



ISSN: 0067-2904

Radiogenic Heat Production from ^{238}U , ^{232}Th , and ^{40}K in Soil and Heat Effect on Radon Exhalation Rate

Shatha F. Alhous^{1*}, Mohammed S. Alsaffar²

¹Physics Department, Faculty of Education for Girls, University of Kufa, Najaf, Iraq

²Technical Instructors Training Institute, Middle Technical University, Baghdad, Iraq

Received: 2/1/2025

Accepted: 17/11/2025

Published: 30/9/2026

Abstract

In this study, thirty soil samples were collected from Al-Qasim district in Babylon city, Iraq, and were prepared, analyzed, and evaluated to calculate the concentration of ^{238}U , ^{232}Th , and ^{40}K concerning their radiogenic heat production using a NaI (TI) gamma spectroscopy detector. The results show that ^{238}U and ^{232}Th are the prevalent radionuclides in radiogenic heat production, with ^{40}K emerging as a trace element. The concentration of ^{238}U , ^{232}Th , and ^{40}K (ppm) in soil samples was with an average of 1.584, 6.996, and 0.754, respectively. The mean radiogenic heat production rate, R_H , and A_g are 0.957 and 0.977 $\mu\text{W}\cdot\text{m}^{-3}$, respectively. The radionuclide contributions to radiogenic heat production at all sampled locations are 42.3 %, 50 %, and 7.7 % for uranium, thorium, and potassium, respectively. All values obtained for this study are lower than the average continental radiogenic heat production of 1 $\mu\text{W}\cdot\text{m}^{-3}$. Therefore, the study area can be classified as a region with low heat production, which indicates that the study area does not hold oil and gas reserves. Additionally, the radon concentration was 87.267 Bq/m³, and its mass exhalation rate was 0.007 mBq/kg/h. In contrast, the results indicated that the radon mass exhalation rate increases as the temperature rises. This study provided insight into the radiogenic heat production rate resulting from the presence of radionuclides in all soil samples.

Keywords: Radiogenic heat production, Mass exhalation rate, Bulk density, gamma-ray detector.

انتاج الحرارة الاشعاعية من ^{40}K , ^{232}Th , ^{238}U في التربة وتأثير الحرارة على معدل زفير الرادون

شذى فرحان الحوس¹, محمد الصفار²

¹قسم الفيزياء، كلية التربية للبنات، جامعة الكوفة، النجف، العراق

²معهد تدريب المدربين التقنيين، الجامعة التقنية الوسطى، بغداد، العراق

الخلاصة

في هذه الدراسة تم جمع ثلاثين عينة تربة من قضاء القاسم في مدينة بابل بالعراق وتم تحضيرها وتحليلها وتقييمها لحساب تركيز ^{238}U , ^{232}Th و ^{40}K فيما يتعلق بإنتاجها الحراري الإشعاعي باستخدام كاشف

*Email : shathaf.alfatlawi@uokufa.edu.iq



مطيافية كاما (TI) Nal. أظهرت النتيجة أن ^{238}U و ^{232}Th هما النويدات المشعة السائدة في إنتاج الحرارة الإشعاعية، أما تأثير ^{40}K فهو طفيف. تركيز ^{238}U ، ^{232}Th و ^{40}K % بوحدة (ppm) في عينات التربة بمتوسط 1.584 و 6.996 و 0.754 على التوالي. ان متوسط معدل إنتاج الحرارة الإشعاعية R_H و A_H هو 0.957 و 0.977 μWm^{-3} على التوالي. تبلغ مساهمات النويدات المشعة في إنتاج الحرارة الإشعاعية في جميع المواقع التي تم أخذ العينات منها بنسبة 42.3% و 50% و 7.7% لليورانيوم والثوريوم والبوتاسيوم على التوالي. جميع القيم التي تم الحصول عليها لهذه الدراسة أقل من متوسط إنتاج الحرارة الإشعاعية القارية البالغ $1 \mu\text{Wm}^{-3}$. لذلك يمكن تصنيف منطقة الدراسة كمنطقة ذات إنتاج حراري منخفض، مما يشير إلى أنها لا تحتوي على احتياطيات نفطية أو غازية. كما بلغ تركيز الرادون 87.267Bq.m^{-3} ومعدل زفيره الكتلي $0.007 \text{ mBq.kg}^{-1}.\text{h}^{-1}$. من ناحية أخرى، لوحظ أن معدل الزفير الكتلي يزداد مع زيادة درجة حرارة الحرارة. قدمت هذه الدراسة تغطية شاملة لمعدل إنتاج الحرارة الإشعاعية نتيجة وجود النويدات المشعة في جميع عينات التربة.

1. Introduction

The phenomenon of radiogenic heat production by soil is a noteworthy yet frequently inadequately understood characteristic. Heat production is used to forecast the distribution of temperature and provide an explanation for variations in temperature in deep drillings. In addition to radiogenic heat output from rocks, advection and refraction effects must also be considered when interpreting variations in heat flow density. Heat production is a crucial aspect to consider when simulating the thermal development of sedimentary rocks, since it affects the maturation of organic matter and the creation of hydrocarbons [1]. The degradation of some radiogenic materials contributes to about 50% of the observed heat flow on the surfaces of Earth. This heat is derived from two main sources that contribute nearly equal amounts: radiogenic heat produced by the decay of isotopes in the mantle and crust, and primordial heat that has existed since the Earth's formation. The transfer of heat inside the Earth's core occurs via geothermal gradients and is responsible for driving most geological events. It promotes mantle convection, rock metamorphism, plate tectonics, mountain formation, and volcanism [2]. Radioactive decay, which takes place beneath the Earth's mantle and crust, generates daughter isotopes and emits geoneutrinos and heat energy, which is also referred to as radiogenic heat. Four specific radioactive isotopes, due to their higher concentrations, are primarily accountable for the bulk of radiogenic heat. These isotopes include potassium-40, thorium-232, and uranium-238. Although certain estimates for the Earth's core are known, it is difficult to quantify the exact amount of radiogenic heat across the whole mantle due to a lack of rock specimens from depths less than 200 km [3]. The structure of mantle convection is debatable; however, it may be stratified with a higher concentration of radioactive heat-producing components in the lower mantle or small pockets richer in radioactive materials across the mantle. The early construction of the Earth's compressed core may have resulted in high heating and rapid heat dissipation, as the mantle solidified, the rate of heat loss subsequently diminished. The estimates for the loss of primordial heat from the mantle range from 7 to 15 TW. This is the remaining heat after removing the heat flow from the core and the radiogenic heat created by the Earth's surface [4]. The geodynamo, which produces the Earth's magnetic field, and the convective outer core both depend on the critical heat transfer originating from the core. Due to the significance of this physical attribute, there are numerous recent studies that monitor and analyze the influence of radionuclides of ground origin on the earth's temperature [5-7]. Therefore, radiogenic heat production is a physical feature that measures the amount of heat emitted per unit time in a particular volume of rock owing to the decay of radiogenic isotopes that are unstable.

Radon has received a great deal of attention in recent years. The defining attribute of this gas is its lack of color and taste, as well as its radioactive nature. There are three major naturally occurring radon isotopes: ^{222}Rn , ^{220}Rn , and ^{219}Rn . In contrast with the overall natural diversity of radon isotopes, ^{222}Rn (which belongs to the radium and uranium-238 decay chain) is important because of its great weight abundance (99.27%). As a result, the name "radon" primarily refers to ^{222}Rn . Radon is naturally released into the atmosphere from the soil as a result of the presence of naturally occurring uranium in the soil [8]. Iraq has such large oil reserves; radiogenic heat production helps in the indirect discovery of oil by analyzing the heat generated by radioactive elements. Heat production basin directly influences the maturation of organic matter into hydrocarbons, facilitating the formation of oil and gas. Because the Earth's temperature is affected by the decay of naturally occurring radioactive material, the current study is carried out to estimate the radiogenic heat production resulting from the decay of ^{238}U , ^{232}Th , and ^{40}K in soil samples obtained from the Al-Qasim district of Babylon, Iraq. Furthermore, the research will investigate the influence of temperature on radon emissions in this region.

2. Methodology

2.1 Study area

The study area encompasses the Al-Qasim district located inside the city of Babylon, which is situated in the center of Iraq, as shown in Figure 1. Al-Qasim district was selected as the site for investigating the radiogenic heat production in its soil, marking the first research of its kind in the area. The geological composition of the Earth has a substantial influence on the radiation background, making it crucial to consider the geology of the studied area. From a geological point of view, Babylon is situated in the center of the alluvial plain, and according to geography, it is located in the middle area of Iraq. It is situated in the unstable shelf region according to Iraq's tectonic division. Thus, it can be said that its geological creation is connected to the geological developments that took place in the area. It is characterized by sediments deposited by rivers, winds, and human activities. The terrain of Babylon is characterized by flatness in general and a progressive departure to the east and south in particular.

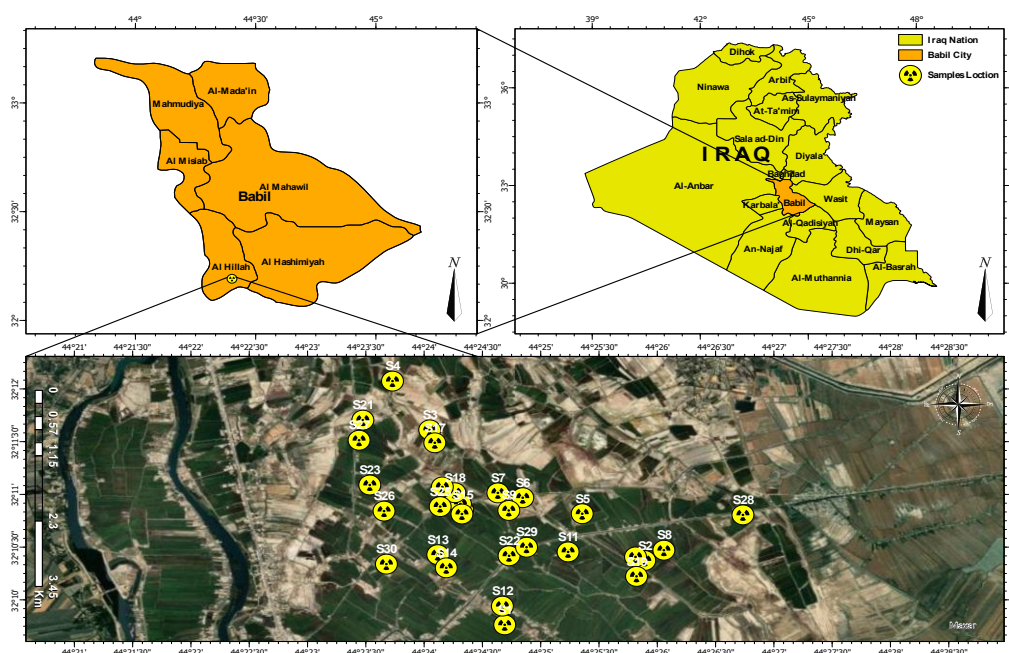


Figure 1: Map of selected soil samples in the Al-Qasim district using GPS.

2.2 Sampling and sample preparation

Thirty soil samples were obtained from the study area at a depth ranging from 0 to 20 cm. Samples were systematically collected, as shown in Figure 1. The coordinates of the location were documented using a Global Positioning System (GPS) device, which was acquired and listed in Table 1. Samples were cleaned and dried at 100 °C for 6 h. Afterward, the samples were pulverized using a mill and sieved through a mesh having a diameter of 1 mm. A 500 g sample of soil was weighed and held for one month in the Marinelli Baker to achieve equilibrium between the radioactive isotopes ^{238}U and ^{232}Th and their respective decay products. Each soil sample, weighing 40 g, was stored in cans for 60 days to prepare it for examination with the CR-39 detector, as shown in Figure 2.

Table 1: Locations of selected samples.

ID	Latitude (N°) and Longitude (E°)
S1	32°16'27.16" N 44°41'15.19" E
S2	32°17'28.85" N 44°43'15.36" E
S3	32°19'35.28" N 44°40'08.03" E
S4	32°20'12.35" N 44°39'54.78" E
S5	32°18'02.75" N 44°42'26.02" E
S6	32°18'28.07" N 44°41'40.98" E
S7	32°18'35.64" N 44°41'05.44" E
S8	32°17'45.14" N 44°43'42.76" E
S9	32°18'07.95" N 44°41'21.03" E
S10	32°17'34.51" N 44°43'02.22" E
S11	32°17'42.42" N 44°42'05.81" E
S12	32°16'56.73" N 44°41'11.92" E
S13	32°17'38.04" N 44°40'19.52" E
S14	32°17'17.26" N 44°40'31.66" E
S15	32°18'08.16" N 44°40'55.05" E
S16	32°18'18.23" N 44°40'51.93" E
S17	32°19'14.87" N 44°40'15.27" E
S18	32°18'35.92" N 44°40'43.91" E
S19	32°17'03.74" N 44°43'03.65" E
S20	32°18'45.08" N 44°40'26.05" E
S21	32°19'50.70" N 44°39'12.38" E
S22	32°17'36.28" N 44°41'21.42" E
S23	32°18'48.17" N 44°39'22.33" E
S24	32°18'02.34" N 44°40'54.07" E
S25	32°18'14.02" N 44°40'22.96" E
S26	32°18'06.93" N 44°39'42.71" E
S27	32°19'18.92" N 44°39'07.02" E
S28	32°18'00.93" N 44°44'55.74" E
S29	32°17'49.84" N 44°41'46.43" E
S30	32°17'23.14" N 44°39'46.07" E



Figure 2: Preparation of soil samples for gamma analysis and radon concentration measurement.

3. Analytical Technique and Statistical Analysis

3.1 Sodium Iodide NaI (TI) Technique

The activity concentration of ^{238}U , ^{232}Th , and ^{40}K was determined via a sodium iodide NaI (TI) detector, while the concentration of ^{222}Rn was measured using a track detector CR-39. A scintillation detector NaI (TI) with a crystal dimension (3×3) inch, equipped by the company (Alpha Spectra Inc, Model 12/12/3), was employed for analyzing gamma rays. A multi-channel analyzer (MCA) called ORTEC-Digi Base is utilized to perform the analysis. The 4096 channels in this MCA are connected to an Analog-to-Digital Converter (ADC) instrument. A computational programmer called 32-MAESTRO is utilized to perform the analysis. A cylindrical lead shield, including a movable lid and a fixed bottom, encloses the detector to reduce background gamma radiation. The calibration curve was established by quantifying the activities of standard radionuclides provided by the IAEA, such as (^{137}Cs , ^{60}Co , ^{57}Co , ^{54}Mn , and ^{22}Na) [9], as shown in Figure 3. The photo-peak of ^{214}Bi at 1764 keV was utilized to investigate the activity of ^{226}Ra (^{238}U), while the photo-peak of ^{208}Tl at 2614 keV was employed to quantify the activity of ^{208}Tl . The level of ^{40}K activity was quantified by analyzing the gamma ray energy peak at 1,460 keV. Also, calibration of the variation in efficiency of the absolute peak detector with gamma ray energy, as shown in Figure 4.

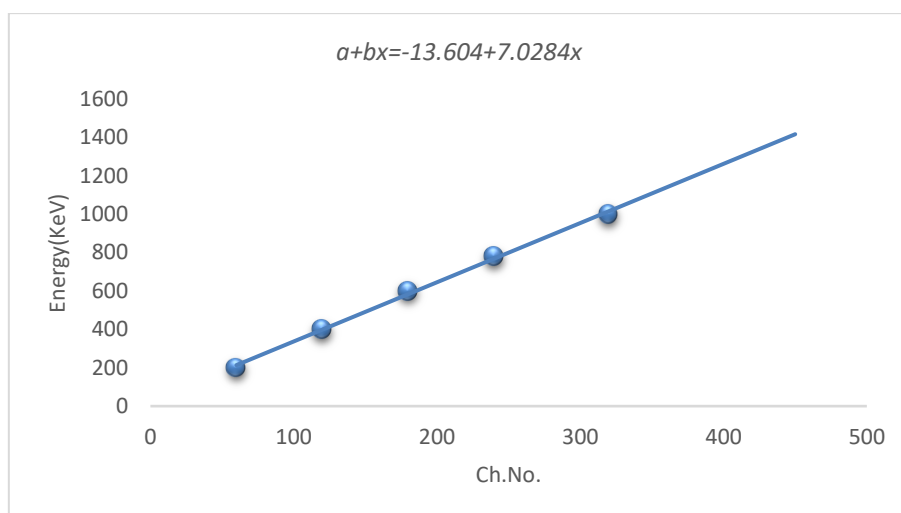


Figure 3: Energy calibration curve for a sodium iodide NaI (Tl) detector.

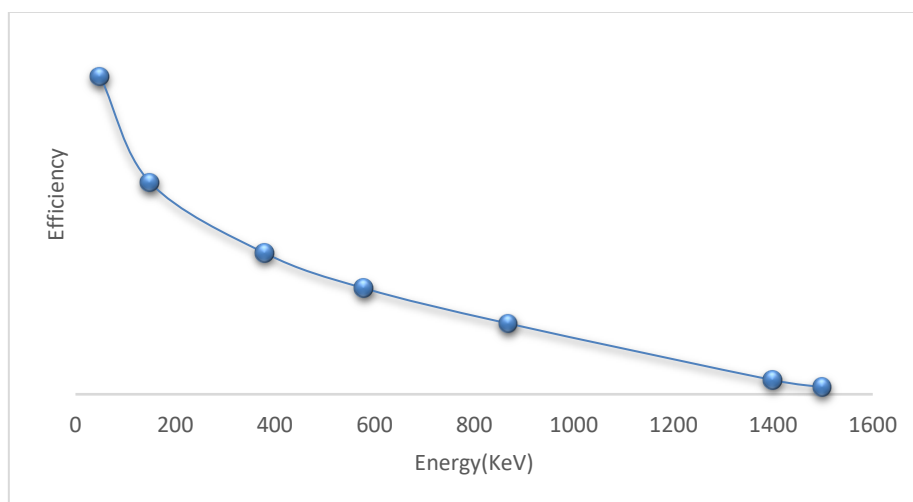


Figure 4: Efficiency calibration curve for a sodium iodide NaI (Tl) detector.

3.2 CR-39 Technique

The measurement of radon concentrations was carried out using a plastic polymer detector called CR-39. The detector was sliced into small segments (1.5×1.5 cm) and inserted inside the can lids before closing them to monitor radon levels. The cans used were 10 cm height with an inner diameter of 5.5 cm. The best conditions for etching the CR-39 detectors after 60 days of exposure were 6.25% NaOH at 70 C°, with an accuracy of ± 0.1 C°, and an etching time of 6 hours. After being cleaned with distilled water, the detectors were briefly immersed in a 3% acetic acid solution. The calibration curve for radon is shown in Figure 5. The detectors were then cleaned once more and allowed to air dry. An optical microscope with a 400X objective lens was used to scan the number of tracks in 40 fields for each detector in order to calculate the track density per cm².

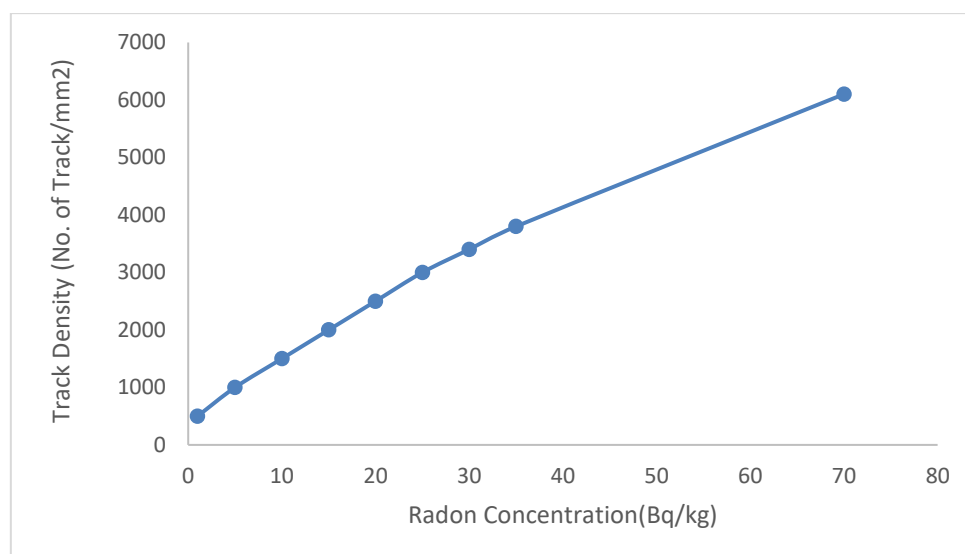


Figure 5: Relationship between radon concentration and track density (calibration curve for radon).

3.3 Statistical Analysis

The Statistical Package for the Sciences (SPSS, version 27) was used to statistically analyze the investigation's findings. The significance p-value was calculated using Pearson Correlation for all data acquired from the samples.

4. Calculations

4.1 Determination of radiogenic heat production

The concentrations of uranium-238 (C_U), thorium-232 (C_{Th}), and potassium-40 (C_K) were determined using Eq. (1), as follows [10]:

$$C_T = \frac{N_{PE}}{P_\gamma \cdot m_s \cdot E_{fd} \cdot T_c} \quad (1)$$

C_T refers to the activity concentration of the radionuclide, N_{PE} denotes the net peak energy, P_γ denotes the probability of gamma-ray decay, m_s denotes the mass of each sample in kg, E_{fd} denotes efficiency of the detector, and T_c denotes the total counting time in seconds.

The radiogenic heat production R_H ($\mu W \cdot m^{-3}$) assessed by quantifying the quantity of each radionuclide in the soil sample in $Bq \cdot kg^{-1}$ and then translating it to parts per million (ppm). Thus, the radiogenic heat production may be calculated using the equation denoted as follows [5-7]:

$$R_H (\mu W \cdot m^{-3}) = \rho (kg \cdot m^{-3}) \times [9.52 \times C_U + 2.56 \times C_{Th} + 3.48 \times C_K] \times 10^{-5} \quad (2)$$

Where ρ represents the soil's bulk density, measured in $kg \cdot m^{-3}$, C_U and C_{Th} in ppm, and C_K in (%). The following are the conversion factors endorsed by the IAEA for certain radionuclides [11]:

1%K = 313 $Bq \cdot kg^{-1}$ of ^{40}K

1 ppm U 12.35 $Bq \cdot kg^{-1}$ of ^{238}U

1ppm Th = 4.06 $Bq \cdot kg^{-1}$ of ^{232}Th

Heat production constants (9.52, 2.56, and 3.48) are empirically derived, and the values used can vary slightly between researchers and different publications, reflecting the heat contribution of each element, likely based on its specific heat release or decay energy.

The bulk density of soil is calculated by dividing its mass by the total volume it occupies. Hence, the volume of the soil is influenced by the volumes of its internal pores, particles, and

inter-particles. The subsequent expression was employed to determine the bulk density for each soil sample [12]:

$$\text{Bulk density (kg. m}^{-3}\text{)} = \frac{\text{dry soil weight (kg)}}{\text{soil volume (m}^3\text{)}} \quad (3)$$

The volume of the soil sample was calculated using a cylindrical container and the corresponding mathematical formula (i.e., volume $\text{m}^3 = \pi r^2 h$).

The subsequent equation was utilized to compute the heat generation from the samples in this study [12 - 14]:

$$A_g (\mu\text{W. m}^{-3}) = [0.26 \times C_U + 0.07 \times C_{Th} + 0.1 \times C_K] \quad (4)$$

The assumption is made that the density of all rocks remains constant at 2700 kg m^{-3} by employing the constants.

4.2 Radon concentration and mass exhalation rate

The traces of alpha particles released by radon gas are captured and recorded by the CR-39 detector. The concentration of radon was determined by employing the following formula [15, 16]:

$$C_R = \frac{\rho}{K \times T} \quad (5)$$

where K refers to the calibration factor (0.212 tr.cm^{-2} per $\text{Bq.m}^{-3}.\text{d}$), T denotes the exposure time (d), and ρ is the density of the tracks. To calculate the mass exhalation rate resulting from heat-induced changes in soil samples heated to 100°C , the subsequent equation was applied [17, 18]:

$$E_M = C_R e^{-(\lambda+\alpha)t} + \frac{CV}{m} \frac{\lambda+\alpha}{1-e^{-(\lambda+\alpha)t}} \quad (6)$$

Where E_M refers to the mass exhalation rate ($\text{mBq.kg}^{-1}.\text{h}^{-1}$), C_R denotes the accumulated radon concentration (Bq.m^{-3}), λ : decay constant of radon (h^{-1}), ($\alpha=0$) denotes the leakage rate from the container (h^{-1}) (if existing), t denotes the accumulation time (1440h), V .the volume of the accumulation kit (m^3), and m is the mass of the sample (kg).

5. Results and Discussion

The soil samples were analyzed to estimate the amounts of ^{238}U , ^{232}Th , and $\%^{40}\text{K}$, which were quantified in ppm and displayed in Table 2. The mean concentrations of these radionuclides were found to be 1.584, 6.996, and 0.754, respectively, as illustrated in Figure 6. Table 2 also displays the radiogenic heat production R_H , heat generation A_g , radon concentration rate C_R , and mass exhalation rate E_M for all soil samples. According to the findings, ^{232}Th is the primary source of radiogenic heat in soil, followed by ^{238}U and ^{40}K , in that order. The amount of radiogenic heat emitted by each radionuclide differs based on the specific geological position and subsurface geology of the sampling site. The heat production was determined, which is dependent on the mass and density of the sample being analyzed. In contrast, heat generation was computed with the assumption that density remained constant. The results demonstrate a significant level of agreement between the outcomes of the two equations, confirming the reliability of this approach for this particular research. The average values for heat, R_H , and A_g were measured to be 0.957 and $0.977 \mu\text{W.m}^{-3}$, respectively, which fall below the suggested threshold of $1 \mu\text{W.m}^{-3}$ [7, 9, 19, 20] as shown in Figure 7. Therefore, the research area might be considered a region with low heat production, and hence, the region is safe for drilling groundwater wells or constructing new communities.

The analysis revealed that the average radon concentration (C_R) was $87.267 \text{ Bq. kg}^{-1}$ and the mass exhalation rate (E_M) was $0.007 \text{ mBqkg}^{-1}.\text{h}^{-1}$, as illustrated in Table 2 and Figure 8. The mass exhalation rate demonstrated a relationship to the concentration of radon, which is significantly affected by the temperature applied during the heat-treatment process. Moreover, the radon concentrations were measured at room temperature to be ($80.91 \text{ Bq. kg}^{-1}$), then the

samples were heated to 100 °C and the radon concentration was (87.267 Bq. kg⁻¹). As a consequence of the treatment temperature of 100 °C, the initial mass exhalation rise [21, 22].

Pearson's correlation and P-value were calculated for the parameters under investigation, and the results are displayed in Table 3. The concentration of uranium was found to have a very significant correlation with thorium but a moderate relationship with potassium. The values of radiogenic heat are significantly influenced by thorium. However, the effect of potassium is negligible and does not exhibit any important statistical relationship across all the investigated parameters. Statistical analysis demonstrates that thorium is the most efficient radionuclide for producing heat, followed by uranium. Although radon concentration is low, it correlates significantly with mass exhalation rate. Finally, all statistical analyses confirm the validity of the findings regarding radionuclides and their correlation with heat.

Table 2: Concentration of ²³⁸U, ²³²Th (ppm) and %⁴⁰K in soil samples with their radiogenic heat levels (μW.m⁻³), radon concentration (Bq. kg⁻¹) and mass exhalation rate (mBq.kg⁻¹.h⁻¹).

ID	C _U	C _{Th}	C _K	R _H	A _g	C _R	E _M
S1	1.886	11.231	0.695	1.326	1.346	66.259	0.013
S2	1.789	10.418	0.670	1.243	1.261	194.156	0.038
S3	1.093	5.615	0.747	0.739	0.752	120.192	0.023
S4	1.190	5.960	0.764	0.789	0.803	55.473	0.010
S5	1.230	6.133	0.803	0.815	0.829	78.587	0.015
S6	0.947	8.743	0.828	0.925	0.941	164.879	0.032
S7	1.060	9.729	0.836	1.023	1.0404	147.928	0.029
S8	1.635	8.694	0.830	1.099	1.116	44.686	0.008
S9	1.878	7.364	0.833	1.070	1.087	86.291	0.017
S10	2.283	6.330	0.851	1.104	1.121	124.815	0.024
S11	2.469	6.576	0.859	1.170	1.188	49.309	0.009
S12	1.246	5.517	0.568	0.755	0.767	154.092	0.030
S13	0.890	5.886	0.579	0.690	0.701	61.637	0.012
S14	1.238	7.463	0.703	0.900	0.914	55.473	0.010
S15	1.514	8.152	0.781	1.026	1.042	135.601	0.026
S16	1.546	5.443	0.735	0.842	0.856	44.686	0.008
S17	1.659	5.098	0.734	0.848	0.861	50.850	0.010
S18	1.522	5.566	0.741	0.845	0.859	38.523	0.007
S19	1.716	6.773	0.769	0.981	0.997	53.932	0.010
S20	1.554	6.428	0.751	0.914	0.929	57.014	0.011
S21	1.514	6.970	0.740	0.940	0.955	118.651	0.023
S22	1.279	6.551	0.767	0.852	0.867	33.900	0.006
S23	1.060	5.911	0.806	0.757	0.770	46.227	0.009
S24	1.587	7.339	0.762	0.986	1.002	52.391	0.010
S25	2.080	8.177	0.695	1.165	1.183	90.914	0.018
S26	1.991	7.290	0.768	1.087	1.105	160.256	0.031
S27	2.008	6.995	0.835	1.078	1.095	77.046	0.015
S28	1.878	6.477	0.703	0.996	1.012	66.259	0.013
S29	1.813	5.221	0.721	0.894	0.909	124.815	0.024
S30	1.959	5.837	0.736	0.975	0.991	63.178	0.012
Ave.	1.584	6.996	0.754	0.957	0.977	87.267	0.007

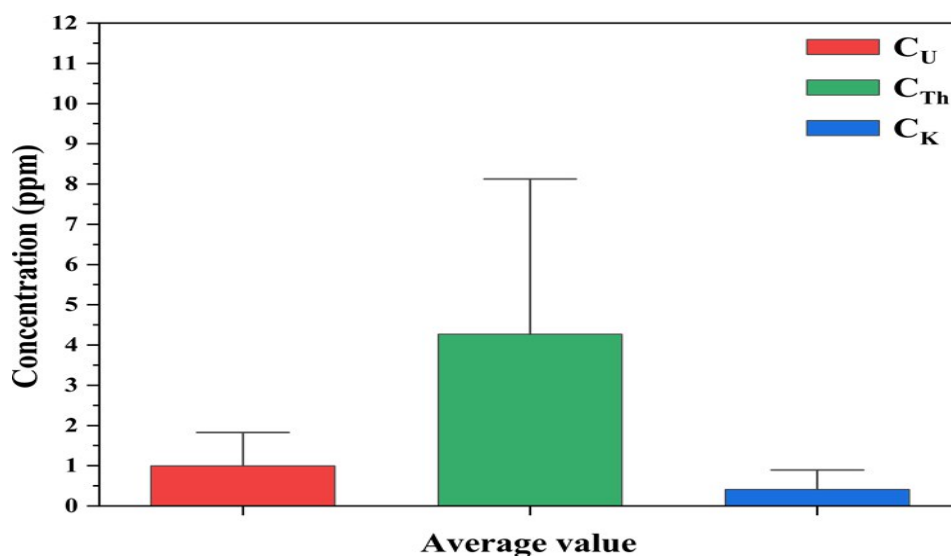


Figure 6: Average concentration of ^{238}U , ^{232}Th , and ^{40}K (ppm) in soil samples.

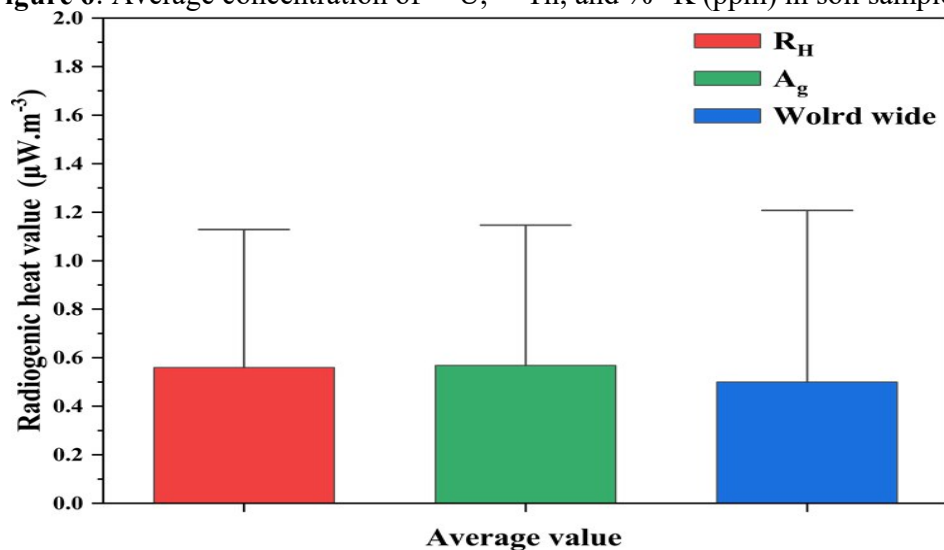


Figure 7: Comparison of radiogenic heat values of the studied area and the worldwide value in $\mu W.m^{-3}$ unit.

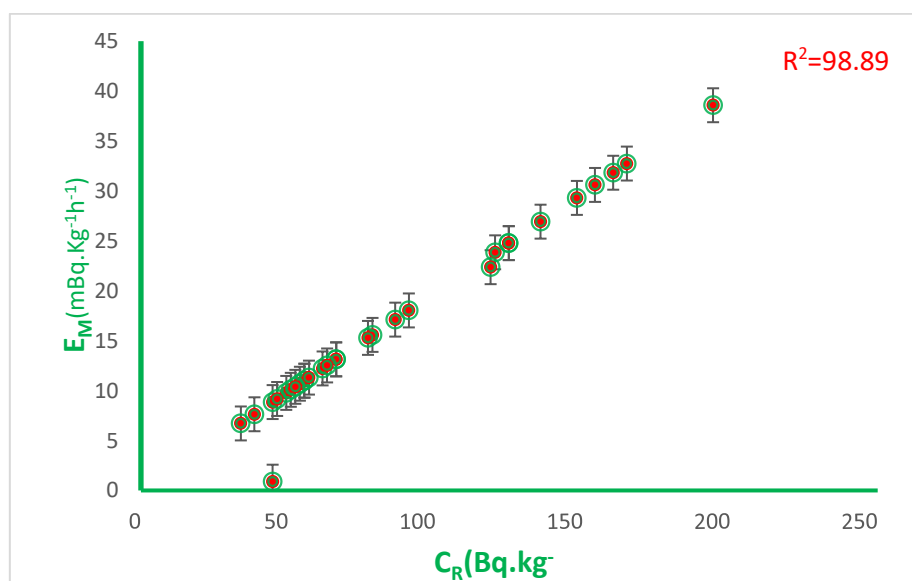


Figure 8: Relationship between radon concentration C_R and mass exhalation rate and E_M .

Table 3: Pearson's correlation and p-value of parameters for studied samples.

Parameters	Pearson's correlation and p-value	^{238}U (ppm)	^{232}Th (ppm)	$\%^{40}\text{K}$	R_H	C_R
Concentration of ^{238}U (ppm)	Pearson Correlation	1				
	Sig. (2-tailed)					
Concentration of ^{232}Th (ppm)	Pearson Correlation	0.090	1			
	Sig. (2-tailed)	0.634				
Concentration of $\%^{40}\text{K}$	Pearson Correlation	0.241	0.116	1		
	Sig. (2-tailed)	0.200	0.543			
Radiogenic heat production (R_H)	Pearson Correlation	0.732**	0.744**	0.279	1	
	Sig. (2-tailed)	0.000	0.000	0.135		
Radon concentration (C_R)	Pearson Correlation	-0.036	0.370*	-0.089	0.224	1
	Sig. (2-tailed)	0.852	0.044	0.641	0.233	
Mass exhalation rate						0.998
Mean	1.58380	6.996	0.753	0.961	87.267	1.583
Std. Deviation	0.402117	1.538	0.070	0.156	45.115	0.402
Minimum	0.890	5.098	0.568	0.690	33.900	0.890
Maximum	2.469	11.231	0.859	1.326	194.156	2.469
**. Correlations						
*. Correlation is significant at the 0.05 level (2-tailed).						

6. Conclusions

This research offered a valuable understanding of the radiogenic heat generation rate resulting from the presence of radionuclides in soil samples. All soil samples contained radioactive elements, which were demonstrated to be contributors to radiogenic heat production. ^{232}Th exhibits the greatest contribution to radiogenic heat generation in soil across all sampled locations, followed by ^{238}U and ^{40}K . The mass exhalation rate and radon concentration exhibit significant correlations, despite the relatively low radon concentration. The radiogenic heat production and generation rate values indicate that it represents a low secondary source of internal heat for the Earth in the study areas, indicating the absence of oil reserves. The calculated radiant heat generation for the study area could form the basis for future research on the impact of radiant heat in the region.

7. Acknowledgment

The authors are grateful for the permission to conduct this research in the nuclear laboratory of the Physics Department at the University of Al-Qadisiyah.

Funding: The research was self-funded.

Conflicts of interest: The authors declare no conflicting interests.

Authors' contributions: Shatha F. Alhous contributed to the design and the overall writing of the manuscript, while Mohammed S. Alsaffar revised the manuscript for important and valuable intellectual content. Authors read and approved the final manuscripts.

Ethical approval: The research involves no human participants or animals.

Compliance with Ethical Standards: Authors have understood and read the statement on

"Ethical responsibilities of Authors".

Data Availability: All data used in this manuscript.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

References

- [1] C. J. Hawkesworth and M. Brown, "Earth dynamics and the development of plate tectonics, Royal Society journals seminar collection," vol. 376, p. 20180228, 2018.
- [2] D. L. Turcotte and G. Schubert, *Geodynamics*: Cambridge University Press, 2002.
- [3] J. Korenaga, "Earth's heat budget: Clairvoyant geoneutrinos, *Nat. Geosci*, vol.4, pp. 581–582, 2011.
Korenaga, J. (2011). *Earth's heat budget: Clairvoyant geoneutrinos, Nat. Geosci.*, 4, 581–582.
- [4] S. Dye, "Geoneutrinos and the radioactive power of the Earth," *Reviews of Geophysics*, vol. 50, pp. 1-19, 2012.
- [5] A. Abbady, "Radiological hazard and radiogenic heat production in some building materials in Upper Egypt," *Journal of Radioanalytical and Nuclear Chemistry*, vol. 268, pp. 243-246, 2006.
- [6] Z. Sas, J. Szántó, J. Kovács, J. Somlai, and T. Kovács, "Influencing effect of heat-treatment on radon emanation and exhalation characteristic of red mud," *Journal of Environmental Radioactivity*, vol. 148, pp. 27-32, 2015.
- [7] A. M. Asere and S. O. Sedara, "Determination of natural radioactivity concentration and radiogenic heat production in selected quarry sites in Ondo State, Nigeria," *NIPES-Journal of Science and Technology Research*, vol. 2, 2020.
- [8] E. G. Vogianis and D. Nikolopoulos, "Radon sources and associated risk in terms of exposure and dose," *Frontiers in public health*, vol. 2, p. 207, 2015.
- [9] I. U. o. Radioecologists, *Handbook of parameter values for the prediction of radionuclide transfer in temperate environments*, vol. 364: International Atomic Energy Agency, 1994.
- [10] T. M. Kadhim, A. A. Alkufi, and S. F. Alhous, "Measurement of the natural radiological activity of soil samples of some general education schools in Al-Qadisiyah Governorate," in *IOP Conference Series: Materials Science and Engineering*, p. 072026, 2020.
- [11] T. Kawano, Y. Cho, P. Dimitriou, D. Filipescu, N. Iwamoto, V. Plujko, *et al.*, "IAEA photonuclear data library 2019," *Nuclear Data Sheets*, vol. 163, pp. 109-162, 2020.
- [12] A. O. Ilori and N. Chetty, "Contributions of ^{238}U , ^{232}Th , and ^{40}K to the radiogenic heat production in selected river sediment samples of South Africa," *Transactions of the Royal Society of South Africa*, vol. 79, pp. 23-28, 2024.
- [13] M. Elsadek, M. Sabra, A.L. Abdeldayem, M.A. Youssef, A.A. Masoud, and S.A. Mansour, "Determination of the radiation dose rate and radiogenic heat production of North Gabal Abu Hibban area, central Eastern Desert, Egypt," *NRIAG J Astron Geophys*, vol. 8, pp. 103-111, 2019.
- [14] A. A. Elewee, M. S. Alsaffar, S. F. Alhous, and M. S. Aswood, "Evaluating the level of ^{226}Ra , ^{232}Th and ^{40}K in different building materials," *Nuclear Analysis*, vol. 4, p. 100158, 2025.
- [15] M. S. Aswood and A. A. Elewee, "Lung dose determined due to inhalation of radon gas from building materials used in Al-Shatra city, Dhi-Qar Governorate, Iraq," *International Journal of Radiation Research*, vol.22, pp. 223-227, 2024.
- [16] A. A. Saadoon and M. S. Aswood, "Radon and thoron concentrations of soil samples in Al-Shatrah, Nasiriyah, Iraq," *AIP Publishing*, vol. 2398, pp. 020015, 2022.
- [17] A. Y. Kadhim, K. H. Al-Ataya, and M. S. Aswood, "Distribution of radon concentration in farmland soil samples in Al-Shamiriyah City, Al-Qadisiyah, Iraq," in *Journal of Physics: Conference Series*, vol. 1591, pp. 012089, 2020.
- [18] S. T. Kadhum, and A.Hussain, "A study of changes in the chemical properties of soil due to irrigation by polluted river water (Army Canal in Baghdad) for a long period," *Engineering and Technology Journal*, vol 29, pp. 1032-1051,2011.
- [19] A.M. Asere, S.O. Sedara, "Determination of Natural Radioactivity Concentration and Radiogenic Heat Production in Selected Quarry Sites in Ondo State, Nigeria," *Int J Sci Technol Res*, vol 2, pp. 256 – 271, 2020.

- [20] A. A. Alkufi and S. A. Kadhim, "Comparison of excess lifetime cancer risk for different age groups for selected flour samples," in *AIP Conference Proceedings*, vol. 2437, pp. 020070, 2022.
- [21] S. Mancini, M. Guida, A. Cuomo, D. Guida, and A. H. Ismail, "Modeling of indoor radon activity concentration dynamics and its validation through in-situ measurements on a regional scale," in *AIP Conference Proceedings*, vol. 1982, pp. 020043, 2018.
- [22] C. Clauser, "Radiogenic heat production of rocks," in *Encyclopedia of solid earth geophysics*, ed Springer, pp. 1304-1310, 2021.