



Radiological hazard assessment due to natural radioactivity content in cement material used in Iraqi Kurdistan region

Hiwa Mohammad Qadr¹

Received: 3 September 2024 / Accepted: 23 October 2024 / Published online: 4 December 2024
© The Author(s) under exclusive licence to Institute of Geophysics, Polish Academy of Sciences 2024

Abstract

An investigation was conducted to determine radon concentrations, radon exhalation rate, and potential radiological hazard parameters associated with cement collected from five factories in Sulaymaniyah city, Kurdistan region, Iraq. Using solid-state nuclear track detectors such as CR39, the samples were analyzed by etching processes. The average radon concentration, radium concentration, and radon exhalation rate were 138.16 Bq m^{-3} , 0.254 Bq kg^{-1} , and $0.317 \text{ Bq m}^{-2} \text{ h}^{-1}$, respectively. In sample 14, radon concentrations were within the suggested range of $200\text{--}600 \text{ Bq m}^{-3}$, and the radon exhalation rate was well below the global average of $57.600 \text{ Bq m}^{-2} \text{ h}^{-1}$. In addition, parameters related to potential radiological hazards were calculated for cement samples, the average annual effective dose indoor and outdoor were 3.49 and 1.31 mSv y^{-1} , so this study's value was within the global average limitations ($1\text{--}5 \text{ mSv y}^{-1}$). Also, the excess lifetime cancer risk indoor and outdoor were 12.5×10^{-3} and 4.69×10^{-3} greater than the world value of 0.29×10^{-3} .

Keywords Cement samples · Radon concentration · Radon exhalation rate · Annual effective dose · Inhalation

Introduction

Naturally occurring radioactive materials (NORMs) emitted from soil, rock, and building materials contain uranium or thorium chain radioactive materials (Shrestha et al. 2024). In the atmosphere, a radioactive background is created from the radon isotopes that are released. To avoid radiation hazards, materials used for construction must be tested for radiation and radon gas levels (Appleton 2012). This radiation emitted from building material refers to ionizing radiation which can ionise atoms of their target material through Columbic interactions with the electrons of the material, and the amount of this Columbic force depends on the kinetic energy of the particles such as alpha radiation, beta radiation (high-energy electron beams), and many other charged particles (Hiwa 2020; Mansy et al. 2024; Qadr 2021). In the environment, radiation from bombs, bullets in war zones, and nuclear

explosions causes pollution which has detrimental effects on humans (Hryhorczuk et al. 2024; Qadr and Salih 2024). These radiations are transmitted to human body via air, food, water, and soil. Thus, different radiation doses alter the DNA and cells of an organism, leading to genetic mutations and changes in embryos (Arena et al. 2014).

Radon and thoron gas is one of the most significant natural radiation sources as a decay product of uranium and thorium in the earth's crust since it is an invisible, no smell, no taste, and no sight (Prusty et al. 2024). Radon enters the human organism mainly through inhalation. It has been proven that radon exposure is one of the risky health problems, and its absorption into respiratory system walls occurs when large amounts of radon are inhaled into lungs (Bulut and Şahin 2024). According to the World Health Organization (WHO), radon is one of the 19 environmental carcinogens (World Health 2009). It was confirmed by the International Agency for Research on Cancer (IARC) that radon and its decay products are carcinogens that represent the second highest risk factor for lung cancer (National Research et al. 1999; Smoking 1986). These warnings reflect the widespread concern over radon's potential health hazards. Radon concentration levels between 200 and 600 Bq m^{-3} are provided by International Commission on Radiological Protection (ICRP) to regulatory authorities (ICRP 1993).

Edited by Prof. Stelios Stoulos (ASSOCIATE EDITOR) / Prof. Aderson Farias do Nascimento (CO-EDITOR-IN-CHIEF).

✉ Hiwa Mohammad Qadr
hiwa.physics@uor.edu.krd

¹ Department of Physics, College of Science, University of Raparin, Sulaymaniyah, Ranya 46012, Iraq

The solid-state nuclear track detector (SSNTD) can be applied to a wide range of scientific and technological applications, such as radon and thoron concentrations in water and soil samples as well as radiation dose assessments (Guo et al. 2020; Sumesh et al. 2024). Due to its high sensitivity, it is the most basic, easiest, and least expensive method of detecting ionizing particles, including alpha particles, protons, neutrons, and fission fragments (Othman et al. 2024). During recent years, many experimental studies have been performed on analysis of radon concentration for different building material samples in various methods, by different research groups (Alrowaili 2023; Rana et al. 2023; Salman & Hassan 2024). This research aims to the assessment of the radon concentration, radon exhalation rate, and some radiological hazard assessment parameters in cement samples in Kurdistan region of Iraq which were collected from Sulaymaniyah city.

Material and method

Sample collection and preparation

Eighteen types of cement samples were collected for the measurement of the specific radioactivity in Sulaymaniyah city, Kurdistan region, Iraq (Fig. 1) and in five factories. First, the samples were dried for 24 h at 70 °C and then were ground into very soft powder by using mortar and pestle and then passed through a standard 2 mm mesh size, the masses of cement samples were weighed by means of an electronic. In this study, cement powder sample was placed in a PVC tube as shown in Fig. 2a, tube made from PVC (polyvinyl chloride) has dimensions of 8 cm high and 6 cm in diameter. The detector is made of plastic material, such as CR39, that is sensitive to alpha particles for long periods of time. It was standard to have a detector thickness of 1.30 g cm^{-3} and a size of $1 \times 1 \text{ cm}^2$ (Khan et al. 2023). In the PVC tube, the detector was quickly mounted on top. Then, the tube covered completely to protect the sample and the detector. A 70-day period was used to store

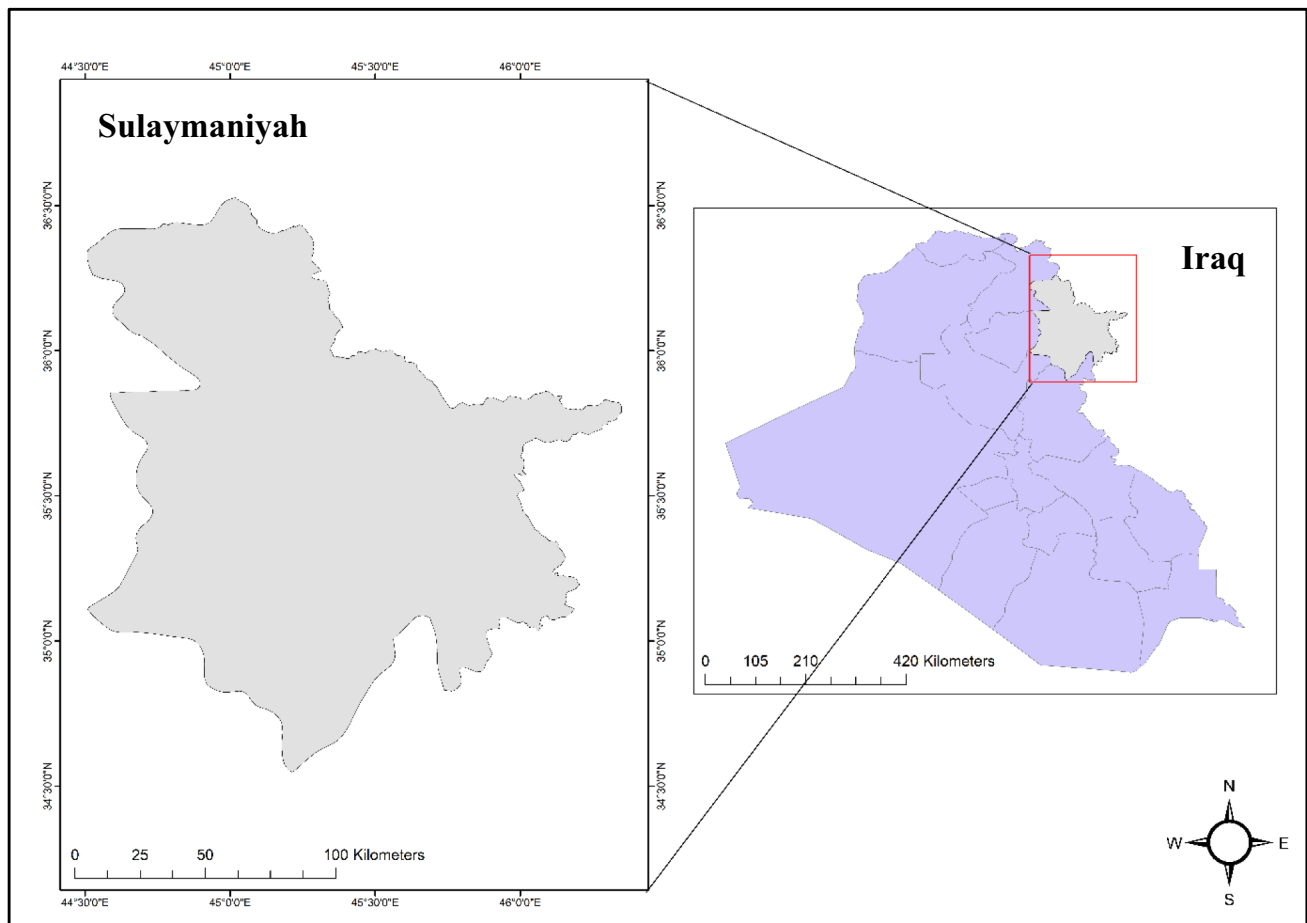


Fig. 1 Map of this study

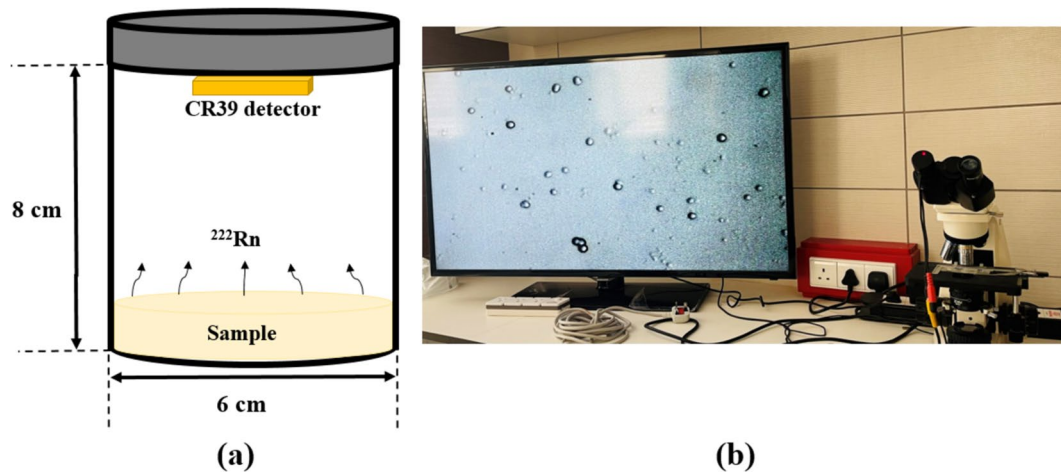


Fig. 2 **a** Preparation of the samples in PVC tube with CR39 detector and **b** photograph of alpha tracks on the detector using microscope

the reagents with samples to measure alpha particles emitted by radon gas, and then, detectors were pulled out for etching process.

Etching process conditions

In order to enhance the effects of alpha particles on the detectors' surface during the electrochemical scavenging process, the detectors were immersed in water bath for 8 h following the irradiation process. This process involved skimming sodium hydroxide (NaOH) with a weight of 6.25 N at a temperature of 70 °C. To stop the further chemical etching process and remove the NaOH, the detector was rinsed with tap water for 20 min after finishing the etching process. After the detector has been washed, it will be dried in the air room for 30 min, before being examined under an optical microscope. The effects of alpha particles which trace on the detectors were counted using a micro-optical microscope after drying. The traces can be seen as a round or elliptical pattern in the microscope image called a “pit,” which varies in brightness based on the pit depth and shape. Figure 2b shows a photograph of alpha tracks on the CR39 detector.

Radon concentration

The track density is calculated in average numbers of tracks per area of field view. In order to calculate and estimate the activity level of radon concentration in different samples C_{Rn} in $Bq\ m^{-3}$ is given by (Vasidov and Vasidova 2020):

$$C_{Rn} = \frac{\rho}{K \times T}, \quad (1)$$

where ρ is the density of track in the cement sample in tracks cm^{-2} , and T is the exposure period in hours

(1680 h). K is the calibration factor of PVC tube in tracks $cm^{-2}\ day^{-1}$ per $Bq\ m^{-3}$, the value of the K factor was equal $0.0593\ tracks\ cm^{-2}\ day^{-1}$ per $Bq\ m^{-3}$ which can be mathematically calculated from this relation (Naji and Hasoon 2021):

$$K = \frac{1}{4}r \left(2 \cos \theta_c - \frac{r}{R_{air}} \right), \quad (2)$$

where r is the radius of the irradiation PVC cup which is equal to 3 cm, θ_c is the critical angle of the CR39 detector which is equal to 35°, and R_{air} is the range of the alpha particle in air which is approximately equal to 4.15 cm (Qadr 2022; Salih et al. 2024).

Radium concentration

Radium concentration C_{Ra} , $Bq\ kg^{-1}$ in the powdered cosmetic samples can be determined by following equation (Muneam and Abojassim 2023):

$$\left(C_{Ra} = \frac{\rho h A}{K m_s T_{eff}} \right), \quad (3)$$

where A , m^2 is the surface area of the PVC tube where the area is equal to πr^2 , h is the height of air in the PVC tube above cement sample surface to the CR39 detector, and m_s is the mass of sample. The following relation was used to determine effective exposure time T_{eff} from exposure period (Durrani and Ilic 1997):

$$T_{eff} = T - \frac{1}{\lambda_{Rn}} (1 - e^{-\lambda_{Rn} T}). \quad (4)$$

Radon exhalation rate

The value of radon exhalation rate in terms of PVC surface E_s for samples in $\text{Bq m}^{-2} \text{h}^{-1}$ is expressed by the following equation (Topçu et al. 2013):

$$E_s = \frac{C_{\text{Rn}} \times T \times V \times \lambda_{\text{Rn}}}{A \times T_{\text{eff}}}, \quad (5)$$

where C_{Rn} is radon concentration in Bq m^{-3} , V is the volume of the PVC tube in m^3 , $\lambda_{\text{Rn}} = 0.007567 \text{ h}^{-1}$ is radon decay constant, A is the surface area of the sample in m^2 , and T is the exposure period in h .

Radiological hazard assessment

Annual effective dose

The following relation of annual effective dose for 1 year AE in mSv y^{-1} to the person due to the radon exposure and its progeny was recommended by United Nations Scientific Committee on the Effects of Atomic (UNSCEAR) (UNSCEAR 2008; Yousef et al. 2024):

$$\text{AED} = C_{\text{Rn}} \times F \times T \times D, \quad (6)$$

where C_{Rn} is radon concentration in Bq m^{-3} , F is the equilibrium factor (0.4) for indoor and (0.6) for outdoor recommended by UNSCEAR (Unsear 2000a, b), T is the number of hours during the year (7008 h) for indoor and (1752 h), and D is the dose conversion factor which is equal to $9 \text{ nSv (Bq h m}^{-3})^{-1}$ adopted by International Commission on Radiological Protection (ICRP-94) (ICRP 1993). In the previous information, UNSCER recommended the following relations of effective dose for indoor and outdoor:

$$\text{AED}_{\text{indoor}} = 0.02523 \times C_{\text{Rn}}, \quad (7)$$

$$\text{AED}_{\text{outdoor}} = 0.00946 \times C_{\text{Rn}}. \quad (8)$$

Excess lifetime cancer risk

The excess lifetime cancer risk ELCR depends on the annual effective dose for both indoor and outdoor, given by (Idriss et al. 2018):

$$\text{ELCR}_{\text{indoor}} = \text{AED}_{\text{indoor}} \times \text{DL} \times \text{RF}, \quad (9)$$

$$\text{ELCR}_{\text{outdoor}} = \text{AED}_{\text{outdoor}} \times \text{DL} \times \text{RF}, \quad (10)$$

where DL and RF represent the average duration of life which is 70 years and the fatal cancer risk per Sievert 0.05 Sv^{-1} recommended by ICRP (ICRP 2009), respectively.

Results and discussion

In the present study, 18 cement samples were analyzed with PVC tube technique. Concentration of radon, exhalation rate of radon, as well as the parameters such as annual effective dose and excess lifetime cancer risk in samples were measured for different cement factories.

Humans are potentially at risk from radon when they inhale it or consume it, since radioactive materials are toxic, ingesting them through the mouth is easy (Little et al. 2024). Table 1 can be shown that radon concentration has been evaluated in the cement samples. The radon concentration ranged from 98.90 to 202.84 Bq m^{-3} with an average value of 138.16 Bq m^{-3} . According to the results, sample number 14 has the highest radon concentration, while sample number 17 has the lowest radon concentration. Additionally, the results indicated that radon concentrations vary depending on the type of cement samples. According to the International Committee on Radiological Protection (ICRP), all studied samples showed radon concentrations below the ICRP recommended range ($200\text{--}600 \text{ Bq m}^{-3}$) (ICRP 1993), with the exception of sample 14.

Figure 3 shows the ratio of the radon concentration in the cement samples that the highest ratio of the radon concentration was 23% in Delta CF sample, and the lowest ratio was 18% in Gasin CF sample. In addition, both Mass and Bazian CF have the same ratio of the radon concentrations with 20%.

Radium concentration measured by CR39 track detector is also tabulated in Table 1. The concentration of radium in cement samples varied from 0.373 to 0.182 Bq kg^{-1} , with the average value of 0.254 Bq kg^{-1} , respectively. Figure 4 shows good correlation ($R^2 = 0.99$) between the results obtained for radon and radium concentrations. The overall value of radium are found lower than world average value of 50 Bq kg^{-1} (Ahmad et al. 2019).

The results of radon exhalation rate in terms of surface measurements in cement samples are also given in Table 1. The data obtained show that the radon exhalation rate in sample 14 has the highest radon exhalation rate ($0.465 \text{ Bq m}^{-2} \text{h}^{-1}$), and sample 17 has the lowest level ($0.227 \text{ Bq m}^{-2} \text{h}^{-1}$), with the overall average of $0.317 \text{ Bq m}^{-2} \text{h}^{-1}$. Consequently, the value of radon exhalation rate in all sample is below than the permitted limit ($57.600 \text{ Bq m}^{-2} \text{h}^{-1}$) (Unsear 2000a, b).

After the CR39 detectors with PVC tube technique were used to measure the radon concentration in the samples, it is possible to estimate the risk of lung cancer caused by

Table 1 Radon concentration, radium concentration, and radon exhalation rate in the cement sample in different factories

Sample number	Cement factories (CF)	C_{Rn} Bq m ⁻³	C_{Ra} Bq kg ⁻¹	E_s mBq m ⁻² + h ⁻¹
1	Tasluja CF	111.55	0.205	0.256
2		120.37	0.222	0.276
3		120.91	0.223	0.277
4		131.22	0.242	0.301
5		159.95	0.294	0.367
6	Bazian CF	106.96	0.197	0.245
7		123.30	0.227	0.283
8		146.69	0.270	0.336
9		149.68	0.276	0.343
10		181.91	0.335	0.417
11	Mass CF	106.42	0.196	0.244
12		126.07	0.232	0.289
13		141.32	0.260	0.324
14		202.84	0.373	0.465
15	Delta CF	143.82	0.265	0.330
16		166.14	0.306	0.381
17	Gasin CF	98.90	0.182	0.227
18		148.78	0.274	0.341
Average		138.16	0.254	0.317
Standard division		26.85	0.049	0.062
Maximum		202.84	0.373	0.465
Minimum		98.90	0.182	0.227

radon and its decay products using the effective annual dose of radon. It was found that the indoor and outdoor annual effective dose of radon (AED) differed depending on the type of samples.

The results show in Table 2 that the average values of AED for indoor and outdoor in the samples of the study were found to be 3.49 mSv y⁻¹ and 1.31 mSv y⁻¹, respectively. A

sample number 14 has the highest annual effective dose due to indoor and outdoor factors, whereas a sample number 17 has the lowest effective dose due to indoor and outdoor factors. As recommended by National Council for Radiation Protection and Measurements (NCRP) and UNSCEAR, this study value was within the global average limitations (1–5 mSv y⁻¹) (ICRP 1993; Perle 2018). Moreover, Table 2

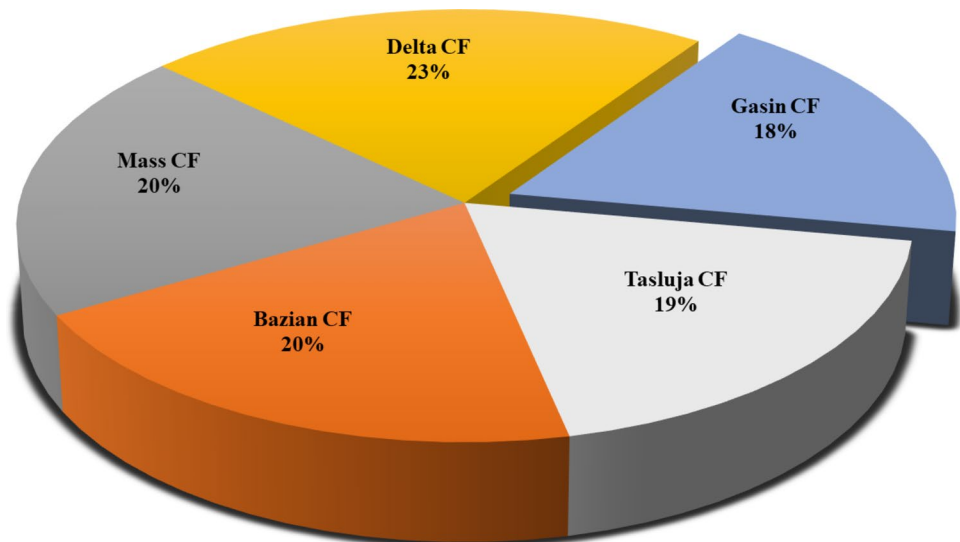
Fig. 3 The ratio levels of radon concentration (Bq m⁻³) in the cement CF samples

Fig. 4 Correlation between radium concentration with radon concentration

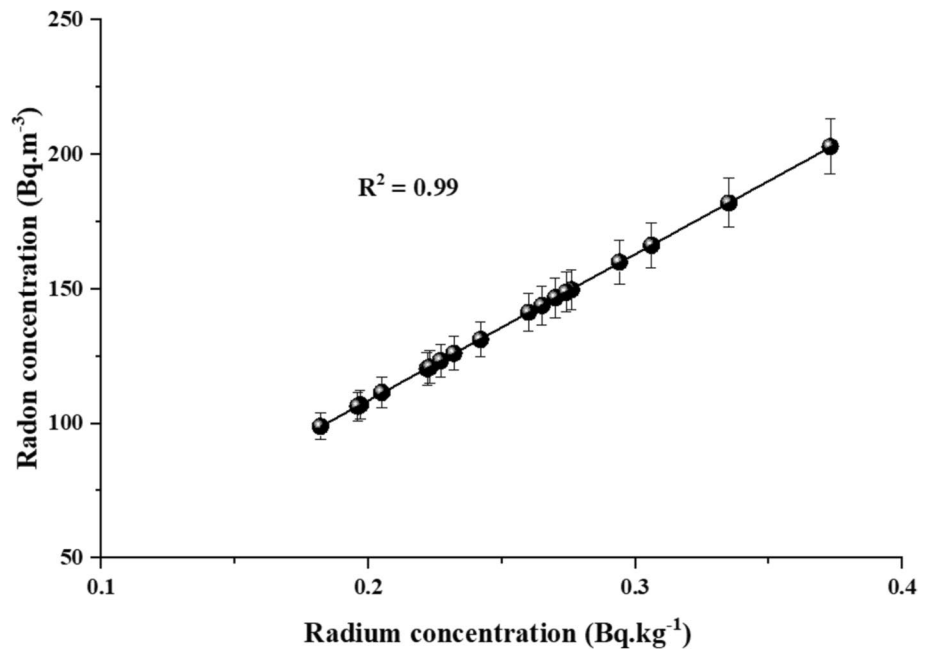


Table 2 Annual effective dose and excess lifetime cancer risk for indoor and outdoor

Sample number	Cement factories (CF)	AED _{indoor} mSv y ⁻¹	AED _{outdoor} mSv y ⁻¹	ELCR _{indoor} × 10 ⁻³	ELCR _{outdoor} × 10 ⁻³
1	Tasluja CF	2.81	1.06	9.85	3.69
2		3.04	1.14	10.63	3.99
3		3.05	1.14	10.68	4.00
4		3.31	1.24	11.59	4.35
5		4.04	1.51	14.12	5.30
6	Bazian CF	2.70	1.01	9.45	3.54
7		3.11	1.17	10.89	4.08
8		3.70	1.39	12.95	4.86
9		3.78	1.42	13.22	4.96
10		4.59	1.72	16.06	6.02
11	Mass CF	2.68	1.01	9.40	3.52
12		3.18	1.19	11.13	4.17
13		3.57	1.34	12.48	4.68
14	Delta CF	5.12	1.92	17.91	6.72
15		3.63	1.36	12.70	4.76
16		4.19	1.57	14.67	5.50
17	Gasin CF	2.50	0.94	17.91	6.72
18		3.75	1.41	9.40	3.52
Average		3.49	1.31	12.50	4.69
Standard division		0.68	0.25	2.66	1.00
Maximum		5.12	1.92	17.91	6.72
Minimum		2.50	0.94	9.40	3.52

shows the values of excess lifetime cancer risk for indoor and outdoor that the average varied from 9.4×10^{-3} to 17.91×10^{-3} for indoor and 3.52×10^{-3} to 6.72×10^{-3} for outdoor, while the average values were 12.5×10^{-3} for indoor and 4.69×10^{-3} for outdoor. These values are greater

than the world value of 0.29×10^{-3} proposed by UNSCEAR. The WHO estimates that indoor exposure to radon increases lung cancer risk by 16% for every 100 Bq m⁻³ (World Health 2009); therefore, lung cancer risk increases linearly with radon exposure.

Table 3 Comparison of the radon concentration and radon exhalation rate in cement samples from this study with other previous studies

Country	C_{Rn} Bq m ⁻³	E_s Bq m ⁻² h ⁻¹	References
Turkey	79.4 ± 0.0212	0.386 ± 0.117	Ahmad et al. (2014)
Pakistan		0.231 ± 0.03	Faheem (2008)
Egypt	62.01	14.06	Shoeib et al. (2024)
Yemen	71.6 ± 1.4	0.357 ± 0.007	Saleh et al. (2021)
Pakistan	1447 ± 198	12.28 ± 1.68	Ahmad et al. (2019)
Iraq	56.72		Ahmed et al. (2022)
Iraq	138.16	0.317	Present study
World average	200–600	57.600	Unsear (2000a, b)

Table 3 shows comparing the values in other studies in the literature with the values in the current study in different countries for radon concentration and radon exhalation rate in cement samples. There is a clear discrepancy between reported values for radon concentration and radon exhalation rate.

Conclusions

This study used a CR39 detector in PVC technique to directly measure radon concentration, radium concentration, and radon exhalation rates in various cement factories. Several radiological indices were calculated to estimate the associated radiological risks from cement samples, including radon annual effective doses and excess lifetime cancer risks. In this work, Delta CF samples had significantly higher radon concentrations than all other CF samples. There is a risk of cancer in the future due to the high recorded values in some values. Radon concentrations in all samples except sample 14 were below the ICRP recommendation. It was found that some samples were higher than the global average limits for both annual effective doses indoors and outdoors as well as excess lifetime cancer risks. According to the study, some samples of cement have been found to pose health risks due to radon exhalation.

Acknowledgements The author wishes to thank the college of science/ University of Raparin for supporting in experimental assistance, Ministry of Higher Education (MHE) Kurdistan Regional Government.

Funding The author received no financial support for the research, authorship, and/or publication of this article.

Data availability Presented in the paper (All relevant data during the current study are within the manuscript).

Code availability Not applicable.

Declarations

Conflict of interest The author states that there is no conflict of interest in the printing of this manuscript.

References

- Ahmad N, Jaafar MS, Khan SA, Nasir T, Ahmad S, Rahim M (2014) Measurement of radon exhalation rate, radium activity and annual effective dose from bricks and cement samples collected from Dera Ismail Khan. *Am J Appl Sci* 11(2):240
- Ahmad N, Nasir T, Rizwan S, Ullah H, Bakhsh M (2019) Evaluation of 222Rn and 226Ra concentrations in cement and limestone of Sheikh Buddin Hill, Pezu, Pakistan using different techniques. *Int J Environ Anal Chem* 99(7):683–691
- Ahmed IK, Khalaf HNB, Mostafa MYA (2022) Estimating radon excess lung cancer at the babylon cement plant in Iraq. *J Nucl Eng Radiat Sci* 8(3):032003
- Alrowaili ZA (2023) Nature of radon, radium, exhalation and uranium concentration from construction materials used in Al Jouf city, Saudi Arabia. *J Radiat Res Appl Sci* 16(3):100579
- Appleton JD (2012) Radon in air and water, Essentials of medical geology: revised edition. Springer, New York, pp 239–277
- Arena C, De Micco V, Macaeva E, Quintens R (2014) Space radiation effects on plant and mammalian cells. *Acta Astronaut* 104(1):419–431
- Bulut HA, Şahin R (2024) Radon, concrete, buildings and human health—a review study. *Buildings* 14(2):510
- Durrani SA, Ilic R (1997) Radon measurements by etched track detectors-applications in radiation protection, earth sciences. World Scientific, New Jersey
- Faheem M (2008) Radon exhalation and its dependence on moisture content from samples of soil and building materials. *Radiat Meas* 43(8):1458–1462
- Guo S-L, Chen B-L, Durrani SA (2020) Solid-state nuclear track detectors, handbook of radioactivity analysis. Elsevier, New Jersey, pp 307–407
- Hiwa MQ (2020) Stopping power of alpha particles in helium gas. *Bull Mosc State Tech Univ NE Bauman Ser Nat Sci* (2 (89)): 117–125
- Hryhorczuk D, Levy BS, Prodanchuk M, Kravchuk O, Bubalo N, Hryhorczuk A, Erickson TB (2024) The environmental health impacts of Russia's war on Ukraine. *J Occupat Med Toxicol* 19(1):1
- ICRP (1993) Protection against radon-222 at home and at work. A report of a task group of the international commission on radiological protection. *Ann ICRP* 23(2):1–45
- ICRP (2009) International commission on radiological protection statement on radon. Ref, 00/902/09
- Idriss H, Salih I, Alaamer AS, Al-Rajhi MA, Osman A, Adreani TE, Abdelgalil MY, Ali NI (2018) Health risk profile for terrestrial radionuclides in soil around artisanal gold mining area at Alsopag, Sudan. *Acta Geophys* 66:673–681
- Khan A, Al Qahtani S, Wijdan ALM, Al-Naggar TI, Alhamami M, Abdalla AM (2023) Efficient and fast detection of alpha particles using CR-39 detector. *Radiat Phys Chem* 213:111237
- Little MP, Bazyka D, Gonzalez ABd, Brenner AV, Chumak VV, Cullings HM, Daniels RD, French B, Grant E, Hamada N (2024) A historical survey of key epidemiological studies of ionizing radiation exposure. *Radiat Res* 202(2):432–487
- Mansy MS, Ghobashy MM, Aly MI (2024) Enhancing gamma and neutron radiation shielding efficiency of LDPE/PVC polymers using cobalt, aluminum, and magnesium oxide fillers. *Radiat Phys Chem* 222:111862

- Muneam RR, Abojassim AA (2023) Assessment of health risk of exposure to alpha-emitters in cheese samples collected from iraqi markets. *Atom Indonesia* 1(1):39–44
- Naji TF, Hassoon SO (2021) Measuring of Radon Gas Concentrations in serum samples of Lung cancer patients in Babylon governorate, Iraq. *J Phys Conf Ser* 1999(1):012054
- National Research C, National Research C, Commission on Life S, Board on Radiation Effects R, Committee on Health Risks of Exposure to R (1999) Health effects of exposure to radon: BEIR VI. National Academy Press, Washington
- Othman SM, El-Mesady IA, El-badawy AS, Ghanim EH (2024) The impact of the broad range of gamma doses on follow-up fission fragment track parameters in CR-39 radiation detector. *Appl Radiat Isot* 208:111253
- Perle S (2018) NCRP report no. 179, guidance for emergency response dosimetry, LWW
- Prusty P, Sahu A, Jha SK (2024) Assessment of radon (^{222}Rn) and thoron (^{220}Rn) in environmental resources of a high-background-radiation area. *India MAPAN* 39(1):139–148
- Qadr HM (2021) Pressure effects on stopping power of alpha particles in argon gas. *Phys Part Nucl Lett* 18:185–189
- Qadr HM (2022) Experimental study of the pressure effects on stopping power for alpha particles in air. *Gazi Univ J Sci* 35(1):272–279
- Qadr HM, Salih NF (2024) Reviewing the different types of heavy materials in the human teeth. *Bull Int Assoc Paleodontology* 18(1):52–62
- Rana D, Jha VN, Patnaik RL, Singh MK, Jha SK, Kulkarni MS (2023) Radon build-up in a prototype dwelling using uranium mill tailings as construction material. *J Radioanal Nucl Chem* 332(8):3113–3120
- Saleh EE, Al-Sobahi AMA, El-Fiki SAE (2021) Assessment of radon exhalation rate, radon concentration and annual effective dose of some building materials samples used in Yemen. *Acta Geophys* 69(4):1325–1333
- Salih N, Aswood M, Saleh D, Qadr H (2024) Determine the concentration of radon and uranium in different types of tea. *Int J Environ Anal Chem*. <https://doi.org/10.1080/03067319.2024.2376902>
- Salman JE, Hassan NM (2024) Evolution of radionuclide concentration and the radiological hazards in building material: a review. *J Taibah Univ Sci* 18(1):2370588
- Shoeib MY, Ahmed DA, Abd-Elraheem AF (2024) A study of ^{226}Ra concentration and radon exhalation rates in different geopolymer cement samples using CR-39 solid state nuclear track detector. *Radiat Phys Chem* 216:111381
- Shrestha AK, Shrestha GK, Shah BR, Koirala RP (2024) Evaluation of natural radioactivity and radiological hazards associated with Nepalese cement. *J Radioanal Nucl Chem* 333(6):2821–2829
- Smoking T (1986) IARC monogr eval carcinog risk chern. *Hum* 38:35–394
- Sumesh CG, Jha SK, Patra AC, Aswal DK (2024) Evolution of analytical methods for radon measurement in India. *Mapan* 39(1):181–192
- Topçu N, Biçak D, Çam S, Ereeş FS (2013) Radon exhalation rate from building materials using CR-39 nuclear track detector. *Indoor Built Environ* 22(2):384–387
- UNSCEAR (2008) Report of the United Nations Scientific Committee on the effects of atomic radiation. general assembly 56. Session (10–18 July 2008). Official Records: 63. session, suppl. no. 46 (A/63/46), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)
- Unsclear S (2000) Effects of ionizing radiation. United Nations, New York, pp. 453–487
- Unsclear UN (2000) Sources and effects of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation
- Vasidov A, Vasidova S (2020) CR-39 track detectors for measurements of radon volume activity and exhalation rates of the new houses of the Tashkent city. *J Radioanal Nucl Chem* 325(2):391–396
- World Health O (2009) WHO handbook on indoor radon: a public health perspective World Health Organization
- Yousef HA, Korany KA, Salama MA, Mitwalli M (2024) Assessment of radon in traditional building materials using polymeric nuclear track detector. *Radiat Eff Defects Solids* 1–10

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Reproduced with permission of copyright owner. Further reproduction prohibited without permission.