Natural Radionuclides Concentrations and Associated Radiation Hazard of Some Building Rocks Used in Taiz City, Yemen

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Abstract:

Building materials comprise a diverse range of natural rocks that contain varying mineral components including radionuclides. Gamma spectrometry-based high-purity Germanium detectors were utilized to measure the activity concentrations of natural radionuclides: Radium-226 (^{226}Ra), Thorium-232 (^{232}Th), and Potassium-40 (^{40}K) in various building rock samples found within and surrounding Taiz city. The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K vary from 27.79 ± 0.77 to 234.49 ± 3.13 Bq.kg^{-1}, 25.82 ± 0.40 to 415.31 ± 2.47 Bq.kg^{-1}, and 457.912.61± to 1139.56 ± 5.43 Bq.kg^{-1} with overall average value of 71.55 Bq.kg-1, 93.87 Bq.kg-1, 966.88 Bq.kg^{-1} respectively, these values were higher than the permissible thresholds. Furthermore, several radiation hazard indices were estimated including the radium equivalent (Ra_{eq}), the external hazard index (H_{ex}), the internal hazard index (H_{in}), the gamma level index (I_{γ}), the dose rate(D_{γ}), the annual effective dose equivalent (AEDE), the excess lifetime cancer risk (ELCR), and the annual gonadal dose equivalent (AGDE). The findings illustrated that Basalt rocks have the minimum values of radiation hazard indices while the Himatite rocks have the maximum values of radiation hazard. The average values of radiation risks for most of building rocks fall below the recommended limits for safety. Based on the Radiation hazard indices of building rock samples, it can be concluded that with the exception of hematite rocks, all the examined rocks are considered safe for use in construction materials and pose non-significant radiation risks. The awareness about natural radioactivity levels of building rocks is critical for planning and performing strategies in radiation safety of buildings.

Keywords: natural radionuclides, radiation hazard, building rocks.

دراسة تركيز النظائر الطبيعية المشعة ومخاطر الاشعاع الناتجة عنها في بعض الصخور المستخدمة في البناء بمحافظة تعز، اليمن

الملخص:

تشمل مواد البناء مجموعة متنوعة من الصخور الطبيعية التي تحتوي على مكونات معدنية وعناصر مختلفة بما في ذلك النظائر الطبيعية النشطة اشعاعيا. وقد هدفت هذه الدراسة الى قياس تركيز بعض النظائر المشعة الموجودة في بعض صخور (أحجار) البناء المستخدمة في محافظة تعز اليمنية وكذلك تقييم المخاطر الصحية الاشعاعية الناجمة عن التعرض الاشعاعي المنبعث من تلك النظائر المشعة. حيث تم استخدام نظام كاشف الجرمانيوم عالي الدقة لقياس تراكيز النظائر الطبيعية المشعة: الراديوم ٢٢٦ (^{226}Ra)، الثوريوم ٢٣٢ (^{232}Th)، والبوتاسيوم ٤٠ (^{40}K) لدى عينات من صخور احجار البناء المختلفة الموجودة في مدينة تعز والمناطق المحيطة بها. وقد اشارت نتائج الدراسة الى ما يلي: تتراوح تراكيز النشاط الاشعاعي لنظائر عناصر: الراديوم ٢٢٦ (^{226}Ra)، الثوريوم ٢٣٢ (^{232}Th)، والبوتاسيوم ٤٠ (^{40}K) : من ٢٧.٧٩ ± ٠.٧٧ إلى ٢٣٤.٤٩ ± ٣.١٣ بيكريل لكل كيلوغرام (Bq/kg)، من ٢٥.٨٢ ± ٠.٤٠ إلى ٤١٥.٣١ ± ٢.٤٧ بيكريل لكل كيلوغرام (Bq/kg)، ومن ٤٥٧.٩١ ± ٢.٦١ إلى ١١٣٩.٥٦ ± ٥.٤٣ بيكريل لكل كيلوغرام (Bq/kg) على التوالي، وهذه القيم تعتبر أعلى من القيم الحدية للجرعات الاشعاعية الممكن التعرض لها حسب معايير السلامة من المخاطر الاشعاعية المعتمدة عالميا. علاوة على ذلك، تم حساب عدة مؤشرات لتقييم المخاطر الإشعاعية الناتجة عن التعرض لإشعاعات النظائر المشعة في الصخور المستخدمة في البناء وشملت: مؤشر مكافئ الراديوم (Ra_{eq})، ومؤشر خطر الاشعاع الخارجي (H_{ex})، ومؤشر خطر الاشعاع الداخلي (H_{in})، ومؤشر مستوى الجاما (I_{γ})، ومعدل الجرعة الاشعاعية (D_{γ})، ومتوسط الجرعة الفعالة السنوية (AEDE)، ومؤشر خطر الإصابة بالسرطان خلال الحياة (ELCR)، ومؤشر متوسط الجرعة الاشعاعية السنوية للغدد التناسلية (AGDE). حيث أظهرت نتائج حسابات هذه المؤشرات أن صخور البازلت لديها أقل القيم لمؤشرات الخطر الإشعاعية بينما أظهرت صخور الهيماتيت أعلى قيم لمؤشرات الخطر الإشعاعية. كما تراوحت القيم المتوسطة للمخاطر الإشعاعية لمعظم صخور (احجار) البناء دون الحدود الموصى بها للسلامة الاشعاعية. وبناءً على نتائج مؤشرات المخاطر الاشعاعية لعينات صخور احجار البناء التي شملها هذا البحث، يمكن الاستنتاج بأن جميع الصخور التي تم دراستها، باستثناء صخور الهيماتيت، تعتبر آمنة للاستخدام في مواد البناء وتشكل مخاطر إشعاعية معقولة وغير معتبرة. إضافة الى ذلك فان الوعي بمستويات الإشعاع الطبيعي المنبعث من مكونات وعناصر صخور البناء أمر هام للتخطيط الحضري وتنفيذ استراتيجيات السلامة الإشعاعية في المباني.

الكلمات المفتاحية: النظائر الطبيعية المشعة، المخاطر الإشعاعية، صخور البناء.

1. Introduction

The surrounding environment contains trace amounts of unstable elements known as radioisotopes, originating from primordial and anthropogenic sources [1]. In the indoor environments, the majority of radiation exposure is attributed to the natural radionuclides in building materials, which could pose a potential health risk to humans [2, 3, and 4].

The natural radioactivity of building materials is typically determined by assessing the concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, it is worth noting that the activity of ^{226}Ra or any of its decay products represents approximately 98.5% of the total activity of uranium-238 (238U). Rocks' accessory minerals have the capability to produce significant quantities of radon gas in the atmosphere [5].

The evaluation of the impacts of radiation exposure originating from terrestrial sources hold paramount significance for human health and environmental. Moreover, the quantification of radiation exposure from natural radionuclides plays a crucial role in the development of safety standards and guidelines [6].

Some studies have been conducted on radioactivity measurements in building materials [3, 7]. The determination of radionuclides concentrations and radioactivity for building rocks is very important due to the potential health risk and civil planning strategies. As well to increase public awareness about its hazards to their health. This study specifically focuses on measuring the natural radioactivity levels of radionuclides: ^{226}Ra, ^{232}Th, and ^{40}K for building rocks commonly used for constructing houses in Taiz city. In addition, this work aims to estimate the associated radiation hazard impacts.

2. Materials and Methods

2.1 Study area

The study area is situated in the Taiz region, located in the southwestern of Yemen. The area is positioned approximately between latitudes 13.5° and 14°, and longitudes 44° and 45°. The elevation of the study area ranged between 1400 to 3000 m above sea level.

2.2 Collection and preparation of rock samples

The building rocks were collected from different sites in and around Taiz city, considering rock types variations and distribution within the study area. A total

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of 21 rock samples from different quarries in study area have been studied including different rocks types such as sandstone, Diorite, Rhyolite, Hematite, Porphyry Rhyolite, Granodiorite, and Basalt rocks. The study samples include different contexts, and provide a reasonable coverage of rock types, from each sampling location, about 2 kg of the rock's sample was collected.

Subsequently, each sample was washed and dried. Afterwards, the rocks were crushed and ground into small pieces and sieved through 500 μm mesh. The samples were weighed, packed in 250 cm^3 plastic container, and allowed to reach secular equilibrium over a period of six weeks. In this equilibrium state, the rate of decay of the daughter isotopes equals that of the parent isotope before being taken for analysis by gamma ray spectrometric [8].

2.3 Experimental technique procedures of radioactivity measurements

The activity concentration of the of ^{226}Ra, ^{232}Th, and ^{40}K activities in rocks samples were estimated using γ-ray spectrometry. The high purity germanium HP(Ge) detector was coupled to a PC-MCA and shielded by a cylindrical lead shield with a fixed bottom and movable cover to reduce gamma ray background. The data acquisition was performed using Gamma Vision software (Version 5.1, EG&G ORTEC) on a multichannel analyzer (MCA). The Canberra GC-6020 HP(Ge) detector with relative efficiency of 60% at 1.33 MeV 60Co, and energy resolution of 2.4 keV full width at half maximum (FWHM) for the 1332.5 keV gamma ray line of 60Co. The instrument is calibrated using a standard source of known activity of ^{226}Ra of the same geometry, the known gamma ray energy lines emitted were used for energy and efficiency calibration of the spectrometer. The detection system is shown in Figure1.

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Figure 1: The detection system

The gamma ray is measured from rocks by placing the sample in the sensitive volume of the detector where all photons that interact with the material within the sensitive volume are registered. The measurements are carried out, after that the peak areas in the spectrum are calculated to avoid the loss of counting. The count rates and the activity per mass unit were calculated for each photopeak based on spectrum analysis.

2.4 Activity concentrations

The activity concentration was determined by analyzing the energy transitions of each radionuclides using the following equation [9].

$$A = Np / (\varepsilon \times \eta \times m) \qquad (1)$$

Where Np = the (cps) sample – (cps) background, ε the abundance of the gamma line in radionuclide, η the detector efficiency of the specific γ-ray and m the mass of the sample (Kg).

Radiation hazard indices

To illustrate the radiation risk associated with the studied radionuclides, which present in the rocks, various types of hazard indices were calculated as follows:

Radium equivalent (Ra_{eq})

This parameter estimates the total activity of all radionuclides present in rocks, serving as an indicator of potential radiation hazard. Ra_{eq} relies on the concentrations of ^{226}Ra, ^{232}Th and ^{40}K. Ra_{eq} has been defined by Beretka and Mathew (1985) and was calculated using relation [8, 12].

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (2)$$

Where A_{Ra}, A_{Th} and A_K are the specific activities of ^{226}Ra, ^{232}Th and ^{40}K in $Bq.kg^{-1}$ respectively. The Ra_{eq} is related to the external gamma dose and internal dose due to radon and its daughters.

The recommended maximum activity level of Ra_{eq} in materials corresponding to annual dose of 1.5 mGy in order to maintain the activity < 370 $Bq.kg^{-1}$[10].

External hazard (H_{ex}): This parameter estimates the external radiation hazard associated with building rocks and is calculated based on the gamma radiation dose rate at a distance of 1 meter from the rocks' surface. To keep the radiation hazard insignificant, this index value must be less than unity, The external hazard index (Hex) was calculated using relation as follows [11]:

$$H_{ex} = A_{Ra} / 370 + A_{Th} / 259 + A_K / 4810 \quad (3)$$

Internal hazard (H_{in}): This indicator estimates the internal exposure to radon and its daughter products and given by Beretka and Mathew equation (1985) as follows:

$$H_{in} = A_{Ra} / 185 + A_{Th} / 259 + A_K / 4810 \quad (4)$$

H_{ex} and H_{in} must not exceed the limit of unity for the radiation hazard to be acceptable [12].

Gamma index (I_γ): This parameter estimates the potential gamma radiation dose rate from building rocks and is calculated based on the combined impact of radium-226, thorium-232, and potassium-40 in the rocks as radiological hazard associated with rock [13]:

$$I_\gamma = A_{Ra} / 300 + A_{Th} / 200 + A_K / 3000 \quad (5)$$

Thus, I_γ can be used for identifying safe materials for construction purpose.

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Absorbed dose rate (D_γ):

This parameter estimates the radiation dose that an individual may receive from exposure to building rocks and is calculated based on the gamma radiation dose rate in air at a distance of 1 meter above the ground surface according to UNSCEAR guidelines using the following formula [11]:

$$D_\gamma = 0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K \quad (6)$$

Where D_γ is the absorbed dose rate in $nGyh^{-1}$. The coefficients 0.462, 0.604, and 0.0417 are the activity concentration to dose rate conversion factors of A_{Ra}, A_{Th}, and A_K, respectively, in $nGy.h^{-1}$ per Bq.kg-1. [11].

Annual effective dose equivalent (AEDE): The average outdoor and indoor annual effective dose rate is calculated using the formulas [7, and 8]. Annual effective dose equivalent considers the outdoor and indoor occupancy factor (OF) 0.2 and 0.8 respectively.

$$\text{AEDE (outdoor) } (mSv\ y^{-1}) = \text{Dose rate } (nGy\ h^{-1}) \times 8760\ h/y \times 0.7 \times 10^{-6}\ Sv\ Gy^{-1} \times 0.2 \quad (7)$$

$$\text{AEDE (indoor) } (mSv\ y^{-1}) = \text{Dose rate } (nGy\ h^{-1}) \times 8760\ h/y \times 0.7 \times 10^{-6}\ Sv\ Gy^{-1} \times 0.8 \quad (8)$$

Where 0.7×10^{-6} Sv.y-1 the conversion factor (CF) from absorbed dose rate in air to effective dose for the adults, and 8760 h/y is the annual time spent in the building in hours [11].

Excess lifetime cancer risk (ELCR): This parameter estimates the lifetime risk of developing cancer as a result of exposure to radionuclides present in rock samples and is calculated based on the annual effective dose equivalent and the current risk coefficients for radiation-induced cancer.

Additionally, the excess lifetime cancer risk (ELCR) was calculated using the following equation [9]:

$$\text{ELCR} = \text{AEDE} \times \text{DL} \times \text{RF} \quad (9)$$

Where AEDE represents the annual effective dose equivalent, DL is the duration of life (assumed as 70 years), and RF is the risk factor (0.05 Sv^{-1}) which is defined as the fatal cancer risk per Sievert for the public [14, 15].

Annual gonadal dose equivalent (AGDE): This parameter estimates the radiation dose that the gonads may receive from radiation exposure and is calculated based on the gamma radiation dose rate and the energy absorption coefficient of the gonads. AGDE is calculated using the following formula [16].

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$$\mathbf{AGDE\ (mSv/y) = (3.09A_{Ra} + 4.18A_{Th} + 0.314A_{K}) \times 10^{-3}} \qquad (10)$$

3. Results and Discussion

3.1 Radioactivity measurements results

The activity concentrations of natural radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) in seven commonly used building rocks in Taiz, Yemen, were quantified in this study. The radioactivity concentrations of radium-226 (^{226}Ra) in building rocks samples are presented in Table 1. For Sandstone rocks samples the activity concentration of ^{226}Ra varies from 76.401.54± Bq.kg^{-1} to 83.041.30± Bq.kg^{-1} with average value of 79.771.42± Bq.kg^{-1}. Similarly, the activity concentration of ^{226}Ra For Porphyry Rhyolite rocks varies from 48.22 ±1.10 Bq.kg^{-1} to 82.60 ±1.81 Bq.kg^{-1} with average value of 63.161.56± Bq.kg^{-1}. On the other hand, Rhyolite rocks samples activities ranged between 40.900.94± Bq.kg^{-1} and 84.741.76± Bq.kg^{-1} with average value of 67.9751.29± Bq.kg^{-1}. Respectively. The activity concentration of ^{226}Ra in Hematite rocks varies from 70.77 ± 1.12 Bq.kg^{-1} to 234.49 ± 3.13 Bq.kg^{-1} with average value of 152.632.13± Bq.kg^{-1}. For the Diorite samples, the activity values varies from 46.94 ±1.97 Bq.kg^{-1} to 68.49 ± 1.21 Bq.kg^{-1} with an average value of 50.711.41± Bq.kg^{-1}. In the Basalt rocks samples, the values varied from 27.79 ± 0.77 Bq.kg^{-1} to 40.73 ± 1.19 Bq.kg^{-1} with a mean value of 35.350.97± Bq.kg^{-1}. The activity concentration for Granodiorite rocks samples varied from 27.81 ± 1.19 Bq.kg^{-1} to 61.35 ± 1.02 Bq.kg^{-1} with average value 51.271.34± Bq.kg^{-1}.

Table 1: Activity concentrations of ^{226}Ra in building rocks

Rocks Type	^{226}Ra Activity (Bq/Kg)		
	Minimum	Maximum	Average
Sandstone	76.40±1.54	83.04±1.30	79.77±1.42
Porphyry Rhyolite	48.22±1.10	82.60±1.81	63.16±1.56
Rhyolite	40.90±0.94	84.74±1.76	67.975±1.29
Hematite	70.77 ± 1.12	234.49 ± 3.13	152.63±2.13
Diorite	46.94 ±1.97	68.49 ± 1.21	50.71±1.41
Basalt	27.79 ± 0.77	40.73 ± 1.19	35.35±0.97
Granodiorite	27.81 ± 1.19	61.35 ± 1.02	51.27±1.34
	Average		**71.55**
	Worldwide average		**50**

From the results, the highest values of ^{226}Ra radioactivity were found in Hematite rocks samples. The elevated levels of natural radionuclide ^{226}Ra in hematite rocks can be attributed to their geological formation processes and the presence of the uranium-238 (^{238}U) decay series, as radium-226 is one of the decay products of uranium-238. In addition, Hematite rocks have the ability to effectively incorporate radium into their crystal structure. [17, 18]. In contrast, compared to other investigated rocks, the concentration of ^{226}Ra in Basalt rocks was relatively low. This finding is supported by some previous studies such as Novikov, et al. (2021) and Al-Malabeh & Al-Bataina (2021) studies [19, 20]. This result may be attributed to the relatively lower levels of uranium and thorium present in Basalt rocks, which are the key sources of ^{226}R. The average values of ^{226}Ra concentration for building rocks samples were higher than the average international radioactivity levels of ^{226}Ra (50 Bq/kg) [11, 21].

The Thorium-232 (^{232}Th) concentrations for all samples studied are shown in Table 2. The results varied from 81.76 ± 0.89 Bq.kg^{-1} to 98.43 ± 1.03 Bq.kg^{-1} with an average value of 91.29 ± 0.83 Bq.kg^{-1} for Sandstone samples and from 58.99 ± 0.68 Bq.kg^{-1} to 105.60 ± 1.28 Bq.kg^{-1} with an average value of 75.061.03± Bq.kg^{-1} for Porphyry Rhyolite samples, from 77.67 ± 0.86 Bq.kg^{-1} to 96.10 ± 1.19 Bq.kg^{-1} with an average value of 81.330.89± Bq.kg^{-1} for Rhyolite samples. The corresponding value for Hematite and Diorite is from 82.90 ± 0.76 to 415.31 ± 2.47 Bq.kg^{-1} with an average value of 249.1051.62± Bq.kg^{-1}, and from 43.21 ± 1.24 Bq.kg^{-1} to 91.89 ± 0.86 Bq.kg^{-1}with an average value of 58.010.93± Bq.kg^{-1}. Similarly, the activity concentration of ^{232}Th for Basalt and Granodiorite from 25.82 ± 0.40 to 56.80 ±0.67 Bq.kg^{-1} with an average value 39.120.62± Bq.kg^{-1} and from 36.47 ± 0.66 to 82.09 ± 0.81 Bq.kg^{-1} with an average value 63.230.75± Bq.kg^{-1} respectively.

Table 2: Activity concentrations of 232Th in building rocks

Rocks Type	Th^{232} Activity (Bq/Kg)		
	Minimum	**Maximum**	**Average**
Sandstone	81.76 ± 0.89	98.43 ± 1.03	91.29 ± 0.83
Porphyry Rhyolite	58.99 ± 0.68	105.60 ± 1.28	75.06±1.03
Rhyolite	77.67 ± 0.86	96.10 ± 1.19	81.33±0.89
Hematite	82.90 ± 0.76	415.31 ± 2.47	249.105±1.62
Diorite	43.21 ± 1.24	91.89 ± 0.86	58.01±0.93

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Table 2: continued

Rocks Type	**Th^{232} Activity (Bq/Kg)**		
	Minimum	**Maximum**	**Average**
Basalt	25.82 ± 0.40	56.80 ±0.67	39.12±0.62
Granodiorite	36.47 ± 0.66	82.09 ± 0.81	63.23±0.75
	Average		**93.87**
	Worldwide average		**50**

The presented results in Table 2 revealed that, the highest values of ^{232}Th activities were belong to Hematite rock samples, while the lowest values were found in Basalt rock samples. This result in line with Kamar et al. (2020) who reported higher levels of ^{232}Th in Hematite rocks compared to other rocks types [22]. The lowest values of radioactivity in the Basalt samples may be due to that Basalt rock consists mainly mafic minerals such as pyroxene and olivine which have lower thorium content, in addition, the cooling rate of Basalt lava flows is faster than that of other rock types, which restricts the migration of thorium and other radioactive elements into the rock [23].

Furthermore, the mean value of ^{232}Th was also higher than the average international radioactivity levels of ^{232}Th (50 Bq/kg) [11, 21].

The concentrations of Potassium-40 (^{40}K) radioactivity in the examined building rocks are displayed in Table 3. The ^{40}K concentrations are in the range of 1036.43 ± 4.87–1139.56 ± 5.43 Bq/Kg, 988.36 ± 4.62 –1101.855.42± Bq/Kg, 957.83 ± 6.05 – 1027.527.38± Bq/Kg, 887.36 ± 7.71 – 1028.086.29± Bq/Kg, 957.836.92 1107.47± - 6.05± Bq/Kg, 457.916.63±1044.18 - 2.61± Bq/Kg and 1007.955.13±1029.35 – 6.64± Bq/Kg for Sandstone, Porphyry Rhyolite, Rhyolite, Hematite, Diorite, Basalt, and Granodiorite respectively, with mean value of 1094.74,5.42± ,7.27±1051.21 ,6.25±909.345 ,5.85±1015.92 ,6.91±1044.69 4.38±637.51, and 1014.755.71± respectively.

The highest values of activity concentration of ^{40}K were found in Sandstone rocks, whereas the lowest values were in Basalt rocks samples. Similarly, Karimi et al. (2012 reported that Sandstone rocks had a relatively higher concentration of ^{40}K compared to other rocks types [24]. This result may be attributed to the presence of potassium-rich minerals, such as muscovite and biotite in Sandstone rocks. On the other hand, Basalt rocks have the lowest values of ^{40}K, this is most likely attributable to the lower levels of potassium content present in Basalt rocks when compared to other rocks types [25].

The mean radioactivity concentrations of ^{40}K from quarry rocks were observed to be higher than the world average value of ^{40}K (500 Bq/ kg) [11, 21].

Table 3: Activity concentrations of ^{40}K in building rocks

Type of Rocks	K^{40} Activity (Bq/Kg)		
	Minimum	**Maximum**	**Average**
Sandstone	1036.43 ± 4.87	1139.56 ± 5.43	1094.74±5.42
Porphyry Rhyolite	988.36 ± 4.62	1101.85±5.42	1044.69±6.91
Rhyolite	957.83 ± 6.05	1027.52±7.38	1015.92±5.85
Hematite	887.36 ± 7.71	1028.08±6.29	909.345±6.25
Diorite	957.83±6.05	1107.47± 6.92	1051.21±7.27
Basalt	457.91±2.61	1044.18±6.63	637.51±4.38
Granodiorite	1007.95±6.64	1029.35±5.13	1014.75±5.71
	Average		**966.88**
	Worldwide average		**500**

Based on radioactivity concentrations, the radioisotopes elements in the building rocks samples were defined in this order ^{40}K >^{232}Th > ^{226}Ra. The The higher levels of ^{40}K activity concentrations in the building rock samples may be attributed to the predominant presence of potassium-bearing minerals such as feldspar, orthoclase, muscovite, biotite, and mica in these rocks [26].

The natural radioactivity average found in building rock samples exhibits variation across different sampling locations. This variance is attributed to the differing concentrations of Radium, Thorium, and Potassium present in the rocks structure.

Additionally, the results of this study demonstrated non-uniform distribution of ^{226}Ra, ^{232}Th, and ^{40}K in building rocks, with the concentration levels varying depending on the geological formation type.

3.1.1 Correlation between radionuclides concentrations in building rocks

With regards to the correlation between the radioactivity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in building rocks to understand the presence of these radionuclides together in the rock at a particular location, the Pearson's Correlation Coefficients (r) and its significant have calculated and listed in Table 4.

Table 4: Correlation between radioactivity concentrations

Variables	Correlation Coefficient (r)	p-value
^{226}Ra and ^{232}Th	0.98	$p < 0.01$
^{232}Th and ^{40}K	0.13	$p > 0.01$
^{226}Ra and ^{40}K	0.21	$p > 0.01$

The findings of the correlation analysis showed high positive correlation between ^{226}Ra and ^{232}Th concentrations in building rocks samples ($r = 0.98$; $p < 0.01$). Whereas the results showed positive but weak correlations between ^{232}Th and ^{40}K concentrations, and ^{226}Ra and ^{40}K concentrations with ($r = 0.13$; $p > 0.01$) and ($r = 0.21$; $p > 0.01$) respectively. This result in consistent with Yalcin et al. (2020). Who reported high strong dependency between ^{226}Ra and ^{232}Th concentrations in the rocks while ^{40}K was reported with a lower correlation with other radionuclides concentrations [27]. Consequently, radionuclides exhibiting a positive correlation with the radioactivity concentrations were demonstrating similar behavior and sharing a common origin.

3.1.2 Comparison of the average concentrations of radionuclides in rocks worldwide

The radioactivity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K of building rocks samples in Taiz city were compared with rocks from different environments of the world as it shown in Table 5.

Table 5: Comparison of radionuclides activity values range in different countries

Country	Radioactivity concentrations values range (Bq. kg^{-1})			Reference
	^{226}Ra	^{232}Th	^{40}K	
Brazil	12 - 203	14 - 285	580 - 1253	[28]
Egypt	28 - 118	38 - 91	719 - 2208	[29]
Turkey	16 - 117	13 - 79	114 - 1060	[30]
Cyprus	1 – 588	1 – 906	50 – 1606	[31]
Ghana	6 – 54	18 – 65	65 – 1200	[32]
Pakistan	7 - 53	11 - 96	66 - 1320	[33]
India	29 - 83	38 - 198	346 - 1024	[26]
Saudi Arabia	11 - 53	11 - 60	61 - 395	[34]
World	33 - 50	45 - 50	420 - 500	[11],[21], [35]
Yemen	28 - 235	26 - 415	458 - 1140	Present study

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The radionuclides concentration ranges of the building rocks samples from Taiz city are higher than the world average range.

The ^{226}Ra and ^{232}Th values range were found to be lower than the values rangs of the samples from Cyprus and higher than other countries listed in Table 5. While the ^{40}K values range was found to be lower than the values ranges of the samples from Brazil, Egypt and Cyprus. However, the values range of this study was found to be higher than other samples from other compared countries.

3.2 Radiation hazards indices results

To estimate the radiation hazard for human beings, some of hazards indices were determined such as radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}), internal hazard index (H_{in}), and gamma index (I_{γ}), the absorbed dose rate (D) and the annual effective dose equivalent outdoor and indoor ($AEDE_{out}$,$AEDE_{in}$), excess lifetime cancer risk (ELCR), and annual genetically dose equivalent (AGDE) as it illustrated in Table 6.

Table 6: The Radiation hazard indices for building rock samples

Type of Rocks	Raeq (Bq. kg^{-1})	H_{ex}	H_{in}	I_{γ}	Dose rate (nGy/h)	AEDE (mSv/y) outdoor	AEDE (mSv/y) indoor	ELCR× 10^{-3}	AGDE (mSv/y)
Sandstone	294.60	0.80	1.01	1.09	137.64	0.17	0.68	0.59	0.97
Porphyry Rhyolite	250.94	0.68	0.85	0.93	118.08	0.146	0.58	0.51	0.83
Rhyolite	262.50	0.71	0.89	0.97	122.89	0.15	0.60	0.53	0.86
Hematite	578.87	1.56	1.97	2.05	258.89	0.32	1.27	1.11	1.80
Diorite	214.61	0.58	0.72	0.81	102.30	0.12	0.50	0.4375	0.72
Basalt	140.38	0.38	0.47	0.53	66.54	0.08	0.33	0.28	0.47
Granodiorite	219.82	0.59	0.73	0.83	104.19	0.13	0.51	0.45	0.74
Mean	280.25	0.76	0.95	1.03	130.08	0.16	0.64	0.56	0.92

The radium equivalent (Ra_{eq}) activities resulting from ^{226}Ra, ^{232}Th, and ^{40}K, were determined by applying Eq. (2). The maximum and minimum radium equivalent activities were 578.87 Bq.kg^{-1} and 140.38 Bq.kg^{-1}, respectively, with a mean value of 280.25 Bq.kg^{-1}. These values are deemed safe for construction purposes since is below the recommended limit (370 Bq.kg^{-1}) [11]. This finding reveals that building rocks in Taiz region do not pose a significant radiological hazard except Hematite rocks where its radium equivalent average value is 578.87 Bq.kg^{-1}. The external and internal radiation hazard indices (H_{ex}, H_{in}), and Gamma index (I_{γ}) were determined

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via calculations employing Equations (3), (4), and (5). For radiation risk to be considered negligible, both internal and external radiation hazard index values and gamma index value must be less than one, corresponds to the upper limit of Raeq (370 Bq.kg^{-1}). The Hex, Hin, and I_γ values for all rocks samples within acceptable limits except Hematite rocks samples where H_{ex}, Hin, and I_γ values were upper than unity, and sandstone rocks where H_{in}, and I_γ values were upper than unity slightly. Since the H_{ex} and H_{in} values are lower than unity for most rocks types, most rocks from Taiz city are considered safe according to the Radiation Protection report 112 [36].

In addition, the absorbed dose rate caused by gamma radiations in air was performed for a uniform distribution of radionuclides (^{226}Ra, ^{232}Th, and ^{40}K) using equation (6). The absorbed dose rate in air ranged from 66.55 to 258.89 nGy/h, with an average of 130.08 nGy/h. The results indicate that all rock samples surpass the safety threshold of 55 nGy.h^{-1} suggested by UNSCEAR [21]. Furthermore, by utilizing equations (7) and (8), the outdoor annual effective dose rates varied from 0.08 to 0.32 mSv/year, with an average of 0.16 mSv/year. While the indoor annual effective dose rates were ranged from 0.33 to 1.27 mSv.y^{-1} with an average of 0.64 mSv.y^{-1}. In order for the radiological health risk to be considered insignificant, both values should be below 1 mSv per year [37]. In this study, the average annual effective dose equivalent adheres to the safety threshold of 1 mSv.y^{-1} suggested by UNSCEAR [21].

By utilizing equation (9), the excess lifetime cancer risk was determined considering a life expectancy of 70 years, resulting in a lifetime cancer risk less than 1×10^{-3} for most building rocks in study area. Among the different rock types, hematite rocks exhibited the highest excess lifetime cancer risk of 1.11×10^{-3}.

The measurement of the annual genetically significant dose equivalent (AGDE, mSv y^{-1}) reflects the dose equivalent absorbed by the reproductive organs (gonads) yearly. UNSEAR (2000) considers the gonads, and bone surface cells as the organs of interest in this context. Consequently, the calculation of AGDE resulting from the natural activities of ^{226}Ra, ^{232}Th, and ^{40}K was performed according to eq. (10). The obtained values of annual genetically significant dose equivalent for rocks samples are ranged from 0.47 to 1.8 mSv/y, with an average of 0.92 mSv/y. The results indicate that all rock types except Hematite are below the limit of 1.0 mSv/y according to the recommendations of International Commission on Radiological Protection [15].

With the exception of Hematite rocks samples, the average values of radiation hazard: Ra_{eq}, H_{in}, H_{ex}, I_{γ}, D_{γ}, $AEDE_{in}$, $AEDE_{out}$, ELCR and AGDE were found to be lower than the prescribed international standards. It is recommended to avoid using these particular types of building rocks for construction purposes.

4. Conclusions

Seven types of building rocks samples were analyzed to determine the background radioactivity levels of ^{226}Ra, ^{232}Th and ^{40}K using γ-ray spectrometry with a high-resolution HPGe detector.

The mean activity concentrations attributed to ^{226}Ra, ^{232}Th, and ^{40}K in the collected samples were found to be 71.55, 93.87, and 966.88 Bq/kg respectively.

The minimum values of Radioactivity concentrations were found for Basalt rocks whereas the maximum values were for Himatite rocks.

The natural radioactivity levels of the examined building rocks were above the permissible thresholds although the radiation hazard indices were within the worldwide range.

To estimate the radiation hazard for human beings; the calculations for radium equivalent activity (Ra_{eq}), external hazard index (H_{ex}), internal hazard index (H_{in}), and gamma index (I_{γ}), the absorbed dose rate (D_{γ}) and the annual effective dose equivalent outdoor and indoor ($AEDE_{out}$, $AEDE_{in}$), excess lifetime cancer risk (ELCR), and annual genetically dose equivalent (AGDE) were performed.

With the exception of certain Hematite rock samples that surpass the acceptable threshold, the majority of the collected rock samples exhibit radiation risk indices below the maximum recommended levels for human exposure. Consequently, most of these building rocks can be utilized in building construction without surpassing the proposed criterion level for radioactivity.

The results of this study provide a strong warning against using certain types of rocks from the investigated area as building materials for constructing houses.

Furthermore, there is a need to outline radiation safety legislation by civil planning and construction authorities to monitor the level of radiation exposure in building rocks quarries and radiation protection procedures during building construction.

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