Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2023, 11, 50-75
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Assessment of Radiation Hazard from External and Internal Exposures at Adham and Surroundings in KSA

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How to cite this paper: Al Thobaiti, E. M., Zeghib, S., & Qutub, M. M. T. (2023). Assessment of Radiation Hazard from External and Internal Exposures at Adham and Surroundings in KSA. *Journal of Geoscience and Environment Protection, 11,* 50-75.
https://doi.org/10.4236/gep.2023.116004

Received: May 31, 2023
Accepted: June 16, 2023
Published: June 19, 2023

Abstract

Twenty-eight environmental samples (eight well water, sixteen granitic rocks and four soils) were collected from different parts of Adham governorate (Adham, Haqal and Al-Jaizah), to assess the radiological hazard and cancer risk from different perspectives. Adham is situated in a valley between two granitic mountain chains, where much of water supply for drinking, house use and irrigation comes from wells collecting water rains. The activity concentrations of naturally occurring ^{40}K, ^{226}Ra and ^{232}Th and radionuclides were measured by gamma-ray spectrometry for all samples using RGK-1, RGU-1 and RGTh-1, IAEA reference standards issued by the International Atomic Energy Agency, for detector efficiency calibration. The measured values were utilized to evaluate the internal and external exposures both outdoors and indoors. Different standard room models were adopted for this respect to evaluate the indoor gamma-rays exposure from construction materials as well as internal exposure to radon gas emanating from them. Radon concentration indoors, exceeded the upper reference level in dwellings set at 300 Bq/m^3 by the world health organization, in many scenarios. The mean value of the total excess lifetime cancer risk (due to external exposure from gamma-rays) was 2.29×10^{-3}, above the world average value of 1.45×10^{-3}. Furthermore, the measured radon concentrations in all water samples exceeded the EPA (Environmental Protection Agency) 11.1 Bq·L^{-1} standard for drinking water, ranging from 12 to 38 Bq·L^{-1} with a mean value of 27 Bq·L^{-1}. The total annual effective dose (due to inhalation and ingestion) from radon in water, ranged from 58 to 192 μSv/y (for adults) exceeding the international permissible limit of 100 μSv/y, in seven out of eight samples. According to obtained results, the internal exposure from radon in directly used water from wells, might be the major reason of any suspected radiological health hazard especially in

Haqal. The second reason might be the internal exposure from indoor radon gas inhalation in poorly ventilated dwellings.

Keywords

Radiation Hazard, Cancer Risk, Radon Exposure, Environmental Radioactivity, Gamma Spectrometry

1. Introduction

The natural radioactivity from the environment is being extensively surveyed worldwide due to its radiological effects on human health in the long run. The strength of emitted gamma radiation depends principally on the geological composition of rocks and soils in each region of the world (UNSCEAR, 2000). They contain naturally occurring radionuclides originating from thorium (^{232}Th) and uranium (^{238}U) series as well as ^{40}K. In particular, granitic rocks show a relative enrichment in uranium and thorium. The decay chain portion in ^{238}U series that starts from ^{226}Ra is the most active one from radiological considerations. Therefore, ^{226}Ra is generally referred to, instead of ^{238}U for this series. The mean concentrations worldwide of ^{40}K, ^{226}Ra, and ^{232}Th in the earth's crust are about 505, 50 and 50 $Bq{\cdot}kg^{-1}$, respectively (UNSCEAR, 2000). Radionuclides are present in diverse quantities in water, food, soils, rocks, atmosphere and building materials. Overall, approximately 90% of the planetary crust is composed of igneous and metamorphic rocks, while sedimentary rocks, approximately cover 75% of the surface of the earth (Faure, 1986). External exposure occurs as a result of irradiation by gamma rays; while internal exposure occurs through inhalation (radon gas essentially). In addition, internal exposures occur through ingestion, due to the presence of radionuclides in water, vegetation and soil. Recent studies about different risk factors for lung cancer showed that in never-smokers, the primary risk factor is indoor radon exposure. For ever-smokers, it is the second-ranked risk factor after tobacco (USEPA, 2017; WHO, 2009). Half of the total ionizing radiation that we are exposed to in our lifetime is due to radon exposure, which is the largest source of natural ionizing radiation that comes from the bedrock of the Earth's crust (Ruano-Ravina et al., 2017). Radon gas enters homes through cracks in walls and foundations and through openings after being diffused out of bedrocks and soil. In addition, the use of contaminated well water for household activities and shower causes a release of radon gas into the air and accumulates in indoor houses giving rise to internal exposure through inhalation. Lung cancer may develop due to extended exposure to alpha particles through inhalation of colourless, odourless and tasteless radon ^{222}Rn gas. Recently (Ruano-Ravina et al., 2016) found that the internal exposure to radon by inhalation is associated with epidermal growth factor receptor mutations and may be related to the occurrence of the ALK (anaplastic lymphoma kinase) translocation that is now well-characterized.

There are health concerns about alleged cancer cases in the area of Haqal. According to the newspaper, the principal suspicious agent is water contamination (OKAZ, 2007). In fact, Adham is situated in a valley between mountain chains of granitic rocks as shown by the satellite google picture in **Figure 1**. A detailed geographical and geological description of the area is found in (Abuelnaga et al., 2021). Most water supply for drinking, irrigation and house use comes from many wells (spread over the whole region) used as reservoirs for collecting water from torrential rains and floods flowing through granitic mountains leading to a leaching dissolution of uranium. Huge sedimentary sand (in different water courses) originating from granites erosion is spread out through valleys and used for manufacturing local bricks for dwellings construction. The presence of radionuclides in water, air, soil and in vegetation, caused inhabitants to be subject to both external and internal exposures through different pathways, indoor and outdoor. These exposures are more enhanced for many inhabitants having their dwellings build on—or in proximity to—granitic rocks.

Our work may be considered as a complementary one to previous work about the same area, conducted by (Abuelnaga et al., 2021), who performed natural radioactivity background measurement by car borne gamma spectrometry and located areas of high radioactivity in Haqal, Adham and Al Jaizah. In addition, they measured radon concentrations in seventeen well water using Rad7 and found that they considerably exceeded the international limit 11.1 $Bq \cdot L^{-1}$. In present study, the evaluation of radiological hazard and cancer risk is assessed from a different perspective. The activity concentrations of naturally occurring ^{232}Th, ^{226}Ra and ^{40}K radionuclides were determined for all collected environmental samples (rocks, soils (sediments resulting from erosion) and well water). These were used to evaluate the internal and external exposures both outdoors and indoors. Different standard room models were adopted for this respect to evaluate indoor gamma-rays exposure from construction materials of dwellings as well as internal exposure to radon gas emanating from them. The excess lifetime cancer risk (ELCR) and annual effective dose rate have been evaluated and compared to world averages. In addition, the radiological health hazard from the use of contaminated well water was evaluated and compared with similar work locally and with world averages. Finally, suggested safety measures and recommendations were issued regarding this sensitive and important issue in our present study.

Similar work on environmental radioactivity (due to rocks, soils and water) were performed in different areas of KSA. Recently, Al Mamun et al. investigated radon in groundwater and the associated health risk in northern Saudi Arabia. They concluded that the assessed risk due to radon exposure was in the safe limit set internationally (Mamun et al., 2022). Al-Ghamdi performed radioactivity measurements in twenty groundwater in Al-Baha region of Saudi Arabia. The risk assessment data showed that all water samples were safe and

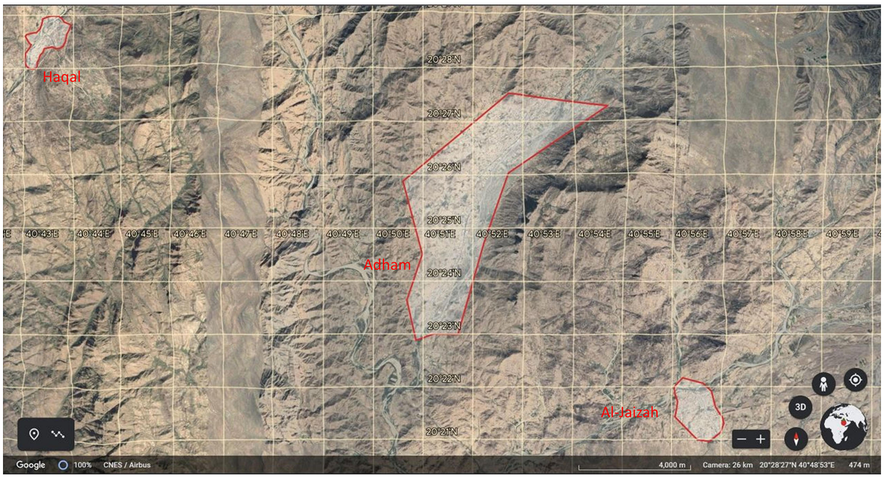

Figure 1. A satellite picture of the three studied areas in Adham Haqal and Al-Jaizah, with their respective longitude and latitude lines.

pose no health risk (Al-Ghamdi, 2019). Althoyaib et al. conducted Rad 7 measurements of natural radioactivity in nineteen groundwater samples from Al-Jawa, Saudi Arabia. The measured concentration of ^{222}Rn ranged from 1.45 to 9.15 Bq·L^{-1} and were below the international limit 11.1 Bq·L^{-1}, using Rad 7 radon detector (Althoyaib et al., 2015).

2. Materials and Methods

2.1. Samples Collection and Preparation

Adham governorate belongs to Makkah province in Southwest of Saudi Arabia. The area of study includes Adam, Haqal and Al-Jaizah and is located along the (40˚40'45" to 40˚59'41") longitude range and (20˚16'00" - 20˚31'00") latitude range. **Figure 1** shows a satellite picture of the three studied areas, which are well defined by their respective longitude and latitude lines. A detailed description of the geologic setting, structure and topography of the studied area was given by (Abuelnaga et al., 2021) (a team from the geological hazard center at King Abdulaziz University-KAU). The three inhabited areas consist mainly of sedimentary basins of granite deposits arising from surrounding mountains as a result of weathering and erosion. A geologic map of Adham governorate issued by the ministry of petroleum and mineral resources is given in Abuelnaga et al., 2021; Ministry of Petroleum and Mineral Resources, 1987.

A total of twenty eight environmental samples were collected from various parts of Adham governorate (Adham, Haqal and Al-Jaizah). These include sixteen granitic rocks, four soils and eight well water samples. The granite samples (each weighing about 2 kg) were prepared for subsequent analysis by crushing them and then sieving them at ~0.25 mm. The water samples were collected initially in sterile high density polyethylene (HDPE) bottles at the site. They were acidified *in situ* with nitric acid to avoid adsorption of radionuclides on the wall of the containers and to prevent any micro-organisms growth. Before measurements, all rock, soil and water samples were kept in tightly sealed polyethylene

Marinelli beakers of volume 500 cm^3 (0.5 liter) each, for a minimum of four weeks, to reach secular equilibrium between ^{226}Ra, ^{232}Th and their progenies. The net masses of all samples were recorded.

2.2. Gamma Rays Spectrometry Measurements

2.2.1. Gamma Spectrometry Using NaI(Tl) Detector

Gamma-rays spectra for all samples have been performed by PC based Multichannel Analyzer (MCA) using NaI(Tl) detector (2.5” × 2.5”). The detector was placed in a well ventilated area. Lead blocks of 5 cm thickness were used for shielding against background radiation. The energy resolution was 6.8% at the 662 keV gamma ray emitted by the ^{137}Cs source. The energy calibration was performed in the range 0.6 to 2.9 MeV using ^{60}Co (1332.5 keV) and ^{137}Cs (661.7 keV) radioisotopes, along with IAEA reference materials for higher energies. The detector efficiency calibration was accomplished using IAEA RGTh-1, RGU-1 and RGK-1 reference radioactive sources (supplied by nuclear engineering at KAU). It is worth noting that similar Marinelli beakers (0.5 liter) for standards and analyzed samples were used under the same geometry conditions and similar matrix. The background spectrum was accumulated for 86400 s (24 hours) with a Marinelli beaker filled with distilled water under identical measurement conditions. All standards and samples spectra were acquired for the same counting time i.e. 32,000 s. Dead time corrections were taken into account when applicable. All measured spectra were analyzed using Computer Assisted Software System for gamma spectrometry analysis. The ^{226}Ra activity was determined from the gamma-ray of ^{214}Bi (1764 keV) (a radon ^{222}Rn progeny), being in equilibrium after ~ 1 month. The ^{232}Th activity was estimated from the gamma ray of ^{208}Tl (2615 keV). The activity concentration for ^{40}K was measured from its gamma peak (1460.8 keV). We have adopted Chiozzi et al. procedure for NaI(Tl) detector efficiency calibration, which takes into account possible interferences of each nuclides (Chiozzi et al., 2000). We used 15% wide ROIs (Region of Interest) centered on the three previous photo-peaks of interest in order to include the full peak area as adopted. The same considerations were applied for the three calibration sources and all measured samples. Similar procedures were adopted by (Rybach et al., 1988; Iqbal et al., 2000; IAEA, 1992) for NaI(Tl) gamma spectrometry of environmental references. The calculation of calibration constants was simplified by the fact that RGK-1 and RGU-1 standard were almost pure K_2SO_4 and U, respectively. Therefore, the U and Th contribution in standard K, and the Th and K contributions in the U standard were negligible. In the Th standard all contributions were taken into account, though K contribution might be neglected. The activity concentration in the Th standards were 6.3, 3250 and 78 Bq/kg for K, Th and U, respectively, while they were <0.63, <4 and 4940 Bq/kg for U standard. K standard has a pure 14,000 Bq/kg activity concentration.

A validation test was performed successfully at KAU Nuclear Engineering department by HPGe gamma spectrometry using the same IAEA reference radioactive sources. A matrix self-absorption correction was applied for water samples for all three gamma rays, though they were very small due to their high energy (i.e. 1460, 1764 and 2615 keV), respectively (Jodłowski, 2006). Jobbágy et al. (2017) made an overview on radon measurement in drinking water and quoted that there are three standard methods for radon measurement in water, which are liquid scintillation counting, emanometry and gamma-ray spectrometry. Due to their superior resolution, HPGe detectors give better qualitative and quantitative results than NaI(Tl) detectors in gamma spectrometry. However, NaI(Tl) detectors have higher detection efficiency and are the favoured choice when the photo-peaks of interest are well separated as in our study of environmental samples, due to their lower price and relatively easy handling (Iqbal et al., 2000).

2.2.2. Gamma Spectrometry Using HPGe Detector

The detector that has been used is a Canberra n-type hyper-pure Germanium (HPGe) detector. It has a 50% relative efficiency with lead shield model 747. High performance DSA-2000 (digital spectrum analyser) provided with Genie 2000 software were used for collecting and analysing spectra. The detector efficiency calibration was achieved using RGTh-1, RGU-1 and RGK-1, IAEA reference radioactive sources. The ^{226}Ra activities were determined from the gamma lines of ^{222}Rn decay products ^{214}Pb (351.9, 295.2 keV) and ^{214}Bi (1120.3 and 609.3 keV) being in equilibrium. The ^{232}Th activities were determined from the gamma peaks of ^{228}Ac (911 and 338.4 keV), ^{212}Pb (238.6 keV) and ^{208}Tl (583.2 keV). The activity concentration for ^{40}K was measured from its gamma peak (1460.8 keV).

2.3. Assessment of Radiological Hazard

2.3.1. Outdoor External Exposure to Gamma Radiation

External exposure affects the whole body. It is caused by gamma-rays originating from ^{232}Th and ^{238}U and their progenies, along with the gamma peak of ^{40}K. Using the conversion factors given by Saito and Jacob, the total outdoor absorbed gamma dose rate (nGy·h^{-1}) in air at a height of 1 m above the ground due to the activity concentrations (Bq·kg^{-1}) of ^{232}Th, ^{226}Ra, and ^{40}K—uniformly distributed in soil—is computed by the formula (Saito & Jacob, 1995; UNSCEAR, 2000):

$$D_{out}\left(\text{nGy}\cdot\text{h}^{-1}\right) = 0.463A_{Ra} + 0.604A_{Th} + 0.0417A_{k} \quad (1)$$

where A_{Th}, A_{Ra} and A_K are the specific activities of ^{232}Th, ^{226}Ra, and ^{40}K in Bq·kg^{-1} respectively. The annual effective dose rate (E_{out}) outdoors is calculated using the following formula:

$$E_{out}\left(\text{mSv}\cdot\text{y}^{-1}\right) = D_{out}\left(\text{nGy}\cdot\text{h}^{-1}\right)\times 8760\left(\text{h}\cdot\text{y}^{-1}\right)\times 0.2\times 0.7\left(\text{Sv}\cdot\text{G}^{-1}\right)\times 10^{-6} \quad (2)$$

where the number 0.2 represents the outdoor occupancy proposed by (UNSCEAR, 2000) and 0.7 Sv·Gy^{-1} is the conversion factor for adults, relating the absorbed dose in air to effective dose. The outdoor excess lifetime cancer risk computed as:

$$ELCR_{out} = E_{out}\left(\text{mSv}\cdot\text{y}^{-1}\right)\times LE\times RF\times 10^{-6} \quad (3)$$

where RF (S·v^{-1}) is the risk factor per Sievert and LE is the life expectancy (70 years). For stochastic effects after exposure to low-dose rate radiation (background), the International Commission on Radiological Protection (ICRP) suggested the value of 5.5 × 10^{-2} S·v^{-1} for the public (ICRP, 2007). In fact, many houses are built on top of rocks and/or nearby the mountain. Evidently, they are more exposed to external radiation than those living far away from the mountain causing a higher outdoor absorbed rate than that computed by Equation (1), due to source geometry effect.

2.3.2. Indoor External Exposure to Gamma Radiation

Indoor exposure to gamma rays is inherently greater than outdoor exposure due to geometry effects if NORM (naturally occurring radioactive materials) are used as building materials. The source geometry changes from half-space outdoors to a surrounding configuration indoors, which leads to enhanced exposure. The indoor exposure to external gamma radiation inside dwellings, from building materials, depends on the activity concentrations of their content from NORM. In addition, it depends on the geometry and dimension of the dwelling, the properties of construction materials such as the elemental composition, density and thickness. Considering a standard room, various researchers have used Monte Carlo simulations to compute the free-in-air dose rate, which resulted from the emission of gamma-rays from the walls, floor and ceiling (Markkanen, 1995; Risica et al., 2001; Mustonen, 1984).

Many dwellings found in the area, used local bricks made of local soils (sedimentary sand from mountains erosion). Few dwellings are built directly with stones cut from local rocks, which are used as bulk building materials. Some houses are built on top of granitic stones. Therefore, we have adopted the configuration of the standard room 4 m × 5 m × 2.8 m with concrete floor and walls with thickness 20 cm, assuming a density of 2350 kg/m^3 and (wooden ceiling or ceiling ignored) (Mustonen, 1984; EC, 1999). The indoor external absorbed dose rates, resulting from gamma rays emitted by ^{232}Th, ^{226}Ra, and ^{40}K radionuclides from the floor and walls of the adopted standard room, was estimated using the formula:

$$D_{ind}\left(\text{nGy}\cdot\text{h}^{-1}\right)=0.67A_{Ra}+0.78A_{Th}+0.057A_{k} \tag{4}$$

where Mustonen's conversion factors for this typical room configuration were used (Mustonen, 1984; EC, 1999). This configuration is compatible with many dwellings found in the area. Similarly, the indoor annual effective dose equivalent ($AEDE$) is obtained using the indoor occupancy factor (0.8) proposed by (UNSCEAR, 2000):

$$E_{ind}\left(\text{mSv}\cdot\text{y}^{-1}\right)=D_{in}\left(\text{nGy}\cdot\text{h}^{-1}\right)\times 8760\left(\text{h}\cdot\text{y}^{-1}\right)\times 0.8\times 0.7\left(\text{Sv}\cdot\text{G}^{-1}\right)\times 10^{-6} \tag{5}$$

The indoor excess lifetime cancer risk is therefore:

$$ELCR_{ind}=E_{in}\left(\text{mSv}\cdot\text{y}^{-1}\right)\times LE\times RF\times 10^{-6} \tag{6}$$

The total excess lifetime cancer risk is therefore:

$$ELCR_{total} = ELCR_{out} + ELCR_{ind} \tag{7}$$

Organs in human body have different sensitivity to radiation described by the weighting tissue factor W_T leading to death or mutation of living cells or a whole organ. The gonads, bone marrow, the bone cells, the thyroid, the lungs and the female breast are among the organs that are much affected by radiation (UNSCEAR, 2000). Therefore, the determination of the annual gonadal dosage equivalent ($AGDE$) is very important for radiation hazard assessment and is defined as (UNSCEAR, 2000):

$$AGDE\left(\mu\text{Sv}\cdot\text{y}^{-1}\right) = 3.09A_{Ra} + 4.18A_{Th} + 0.314A_k \tag{8}$$

Elevated levels of $AGDE$ are found to affect the bone marrow responsible of red blood cells production, leading to leukemia (cancer of the blood), which is often fatal (Tholkappian et al., 2018).

It is worth mentioning that the International Commission for Radiation Protection has assigned gonads the value of 0.08 (ICRP, 2007) instead of the previous value of 0.2 for their tissue weighting factor (ICRP, 2007).

2.3.3. Indoor Exposure to Radon Gas

Internal exposure is from radon inhalation, which causes radon decay products to deposit in the human respiratory tract causing lung cancer eventually. Recent EURATOM regulations have established a new national reference level for radon in residence ≤ 300 (EU, 2014). It is approved to identify existing houses that exceeded the limit level and radon-reducing measures should be implemented accordingly. A realistic widely used approach to assess radon exposure in indoor air, was described in the literature by (Anjos et al., 2011). We have adopted the same standard room (4 m × 5 m × 2.8 m), in which the radon concentration inside, is given by the following formula (Anjos et al., 2011):

$$C_{Rn} = \frac{\frac{E_x S}{V} + C_0\lambda_v}{\lambda + \lambda_v} \tag{9}$$

where C_0 is the concentration of radon ($\text{Bq}\cdot\text{m}^{-3}$) in the outside air, E_x is the exhalation rate per unit area; λ is the decay constant of radon ($7.54 \times 10^{-3}\ \text{h}^{-1}$) and λ_v is the air removal rate due to ventilation (h^{-1}). V is the air volume of the room (m^3), and S (m^2) represents the exhaling area of contributing surfaces (floor, walls and ceiling if applicable). Equation (9) is the steady state solution for the temporal variation of the mass balance linear differential equation for radon concentration inside a single room (Anjos et al., 2011):

$$\frac{\partial C_{Rn}}{\partial t} = \frac{E_x S}{V} + C_0\lambda_v - C_{Rn}\left(\lambda + \lambda_v\right) \tag{10}$$

The radon exhalation rate per unit area, is calculated from the measured ^{226}Ra activity concentration (A_{Ra}) according to the following formula (for dry condition) (UNSCEAR, 1988):

$$E_x = \frac{1}{2} A_{Ra}\lambda\rho\eta d \tag{11}$$

where d is the wall thickness (m), ρ is the material density (assumed 2600 $kg \cdot m^{-3}$) and η is the emanation coefficient that represents the fraction of radon that reaches to the wall surface by diffusion process. The reported typical C_0 value (10 $Bq \cdot m^{-3}$) is considered as a typical value around the world for outside air radon concentration (UNSCEAR, 1988; UNSCEAR, 2000). Al-Jarallah (2001) has reported typical values of radon emanation coefficient (η) in granites ranging from <0.025 to 0.45). For a safe assessment of the exhalation rate, the maximum value of η = 0.45 was used in the calculation as done by (Anjos et al., 2011).

Considering that furniture occupy part of the room volume, the ratio S/V = 2.0 m^{-1} was adopted in this work again (Anjos et al., 2011; Zeghib et al., 2016). However, in rural areas, it is normal to find rooms packed with furniture, luggage, boxes, containers for example, so that the value S/V = 2.5 m^{-1} could be met easily. Therefore, it is legible to consider two scenarios to assess the sensitivity of this parameter in the radon concentration computations by considering the two values of the ratio S/V = 2.0 and 2.5 m^{-1}. To get an insight, the ratio S/V=2 or S/V = 2.5 means that furniture and accessories occupy 37.2 % or 50.3% of the room volume. In addition, we noticed that many dwellings in the studied area, are constructed with locally manufactured bricks from river sand (sediment) originating from the erosion of surrounding granitic mountains. Few are constructed with granitic rocks, especially in rural areas. Therefore, we extended our analysis to include the variation of radon concentration with thickness d (3, 5 and 8 cm). In addition, according to (UNSCEAR, 1988) reports, the values for the rate of air removal duo to ventilation λ_v (h^{-1}) are considered to be between 0.1 h^{-1} and 3 h^{-1} for home residency. For extremely poor ventilation λ_v is considered to be less than 0.1 h^{-1}, while the value of λ_v = 0.5 h^{-1} is considered for adequate ventilation (i.e. for mechanical air exchange systems in the residence) (Anjos et al., 2011). The computation of radon concentration in the standard room was done for (0.1 h^{-1} and 0.5 h^{-1}) λ_v values for all considered samples, to appreciate the important role of the ventilation.

2.3.4. Indoor Exposure to Radon Contaminated Water

The annual effective dose for radon ingestion AED_{ing} in drinking water is evaluated by the following formula (UNSCEAR, 1993, 2000):

$$AED_{ing} = C_{Rn} \times AIW \times EDC \tag{12}$$

where C_{Rn} is the radon concentration in water samples in ($Bq \cdot l^{-1}$). AIW is the annual intake of water (for adults it is 2 litres /day i.e. 730 l/y). For children and infants it is 330 and 230 litres/y, respectively. EDC is the effective dose conversion factors in (nSv/Bq). The adopted values are 3.5, 5.9 and 23 (nSv/Bq) for adults, children and infants, respectively (UNSCEAR, 2000).

Furthermore, the usage of water for showering and other household activities causes radon in water to be released into the indoor air. The annual effective dose for radon inhalation (AED_{inh}) in drinking water is evaluated by the following formula (UNSCEAR, 1993, 2000):

$$AED_{inh} = C_{Rn} \times R_a \times F \times O \times DCF \tag{13}$$

where R_a is the air to water ratio for radon (10^{-4}). It represents the radon in water to air transfer ratio in domestic environment i.e. 10000 to 1. The factor O is the average indoor occupancy time for a person annually (7000h/y). The equilibrium factor F of radon to its decay products is (0.4). DCF is the dose conversion factor for exposure (9 nSv/(Bq·h·m^{-3})). All the values of different parameters were taken from (UNSCEAR, 1993, 2000).

3. Results and Discussion

3.1. Activity Concentrations

Sixteen granitic rocks were collected from different localities of Adham, Haqal and Al-Jaizah. Unfortunately our survey meter did not work. Therefore, we were unable to locate and select the most radioactive granites in the accessible area, guided by the car born gamma spectrometry contour charts. **Table 1** lists the activity concentrations for granitic rocks, keeping in mind that there are others with much stronger radioactivity as proved by car borne gamma spectrometry for the three areas (Abuelnaga et al., 2021).

The measured values of the activity concentrations for granitic rocks were found to lie in the ranges: 12.6 - 83.3, 22.7 - 91.8 and 330.1 - 1209.7 Bq·kg^{-1}, with overall mean values of 47.4 Bq·kg^{-1}, 39.4 Bq·kg^{-1}and 821.3 Bq·kg^{-1}, for ^{232}Th, ^{226}Ra and ^{40}K, respectively. Our measured average values for ^{226}Ra and 232Th are close to the international representative average values for granite stones (45.7 kg^{-1} for ^{226}Ra and 38.0 Bq·kg^{-1} for ^{232}Th) (UNSCEAR, 1993). They were within world average values.

It is worth noting that a validation test has been performed on granite R12 using HPGe detector. The measured activity concentrations were 961, 86, and 28 Bq/kg for ^{40}K, ^{226}Ra and ^{232}Th, respectively. Correspondingly, the NaI(Tl) measurements were 956, 91 and 24 Bq/kg, respectively. These close results show that the adopted technique is adequate. It is worth mentioning that the technique takes into account radionuclide interferences (spectral stripping method) using IAEA references set (Rybach, 1988; Iqbal et al., 2000; IAEA, 1992; Chiozzi et al., 2000). In addition, granites with higher radioactivity surely exist in all three areas of study as was found previously in Ranyah (KSA) by (Zeghib et al., 2016) who described them as anomalous. Unfortunately, in this study, our portable survey meter did not function on site making the collection of granitic rocks random. In reality, car born gamma spectrometry performed by our colleagues (Abuelnaga et al., 2021) detected "hot" areas in Adham, Haqal and Al-Jaizah of which most of them are very difficult to reach. Nevertheless, **Table 2** shows a comparison with other work locally and worldwide about building material.

It is shown in **Table 2** that there are highly radioactive granites world wide, for example in KSA (Zeghib et al., 2016; Fallatah & Khattab, 2023), Greece (Stoulos et al., 2003) and Egypt (Gaafar et al., 2022).

3.2. Outdoor and Indoor Exposure to Gamma Radiations from Rock and Soil Samples

The associated radiation hazard quantities were given in Table 3, which includes the indoor and outdoor absorbed dose rates, annual effective dose equivalent, excess lifetime cancer risk and annual gonadal dose (AGDE).

Table 1. Measured activity concentrations (Bq/kg) of ^{226}Ra, ^{232}Th, and ^{40}K for rock and soil samples from studied area.

Sample	^{232}Th	^{226}Ra	^{40}K
Granitic Rock			
R1	39.0	29.9	919.8
R2	33.3	22.7	850.8
R3	69.2	23.6	948.9
R4	28.2	77.6	857.6
R5	21.5	47.4	1085.7
R6	32.9	48.5	1209.7
R7	76.9	28.8	387.0
R8	29.4	43.3	919.0
R9	12.6	37.4	810.8
R10	41.0	73.0	560.2
R11	33.7	91.1	860.0
R12	23.9	91.8	956.1
R13	18.5	24.2	747.1
R14	47.1	48.7	639.3
R15	83.3	23.5	330.1
R16	18.0	20.5	1058.7
Mean	39.4	47.4	821.3
Stdev	21.2	24.7	241.0
Max	83.3	91.8	1209.7
Min	12.6	22.7	948.9
Soil samples			
S1	23.1	11.3	860
S2	19.5	26.1	477
S3 Bricks	43.1	46.1	582
S4*	22.8	30.8	1247
Mean	27.1	28.6	791

* Fertilized soil.

Table 2. Average and ranges of the activity concentrations of the natural radionuclides ($Bq \cdot kg^{-1}$) in building materials and comparison with some results in other parts of KSA.

Nuclide	226-Ra	232-Th	40-K	References
Ranya Normal granites	38.3 (10 - 77)	34.4 (10 - 73)	1190 (985 - 1531)	(Zeghib et al., 2016)
Ranyah Anomalous granites	667 (305 - 1120)	320 (161 - 491)	586 (282 - 893)	
Italy Granitoid outcrops	44 (29 - 53)	56 (51 - 60)	1133 (711 - 1355)	(Puccini et al., 2014)
Greece Granites	67 (2 - 95)	95 (1 - 450)	1200 (50 - 3800)	(Stoulos et al., 2003)
Malaysia Ceramic	91 ± 49	69 ± 43	640 ± 273	(Abdullahi et al., 2020)
Pakistan Rivers sediments	50.66	70.15	531.70	(Qureshi et al., 2014)
KSA Commercial Granites	9.7 - 133	4.9 - 144.9	168 - 1806	(Aydarous et al., 2010)
Egypt Granites	103 ± 91	78 ± 19	1484 ± 334	(Abdel Gawad et al., 2022)
KSA Hail Granites	103 (19 - 255)	487 (47 - 1058)	255 (135 - 1519)	(Fallatah & Khattab, 2023)
Turkey Volcanic tuff stones no average	(2 - 263)	(8 - 401)	(99 - 2107)	Turhan et al., 2015)
KSA Ranyah Soils	15(6 - 54)	15 (7 - 52)	493 (299 - 761)	(Aydarous et al., 2022)
Nigeria Granites	47 (17 - 85)	83 (62 - 114)	1426 (1315 - 1551)	(Ademola& Ayeni, 2010)
Egypt Albite Granites	215 - 1300	130 - 1424	1108 - 2167	(Gaafar et al., 2022)
KSA Adham governorate	47(23 - 92)	39 (13 - 83)	821 (330 - 1210)	Present work

All rock and soil samples are included in **Table 3**, except fertilized soil 4. Soil S3 represents a locally manufactured construction brick. According to EU regulations, the limit of indoor absorbed dose rates due to external gamma radiation dose from building materials was set at 1.5 mGy/y which is equivalent to 170 $nGy \cdot h^{-1}$, and 1 mSv per year for the indoor annual effective dose equivalent (EU, 2014). In case of the adopted standard room, the indoor absorbed dose rate ranged from 60 to 136 $nGy \cdot h^{-1}$ with and a mean of 102 $nGy \cdot h^{-1}$. All samples are below 170 $nGy \cdot h^{-1}$ but their mean (102 $nGy \cdot h^{-1}$) has surpassed the world average of 84 $nGy \cdot h^{-1}$ (UNSCEAR, 2000).

The outdoor absorbed dose rate ranged from 44 to 98 $nGy \cdot h^{-1}$ with and a mean of 75 $nGy \cdot h^{-1}$. The obtained values are consistent with the world averages and range values of 18 to 93 (10 - 200). The indoor effective dose rate ranged from 0.29 to 0.67 $nGy \cdot h^{-1}$ with and a mean of 0.50 $mSv \cdot y^{-1}$ exceeding the exemption limit of 0.3 $mSv \cdot y^{-1}$ (EU, 2014). All samples are below the reference level of 1 $mSv \cdot y^{-1}$ (UNSCEAR, 2000). **Figure 2** and **Figure 3** display the absorbed dose rate (nGy/h) and annual effective dose equivalent (mSv/y), respectively, (outdoor, indoor and total) due to the natural radiation exposure from different rock and soil samples in the present study.

It is worth noting that all rock samples have been collected near granitic mountains in proximity to, or surrounding habited areas. Inhabitants in these areas are living in dwellings build in proximity to granitic rocks and/or on the top of granitic rocks. Therefore, it is conceivable to estimate ELCR from representative collected samples, though there are certainly granites with higher radioactivity than the collected ones.

Table 3. Outdoor and indoor absorbed dose rates ($nGy \cdot h^{-1}$), annual effective dose equivalent ($mSv \cdot y^{1}$), excess lifetime cancer risk and annual gonadal dose equivalent.

Sample #	Dout ($nGy \cdot h^{-1}$)	Eout ($mSv \cdot y^{1}$)	ELCRout ($\times 10^{-3}$)	Dind ($nGy \cdot h^{-1}$)	Eind ($mSv \cdot y^{1}$)	ELCRind ($\times 10^{-3}$)	ELCR tot ($\times 10^{-3}$)	AGDE ($mSv \cdot y^{-1}$)
R1	75.8	0.09	0.36	102.88	0.50	1.94	2.30	544
R2	66.1	0.08	0.31	89.68	0.44	1.69	2.01	476
R3	92.3	0.11	0.44	123.88	0.61	2.34	2.78	660
R4	88.7	0.11	0.42	122.87	0.60	2.32	2.74	627
R5	80.2	0.10	0.38	110.41	0.54	2.09	2.46	577
R6	92.8	0.11	0.44	127.11	0.62	2.40	2.84	667
R7	75.9	0.09	0.36	101.34	0.50	1.91	2.27	532
R8	76.1	0.09	0.36	104.33	0.51	1.97	2.33	545
R9	58.7	0.07	0.28	81.10	0.40	1.53	1.81	423
R10	81.9	0.10	0.39	112.82	0.55	2.13	2.52	573
R11	98.4	0.12	0.46	136.34	0.67	2.58	3.04	692
R12	96.8	0.12	0.46	134.65	0.66	2.54	3.00	684
R13	53.5	0.07	0.25	73.23	0.36	1.38	1.64	387
R14	77.7	0.10	0.37	105.81	0.52	2.00	2.36	548
R15	75.0	0.09	0.35	99.53	0.49	1.88	2.23	524
R16	64.5	0.08	0.30	88.12	0.43	1.66	1.97	471
S1	55.0	0.07	0.26	74.58	0.37	1.41	1.67	401
S2	43.7	0.05	0.21	59.86	0.29	1.13	1.34	312
S3 Bricks	71.6	0.09	0.34	97.67	0.48	1.84	2.18	505
mean	74.99	0.09	0.35	102.43	0.50	1.93	2.29	534
Stdev	15.30	0.02	0.07	21.29	0.10	0.40	0.47	106
MAX	98.40	0.12	0.46	136.34	0.67	2.58	3.04	692
MIN	43.74	0.05	0.21	59.86	0.29	1.13	1.34	311
World mean	59	0.07	0.29	84	0.41	1.16	1.45	300
World range	19.5 - 88.0	0.02 - 0.11	0.09 - 0.42	37.3 - 168	0.18 - 0.82	0.70 - 3.17	0.80 - 3.59	141 - 621

[a] UNSCEAR, 2000.

The variations of the ELCR (outdoor, indoor and total) due to natural radiation exposure from different rock and soil samples are shown in **Figure 4**. The ELCRtot, and ELCRout, values were ranging from 1.34 to 3.04 × 10^{-3} and 0.21 to 0.46 × 10^{-3}, with mean values 2.29 and 0.35 × 10^{-3}, respectively. The obtained results are mostly above the world average values of 1.5 × 10^{-3}, and 0.3 × 10^{-3}, for, ELCRout, and ELCRtot, respectively (UNSCEAR, 2000). However, the indoor ELCRind values ranging from 1.13 to 2.58 × 10^{-3} with a mean value of 1.93 × 10^{-3}, were within the world average value (1.2 × 10^{-3}).

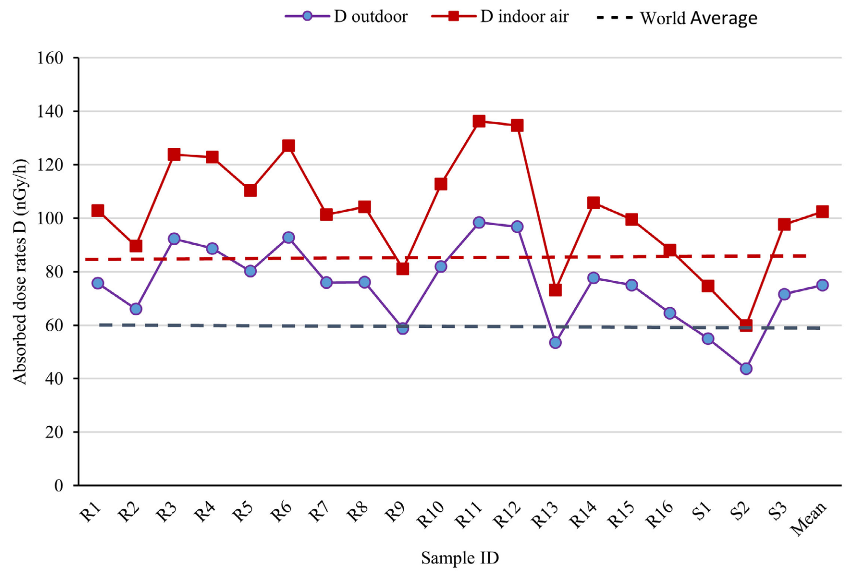

Figure 2. Absorbed dose rate (indoor and outdoor) due to exposure of natural radionuclides from different rock and soil samples. The broken lines show the world averages for both D outdoor (red) and D indoor (blue).

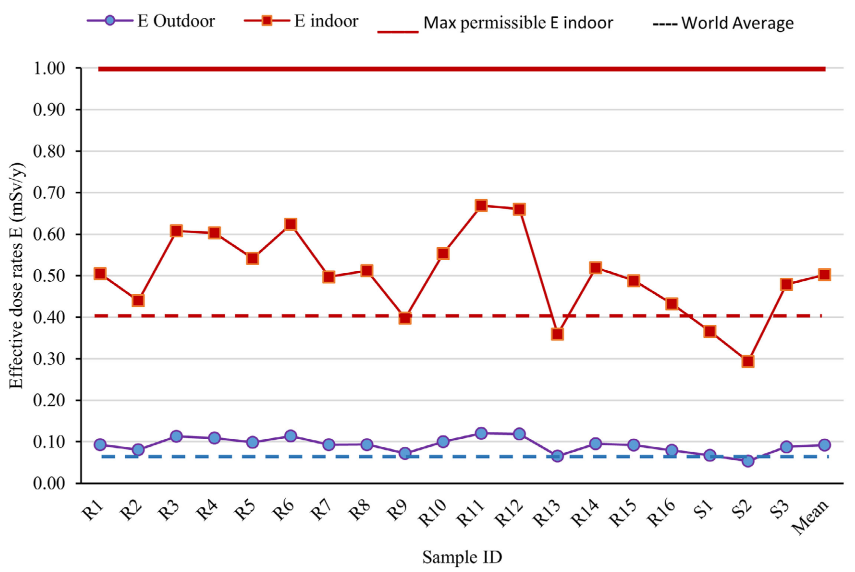

Figure 3. Annual Effective dose equivalent (indoor, outdoor and total) due to exposure of natural radionuclides from different rock and soil samples.

Figure 5 shows the total AEDE and annual gonadal effective dose (AGED) due to exposure of natural radionuclides from different rock and soil samples. The total AEDE is still less than the reference value of 1 mSv·y^{-1} as shown in Figure 5. The AGED values ranging from 311 to 692 (μSv·y^{1}) with a mean value of 534 (μSv·y^{1}) were within the world average and range values 300 (141 - 621) (μSv·y^{1}). However the reported average value of 534 (μSv·y^{1}) is higher than world mean of 300 reported by (UNSCEAR, 2000). It is worth noting that the tissue weighting factor for gonads has been updated from 0.2 (1990) to 0.08 (2007) according to (ICRP, 2007).

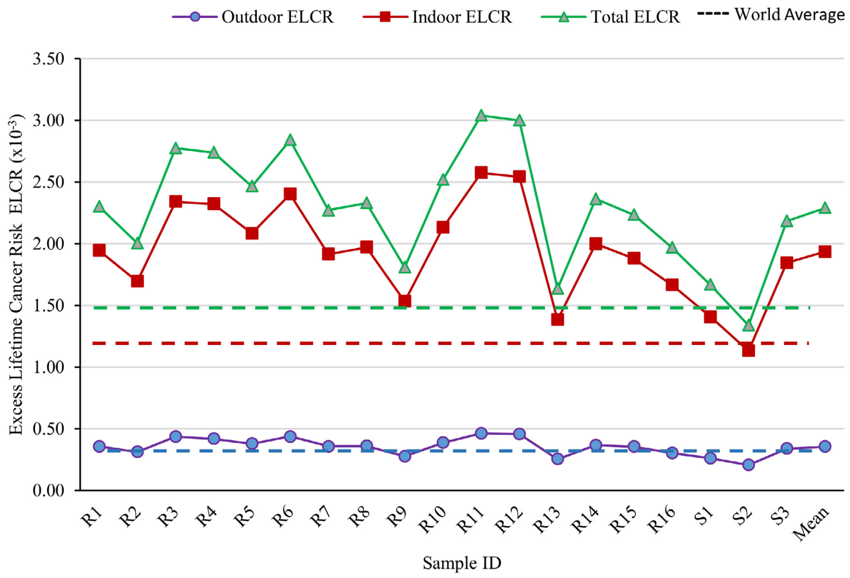

Figure 4. Excess lifetime cancer risk (indoor, outdoor and total) due to exposure of natural radionuclides from different rock and soil samples. The broken lines show the world averages for Outdoor ELCR (blue), Indoor (red) and Total ELCR (green).

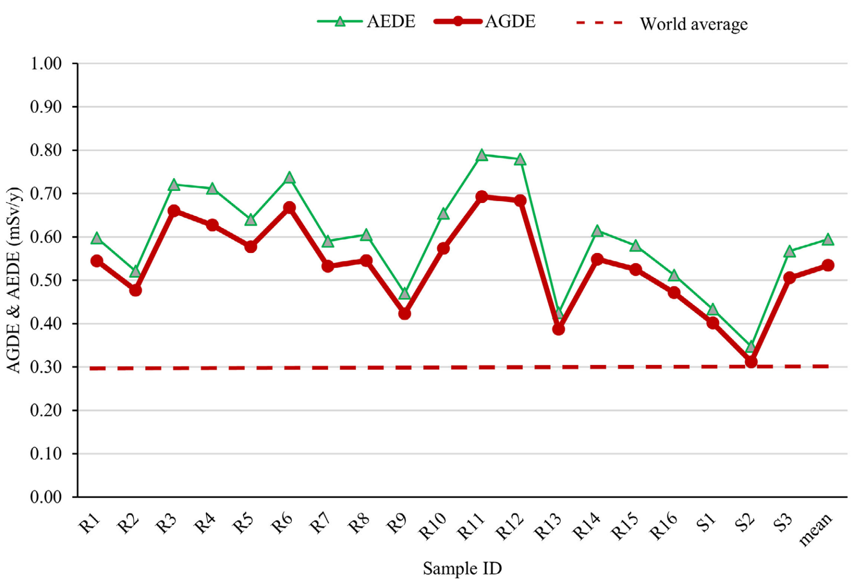

Figure 5. Total Annual Effective Dose Equivalent (AEDE) and Annual Gonadal Effective Dose (AGED) due to exposure of natural radionuclides from different rock and soil samples.

3.3. Internal Exposure to Radon Gas in Indoor Air

It is worthy of mention that the limiting value of 300 Bq/m^3 for indoor radon in homes is roughly equivalent to 10 mSv·y^{-1} according to (ICRP, 2009). **Figure 6** shows the radon concentration in indoor air arising from building material in the adopted standard room for different scenarios. A recapitulation of the computed radon concentration indoors, emanating from building materials in case of adequate ventilation (λ_v = 0.5 h^{-1}) is a follows. All samples in all envisaged scenarios (thickness and *S/V* ratio variations) did not reach or exceed the reference level for radon in dwellings of 300 Bq/m^3 set by the council of European Union (EU, 2014). However, the world health organization (WHO) recommendation is as quoted "establishing a national annual average residential radon concentration reference level of 100 Bq/m^3, but if this level cannot be reached under the prevailing country-specific conditions, the reference level should not exceed 300 Bq/m^3" (WHO, 2009).

Therefore, in case that the minimum reference level set by WHO at 100 Bq/m^3 is adopted, two samples exceeded it in case of a thickness of 5cm and *S/V* = 2.5 for adequate ventilation, but none for *S/V* = 2. Deliberately, the situation is of more concern in case of poor ventilation (λ_v = 0.1 h^{-1}). At a thickness of 5 cm for example, four samples exceeded the reference level for radon in dwellings of 300 Bq/m^3 in both *S/V* = 2.5 and *S/V* = 2 scenarios. Moreover, eighteen samples (out of nineteen) exceeded the minimum reference level set by WHO at 100 Bq/m^3 in case of *S/V* = 2.5, and 17 samples in case of *S/V* = 2. In reality, we have seen (in the three parts of the studied area) houses build completely with granitic rocks or locally manufactured bricks (with ~ 10 cm thickness) out of sedimentary sand resulting from mountain erosion by rain water. Therefore the scenario of 8 cm thickness was included in this study (assuming the same emanation factor 0.45 for safety assessment as explained before). **Figure 7** shows that most samples (around ten) exceeded the upper limit (300 Bq/m^3) in case of poor ventilation. However, when the ventilation is adequate, none of the samples exceeded the limit. Therefore, ventilation is the most influencing factor for indoor radon control.

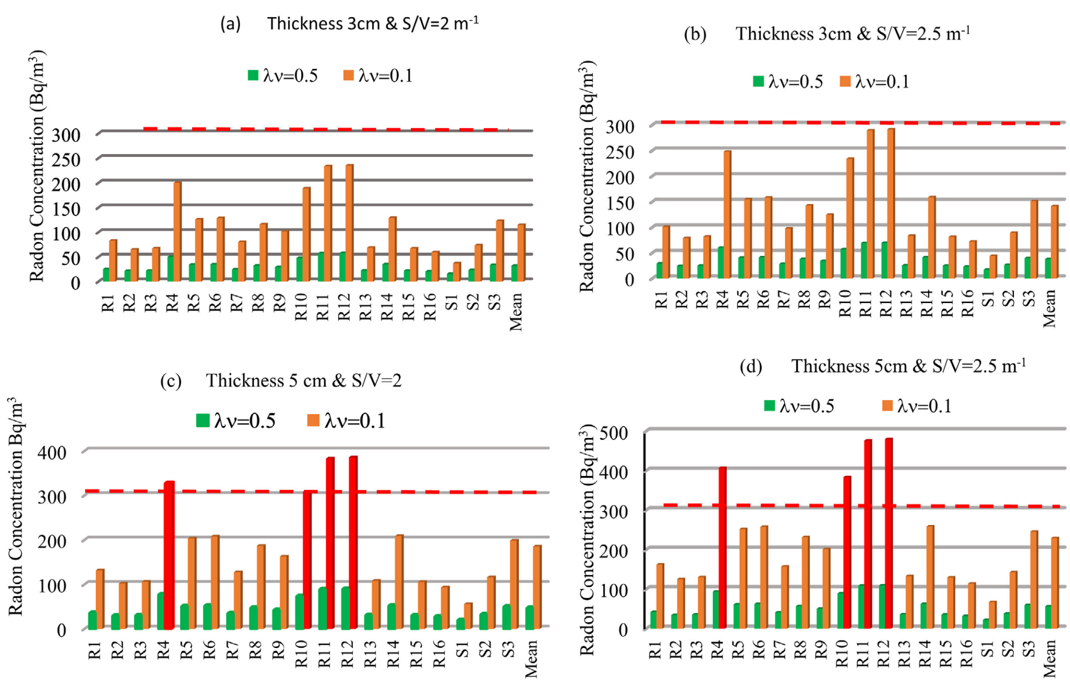

Figure 6. Indoor radon concentration for adequately and poorly ventilated standard room with different scenarios: (a) Thickness 3 cm & *S/V* = 2 m^{-1}; (b) Thickness 3 cm & *S/V* = 2.5 m^{-1}; (c) Thickness 5 cm & *S/V* = 2 m^{-1}; (d) Thickness 5 cm & *S/V* = 2.5 m^{-1}.

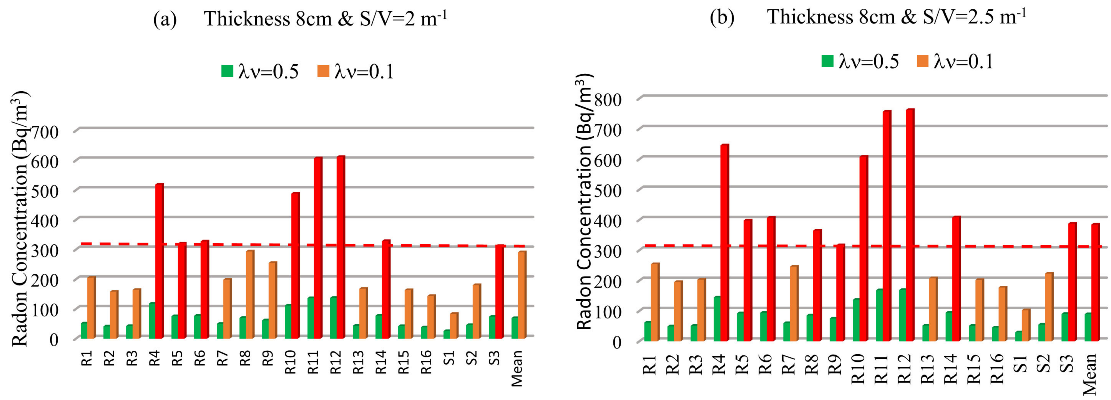

Figure 7. Indoor radon concentration for adequately and poorly ventilated standard room with different scenarios: (a) Thickness 8cm & $S/V = 2\ m^{-1}$; (b) Thickness 8 cm & $S/V = 2.5\ m^{-1}$.

Furthermore, in case of adequate ventilation ($\lambda_v = 0.5\ h^{-1}$) and thickness 8 cm, four samples exceeded the lower reference WHO level for radon in dwellings (100 Bq/m^3) in both $S/V = 2.5$ and $S/V = 2$ scenarios. However, in case of poor ventilation ($\lambda_v = 0.1\ h^{-1}$), the number of samples that reached or exceeded the reference level is eight (out of nineteen) at $S/V = 2$ and eleven at $S/V = 2.5$. It is worth mentioning that the locally manufactured brick S3 has exceeded this EC reference limit which is the upper limit set by WHO, in case of poor ventilation. The situation is worse if we consider the lower reference limit set by WHO, which is 100 Bq/m^3. In this case, all samples surpassed it except soil S1.

Since, the collected granite rocks were collected randomly without any selection (survey meter did not work), the results indicate that there is a cancer risk in case of poor ventilation. Ventilation is the principal key factor of reducing radon concentration in dwelling in all circumstances.

The second influencing factor is the thickness. Indoor radon concentration increases with increasing thickness as expected (~linearly). For example, let us consider granite R12. When the thickness increases from 5 cm to 8 cm, the radon concentration increases by approximately a factor of 1.59.

The third influencing factor is the ratio S/V. When the standard room is packed more with furniture and household accessories, the volume of indoor air diminishes leading to an increase of radon concentration emanating from exhaling surfaces (floor and walls in the considered standard room), which is described by an increase of the ratio S/V. Therefore, apart from the thickness influencing factor, living in a more packed room along with poor ventilation is the worst scenario to cause excessive cancer risk.

Finally, it is worth noting that we have adopted the maximum measured value of 0.45 by (Al-Jarallah, 2001; Anjos et al., 2011) for the emanation coefficient in our calculation as (Anjos et al., 2011) did, for safety assessment. However, at the same time, we have used the maximum WHO reference limit of 300 Bq/m^3 for indoor radon concentration in our **Figure 6** and **Figure 7**. Therefore, reducing the emanation coefficient to one third of its previous value (0.15 for example) while considering the lower reference limit set by WHO at 100 Bq/m^3 (one third of the upper WHO reference limit), would lead to the same conclusions (WHO, 2009). It is very important to note that the World Health Organization declared that there is about 16% increase in risk of lung cancer per 100 Bq/m^3 increase in long time average radon concentration, assuming a linear dose-response between them (WHO, 2009). In other words, the dose-response relation is assumed to be linear between risk of lung cancer and radon exposure in the long term. In fact, WHO recommends a limit of 100 to 300 Bq/m^3 and the United States environmental protection agency EPA recommends a limit of 148 Bq/m^3 (~ half of WHO upper limit) (WHO, 2009).

Up to now, we have considered only the indoor radon exposure due to building material in the widely adopted standard room. Next, we are going to consider radon exposure from the use of radioactively contaminated water for drinking and household use.

3.4. Internal Exposure to Radon Contaminated Water

Eight well water samples were collected from Adham, Haqal and Al-Jaizah during the end of summer season 2022 (hot weather with less precipitation (rain)). **Table 4** shows the measured activity concentrations in ($Bq \cdot L^{-1}$) of ^{226}Ra, 232Th, and ^{40}K for well water samples from Adham governorate and their approximate GPS locations.

Radon concentration is obtained from the measured ^{226}Ra activity concentration using the high energy 1764 keV gamma line of ^{214}Bi (a radon ^{222}Rn progeny), after secular equilibrium being reached (~ 4 weeks). It is important to note that our results about well water radon concentrations measured by NaI(Tl) gamma spectrometry are not as accurate as HPGe gamma spectrometry. It is worth noting that reliable radon concentrations measurements with RAD7 apparatus were performed on site by (Abuelnaga et al., 2021) for the same regions but at different season, time and/or different wells than ours. RAD7 radon measuring instrument is widely used in laboratories and research work around the globe.

Table 5 (column 1) shows the average and range of RAD7 onsite measurements in all three areas. It is clear, that *in situ* RAD7 measurements are higher than our results (using scintillation detector NaI(Tl)). Many factors may contribute to this difference, keeping in mind that both measurements were performed at different season, date and/or different wells. Radon concentrations vary with season, temperature, rain precipitations, measuring equipment. On the other hand, an eventual loss of radon kept for longtime in sealed HDPE Marinelli, may have occurred and affected the results, though the secular equilibrium was attained after one month. This eventual loss does not affect our conclusions since it appears that the real values seem to be high according to RAD7 measurements in the same studied areas. Therefore, the situation is more critical in terms of radiological hazard for inhabitants than our experimental results for well water indicate. According to our results, all well water samples exceeded the maximum permissible concentration level for radon in public drinking water, which is 11.1

Bq/L set by the US environmental protection agency (USEPA, 2017). Therefore, our results confirmed the elevated radon concentrations in all seventeen well waters in the same three studied areas (Adham, Haqal and Al-Jaizah), that were measured more precisely on site by (Abuelnaga et al., 2021), using RAD7 radon measurement apparatus. They found that the average values were approximately 2.8, 3.5 and 6 times the EPA reference limit in Al Jaizah, Adham and Haqal, respectively. **Table 5** shows the averages and ranges of both *in situ* RAD 7 measurements and NaI(Tl) measurement of radon concentrations in well waters, in the areas of study.

The results in **Table 5** show that well waters in Haqal are more radiologically contaminated than other areas. This may be related to the alleged cancer cases in Haqal area as reported by the local newspaper (OKAZ, 2007). Abuelnaga et al. have argued that the variations in the results are related to the variety of rock units surrounding the wells in relation to the geological formations in each study area, as illustrated in the car borne gamma spectrometry contour charts (Abuelnaga et al., 2021). A comparison of radon concentration in ground and well waters locally and worldwide is given in **Table 6**.

Table 4. Measured activity concentrations (Bq/L) of ^{226}Ra, ^{232}Th, and ^{40}K for well water samples from Adham region and their approximate GPS locations.

Sample/site	^{232}Th	^{226}Ra	^{40}K	Location (GPS)
W1/Haqal 1	14.3	33.4	311.3	N 20˚28'14" E 40˚43'07"
W2/Adham1	6.6	27.4	241.7	N 20˚26'40" E 40˚52'45"
W3/Al-Jaizah1	9.9	11.5	287.2	N 20˚22'14" E 40˚56'08"
W4/Adham 2	4.4	24.5	206.9	N 20˚26'28" E 40˚52'36"
W5/Adham 3	21.2	29.2	184.9	N 20˚26'51" E 40˚53'06"
W6/Haqal 3	25.8	31.4	312.2	N 20˚28'28" E 40˚43'38"
W7/Al-Jaizah2	8.3	19.7	197.5	N 20˚22'22" E 40˚56'09"
W8/Haqal 2	15.1	37.9	269.3	N 20˚28'34" E 40˚43'31"
Mean	13.2	26.9	251.4	
Stdev	7.2	8.3	51.1	
Max	25.8	33.4	550.1	
Min	4.4	11.5	184.9	

Table 5. *In situ* RAD 7 measurements and NaI(Tl) measurement of radon concentrations (C_{Rn} (Bq/L) in well waters in the area of study*.

On site Rad-7 radon detector (Abuelnaga et al., 2021). C_{Rn} (Bq/L)		NaI(Tl) in gamma spectrometry Laboratory. Present work. C_{Rn} (Bq/L)
Location	Average (Range)	Average (Range)
Adham	39 (33 - 46)	27 (24 - 29)
Haqal	69 (51 - 89)	34 (31 - 38)
Al Jaizah	31 (26 - 40)	16 (12 - 20)

*Both measurements performed at different season, date and/or different wells.

Table 6. Radon concentration in ground and well waters locally and worldwide.

Location	Range ($Bq \cdot L^{-1}$)	References
KSA—Adham governorate	17.06 - 89.54	(Abuelnaga et al., 2021)
KSA—Hafr Al Batin and Thybiah	0.03 - 3.20	(Mamun et al., 2022)
KSA—Al-Baha Region	0.24 - 1.52	(Al-Ghamdi, 2019)
KSA—Al-Jawa Region	1.45 - 9.15	(Althoyaib et al., 2015)
KSA—Al-Zulfi—Al Qassim	0.3 - 3.66	(Alharbi et al., 2018)
Sudan—Khartoum	1.58 - 345.10	(Idriss et al., 2011)
Algeria—Tassili	0.67 - 21.25	(Amrani et al., 2000)
Jordan	2.8 - 116	(Al-Kazwini et al., 2003)
Poland	35.3 and 272.0	(Przylibski et al., 2022)
Nigeria—Ibadan	2.18 to 76.75	(Ademola & Oyeleke, 2017)
Turkey—Western black sea region	<3.00 to 12.03	(Özdemir Öge & Özdemir, 2019)
Pakistan	6.0 - 13.6	(Haroon & Muhammad, 2022)
China—Baoji	30.0 - 127	(Xinwei, 2006)
KSA—Adham governorate	12 - 38	Present study

As we can see from **Table 6**, there are a lot of variations in measured values across the world and within the same country, with some values exceeding 100 $Bq \cdot L^{-1}$ in Sudan, Jordan, Poland and China (Idriss et al., 2011; Al-Kazwini & Hasan, 2003; Przylibski et al., 2022; Xinwei, 2006). The maximum value measured in Adham governorate was 89.54 $Bp \cdot L^{-1}$ in Haqal area (Abuelnaga et al., 2021). In fact, there may be higher radon concentrations elsewhere in the study area. The references in **Table 6** were chosen to show that our measured ranges are within the reported world values. The annual effective dose (AED) for children, infants and adults due to the internal exposure to radon gas in well waters through ingestion and inhalation is illustrated in **Figure 8**.

The obtained results for the total annual effective dose show that all water samples, except one (W1), exceeded the international permissible limit of 100 μSv/Y for adults and infants. For children two water samples (W1 and W7) were below the permissible limit. In case of adults, the total annual effective dose (due to inhalation and ingestion) ranged from 58.3 to 192.3 μSv/y). Since higher values were obtained by RAD7 measurements for more well waters (seventeen) in the same studied areas, the situation is of real concern in all three studied areas, for radiation protection authorities.

Finally, it is worth noting that direct use water directly from the well or during a short time between extraction and use, may result in increased radon exposure (IAEA, 2019). **Figure 9** shows many pump hose pipes probably feeding houses with water directly from a well dug in a rain water stream, which is surrounded by sedimentary sand originating from mountain granites by erosion.

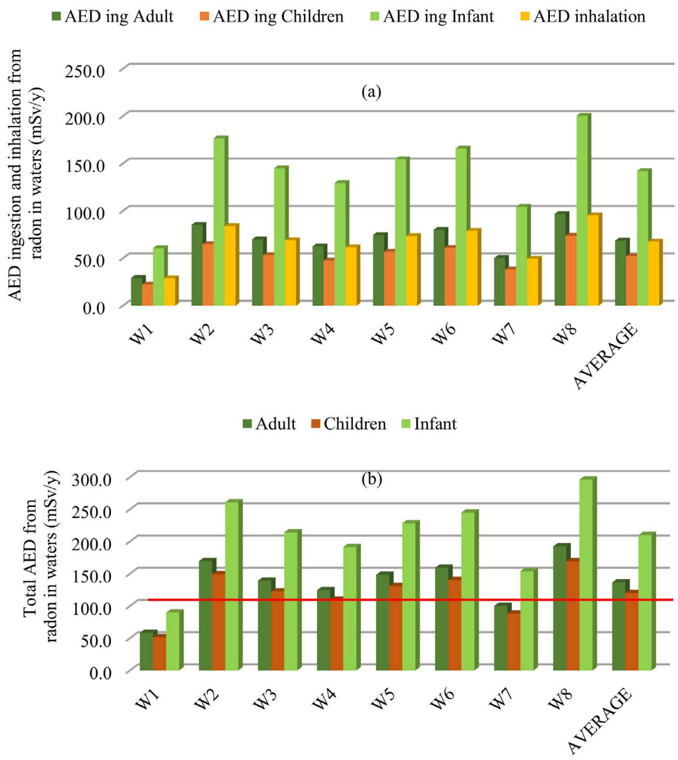

Figure 8. AED for adults, children and infants due to radon in well waters (red line indicates the international permissible limit: (a) Ingestion and inhalation separately; (b) Total AED.

Figure 9. Picture of a well from Al-Jaizah, showing pump hoses (at the top of the well) feeding houses with water directly from the well (dug in rain water stream) surrounded by sedimentary sand originating from erosion of surrounding granitic mountains.

4. Conclusion

Radon concentration indoors, exceeded the upper reference level in dwellings set at 300 Bq/m^3 by the world health organization, in many scenarios, especially in poorly ventilated standard room. All analyzed well water samples surpassed considerably the EPA reference level (11.1 Bq·L^{-1}) for radon in drinking water with an average of 27 Bq/L in this study using gamma spectrometry. The maximum value was obtained at Haqal (38 Bq/L) in our present work, while a value of 89 Bq/L was obtained in a previous study about the same area (Abuelnaga et al., 2021), using RAD 7 onsite measurements. The internal exposure from radon in water house uses might be the major reason of alleged cancer cases in Haqal region as reported by the newspaper OKAZ. The second contributing factor is the internal exposure from indoor air due to radon gas inhalation in closed areas with poor ventilation, especially for inhabitants living in proximity to granitic mountains. These conclusions remain speculative (due to the limitations of the instruments used in this research work) until a more involved "case study" is undertaken, taking into account different aspects of the issue. It is imperative to conduct rigorous assessment of radiation hazard due to external exposure to gamma rays (indoor and outdoor) and internal exposure to radon gas, inside dwellings adjacent to mountains or build on top of granitic rocks using reliable calibrated instruments. Nevertheless, for health safety of the residents, the following recommendations are suggested under all circumstances:

1) Assure good ventilation for all houses in all studied areas because they were built in a traditional way without taking into account radon exposures and pathways.

2) Avoid using well water of elevated radioactivity for drinking, showering, household use to avoid excessive radon in water to air transfer in domestic environment. In case it is not possible, avoid at least, using well water directly from wells using pumps, due to its eventual elevated radioactivity.

3) Avoid using well water of elevated radioactivity for irrigation to protect agricultural crop from radioactive contamination, which deserves an analysis study using high resolution gamma spectrometry with high efficiency HPGe detectors, which was one of the limitations of this research work.

4) Perform continuous radon gas monitoring in suspected homes/areas and its variability at different seasons, and take necessary actions accordingly.

This work has added new insights into the natural radiological hazard in a region of the Kingdom of Saudi Arabia and provides the Saudi Geological Survey (SGS) with valuable information. Similar inhabited geographical and geological areas may exist in other parts of KSA (and elsewhere), which need a risk assessment study especially if well water is the main supply for inhabitants. More important, people should be aware that ventilation inside dwellings reduces cancer risk due to radon exposure in all circumstances. A simple awareness program for inhabitants would significantly reduce cancer risk from environmental health hazard, knowing that radon in dwellings is the second cause of cancer fatality in the world after smoking.

Acknowledgements

The authors would like to thank the administration of the Nuclear Engineering Department for providing us with the IAEA reference materials and necessary support. Our thanks to the Mining Engineering Department (Professor Hussin A. M. Ahmed) for crushing the granite samples. Our thanks to the Geohazard research center for supporting us with one of their collaborator (Sultan Almalki) to guide us collecting granites from relatively high radiation areas in Adham, Haqal and Al-Jaizah using radiation contour maps—generated by their car born gamma spectrometry system—for all three areas of study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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