Radon in Commercial Cigarettes and Associated Health Risks: An Evaluation of Lung Cancer Risk and Radiation Dose in the Kurdistan Region of Iraq

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***Abstract*—This study evaluates radon concentrations and associated health risks in 40 commercially available cigarette brands from the Kurdistan Region. Two measurement techniques are employed: RAD-7 (active method) and CR-39 (passive method). Using the CR-39 detector, radon concentrations ranged from 101.99 ± 10.1 Bq·m^{-3} in the S6 (Cigaronne) sample to 339.98 ± 18.44 Bq·m^{-3} in the S32 (Gauloises Gold) sample, with an average concentration of 190.84 ± 13.67 Bq·m^{-3}. The RAD-7 measurements show values between 96.01 ± 9.8 Bq·m^{-3} and 282.72 ± 16.81 Bq·m^{-3} in the same samples, averaging 180.30 ± 13.00 Bq·m^{-3}. A strong correlation (R^2 = 0.9271) is observed between the two methods, confirming the reliability of the results. The effective radium content in all cigarette samples remains below internationally recommended safety limits, with Gauloises Gold showing the highest levels. Estimated annual effective doses ranged from 2.57 ± 1.61 mSv·y^{-1} to 8.58 mSv·y^{-1}, remaining within acceptable limits established by the International Commission on Radiological Protection. Lung cancer risk due to radon exposure varies among brands, with an average of 208 ± 14.27 cases per million individuals. A significant correlation is found between ^{222}Rn concentration and estimated annual lung cancer incidence. These findings highlight radon exposure from cigarette smoke as a contributing risk factor for lung cancer, underscoring the need for public health awareness regarding the radiological hazards of smoking.**

***Index Terms*—Annual effective dose, CR-39, Lung cancer, RAD-7, Radon, Tobacco cigarette.**

I. Introduction

Regular measurements of radon gas concentrations are vital to maintaining a healthy environment, as it forms ^{222}Rn, a colorless and odorless radioactive noble gas naturally occurring in uranium-rich areas (Hashim et al., 2015, Othman et al., 2023b, Abdulkhaleq Asaad and Hassan Ahmed, 2025). Given its radioactivity, radon is a carcinogen (IARC, 1988). Radon emanates from rocks and into the atmosphere when radium decays. Radon builds up in mines and homes. Radon primarily enters homes through soil, with a smaller amount coming from construction materials and water (Atsdr, 1997). Controlling radon, a noble gas, is challenging but possible with ventilation. Lead, with a half-life of 22.3 years, is nearly stable and collectable, making it a significant health risk (Gehr et al., 2000). The stable lead isotope ^{206}Pb ends the decay (Hashim et al., 2015).

Approximately 3,000 individuals succumb to lung cancer daily (WHO, 2008). The principal cause of lung cancer is tobacco use, responsible for 90% of occurrences, but radon is the leading cause among non-smokers (Biesalski et al., 1998). Radon exposure increases lung cancer risk (IARC, 1988). Radon and its breakdown products enter the lungs through the air, decay, and produce radiation. During disintegration, radon and its descendants emit alpha radiation. If DNA damage occurs, radiation can harm the lungs and lead to cancer (Othman et al., 2024). The International Agency for Research on Cancer has classified inorganic lead as potentially carcinogenic to humans due to its chemical effects on radon progeny (IARC, 2006). “Human neurotoxicity also exists with lead (Atsdr, 1997)”.

Chemically analyzing tobacco smoke is difficult. Brand-specific curing, filtration, and additives vary in commercial cigarettes (Stedman, 1968). Tobacco smoke contains thousands of chemicals. Many are potent carcinogens. Tobacco and other smokes contain polycyclic aromatic hydrocarbons. Other elements of tobacco smoke include nicotine and nitrosamines exclusive to tobacco. In 1950, Doll and Hill released a paper unequivocally associating lung tumors with smoking tobacco (Doll and Hill, 1950). The 1986 International Agency for Research on Cancer monograph concluded that smoking cigarettes causes cancer (IARC, 1986). By 2000, smoking had peaked or decreased in all industrialized nations but increased in emerging nations (Biesalski et al., 1998). Today, cigarette smoking causes most lung cancer. Up to 5 million people die from tobacco use yearly, according to the WHO (WHO, 2009). Radon affects smokers more than non-smokers (EPA, 2003, Alkufi et al., 2024, Othman, 2024, Qadr and Muhamad Amin, 2025).

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Despite their dangers, many in this high-pressure setting turn to cigarettes for a quick escape. They suffer, but others sometimes suffer too. Numerous studies have indicated that the practice is dangerous. Tobacco smoke is poisonous, genotoxic, and carcinogenic and causes poor pregnancy outcomes (Hashim et al., 2015, Akinyose et al., 2018). Burning produces the majority of the 4000 chemicals in tobacco smoke. Over 40 substances are carcinogenic, including radionuclides like polonium ^{210}Po and lead ^{210}Pb (Kuper et al., 2002). Multiple authors have tested cigarette smoke's radioactivity, demonstrating that ionizing radiation may expose lung tissues to considerable levels. Smoking causes 10 times more lung cancer than non-smoking (Najam et al., 2024, Thabayneh et al., 2017, Qasim et al., 2018, AL-Mosuwi et al., 2022, Ali and Ibrahim, 2020, Felix and Ntarisa, 2024).

Radon and its decay products are the primary source of radioactivity, with short-lived progeny accounting for half of natural doses. Exposure to radon can cause lung cancer and bronchial damage (Hashim et al., 2015, Hussein et al., 2018). The main cause of cancer fatalities worldwide is lung cancer (Abdel Ghany, 2007, Namq et al., 2024). Lung cancer, primarily caused by tobacco use, causes 160,000 annual deaths in the US, with a rising proportion among women and heightened risk among radon-exposed smokers (ACS, 2004). Radon, an ionizing radiation, is a confirmed carcinogen and is the sole recognized consequence of human exposure to the atmosphere (Hashim et al., 2015, Hameed et al., 2021). Radon progeny may cause 10% of lung cancer deaths and 30% of non-smokers' deaths in the US. Alpha-particle emissions from radon damage DNA and free radicals in respiratory epithelium (Lubin, 1994, Aziz et al., 2015, Smail et al., 2023).

Radon is the second leading cause of lung cancer in non-smokers, killing 21,000 annually. About 3,000 of these deaths are non-smokers (EPA, 2009). Exposure to an average indoor radon level of 4.81×10^{-7} Bq.m^{-3} increases the risk of lung cancer, whereas smoking exposes individuals to 20 in 1,000 (WHO, 2009). Secondhand smoke, a significant contributor to lung cancer, increases exposure to the substance by 20% to 30% in individuals cohabiting with a smoker (Sethi et al., 2012). Research supports that inhaling others' tobacco smoke is a causative factor for lung cancer (Hashim et al., 2015). The EPA warns that combined exposure to radon gas and tobacco smoke, particularly direct and secondhand smoke, can significantly increase lung cancer risk, especially among smokers (EPA, 2009). Smoking in indoor spaces increases radon decomposition-related particle-absorbing compounds, which transfer from ambient air to smoke and accumulate near smokers' bronchial bifurcation (Hashim et al., 2015). Smokers and non-smokers may both be more likely to develop lung cancer due to the combined effects of alpha radiation exposure from radon and thoron (Ghany, 2006).

This study aims to clarify the radiological health concerns linked to tobacco smoking in the Kurdistan region. Radon levels in smoked cigarettes were evaluated utilizing radon monitoring systems that combine active RAD-7 detectors with passive CR-39 solid-state nuclear track detectors (SSNTDs). The evaluation of annual effective dose equivalents (AEDEs) and pulmonary doses from these tobacco cigarettes enables the assessment of the prospective population at risk of lung cancer attributable to radon emissions from markets in Kurdistan.

II. Materials and Methods

A. Sample Collection

Fifty-two samples from 40 distinct tobacco brands sourced from local marketplaces in the Kurdistan region, originating from 15 different nations, are compiled and shown in Table I.

B. Sample Preparation

Samples of unadulterated tobacco, each weighing approximately 20 g, were extracted from their respective papers and filters. To eradicate moisture, the samples were exposed to sunlight for 2 days during the summer (Hashim et al., 2015, AL-Mosuwi et al., 2022). The desiccated samples were pulverized into a powder and subsequently passed through a fine standard sieve, resulting in a purified powder that was free of coarse particles and contaminants (AL-Mosuwi et al., 2022). Next, approximately 20 g of powder from each tobacco sample were positioned 25 cm apart in the lower section of a long cylindrical container (Rahman, 2006, Matiullah, 2013, Thabayneh, 2018, Ali and Ibrahim, 2020, Azeez et al., 2021, AL-Mosuwi et al., 2022, Abdulkhaleq Asaad and Hassan Ahmed, 2025), as shown in Fig. 1. The container had a 3.5-centimeter radius and a 3-centimeter height (AL-Mosuwi et al., 2022, Azeez et al., 2021, Awla and Mansour, 2023). The powder samples were affixed to the sealed end of the rubber stopper surface. This setup allowed for the precise and accurate discrimination and measurement of radon and thoron with a high level of resolution, as described in references (Durrani and Ilic, 1997, Mansour, 2000).

Fig. 1 illustrates the intentional construction of the detection system and its secure encasement to prevent leakage. This illustration has been stored at ambient temperatures for approximately 60 days. Throughout this period, the ^{226}Ra, ^{222}Rn, and their progeny within the chamber have maintained secular equilibrium.

C. Setup of Detection System

The radon monitoring system used an active method with a long-tube technique connected to the RAD-7 radon detector. It also had nuclear track detectors of type CR-39 (CR-39NTDs) as a passive way to determine the radon activity level in cigarette samples. An indoor hemisphere detecting chamber on the RAD-7 can find alpha particles with the help of a solid-state semiconductor detector (Durridge, 2015, Azeez et al., 2021, Azeez et al., 2024).

D. Activity Concentration of ^{222}Rn through Active and Passive Methods

The study measured radon in tobacco samples using CR-39 SSNTDs and the long-pipe technique, supported by

TABLE I
Represents the Sample Number, Sample Code, Tobacco Brand Sample, and their Origin Country

Sample No.	Sample code	Tobacco brand sample	Origin
1	S1	Napoli black	Italy
2	S2	Napoli white	Italy
3	S3	MT green	Armenia
4	S4	MT blue	Armenia
5	S5	MT white	Armenia
6	S6	Cigaronne	Armenia
7	S7	ALEX	Armenia
8	S8	Masis	Armenia
9	S9	AKHTAMAR Classic	Armenia
10	S10	3000-night blue	USA
11	S11	OSCAR SILVER	USA
12	S12	OSCAR WHITE	USA
13	S13	Marlboro gold	USA
14	S14	Marlboro black	USA
15	S15	PARLIAMENT	USA
16	S16	Master	USA
17	S17	MORE	USA
18	S18	Viceroy	USA
19	S19	UNITED	USA
20	S20	Winston	USA
21	S21	ESSE silver	Korea
22	S22	ESSE black	Korea
23	S23	ESSE blue	Korea
24	S24	Pine	Korea
25	S25	MM black	Bulgaria
26	S26	MM white	Bulgaria
27	S27	Milano silver	UAE
28	S28	Milano blue	UAE
29	S29	Miami	UAE
30	S30	Mond grape	UAE
31	S31	AFFAIR	UAE
32	S32	Gauloises GOLD	France
33	S33	Gauloises compact RED	France
34	S34	Gitanes	France
35	S35	MAC	Switzerland
36	S36	Kent white	UK
37	S37	Kent black	UK
38	S38	Rothmans	UK
39	S39	DUNHILL	UK
40	S40	Graven	UK
41	S41	Royals	India
42	S42	Pleasure (Lights) KS-20-H	South Korea
43	S43	Senator Red	Russia
44	S44	Senator green	Russia
45	S45	Forman	Russia
46	S46	21 vek	Russia
47	S47	captain black	Denmark
48	S48	Sumer	Iraq
49	S49	DUBRA	Iran
50	S50	Mexico	Mexico
51	S51	Chapman	Germany
52	S52	Aspen	Germany

a RAD-7 electronic radon detector. The CR-39 polymer detects alpha particles, while the RAD-7 provides rapid, independent measurement of ^{220}Rn and ^{222}Rn concentrations. The experimental setup included a valve-connected vinyl tube with desiccant, a RAD-7 unit, and a cylindrical plastic tube (Durridge, 2015). Cylinder lengths of 25 cm and

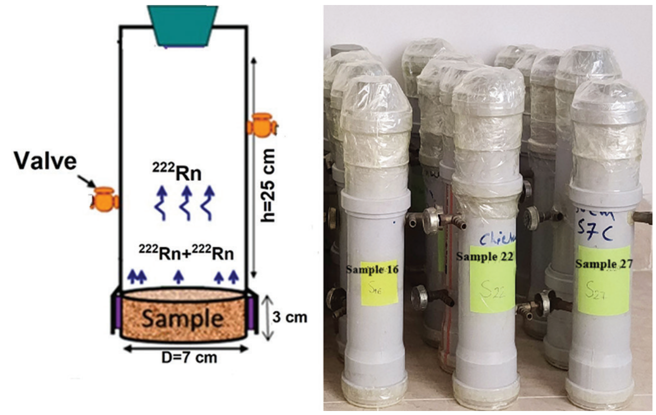

Fig. 1. The Radon detection technique of tobacco samples.

2.817 cm in the surface propagation range inhibit thorium gas accumulation. Our calculations show that thoron activity will drop to 20% after 16.9 cm, or 6 times air diffusion. In this experiment, the sample surface and detector were 25 cm apart. Thoron concentration near the detector is below 5% of the sample surface (Othman et al., 2022b). Fig. 2a illustrates the leak-proof design of the detection system. The tobacco samples were stored for 2 months, allowing ^{226}Ra, ^{222}Rn, and their decay products to reach secular equilibrium inside the spherical cylinder. During this period, alpha particles emitted from radon and its progeny were recorded using CR-39 SSNTDs.

After 8 weeks, a RAD-7 radon monitor connected to a long tube chamber measured radon levels (Fig. 2b), with the device distinguishing ^{218}Po (6 MeV) and ^{214}Po (7.69 MeV) pulses and reporting results in Bq·m^{-3}, with a minimum detectable activity of 3.7 Bq·m^{-3} (Durridge, 2015). The experiment was carried out in low-humidity conditions (<8%) with the RAD-7 purged for 10 min before testing. A blank container was used for quality control, and the background radon concentration of 5 ± 0.5 Bq·m^{-3} was subtracted from the sample measurements (Awla and Mansour, 2023). The CR-39 detector was etched in 6.25 N NaOH for 6 h, rinsed with distilled water, and dried with a hair dryer. Track density was then evaluated using optical microscopy at 400× magnification (Othman et al., 2022a).

D. Calculations

Activity concentration for ^{222}Rn gas

The radon activity concentration C(Rn) in the measurement tube of the CR-39 detector was calculated by (Mansour, 2000, Khan and Azam, 2012, Alshahri et al., 2019).

$$C(\mathrm{Rn})\left(\mathrm{Bq.m^{-3}}\right) = \frac{\rho}{\mathrm{K_{Rn}} \times T_e} \quad (1)$$

Where ρ is the track density in tracks per cm^2, T is the exposure duration time, and K_{Rn} is the calibration factor. The K_{Rn} factor was measured as 0.27 ± 0.02 tracks per Bq·m^3·cm^2·d^{-1} (Abo-Elmagd and Daif, 2010, Azeez et al., 2021).

The equation below was used to calculate the effective exposed time (Te) based on the exposure time (T) (Durrani and Ilic, 1997, Othman et al., 2022a).

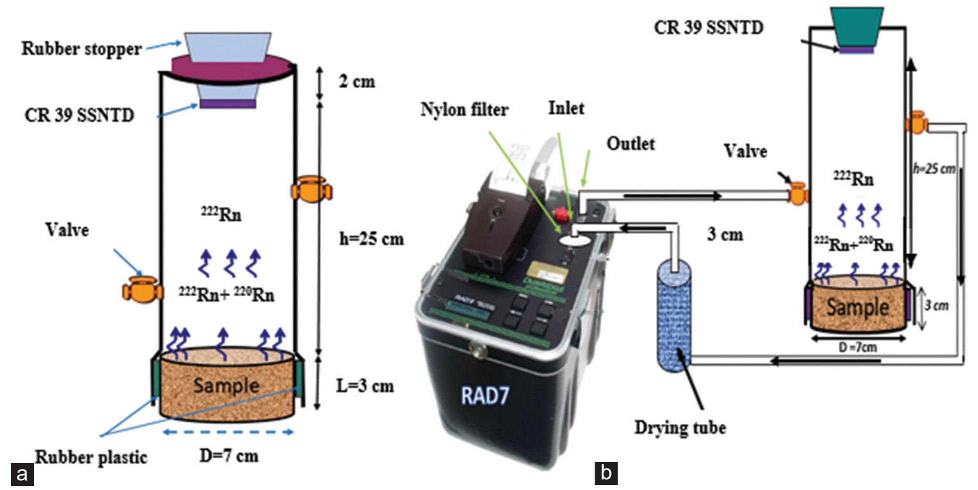

Fig. 2. A diagrammatic representation of the active and passive approaches used to quantify the radon levels in samples (Othman et al., 2022b).

$$T_e = T - \frac{1}{\lambda}\left(1 - e^{-\lambda T}\right) \quad (2)$$

In this work, the effective exposure time Te is 54.47 days, whereas the exposure length T is 60 days, and λ is the decay constant of radon (0.181 d^{-1}).

The statistical error

The statistical error was computed using the formula below (Othman et al., 2023a):

$$\sigma = \frac{\sqrt{\sum N_i}}{n \times A} \quad (3)$$

Where N_i is the total number of tracks, A = The area of field of view, and n = The total number of field of views.

The minimum detectable activity (MDA) is the smallest amount of activity that a particular detection system can identify, serving as a measure of the system's sensitivity. The minimum detectable activity (MDA) of the CR-39 detector was established using previously mentioned approaches (Currie, 1968, Strom and MacLellan, 2001, Saleh et al., 2021). For 60 days, the detector's MDA was 29 $Bq.m^{-3}$ (Othman et al., 2022b).

Effective radium content

The effective radium content ($(AC_{Ra})_{eff}$) indicates the quantity of radium that is in radioactive equilibrium with the measured radon that the sample emits. The equation has been employed to assess the effective radium content of the sample (Somogyi, 1990, Ahmad et al., 2014).

$$\left(AC_{Ra}\right)_{eff}(Bq.kg^{-1}) = \frac{\rho \times h \times A}{K_{Rn} \times T_e \times M} \quad (4)$$

The variable ρ signifies track density measured in tracks per cm^2, Te represents effective exposure time, M denotes the mass of the samples, and K_{Rn} indicates the calibration factor. In addition, h refers to the distance from the base of the sample surface to the detector (0.25 m), while A defines the area of the sample.

Annual effective dose

The annual effective dose from consumption of tobacco is calculated using the formula (Abdalsattar et al., 2017, Asaad and Ahmed, 2025).

$$AED(mSv.y^{-1}) = C(Rn) \times H \times F \times T \times DCF \quad (5)$$

Where (AED) is the annual effective dose (mSv.y^1), (H) is the occupancy factor, indicating the proportion of total time spent in the exposure environment; in this context, H=0.8 is utilized in accordance with normal indoor radon protocols, presuming that smoking predominantly occurs indoors, (T) defines the time in hours per year, with (T=8760 h/y), and (DCF) represents the dose conversion factor, equal to [9×10^{-6}] (m Sv)/(Bq·h·m^{-3}) (AL-Mosuwi et al., 2022, Hashim et al., 2015).

AEDE for the lungs

The calculation of the annual effective dose equivalent (AEDE) involves applying both radiation and tissue weighting factors to the absorbed dose in a specific region of interest. For alpha particles, which are highly ionizing and biologically damaging, a radiation weighting factor of WR=20 is recommended (Othman et al., 2022a; Azhdarpoor et al., 2021). The tissue weighting factor WT represents the relative sensitivity of an organ or region to radiation-induced stochastic effects, and values of 0.06 for the tracheobronchial (T–B) region, 0.06 for the pulmonary plus pulmonary-lymphatic (P+PL) region, and 0.12 for the lungs have been adopted (Khan, 2021). Accordingly, the AEDE for each region is calculated as follows:

$$AEDE(mSv.y^{-1}) = AED \times WR \times WT \quad (6)$$

This means that the effective dose contribution from each respiratory region directly reflects not only the absorbed energy but also the biological effectiveness of alpha particles and the radiosensitivity of the specific tissue considered, thereby allowing for a more realistic estimation of health risk.

$$D_{(Lung)} = 0.04 \times C(Rn) \quad (7)$$

Lung cancer cases per year per million people (LCPPP)

The LCPPP were estimated using the risk coefficient for radon-induced lung cancer per unit effective dose, quantified as 18×10^{-6} mSv^{-1}. The computation was performed utilizing the subsequent equation (Hashim et al., 2015, AL-Mosuwi et al., 2022, Abdalsattar et al., 2017).

$$LCPPP = AEDE_{Lung}\times(18\times10^{-6}\ mSv^{-1}.y) \quad (8)$$

III. Results and discussion

A. Measured Radon Concentration and Effective Radium Content

This study assessed radon concentrations using two techniques: RAD-7 as an active approach and CR-39 as a passive method across 52 distinct imported brands of tobacco cigarettes in the Kurdistan region market. Table II encapsulates the findings of this study regarding radon gas concentrations and effective radium content in tobacco cigarette brands within the Kurdistan region market.

The radon concentration in the samples varied from 101.99±10.1 $Bq.m^{-3}$ in the S6 (Cigaronne) sample to 339.98 ± 18.44 $Bq.m^{-3}$ in the S32 (Gauloises Gold) sample, with an average of 190.84±13.67 $Bq.m^{-3}$, as determined by the passive method. The RAD-7 measured radon levels that ranged from 96.01 ± 9.8 $Bq.m^{-3}$ in the S6 (Cigaronne) sample to 282.72 ± 16.81 $Bq.m^{-3}$ in the S40 (Graven) sample, with 180.30 ± 13.00 $Bq.m^{-3}$ being the average. Fig. 3 depicts the outcomes of the radon concentration assessed by the two methodologies. The results show that only one of the 52 cigarette samples had a radon level higher than the ICRP's allowed range (200–300 $Bq.m^{-3}$), as measured by the CR-39 detector (ICRP, 2009). The remaining samples' activity levels were measured by both techniques and fell below the recommended range. In this context, the radon activity concentration in a distinct color is dissimilar, likely due to the presence of the same primary components of tobacco but varying in minor additives specific to each brand's formulation. This could potentially explain the varying results in radon activity concentration.

A robust correlation (R^2 = 0.9271) exists between the passive and active methods for determining the activity of ^{222}Rn gas in cigarette samples, as illustrated in Fig. 4.

Table II indicates that the highest value of was observed in sample 32, corresponding to 16.36 ± 4.04 $Bq.kg^{-1}$ from Gauloises Gold (originating from France), whereas the lowest value of was recorded in sample 6, amounting to 4.91±2.22 $Bq.kg^{-1}$ from Cigaronne (originating from Armenia), with an average value of 9.20 ± 3.00 $Bq.kg^{-1}$. The current results indicate that the measurements in tobacco cigarettes were below the prescribed threshold of 370 $Bq.kg^{-1}$ (UNSCEAR, 2000).

B. Comparison of Radon Concentration in Tobacco Samples with Previous Studies

This section compares radon concentrations in tobacco across multiple studies, attributing variations to factors such as soil radioactivity and fertilizer application. The document contains a table that encapsulates findings from various nations and citations. Table III presents the concentration of radon in tobacco smoking samples from prior investigations. The

TABLE II
Displays Radon Concentration By CR-39 (C (Rn)($Bq.m^{-3}$)), Radon Concentration By RAD-7(C (Rn)($Bq.m^{-3}$), and Effective Radium Content $(AC_{Ra})_{eff}$ ($Bq.kg^{-1}$)

Sample code	Radon concentration by CR-39 C (Rn) ($Bq.m^{-3}$)	Radon concentration by RAD-7 C (Rn) ($Bq.m^{-3}$)	$(AC_{Ra})_{eff}$ ($Bq.kg^{-1}$) by CR-39
S1	144.83±12.03	130.16±11.41	6.97±2.64
S2	143.4±11.97	128.73±11.35	6.9±2.63
S3	150.27±12.26	135.6±11.64	7.23±2.69
S4	160.47±12.67	145.8±12.07	7.72±2.78
S5	194.47±13.95	179.8±13.41	9.36±3.06
S6	101.99±10.10	96.01±9.80	4.91±2.22
S7	154.28±12.42	148.3±12.18	7.42±2.72
S8	142.79±11.95	126.81±11.26	6.87±2.62
S9	183.59±13.55	167.61±12.95	8.84±2.97
S10	288.98±17.00	255±15.97	13.91±3.73
S11	241.38±15.54	221.4±14.88	11.62±3.41
S12	280.48±16.75	258.5±16.08	13.50±3.67
S13	208.75±14.45	190.97±13.82	10.05±3.17
S14	204.05±14.28	196.27±14.01	9.82±3.13
S15	156.39±12.51	133.09±11.54	7.53±2.74
S16	223.7±14.96	210.4±14.51	10.77±3.28
S17	160.2±12.66	137.05±11.71	7.71±2.78
S18	140.07±11.84	116.92±10.81	6.74±2.60
S19	167.88±12.96	144.73±12.03	8.08±2.84
S20	152.65±12.36	129.5±11.38	7.35±2.71
S21	149.59±12.23	132.44±11.51	7.20±2.68
S22	176.79±13.30	157.64±12.56	8.51±2.92
S23	251.58±15.86	232.48±15.25	12.11±3.48
S24	278.78±16.70	260.94±16.15	13.42±3.66
S25	169.99±13.04	187.48±13.69	8.18±2.86
S26	161.83±12.72	179.32±13.39	7.79±2.79
S27	166.59±12.91	184.08±13.57	8.02±2.83
S28	164.55±12.83	182.04±13.49	7.92±2.81
S29	210.79±14.52	238.28±15.44	10.14±3.18
S30	248.18±15.75	240.94±15.52	11.94±3.46
S31	200.59±14.16	179.59±13.40	9.65±3.11
S32	339.98±18.44	281.06±16.76	16.36±4.04
S33	263.14±16.22	254.22±15.94	12.66±3.56
S34	193.79±13.92	184.87±13.60	9.33±3.05
S35	239.68±15.48	213.76±14.62	11.53±3.40
S36	176.79±13.30	157.87±12.56	8.51±2.92
S37	186.31±13.65	170.83±13.07	8.97±2.99
S38	250.22±15.82	227.12±15.07	12.04±3.47
S39	145.17±12.05	131.87±11.48	6.99±2.64
S40	309.38±17.59	282.72±16.81	14.89±3.86
S41	119.67±10.94	131.85±11.48	5.76±2.40
S42	129.19±11.37	138.37±11.76	6.22±2.49
S43	210.79±14.52	202.47±14.23	10.14±3.18
S44	297.82±17.26	275.5±16.60	14.33±3.79
S45	108.11±10.40	99.79±9.99	5.20±2.28
S46	161.76±12.72	169.54±13.02	7.78±2.79
S47	155.23±12.46	162.01±12.73	7.47±2.73
S48	125.11±11.19	136.89±11.70	6.02±2.45
S49	132.59±11.51	141.37±11.89	6.38±2.53
S50	221.66±14.89	208.41±14.44	10.67±3.27
S51	112.19±10.59	128.39±11.33	5.40±2.32
S52	265.18±16.28	248.73±15.77	12.76±3.57
Average±SD	190.84±13.67	180.30±13.00	9.20±3.00

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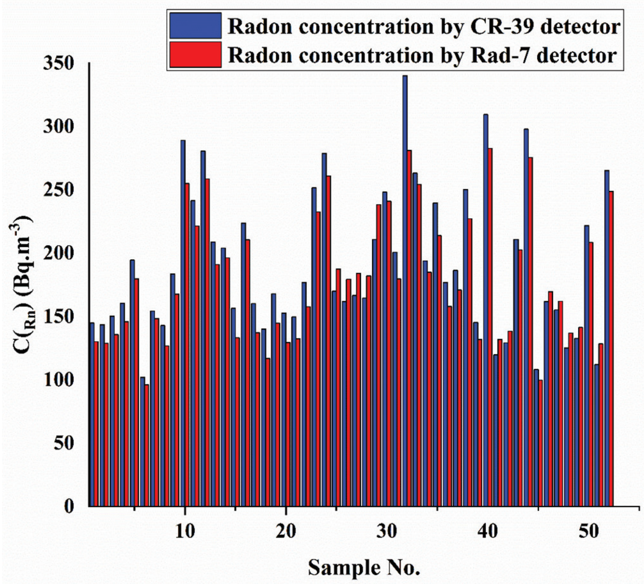

Fig. 3. Radon concentration measured by detectors CR-39 and RAD-7 in the tobacco cigarette smoking in the present study.

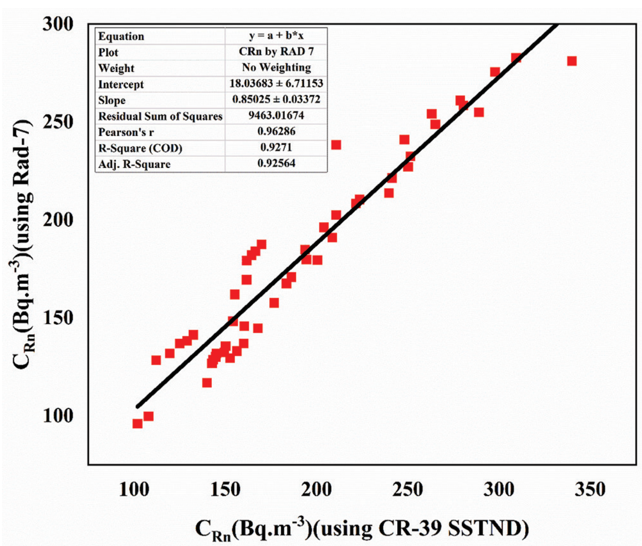

Fig. 4. Correlation of radon concentration determined using the passive technique (CR-39) with the active method (RAD-7).

results indicate that the mean radon concentration in this study surpasses that reported by Ali and Ibrahim (2020); however, it remains beneath the levels recorded in the literature presented in table III. The soil's increased radioactivity or the use of fertilizers with high uranium levels could be the cause. It will infiltrate through the roots (Ridha and Hasan, 2016). The disparity arose from the distinct geological composition of Iraq's soil compared to that of Kurdistan and other tobacco-producing nations, in addition to the chemical fertilizers employed in cultivation (Hashim, 2019).

C. Radiation Dose Assessment: Annual Effective Dose and Lung Cancer Risk

The radiation dose implications of radon in tobacco brands were quantified by assessing the annual effective dose to lung tissues and estimating the probability of developing lung cancer. Table IV and Fig. 5 present the annual effective dosage (AED) for forty distinct brands of tobacco cigarettes available in the Kurdistan market. The AED varies from 2.57 ± 1.61 $mSv.y^{-1}$ in S6 to 8.58 $mSv.y^{-1}$ in S32, with a mean of 4.81 ± 2.17 $mSv.y^{-1}$. All samples exhibited a yearly effective dose within the permissible limits of 3-10 $mSv.y^{-1}$, as stipulated by ICRP regulations (ICRP, 1993). The AEDE for lungs $AEDE_{Lung}$, tracheobronchial (T-B) $AEDE_{(T-B)}$, pulmonary and pulmonary lymph region (P+PL), $AEDE_{(P+PL)}$, and, as well as the dose rate to the lung $D_{(Lung)}$, have been computed based on the consumption of cigarette brands available in the markets of Kurdistan. The risk factors are shown in Table IV's columns 2 through 4. The values range from 6.17 ± 2.48 to 20.59 ± 4.54 mSv. y^1, with an average of 11.56 ± 3.36 $mSv.y^1$. The values

TABLE III
PRESENTS A COMPARISON OF THE RADON CONCENTRATION IN SMOKING CIGARETTES FROM PREVIOUS STUDIES WITH THE RESULTS OF THE CURRENT STUDY

Country	Radon concentration C (Rn)($Bq.m^{-3}$)	Sample type	References
Iraq/Kirkuk	44.54	CRAVEN	(Ali and Ibrahim, 2020)
	100.22	AFFAIR	
	50.92	KENT (blue)	
Iraq/Mosul	91.63±4.02	KENT	(Abd Al-Masih, 1999)
	69.43±11.33	ASPEN	
	95.32±19.2	Parliament	
Iraq/Kerbala	403.087	Pine	(Abdalsattar et al., 2017)
	208.767	Miami	
	388.139	Graven	
	156.450	Marlboro	
	287.242	Mac	
	294.716	Royale	
Iraq	27.78	PINE	(Qasim et al., 2018)
	20.18	ESSE	
	118.14	AFFIR	
Iraq	270.917	Miami	(Hashim et al., 2015)
	777.778	Graven	
	366.901	Aspen	
	227.856	Pine	
Iraq/Basrah	267.4	Oscar	(AL-Mosuwi et al., 2022)
	203.7	Royale	
	292.2	Aspen	
	238.8	Graven	
	338.7	Pine	
	333.0	Marlboro	
Palestine and Jordan	120.4	Winston/blue	(Thabayneh et al., 2017)
	164.7	Alfakher (mint)	
Myanmar	71.20–232.20	-------------	(Lwin et al., 2011)
Saudi Arabia/Jeddah	97–204	---------------	(Farid, 2012)
Iraq/Baghdad	38	Marlboro	(Fatima et al., 2023)
	48	DUNHILL	
Iraq	89.8	Miami	(Hameed et al., 2021)
	90.6	Kent Silver	
	135.5	Mikado	
	78.7	Oscar Silver	
	112.6	Gold Seal	
	84.7	Pine Silme	
	144.6	Graven	

TABLE IV
The Annual Effective Dose, Annual Effective Dose Equivalent of the Lung (msv) and Dose Rate to Lung, and LCC in Different Brands of Tobacco Smoking Cigarettes by CR-39 Detector

Sample code	AED $mSv.y^{-1}$	$AEDE_{Lung}$ $mSv.y^{-1}$	$AEDE_{(T-B)}$ $mSv.y^{-1}$	$AEDE_{(P+PL)}$ $mSv.y^{-1}$	$D_{(Lung)}$ $nGy.h^{-1}$	LCPPP×10^{-6}
S1	3.65±1.91	8.76±2.96	4.38±2.09	4.38±2.09	5.79±2.41	157.68±12.56
S2	3.62±1.90	8.69±2.95	4.34±2.08	4.34±2.08	5.74±2.40	156.42±12.51
S3	3.79±1.95	9.1±3.02	4.55±2.13	4.55±2.13	6.01±2.45	163.8±12.80
S4	4.05±2.01	9.72±3.12	4.86±2.20	4.86±2.20	6.42±2.53	174.96±13.23
S5	4.91±2.22	11.78±3.43	5.89±2.43	5.89±2.43	7.78±2.79	212.04±14.56
S6	2.57±1.60	6.17±2.48	3.08±1.75	3.08±1.75	4.08±2.02	111.06±10.54
S7	3.89±1.97	9.34±3.06	4.67±2.16	4.67±2.16	6.17±2.48	168.12±12.97
S8	3.6±1.90	8.64±2.94	4.32±2.08	4.32±2.08	5.71±2.39	155.52±12.47
S9	4.63±2.15	11.11±3.33	5.56±2.36	5.56±2.36	7.34±2.71	199.98±14.14
S10	7.29±2.70	17.5±4.18	8.75±2.96	8.75±2.96	11.56±3.40	315±17.75
S11	6.09±2.47	14.62±3.82	7.31±2.70	7.31±2.70	9.66±3.11	263.16±16.22
S12	7.08±2.66	16.99±4.12	8.5±2.92	8.5±2.92	11.22±3.35	305.82±17.49
S13	5.27±2.30	12.65±3.56	6.32±2.51	6.32±2.51	8.35±2.89	227.7±15.09
S14	5.15±2.27	12.36±3.52	6.18±2.49	6.18±2.49	8.16±2.86	222.48±14.92
S15	3.95±1.99	9.48±3.08	4.74±2.18	4.74±2.18	6.26±2.50	170.64±13.06
S16	5.64±2.37	13.54±3.68	6.77±2.60	6.77±2.60	8.95±2.99	243.72±15.61
S17	4.04±2.01	9.7±3.11	4.85±2.20	4.85±2.20	6.41±2.53	174.6±13.21
S18	3.53±1.88	8.47±2.91	4.24±2.06	4.24±2.06	5.6±2.37	152.46±12.35
S19	4.24±2.06	10.18±3.19	5.09±2.26	5.09±2.26	6.72±2.59	183.24±13.54
S20	3.85±1.96	9.24±3.04	4.62±2.15	4.62±2.15	6.11±2.47	166.32±12.90
S21	3.77±1.94	9.05±3.01	4.52±2.13	4.52±2.13	5.98±2.45	162.9±12.76
S22	4.46±2.11	10.7±3.27	5.35±2.31	5.35±2.31	7.07±2.66	192.6±13.88
S23	6.35±2.52	15.24±3.90	7.62±2.76	7.62±2.76	10.06±3.17	274.32±16.56
S24	7.03±2.65	16.87±4.11	8.44±2.91	8.44±2.91	11.15±3.34	303.66±17.43
S25	4.29±2.07	10.3±3.21	5.15±2.27	5.15±2.27	6.8±2.61	185.4±13.62
S26	4.08±2.02	9.79±3.13	4.9±2.21	4.9±2.21	6.47±2.54	176.22±13.27
S27	4.2±2.05	10.08±3.17	5.04±2.24	5.04±2.24	6.66±2.58	181.44±13.47
S28	4.15±2.04	9.96±3.16	4.98±2.23	4.98±2.23	6.58±2.57	179.28±13.39
S29	5.32±2.31	12.77±3.57	6.38±2.53	6.38±2.53	8.43±2.90	229.86±15.16
S30	6.26±2.50	15.02±3.88	7.51±2.74	7.51±2.74	9.93±3.15	270.36±16.44
S31	5.06±2.25	12.14±3.48	6.07±2.46	6.07±2.46	8.02±2.83	218.52±14.78
S32	8.58±2.93	20.59±4.54	10.3±3.21	10.3±3.21	13.6±3.69	370.62±19.25
S33	6.64±2.58	15.94±3.99	7.97±2.82	7.97±2.82	10.53±3.24	286.92±16.94
S34	4.89±2.21	11.74±3.43	5.87±2.42	5.87±2.42	7.75±2.78	211.32±14.54
S35	6.05±2.46	14.52±3.81	7.26±2.69	7.26±2.69	9.59±3.10	261.36±16.17
S36	4.46±2.11	10.7±3.27	5.35±2.31	5.35±2.31	7.07±2.66	192.6±13.88
S37	4.7±2.17	11.28±3.36	5.64±2.37	5.64±2.37	7.45±2.73	203.04±14.25
S38	6.31±2.51	15.14±3.89	7.57±2.75	7.57±2.75	10.01±3.16	272.52±16.51
S39	3.66±1.91	8.78±2.96	4.39±2.10	4.39±2.10	5.81±2.41	158.04±12.57
S40	7.81±2.79	18.74±4.33	9.37±3.06	9.37±3.06	12.38±3.52	337.32±18.37
S41	3.02±1.74	7.25±2.69	3.62±1.90	3.62±1.90	4.79±2.19	130.5±11.42
S42	3.26±1.81	7.82±2.80	3.91±1.98	3.91±1.98	5.17±2.27	140.76±11.86
S43	5.32±2.31	12.77±3.57	6.38±2.53	6.38±2.53	8.43±2.90	229.86±15.16
S44	7.51±2.74	18.02±4.24	9.01±3.00	9.01±3.00	11.91±3.45	324.36±18.01
S45	2.73±1.65	6.55±2.56	3.28±1.81	3.28±1.81	4.32±2.08	117.9±10.86
S46	4.08±2.02	9.79±3.13	4.9±2.21	4.9±2.21	6.47±2.54	176.22±13.27
S47	3.92±1.98	9.41±3.07	4.7±2.17	4.7±2.17	6.21±2.49	169.38±13.01
S48	3.16±1.78	7.58±2.75	3.79±1.95	3.79±1.95	5.00±2.24	136.44±11.68
S49	3.35±1.83	8.04±2.84	4.02±2.00	4.02±2.00	5.30±2.30	144.72±12.03
S50	5.59±2.36	13.42±3.66	6.71±2.59	6.71±2.59	8.87±2.98	241.56±15.54
S51	2.83±1.68	6.79±2.61	3.4±1.84	3.4±1.84	4.49±2.12	122.22±11.06
S52	6.69±2.59	16.06±4.01	8.03±2.83	8.03±2.83	10.61±3.26	289.08±17.00
Average±Standard deviation	4.81±2.17	11.56±3.36	5.78±2.38	5.78±2.38	7.63±2.73	208.00±14.27

also range from 3.08 ± 1.75 to 10.3 ± 3.21 $mSv.y^{-1}$, with an average of 5.78 ± 2.38 $mSv.y^{-1}$. They also range from 3.08 ± 1.75 $mSv.y^{1}$ to 10.3 ± 3.21 $mSv.y^{-1}$, with 5.78 ± 2.38 $mSv.y^{-1}$ being the average, and from 4.08 ± 2.02 to 13.6 ± 3.69 $nGy.h^{1}$, with 7.63 ± 2.73 $nGy.h^{1}$ being the average pulse dose to the lungs. The average annual effective dose for the tracheobronchial (T-B) and pulmonary lymphatic regions (P + PL) in the current investigation was below

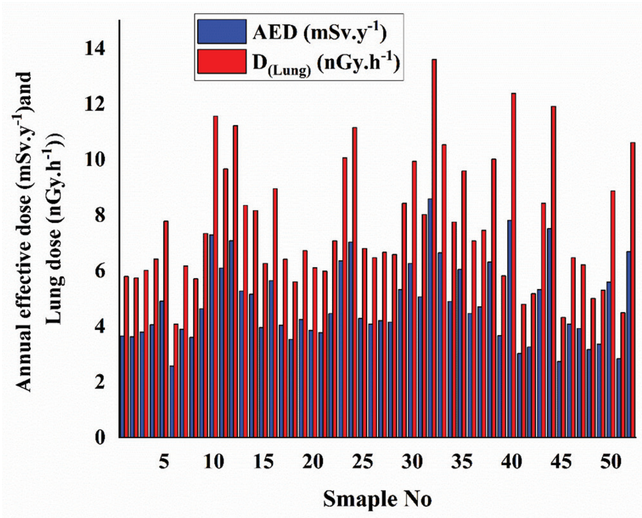

Fig. 5. Annual effective dose and lung doses among samples of tobacco smoking samples.

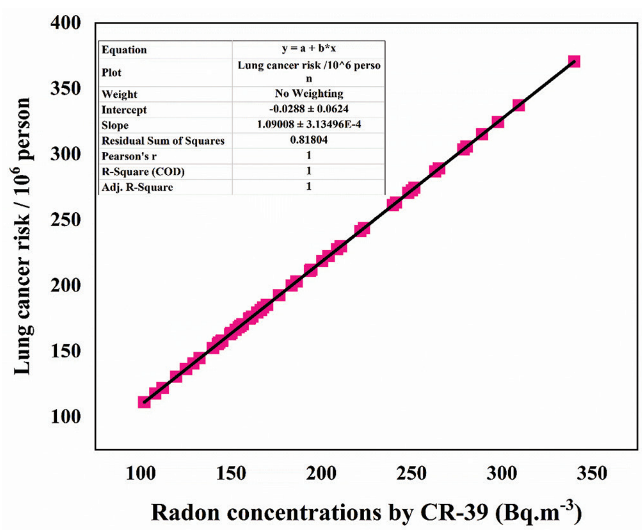

Fig. 6. Correlation between radon levels determined by CR-39 detector and annual lung cancer incidence per million people among tobacco users.

the ICRP's recommended range, with the exception of the lungs $AEDE_{Lung}$.

The risk of lung cancer associated with radon exposure varied among 40 cigarette brands, with values ranging from 111.06 ± 10.54 in S6 to 370.62 ± 19.25 in S32. This statistic yields an average of 208 ± 14.27 per million individuals. The results are consistent with the recommended range of 170-230 per million individuals, with the exception of 28.84% of samples that exceeded the permissible threshold, as demonstrated by (ICRP, 2009). The recommended level is between 170 and 230 per million persons. The Kurdistan region market features 40 distinct brands of tobacco cigarettes, and Fig. 6 demonstrates the excellent association between radon concentrations and the annual incidence of lung cancer per million individuals (Hashim et al., 2015, Abdalsattar et al., 2017). This indicates a linear link between radon concentration and the yearly effective dose rates of cancer, which grow with exposure. Radon is the second leading cause of lung cancer, following tobacco consumption. Moreover, smoking elevates the risk of radon exposure for smokers, as both tobacco use and radon synergistically contribute to the development of lung cancer (Ragab and Aly, 2021). In conclusion, this study's results slightly outperform those of earlier studies on specific tobacco samples in the Iraqi market.

IV. Conclusion

The study examines radon concentrations in cigarette smoking in Kurdistan, highlighting the significant health, economic, and societal impacts of radon, a carcinogen affecting respiratory and digestive systems. The study found that radon levels in 40 tobacco cigarette brands ranged from 101.99±10.1 $Bq.m^{-3}$ in Cigaronne to 339.98±18.44 in Gauloises Gold, with an average of 190.84±13.67 $Bq.m^{-3}$ measured passively. Radon concentrations ranged from 96.01±9.8 $Bq.m^{-3}$ in the S6 (Cigaronne) sample to 282.72±16.81 in the S40 (Graven) sample, with an average of 180.30±13.00 $Bq.m^{-3}$. A strong correlation (R^2 = 0.9271) exists between passive and active methods for assessing ^{222}Rn gas activity in cigarette samples. The study found that tobacco cigarettes in Kurdistan have an effective radium content below the recommended threshold, with samples from Gauloises Gold having the highest value. Most brands' average annual effective dose fell within the ICRP's standards; however, Gauloises Gold and Graven had frighteningly high radon levels. Smokers face a serious health danger from this heightened concentration, which increases lung cancer risk. The risk of lung cancer generated by radon varies across 40 brands, with an average of 208 ± 14.27 cases per million individuals. All brands of tobacco cigarettes show a strong association between radon concentrations and annual lung cancer incidence per million individuals. These findings highlight an important public health problem. To mitigate this risk, immediate regulatory action is required to monitor and restrict radon levels in tobacco products. Furthermore, public awareness campaigns must be undertaken to educate consumers about this additional, preventable harm linked with smoking, emphasizing the overarching message of tobacco law and smoking cessation.

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