SSRG International Journal of Applied Physics
ISSN: 2350-0301/ https://doi.org/10.14445/23500301/IJAP-V13I3P102

Volume 13 Issue 3, 6-22, Sep-Dec 2026
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Original Article

Analysis of Gamma Radiation Exposure and Health Risk Indices in Construction Rocks from Al-Mahra, Yemen

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Received: 01 September 2026 Revised: 02 October 2026 Accepted: 17 October 2026 Published: 03 November 2026

Abstract *- Exposure to natural background radiation occurs continuously, particularly indoors, where people spend much of their time. Rocks used as building materials may contain radioactive nuclides that contribute to radiation exposure. This study evaluates the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in rock samples used as building materials in Al-Mahara Governorate, Yemen, using a High-Purity Germanium (HPGe) detector. Th activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were 41.99± 4.23, 32.38± 4.38, and 610.9± 34.22 Bq/kg, respectively, which are higher than the global averages of 35, 30, and 400 Bq/kg, respectively. The calculated radiation risk. The average values of the radiological hazard parameters for all investigated rock types were: Raeq = 135.773 Bq/kg, D_r = 64.3464 nGy/h, D_eff (indoor) = 0.31566 mSv/y, and D_eff (outdoor) = 0.07891 mSv/y. The average values of the external hazard index (H_{ex}) and internal hazard index (H_{in}) were 0.3655 and 0.47899, respectively, while the Excess Lifetime Cancer Risk (ELCR) and annual gonadal dose equivalent (AGDE) were 0.27701 and 0.45691 mSv/y, respectively. Consequently, Andesite Tuff is unsafe for interior residential construction, and its quarrying for housing should be restricted. All organ-specific doses (ET) remain significantly below the public limit of 1 mSv/y .*

Keywords *- Radionuclides, Radiological risks, Gamma spectrometer, Construction rocks.*

1. Introduction

Radiation from a variety of sources is constantly present in the human population. While some of these sources come from human activity, others are natural. Exposure to natural radiation varies by geographical location, geological factors. Furthermore, the altitude above sea level considerably influences the dosage rate of cosmic radiation [1]. Primordial radionuclides 226Ra, 232Th and 40K are contained in the Earth's crust. Thus, the minerals used for building materials extracted from the earth crust are sources of exposure to γ radiation indoors and outdoors. These radionuclides emit γ radiation, which is a source of external radiation exposure, while radon gas emitted from building materials is a source of internal radiation exposure [2, 3]. People living in mountainous regions with a high concentration of natural radionuclides in minerals are exposed to a higher level of external radiation. Therefore, the natural occurring radionuclides in raw materials of different construction materials must be measured. The evaluation is important for evaluating the potential risks of radiation to human health and for developing regulations concerning the use and supervision of these substances [4]. Occurring radioactive isotopes, which are a result of various geological and cosmic processes to which we are exposed, include U-238, Th-232, and K-40, which may in fact see great increase as a result of human activity like mining and industrial practices [5]. It is also important to note the levels of different radioactive elements present in building materials, which in turn gives us insight into the health risks which their use in public, residential, and industrial construction may present [6].]. In healthcare, it is essential to evaluate the dose of naturally occurring gamma radiation, as humans are constantly exposed to natural radiation, which constitutes the largest source of external radiation dosage for the public [7].In this study, we looked at the specific activity of primary radionuclides (Ra-226, Th-232, and K-40) in which we analyzed five types of rocks that are used for construction purposes with the use of a gamma spectrometry system. We also put our data up against what is published in Yemen and also against what similar studies in other parts of the world report, and the average global values which UNESCAR (2000) has put forth. To determine what the radiological risks are, we calculated a range of health risk parameters, which include radium equivalent, absorbed dose rate, internal and external dose indicators, effective dose equivalent, gonadal dose equivalent, lifetime cancer risk and health risks to body tissues and organs. We also went and looked at what is considered safe levels of radiation in the literature to put our results in perspective and to evaluate what the radiation risks to individuals [8]. The findings of this

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investigation are also contrasted with published values from different areas of Yemen and with global averages and recommended safety limits. This research holds significant importance for both public health and scientific perspectives. The findings serve as a baseline and may act as a guide for future studies. Additionally, they could help inform regulations aimed at limiting the use of construction materials that pose risks to the public [9].

Research Gap and Problem Statement: No systematic radiological survey has described the radioisotope profiles and health risk indices of local construction rocks, despite the fact that there is active residential and commercial quarrying throughout the Al-Mahra Governorate in eastern Yemen. Without objective information about radiation safety, residents construct homes out of local extrusive igneous, tuff, limestone, and basaltic rock. Furthermore, current international publications frequently differentiate between global standard means and required security thresholds and lack organ-specific dose assessments.

The primary objectives are to: (1) measure activity concentrations of 226Ra, 232Th, and 40K across representative rock types; (2) evaluate comprehensive radiological risk indices, including Raeq, Dr, Deff (indoor/outdoor), Hex, Hin, AGDE, and organ-specific doses (ET); (3) identify rock types exceeding international safety limits; and (4) compare Al-Mahra's radiological profile with other Yemeni regions and international survey data.

2. Experimental Details

2.1. Sample Collection and Preparation

As part of a larger project on building materials in Al-Mahra Governorate, eastern Yemen, a total of 18 rock samples were collected from various quarries. For the present study, five representative samples were selected, one for each of the main rock types widely used in construction: extrusive igneous, andesite tuff, volcanic tuff, limestone, and massive basat. The sampling locations are presented in Table 1.

Table 1. The location details of collected rock samples

No	Sample code	Sample name	Latitude	Longitude
1	04-A1	Extrusive igneous	˚15.6890	˚50.6445
2	07-A3	Andesite tuff	˚15.6683	˚50.6298
3	13-A9	Volcanic tuff	˚15.2225	˚51.1069
4	15-A11	Limestone	˚14.3635	˚48.9817
5	17-A13	Massive basalt	˚14.2150	˚48.8554

The samples were crushed, ground and sieved to obtain a uniform particle size of 36 μm. The powdered samples were then dried in an oven at 120°C for 24 h to remove moisture. From each sample, an aliquot of 200 g was taken and placed in a 200 ml plastic container with the same geometry as the calibration standard.

The containers were hermetically sealed to prevent the escape of radon. Each sample was then counted for 18 h (64,800 s). and stored for four weeks at room temperature to achieve secular equilibrium between ^{226}Ra, ^{232}Th and their decay products and transported to the National Atomic Energy Commission (NAEC) for radioactivity measurement.

2.2. Gamma-Ray Spectrometry and Activity Determination

The activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the rock samples were determined using a gamma-ray spectrometry system equipped with a High-Purity Germanium (HPGe) detector, as illustrated in Figures 1(a) and 1(b). The detector (Model GC3518, S/N: b03136) is a p-type coaxial HPGe crystal (63 mm diameter × 61 mm length) with a relative efficiency of 35% and an energy resolution of 1.8 keV FWHM at the 1332.5 keV line of ^{60}Co.

The detector is housed inside a low-background shield of 8 cm thick lead, internally lined with 2 mm Cu and 2 mm Cd foils. To ensure secular equilibrium between ^{226}Ra and its progeny, the samples were sealed for one month prior to counting. The activity of ^{226}Ra was determined via ^{214}Pb (295.2 keV, 351.9 keV) and ^{214}Bi (609.3 keV, 1120.3 keV). The activity of ^{232}Th was evaluated using ^{228}Ac (338.4 keV, 911.0 keV), ^{212}Pb (238.6 keV) and ^{212}Bi (727.3 keV). The activity of ^{40}K was determined directly from its photopeak at 1460.8 keV.

Energy calibration was performed using standard sources of ^{241}Am (59.54 keV), ^{137}Cs (661.66 keV) and ^{60}Co (1173.23 keV, 1332.49 keV) covering the energy range of 50 keV to 2800 keV. The channel-energy relationship is presented in Table 2 and Figure 2.

Efficiency calibration was carried out using a certified multinuclide standard reference material in the identical 200 ml container geometry as the samples. The specific activity A (Bq/kg) was calculated using the relation:

$$A = N/\mathcal{E}\, I\gamma\, T\, Ms \qquad (1)$$

where A is the specific activity of the radionuclides, N is the net count rate [$N = N_{Peak} - N_{Background}$], $\mathcal{E}$ is the full energy peak efficiency of the specific γ peak, I_γ the emission probability of γ disintegration, and M_S is the mass of the sample (kg).



Fig. 1(a) HPGe detector



Fig. (1b) Computer-based MCA

The following table 2 gamma ray energy calibration results.

Table 2. Gamma ray energy calibration results

Radioisotopes	Energy (KeV)	Channel Number
s-137	61.26	942
o-60	173	443
o-60	332.5	911
m-241	9.54	75

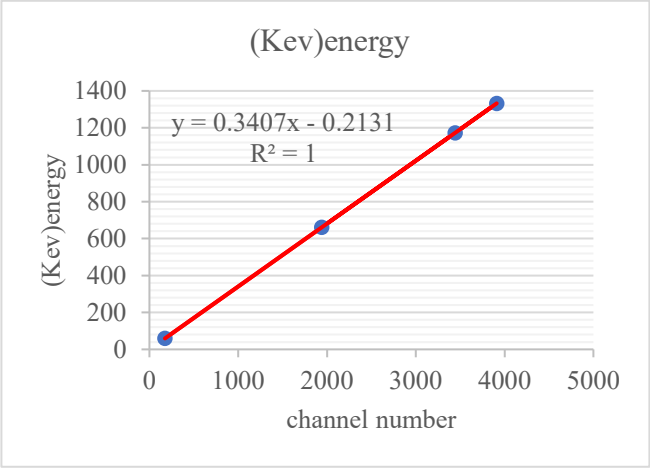


Fig. 2 Gammy energy calibration curve for HPGe detector used in this work

3. Radiological Risk Assessment

3.1. Radium Equivalent Activity (Raeq)

A naturally occurring radioactive isotope has been identified, characterized by various materials, to evaluate its radioactivity, commonly referred to as radium equivalent. This isotope accounts for approximately 98.5% of? radiation exposure, with the yield in the uranium series being primarily due to 226Ra and its descendants. The Raeq is calculated using (equation 2) [10].

$$Raeq = Ra_{eq} = A_{R\,a} + 1.43\ A_{Th} + 0.077A_K \quad (2)$$

Where ARa, ATh, AK are the activity concentration of 226Ra, 232Th and 40K in samples (in Bq kg-1).

3.2. Absorbed Gamma Dose Rate (Dr)

The outdoor terrestrial absorbed gamma dose rate in air 1 m above ground level was computed assuming a uniform distribution of radionuclides were calculated using equation 3 [11].

$$Dr\ (nGy/h) = 0.462ARa + 0.604ATh + 0.0417AK \quad (3)$$

Where ARa, ATh, AK are the activity concentrations of 226Ra, 232Th and 40K in samples.

3.3. Annual effective Dose Equivalent (AEDE or Deff)

The annual effective dose rates for both outdoor and indoor yearly effective doses are determined utilizing equations 4, 5. The AEDE incorporates the occupancy factors for outdoor 0.2 and indoor 0.8.

Deff (mSv y-1) = Dr (nGy h-1) × 0.2 × 8760 hy-1 ×0.7 ×10-6 Sv.Gy-1 for outdoor (4)

Deff (mSv y-1) = Dr (nGyh-1) × 0.8 × 8760 hy-1 ×0.7 ×10-6 Sv.Gy -1 for indoor (5)

The conversion factor from Dr to Deff for adults is 0.7× 10-6 Sv.y-1, whereas the annual time spent in the building is 8760 h y-1.

3.4. External Radiation Hazard (Hex)

External risk (Hex) refers to having been exposed to external radiation emitted by? rays. This factor assesses the potential threat from external radiation linked to which arises from the decay of isotopes such as 226Ra, the 232Th series, and 40K. To ensure that the environment stays safe and no radiation protective measures are required, this coefficient must not exceed the value of one. This threshold is derived from the established permissible equivalent radium limit for construction materials, quantified at 370 Bq/kg. Hex was computed using formula 6 [12, 13].

$$Hex = ARa/370 + ATh/259 + AK/4810 < 1 \quad (6)$$

3.5. Internal Radiation Hazard Index (Hin)

This parameter assesses the internal radiation exposure attributable to radon 222Rn and its decay products. Short-lived 222Rn it's daughter products pose significant internal hazards to the respiratory system through inhalation pathways. To restrict external gamma exposure from building materials below 1.5 mGy/y, the external hazard index (Hex) must not exceed unity. The Hin was calculated by equation 7 [14].

$$Hin = ARa/185 + ATh/259 + AK/4810 \quad < 1 \quad (7)$$

3.6. Excess Lifetime Cancer Risk (ELCR)

The development of illnesses, particularly cancer, in humans may result from the harmful effects of prolonged exposure to radiation emitted by terrestrial radioactive materials. Consequently, the lifetime excess cancer risk (ELCR) can be defined as the probability of developing cancer due to exposure to ? radiation from the naturally occurring radioactive substances present in the geological formations or soil near a person's home. The ELCR value can be calculated using equation 8 [15].

$$ELCR = AEDE \times DL \times RF \quad (8)$$

Where AEDE is annual effective dose equivalent, DL is the mean age (70 years), RF is a risk parameter (Sv-1) for deadly cancer per Sievert. For random effects, ICRP 60 recommended 0.05 for the general population [16].

3.7. Annual Gonadal Dose Equivalent (AGDE)

The annual radiation dosage received by reproductive organs and sensitive areas of the human body, such as bone marrow, breast tissue, and surface bone cells, is known as the annual gonadal dose equivalent (AGDE)[17]. This measurement helps assess the radiological impact on these vulnerable organs and tissues. The quantity of AGDE resulting from the degradation of isotopes 226Ra, 232Th series, and 40K can be calculated using formula 9 [13,22].

$$AGDE\ (mSvy\text{-}1) = (3.09ARa+4.18ATh+0.314AK) \times 10^{-3} \quad (9)$$

Effective dose rate to different body organs and tissues (ET) Using the data obtained from the present study (The equivalent dose D outdoor and indoor) described in the previous section, the effective dose (ET) received by the different organs and tissues of the human body was determined by multiplied equivalent dose D by its corresponding tissue weighting factor (WT), as recommended by (ICRP) and by using equation 10 [19] .

$$ET\ (mSv/y) = DT\ WT \quad (10)$$

where DT is the equivalent dose outdoor and indoor, WT is weighting factor assigned by ICRP in their 1990 review of the data are given in Table 3 [19].

Table 3. The tissue and organ weighting factors

No.	Tissue	Weighting factor W_T
1	Gonads	0.08
2	Bone-marrow	0.12
3	Stomach	0.12
4	Liver	0.04
5	Skin	0.01
6	Lung	0.12

4. Results and Discussion

4.1. Activity Concentrations

The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K found in five types of rocks commonly used in construction within Al- Mahra area are presented in Table 4.

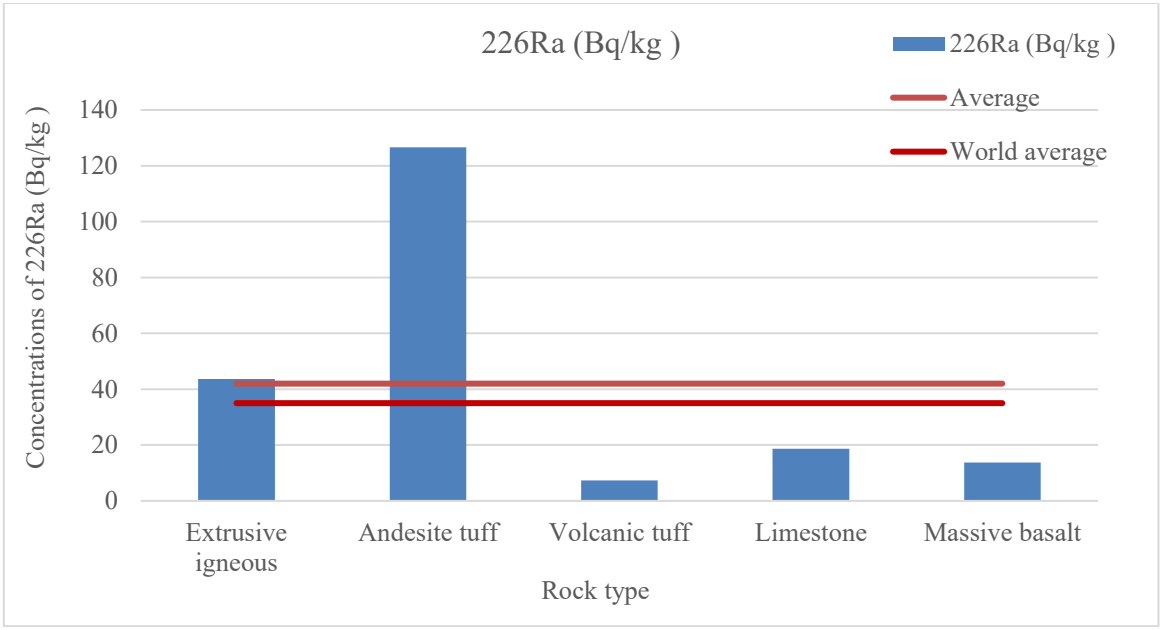
Table 4. Comparison of Natural Radionuclide Activity Concentrations in Al-Mahra Construction Rocks with UNSCEAR Global Reference Values

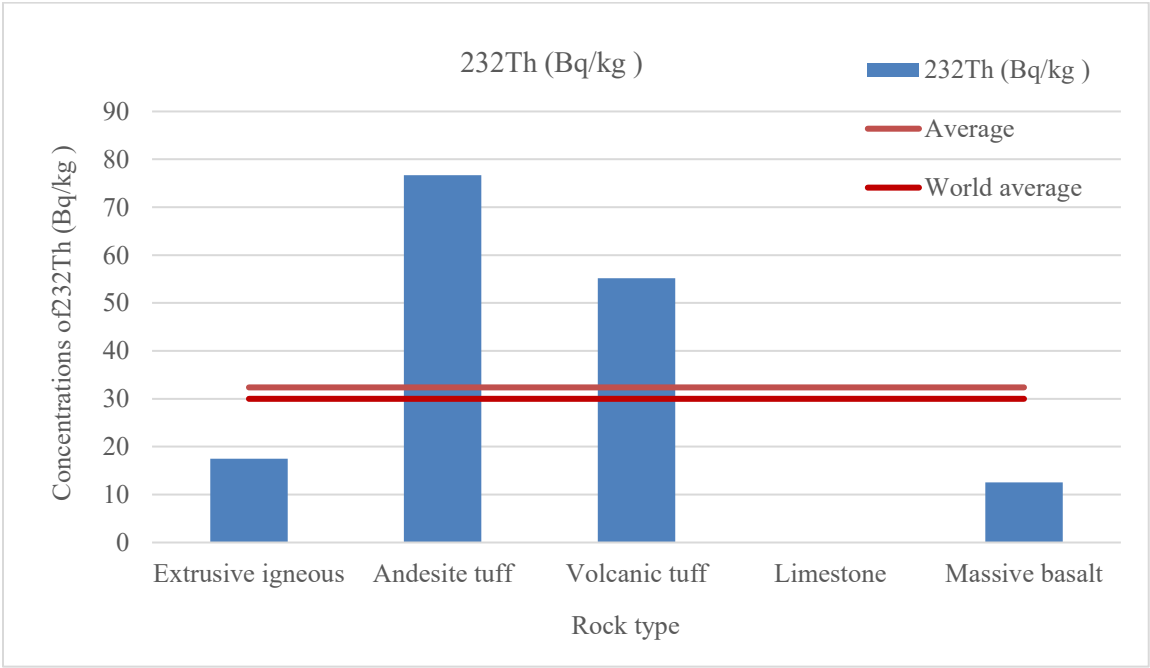
Rock type	226Ra (Bq/kg)		232Th (Bq/kg)		40K (Bq/kg)	
	Av.	sd	Av.	sd	Av.	sd
Extrusive igneous	43.6	3.87	17.46	2	577.9	35.8
Andesite tuff	126.6	9.9	76.66	7.5	1314	65.3
Volcanic tuff	7.34	2.75	55.18	8.6	799.6	49.09
Limestone	18.7	2.53	0	0	47.82	3.61
Massive basalt	13.71	2.14	12.58	1.8	315.6	17.64
Average	41.99		32.38		610.9	
UNSCEAR Global Baseline	35		30		400	

For extrusive igneous rock samples, the activity concentration of radium-226 is measured at 43.6± 3.87 Bq/kg. Similarly, for andesite tuff rock samples, the activity concentration is 126.6 ± 9.9 Bq/kg. In volcanic tuff, the concentration of ^{226}Ra is 7.34 ± 2.75 Bq/kg. For limestone rock samples, the activity value is 18.7 ± 2.53 Bq/kg. The massive basalt rock samples show a concentration of ^{226}Ra at 13.71 ± 2.14 Bq/kg. The average values of ^{226}Ra across these rock types are 43.6, 126.6, 7.34, 18.7, and 13.71 Bq/kg, respectively. Based on the obtained data, the highest levels of radioactivity for 226Ra were observed in igneous rocks and andesites, with the measured values exceeding the permissible limit of 35 Bq/kg.

The specific activity levels of ^{232}Th in various rock types are as follows: 17.46±2 Bq/kg for extrusive igneous rock, 76.66±7.5 Bq/kg for andesite tuff, 55.18±8.6 Bq/kg for

volcanic tuff, a Minimum Detectable Activity (MDA) value, and 12.58±1.8 Bq/kg for limestone and massive basalt. The mean values for these rock types are 17.46, 76.66, 55.18, MDA, and 12.58 Bq/kg, respectively. The data presented in Table 4 indicate that the concentration of 232Th in andesite rock and volcanic tuff exceeds the internationally recommended limit of 30 Bq/kg [20]. The activity concentrations of ^{40}K in the examined building rocks are as follows: 577.9±35.8 Bq/kg for igneous rock, 1314±65.3 Bq/kg for andesite tuff, 799.6±49.09 Bq/kg for volcanic tuff,47.82±3.61 Bq/kg for limestone, and 315.6±17.64 Bq/kg for massive basalt. The mean values for these rocks are 577.9, 1314, 799.6, 47.82, and 315.6 Bq/kg, respectively. The highest activity levels of 40K were found in extrusive igneous rock, andesite tuff, and volcanic tuff, where the radiation concentration values exceeded the estimated global mean of 400 Bq/kg [20]. Overall, the activity concentrations of the rock samples were found to be above the global mean values established by UNSCEAR-2000, which are 400 Bq/kg for 40K, 30 Bq/kg for 232Th, and 35 Bq/kg for 226Ra [25]. Figure 3 illustrates the activity concentrations of 226Ra, 232Th, and 40K in the tested rock samples.





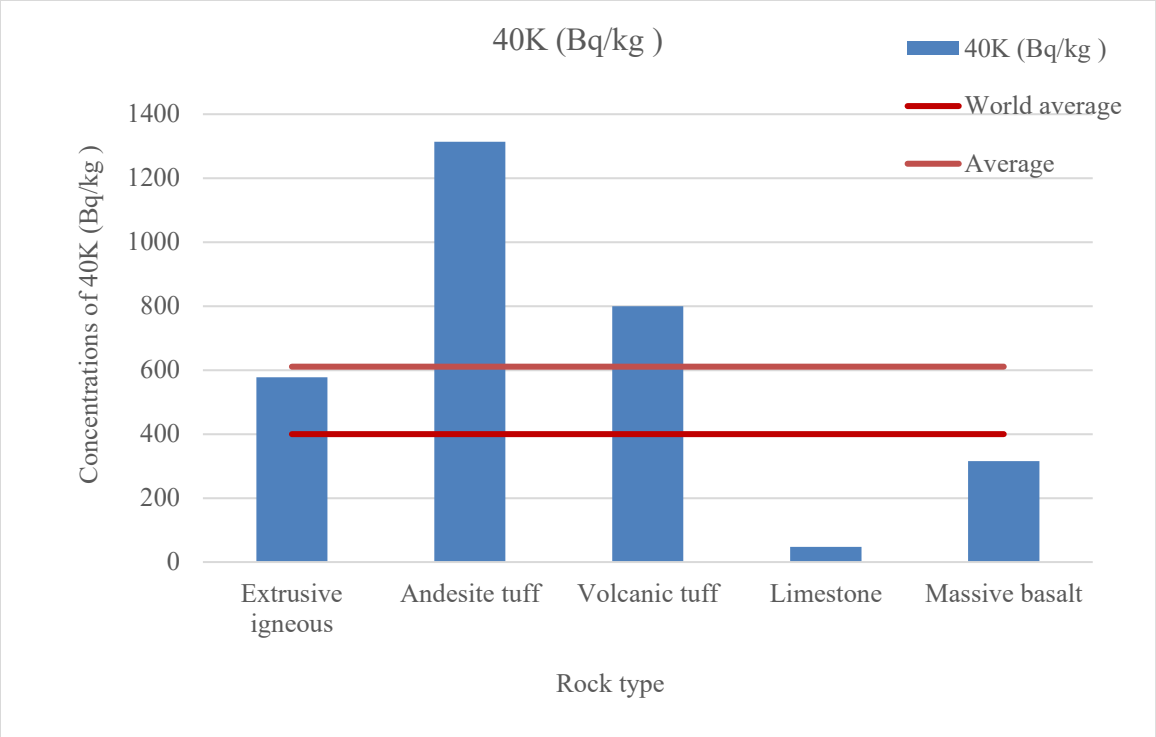


Fig. 3 illustrates the concentration levels of natural radionuclides in samples of building rock

Table 5 and Figure 4 compare the mean radioactivity concentrations obtained in Al-Mahra with published survey data from other Yemeni governorates and selected global studies. Al-Mahra's mean activity concentrations (226Ra: 41.99, 232Th: 32.38, 40K: 610.9 Bq/kg) are moderately higher than global baselines [25], yet substantially lower than high-background Yemeni regions such as Abyan (306 Bq/kg 226Ra, 1434 Bq/kg 232Th) and Hifan (112.1 Bq/kg 226Ra, 301 Bq/kg 232Th) .

Table 5. Comparison of radioactivity levels in the present work with other studies from various regions of Yemen

Sr. No	Places	Average concentrations (Bq kg^{-1})			References
		^{226}Ra	^{232}Th	^{40}K	
1	Taiz	71.55	93.87	966.88	[13]
2	Shabwah and Hadramout	45	106	1235	[21]
3	Abyan	306	1434	1246	[22]
4	Hifan	112.1	301	3875.9	[23]
5	Yafea	31.97	13.8	196.46	[24]
6	North Sana'a	21.79	19.5	939.1	[25]
7	Aden	57.09	80.26	846.21	[26]
8	Hadramout and maharah	41.9	32.38	610.9	Present study
9	World average	35	30	400	[20]
max		306	1434	3875.9	
min		21.79	13.8	75	
Average		76.74	216.68	1039.15	

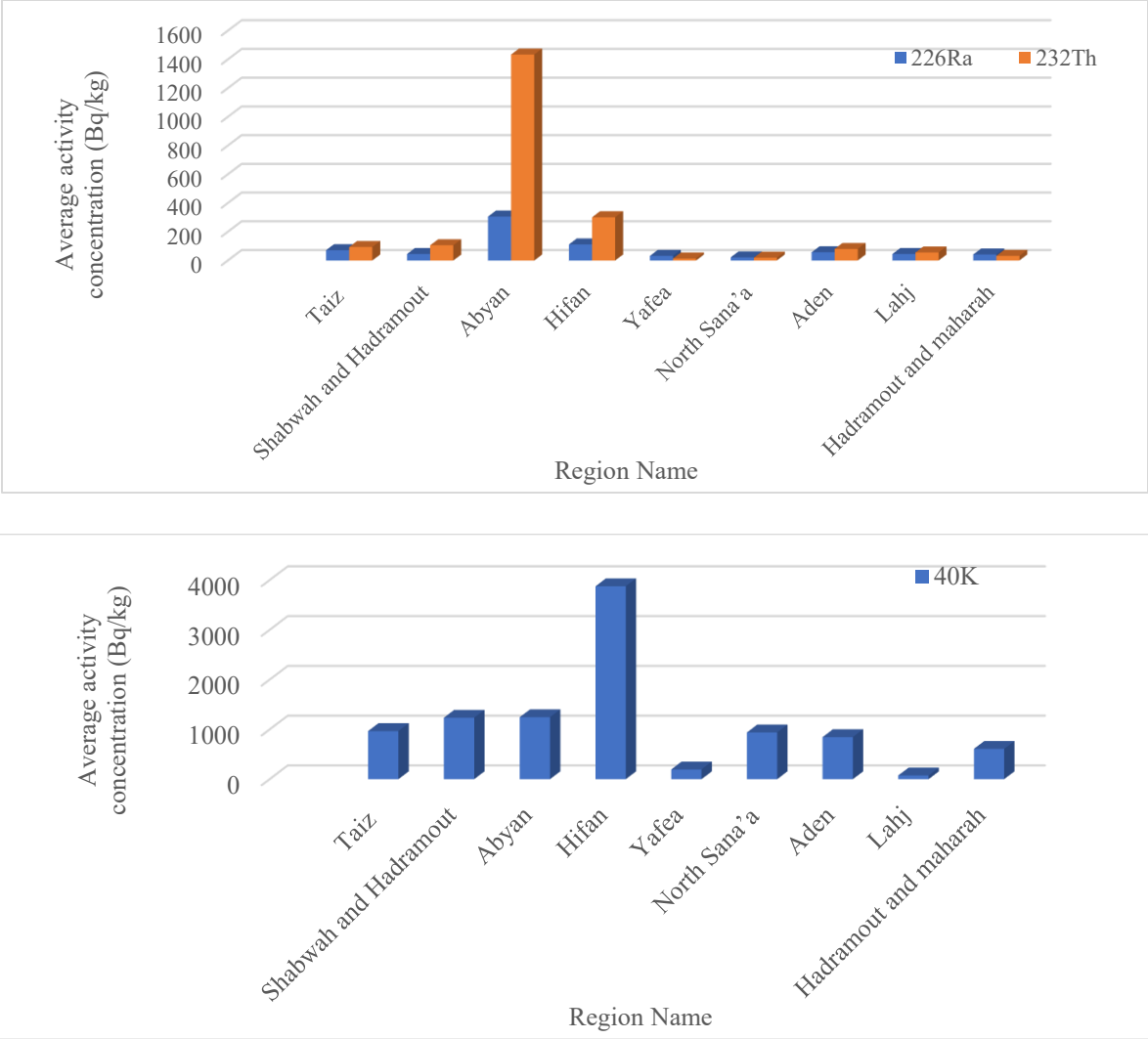
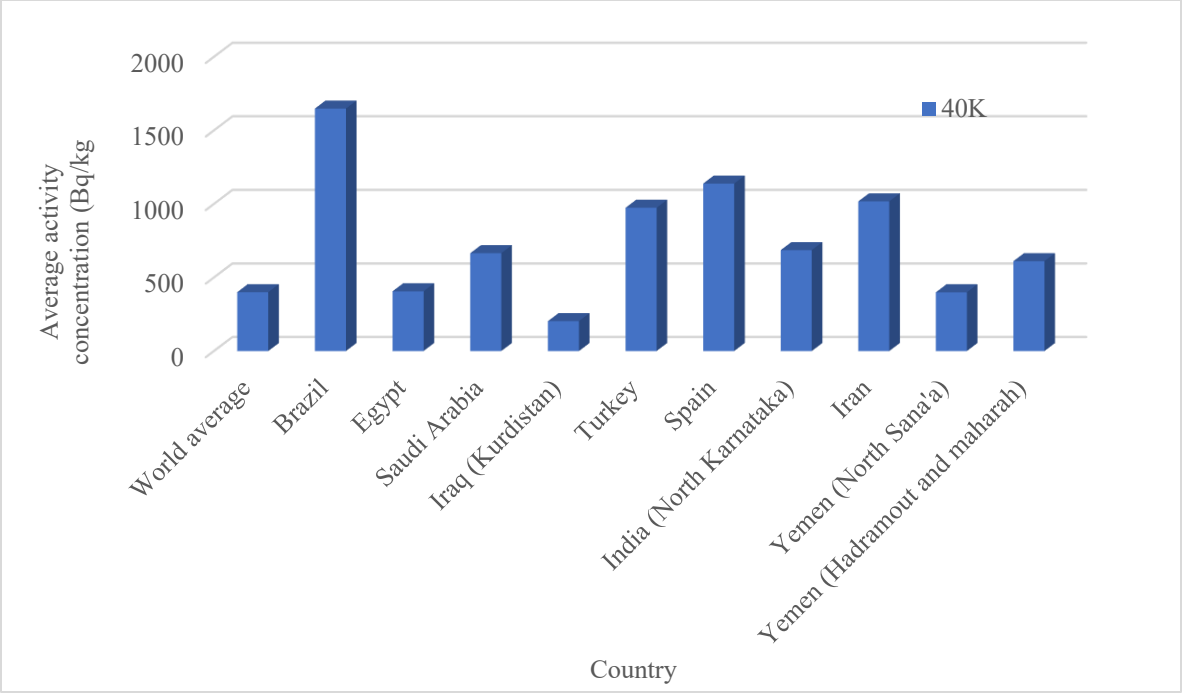


Fig. 4 Comparison of the radioactivity concentration under study with different areas of Yemen

Moreover, the obtained results of the concentrations of 226Ra, 232Th, and 40K in the studied region were also compared with similar research works done in different countries around the globe and also compared with the world average, as summarized in Table 6 and shown in Figure 5.

Table 6. Comparison of naturally occurring radionuclides (226Ra, 232Th, and 40K) in the investigated rocks with the published findings for several countries of the globe

Sr. No	Country/Place	Mean specific activity (Bq kg-1)			
		226Ra	232Th	40K	Reference
1	World average	35	30	400	[20]
2	Brazil	31	73	1648	[27]
3	Egypt	15.64	14.46	405.8	[28]
4	Saudi Arabia	28.82	34.83	665.08	[29]
5	Iraq(Kurdista)	5.65	21.4	203.34	[21]
6	Turkey	80	101	974	[30]
7	Spain	84	42	1138	[31]
8	India (North	32.6	32.79	685.8	[32]
9	Iran	77.4	44.5	1017.2	[33]
10	Yemen (North Sana'a)	20.97	19.15	399.3	[30]
11	Yemen (Hadramout and Maharah)	41.9	32.38	610.9	Present study



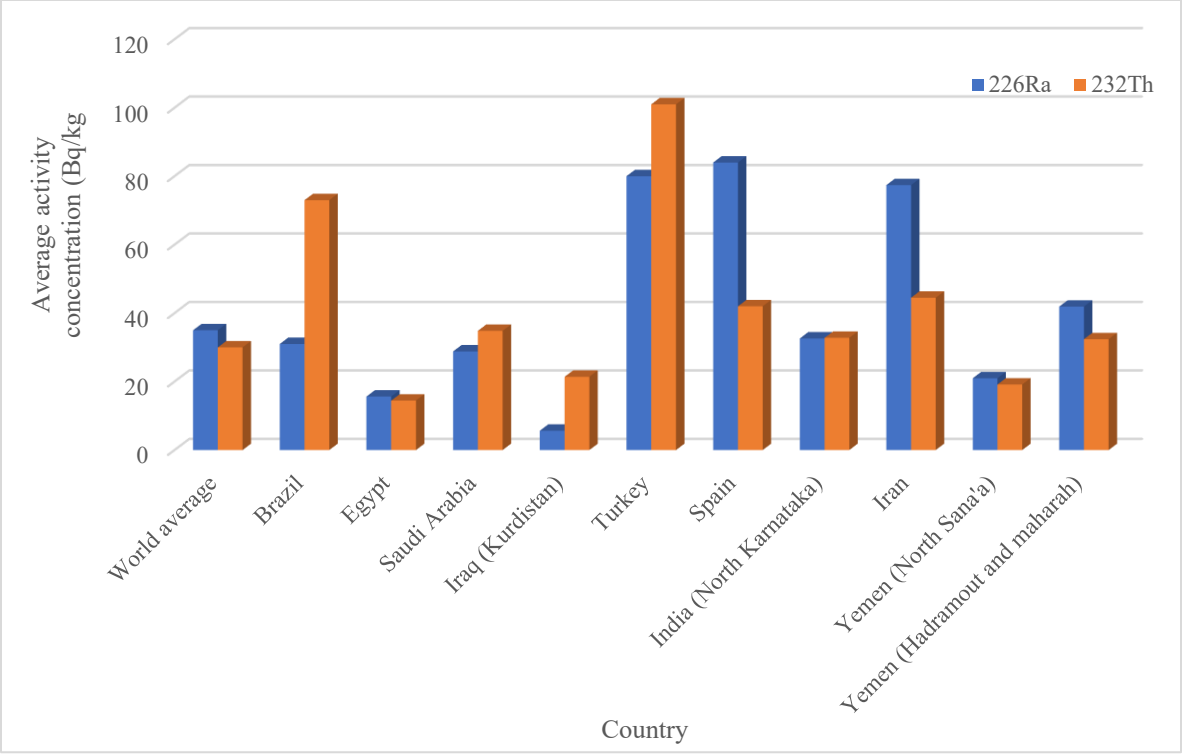


Fig. 5 Comparison of the current study with different countries of the world

4.2. Assessment of Radiological Health Risk Parameters

Table 7 shows of the meticulously calculated results about the indexes of radiation hazards posed to human beings, which includes parameters such as the radium equivalent (Raeq), the absorbed dose rate (Dr), as well as the indicators that signify both internal and external hazards (Hin, Hex), along with the annual dose assessments conducted for both indoor and out exposures (AEDE or Deff), the Annual Gonadal Exposure (AGDE), and finally, the estimation of the Excess Lifetime Cancer Risk (ELCR), all of which are essential for understanding the implications of radiation exposure on human health.

Table 7. Analysis of the radium equivalent activity measured in various building rock samples, highlighting their radiological properties

Rock type		Extrusive igneous	Andesite tuff	Volcanic tuff	Limestone	Massive basalt
Radiological Hazard						
Raeq (Bq/kg)	Avera	113.07	338.36	148.08	23.3821	56.011
	Sd	9.4866	25.651	18.829	2.80797	6.0728
Dr (nGy/h)	Avera	54.702	159.34	70.043	10.5961	27.069
	Sd	4.4811	11.807	8.5065	1.31434	2.8079
Deff (ind) (mSv/y)	Averag	0.2683	0.7818	0.3433	0.05198	0.1325
	Sd	0.022	0.0572	0.0413	0.00645	0.0137
Deff (0ut) (mSv/y)	Averag	0.0671	0.1954	0.0851	0.013	0.0339
	Sd	0.0055	0.0148	0.0103	0.00161	0.0034
Hex	Average	0.3054	0.9119	0.3993	0.06048	0.1511
	Sd	0.0256	0.0699	0.0504	0.00759	0.0164
Hin	Averag	0.4232	1.2535	0.4187	0.11102	0.1887
	Sd	0.0361	0.0965	0.0588	0.01443	0.0228
ELCR	Averag	0.2355	0.6859	0.3016	0.04562	0.1165
	Sd	0.0193	0.0503	0.0362	0.00566	0.0128
AGDE (mSv/y)	Averag	0.3892	1.1247	0.5041	0.0728	0.1941
	Sd	0.0316	0.0825	0.0596	0.00895	0.0198

Table 7 provides a detailed analysis of the radium equivalent activity measured in various building rock samples, highlighting their radiological properties. Among the samples analyzed, the radium equivalent activity values showed a significant range, with the maximum recorded value reaching 338.386 Bq kg^{-1} and the minimum value at a comparatively low 23.3821 Bq kg^{-1}

The calculated average value stood at 135.773 Bq kg-1. Importantly, this average remains well below the acceptable threshold of 370 Bq kg-1, as set by the Organization for Economic Co- operation and Development (OECD) to protect public health from radiological risks [34]. This finding clearly indicates that the use of the examined rock samples in construction poses minimal risk, confirming their suitability as building materials for various architectural applications. The measured absorbed gamma dose rates in the air varied significantly, ranging from 10.5961 nGy/h to a maximum of 159.324 nGy/h, with an average dose rate of 64.3464 nGy/h. These findings indicate that all analyzed rock samples exceeded the established limit of 57 nGy/h recommended by UNSCEAR [21], with the exception of the limestone and massive basalt rock samples. This suggests a variation in radiological safety among different geological materials.

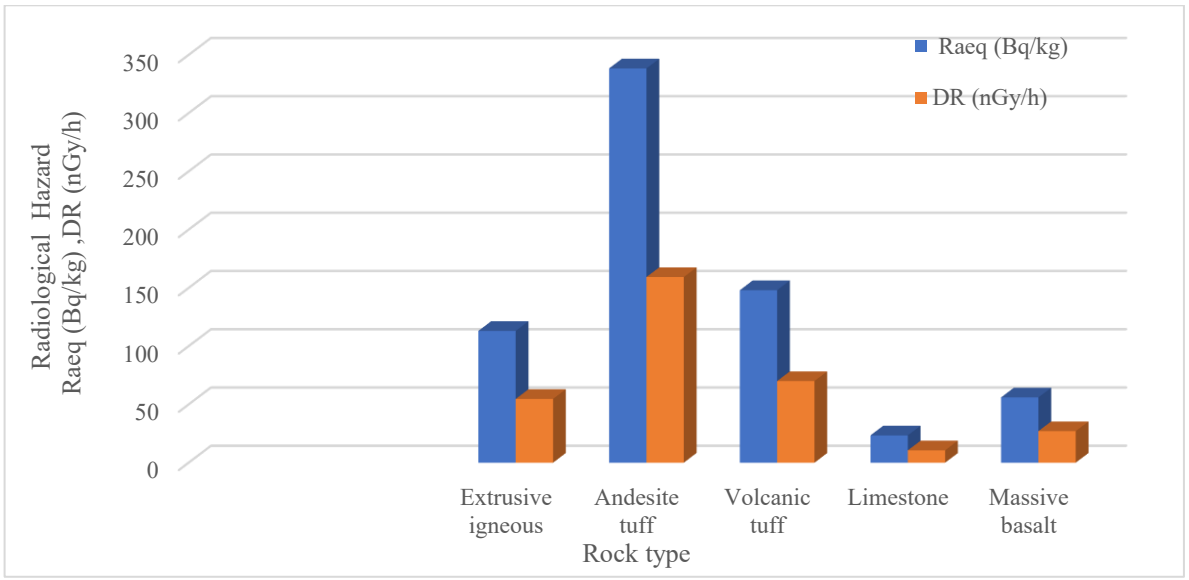
The indoor annual effective dose rates ranged from a minimum of 0.05198 mSv/year to a maximum of 0.78158 mSv/year, with an average of approximately 0.31566 mSv/year. In comparison, the outdoor annual effective dose rates varied from 0.013 mSv/year to 0.1954 mSv/year, with an average value of around 0.07891 mSv/year. This data highlights the differences in radiation exposure between indoor and outdoor environments. To ensure that radiological health risks are negligible or minor, both calculated values must remain below the critical threshold of 1 mSv per year. This threshold is essential for evaluating safety regarding radiation exposure.

The present study reveals that the calculated mean annual effective dose equivalent is within the internationally accepted limit of 1 mSv/y, as reported by UNSCEAR [21]. The radiological health hazards associated with both parameters remain insignificant, as both measured values are below 1 mSv/y. The findings indicate that the mean annual effective dose equivalent for both indoor and outdoor environments is less than the critical limit of 1 mSv/y established by UNSCEAR [21].

The H_{ex} and H_{in} values for all rock samples were within acceptable limits, except for the Andesite tuff rock samples, which exhibited H_{ex} and H_{in} results above one. This indicates that the tested rocks are generally safe for use as building materials for housing, with the exception of the Andesite tuff rock samples, according to the radiation safety report 112 [17].

The values of the Excess Lifetime Cancer Risk (ELCR) ranged from 0.04562 to 0.68589, with an average of 0.27701. The results indicate a lifetime cancer risk of less than 1 for all

types of building rocks. This average ELCR value is below the globally recommended limit (UNSCEAR, 2000) [42]. The Annual Gonadal Dose Equivalent (AGDE) values varied between 0.0728 and 1.12417 mSv/y, with a mean of 0.45691 mSv/y. According to the guidelines from the International Commission on Radiological Protection, all rock types, except for Andesite tuff, Volcanic tuff, and Extrusive igneous rocks, are below the safe limit of 0.36 mSv/y. Except for the samples of Andesite tuff rocks, the average values of various radiation hazard indicators such as Ra_{eq}, D_r, D_{eff} (both indoor and outdoor), H_{ex}, H_{in}, ELCR, and AGDE remained below the internationally permissible levels. Figure 6 illustrates the averages of these parameters calculated for the analyzed rock samples.



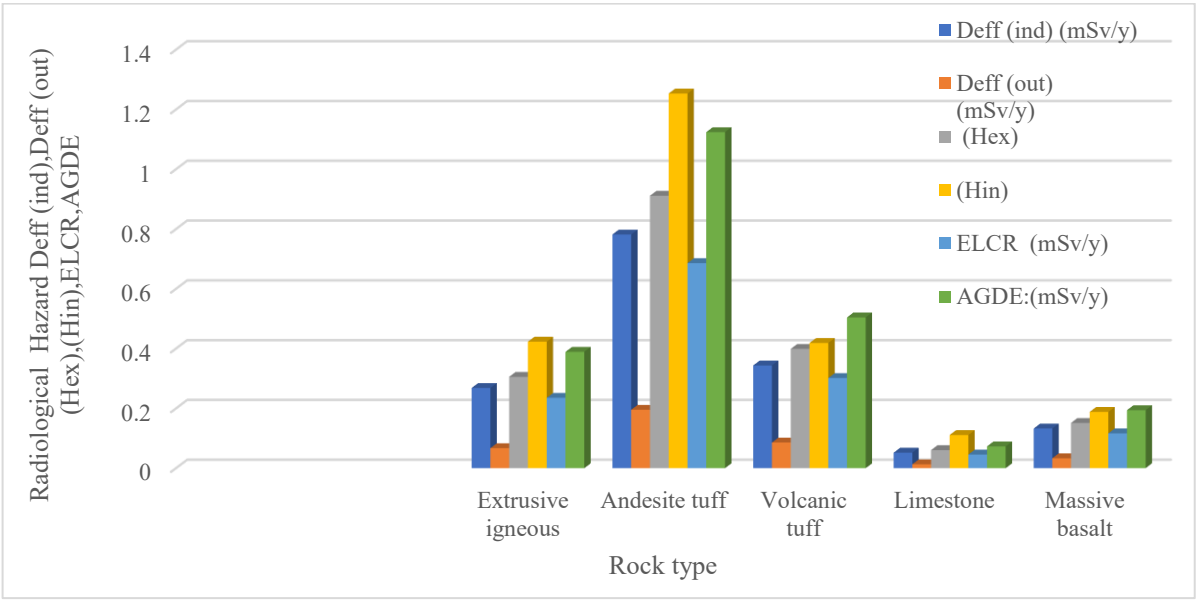


Fig. 6 Shows average radiation hazard indicators in building rock samples

The findings presented in Table 8 indicate significant differences in radiation risk factors among various locations in Yemen. The regions of Abian and Hifan recorded the highest levels of radium equivalent activity (Ra_{eq}), absorbed Dose Rate (D_R), effective dose (both indoor and outdoor), Excess Lifetime Cancer Risk (ELCR), and hazard indices. These values exceed globally recognized thresholds, suggesting that these areas are at a comparatively high radiological risk. Conversely, regions such as northern Sana'a, Shabwa-Hadramaut, and Taiz show intermediate values that are at or slightly above the average global levels. In contrast, the radiation exposure parameters in Lahj and Hadramaut-Mahra are the lowest, indicating minimal radiological risk in those areas.

Table 8. Comparison of radiological hazard indexes of the present study with different regions of Yemen

Region	Raeq (Bq/kg)	DR (nGy/h)	Deff (ind) (mSv/y)	Deff (out) (mSv/y)	ELCR	Hex	Hin	AGDE (mSv/y)
Taiz	280.2	129.9	0.637	0.159	0.559	0.757	0.95	0.917
Shabwah and Hadramout	291.7	136.2	0.668	0.167	0.586	0.788	0.909	0.97
Abyan	2453	1059	5.194	1.299	4.558	6.623	7.45	7.331
Hifan	841	395	1.938	0.484	1.7	2.271	2.574	2.822
Yafea	66.83	31.23	0.153	0.038	0.134	0.181	0.267	0.218
North Sana'a	122	60.96	0.299	0.075	0.262	0.329	0.388	0.444
Aden	237	110	0.54	0.135	0.474	0.64	0.794	0.778
Lahj	130.9	57.65	0.283	0.071	0.248	0.353	0.475	0.397
Hadramout and Maharah	135.2	64.31	0.315	0.079	0.277	0.365	0.479	0.457
max	2453	1059	5.194	1.299	4.558	6.623	7.45	7.331
min	66.83	31.23	0.153	0.038	0.134	0.181	0.267	0.218
average	506.4	227.1	1.114	0.279	0.978	1.367	1.587	1.592
Permissible limits	370	57	0.46	0.07	0.3	<1	<1	0.36

The data show in Table 9 and Figure 7, substantial variability in natural radiation levels risk in the ten locations studied. Italy (Ustica Island) recorded the highest radiological values, which surpassed globally recognized thresholds, indicating potential health risks. Turkey (Cappadocia), India (Chikmagalur), and Egypt (Bir El-Sed) ranked second with relatively high radiation levels. In contrast, Iraq (Kurdistan) demonstrated the lowest values with a rate of 51.91 Bq/kg and a hazard index below the safe limit. The ELCR was significantly higher in the Italian, Indian and Turkish sites, necessitating stringent protective measures for the local population and visitors, especially with regard to long-term internal exposure.

Table 9. Comparison of radiation risk indexes of the current research with various countries. of 226Ra, 232Th, and 40K in the studied

Country	Raeq (Bq/kg)	DR (nGy/h)	Deff (ind) (mSv/y)	Deff (out) (mSv/y)	ELCR	Hex	Hin	AGDE (mSv/y)
Italy (Ustica)	517	237	1.16	0.29	1.02	1.4	1.84	1.66
Egypt (Bir El-sed)	214	102	0.5	0.13	0.44	0.58	0.73	0.73
Yemen, north Sana'a	122	61	0.3	0.07	0.26	0.33	0.39	0.44
Iraq (Kurdistan)	51.9	24	0.12	0.03	0.1	0.14	0.16	0.17
India (around Chickmagalur)	218	102	0.5	0.13	0.44	0.59	0.69	0.73
Turkey(Cappadocia)	259	117	0.58	0.14	0.51	0.7	0.87	0.82
Saudi Arabia(Albaha region)	145	70.3	0.34	0.09	0.3	0.39	0.49	0.5
Tanzania(Oldoinyo Lengai)	192	92.1	0.45	0.11	0.4	0.52	0.66	0.66
Spain(Palma Urcu ravine (Juive))	103	48.1	0.24	0.06	0.21	0.28	0.35	0.34
Yemen (Hadramout and Maharah)	135	64.3	0.32	0.08	0.28	0.37	0.48	0.46

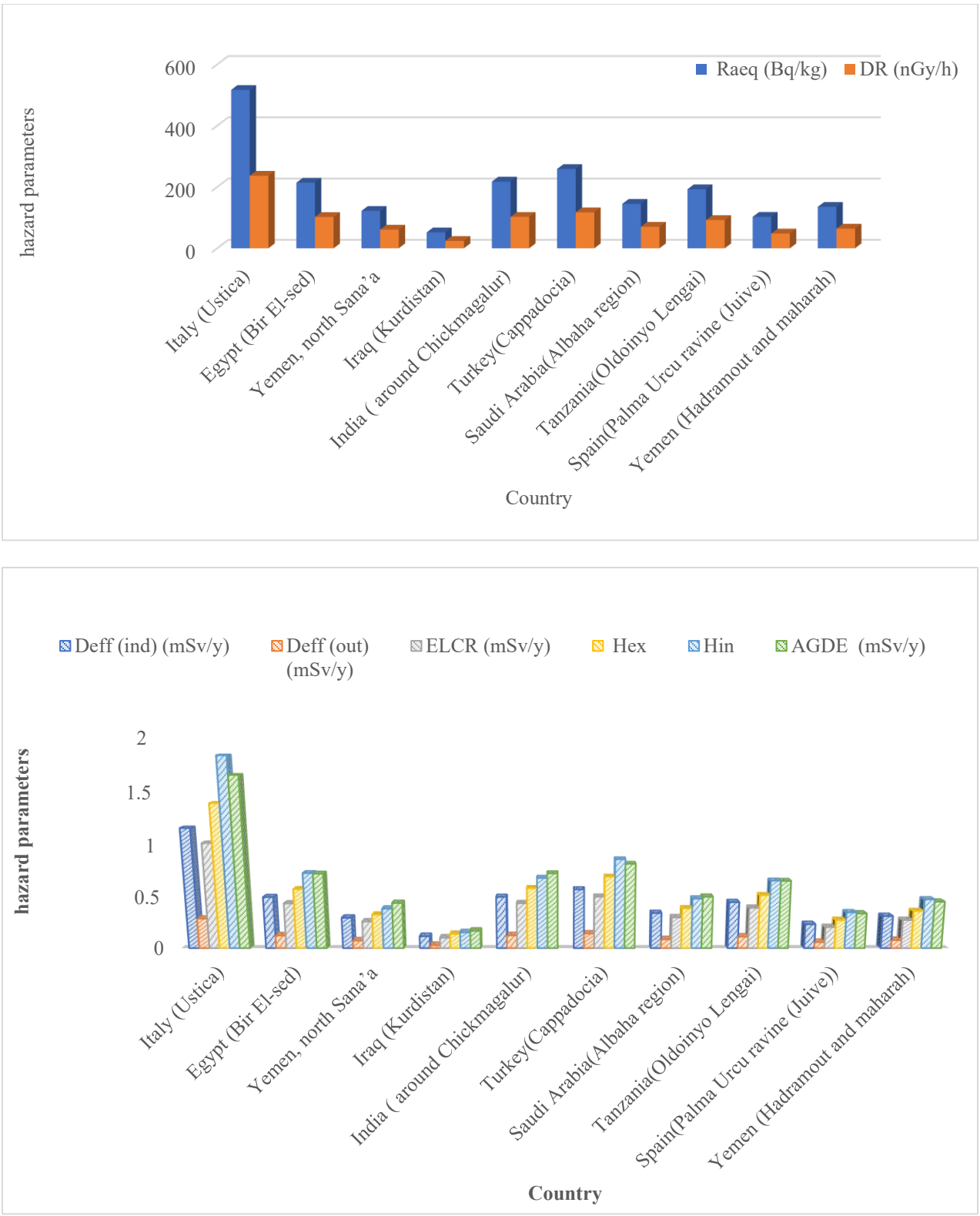


Fig. 7 Comparison of radiation risk indicators of the present work with different countries

The health risks associated with different organs and tissues, both indoors and outdoors, were calculated. This involved substituting the weighting factor (WT) values from Table 3 corresponding to each organ. The results of these calculations are presented in Table 10.

Table 10. Effective dose outdoor and indoor for body organs and tissues (ET) mSv/y

Rock type		Extrusive igneous	Andesite tuff	Volcanic tuff	Limestone	Massive basalt
Gonads	E(outdo)	0.0054	0.0156	0.0069	0.001	0.0027
	E(indoor)	0.0215	0.0625	0.0275	0.0042	0.0106
Bone Marrow	E(outdo)	0.0081	0.0234	0.0103	0.0016	0.004
	E(indoor)	0.0322	0.0938	0.0412	0.0062	0.0159
Stomach	E(outdo)	0.0081	0.0234	0.0103	0.0016	0.004
	E(indoor)	0.0322	0.0938	0.0412	0.0062	0.0159
Liver	E(outdo)	0.0027	0.0078	0.0034	0.001	0.0013
	E(indoor)	0.0107	0.0313	0.0137	0.0021	0.0053
Skin	E(outdo)	0.0007	0.002	0.0009	0.0001	0.0003
	E(indoor)	0.0027	0.0078	0.0034	0.001	0.0013
Lung	E(outdo)	0.0081	0.0234	0.0103	0.0016	0.004
	E(indoor)	0.0322	0.0938	0.0412	0.0062	0.0159

Table 10 and Figure 8 present a comparison of health risks associated with various organs and tissues in both outdoor and indoor environments, depending on the type of rock. The findings show that indoor environments consistently indicate higher risk values than outdoor settings for all analyzed organs, primarily due to the accumulation of radon and its progeny. Additionally, it was noted that the lungs, stomach, and bone marrow exhibit relatively the highest radiation risk compared to other tissues, while the gonads and liver have a moderate risk, and the skin has the lowest radiation sensitivity. Overall, the effective doses calculated for all organs and tissues remain significantly below the public dose threshold of 1 mSv/y, as reported by the ICRP [19].

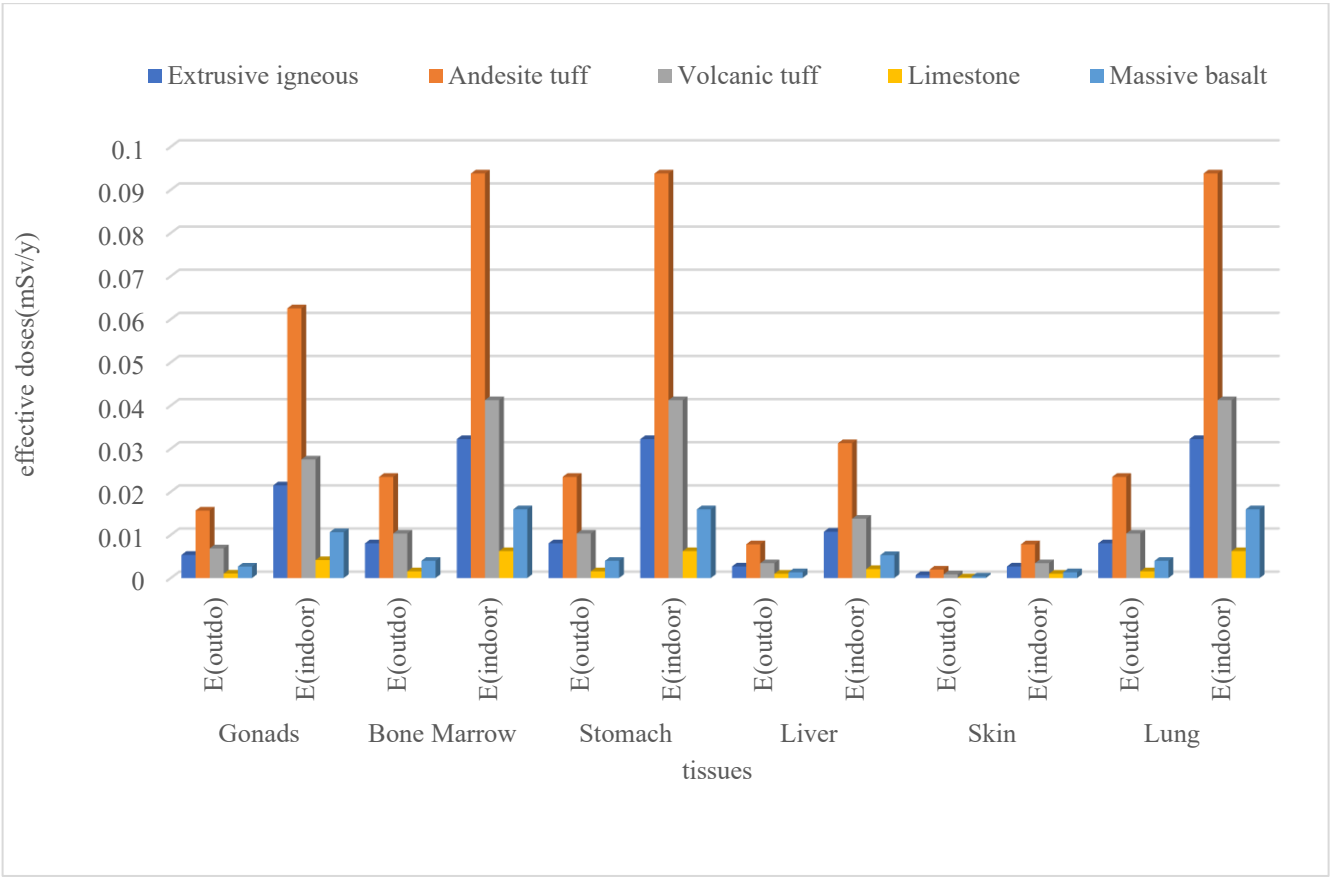


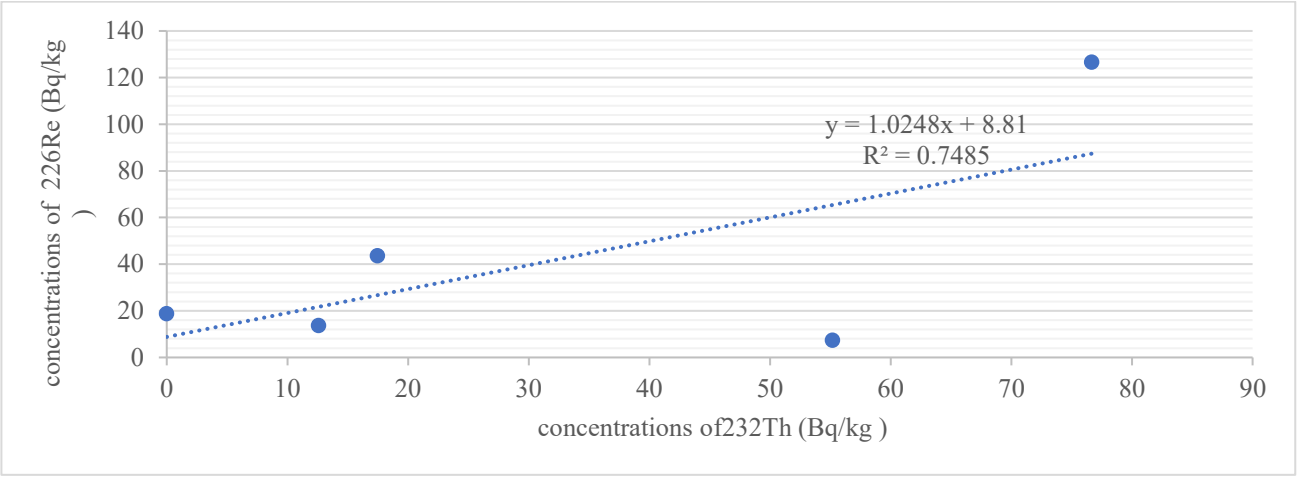
Fig. 8 The comparison of the health risks of tissues

4.3. Correlation Studies

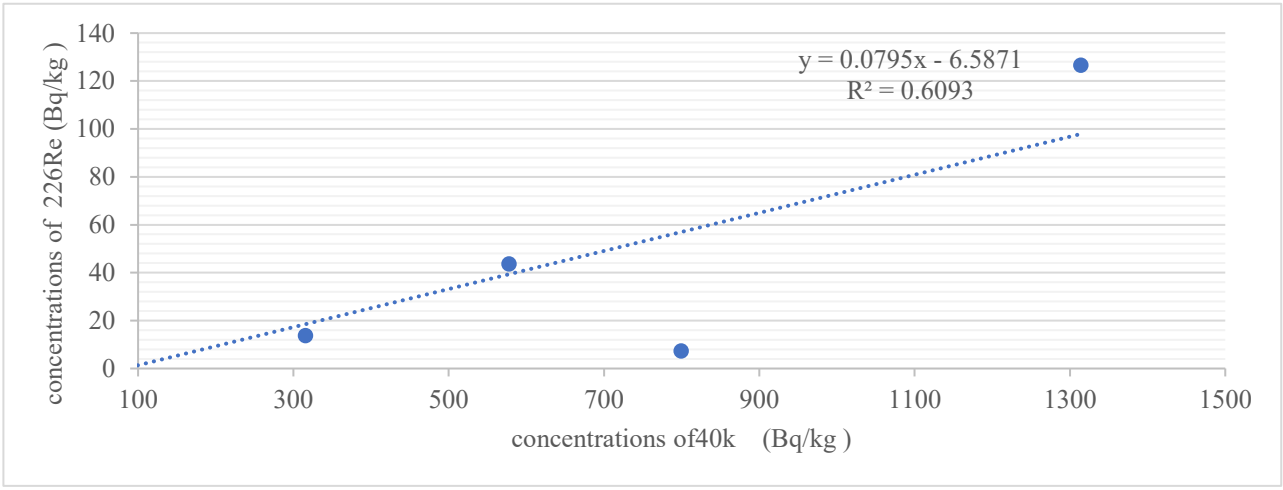
A strong positive correlation was observed ^{226}Ra and ^{232}Th (r = 0.86), indicating that these two nuclides, as illustrated in Figure 9(a). Additionally, the results demonstrate a significant correlation between ^{226}Ra and ^{40}K (r = 0.78), that with ^{232}Th, as shown in Figure 9(b). Table 11 indicates the correlation coefficients between concentrations of ^{226}Ra, ^{232}Th, and ^{40}K and various radiation hazard indicators, including Ra_{eq}, D_R, D_{eff}(in), D_{eff}(out), H_{ex}, H_{in}, ELCR, and AGDE. The correlation coefficients ranged from 0.87 to 0.98, indicating a high and positive correlation between most variables. Figure 10 (a), (b) indicates the relationship between ^{226}Ra and H_{ex}, as well as ^{232}Th and H_{in}. A very strong relationship was observed between the absorbed gamma dose and the excess lifetime cancer risk (r = 1.0) for the rock samples, as shown in Figure 11. This indicates that the excess cancer risk is primarily influenced by the amount of absorbed gamma dose rate. The strong positive correlations observed among the primary radionuclides (^{226}Ra, ^{232}Th and ^{40}K) suggest a possible common geological origin in the studied rock formations. In contrast, the very high correlations observed among the derived radiological hazard indices (Ra_eq, D, H_ex, H_in, I_γ) are due to their mathematical dependence, as they are calculated from the same primary activity concentrations using related equations, and therefore should not be interpreted as independent evidence.

Table 11. The correlation matrix among concentrations of terrestrial radionuclides and radiological indexes in rock samples.

Variable	226Re	232Th	40k
226Re	1		
232Th	0.8602	1	
40k	0.78055	0.9639	1
Raeq	0.88806	0.9884	0.975
DR	0.89485	0.9329	0.977
Deff (ind)	0.88742	0.945	0.977
Deff (out) (mSv/y)	0.88742	0.9329	0.978
(Hex)	0.89314	0.945	0.976
(Hin)	0.94144	0.8788	0.978
ELCR	0.94507	0.8936	0.977
AGDE	0.88238	0.9362	0.979

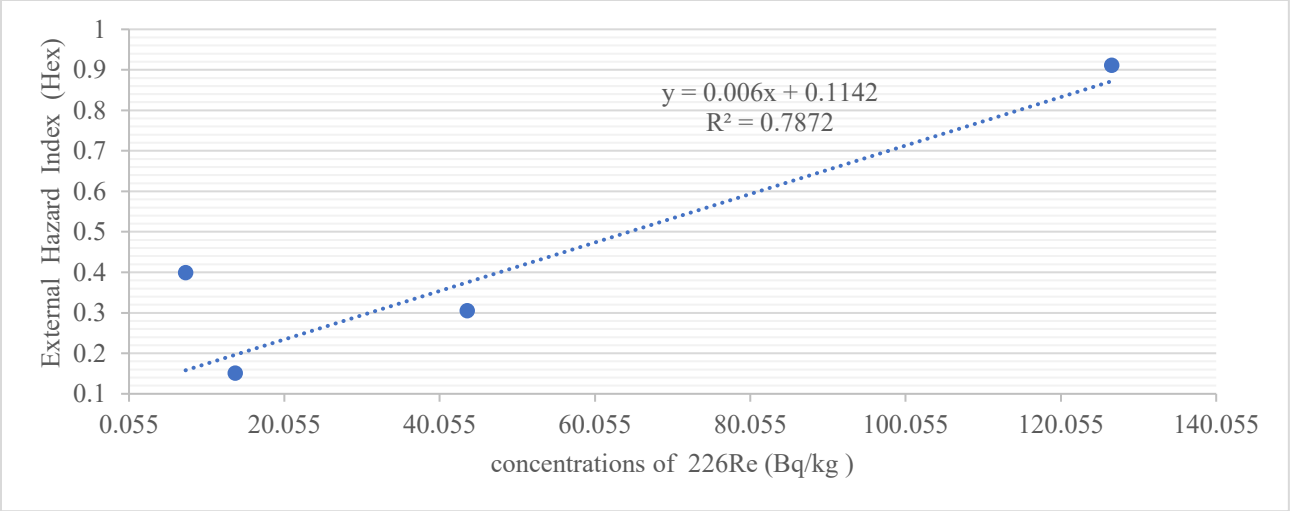


(a)

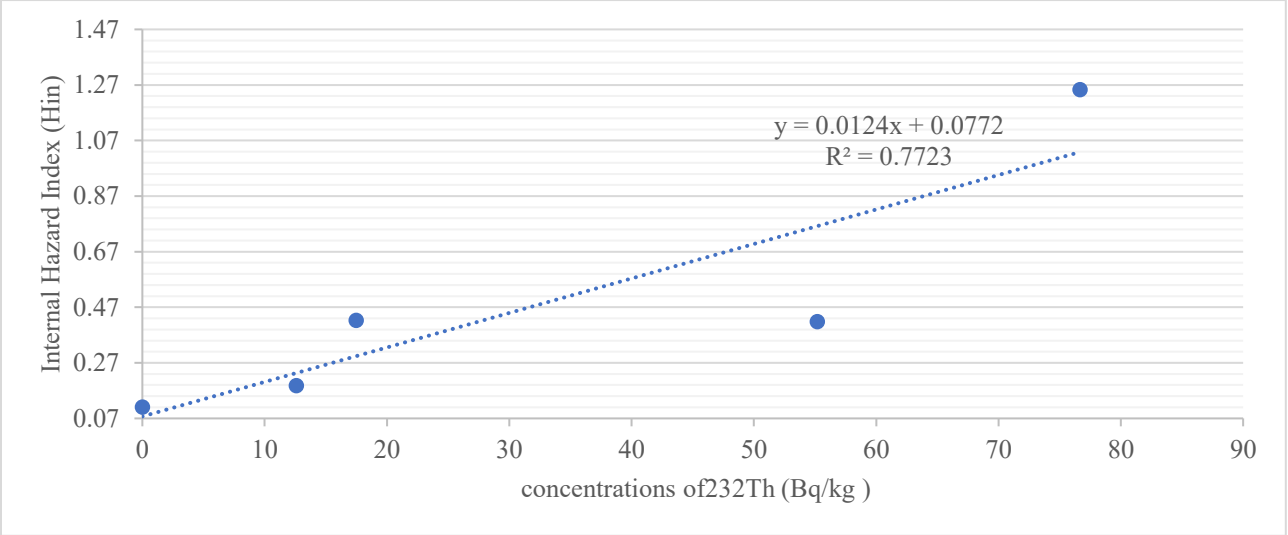


(b)

Fig. 9 Correlation between (a) Thorium and radium concentration (b) Potassium and radium concentration in rock samples



(a)



(b)

Fig. 10 Correlation between (C) radium concentration and Hex (D) thorium concentration and Hin

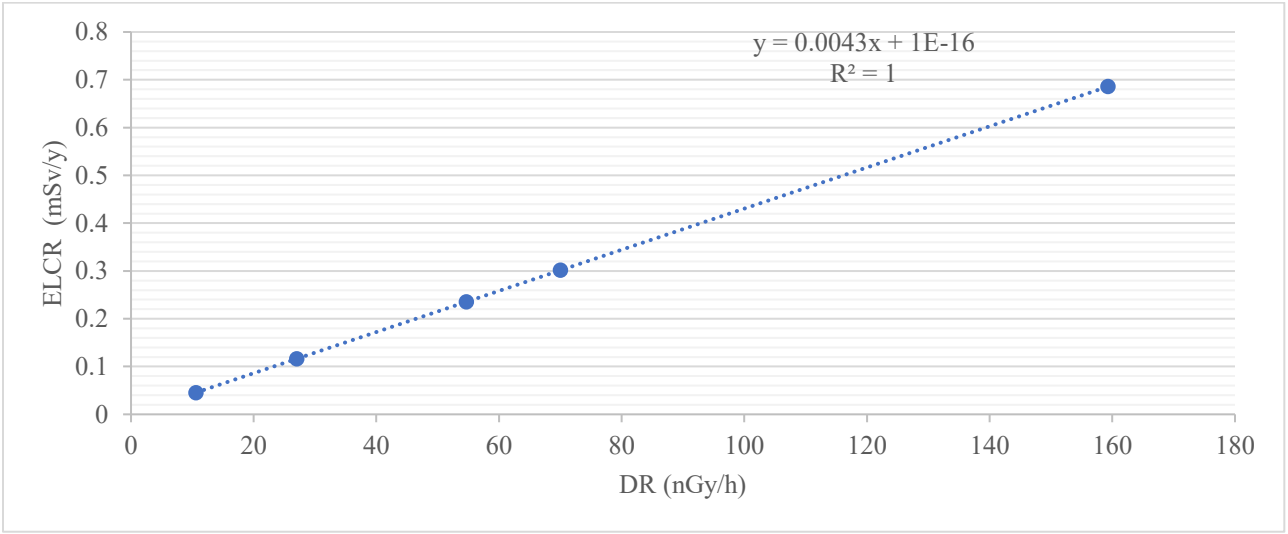


Fig. 11 Relationship among gamma absorbed dose rate and excess lifetime cancer risk

5. Conclusion

A comprehensive analysis of rock samples from Al-Mahra Governorate in Yemen was conducted using an HPGe detector to evaluate their radioactivity levels. The average radioactive measurements showed 41.99 Bq/kg for Ra-226, 32.38 Bq/kg for Th-232, and 610.9 Bq/kg for K-40.

These results were compared with global averages of 35 Bq/kg for Ra-226, 30 Bq/kg for Th- 232, and 400 Bq/kg for K-40, which are slightly above global averages but still within internationally permissible limits, and lower than those recorded in several other regions of Yemen. The study found higher concentrations of radionuclides in Andesite tuff rocks and lower levels in limestone. Radiological risks were evaluated by calculating several radiation hazard parameters, such as Raeq, Dr, Hin, Hex, AEDE, AGDE, and ELCR, for assessing radiation threats to the public and revealing moderate to low radiation values compared to other regions, indicating reduced health risks. Hazard indicators (Hex and Hin) remained within internationally sanctioned limits, suggesting reduced health risks from natural radiation exposure. The evaluation of health risks related to various tissues and organs revealed that the radiation exposure is significantly below the established public dose threshold of 1 mSv/year, as recommended by the ICRP. Al-Mahra region is not characterized by high radiation hazards compared to other regions in Yemen. The radiation levels in these areas are considered relatively safe. Correlation analysis showed a strong relationship between the concentrations of radionuclides and radiation hazard indicators. Overall, rock samples from Extrusive igneous, Volcanic tuff, limestone, and Massive basalt were found to be safe for use as building materials as their hazard indices were below the recommended limits. However, Andesite tuff samples with an average of 126.6 Bq/kg for ^{226}Ra, 76.66 Bq/kg for ^{232}Th and 1314 Bq/kg for ^{40}K showed an internal hazard index (Hin) of 1.25 exceeding unity, and therefore this rock type is not recommended for construction purposes, and its quarry should be restricted.

Conflicts of Interest

The authors declare no competing interests.

Funding Statement

No funding.

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