Nuclear Engineering and Technology 56 (2024) 1925–1931

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Assessment of natural radioactivity in soil and olive mill pomace utilizing nal (TI) gamma-ray spectrometry and low background alpha/beta counting system

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ARTICLE INFO

Keywords:
Radon
Mass exhalation rate
Emanation coefficient
Radiological hazards
Natural radioactivity

ABSTRACT

The study conducted in the northwest region of Jordan aimed to assess the levels of natural radioactivity in soil and olive mill pomace (OMP) samples. The researchers used Nal (TI) gamma-ray spectrometry to measure the activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in the samples. The average activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in the soil samples were found to be 18.624 ± 5.82, 12.276 ± 5.728, 518.33 ± 212.57, and 0.140 ± 0.09 (Bq, kg^{-1}), respectively. In the OMP samples, the average activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were 7.272 ± 4.386, 3.454 ± 1.503, and 169.997 ± 81.873 (Bq kg^{-1}), respectively, and no ^{137}Cs was detected.

The study also investigated fundamental parameters associated with radon, specifically the radon emanation coefficient (Rn_{EC}) and radon mass exhalation rate (E_x). The Rn_{EC} values ranged from 0.621 to 0.78 (Bq kg^{-1}), with an average value of 0.71 ± 0.06 (Bq kg^{-1}). The estimated E_x from the soil samples ranged from 65.83 to 124.86 (mBq kg^{-1}h^{-1}), with an average value of 99.74 ± 21.73 (mBq kg^{-1}h^{-1}).

Regarding radiological hazards, the study examined various parameters, including radium equivalent activity, external and internal hazard indices, gamma and alpha indices, absorbed gamma dose rate, and excess lifetime cancer risk. All of these assessed values were found to be below the worldwide recommended limits for radiological safety.

Additionally, the study analyzed the concentrations of gross alpha and gross beta radioactivities in soil and OMP samples. The soil samples had an average gross alpha activity of 4.642 ± 1.04 (Bq kg^{-1}) and an average gross beta activity of 48.13 ± 14.50 (Bq kg^{-1}). The OMP samples showed an average gross alpha activity of 0.32 ± 0.27 (Bq kg^{-1}) and an average gross beta activity of 59.19 ± 12.94 (Bq kg^{-1}).

Overall, the obtained results are crucial for evaluating the radiological risks associated with natural radioactivity in the northwest region of Jordan. The findings establish baseline data for comparison and reference for radioactivity levels in the environment.

1. Introduction

Over 85% of the estimated global radiation dose is attributed to natural sources emphasizing the growing concern about environmental radiation and its impact on human health and ecosystems [1]. While the extensive distribution of radionuclides like ^{226}Ra in the environment is well-known, understanding their behavior, especially in relation to OMP, remains an area needing further exploration [2]. The existence of natural radioactivity in the environment, including ^{226}Ra and its decay products, is a subject of considerable concern due to its possible effects on human health and the surrounding ecosystem [3,4].

Among the naturally occurring radioactive elements, ^{226}Ra plays a crucial role in contributing to the overall radioactivity levels in various environmental media [5,6]. Its decay products can attach to dust particles and be inhaled, leading to potential health risks, particularly in indoor environments [7,8], and [9]. Understanding the behavior of ^{226}Ra and its decay products in the environment is essential for assessing the associated radiological hazards and implementing appropriate

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https://doi.org/10.1016/j.net.2023.12.055
Received 15 November 2023; Received in revised form 25 December 2023; Accepted 28 December 2023
Available online 31 December 2023

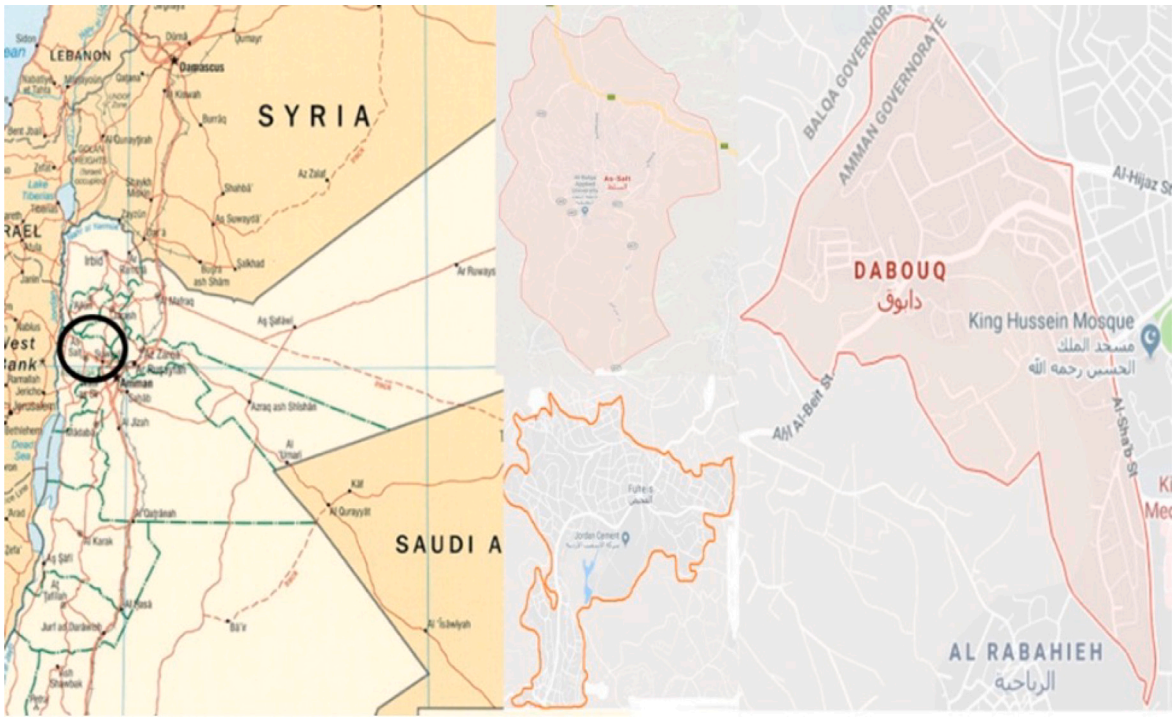

Fig. 1. Map of the location of the collected samples in circle l (soil and OMP).

safety measures. This study aims to bridge this gap by specifically investigating two fundamental parameters that aid in characterizing ^{226}Ra behavior are the Rn_{EC} and E_x. These parameters determine the rate at which ^{226}Ra is released from the solid matrix into the surrounding atmosphere, contributing to indoor and outdoor ^{226}Ra levels.

The study of OMP has gained significance due to its increasing usage and versatile applications in our daily lives. OMP serves as a valuable byproduct contributing to sustainability by offering a renewable energy source through biomass fuel conversion, thereby reducing reliance on fossil fuels and mitigating greenhouse gas emissions. Furthermore, OMP's potential as animal feed contributes to the circular economy by recycling organic waste back into the agricultural system, supporting sustainable livestock farming practices. Additionally, its composting capabilities facilitate the production of organic fertilizer, promoting soil health and bolstering agricultural productivity. The radiological aspect of OMP, however, requires further examination to ensure environmental and public health safety. New and exciting developments in biorefinery technologies have made it possible to extract valuable compounds from OMP, including phenolic compounds, which are used in many ways in the cosmetics, pharmaceuticals, and food industries. By harnessing the multifaceted properties of OMP, we can effectively address environmental challenges associated with waste disposal and promote resource efficiency, emphasizing the significance of its sustainable utilization in our daily lives.

NaI (TI) gamma-ray spectrometry is used to find out how much ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs are in samples of soil and OMP. This method's sensitivity makes it ideal for assessing the activity levels of these radionuclides and understanding their environmental impact [10, 11], and [12]. The investigation will further include an assessment of the radiological hazards associated with natural radioactivity in the soil samples.

Moreover, a low-background alpha/beta counting system has been employed for the measurement of gross alpha and gross beta activities in the collected soil and OMP samples. This methodology ensures minimal interference from external radioactivity, allowing for precise measurement of the samples' gross alpha and beta activities. The research aims to provide highly reliable data for assessing the radiological impact of radon and other natural radioactivity in the studied environmental matrices.

In summary, this study provides essential data for assessing the radiological risks and contributes to environmental and public health policy. Moreover, it offers vital insights into the levels of natural radioactivity in soil and OMP samples in the northwest region of Jordan. These findings significantly enhance our understanding of radioactivity distribution in the area, which is crucial for evaluating potential radiological hazards. The detailed analysis and results are instrumental for the implementation of appropriate safety measures, making this research highly beneficial for the scientific community and adding valuable knowledge to the field of environmental radiology and public health.

2. Methodology

2.1. Samples collection, preparations, and measurements

In this study, samples of soil and OMP were collected from three different regions in northwestern Jordan (Fuhies (Latitude: 31° 57′ 47″ N, Longitude: 35° 55′ 49″E), Al-Salt (Latitude: 32° 02′ 21″ N, Longitude: 35° 43′ 38″E), and Dapouq (Latitude: 31° 59′ 20″ N, Longitude: 35° 48′ 23″E)) as depicted in Fig. 1. Within the larger Levant region, Jordan's northwest is unique due to a variety of rock formations and geological features. The region encompasses sedimentary formations, including limestone, sandstone, and marl, along with select occurrences of igneous and metamorphic rock types.

Undisturbed and uncontaminated soil samples were obtained from three study areas by collecting samples at a depth of 0.2–0.3 m below ground level. After sieving the samples through a 2 mm mesh to remove unwanted materials, they underwent a one-day [13] process of drying at a temperature of 110 °C to remove any moisture. Then, the samples went through sieving until they achieved a grain size of approximately 500 μm [14] to achieve homogeneity between samples. Following that, a mass of 350 grams of samples was measured and subsequently transferred into Marinelli beakers with a volume of 500 mL. To determine

the Rn_{EC} in the soil samples, the beakers were securely sealed and left undisturbed for a minimum of four hours. This duration allowed for the achievement of radioactive equilibrium between ^{226}Ra and ^{222}Rn and their short-lived decay products.

Gamma ray spectrometry with a 78 mm Nal (TI) was used to find out how active the ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs were in the samples. The energy resolution of the detector is 8%. It was connected to a 1024-bit microcomputer multichannel pulse height analyzer in order to capture and analyze the gamma spectra. A cylindrical shield, measuring 3.7 cm in thickness and 20.5 cm in height, was employed to provide protection to the detector and minimize the presence of background noise in the gamma-ray spectra. The calibration of the gamma-ray spectrometer was conducted using conventional sources. The samples were subjected to four repetitions, each lasting 18,000 s, prior to calculating the mean.

In order to investigate the levels of gross alpha and gross beta activities in the samples, about 2 grams of each sample were evenly distributed onto a stainless steel planchet. The samples were coated with a diluted solution of UHU glue and exposed to an infrared lamp until they were fully glued [15].

2.2. Measurements of radon emanation coefficient (Rn_{EC}) and radon mass exhalation rate (E_x)

The Rn_{EC} of soil samples was determined using gamma-ray spectrometry, utilizing two gamma-ray measurements. In the initial gamma-ray measurement, the soil samples underwent a drying process at a temperature of 115 °C for a duration of one day, following which they were enclosed within a Marinelli beaker. The samples were stored for a duration of six hours in order to establish secular equilibrium between (^{222}Rn) and its predominant, short-lived daughter products. In a similar way, the second measurement of gamma-ray emissions was conducted one month later in order to establish a state of secular equilibrium between ^{222}Rn and its progeny with radium ^{226}Ra.

The measurement of the Rn_{EC} in soil samples was conducted by assessing the net count rate of specific gamma-ray lines emitted by radon decay products [16]. Gamma-ray lines of ^{214}Pb (330.633 keV, 349.260 keV) and ^{214}Bi (614.937 keV, 1120.29 keV, 1749 keV) were used for the measurement of Rn_{EC}. The calculation of (Rn_{EC}) was performed based on the provided measurements using the following relation [17]:

$$Rn_{EC} = \frac{N}{N_0 + N}, \tag{1}$$

where N_0 represents the net count rate of gamma-ray lines during the period of secular equilibrium between radon daughter products and radon. The variable N represents the net count rate of gamma-ray lines emitted by the daughter products of radon when a state of radioactive equilibrium is achieved between radon and its daughter products, as well as radium [17].

The calculation of E_x was performed using the following relation [17]:

$$E_x(\mathrm{Bqkg^{-1}h^{-1}}) = A_{Ra} \times Rn_{EC} \times \lambda_{Rn}, \tag{2}$$

where A_{Ra} is the ^{226}Ra concentration (Bqkg^{-1}) and λ_{Rn} is the ^{222}Rn decay constant, which is approximately 0.00768 per hour (h^{-1}).

2.3. Radiological hazards assessment

The potential radiological hazards associated with soil samples primarily rely on the levels of activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K. Analyzing the activity concentrations and the annual doses of gamma radiation that people who work or live in a radiation environment receive will allow you to estimate the radiological hazards. However, it is crucial to keep in mind that both individual activities and the local climate have an impact on the annual gamma radiation dose. The parameters used to evaluate the possible radiation hazards posed by soil samples include the following indices and measurements: external hazards index, gamma index, internal hazards index, alpha index, absorbed gamma dose rate in outdoor air, annual effective dose equivalent, and excess lifetime cancer risk.

2.3.1. Radium equivalent activity (Ra_{eq})

Radium equivalent activity (Ra_{eq}) is a radiological parameter used to assess the potential radiation hazard of a material or environmental sample that contains various radionuclides. The radium equivalent activity is calculated using the following formula [18]:

$$Ra_{eq}(\mathrm{Bqkg^{-1}}) = A_{Ra} + 1.43 \times A_{Th} + 0.077 \times A_K, \tag{3}$$

where A_{Ra}, A_{Th} and A_K are the activity concentrations (Bqkg^{-1}) of ^{226}Ra, ^{232}Th, and ^{40}K, respectively, in the samples.

2.3.2. External hazards index (H_{ex})

The estimation of the external hazards index (H_{ex}) is achieved through the measurement of gamma-ray exposure originating from the soil. This exposure is a result of the non-uniform distribution of ^{226}Ra, ^{232}Th, and ^{40}K within the soil [3]. The main objective of assessing H_{ex} is to ensure that the radiation dose remains within the permissible dose equivalent limit of 1 mSvy^{-1} [19]. The evaluation of the H_{ex} in soil samples was performed using the following relation [18]:

$$H_{ex} = \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \tag{4}$$

the value of H_{ex} should not surpass a unity threshold in order for the radiation hazard to be considered negligible.

2.3.3. Internal hazards index (H_{in})

The assessment of internal radiation exposure is conducted using an amount known as the internal hazards index (H_{in}). In the context of the respiratory system, H_{in} is associated with the inhalation of radioactive gases, specifically radon and thorium, along with their short-lived decay products that emit alpha particles. Therefore, the evaluation of (H_{in}) in soil samples was conducted using the following equation [18]:

$$H_{in} = \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_K}{4810} \tag{5}$$

the value of H_{in} should not surpass a unity threshold to have negligible hazardous effects of radon and its short-lived progeny on the respiratory organs [3].

2.3.4. Gamma index (I_γ)

The European Commission has implemented a highly comprehensive radiological hazard index, known as the gamma index, which is specifically designed for the evaluation of soil conditions. (I_γ) The estimation of (I_γ) for soil samples was conducted based on the relation provided in the European Commission report [20].

$$I_\gamma = \frac{A_{Ra}}{300} + \frac{A_{Th}}{200} + \frac{A_K}{3000} \tag{6}$$

the value of I_γ should not surpass a unity threshold in order for the radiation hazard to be considered negligible.

2.3.5. Alpha index (I_α)

The assessment of the internal risk posed by alpha particles is quantified through the utilization of the alpha index (I_α). In the context of soil samples, this index is employed to evaluate the potential impact of elevated activity concentrations of ^{226}Ra exceeding the threshold of 200 (Bqkg^{-1}). Such high concentrations may lead to increased levels of radon in the air, both indoors and outdoors, surpassing the recommended limit of 200 Bqm^{-3} due to radon emanation from the soil. The alpha index (I_α) for soil samples can be determined using the following relation [3]:

$$I_\alpha = \frac{A_{Ra}}{200}, \tag{7}$$

the value of I_α should not surpass a unity threshold in order for the radiation hazard to be considered negligible.

Table 1
Activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in the soil samples (Bq kg^{-1}).

SampleID	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})	^{137}Cs (Bq kg^{-1})
1A Fuhies	26.18	20.66	832.58	0.10
1B Al-Salt	19.76	8.57	629.13	0.10
2B Al-Salt	21.12	10.88	378.73	0.10
1C-Dapouq	15.07	15.10	444.46	0.30
2C-Dapouq	10.99	6.17	306.74	0.10
Average	18.624 ± 5.82	12.276 ± 5.73	518.33 ± 212.57	0.14 ± 0.09
Range	10.99–26.18	6.17–20.66	306.74–832.58	0.10–0.30
Worldwide	40	40	370	N/A

2.3.6. Absorbed gamma dose rate (AGDR)

The absorbed gamma dose rate (AGDR) in the outdoor air, measured at a height of 1 meter above ground level, corresponds to the radiation dose received by an individual due to gamma rays emitted by radionuclides such as ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs present in soil samples. The AGDR can be calculated based on the activity concentrations of these radionuclides in the soil samples using the following relation [3]:

$$AGDR(\mathrm{nGyh^{-1}}) = (0.462) \times A_{Ra} + (0.604) \times A_{Th} + (0.0417) A_K, \quad (8)$$

where 0.461, 0.623, and 0.0417 are the dose conversion coefficients in air (outdoor) are (nGyh^{-1}/Bqkg^{-1}) for ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs, respectively.

2.3.7. Annual effective dose equivalent (AEDE)

The estimation of the annual effective dose equivalent (AEDE) for the outdoor environment involved the utilization of a dose conversion factor derived from the absorbed gamma dose rate in the air. This factor enables the determination of the effective dose equivalent experienced by an adult individual due to radiation exposure. In the case of soil samples, the AEDE was calculated using the following relation [3]:

$$AEDE(\mathrm{mSvy^{-1}}) = AGDR(\mathrm{nGyh^{-1}}) \times 8760(\mathrm{hy^{-1}}) \times 0.2(OF) \times 0.7(\mathrm{SvGy^{-1}}) \times 10^{-6} \quad (9)$$

where the total number of hours in a year is 8760, the outdoor occupancy factor (OF) is represented by the value 0.2, while the dose conversion factor for environmental exposure to gamma-rays of moderate energy is denoted as 0.7 SvGy^{-1}.

2.3.8. Excess lifetime cancer risk (ELCR)

The recommended approach by the International Commission of Radiological Protection (ICRP) for evaluating the excess lifetime cancer risk (ELCR) linked to soil samples is as follows [19]:

$$ELCR = AEDE \times DL \times RF \quad (10)$$

where DL is the typical lifespan of an adult (70 years) and RF is the risk factor for stochastic effects in adults (0.05 Sv^{-1}) [19].

2.4. Gross alpha and gross beta activity measurement

Gross alpha and gross beta activities refer to the total radioactivity associated with alpha and beta particle emissions, respectively, without identifying individual radionuclides. The determination of gross alpha and gross beta activity in soil and OMP samples was conducted using a LB α/β counting system (LB4200, CANBERRA). The system is outfitted with sixteen gas flow detectors that employ P10 gas, which consists of 90% argon and 10% methane. The system was calibrated simultaneously using disk-shaped standard sources (^{241}Am for alpha and ^{90}Sr for beta particles). The counting efficiency of the system was 2.94% for alpha particles and 28.92% for beta particles using potassium chloride as the high-purity reagent standard reference sample. For the soil samples, the MDAs were 0.11 (Bqkg^{-1}) for gross alpha and 0.16 (Bqkg^{-1}) for gross beta. The gross alpha and gross beta activities in the samples were measured by using the following relation [3]:

$$A_{\alpha,\beta}(\mathrm{Bqkg^{-1}}) = \frac{Net\ Count\ Rate\ (N_s - N_B)}{m \times \epsilon_{eff}(\%)} \quad (11)$$

where the variables N_s, N_B, m, and ϵ_{eff} represent the count rate of the sample in counts per second, the count rate of the background in counts per second, the mass of the dry sample in kilograms, and the counting efficiency of the detector for alpha and beta measurements, respectively.

3. Results

3.1. Activity concentrations in soil and OMP samples

A summary of the activity concentration of primordial radionuclides in the soil and OMP samples is presented in Tables 1 and 2, respectively. The activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in soil samples varied from 10.99 to 26.18 (Bqkg^{-1}), 6.17 to 20.66 (Bqkg^{-1}), and 306.74 to 832.58 (Bqkg^{-1}), respectively. The average of ^{226}Ra, ^{232}Th, and ^{40}K activity concentrations were 26.35 ± 7.02 (Bqkg^{-1}), 20.28 ± 5.31 (Bqkg^{-1}), and 297.73 ± 44.19 (Bqkg^{-1}), respectively. The data indicates that ^{40}K exhibits the highest level of specific activity in comparison to ^{226}Ra and ^{232}Th, as shown in Fig. 2. The average values of ^{226}Ra and ^{232}Th are comparable to the worldwide average values of 40 (Bqkg^{-1}) for ^{226}Ra and ^{232}Th. The average of ^{40}K is higher than the worldwide average value of 370 (Bqkg^{-1}) [3]. The fluctuations in activity levels can be attributed to disparities in geological and geographical conditions, as well as variations in geochemical characteristics.

In OMP samples, the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K varied from 2.33 to 16.82 (Bqkg^{-1}), 1.82 to 7.07 (Bqkg^{-1}), and 52.22 to 301.91 (Bqkg^{-1}), respectively. The average radio-element concentrations of ^{226}Ra, ^{232}Th, and ^{40}K were 7.27 ±4.39(Bqkg^{-1}), 3.45 ± 1.5 (Bqkg^{-1}), and 170.00 ± 81.87 (Bqkg^{-1}), respectively. It is imperative to emphasize that the levels of radiation in the OMP samples are considerably low, comparable to those established by UNSCEAR (2000) [3].

3.2. Radon emanation coefficient (Rn_{EC}) and radon mass exhalation rate (E_x)

Table 3 listed the values of Rn_{EC} and E_x for soil samples. Rn_{EC} measured for soil samples varied from 0.621 to 0.740 with a mean value of 0.711 ± 0.06. E_x varied from 65.83 to 124.86 (mBqkg^{-1}h^{-1}) with an mean value of 99.73 ± 21.73 (mBqkg^{-1}h^{-1}). The observed slight variation in the Rn_{EC} implies that the soil samples from selected regions exhibit comparable grain size and lack significant enrichment of radium near the grain surface. Additionally, the Rn_{EC} is inversely affected by the small surface area of the grains. Numerous variables, such as variations in radium concentration within the samples, the distribution of radium within the mineral grains, the crystallization of grain surfaces, the permeability of the grains, and the texture and size of the grains, all have an impact on this coefficient. The observed

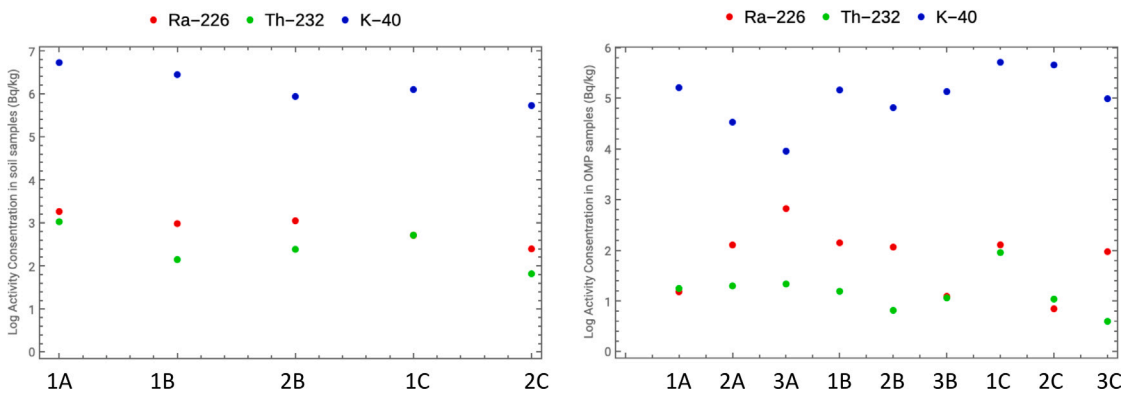

Fig. 2. Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in the soil and OMP samples (Bq kg^{-1}).

Table 2
Activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the OMP samples (Bq kg^{-1}).

SampleID	^{226}Ra (Bq kg^{-1})	^{232}Th (Bq kg^{-1})	^{40}K (Bq kg^{-1})
1A Fuhies	3.26	3.48	182.91
2A Fuhies	8.21	3.66	92.54
3A Fuhies	16.82	3.8	52.22
1B Al-Salt	8.56	3.29	174.68
2B Al-Salt	7.87	2.26	123.33
3B Al-Salt	2.98	2.89	169.29
1C Dapouq	8.23	7.07	301.91
2C Dapouq	2.33	2.82	286.02
3C Dapouq	7.19	1.82	147.07
Average	7.27 ± 4.39	3.45 ± 1.5	170.00 ± 81.87
Range	2.33–16.82	1.82–7.07	52.22–301.91

Table 3
Radon emanation coefficient Rn_{EC} and radon mass exhalation rate E_x (m Bqkg^{-1}h^{-1}) for soil samples.

Sample ID	Rn_{EC}	E_x (m Bqkg^{-1}h^{-1})
1A Fuhies	0.621	124.86
1B Al-Salt	0.740	112.30
2B Al-Salt	0.692	112.24
1C Dapouq	0.721	83.45
1C Dapouq	0.780	65.83
Average	0.711 ± 0.06	99.73 ± 21.73
Range	0.621–0.740	65.83–124.86

disparities in the E_x between different locations can be ascribed to variations in the radium concentrations present in the soil. The complex interactions between the material's properties, radon generation, and release mechanisms make it challenging to establish a straightforward linear correlation between the emanation factor or mass exhalation rate of ^{222}Rn and the concentration of its parent isotope, ^{226}Ra.

3.3. Radiological hazards assessment

Table 4 shows the mean values of Ra_{eq}, H_{ex}, H_{in}, I_γ, I_α, AGDR, AEDE, and ELCR in soil samples. The Ra_{eq} results varied from 43.432 to 119.832 (Bqkg^{-1}) with a mean value of 76.090 ± 27.98 (Bqkg^{-1}), which is lower than the recommended maximum value of 370 (Bqkg^{-1}) [21]. The values of the H_{ex} ranged from 0.117 to 0.324, with a mean value of 0.205 ± 0.08. These values fall below the prescribed threshold for a radiologically secure substance. [3]. The (H_{in}) values range from 0.147 to 0.394, with a mean value of 0.256 ± 0.098, which is less than the standard as recommended for radiologically safe material. The (I_γ) values ranged from 0.170 to 0.468, with a mean value of 0.296 ± 0.119. This value falls below the prescribed threshold for a radiologically secure substance [3]. The (I_α) values in the samples ranged from 0.055 to 0.131, with a mean value of 0.093 ± 0.029, which is less than the standard as recommended for radiologically safe material [22].

The mean values of the AGDR in the air (outdoor) at 1 m above ground level are 37.865 ± 15.127 nGyh^{-1}, ranging from 21.714 to 59.671 (nGyh^{-1}). All sampling points that had AGDR values were less than the world-wide average of 57 nGyh^{-1} [3]. The values of AEDE in soil samples for an outdoor environment ranged from 0.027 to 0.073 mSvy^{-1}, with a mean of 0.046 ± 0.019 mSvy^{-1}. The AEDE values at all sampling locations were found to be below the internationally recognized safe limit of 0.07 mSvy^{-1} for outdoor environments, as stated in [3]. The soil samples exhibited ELCR values ranging from (0.093 to 0.256) × 10^{-3}, with an average value of (0.163 ± 0.065) × 10^{-3}. The ELCR in all sampling locations was observed to be below the globally estimated average value of 0.29 × 10^{-3} [23].

3.4. Gross alpha and gross beta activity measurement

Based on the data presented in Table 5, it can be observed that the gross alpha activity in the soil samples exhibited a range of 3.27 to 6.04 (Bqkg^{-1}), with a calculated mean value of 4.64 ± 1.04 (Bqkg^{-1}). In a similar vein, the soil samples exhibited a range of gross beta activity ranging from 30.79 to 67.07 (Bqkg^{-1}), with a mean value of 48.13 ± 14.50 (Bqkg^{-1}). The distributions of gross alpha and gross beta activities suggest that the gross alpha activity is comparatively lower than the gross beta activity, as shown in Fig. 3. This discrepancy may be attributed to the lower activity concentrations of ^{226}Ra and ^{232}Th in comparison to the activity concentration of ^{40}K. According to the data presented in Table 5, it can be observed that the gross beta activity is tenfold greater than the gross alpha activity in soil samples. The data presented in Table 6 reveals that the gross alpha activity in OMP samples exhibited a range of 0.10 to 0.86 (Bqkg^{-1}), with a mean value of 0.32 ± 0.27 (Bqkg^{-1}). In a similar vein, the gross beta activity observed in OMP samples exhibited a range of 42.82 to 75.34 (Bqkg^{-1}), with a mean value of 59.19 ± 12.94 (Bqkg^{-1}). The magnitude of the gross alpha activity observed in OMP samples was found to be significantly lower in comparison to the gross beta activity, as shown in Fig. 3. This disparity may be attributed to the relatively lower activity concentrations of ^{226}Ra and ^{232}Th in comparison to the concentration of ^{40}K. Additionally, it is worth noting that the utilization of fertilizer can potentially elevate the concentration of beta radioactivity.

Table 7 presents a comprehensive comparison of gross alpha and gross beat activity in soil samples from various regions. The results reveal a substantial variation in gross alpha and gross beta activity. This variation can be attributed to diverse geological, geographical, and environmental conditions.

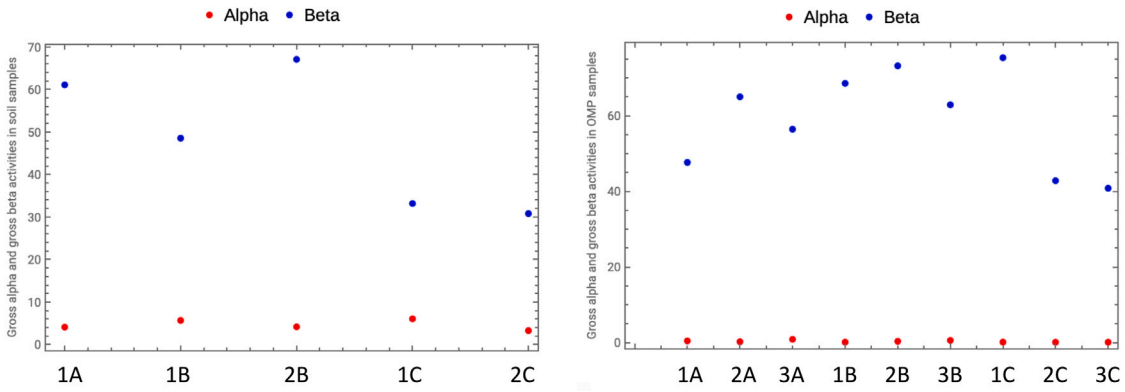

Fig. 3. Gross alpha and gross beta activity ($Bqkg^{-1}$) in the soil and OMP samples.

Table 4
The average values of Radium equivalent activity (Ra_{eq}) ($Bqkg^{-1}$), external radiation hazard index (H_{ex}), internal radiation hazard index (H_{in}), gamma index (I_γ), alpha index (I_α), absorbed gamma dose rate (AGDR) ($nGyh^{-1}$), annual effective dose equivalent (AEDE) ($mSvy^{-1}$) and excess lifetime cancer risk (ELCR) in soil samples.

Sample ID	Ra_{eq} ($Bqkg^{-1}$)	H_{ex}	H_{in}	I_γ	I_α	AGDR ($nGyh^{-1}$)	AEDE ($mSvy^{-1}$)	ELCR × 10^{-3}
1A	119.832	0.324	0.394	0.468	0.131	59.671	0.073	0.256
1B	80.458	0.217	0.271	0.318	0.099	40.696	0.050	0.175
2B	65.841	0.178	0.235	0.251	0.106	32.32	0.040	0.139
1C	70.886	0.191	0.232	0.274	0.075	34.926	0.043	0.150
1C	43.432	0.117	0.147	0.170	0.055	21.714	0.027	0.093
Average	76.090 ± 27.98	0.205 ± 0.08	0.256 ± 0.098	0.296 ± 0.119	0.093 ± 0.029	37.865 ± 15.127	0.046 ± 0.019	0.163 ± 0.065
Worldwide	370	1	1	1	1	57	0.07	0.29

Table 5
Gross alpha and Gross beta activity ($Bqkg^{-1}$) in soil samples.

Sample ID	Gross alpha ($Bqkg^{-1}$)	Gross beta ($Bqkg^{-1}$)
1A Fuhies	4.08	33.17
1B Al-Salt	3.27	48.54
2B Al-Salt	4.16	30.79
1C Dapouq	6.04	61.08
1C Dapouq	5.66	67.07
Average	4.64 ± 1.04	48.13 ± 14.50

Table 6
Gross alpha and Gross beta activity ($Bqkg^{-1}$) in OMP samples.

SampleID	Gross alpha ($Bqkg^{-1}$)	Gross beta ($Bqkg^{-1}$)
1A Fuhies	0.45	47.65
2A Fuhies	0.23	65.01
3A Fuhies	0.86	56.43
1B Al-Salt	0.12	68.56
2B Al-Salt	0.34	73.2
3B Al-Salt	0.58	62.89
1C Dapouq	0.13	75.34
2C Dapouq	0.09	42.82
3C Dapouq	0.10	40.82
Average	0.32 ± 0.27	59.19 ± 12.94

Table 7
Comparison of gross alpha and gross beta activity ($Bqkg^{-1}$) in soil samples across various regions/countries.

Country	Gross alpha ($Bqkg^{-1}$)	Gross beta ($Bqkg^{-1}$)	References
Iraq	2.15–36.23	2.15–36.23	[24]
Serbia	66.7–102.4	285.7–607.4	[19]
Bangladesh	1.13–5.66	30.74–132	[25]
Malysia	15–9634	142–6173	[13]
Saudi Arabia	4.16–6.36	23.39–76.07	[26]
Jordan	3.27–6.04	30.79–67.07	Present study

4. Conclusions

The study's goals were to look at the amounts of radionuclides ^{226}Ra, ^{232}Th, and ^{40}K in soil and OMP, as well as the radon emanation coefficient and the radon mass exhalation rate. It also wanted to figure out the radiological risk factors for soil samples collected in northwest Jordan. It was found that the amounts of ^{226}Ra and ^{232}Th activity in both the soil and OMP samples were lower than the average levels seen around the world. Although it was lower than that in OMP, the activity concentration of ^{40}K was higher than the average values seen globally in soil. The radiological hazards analysis revealed that the estimated average values of H_{ex}, I_γ, H_{in}, and I_α for soil samples were found to be below the recommended standard levels. The calculated mean AGDR for the soil samples was found to be lower than the globally weighted average. The mean AEDE value for the soil samples was found to be below the recommended safety threshold for outdoor soil. The estimated average ELCR for the soil samples was found to be lower than the global average. Furthermore, the levels of gross alpha and gross beta activities were measured in soil and OMP samples. The findings of this study suggest that the activities were determined to be within the acceptable threshold. Based on the results obtained from the conducted studies, it can be deduced that the soils and OMP samples analyzed in the chosen regions of Jordan do not pose significant radiological hazards to the indigenous population.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors express their gratitude to the nuclear and radiation group at Al-Majmaah University for their support and contributions. We also extend our sincere thanks to the editor and reviewers for their insightful comments and suggestions, which have significantly enhanced the quality of this manuscript.

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