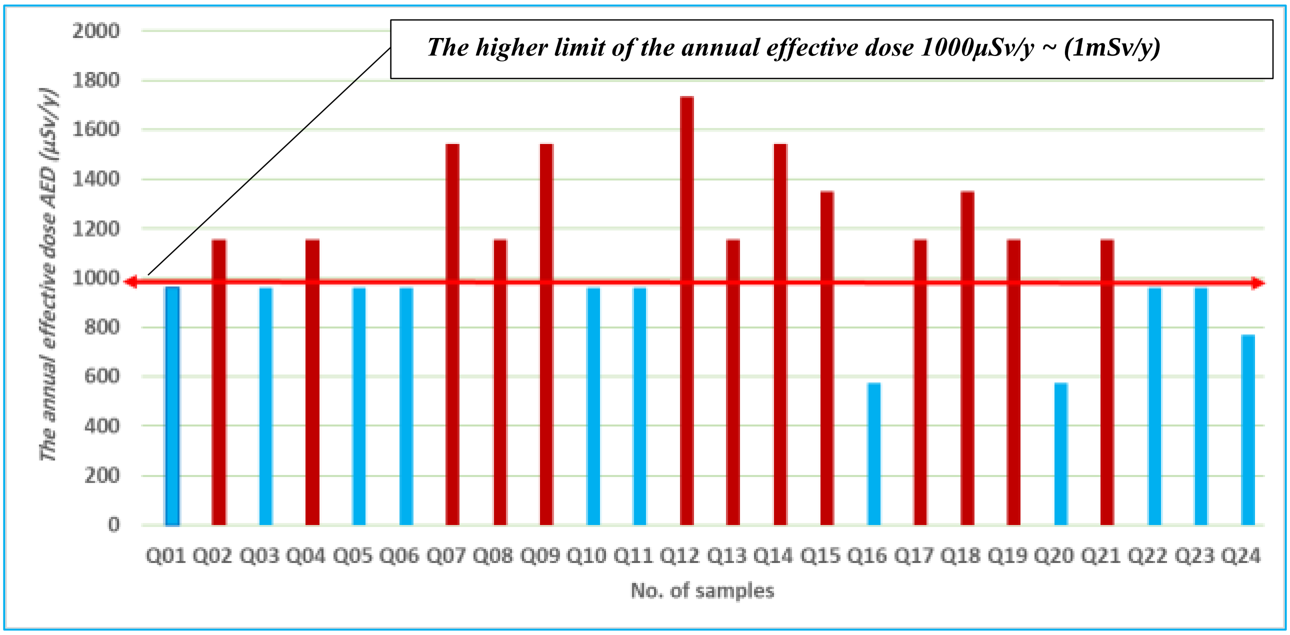

Figure 4. *The annual effective dose* rates for khat samples

4. Conclusion

Based on the results obtained from the experimental study for evaluating the concentration of radon in Khat (Catha edulis) leaves collected from Utmah Reserve - Yemen , we come up with the following conclusions:

- The study revealed a significant concentration of radon in khat leaves from Utmah Reserve, Yemen.
- The average radon level in these khat leaves raises health concerns.
- The estimated annual radiation dose from khat consumption was substantial and exceeds accepted safety limits.
- Regular and prolonged consumption of khat may increase risks associated with radiation exposure.
- The study underscores the need for further research into the long-term health impacts of khat consumption.

- There is an urgent need to enhance community awareness regarding the risks of radon exposure.

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