# ASSESSMENT OF RADON EXHALATION RATE AND RADIUM CONTENT IN SOIL SAMPLES FROM EAST WEST BANK, PALESTINE

by

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**The study focused on measuring and calculating radiological characteristics related to radon concentration, radium content, radon exhalation rates, and radiation exposure in soil samples collected from various sites in the eastern West Bank, Palestine. The findings revealed notable variations in radon ($^{222}$Rn) concentration across the study samples, ranging from 169.3 Bqm$^{-3}$ in west Jericho city to 6184.4 Bqm$^{-3}$ in Al-Maghtas, with a total average of 1705 Bqm$^{-3}$. Similarly, effective radium content values varied significantly, ranging from 8.2-301.2 Bqkg$^{-1}$, with a total average of 74 Bqkg$^{-1}$. The average radon exhalation rates also exhibited considerable variability, ranging from 73.2 mBqm$^{-2}$h$^{-1}$ (3.1 mBqkg$^{-1}$h$^{-1}$) to 1419.8 mBqm$^{-2}$h$^{-1}$ (54.7 mBqkg$^{-1}$h$^{-1}$), with an average rate of 543 mBqm$^{-2}$h$^{-1}$ (19.5 mBqkg$^{-1}$h$^{-1}$). These results were compared to similar studies, where similarities and differences were noted. Based on concentration data and observed correlations, certain areas from which the samples were collected appear to pose significant health risk to residents. Consequently, these findings are significant and can be used as a reference for monitoring changes in radiation levels within the Jericho environment over time.**

*Key words: radon exhalation rate, radium content, CR-39 detector, sealed-can technique, cancer, Jericho*

## INTRODUCTION

Radon ($^{222}$Rn) is a naturally occurring gas that emanates from the soil and accumulates in closed indoor spaces, especially basements. The $^{222}$Rn is an inert noble gas with a short half-life of 3.82 days [1]. During its decay, it emits alpha particles which pose health risks mainly through inhalation or ingestion. Long-term exposure to $^{222}$Rn gas is associated with an increased risk of lung cancer [2]. According to the Environmental Protection Agency (EPA), $^{222}$Rn is responsible for approximately 21000 lung cancer-related deaths worldwide each year. Notably, around 2900 of these fatalities occur among individuals who have never smoked. The recommended action level for indoor $^{222}$Rn is 4 pCiL$^{-1}$ (148 Bqm$^{-3}$). This concentration increases the risk of lung cancer to a level equivalent to smoking eight cigarettes daily over a lifetime [3]. However, some experts believe that even lower levels of $^{222}$Rn can be harmful [4, 5]. If an indoor radon concentration exceeds the recommended radon level, a radon mitigation system should be implemented [3]. As a result, numerous studies concentrate on measuring indoor $^{222}$Rn concentrations [6-8].

While soil measurements do not directly correspond to air measurements, evidence indicated a positive correlation between radon $^{222}$Rn in soil and $^{222}$Rn in air [6, 9]. To better understand how soil measurements contribute to more accurate air radon predictions $^{222}$Rn should be studied concerning its exhalation from various soil types and its interaction with and entrapment in buildings. [6,10]. The soil concentration of $^{222}$Rn can vary notably due to factors like soil type, moisture, local geological conditions, and the depth at which measurements are conducted [11, 12]. Setting specific thresholds for taking action based on $^{222}$Rn levels in the soil is uncommon, as priority is generally placed on indoor radon $^{222}$Rn levels due to their direct relevance to human exposure and associated health risks.

Importantly, now more than ever, $^{222}$Rn may be a pressing issue for society because climate change ef-

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fects can be associated with increasing radon exposure. Each year, ice layers cover progressively less ground and persist for shorter periods, likely leading to an increase in the annual release of radon gas from the ground [13]. Additionally, humans are trending towards staying indoors even more often as harsh climates encourage staying cool inside with air conditioning units. This will reduce airflow from outside and increase the amount of radon accumulating inside [5].

The $^{222}$Rn indoors and in air is not the only concern; radium in soil, which decays into $^{222}$Rn, can also introduce radioactivity into crops and plants we consume [14]. Phosphate fertilizers applied in agriculture increase radon levels in soil due to their high uranium content, originating from the phosphate rocks used in their production [15]. This is the first study of radon soil concentrations in the eastern West Bank (Jericho and Al Aghwar governorate), Palestine, utilizing the CR-39 sealed-can techniq

ue. The region uses traditional building materials, such as limestone and granite which are earthen/naturally occurring and may contain higher-than-usual concentrations of radon or radium [9, 16, 17]. Previous studies have examined the West Bank, but not all the zones included in the survey were covered [12, 18].

The present work aims to determine the radon exhalation rate and radium contents in soil samples collected from various areas in the Jericho and Al Aghwar Governorate. It also synthesizes and compares the findings with $^{222}$Rn soil data from similar studies. The results obtained here can be used to determine the average dose rates and radioactivity background levels. Our findings hold significant implications regarding the well-being of numerous Palestinians residing in the Jericho and Al Aghwar governorates and call for thorough research into health and safety in areas without active monitoring $^{222}$Rn concentrations.

## MATERIALS AND METHODS

### Study area

Jericho and Al Aghwar governorate is a Palestinian region located in the eastern part of West Bank, with Jericho city as its administrative center. Recognized as the oldest city in the world, Jericho is one of the 16 governorates of Palestine and lies at co-ordinates 31°52'16"N, 35°26'39"E. The geological outcropping in the Jericho district is formed by sedimentary rocks dating from Quaternary and Upper and Lower Cretaceous formations. As shown in fig. 1, the region is situated along the southern Jordan River and the northern Dead Sea and is therefore well irrigated. According to the Palestinian Central Bureau of Statistics (PCBS), the total population of Jericho and Al Aghwar (Jordan Valley) governorate in 2019 was 51500 persons, accounting approximately 1.8 % of the total population of the West Bank State of Palestine. The Jericho region covers a total area of 592.82 km$^2$, with a population density of 67 persons per one km$^2$ [20]. Positioned over 200 m below sea level, Jericho city is one of the world's low-altitude cities, located 258 meters below sea level, which

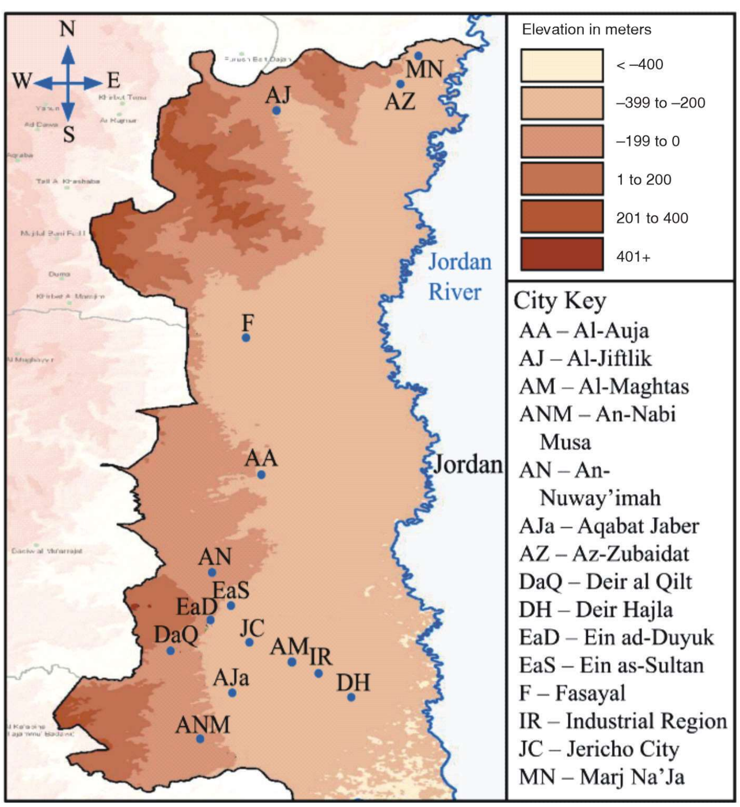


**Figure 1. Map of sampling locations in the Jericho governorate with their elevation [19]**

makes it the lowest city in the world. The city's average temperature is 24 °C , and its humidity is 49 % [19, 21].

The Jericho and Al Aghwar districts are characterized by thriving agricultural and tourism sectors, which serve as the primary livelihoods for its residents. In recent years, considerable growth and expansion in date palm farming and industrial activities have created an increasing demand for innovative solutions to ensure a sufficient water supply for irrigation needs [19]. Using agricultural fertilizer combined with naturally warm soil creates conditions that favor elevated $^{222}$Rn concentrations, highlighting the importance of $^{222}$Rn testing [15].

### Samples collection process

Solid-state nuclear track detectors (SSNTD) are becoming a popular tool for $^{222}$Rn measurements in soil. A particular detector, CR-39 has several characteristics that make it well-suited for this study. The CR-39 detector is effective for measuring soil and air samples; however, complications arise when measuring in water, as humidity can harm the integrity of the CR-39 material [18, 22].

All samples taken in this study were dry soil samples. The CR-39 detectors can detect alpha particles of all energies emitted from radon and its daughters. Figure 2(a) illustrates the natural decay series of $^{238}$U through to $^{218}$Po, where black continuous arrow represants $\alpha$-decay and segmented arrow represents $\beta$-decay. The half-life of $^{222}$Rn is only 3.82 days, whereas $^{226}$Ra has a much longer half-life of 1600 years. This significant disparity indicates that $^{222}$Rn has a notable impact during data collection, whereas the influence $^{226}$Ra is negligible [1]. When alpha particles reach the detector, they create tracks, with the number of tracks being proportional to the average $^{222}$Rn concentration [23].

Eighty-five soil samples were randomly collected from various sites across the Jericho and Al Aghwar governorate, at a depth of 5 cm beneath the top layer of debris. The samples were coded and classified. The samples were compressed and crushed into particles less than 2 mm in diameter. They were then dried in a temperature-controlled oven at 110 °C for 24 hours.

The CR-39 detectors were cut into small pieces (1 cm × 1 cm) and affixed to the top of a plastic container, measuring 24 cm in height and 12.5 cm in diameter, as shown in fig. 2(b). Approximately 185 cm$^3$ of the collected samples were placed into each container, and the detector was exposed to radon for 90 days. After the exposure period, the detectors were retrieved and subjected to constant chemical etching in 6.25 M NaOH at (70 ± 0.1 °C) for 6 hours [24]. At the end of the etching process, the detectors were washed with distilled water and dipped for a few seconds in a 3% acetic acid solution. Subsequently, they were rinsed once more and left to dry in the air. Finally, each detector was visually analyzed using an optical microscope at 400× magnification to count the number of tracks [25].

## THEORETICAL CONSIDERATIONS

### The $^{222}$Rn concentration

The observed track density was utilized to calculate the $^{222}$Rn concentration in Bqm$^{-3}$ using the provided calibration factor. The track density was converted into radon concentrations in Bqm$^{-3}$ with the calibration factor ($k$) supplied by the manufacturer. According to this calibration factor, each track per cm² per day on the CR-39 detectors corresponds to an exposure of 12.3 Bqm$^{-3}$ of radon gas and its daughters [16]. The $^{222}$Rn concentration at secular equilibrium $C_{\mathrm{Rn}}$ can be estimated by the following eq. [18]

$$C_{\mathrm{Rn}} = k\frac{\rho}{T_{\mathrm{eff}}} \tag{1}$$

$$T_{\mathrm{eff}} = t + \tau(\mathrm{e}^{-\lambda t} - 1) \tag{2}$$

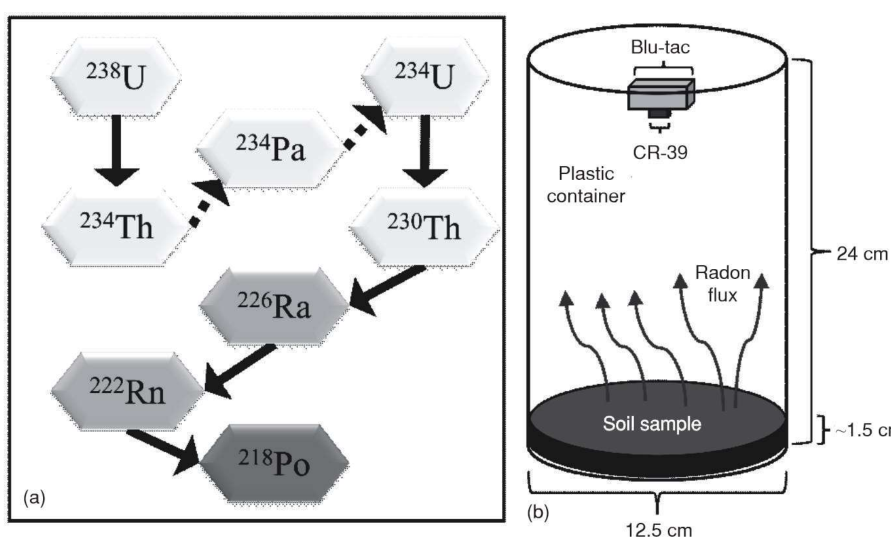


**Figure 2(a). Natural decay series of $^{238}$U down to $^{218}$Po where black continuous arrow represents α-decay and segmented arrow represents β-decay and (b) soil sample, container, and CR-39 device setup**

where $k$ [Bqm$^{-3}$] is the calibration factor per track per cm$^2$ per hour, $\rho$ – the track density in tracks per cm$^2$, $T_{\text{eff}}$ – the effective exposure time in hours, $\tau$ – the mean life of radon (5.5 days = 132 hours), $t$ – the total exposure time (90 days = 2160 hours), and $\lambda$ – the $^{222}$Rn decay constant ($7.56 \cdot 10^{-3}$h$^{-1}$) [16, 18].

### The effective radium content

Knowing the concentrations of radium is crucial because it serves as an indicator of the presence of radon in the sample, given their direct proportionality. The effective radium content $C_{\text{Ra}}$ in soil samples was calculated using the following equation [10, 18]

$$C_{\text{Rn}} = \frac{\rho h A}{k T_{\text{eff}} M} \tag{3}$$

where $h$ [m] is the distance between detector and top of sample, $A$ [m$^2$] – the surface area radon is exhaled through, $k$ (cm$^{-2}$h$^{-1}$ per Bqm$^{-3}$) – the calibration factor in tracks, and $M$ [kg] – the mass of the sample.

Calibration was conducted using a dosimeter of identical size to the containers used for sample filling during the study. This dosimeter includes a detector and a known quantity of radium whose radioactivity was known.

### The exhalation rates

The surface exhalation rate ($E_A$) was calculated using the relation [12, 18]

$$E_A = \frac{\lambda C V}{A T_{\text{eff}}} \tag{4}$$

where $C$ [Bqm$^{-3}$h] is the integrated radon exposure, $A$ [m$^2$] – the area covered by the can, and $V$ [m$^3$] – the volume of the can. Similarly, the mass exhalation rate ($E_M$) was determined by the following relation [12, 18]

$$E_M = \frac{\lambda C V}{M T_{\text{eff}}} \tag{5}$$

### The dissolved $^{222}$Rn concentration

The dissolved radon concentration ($C_S$) in soil samples was calculated using the following equation [26-28]

$$C_S = \frac{h t \lambda C_{\text{Rn}}}{L} \tag{6}$$

where $L$ [m] is the depth of the sample.

### The annual effective dose

The estimated annual effective dose (AED) due to $^{222}$Rn concentrations is calculated according to the recommendations of the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), in the 2000 annual report. The AED can be determined using the following relation [27]

$$AED = C_{\text{Rn}} \cdot F \cdot T \cdot \text{Q} \tag{7}$$

where $F$ is the conversion factor ($F$ = 9 nSv (Bqm$^{-3}$h)$^{-1}$), $T$ – the hours of indoor occupancy per year (8760 hours in a year and 80 % indoor occupancy time): $T_{\text{in}}$ = 7008 hours and $T_{\text{out}}$ = 1752 hours, and Q – the equilibrium fraction: 0.4 indoor, 0.6 outdoor [27]

$$AED_{\text{in}} = 0.02523 \cdot C_{\text{Rn}} \tag{8}$$

From the equation, we can calculate the annual effective dose for indoors and outdoors according to the following relations [26]

$$AED_{\text{out}} = 0.00946 \cdot C_{\text{Rn}} \tag{9}$$

### The effective alpha dose equivalent and emanation fraction

The level of the alpha dose attributable to the presence of $^{222}$Rn in the air plays a significant role while calculating exposure to $^{222}$Rn. According to the Commission of European Communities (CEC) report, there is an effective dose equivalent of 0.05 mSv per year and per every 1 Bqm$^{-3}$ of $^{222}$Rn in the average annual air concentration. It is possible to estimate the alpha dose by using the specific activity of $^{226}$Ra based on the hypothesis of secular equilibrium which is equivalent to an effective dose rate of 0.05 mSv per year $^{238}$U [29]. The $ED_\alpha$ (effective alpha dose equivalent) can be expressed as [30]

$$ED_\alpha = 0.18 \, \text{f} \, C_{\text{Ra}} + 0.45 \tag{10}$$

where f is the emanation fraction.

The emanation fraction (or the emanation coefficient of radon) f is the fraction of radon that reaches the external atmosphere through the diffusion process. The emanation fraction is an important radiological index used to evaluate the amount of $^{222}$Rn released from environmental samples. The emanation fraction was determined through the following eq. [30]

$$\text{f} = \frac{E_{\text{M}}}{C_{\text{Ra}} \lambda_{\text{Rn}}} \tag{11}$$

## RESULTS AND DISCUSSION

### Radon soil concentrations and effective radium content

Eighty-five different soil samples collected from various sites of the Jericho and Al Aghwar governorate were measured and calculated using sealed-can technique. Table 1 provided details on the locations, $^{222}$Rn concentrations, active radium contents, and dissolved $^{222}$Rn concentrations. The concentrations of $^{222}$Rn in the collected samples varied from 169 Bqm$^{-3}$ to 6184 Bqm$^{-3}$, with an average concentration of 1388 Bqm$^{-3}$. Table 1 highlights that the lowest $^{222}$Rn concentration was detected in Jericho city, while the highest was recorded in Al-Maghtas (Baptism), located southeast of Jericho city. The results further reveal that the highest average $^{222}$Rn concentration was observed in soil samples collected from Deir Hajla (3935 Bqm$^{-3}$). The lowest average concentration was measured in An- Nuway'imah (225 Bqm$^{-3}$), north of Jericho city.

The effective radium content ranged from 8-301 Bqkg$^{-1}$, with an average value of 74 Bqkg$^{-1}$. This average $^{226}$Ra content in soil samples (74 Bqkg$^{-1}$) exceeds the worldwide average of 35 Bqkg$^{-1}$ but remains below UNSCEAR's recommended action level for radium equivalent (370 Bqkg$^{-1}$) [31]. Additionally, tab. 1 also shows the dissolved $^{222}$Rn concentrations in the soil samples, which vary from 254 Bqm$^{-3}$ to 9338 Bqm$^{-3}$, with an average of 2072 Bqm$^{-3}$.

Figure 3(a) illustrates the variations in measured mean $^{222}$Rn soil concentrations across different zones within the Jericho and Al Aghwar governorate, including data from chemical fertilizer (CF), industrial soil (IS), and natural fertilizer (NF) sources. Notable differences are observed among these zones, with the chemical fertilizer area exhibiting the highest mean $^{222}$Rn soil concentrations. These findings underscore the crucial need for conducting localized $^{222}$Rn testing. Variations in $^{222}$Rn concentrations in the samples may be due to characteristics such as the soil uranium content. This could also indicate that the sites have a high level of phosphate content from agricultural fertilizers [15, 18]. Soil gas concentration of $^{222}$Rn can vary widely due to weather conditions, climatic factors, soil type, the season of soil collection, and soil composition [11, 12, 32]. Figure 3(b) shows the frequency distribution of $^{222}$Rn concentration in soil samples in the Jericho governorate region. The $^{222}$Rn concentration at 1.0 ± 0.25 kBqm$^{-3}$ has the highest frequency.

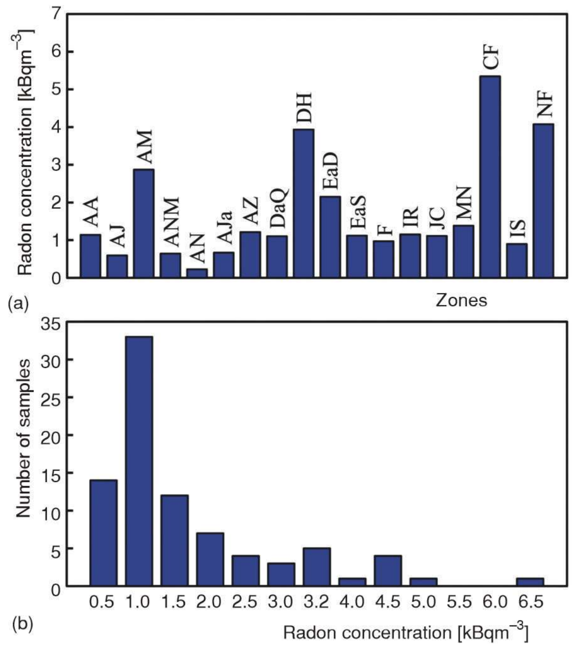


**Figure 3(a). Average $^{222}$Rn concentration in each zone in this study plus data on chemical fertilizer (CF), industrial soil (IS), and natural fertilizer (NF), (b) The number of soil samples which fell in each $^{222}$Rn concentration range**

## The exhalation rates

Table 2 shows the surface and mass exhalation rates for soil samples collected from various zones of

**Table 1. The $^{222}$Rn concentrations ($C_{Rn}$), radium concentrations ($C_{Ra}$), and the dissolved $^{222}$Rn concentrations ($C_S$) in different soil samples collected from Jericho Governorate**

| Zone | Number of samples | $C_{Rn}$ [Bqm$^{-3}$] | | | $C_{Ra}$ [Bqkg$^{-1}$] | | | $C_s$ [Bqm$^{-3}$] | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | min | max | mean | min | max | mean | min | max | mean |
| Al-Auja (AA) | 5 | 465 | 2806 | 1139 | 23 | 137 | 56 | 698 | 4209 | 1709 |
| Al-Jiftlik (AJ) | 3 | 299 | 968 | 594 | 15 | 47 | 29 | 448 | 1453 | 891 |
| Al Maghtas (Baptism)* | 9 | 608 | 6184 | 2869 | 30 | 301 | 140 | 912 | 9338 | 4321 |
| An Nabi Musa* | 3 | 207 | 966 | 642 | 10 | 47 | 31 | 311 | 1449 | 963 |
| An-Nuwayimah* | 3 | 172 | 299 | 225 | 8 | 15 | 11 | 257 | 448 | 338 |
| Aqabat Jaber* | 3 | 514 | 923 | 669 | 25 | 45 | 33 | 771 | 1348 | 1003 |
| Az-Zubidat | 3 | 382 | 2292 | 1213 | 19 | 112 | 59 | 573 | 3438 | 1820 |
| Deir al Qilt* | 3 | 721 | 1506 | 1105 | 35 | 73 | 54 | 1081 | 2259 | 1657 |
| Deir Hajla* | 3 | 3255 | 4342 | 3935 | 159 | 211 | 192 | 4882 | 6513 | 5902 |
| Ein ad-Duyuk | 3 | 998 | 3406 | 2149 | 49 | 166 | 105 | 1497 | 5108 | 3224 |
| Ein as-Sultan | 3 | 514 | 1471 | 1120 | 25 | 72 | 55 | 771 | 2207 | 1680 |
| Fasayal | 3 | 570 | 1216 | 970 | 28 | 59 | 47 | 856 | 1824 | 1456 |
| Industrial region* | 4 | 589 | 1617 | 1151 | 29 | 79 | 56 | 883 | 2425 | 1727 |
| Jericho city | 30 | 169 | 4169 | 1212 | 8 | 45 | 54 | 254 | 6254 | 1668 |
| Marj Naja | 4 | 818 | 2402 | 1382 | 40 | 117 | 67 | 1227 | 3603 | 2073 |
| Chemical fertilizer | 1 | | | 5346 | | | 174 | | | 3564 |
| Industrial soil | 1 | | | 896 | | | 29 | | | 597 |
| Natural fertilizer | 1 | | | 4075 | | | 132 | | | 2717 |
| Total average | 85 | 1705 | | | 74 | | | 2072 | | |

* Stars regions are deserts; the others are with agricultural activity

the Jericho governorate region. In the present study, the mean surface exhalation rate for $^{222}$Rn ranges from 73.2-1419.8 mBqm$^{-2}$h$^{-1}$ with a total average of 543 mBqm$^{-2}$h$^{-1}$. The lowest surface exhalation rates of $^{222}$Rn were found in soil samples collected from the western part of Jericho city, while the highest rates were in samples taken from the Deir Hajla site. The average surface exhalation rate in soil samples observed is within the estimated world average for surface exhalation rate from the soil which is 57600 mBqm$^{-2}$h$^{-1}$ [33]. The mean values of mass exhalation rate for $^{222}$Rn range from 3.1-54.7 mBqkg$^{-1}$h$^{-1}$ with a total average value of 19.5 mBqkg$^{-1}$h$^{-1}$.

### The annual effective dose and effective alpha dose equivalent

Table 3 presents the effective alpha dose equivalent $ED_\alpha$ where the mean values range from 0.5-1.8 mSv with a total average value of 0.9 mSv, which is two times higher than the corresponding worldwide average indoor value of 0.41 mSv [31, 34].

The annual effective doses due to outdoor and indoor exposure are shown in tab. 3. The mean annual effective dose indoors ranged from 5.7 mSv at the An-Nuway'imah site to 99.2 mSv at the Deir Hajla site, with an overall average of 35.0 mSv. The outdoor average annual effective dose varied from 2.1-37.2 mSv with a total average of 13.2 mSv. The results indicate that the highest annual effective dose values, both indoors and outdoors, were recorded in most samples from the studied area, exceeding the recommended action level of 10 mSv as reported in references [31, 34].

### Effective radium content compared to $^{222}$Rn

To understand the radioactive properties of the soil such as radon flux, the radium content is a key component. Therefore, it is possible to analyze the current data to determine the relationship between radium content and radon exhalation rates [35]. Figure 4(a) displays $^{222}$Rn soil concentrations paired with the actual radium content.

This is important to show how much radium decays. Figure 4(b) compares effective radium content with the surface exhalation rate of $^{222}$Rn. In fig. 4(c), a similar comparison is made with mass exhalation rate. A positive correlation has been observed between the effective radium content and both $^{222}$Rn concentrations and the exhalation rates in the soil. The correlation coefficient between the values of effective radium content, $^{222}$Rn concentration values, and exhalation rates have $R^2$ values ranging from 0.91 to 0.99. This indicates a strong correlation, consistent with findings from other studies [18, 41].

Figure 4(d) shows the minimum and maximum soil $^{222}$Rn concentrations in Palestinian regions such as Jericho (the current study location), and other West Bank cities or regions, including Hebron [12], Bethlehem [18], and the Dead Sea [36]. It also includes data from the surrounding regions and cities in the Middle East, such as the West Nile Delta in Egypt [37]; Beirut in Lebanon (along with data gathered from other nearby governates in south Lebanon during the Lebanon survey) [38], Damascus in Syria (covering Damascus governorate in Syria and supplemented with data from the Daraa- Jordan border) [39], Dikili in

**Table 2. Surface exhalation rate $E_A$ and mass exhalation rate $E_M$ in different soil samples collected from Jericho Governorate**

| Zone | $E_A$ [mBqm$^{-2}$h$^{-1}$] | | | $E_M$ [mBqkg$^{-1}$h$^{-1}$] | | |
|---|---|---|---|---|---|---|
| | min | max | mean | min | max | mean |
| Al-Auja | 168 | 1010 | 410 | 6.5 | 39 | 16 |
| Al-Jiftlik | 108 | 349 | 214 | 4 | 14 | 8 |
| Al Maghtas (Baptism) | 219 | 2226 | 1033 | 8 | 86 | 40 |
| An Nabi Musa | 47.6 | 348 | 231 | 3 | 13 | 9 |
| An-Nuwayimah | 61.2 | 108 | 81 | 2.5 | 4 | 3 |
| Aqabat Jaber | 185 | 332 | 241 | 7 | 13 | 9 |
| Az-Zubidat | 138 | 825 | 437 | 5 | 32 | 17 |
| Deir al Qilt | 260 | 542 | 398 | 10 | 21 | 15 |
| Deir Hajla | 1172 | 1573 | 1420 | 45 | 60 | 55 |
| Ein ad-Duyuk | 359 | 1226 | 774 | 14 | 47 | 30 |
| Ein as-Sultan | 185 | 530 | 403 | 7 | 20 | 16 |
| Fasayal | 205 | 438 | 349 | 8 | 7 | 14 |
| Industrial region | 212 | 582 | 415 | 8 | 23 | 16 |
| Jericho City | 61 | 1501 | 396 | 2 | 59 | 17 |
| Marj Naja | 294 | 865 | 498 | 11 | 33 | 19 |
| Chemical fertilizer | | | 1283 | | | 44 |
| Industrial soil | | | 215 | | | 8 |
| Natural fertilizer | | | 978 | | | 38 |
| Total average | 543 | | | 21 | | |

**Table 3. Effective alpha dose equivalent $ED_{\alpha}$, indoor annual effective dose $AED_{in}$, and outdoor annual effective dose $AED_{out}$ in different soil samples collected from Jericho Governorate**

| Zone | $E_D$ [mSv] | | | $AED_{in}$ [mSv] | | | $AED_{out}$ [mSv] | | |
|---|---|---|---|---|---|---|---|---|---|
| | min | max | mean | min | max | mean | min | max | mean |
| Al-Auja | 0.6 | 1.4 | 0.8 | 1.7 | 70.8 | 28.7 | 4.4 | 26.5 | 12.4 |
| Al-Jiftlik | 0.5 | 0.8 | 0.6 | 7.5 | 24.4 | 15 | 2.8 | 9.2 | 5.6 |
| Al Maghtas (Baptism) | 1.4 | 2.5 | 0.7 | 15.3 | 156 | 72.4 | 5.8 | 58.5 | 27.1 |
| An Nabi Musa | 0.5 | 0.8 | 0.7 | 5.2 | 24.3 | 16.2 | 1.9 | 9.1 | 6 |
| An-Nuwayimah | 0.4 | 0.6 | 0.5 | 4.4 | 7.5 | 5.7 | 1.6 | 2.8 | 2.1 |
| Aqabat Jaber | 0.6 | 0.8 | 0.7 | 8.7 | 13 | 16.9 | 4.9 | 23.4 | 8.7 |
| Az-Zubidat | 0.6 | 1.2 | 0.9 | 9.6 | 57.8 | 30.6 | 3.6 | 21.7 | 11.5 |
| Deir al Qilt | 0.7 | 0.9 | 0.8 | 18.2 | 38 | 27.9 | 6.8 | 14.2 | 10.4 |
| Deir Hajla | 1.5 | 1.9 | 1.8 | 82.1 | 109.5 | 99.2 | 30.8 | 41.1 | 37.2 |
| Ein ad-Duyuk | 0.8 | 1.6 | 1.2 | 25.2 | 85.9 | 54.2 | 9.4 | 32.2 | 20.3 |
| Ein as-Sultan | 0.6 | 0.9 | 0.8 | 13 | 37.1 | 28.3 | 4.9 | 13.9 | 6.7 |
| Fasayal | 0.6 | 0.9 | 0.8 | 14.3 | 30.7 | 24.5 | 5.4 | 11.5 | 9.2 |
| Industrial region | 0.6 | 1 | 0.8 | 14.9 | 40.8 | 29.1 | 5.6 | 15.3 | 10.9 |
| Jericho City | 0.5 | 1.8 | 0.8 | 4.3 | 13.1 | 28 | 1.6 | 39.4 | 10.3 |
| Marj Naja | 0.7 | 1.2 | 0.9 | 20.6 | 60.6 | 34.9 | 7.7 | 22.7 | 13.1 |
| Chemical fertilizer | | | 1.6 | | | 90 | | | 33.7 |
| Industrial soil | | | 0.6 | | | 15.1 | | | 5.6 |
| Natural fertilizer | | | 1.3 | | | 68.5 | | | 25.7 |
| Total average | 0.9 | | | 35 | | | 13.2 | | |

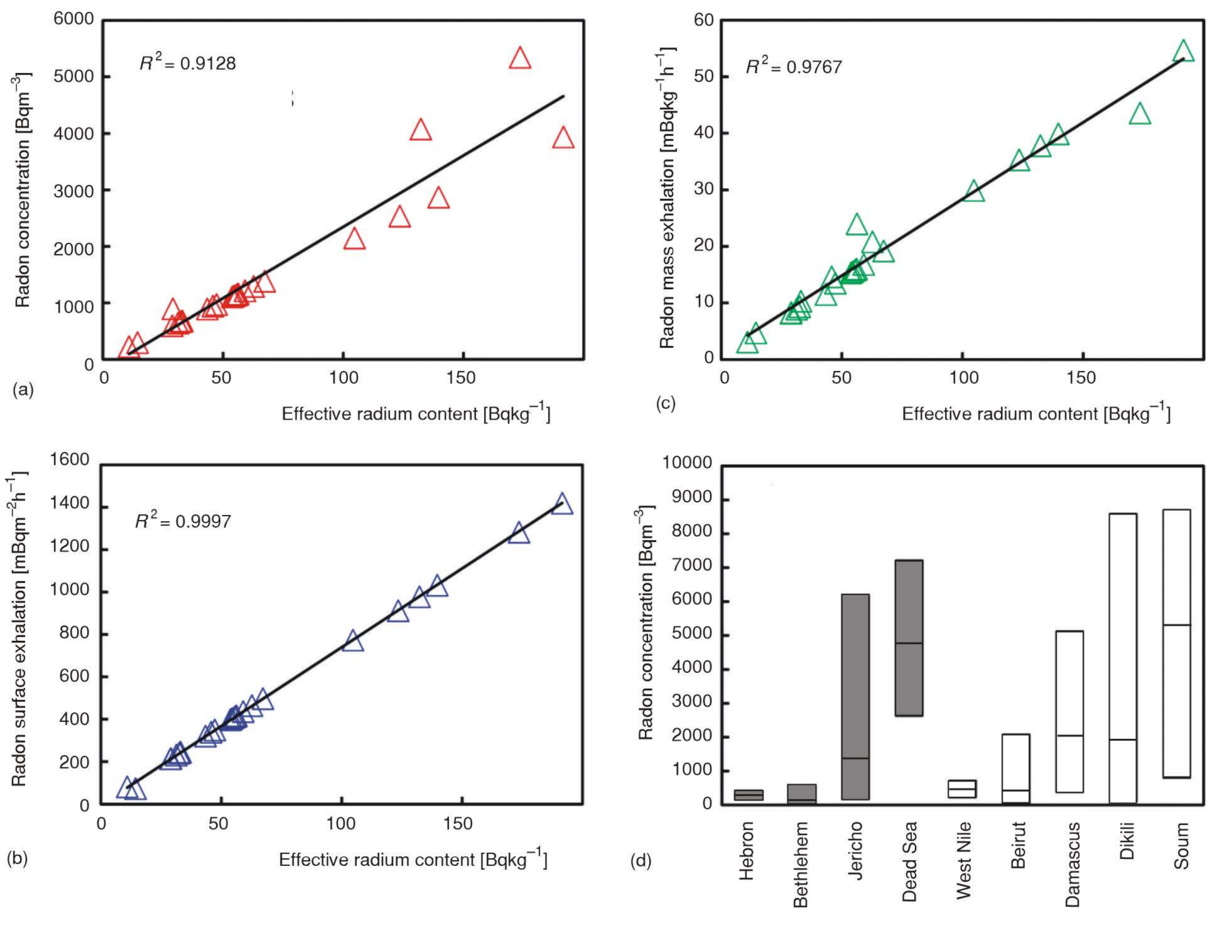


**Figure 4(a). Correlation between the effective radium content and the $^{222}$Rn concentrations, (b) correlation between the effective radium content and the radon surface area exhalation rates, (c) correlation between the effective radium content and the radon mass exhalation rates, (d) the minimum to the maximum of the soil $^{222}$Rn concentrations in Palestinian regions (in dark) such as Jericho, the present study location, and other West Bank cities or regions: Hebron [12]; Bethlehem [18]; and the Dead Sea [36]; and surrounding cities in the middle east (in white): the West Nile Delta in Egypt [37]; Beirut in Lebanon [38]; Damascus governorate in Syria [39]; Dikili in Turkey [40]; Soum region in Northwest Jordan [32]**

Turkey [40], and the Soum region in northwest Jordan [32]. These regions are located near Palestine, which makes them ideal for comparison with Jericho and Al Aghwar governorates data.

Figure 4(d) illustrates that the soil $^{222}$Rn concentration levels in the Jericho governorate are significantly higher than those in the Hebron and Bethlehem regions, indicating a relatively greater risk in the Jericho governorate. Moreover, the concentration of $^{222}$Rn in Jericho exceeds the levels reported in the West Nile Delta, Beirut, and Damascus [12, 18, 37-39]. However, the Jericho and Al Aghwar Governorate did not exhibit the highest recorded $^{222}$Rn concentrations, presented in fig. 4(d), as the levels in the Dead Sea region, Soum, and Dikili surpassed those recorded in Jericho [36, 40].

Table 4 summarizes $^{222}$Rn concentrations in soil samples from studies conducted worldwide. In the Bethlehem region of Palestine, soil $^{222}$Rn concentrations ranged from 19.10-572.9 Bqm$^{-3}$, with a total average value of 145.0 Bqm$^{-3}$ measured at a depth of 5.0 cm below the surface [18]. Another study, conducted in Hebron, Palestine, reported $^{222}$Rn concentrations ranging from 160-425 Bqm$^{-3}$ with an average of 294 Bqm$^{-3}$ measured at the surface level zero cm [12].

The overall average value from our study is approximately ten times higher than the total average value observed in Bethlehem and roughly five times higher than that in Hebron. Figure 3(a) shows that the highest mean $^{222}$Rn concentration in the Jericho and Al Aghwar governorate was found in Deir Hajla at 3934.6 Bqm$^{-3}$ from three samples. This is about 27 times the average value observed in Bethlehem and about 13 times the average from Hebron. As shown in fig. 3(b), the modal range of $^{222}$Rn soil concentration in the Jericho and Al Aghwar governorate samples is between 500-1000 Bqm$^{-3}$, which exceeds the average $^{222}$Rn soil concentration found in both Hebron and Bethlehem.

Figure 5 displays a map showing the average soil $^{222}$Rn concentrations in Jericho and nearby cities in the West Bank, Palestine. The map reveals that, on average, Jericho exhibits higher soil $^{222}$Rn concentrations compared to Bethlehem and Hebron, Palestine. However, rocky formations and phosphate-rich soil found across parts of southern Palestine and along the banks of the Dead Sea contribute notably to higher $^{222}$Rn soil concentrations [36].

**Table 4. The comparison of $^{222}$Rn concentrations for soil samples with other studies**

| Region | No. of samples | $C_{Rn}$ [Bqm$^{-3}$] min | max | mean | Depth [cm] | Device | Reference |
|---|---|---|---|---|---|---|---|
| Canada | 26 | 6800 | 74700 | 1300 | 80 | RM-2 | [11] |
| China – Guangdong Providence | 12 | 3270 | 187050 | 37500 | 80 | RAD7 | [42] |
| China – Shenzhen city | 35 | 15000 | 118000 | 43000 | 80 | RAD7 | [43] |
| Dead Sea | 64 | 2627 | 7215 | 4800 | 50 | [1]PCF | [36] |
| Egypt | 30 | 224.85 | 717.78 | 412 | 20 | CR-39 | [37] |
| Greece | 20 | 15000 | 133000 | 90000 | 90 | [2]AG | [44] |
| India | 20 | 941 | 10050 | 4560.65 | 100 | RAD7 | [45] |
| Iraq – Karbala city | 55 | 28.44 | 479.76 | 220.33 | 50 | CR-39 | [46] |
| Iraq – Duhok | 33 | 198 | 374 | 274 | 15 | RAD7 | [47] |
| Jordan – Soum – winter | 21 | 800 | 8700 | 5300 | 50 | CR-39 | [32] |
| Jordan – Soum – spring | 21 | 1200 | 13100 | 6900 | 50 | CR-39 | [32] |
| Jordan – Soum – autum | 21 | 1600 | 26700 | 8400 | 50 | CR-39 | [32] |
| Lebanon | 16 | 40.24 | 2082.13 | 451.01 | 0 | CR-39 | [38] |
| Mount Scopus – Ghareb Formation | 260 | 3219 | 66341 | 26300 | 50 | 1PCF | [36] |
| Russia | 40 | 1700 | 24000 | 11000 | 70 | [3]T3 | [48] |
| Saudi Arabia – Jazan | 16 | 49.6 | 150.3 | 82.62 | NA | CR-39 | [49] |
| Sudan | 48 | 2110 | 9500 | 5615 | 30 | CR-39 | [50] |
| Syria | 36 | 76 | 32500 | 2103 | 40 | [4]LC | [39] |
| Turkey – Dikili | 36 | 98 | 8594 | 1920 | 50 | LR-115 | [40] |
| Turkey – Kahramanmaras | 13 | 62.87 | 421.89 | 179.36 | 5 | CR-39 | [51] |
| Palestine – Bethlehem | 82 | 19.1 | 572.9 | 145 | 5 | CR-39 | [18] |
| Palestine – Hebron | 27 | 160 | 425 | 294 | 5 | CR-39 | [12] |
| Palestine – Hebron | 27 | 144 | 578 | 357 | 20 | CR-39 | [12] |
| Palestine – Hebron | 27 | 212 | 677 | 433 | 40 | CR-39 | [12] |
| Palestine – Hebron | 27 | 287 | 866 | 512 | 60 | CR-39 | [12] |
| Palestine – Tulkarm | 17 | 281.0 | 826.0 | 505.2 | 5 | CR-39 | [16] |
| Palestine – Jenin | 19 | 116.0 | 746.0 | 528.4 | 5 | CR-39 | [16] |
| Palestine – Tubas | 4 | 346.5 | 650.4 | 515.3 | 5 | CR-39 | [16] |
| Palestine – Jericho governorate | 85 | 169.3 | 6184.4 | 1388 | 5 | CR-39 | Present study* |

[1]PCF – Poly-carbonate Foil, [2]AG – Alpha Guard, [3]T3 – Type III-b passive track, [4]LC – Lucas Cell

Although this study focuses on soil $^{222}$Rn concentrations, the relationship between $^{222}$Rn concentration levels in soil and air justify the need to address the potential risks associated with air $^{222}$Rn [6]. In the air, $^{222}$Rn is considered hazardous when concentrations exceed 148 Bqm$^{-3}$ [5]. This risk is comparable to smoking eight cigarettes daily throughout a lifetime [3].

## CONCLUSIONS

For the first time, $^{222}$Rn concentrations have been successfully measured in the eastern West Bank, including Jericho and Al Aghwar governorate in Palestine. Various radiological characteristics were analyzed to evaluate the risk across different areas within the Jericho governorate. The $^{222}$Rn concentrations in the analyzed samples range from 169.-6184.4 Bqm$^{-3}$, with a total average value of 1705 Bqm$^{-3}$ measured at a depth of 5 cm below the surface.

Analysis of the concentration data reveals that certain areas within the Jericho and Al Aghwar governorate face significantly higher risk compared to other regions in Palestine. Additionally, the International Commission on Radiological Protection (ICRP) recommends that soil $^{222}$Rn concentrations remain within the range of 200-600 Bqm$^{-3}$ at maximum. This indicated that a substantial portion of the soil samples analyzed in this study pose a risk to resident's health in the affected areas [34]. This is potentially attributed to the use of fertilizers for farming in the region, which is one of its largest economic sectors [20]. Consequently, monitoring is recommended for agricultural and housing development activities, given the elevated levels of $^{222}$Rn and radium content.

Moreover, this investigation has identified a significant correlation between $^{222}$Rn concentration, radium concentration, and $^{222}$Rn exhalation rates in soil samples from the study's geographical area. Our findings are essential in raising awareness about soil mate-


*Present study region

**Figure 5. Map of Palestine showing $^{222}$Rn soil concentrations in Bqm$^{-3}$ [12, 16, 18, 36]. Map taken from Google Maps [52]**

rials that pose risks to the residents of the Jericho and Al Aghwar governorates.

This study, while establishing its findings, was juxtaposed with data from both national and global sources. Such comparisons are important for advancing research on radon risk and understanding global averages.

Furthermore, the findings provide a valuable reference point for future monitoring of potential radioactivity pollutants. To better understand variations in radioactive radionuclides concentrations, conducting additional experiments and measurements is highly recommended due to their significant environmental impact.

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## ETHICS DECLARATIONS

### Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this document.

### Ethical statement

This article does not involve any research, conducted by the authors, that includes animals or human participants.

## AUTHORS' CONTRIBUTION

The corresponding author W. M. Khalilia, proposed the research idea, conducted sample collection and storage, revised the manuscript, interpreted the results, contributed to the discussion, and managed the project administration. K. M. Thabayneh conceptualized and designed the study methodology, interpreted the results, contributed to the discussion, and wrote the original manuscript. L. A. Mashal performed the experimental procedure, measured the samples, analyzed the data, conducted the literature review, and drafted the manuscript. A. R. Faugno participated in the literature review, data analysis, and data curation, while also providing corrections to the manuscript. A. al-Wahish critically reviewed and edited the manuscript, approved the final version, and contributed to the interpretation and discussion of the results.

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## ПРОЦЕНА ЈАЧИНЕ ИСПАРАВАЊА РАДОНА И САДРЖАЈА РАДИЈУМА У УЗОРЦИМА ЗЕМЉИШТА СА ИСТОКА ЗАПАДНЕ ОБАЛЕ ПАЛЕСТИНЕ

Рад је усмерен на мерење и израчунавање радиолошких карактеристика у вези са концентрацијом радона, садржајем радијума, јачином испаравања радона и изложеношћу зрачењу, у узорцима земљишта прикупљеним са различитих локација на источној страни Западне обале Палестине. Налази откривају значајне варијације у концентрацији радона ($^{222}$Rn) у испитиваним узорцима које се крећу од 169.3 Bqm$^{-3}$ у западном граду Јерихону до 6184.4 Bqm$^{-3}$ у Ал-Магтасу са укупном просечном вредношћу од 1705 Bqm$^{-3}$. Слично томе, ефективне вредности садржаја радијума показале су широк распон од 8.2-301.2 Bqkg$^{-1}$, са укупном просечном вредношћу од 74 Bqkg$^{-1}$. Такође, просечне јачине испаравања радона показале су значајну разноликост, у распону од 73.2 mBqm$^{-2}$h$^{-1}$ (3.1 mBqkg$^{-1}$h$^{-1}$) до 1419.8 mBqm$^{-2}$h$^{-1}$ (54.7 mBqkg$^{-1}$h$^{-1}$). Утврђено је да је укупна просечна вредност јачине испаравања радона у овим узорцима земљишта 543 mBqm$^{-2}$h$^{-1}$ (19.5 mBqkg$^{-1}$h$^{-1}$). Резултати истраживања упоређени су са сродним радовима где су уочене сличности и разлике. На основу података о концентрацији и ових корелација, може се закључити да одређена подручја са којих су узорци прикупљени представљају значајан ризик по здравље људи. Стога се добијени резултати могу користити као референтни за процену било каквих промена у нивоу радијације у окружењу Јерихона.

*Кључне речи: јачина испаравања радона, садржај радијума, CR-39 детектор, комора за развијање детектора, канцер, Јерихон*