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Radiological Risk Assessment for Exposure to Indoor Radon in North of Jordan

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Abstract

Measurements of indoor radon concentrations were performed using electret passive radon monitors (E-PERM) in 69 dwellings in the northern part of Jordan. The average indoor radon activity concentrations in dwellings varied from 4 Bq·m^{-3} to 961 Bq·m^{-3} with a mean value of 86 Bq·m^{-3}. The annual effective dose for dwellings' inhabitants due to radon inhalation ranged from 0.7 mSv to 2.1 mSv with a mean value of 2 mSv, higher than the world average value of 1.2 mSv. The overall annual mean effective dose rate from radon and its decay progenies was calculated to generate an excess lifetime fatal cancer risk of around 7×10^{-3}. The effect of geological formations on indoor radon concentrations was assessed using the one-way analysis of variance method (ANOVA) which showed a significant correlation between indoor radon concentrations and the geological formations underneath the dwellings. The lowest mean value of indoor radon concentration by lithogy was 30 Bq·m^{-3} corresponding to dwellings built on a Quaternary sediments, whereas Cretaceous geological formations with limestone lithologies showed a much higher mean value of indoor radon concentration of 110 Bq·m^{-3}. A radon potential map was produced. This map is a first step towards mapping indoor radon concentrations nationwide in Jordan.

Keywords

Indoor Radon, Geology, Radon Mapping, Lifetime Cancer Risk, E-PERM

1. Introduction

Radon (^{222}Rn) is a radioactive noble gas that forms from the decay of ^{226}Ra, which is found in uranium-containing soils and rocks (EPA, 2003; WHO, 2009). which is present in uranium-rich soils and rocks. The accumulation of radon inside buildings mainly occurs due to its release from rock and soil beneath the structures. It then enters indoor spaces through cracks and openings in the floors and walls. Although building materials can contain small amounts of radium and potentially contribute to indoor radon levels, their effect is typically considered negligible compared to the influence of the underlying ground (Appleton, 2007; Kovaltchouk, 2024).

The highest radon levels are observed over lithologies with high uranium content (Ielsch et al., 2001). High uranium content is associated with particular types of bedrock such as granites, sedimentary phosphatic rocks, and limestones (Barnet & Pacherová, 2013; Ciotoli et al., 2017; Tung, Leung, Jiao, Wiegand, & Wartenberg, 2013). Particularly elevated radon concentrations indoor may also occur near mineral deposits rich in radioactive elements, such as ilmenite and rare-earth deposits (Van Dung et al., 2022). Natural environmental radioactivity and the associated dose rate depend on geological formation and soil type of the location (Saleh, Ramli, Alajerami, & Aliyu, 2013). Specific radiation levels in terrestrial environments relate to the geological compositions of all lithological partitioned areas (Dragović, Janković, & Onjia, 2006). Igneous rocks such as granite, and phosphate rocks show high radiation levels, they have enriched with uranium and thorium (Tzortzis, Svoukis, & Tsertos, 2004), while sedimentary rocks show low radiation levels. Underlying geological formations influence strongly the activity concentrations of natural radionuclides (UNSCEAR, 2000b). Indoor radon levels are influenced by factors such as geology, building materials, and lifestyles of the building occupants. From these factors, rocks and soil are the main source of indoor radon (Alonso et al., 2019; Cosma, Cucus-Dinu, Papp, Begy, & Sainz, 2013; Giustini, Ciotoli, Rinaldini, Ruggier, & Voltaggio, 2019; Szabó, Jordan, Horváth, & Szabó, 2013). Even though elevated radon levels may occur in dwellings irrespective of the location, certain areas are prone to have high concentrations. Therefore, to prevent radon hazards, the identification of radon prone areas is necessary (ICRP, 2007).

Several studies were conduced in different parts of the world to determine radon concentration indoors and to estimate the radon health risk in relationship with geological formations (Ciotoli et al., 2017; Florică et al., 2020; Haneberg et al., 2020; Hasan, Janik, Pervin, & Iimoto, 2023; Ivanova et al., 2019; Minda et al., 2009; Nuhu et al., 2021; Pervin, Yeasmin, Khandaker, & Begum, 2022; Popit &

Vaupotič, 2002; Sarrou & Pashalidis, 2003). These studies have established that there is a link between the radon concentration and the underlying geology (Hámori, Tóth, Losonci, & Minda, 2006; Levesque et al., 1997).

Exposure to ionizing radiation poses hazards to human health. Radon gas is in general the main contributor to the radiation dose received by the population members and accounts to near 54% of the effective equivalent dose received by mankind (NRPA, 2000; UNSCEAR, 2000b). With a short half-life ($T_{1/2}$ = 3.823 days), Radon (^{222}Rn) spontaneously undergoes radioactive alpha decay. Moreover, the short lived radon decay products ^{218}Po ($T_{1/2}$ = 3.0 min) and ^{214}Po ($T_{1/2}$ = 164 s), upon radioactive alpha decay also release high amounts of energy and contribute further to the biological effects. This combination of high energy release with radionuclide short half-lives leads to high risk of cancer in sensitive human organs, such as lungs, caused by ^{222}Rn inhalation (Ravikumar & Somashekar, 2013).

^{222}Rn was ranked by the International Agency for Research on Cancer (IARC) as a first-class human carcinogen, and it is considered the second main cause of lung cancer after smoking (WHO, 2009). According to the World Health Organization (WHO), radon is responsible for up to 15% of lung cancer cases worldwide (WHO, 2009). A large scale study carried out in four regions from three different countries with high levels of natural radioactivity, namely, Altai and Novosibirsk regions in Russia; Guangdong province in China; and Auvergne region in France. The study has shown the statistical association between ionizing radiation exposure, particularly to radon isotopes, and the incidence of cancer and birth defects in the population (Zlobina et al., 2022).

The International Commission on Radiological Protection (ICRP) and WHO recommended the adoption of the reference level of 100 $Bq \cdot m^{-3}$ of radon (annual average) in the indoor air (ICRP, 2014; WHO, 2009). For practical reasons related to the park of existing buildings, the International Atomic Energy Agency (IAEA) and the European Union (EU) recommended and adopted a reference level of 300 $Bq \cdot m^{-3}$ for radon indoor residential buildings (EURATOM, 2013; IAEA, 2015).

Furthermore, international organizations, such as the IAEA, and the (EU) encouraged Member States to establish national action plans addressing long-term risks from radon exposures in dwellings (EURATOM, 2013). Over the last few decades, national radon projects have been carried out in several countries, such as Checkia (Neznal, Neznal, Matolin, Barnet, & Miksova, 2004), United Kingdom (Green, Miles, Bradley, & Rees, 2002), United States of America (White, Bergsten, Alexander, Rodman, & Philip, 1992), Germany (Kemski, Klingel, & Siehi, 1996), Finland (Weltner, Makelainen, & Arvela, 2002) and Ireland (Fennel et al., 2002). Following the mapping of radon concentrations and identification of radon prone zones, several countries also adopted measures for radon mitigation and radon prevention (Bossew, 2015).

In Jordan, there have been no significant studies at national level on ^{222}Rn concentrations indoor buildings and on the mapping ^{222}Rn soil potential. The variety of lithological formations in Jordan, like acid intrusive red rocks (igneous rocks), oil shale, phosphate, gypsum, limestone, dolomite, marble, unconsolidated sediments, sandy, marl, and basalt may create significant variations in the activity concentrations of natural radionuclides in the rocks and soils. In particular, in regions with higher natural radiation levels, such as the phosphatic belt that covers a vast area of Jordan (Alomari, Saleh, Hashim, & Alsayaheen, 2019a; Alomari, Saleh, Hashim, Alsayaheen, & Abukashabeh, 2019b). Detailed studies are needed to evaluate the radiological risk from the exposure of population members to radon indoors.

The current study aimed to determine radon concentration levels indoors and to assess the annual effective dose to inhabitants caused by radon inhalation in dwellings. Three Governorates in the northern part of Jordan were selected as a study area because this region features several lithologies (Burdon & Quennell, 1959). This work was also planned to investigate also the influence of geological formations on the activity concentrations of radon indoors. This research is a first step towards creating a nationwide map of indoor radon concentrations in Jordan and performing a radon exposure risk assessment at the national level.

2. Materials And Methods

2.1. Description of the Study Area

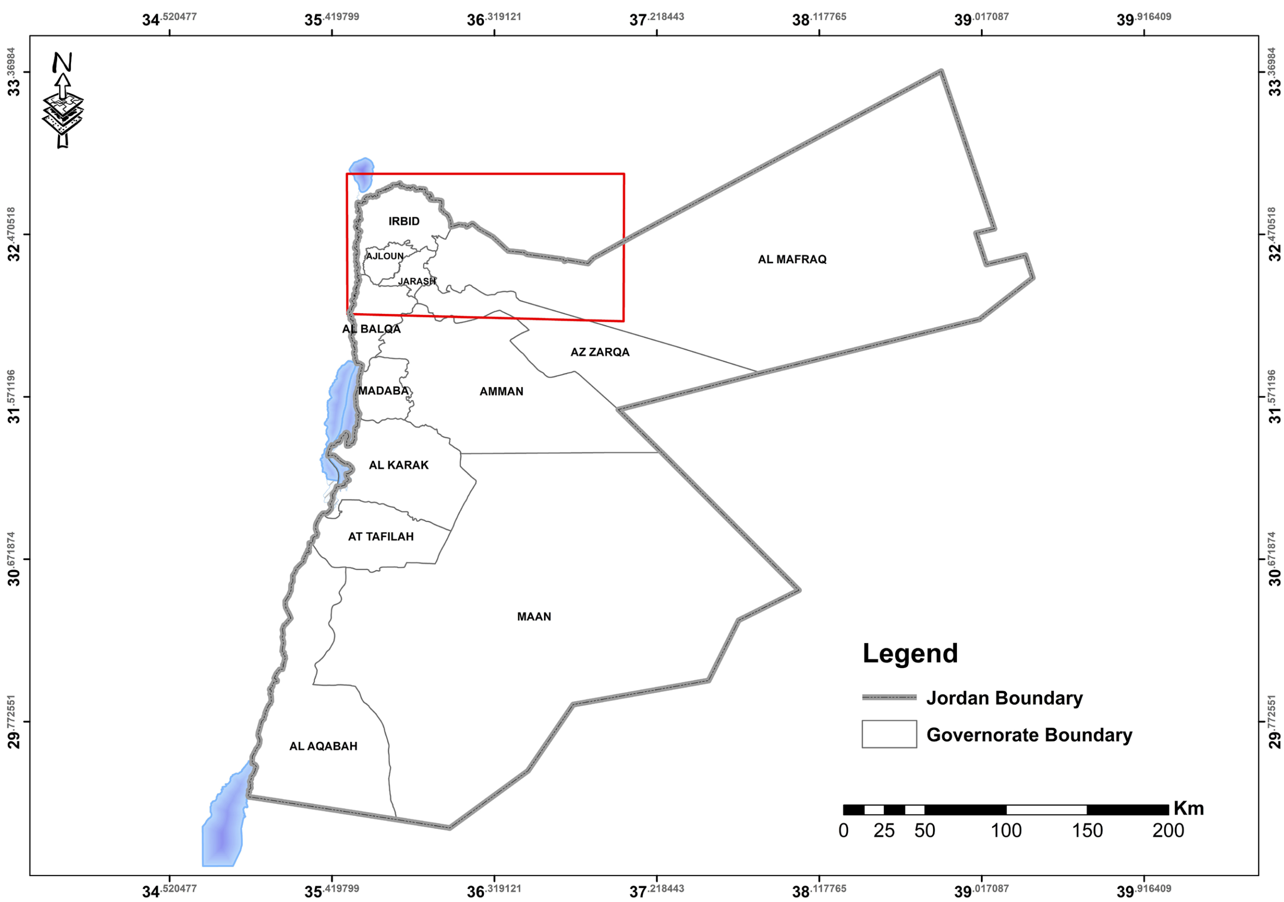

Figure 1. Map of Jordan showing the study area in the northern part of Jordan.

The northern part of Jordan, located between 32.2˚ - 32.7˚ North and 35.6˚ - 36.8˚ East and encompassing three Governorates, was selected as the study area for determination of radon concentrations in dwellings Figure 1. The region has a total area of approximately 30,000 km^2 and a population close to 2 million inhabitants, accounting for approximately 26% of the total population of Jordan (Jordan Department of Statistics, 2017). The altitude of the study area varies from 580 m in Al Mafraq (East) to 620 m above the sea level in Irbid (West).

The selected study area has a Mediterranean climate with moderate to hot temperatures in the dry summer and cooler and rainy weather in the winter. The monthly average temperature varies from 10˚C to 30˚C throughout the year. The daily average temperature varies from 8˚C to 20˚C in the winter and from 20˚C to 34˚C in the summer, with maxima temperatures reaching 46˚C.

The territory of Jordan displays nine main geological formations, namely the Precambrian, Cambrian, Ordovician, Silurian, Triassic, Jurassic, Cretaceous, Tertiary, and Quaternary geological formations (Bender, 1974). The geological formations in the selected study area are mainly Quaternary and Cretaceous geological formations, with four lithologies, namely, basalt, sediments, limestone, and phosphate Figure 2.

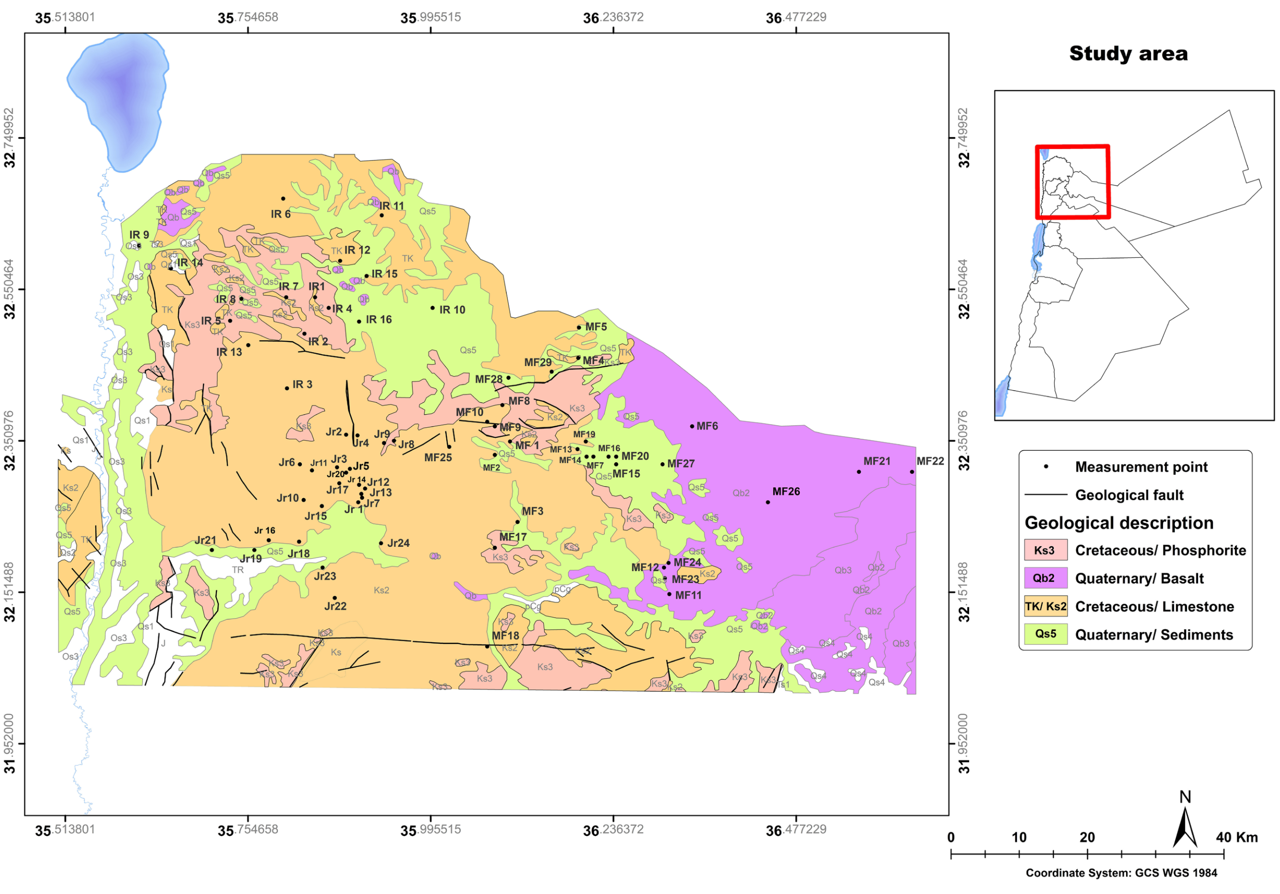

Figure 2. Geological map with lithological formations of the study area at the northern part of Jordan and indoor radon measurement points.

Three Governorates in the northern part of Jordan were selected as a study area because this region features several lithologies (Bender, 1974), and a first step towards creating a nationwide map of indoor radon concentrations at the national level based on geological formations. The project is continued to include all areas of Jordan to complete indoor radon mapping in Jordan as first study on the national level. The Quaternary geological formations can be found across Jordan (northern, central, northeastern and southeastern parts of the country), and consist mainly of basalt and unconsolidated sedimentary deposits. Cretaceous geological formations are predominantly located in the southeastern, eastern, northern and central parts of Jordan and are composed of phosphate, gypsum, and limestone (Burdon & Quennell, 1959).

2.2. Measurement of Radon Activity Concentrations

The selection of radon measuring points was based on the distribution of the main geological units. Geological maps were used in order to ensure that all geological formations of the study area were included in the radon measurement plan.

Sixty-nine householders **Figure 2**, agreed to take part in this campaign for performing indoor radon measurements. To enhance comparability of the results, the location and house type were carefully selected. Four main lithology formations underlying the houses (soil), which are namely, basalt, sediments, limestone, and phosphate. Selected houses were one-storied houses with no basement, recently built, and made with cement, bricks and stone. The type of houses selected were representative for the region.

The geographic distribution of radon measurement points took into account the geology of the area and 66% of dwellings selected were built on Cretaceous geological formations while 34% of dwellings selected had been built on Quaternary geological formations.

Radon measurements were performed in the living room of the houses, located in the ground floor. On average, the volume of these rooms was about 75 m^3. The detectors were positioned 1 - 1.5 metres above the floor and 1 metre away from the walls, following Environmental Protection Agency (EPA) guidelines, which correspond to the average inhalation height of the public (USEPA, 2019). Detectors were exposed for one month and the measurements were performed in all houses in July 2023. Radon measurements were therefore made over a relatively short period in the summer, and do not account for eventual seasonal radon fluctuations during the year. It can be useful to have a initial understanding of the typical range of radon concentrations in the region. Further investigations will be necessary to obtain a more detailed overview of the radon distributions in the Jordan dwellings.

The measurement of indoor radon activity concentrations was carried out using simultaneously 69 Electret Passive Environmental Radiation Monitor (E-PERM) (Rad Elec Inc., Maryland, USA) **Figure 3**.

As for the measurement process, initial reading of the electret was taken inside the laboratory and after that, the electret was loaded inside a plastic chamber, which was switched to the off-position and transported to the study area for radon measurement. E-perm devices have different type of chambers depending on the duration of the measurement. In this study, an S-type chamber with a volume of 200 ml, typically employed for short-term measurements, was utilised. At the indoor measurement location, the S-type Chamber was turned back to the on-position to proceed with the radon measurement. After the 1 month exposure time, the S chamber was turned to the off-position and transported to the laboratory for a final reading of the electret.

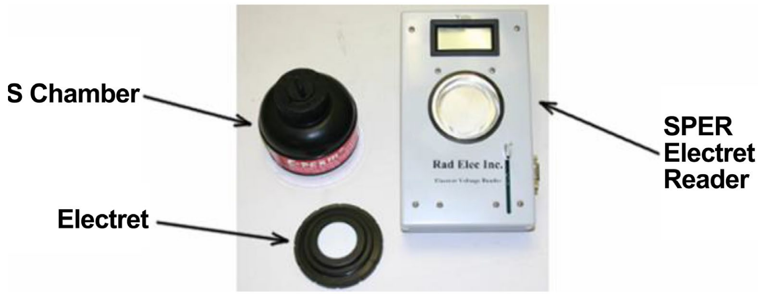

Figure 3. Electret passive environmental radiation monitor (E-PERM) used for radon concentration measurement.

The E-perm S-type Chamber, made of an electrically conductive plastic material, features an annular filter positioned on top of six entry holes. The purpose of the entry holes and the filter is to ensure entry of ^{222}Rn only, excluding ^{220}Rn and other environmental ions. When a measurement is made, the electret disk is attached to a holder screwed into the bottom of the chamber. Any change in the surface voltage of the electret is proportional to the time-integration of radon concentration during the measurement period. When the diffused radon decays inside the chamber, the emitted alpha particles induce the ionization of air molecules. Since the electret is positively charged it attracts the negative ions, whereas positive ions move to the chamber wall and dissipate there. The collection of negative ions onto the surface of the electret leads to a decrease in its surface voltage, hence, this reduction in surface voltage is proportional to the concentration of radon inside the chamber which is, in turn, proportional to the integration of radon concentration within the measurement area.

Once the voltage reduction of the electret is measured, and with the use of appropriate calibration factors and exposure time, the mean radon concentration can be calculated as in Equation (1) (Pugliese, Quarto, Loffredo, Mazzella, & Roca, 2013):

$$C_{Rn} = \left[\frac{(v_i - v_f)}{c_f * T} - (G_{gamma} * c_1) \right] * 37 \quad (1)$$

In this equation, C_{Rn} is radon concentration, V_i and V_f are initial and final electret voltages, respectively, T is the duration of exposure in days, G_{gamma} is the gamma background dose rate in μGy·h^{-1}, c_f is the monitor's calibration factor calculated as in Equation (2):

$$c_f = c_2 + c_3 \frac{(v_i + v_f)}{2}. \quad (2)$$

C_1, C_2 and C_3 are constants provided by the manufacturer, these constants are dependent on the type of E-PERM chamber.

Due to the penetration power of ambient gamma radiation, the ionization of air molecules can be partially induced by such radiation in addition to the ionization induced by radon decay. Hence, the mean radon concentration measured by E-PERM can be affected by indoor gamma radiation, and it is necessary to subtract such effects of the background gamma radiation in order to avoid overestimation of radon concentration values. For this reason, the rooms where E-PERMs were placed were also monitored for gamma radiation with an Inspector radiation survey meter (S.E. International, USA), which was used for *in situ* determination of the ambient Gamma Dose Rate (GDR). For the readings of GDR in μR·h^{-1}, a conversion to nGy·h^{-1} was performed using the conversion factor 1 μR·h^{-1} ≈ 8.7 nGy·h^{-1}. In the study region, the average GDR in dwellings was 0.07 μGy·h^{-1}.

The experimental uncertainty of radon concentration measurement using E-Perm depends on the GDR measurement, the voltage difference value, the exposure time and the calibration factor but, generally, it is lower than 10% (Kotrappa, Dempsey, Ramsey, & Stieff, 1990).

2.3. Radiological Risk Assessment Due to Indoor Radon

The Annual Effective Dose received by the residents due to the inhalation of radon (AED_{int}) was evaluated using the following equation (UNSCEAR, 1993):

$$\mathrm{AED}_{\mathrm{int}}\left(\mathrm{mSv}\cdot\mathrm{y}^{-1}\right) = C_{Rn} \times F \times T \times D_f \quad (3)$$

where C_{Rn} is the measured indoor ^{222}Rn concentration in Bq·m^{-3}, F is an adjustment factor representing the degree of radioactive equilibrium between radon and radon daughters. For measurements of radon in indoor air, C_{Rn} was assumed as equal to 0.4 as adopted by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the ICRP (WHO, 2010). T is the number of hours spent by residents indoor during one year. An indoor occupancy factor of 0.8 was used to represent the fraction of time spend indoors by residents. Consequently, during one year, residents spend about 7008 h indoor (T = 365 days × 24 h/day × 0.8). D_f is the activity to dose conversion factor and is equal to 9 × 10^{-6} mSv·m^3·Bq^{-1}·h^{-1} for ^{222}Rn (ICRP, 2017).

The excess lifetime fatal cancer risk (ELCR) estimates the probability for developing a fatal cancer because of the exposure to radon over a person's lifetime. This was calculated using the following equation:

$$\mathrm{ELCR} = \mathrm{AED}\left(\mathrm{Sv}\cdot\mathrm{y}^{-1}\right) \times \mathrm{DL}(\mathrm{y}) \times \mathrm{RF}\left(\mathrm{Sv}^{-1}\right) \quad (4)$$

where AED is the annual effective dose, DL is the average lifetime of a person and assumed to be 70 years, and RF is the fatal cancer risk factor assumed to be 0.05 Sv^{-1} as recommended by ICRP-106. An annual effective dose of 1 $mSv \cdot y^{-1}$ leads to a mean risk value for indoor radon exposure of 3.5×10^{-3} (Valentin, 2007).

2.4. Mapping Radon Activity Concentrations

A portable GPS receiver (Garmin Ltd.) was employed to record the geographic coordinates of each radon measurement location and introduced in digital geological maps. Coordinates for each sampling location were converted into the degree decimal unit. The World Geodetic System 1984 (WGS84) was adopted for the definition of the coordination system and the data representing activity concentration of radon were recorded on digital maps. The Kriging technique was applied using a Geological Information System (GIS) software, and the ArcMap version 10.2 was utilized to estimate activity concentrations of radon. The Ordinary Kriging is an estimation technique known to be among the best linear unbiased estimators with the advantage of using the semivariogram information (Armstrong, 1998).

The data processing and statistical analysis of measured indoor radon activity concentrations was performed using the Statistical Package of Social Sciences (SPSS 19.0, IBM, Chicago, IL, USA).

3. Results and Discussion

3.1. Descriptive Statistics of Indoor Radon Activity Concentrations

Statistical Package of Social Science (SPSS) was used to analyze and describe the radon concentrations and their corresponding radiological health effects. The frequency distribution of indoor radon activity concentrations determined in the houses is shown in **Figure 4**. The class of radon concentrations with the highest frequency was the class ranging from 4 $Bq \cdot m^{-3}$ to 159 $Bq \cdot m^{-3}$ and contained 93%, of the radon measurements made. However, there were several cases (5 houses) with average radon concentrations exceeding the limit of 300 $Bq \cdot m^{-3}$ recommended by the IAEA, and 11 houses (15% of total) displayed indoor radon concentrations higher than the WHO proposed limit of 100 $Bq \cdot m^{-3}$ (WHO, 2009). The normality of indoor radon activity concentrations was measured by employing kurtosis and skewness. As per (Gupta, 1994), the shape's lack of symmetry or symmetry for a frequency distribution is measured via skewness. Kurtosis can be defined as a peakedness measure. **Table 1** shows a mean value of 3.6 for skewness (signifying a positive skewness). The curve tends to be more peaked than the normal curve with positive kurtosis value.

The basic descriptive statistics such as minimum, maximum, mean, standard deviation, Skewness, and Kurtosis of radon concentrations are presented in **Table 1**. The values of indoor radon activity concentrations performed in the 69 houses ranged from 4 $Bq \cdot m^{-3}$ to 961 $Bq \cdot m^{-3}$, with a mean value of 86 $Bq \cdot m^{-3}$. This average indoor radon concentration for the sudy area is lower than the WHO proposed maximum level tolerated for dwellings of 100 $Bq \cdot m^{-3}$ (WHO, 2009), but it is higher than the average world value of 40 Bq·m^{-3} (UNSCEAR, 1988).

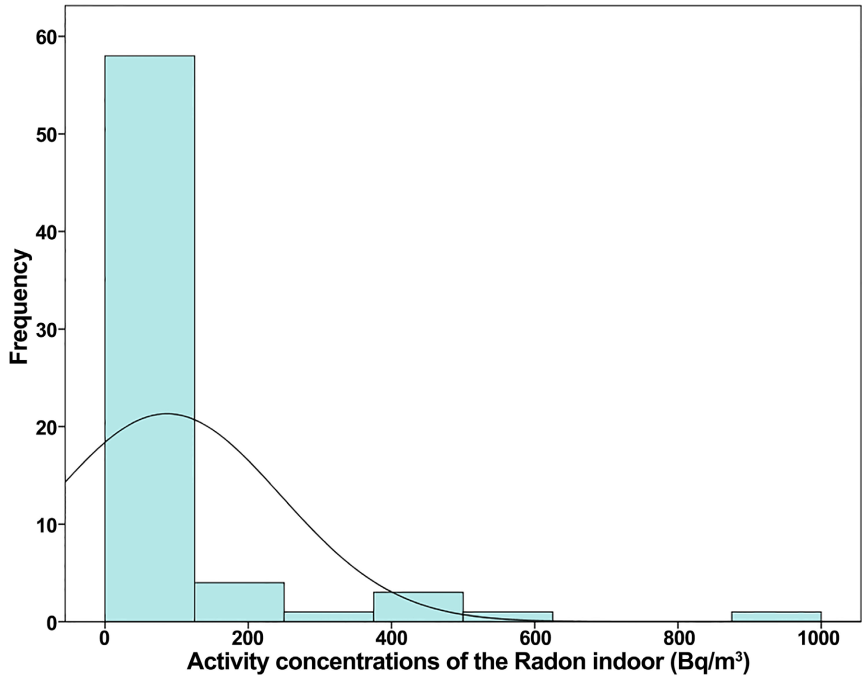

Figure 4. Frequency distribution of indoor radon activity concentrations measured in dwellings. In the histogram, each class corresponds to an interval of 159 Bq·m^{-3}.

Table 1. Statistical summary for indoor radon concentration in the study area.

Geology/Lithology	Sample size (n)	Median	Mean	Std. error	Std. deviation	Min.	Max.	Skewness	Kurtosis
Cretaceous/Phosphorite	10	27	97	52	137	20	387	2.1	4.1
Quaternary/Basalt	8	19	89	68	180	4	494	2.6	6.7
Cretaceous/Limestone	36	47	110	31	190	4	961	3.3	11.8
Quaternary/Sediments	15	20	30	7	29	5	112	1.6	2.5
Total	69	31	86	19	159	4	961	3.6	15.0

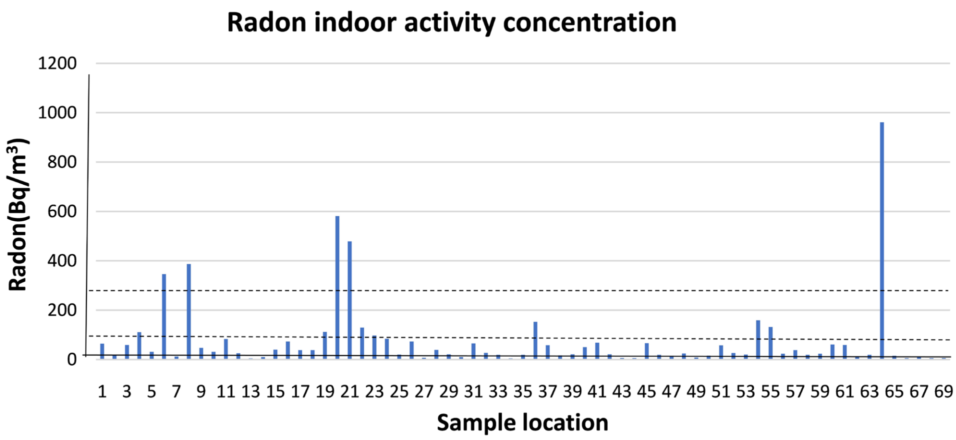

Figure 5. Comparison of indoor radon activity concentrations in dwellings with WHO and EU reference limits.

Figure 5 shows the indoor radon activity concentration for all measurement locations in comparison to the interim recommended reference level of 300 Bq·m^{-3} adopted by the EU, and of 100 Bq·m^{-3} recommended by the WHO (ICRU, 2012; WHO, 2009). Clearly, radon is well present indoors of dwellings in the hot season and it may be expected that radon concentrations in winter, with reduced house aeration, would be higher.

Table 2. Comparison of the mean indoor radon concentrations in different countries worldwide.

Country	Mean indoor concentration (Bq·m^{-3})
Finland	120
Norway	73
France	62
Denmark	53
Germany	50
Canada	107
Hungary	107
USA	46
Czech Republic	140
Egypt	9
Albania	120
Iran	82
Armenia	104
Slovenia	87
Spain	86
Luxembourg	110
North of Jordan (current study)	86
Indoor world average	40
WHO	100
IAEA	300
ICRP	100

As a result of Coordinated Research Programme on Radon in the Environment, sponsored by IAEA, **Table 2** lists the indoor radon levels in different localities (UNSCEAR, 2000a). Values of mean indoor radon concentrations found in the current study are comparable with other countries such as results reported from Iran, Slovenia, and Spain. Indoor radon levels in houses of Lebanon were measured. The average radon levels was found to be 23 Bq·m^{-3} (UNSCEAR, 2000a). In 2013, indoor radon levels were measured in Izmir province, the average radon concentration level was found 210 Bq·m^{-3} (Özbay & Karadeniz, 2016). Nationwide investigation of radon levels in Syrian houses was carried out. The mean indoor radon was found to be 45 Bq·m^{-3} (Othman, Hushari, Raja, & Alsawaf, 1996). Radon concentrations were measured in the village KufrKhal-Jerash north of Jordan, the results showed that the average radon concentrations varied from 17 to 129 Bq·m^{-3} with a mean value of 70 Bq·m^{-3} (Abumurad, 2024). Indoor radon measurements were carried out in houses of Kuwait. The results show that the radon concentration in the dwellings of Kuwait show a mean value of 14 Bq·m^{-3} (Bem, Domanski, Bakir, & Al-Zenki, 1996).

3.2. Indoor Radon Activity Concentrations Based on Geological Formations

The lowest mean value for the indoor radon activity concentration by lithology corresponds to Quaternary geological formations with lithologies composed of unconsolidated sedimentary rock and clayey soil with a mean value of 30 Bq·m^{-3}. The highest mean value for indoor radon activity concentration corresponds to Cretaceous geological formations with limestone lithologies, with a mean value of 110 Bq·m^{-3}. The houses built on the Cretaceous formations with limestone lithologies exceeded the WHO recommended level. These Cretaceous geological formations, rich in limestone, are known for being a main source of phosphate ore which displays a relatively high content of ^{238}U and ^{232}Th (Bender, 1974). Among the four lithologies existing in the study area, only the quaternary sediment deposits originated radon concentrations indoors significantly lower than the radon reference level recommended by the WHO. The highest radon concentration of 961 (Bq·m^{-3}) was found for the dwellings, underlain by limestone lithology formation. High radon concentrations measurements were also observed for the dwellings underlain by phosphorite lithology formation. The source of phosphate and limestone in Jordan is the cretaceous formation. Thorium and uranium are largely associated with phosphate and Limestone which is of cretaceous geological formations (Alnawafleh, Tarawneh, & Alrawashdeh, 2013). A higher radon concentration was recorded in dwellings underlaid by cretaceous geological formation, because of their high content of radionuclides, when compared with other lithology type.

Figure 6 shows the average indoor radon activity concentrations, with their respective standard error bars, for the geological formations existing in the study area and can be compared with the WHO recommended level of 100 Bq·m^{-3} (WHO, 2009).

Indoor radon concentrations in relation to geology in other areas were also investigated. Indoor radon concentrations were measured in Bhilangana Valley, India. Radon concentration was found to depend on the geology of the area (Choubey & Ramola, 1997). Another study, presented by Borgoni et al. (2011), the study examines the relationship between indoor radon concentration and geological factors, focusing on the Lombardy region of Italy. The research indicates a spatial correlation between high indoor radon concentration areas and specific geological structures (Borgoni, Tritto, Bigliotto, & De Bartolo, 2011). A significant effect of rock type under a building on radon variation has been confirmed (Ivanova et al., 2019). The higher radon concentration originated from the igneous and sedimentary rocks in comparison to other types of rocks. Indoor radon levels in Norwegian dwellings located in different geological settings are compared with geological information. The results show a significant correlation between indoor radon levels and geological factors in Norway (Sundal, Henriksen, Soldal, & Strand, 2004). short-term home radon test in Kentucky, United States, were conducted to produce a geologically based indoor-radon potential map (Haneberg et al., 2020). The results of the study show that houses underlain by Ordovician and limestones have the highest indoor-radon potential, which is comparable of the current study, while houses underlain by coarse clastic rocks and surficial deposits tend to have lower indoor-radon potential. According to Zhu et al. (1998), rocks are the predominant source of indoor radon in southern Belgium (Zhu, Charlet, & Tondeur, 1998). The study shows a correlation between geological features and indoor radon concentrations. Indoor radon concentrations in relation to geology in Slovenia were also investigated. The lowest indoor radon levels was found in buildings on Quaternary sediments, whereas the highest indoor radon concentrations were found for Cretaceous limestone (Popit & Vaupotič, 2002), and this is in full agreement with the results found in this study.

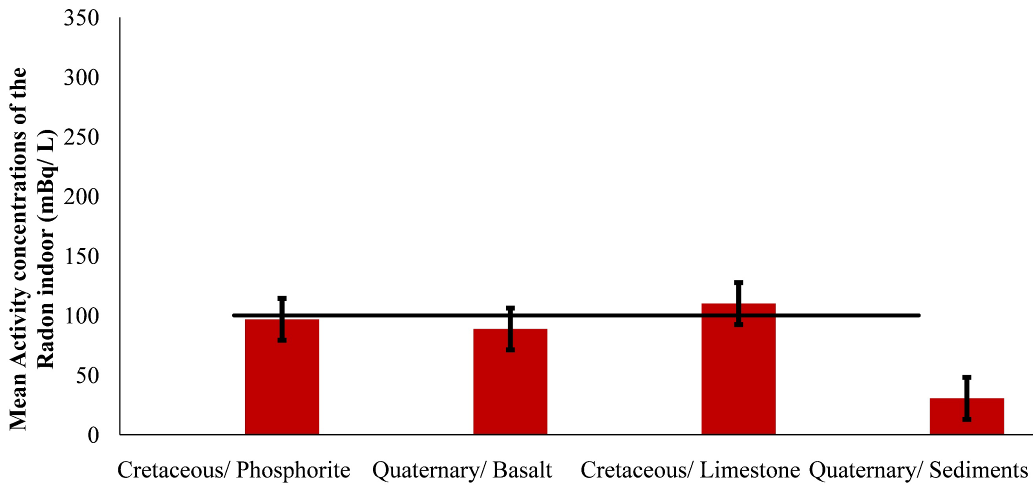

Figure 6. Indoor mean radon activity concentration for each lithology.

3.3. Annual Effective Dose and the Excess Lifetime Cancer Risk Due to Radon Inhalation

The (AED) due to inhalation of indoor radon was determined in this study for the inhabitants of dwellings within the northern part of Jordan. Values obtained for the annual effective dose ranged from 0.7 mSv to 2.1 mSv, with a mean value of 2 mSv. The highest mean value determined for AED corresponds to dwellings built on Cretaceous geological formations and limestone lithologies, whereas the lowest mean value for AED corresponds to dwellings built in regions with Quaternary geological formations.

The UNSCEAR, has estimated the average effective dose of human exposure to natural sources of radiation at 2.4 mSv·y^{-1}, in which about 52% (1.2 mSv·y^{-1}) is caused by the inhalation of radon gas (UNSCEAR, 2000a). Therefore, the average AED due to radon inhalation in the northern part of Jordan, 2 mSv·y^{-1}, is above the estimated worldwide average of 1.2 mSv·y^{-1}. This could possibly represent a health hazard for the residents in the area. The overall mean value of ELCR from exposure to indoor radon was assessed to be 7×10^{-3}, which is slightly higher than the risk value of 3.5×10^{-3} considered acceptable by ICRP (ICRP, 2014).

3.4. Mapping Radon Activity Concentrations

A digitized map representing the distribution of radon activity concentration indoors in the northern part of Jordan is shown in **Figure 7**.

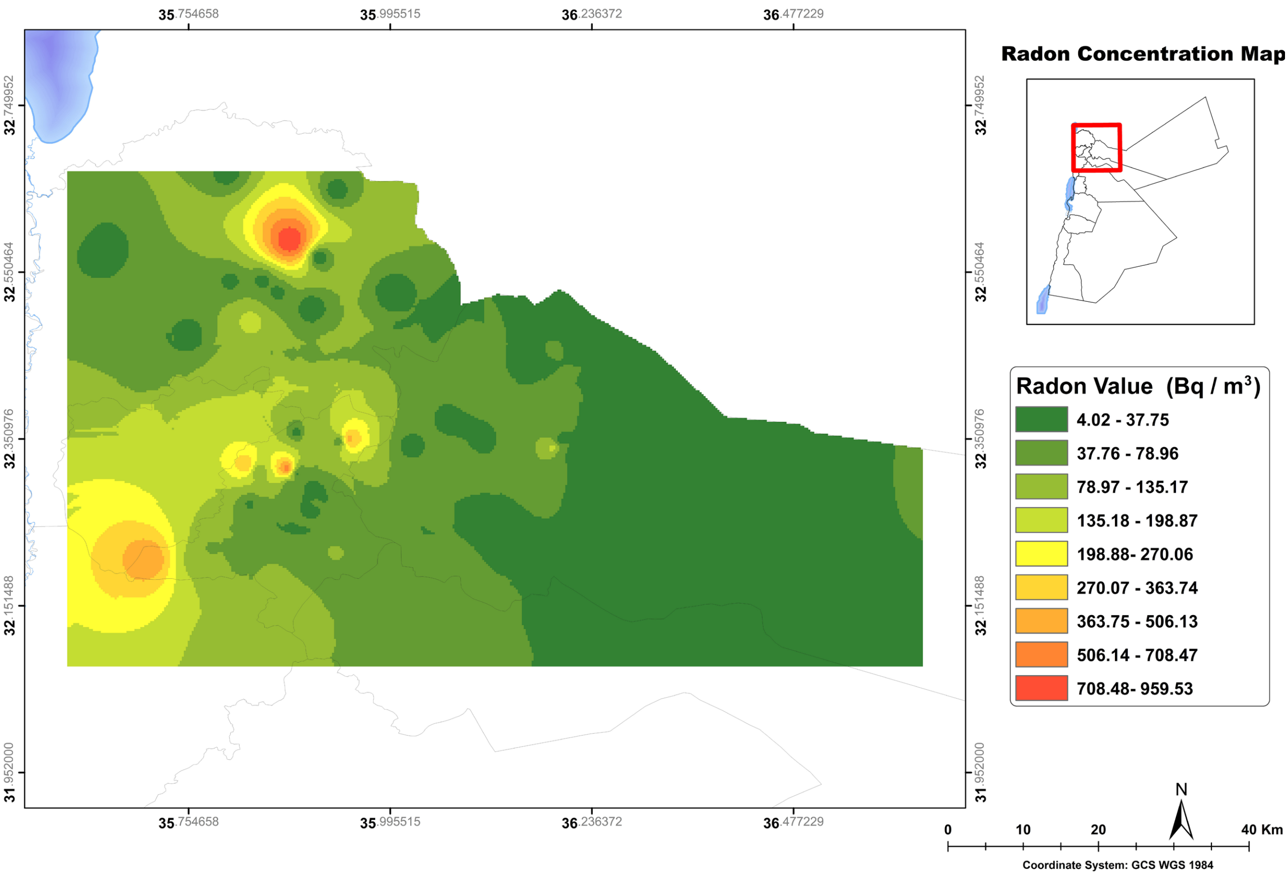

Figure 7. Indoor radon map for the study area (northern part of Jordan).

Different areas in the northern part of Jordan showed high radon activity concentrations indoors **Figure 7**. These areas correspond to Cretaceous geological formations that are sources of phosphate ores in Jordan, rich in ^{238}U and ^{232}Th, and sources of limestone as well (Bender, 1974). The northeastern part of Jordan also featured areas with low levels of radon concentrations. These areas correspond to the Quaternary geological formations that are mainly composed of basalt

Figure 3. Basalt is a volcanic rock derived from volcanic magma that is believed to had spread over different areas within Jordan, mostly the northeastern parts of the country (Bender, 1974). In general, basalt rocks contain low levels of natural radioactivity, and thus originate low levels of radon concentrations (Arnedo et al., 2017; Othman & Yassine, 1995).

Areas of comparatively high radon concentrations are depicted in red and orange colors on the map (with values ranging between 300 Bq·m^{-3} and 959 Bq·m^{-3}) and these are the areas where indoor radon even exceeds the IAEA and EU recommended level of 300 Bq·m^{-3} Figure 7. It should be noted that, according to the UNSCEAR and WHO, this value of 300 Bq·m^{-3} of the adopted interim level for average radon concentration in dwellings still represents an effective dose of approximately 10 mSv per year, and the potential occurrence of biological effects still is statistically significant (UNSCEAR, 2000a; WHO, 2010).

3.5. Correlation between Radon Concentrations Indoors and Lithologies

The nonparametric independent sample test in SPSS (IBM) has a built-in pairwise comparison test that compares the median values when the null hypothesis is rejected. The null hypothesis is rejected whenever the *p*-value is less than the significant level ($\alpha = 0.05$), and the alternative hypothesis is accepted. The Kruskal-Wallis test under the nonparametric independent sample test was used to compare the median values of the measured parameters across the geological formations under the null and alternative hypothesis. The Kruskal-Wallis test was conducted on the median values of radon concentrations among the geological formations. The result of the test returns a *p*-value of 0.026, hence the null hypothesis is rnejected.

A pairwise comparison test was conducted. The result is presented in Table 3, indicating the median value of radon concentrations over Quaternary/Sediments geological formation is statistically different from that of formations Cretaceous/Limestone with p = 0.008. Nevertheless, it is not significantly different from the median value of the ^{222}Rn activity concentrations in rest of the geological formations.

Table 3. A pairwise comparison test for geological formations/lithologies with respect to radon concentration.

Geological formations		Test statistic	Std. Error	Sig.
Quaternary/Basalt	Quaternary/Sediments	−0.105	8.877	0.991
Quaternary/Basalt	Cretaceous/Phosphorite	14.857	10.565	0.160
Quaternary/Basalt	Cretaceous/Limestone	−15.388	8.147	0.059
Quaternary/Sediments	Cretaceous/Phosphorite	14.752	8.877	0.097
Quaternary/Sediments	Cretaceous/Limestone	15.283	5.791	0.008
Cretaceous/Phosphorite	Cretaceous/Limestone	−0.531	8.147	0.948

For each lithology, the distribution was found to be positively skewed. None of lithologies were found Symmetric which suggest that almost non normal distribution can be associated with the radon concentration as shown in Figure 8. Extreme outliers for radon concentration were found for Limestone lithology formations, while normal outliers for radon concentrations were seen for basalt and Phosphorite lithology formations. For sediment formation no outliers were seen.

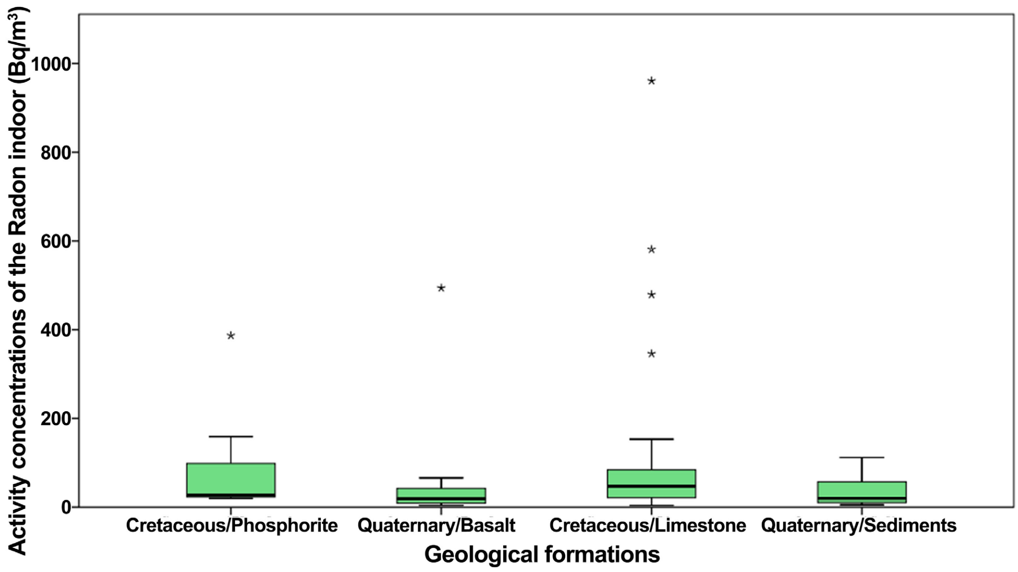

Figure 8. Box plot showing distribution and the variability of radon concentration for each geological formation in the north of Jordan.

4. Conclusion

Radon measurements in northern Jordanian dwellings ranged from 4 to 961 $Bq·m^{-3}$, averaging 86 $Bq·m^{-3}$. Results showed that 93% of homes had levels below the 300 $Bq·m^{-3}$ limit set by the IAEA and EU, while only 16% exceeded the WHO-recommended limit of 100 $Bq·m^{-3}$. This study in northern Jordan measured radon levels during the summer and highlighted a strong link between radon concentrations and geological features with higher levels over Cretaceous limestone and phosphate-rich areas. A national radon map would help manage indoor radon risks, enabling homeowners to estimate radon levels based on local bedrock, even without testing. A preliminary assessment evaluated the radiological health risks from indoor radon exposure to residents in northern Jordan, estimating the lifetime cancer risk during the summer season. Since radon levels vary seasonally, updated risk assessments are needed. To guide public health policies, further research on radon's long-term health effects is essential, with a focus on raising awareness of radon dangers. A comprehensive national survey is crucial to accurately assess indoor radon levels across dwellings.

Author Contributions

Conceptualization, Ahmad Alomari and Fernando P. Carvalho; Methodology, Alaa Jaffal, Salah Alnjadat, Khalid alqadhi, Amjed Hijjawi, Amani Sharaf, Refaat Banikhalaf and Amal Alsayaheen; Software, Muneer Saleh, Refaat Bani khalaf; Validation, Rabie Abu Saleem; Formal analysis, Muneer Saleh; Investigation, Rabie Abu Saleem, Amal Alsayaheen; Resources, Alaa Jaffal, Amjed Hijjawi and Amani Sharaf; Data curation, Fernando P. Carvalho and Muneer saleh; Writing—original draft preparation, Ahmad Alomari; Writing—review and editing, Fernando P. Carvalho; review and editing: Gennaro Venoso, Visualization, Fernando P. Carvalho and Ahmad Alomari; Supervision, Ahmad Alomari and Fernando P. Carvalho; Project administration, Ahmad Alomari.

All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author.

Declaration of Interest Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

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

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