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# Assessment of Radon Gas, Heavy Metals, and Physicochemical Parameters in Groundwater of Al-Qassim Region, Kingdom of Saudi Arabia

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## Abstract

In this study the radon-222 ($^{222}Rn$) concentrations for the groundwater quality in selected area of Saudi Arabia—AL Qassim is measured beside the physicochemical parameters (pH, total dissolved solids [TDS], and electrical conductivity [EC]), and heavy metal content. Eight groundwater samples were analyzed using advanced techniques, including the RAD7 detector with the RAD-$H_2O$ accessory for radon detection, EZ9909SP water quality testing, and inductively coupled plasma mass spectrometry (ICP-MS) for heavy metal content. The results showed that radon concentrations ranged between 0.0536 and 0.0729 Bq/L with mean 0.064 Bq/L. This remained within the WHO limits of 100 Bq/L and the US Environmental Protection Agency limits of 11 Bq/L. All annual effective doses, both ingested and inhaled, were below the WHO and European Commission safety threshold of 0.1 mSv/yr. Chemical and physical parameters were within acceptable limits: pH values ranged from 6.84 to 7.57, with mean 7.31, total dissolved solids (TDS) values ranged from 695 to 4240 mg/L with mean 1943.13 mg/L, and electrical conductivity (EC) values ranged from 1398 to 8450 (μs/cm), with mean 3879.63 (μs/cm). As for heavy metals, most elements—including mercury, copper, zinc, and lead—were below the limit of quantification (LOQ) in all samples. However, nickel (Ni) was detected in three samples, with concentrations ranging from 0.16 to 0.34 μg/L, with an average of 0.24 μg/L. These values indicate that the water is safe and not significantly affected by contamination from this element. Using the Pearson correlation coefficient calculated via Microsoft Excel, the relationship between radon concentration ($Rn^{222}$) and selected water quality parameters was evaluated. The results revealed a weak positive correlation (r = 0.28416) between radon and pH, indicating a slight tendency for radon levels to increase with higher pH values. In contrast, moderate to strong negative correlations were observed with both total dissolved solids (TDS) (r = −0.6506) and electrical conductivity

(EC) (r = −0.6521). Notably, a very strong positive correlation (r = 0.9969) was found between radon and nickel concentrations, based on three samples, indicating an almost proportional relationship.

## Subject Areas

Nuclear Technology

## Keywords

Radon, Groundwater, Health Risks, The Physicochemical Parameters

# 1. Introduction

Radon is a naturally occurring radioactive gas that is released from rocks and soil as a result of uranium decay, which has been present in the earth's ground since its formation [1]. Groundwater contains much higher levels of radionuclides compared to surface water [2], as it flows through soil and rock formations, which dissolve many radioactive chemicals and minerals. Consequently, regions with granites and other uranium-rich rocks typically have higher average radon count rates [2]. Radon naturally enters the environment through voids and cracks in rocks and soil; it can rapidly dissolve into groundwater and reach water supply wells [2]. Radon in water can enter the human body through two different ways. First, radon in drinking water can enter the human body through the gastrointestinal tract resulting in an ingestion radiation dose. Secondly, radon can escape from household water and contribute to the radon concentration in air, which can then enter the human body through the respiratory tract to deliver the inhalation radiation dose [3]. Thus, leakage of this gas from the ground into indoor air or its dissolution into groundwater poses serious health risks when inhaled or ingested, including an increased risk of lung and stomach cancer [4]. Therefore, exposure to radon and its short-lived decay products accounts for half of the effective doses from all types of ionizing radiation [5]. Given these health risks, many studies have been conducted to measure the concentration of radon in groundwater and evaluate its effects.

In Saudi Arabia, several studies have been conducted to measure radon in groundwater and assess its health impacts. For instance, Al-Mamoun and Al-Azmi used the RAD7 radon detector to estimate radon concentrations from different groundwater sources, they collected 38 samples in Hafar Al-Batin. Estimates of radon activity concentrations in the groundwater samples ranged between 0.03 and 3.20 Bq/L [6]. In another study conducted in the Qassim region, Al-Harbi, Abbadib, and Al-Taher also studied 30 groundwater samples from the Buraydah area, using the RAD7 device connected to the RAD-$H_2O$ accessory, and the results showed that the radon concentrations in the water ranged from 0.76 to 9.15 Bq/L [7]. Similarly, in the Jazan region, Al-Arabi, Suleiman, and Abu Al-

Majd, 110 water samples were collected from 11 locations and measured the radon concentration in groundwater using CR-39 detector technology, and results ranged between 1.74 and 4.32 Bq/L [4].

In India, R. Somashekar and P. Ravikumar found radon measurements from Varahi and Markandeya command regions using the RAD-7 with RAD $H_2O$ technology. The detected $^{222}$Rn activities in 16 groundwater samples in the Varahi command area ranged from 0.2 to 10.1 Bq/L, the $^{222}$Rn activity in 14 groundwater samples from the Markandeya command area ranged from 2.21 to 27.3 Bq/L [8].

In Iraq, Qader et al. collected 24 groundwater samples from Erbil, using a RAD 7 radon detector equipped with RAD-$H_2O$, where the values of radon activity concentration ranged from 4 to 12.18 Bq/L [2].

Ajiboye *et al.* studied the concentrations of $^{222}$Rn activity in 145 groundwater samples collected across six states in southwestern Nigeria. The groundwater samples studied showed variations in the range from 1.6 Bq/L to 271 Bq/L [9].

While radon concentration is a risk in groundwater, overall water quality also depends on various physical and chemical parameters such as pH, electrical conductivity, and total dissolved solids.

Physicochemical Parameters of groundwater such as pH is an important water quality parameter that influences the solubility and bioavailability of chemical elements, including nutrients and heavy metals. It is defined as the negative logarithm of the hydrogen ion concentration ($H^+$) and is mathematically expressed as [2]: $pH = -\log_{10}[H^+]$.

The pH scale ranges from 0 to 14, with 7 being neutral. A pH value below 7 indicates acidity, while a pH above 7 indicates alkalinity (basicity), pH reflects the relative amount of free hydrogen ($H^+$) and hydroxyl ions ($OH^-$) in water. Water with a higher concentration of free hydrogen ions is acidic, whereas water with a higher concentration of free hydroxyl ions is basic. Excessively high or low pH levels can be hazardous when using water [10] [11]. According to the World Health Organization, the pH value ranges from 6.5 to 8.5 [12].

Total dissolved solids (TDS) refer to the total weight of all solids dissolved in a given volume of water, expressed in the unit of a milligram per unit volume of water (mg/L) [2]. Water with a TDS level of below 600 mg/L is typically thought to taste good, while water with TDS levels exceeding about 1000 mg/L becomes increasingly disagreeable [13], and the US Environmental Protection Agency (EPA) recommends a limit of 500 mg/L [14].

Electrical Conductivity (EC) quantifies water's ability to conduct electricity, which is influenced by the presence of dissolved salts, acids, and bases, EC reflects the total concentration of ions in water, with higher ion concentrations resulting in higher electrical conductivity [15]. The SI unit for electrical conductivity is micro siemens per centimeter (μs/cm) [16]. The drinking water limit in the European Union and the World Health Organization is 2500 (μs/cm) [13] [17] [18].

Globally, reported values for these criteria vary widely between regions. For example, groundwater in Indonesia has been reported with pH values between 6.01

and 7.24, TDS ranging from 429 to 501 mg/L, and EC between 618 and 1351 μS/cm [19]. In India, groundwater has shown pH levels ranging from 7.02 to 7.65, with TDS ranging from 690 to 1560 mg/L and EC from 442 to 998 μS/cm [20]. In Italy, pH values ranged between 7.3 and 8.0, total dissolved solids (TDS) levels ranged between 336 and 2790.1 mg/L, and EC levels ranged between 412 and 4180 μS/cm [21]. Meanwhile, groundwater samples in Iraq had pH values ranging from 7.11 to 7.29, total dissolved solids (TDS) levels ranging from 1520 to 5773 mg/L, and electrical conductivity (EC) levels ranging from 2351 to 8901 μS/cm [18]. In Nigeria, groundwater pH values ranged from 6.35 to 8.31, total dissolved solids (TDS) levels ranging from 247.5 to 589.7 mg/L, and electrical conductivity (EC) values ranging from 450 to 1190 μS/cm [22]. Similarly, Tunisia showed pH values ranging from 7.21 to 9.64, total dissolved solids (TDS) levels ranging from 261 to 2048 mg/L, and electrical conductivity (EC) values ranging from 653 to 5120 μS/cm [23]. In Pakistan, reported pH values ranged from 7.10 to 8.40, TDS levels from 987 to 2114 mg/L, and EC values from 1592 to 3098 μS/cm [24].

The presence of potentially hazardous metals in groundwater is a significant environmental concern. These metals, including arsenic (As), zinc (Zn), lead (Pb), mercury (Hg), manganese (Mn), iron (Fe), copper (Cu), and nickel (Ni), enter groundwater sources through both natural processes and human activities. Drinking water sources must be investigated in order to protect against health hazards [25]. The World Health Organization (WHO) has set guideline values for elements in drinking water to ensure safety. The recommended limits are as follows: Mercury (Hg) is 6 μg/L, and copper (Cu) is 2000 μg/L, lead (Pb) is 10 μg/L, nickel (Ni) is 70 μg/L, and zinc (Zn) No guideline value; it does not pose a health risk at the levels found in drinking water [26].

In recent years, many studies have been conducted on the presence of heavy metals in groundwater due to their significant impact on public health. For example, In India, lead concentrations were found to range from 6.7 to 82.7 μg/L, nickel from 8.92 to 181.8 μg/L, copper from 3.1 to 83.5 μg/L, and zinc from 6.4 to 746.9 μg/L [27]. In Italy, copper (Cu) levels ranged between 0.83 and 85.9 μg/L, lead (Pb) between 0.90 and 7.5 μg/L, nickel (Ni) between 0.61 and 263.8 μg/L, and zinc (Zn) between 0.85 and 786.2 μg/L [28]. In Türkiye, mercury levels ranged from 0 to 0.140 μg/L, copper from 0 to 0.060 μg/L, lead from 0 to 1.497 μg/L and nickel from 0 to 30.058 μg/L [29]. In Malaysia, copper (Cu) levels ranged from 0.07 to 2.22 μg/L, while lead (Pb) levels ranged from 0.03 to 4.35 μg/L. Zinc (Zn) levels ranged from $<0.17$ to 118.97 μg/L [30].

## 2. Methodology

### 2.1. Sample Collection and Study Area

Eight samples were collected from various groundwater wells in various regions of Saudi Arabia of Al Qassim region. Eight wells were selected for this study to achieve a balanced spatial distribution of samples, covering the main geographic area of the study, which includes several governorates with varying groundwater use patterns, including agriculture, housing, and industry. This selection contributes to providing a comprehensive assessment of groundwater quality across the region. Table 1 shows the sample locations, Well depth (m), Sampling date and Water level.

**Table 1.** The sample locations, well depth (m), sampling date and water level.

| Sample No. | Coordinates | Well depth (m) | Sampling date | Water level |
|---|---|---|---|---|
| Q1 | N 26˚26.652"<br>E 043˚53.515" | 53 | 16/April/2025 | Deep groundwater |
| Q2 | N 26˚24.849"<br>E 043˚52.952" | 400 | 16/April/2025 | Deep groundwater |
| Q3 | N 26˚10'54.1"<br>E 43˚40'01.6" | 160 | 16/April/2025 | Deep groundwater |
| Q4 | N 26˚12'18.2"<br>E 43˚45'44.6" | 450 | 16/April/2025 | Deep groundwater |
| Q5 | N 26˚24'47.9"<br>E 43˚25'45.6" | 200 | 16/April/2025 | Deep groundwater |
| Q6 | N 26˚19'49.8"<br>E 43˚31'23.8" | 200 | 16/April/2025 | Deep groundwater |
| Q7 | N 26˚17'32.6"<br>E 43˚52'44.0" | 100 | 16/April/2025 | Deep groundwater |
| Q8 | N 26˚15'56.9"<br>E 43˚51'02.2" | 64 | 16/April/2025 | Deep groundwater |

Qassim Region as shown in Figure 1 located in the center of the Kingdom with a total area of 73,293 $Km^2$, equivalent to 3.41% of the country's total area. It lies between latitudes 25˚00' and 27˚00' north and longitudes 42˚30' and 45˚00' east. The region is located about 300 Km northwest of Riyadh in central Saudi Arabia. Its altitude above sea level ranges between 600 and 850 meters, The Qassim region is characterized as an important agricultural area in Saudi Arabia due to its fertile soil and groundwater, which forms the main source of water supply [31] [32].

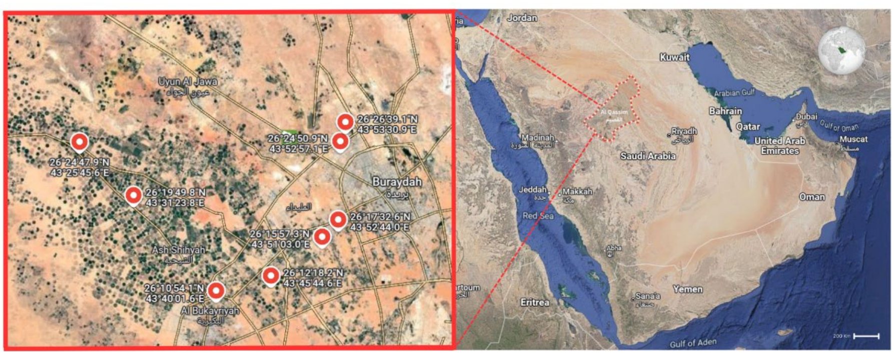


**Figure 1.** Qassim region from Google Maps and the sample's location in the red dot.

## 2.2. Radon Measurement

### 2.2.1. Dosage Calculation

The following relationships was used to compute the annual effective dose AED ( $\mu Sv/y$ ) of water consumption by ingestion and inhalation across different age groups. The annual effective dose for ingestion of water was calculated using the following equation [6] [9] [33]:

$$AED_{ing} = C_{Rn} \times AIW \times EDC \quad (1)$$

where $AED_{ing}$: is the annual effective dose for ingestion ( $\mu Sv/y$ ).

$C_{Rn}$: is the radon concentration in water (Bq/L).

AIW: represents the annual intake of water in the different age groups [6] [9] [33]:

- 230 L/y for age range 1 year infant.
- 330 L/y for 2 - 17 years children.
- 730 L/y for ≥17 years adult.

EDC: is the effective dose coefficient [6] [9] [33]:

- 23 (nSv/Bq) for infant.
- 5.9 (nSv/Bq) for children.
- 3.5 (nSv/Bq) for adult.

The following equation was used to calculate the annual effective dose for water inhalation [6] [9] [33]:

$$AED_{inh} = C_{Rn} \times R_a \times F \times O \times DCF \quad (2)$$

where $AED_{inh}$: is the annual effective dose for inhalation ( $\mu Sv/y$ ).

$C_{Rn}$: is the radon concentration in water (Bq/L).

$R_a$: is the air-to-water ratio for radon $10^{-4}$ [6] [9] [33].

F: is the equilibrium factor of radon to its decay product 0.4 [6] [9] [33].

O: is the average indoor occupancy time for a person annually 7000 (h/y) [6] [9] [33].

DCF: is the dose conversion factor for exposure 9nSv/(Bq.h.m$^{-3}$) [6] [9] [33] [34].

The total annual effective dose ($AED_T$): is the sum of the annual effective dose for ingestion ($AED_{ing}$) and the annual effective dose for inhalation ($AED_{inh}$) [6].

The effective dose per liter ( $nSv/L$ ): (By ingestion) a dose conversion factor of $5 \times 10^{-9}$ (Sv/Bq) proposed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 1993) was utilized [7] [34].

### 2.2.2. Measurement Procedures

Radon concentrations in groundwater samples were measured using a Durridge RAD7 (Durridge, United States) equipped with a RAD-$H_2O$ accessory. 250 ml bottles were connected to the device. Using a planar silicon detector implanted to detect radon's alpha-decay offspring, $^{218}Po$ and $^{214}Po$, the RAD7 enables the determination of radon quantities in the air. The RAD7 measures the amount of radon-222 in the air at $^{218}Po$ ($\alpha$ energy = 6.00 MeV) and $^{214}Po$ ($\alpha$ energy = 7.67 MeV), using a strong electric field on a silicon semiconductor sensed at ground potential. The measurement technique is based on a closed-loop aeration technique. Air is constantly recirculated inside a closed loop through the water sample, permitting radon gas to transfer from the water to the air until equilibrium is reached. The system includes three main components as shown in **Figure 2**:

- The RAD7 device;
- A 250 ml water bottle equipped with an aerator;
- A drying tube. Relative humidity becomes maintained below 10% (as recommended in the device's user manual, relative humidity must be 10% or decrease using a desiccant [35]).

**Figure 2.** RAD $H_2O$ [35].

Before each experiment, the device was operated for 10 minutes to empty the counting chamber of radon residues. That is an important step to ensure accurate measurements.

## 2.3. Procedures for Measuring Physical and Chemical Parameters

The pH, total dissolved solids (TDS), and electrical conductivity (EC) of groundwater samples were measured using an EZ9909SP water quality tester. Prior to measurements, the instrument was calibrated according to the manufacturer's instructions. The probe was directly immersed in 100 ml of each groundwater sample as shown in **Figure 3**, and the readings were recorded on the digital display after the readings stabilized.

## 2.4. Heavy Element Analysis Measurement Procedures

- Sample Preparation:

Figure 3. An EZ9909SP water quality tester.

1) Filtration: Using a 0.45 μm filter to remove solid impurities.

2) Addition of nitric acid: Typically 1% to preserve the sample and prevent metal precipitation.

3) Concentration Adjustment: Sometimes the sample is diluted to match the calibration range. Use multi-element standard solutions (e.g., 0.1, 1, 10, 100 ppb).

4) Addition of internal standards: (e.g., indium In-115) to correct for bias.

Some elements, such as mercury (Hg), are unstable in $HNO_3$, so HCl is added to maintain stability.

## 3. Results and Discussion

### 3.1. Results of Measuring Radon Gas Concentration and Its Risks Using the Rad 7 Detector

Radon concentration measurements in groundwater were conducted in selected region of Saudi Arabia—AlQassim—using a RAD7 detector. Table 2 gives the radon concentration and standard deviation. Radon concentrations measured in groundwater samples ranged from 0.0536 Bq/L (Q7) to 0.0729 Bq/L (Q2), with an overall mean of 0.0640 Bq/L. The standard deviation ranged from 0.0142 to 0.0190 Bq/L, with a median of 0.0166 Bq/L as shown in Figure 4. All values were below the World Health Organization (WHO) upper limit of 100 Bq/L [36], and the U.S Environmental Protection Agency's (EPA) recommended limit of 11 Bq/L [37], indicating that the radon concentrations in these groundwater samples are within acceptable safety limits for drinking water.

While in Table 3 the effective ingestion dose for different ages, the effective inhalation dose, and the annual effective dose per liter are given.

The annual effective dose from groundwater ingestion was evaluated for three age groups: infants, children, and adults. The ingestion dose for adults ranged from 0.1369 (Q7) to 0.1862 (Q2) μSv/y, with a mean of 0.1634 μSv/y. For children, the values ranged from 0.1043 (Q7) to 0.1419 (Q2) μSv/y, with a mean of 0.1246 μSv/yr. Infants exhibited the highest ingestion doses among all groups, with values ranging from 0.2835 (Q7) to 0.3856 (Q2) μSv/y, with a mean of 0.3385 μSv/y.

Table 2. Radon concentration and standard deviation.

| Sample No. | Sample mean radon concentration $\left(\frac{Bq}{L}\right)$ | Standard deviation $\left(\frac{Bq}{L}\right)$ |
|---|---|---|
| Q1 | 0.062 | 0.0142 |
| Q2 | 0.0729 | 0.0167 |
| Q3 | 0.0613 | 0.0182 |
| Q4 | 0.0636 | 0.0160 |
| Q5 | 0.0702 | 0.0145 |
| Q6 | 0.0673 | 0.0169 |
| Q7 | 0.0536 | 0.0173 |
| Q8 | 0.0611 | 0.0190 |
| Min | 0.0536 | 0.0142 |
| Max | 0.0729 | 0.0190 |
| Average | 0.0640 | 0.0166 |

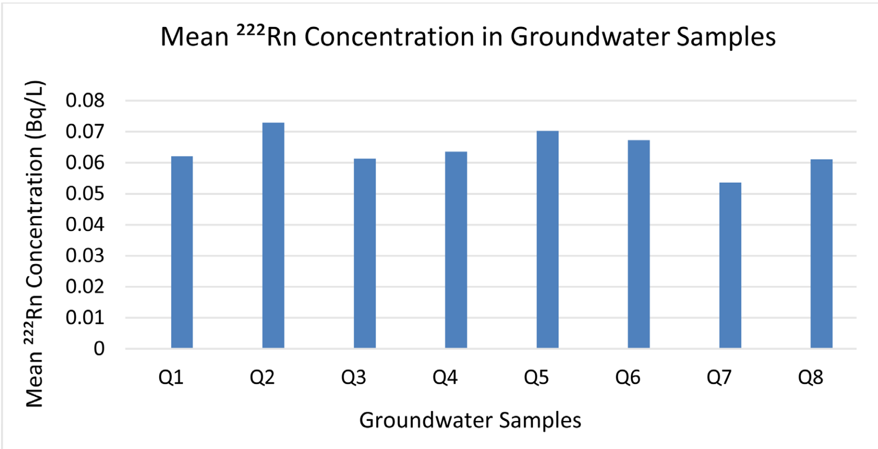


Figure 4. The mean concentration of $^{222}Rn$ in groundwater samples collected during the current study.

The annual effective dose from inhaled radon among adults ranged from 0.1350 (Q7) to 0.1837 (Q2) µSv/y, with a mean of 0.1615 µSv/y.

The annual effective dose per liter (EDL) values ranged from 0.268 (Q7) to 0.3645 (Q2) nSv/L, with an average 0.3205 nSv/L.

Overall, all calculated annual effective doses from both ingestion and inhalation of radon, as well as the effective dose per liter, remained well below the World Health Organization (WHO) [36], and European Commission (EC) guidelines of 0.1 mSv/yr (100 µSv/yr) [6] [38]. These results indicate that the studied groundwater samples do not pose a significant radiological health risk based on radon exposure from ingestion or inhalation routes.

Considering the current results and comparing them with current global standards, reported groundwater radon concentrations from several countries were examined Table 4 and shown in Figure 5.

Table 3. Radiological risk assessment.

| Sample No. | Annual mean effective dose $\left(\frac{\mu Sv}{y}\right)$ | | | | | Annual effective doses per liter (EDL) $\left(\frac{\mu Sv}{y}\right)$ |
|---|---|---|---|---|---|---|
| | Ingestion | | | Inhalation (adults) | Total (adults) | |
| | Infants | Children | Adults | | | |
| Q1 | 0.32789 | 0.120714 | 0.15841 | 0.15624 | 0.31465 | 0.31 |
| Q2 | 0.385641 | 0.1419363 | 0.1862595 | 0.183708 | 0.3699675 | 0.3645 |
| Q3 | 0.324277 | 0.1193511 | 0.1566215 | 0.154476 | 0.3110975 | 0.3065 |
| Q4 | 0.336444 | 0.1238292 | 0.162498 | 0.160272 | 0.32277 | 0.318 |
| Q5 | 0.371358 | 0.1366794 | 0.179361 | 0.176904 | 0.356265 | 0.351 |
| Q6 | 0.356017 | 0.1310331 | 0.1719515 | 0.169596 | 0.3415475 | 0.3365 |
| Q7 | 0.283544 | 0.1043592 | 0.136948 | 0.135072 | 0.27202 | 0.268 |
| Q8 | 0.323219 | 0.1189617 | 0.1561105 | 0.153972 | 0.3100825 | 0.3055 |
| Min | 0.2835 | 0.1043 | 0.1369 | 0.1350 | 0.27202 | 0.268 |
| Max | 0.3856 | 0.1419 | 0.1862 | 0.1837 | 0.3699675 | 0.3645 |
| Average | 0.3385 | 0.1246 | 0.1634 | 0.1615 | 0.3243 | 0.3205 |

Table 4. Comparison of the average value of groundwater $^{222}$Rn concentration in selected countries, with the WHO and EPA limits, with the limits and average values in the current study:

| Country/Organizing | $^{222}$Rn concentration $\left(\frac{Bq}{L}\right)$ | Reference |
|---|---|---|
| World Health Organization (WHO) | 100 | [36] |
| U.S. Environmental Protection Agency (EPA) | 11 | [37] |
| Saudi Arabia | 0.03 - 3.20 with mean 1.16 | [6] |
| India | 0.2 - 10.1 with mean 2.07 and 2.21 - 27.3 with mean 9.30 | [8] |
| Iraq | 4 - 12.18 with mean 7.92 | [2] |
| Nigeria | 1.6 - 271 with mean 35.9 | [9] |
| Tunisia | 0 - 2860 with mean 867 | [39] |
| Portugal | 2 - 1690 with mean 352.787 | [40] |
| Malaysia | 10 - 20 with mean 16.06 | [41] |
| Türkiye | 1.98 - 20.80 with mean 9.05 | [42] |
| Romania | 0.5 - 129.3 with mean 15.4 | [43] |
| Emirates | 0.05 - 1.76 with mean 0.64 | [44] |
| Current study | 0.0536 - 0.0729 with mean 0.064 | - |

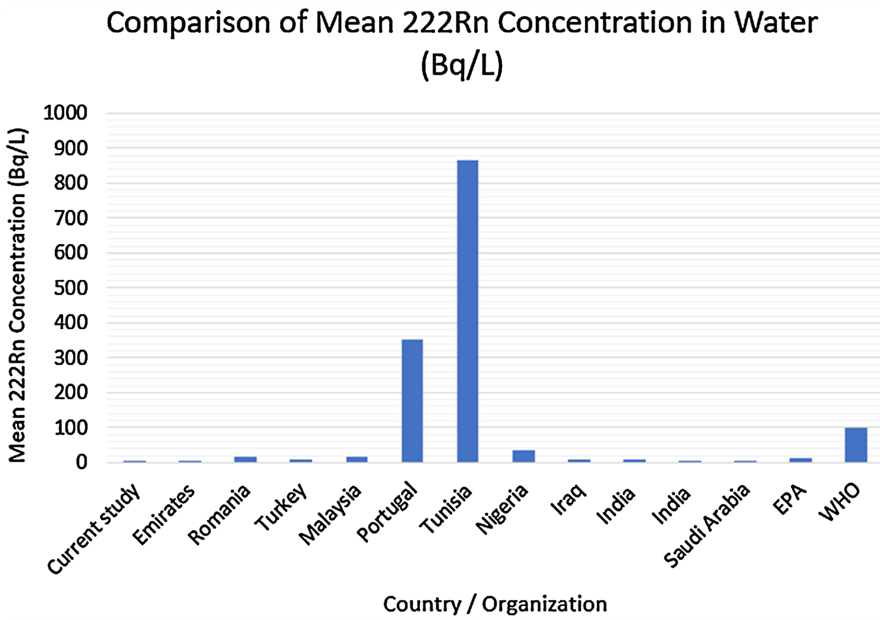


**Figure 5.** Comparison of mean $^{222}$Rn concentrations in groundwater with different countries and organizations.

For example, in Saudi Arabia, radon concentrations were reported to range from 0.03 to 3.20 Bq/L, with a mean of 1.16 Bq/L [6], indicating relatively low radon concentrations. In India, the range was between 0.2 and 10.1 Bq/L with a mean of 2.07 Bq/L, and in another region, between 2.21 and 27.3 Bq/L with a mean of 9.30 Bq/L [8]. In Iraq, reported radon concentrations ranged from 4 to 12.18 Bq/L, with a mean of 7.92 Bq/L [2].

Some countries recorded high concentrations globally. For example, radon levels in Nigeria ranged from 1.6 to 271 Bq/L, with an average of 35.9 Bq/L [9]. Meanwhile, in Tunisia, reported radon levels ranged from 0 to 2860 Bq/L, with an average of 867 Bq/L, significantly exceeding international standards [39]. Similarly, Portugal recorded high levels in groundwater, with reported radon concentrations ranging from 2 to 1690 Bq/L with an average of 352.79 Bq/L [40].

Moderate levels (low/medium radon concentrations) were reported in Malaysia from 10 to 20 Bq/L, with an average of 16.06 (Bq/L) [41], Türkiye from 1.98 to 20.80 Bq/L, with an average of 9.05 Bq/L [42], and Romania from 0.5 to 129.3 Bq/L, with an average of 15.4 Bq/L [43], while the UAE was significantly lower than the reported ranges; in this case from 0.05 to 1.76 Bq/L with an average of 0.641 (Bq/L) [44].

### 3.2. Results of Physical and Chemical Properties Including pH, Total Dissolved Solids (TDS), and Electrical Conductivity (EC) Using the EZ9909SP Water Quality Tester

The physical and chemical properties of groundwater samples were analyzed, specifically pH, total dissolved solids (TDS), and electrical conductivity. **Table 5** presents the results. The pH values in the samples ranged from 6.84 (Q1) to 7.57 (Q7), with a mean of 7.31. All pH values were within the WHO guideline range of 6.5 to 8.5 [12].

Total dissolved solids values in the samples ranged from 695 (Q2) to 4240 (Q1) mg/L, with a mean of 1943.13 mg/L. Some samples, such as Q1, Q3, Q4, Q6, Q7, and Q8, exceeded the WHO and US Environmental Protection Agency (EPA) guideline ranges [13] [14].

The electrical conductivity values of the samples ranged from 1398 (Q2) to 8450 (Q1) µS/cm, with a mean of 3879.63 µS/cm. Some samples, such as Q1, Q3, Q4, Q7, and Q8, exceeded the European Union and the World Health Organization (WHO) guideline ranges [13] [17] [18] as given in **Table 5** and shown in **Figure 6**.

Table 5. Results of physical and chemical properties including pH, total dissolved solids (TDS), and electrical conductivity (EC) using the EZ9909SP water quality tester.

| Sample No. | pH | TDS (mg/L) | EC (µS/cm) |
|---|---|---|---|
| Q1 | 6.84 | 4240 | 8450 |
| Q2 | 7.56 | 695 | 1398 |
| Q3 | 6.93 | 1570 | 3140 |
| Q4 | 7.28 | 1280 | 2560 |
| Q5 | 7.48 | 830 | 1663 |
| Q6 | 7.56 | 1160 | 2340 |
| Q7 | 7.57 | 2660 | 5330 |
| Q8 | 7.27 | 3070 | 6150 |
| Min | 6.84 | 695 | 1398 |
| Max | 7.57 | 4240 | 8450 |
| Average | 7.31 | 1943.13 | 3879.63 |

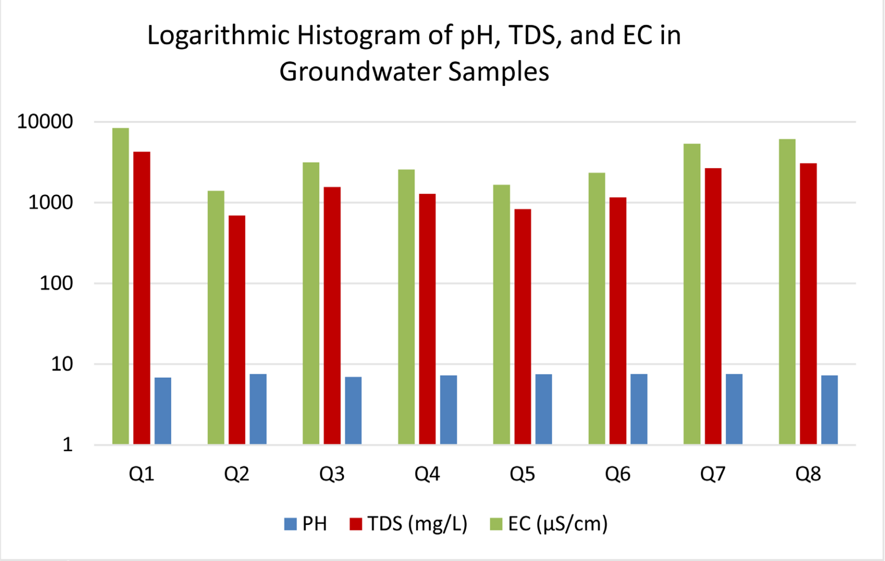


Figure 6. Logarithmic histogram illustrating the distribution of pH, TDS, and EC values in the groundwater samples collected during the current study.

The high EC and TDS values observed in several samples (e.g., Q1, Q3, Q4, Q6, Q7, and Q8) suggest potential contributions from natural hydrogeochemical processes, such as the dissolution of salts from deep geological strata and the mobilization of ions through mineral-rich soil layers. However, anthropogenic sources particularly agricultural runoff and inadequate wastewater disposal may also play a role. To safeguard groundwater quality, it is crucial to implement integrated water resource management strategies, including routine monitoring programs and the development of efficient wastewater treatment and disposal infrastructure. Additionally, pre-treatment of water exhibiting elevated electrical conductivity and TDS should be considered prior to its use for drinking purposes. Enhancing community awareness and promoting stakeholder engagement are also vital for fostering sustainable groundwater management practices.

In **Table 6** the comparision of pH, TDS, and electrical conductivity of groundwater in selected countries and regulatory limits with the current study are given and shown in **Figures 7-9**. The pH values in Indonesia were found to range from 6.01 to 7.24 [19]. while in Iraq, pH values were between 7.11 to 7.29 [18]. In Europe, Italy showed values ranging from 7.3 to 8.0, within the acceptable values [21]. In addition to Italy, India from 7.02 to 7.65 [20], Nigeria from 6.35 to 8.31 [22], and Pakistan from 7.10 to 8.40 [24] performed well relative to WHO standards as well. Tunisia on the other hand, had a much wider variation in pH from 7.21 to 9.64 with amount of samples exceeding acceptable levels [23].

Regarding total dissolved solids, Indonesia had from 429to 501 mg/L [19]. Nigeria from 247.5 to 589.7 mg/L [22] reported good quality drinking water. Whereas, several countries exceeded WHO guidelines. India from 690 to 1560 mg/L [20], Pakistan from 987 to 2114 mg/L [24], Tunisia from 261 to 2048 mg/L

**Table 6.** The comparision of pH, TDS, and electrical conductivity of groundwater in selected countries with the current study

| Country/Organizing | pH | TDS $\left(\frac{mg}{L}\right)$ | EC $\left(\frac{\mu s}{cm}\right)$ | Reference |
|---|---|---|---|---|
| World Health Organization (WHO) | 6.5 to 8.5 | ≤1000 | 2500 | [12] [13] [18] |
| European Union | - | - | 2500 | [17] |
| Indonesia | 6.01 - 7.24 | 429 - 501 | 618 - 1351 | [19] |
| Iraq | 7.11 - 7.29 | 1520 - 5773 | 2351 - 8901 | [18] |
| Italy | 7.3 - 8.0 | 336 - 2790.1 | 412 - 4180 | [21] |
| India | 7.02 - 7.65 | 690 - 1560 | 442 - 998 | [20] |
| Nigeria | 6.35 - 8.31 | 247.5 - 589.7 | 450 - 1190 | [22] |
| Tunisia | 7.21 - 9.64 | 261 - 2048 | 653 - 5120 | [23] |
| Pakistan | 7.10 - 8.40 | 987 - 2114 | 1592 - 3098 | [24] |
| Current study | 6.84 - 7.57 | 695 - 4240 | 1398 - 8450 | - |

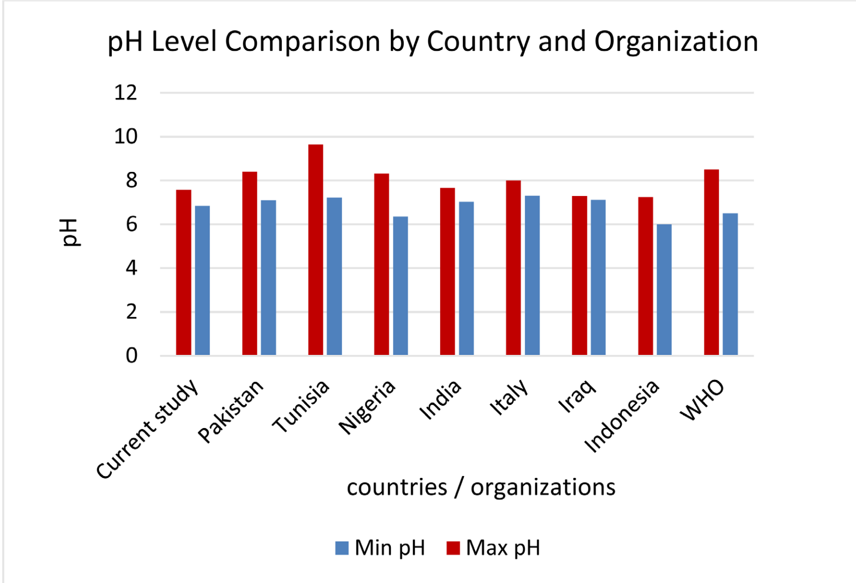


**Figure 7.** Comparison of pH values in groundwater samples from the current study with those reported in other countries and with the recommended range set by the World Health Organization (WHO).

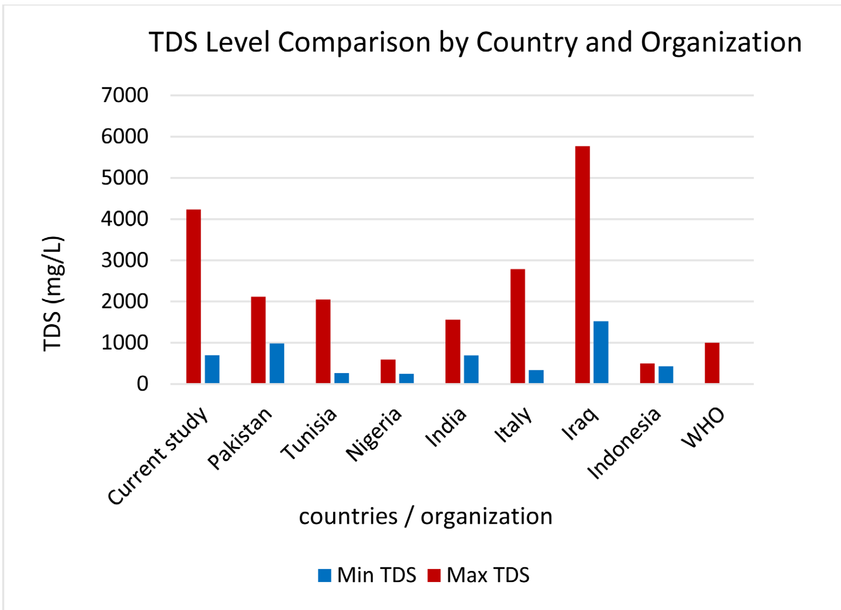


**Figure 8.** Comparison of Total Dissolved Solids (TDS) concentrations in groundwater between the current study and various international data, along with the WHO guideline value (≤1000 mg/L).

[23], and Italy ranging from 336 to 2790.1 mg/L [21]; as well as the highest dissolved solids are seen in Iraq from 1520 to 5773 mg/L [18].

Based on electrical conductivity (EC), Indonesia made good use of the pH method with its EC containing from 618 to 1351 µS/cm [19]. India from 442 to 998 µS/cm [20], and Nigeria from 450 to 1190 µS/cm [22] reported moderate levels of acceptance. However, Tunisia from 653 to 5120 µS/cm [23], Pakistan

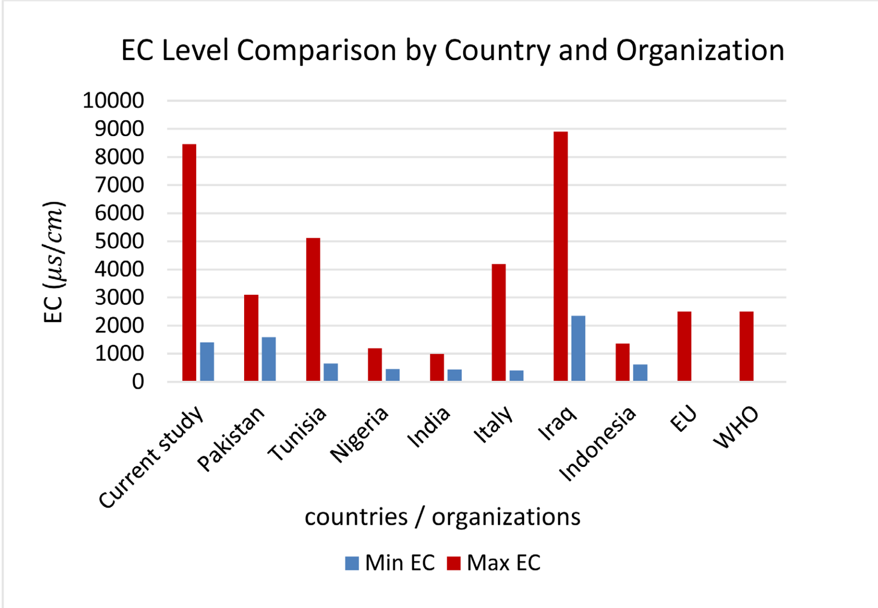


Figure 9. Variation in electrical conductivity (EC) values in groundwater across the current study, other countries, and international organizations.

from 1592 to 3098 µS/cm [24] and Iraq from 2351 to 8901 µS/cm [18], reported high conductivity, with many exceeding recommended guidelines. Italy reported from 412 to 4180 µS/cm [21].

### 3.3. Results of Measurement of Heavy Elements Using Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

In this study, groundwater samples from four different areas in the Qassim region—Buraydah (Q2), Al-Bukayriyah (Q4), Al-Malida (Q6), and Al-Fuwailiq (Q8)—were analyzed to evaluate the concentrations of some heavy metals: nickel (Ni), lead (Pb), copper (Cu), mercury (Hg), and zinc (Zn).

The results are given in **Table 7** and are showed that most of the studied elements were below the instrument's limit of quantification (LOQ), indicating that their concentrations were so low that the analytical system could not accurately quantify them. This is a positive indicator of water quality and the absence of contamination by these heavy metals. It is worth noting that the LOQs were very low, reflecting the high sensitivity of the device used, which was 0.04 µg/L for both lead and nickel, 0.05 µg/L for mercury, and 80 µg/L for both copper and zinc.

Among the heavy metals included in the analysis, nickel was the only element detected at quantifiable concentrations in some samples, while the other elements all showed values below the LOQ. The results indicated that the nickel concentration in the Al-Mulida sample (Q6) reached 0.34 µg/L, the highest recorded concentration among the samples. In comparison, nickel concentrations were 0.22 µg/L in the Al-Bukayriyah sample (Q4) and 0.16 µg/L in the Al-Fawilaq sample (Q8). Nickel was not detected in the Buraidah sample (Q2), where its concentration was below the LOQ.

**Table 7.** Concentration of elements in samples in μg/L.

| Sample No. | Hg (μg/L) | Cu (μg/L) | Pb (μg/L) | Ni (μg/L) | Zn (μg/L) |
|---|---|---|---|---|---|
| Q2 | <LOQ | <LOQ | <LOQ | <LOQ | <LOQ |
| Q4 | <LOQ | <LOQ | <LOQ | 0.22 | <LOQ |
| Q6 | <LOQ | <LOQ | <LOQ | 0.34 | <LOQ |
| Q8 | <LOQ | <LOQ | <LOQ | 0.16 | <LOQ |
| Min | - | - | - | <LOQ | - |
| Max | - | - | - | 0.34 | - |
| Average | - | - | - | 0.24 | - |

It is important to note that all recorded nickel concentrations were below the maximum allowable limit set by the World Health Organization (WHO), which is 70 μg/L [26]. For example, the highest value recorded in this study (0.34 μg/L in the Al-Mulidaa sample) represents only about 0.49% of the permissible limit, indicating that the presence of nickel in the studied samples does not pose any health risk.

The absence of the other heavy metals above the LOQ suggests that the studied samples have low heavy metal content, reflecting the good quality of the groundwater and its lack of exposure to clear pollution sources. This is a positive indicator of the chemical safety of the water and supports its suitability for human consumption within acceptable limits. However, it is recommended to continue periodic monitoring of water quality to ensure that this quality is maintained and to avoid any changes that may occur in chemical element concentrations as a result of human activities or environmental changes.

In **Table 8** the range and average values of heavy metal concentrations in groundwater in other countries are given. As reported in studies, values in Türkiye ranged from 0 to 0.140 μg/L, with a mean of 0.029 μg/L, which is well below the WHO upper limit, indicating slight mercury contamination [29].

Copper concentrations varied widely across the sampled regions. In India, copper concentrations ranged from 3.1 to 83.5 μg/L, with a mean of 43 μg/L [27]. In Italy, copper concentrations ranged from 0.83 to 85.9 μg/L (with a mean of 3.87 μg/L) [28]. Malaysia reported a lower range of concentration values, with a range of 0.07 to 2.22 μg/L and a mean of 0.49 μg/L [30]. The average copper concentration in Egypt was much higher, at 209.94 μg/L [45]. In Türkiye, the lowest copper concentrations ranged between 0 and 0.060 μg/L (with a mean of 0.005 μg/L), indicating the presence of trace amounts of copper [29].

Lead has been detected in several studies at varying concentrations. In India, concentrations ranged between 6.7 and 82.7 μg/L, with a mean of 44.7 μg/L [27]. Egypt recorded average lead concentration of 30.04 μg/L [45]. In Italy, lead concentrations ranged between 0.90 and 7.5 μg/L (with a mean of 1.22 μg/L) [28]. In Malaysia, lead levels ranged from 0.03 to 4.35 μg/L (with a mean of 0.84 μg/L) [30]. Türkiye again recorded the lowest levels, ranging from 0 to 1.497 μg/L, with an average of only 0.095 μg/L [29].

nickel levels were also recorded in some locations. India recorded nickel concentrations ranging from 8.92 to 181.8 μg/L, with an average of 95 μg/L [27]. Egypt recorded an average nickel concentration of 41.1 μg/L [45]. Italy recorded levels ranging from 0.61 to 263.8 μg/L (with an average of 3.66 μg/L) [28]. Nickel levels in Türkiye ranged from 0 to 30.058 μg/L with an average of 1.598 μg/L [29]. Zinc levels varied widely. India reported zinc concentrations ranging from 6.4 to 746.9 μg/L (with average of 376 μg/L) [27]. Egypt reported a higher average of 490.21 μg/L [45]. Zinc levels in Italy ranged from 0.85 to 786.2 μg/L with an average of 12.8 μg/L [28]. Malaysia reported an average zinc concentration of 5.51 μg/L; most were below the detection limit of 0.17 μg/L [30] as given in **Table 8**.

**Table 8.** Comparisons of heavy metals with WHO and other countries.

| Country/Organizing | Hg (μg/L) | Cu (μg/L) | Pb (μg/L) | Ni (μg/L) | Zn (μg/L) | Reference |
|---|---|---|---|---|---|---|
| World Health Organization (WHO) | 6 | 2000 | 10 | 70 | - | [26] |
| India | - | 3.1 - 83.5 with mean 43 | 6.7 - 82.7 with mean 44.7 | 8.92 - 181.8 with mean 95 | 6.4 - 746.9 with mean 376 | [27] |
| Italy | - | 0.83 - 85.9 with mean 3.87 | 0.90 - 7.5 with mean 1.22 | 0.61 - 263.8 with mean 3.66 | 0.85 - 786.2 with mean 12.8 | [28] |
| Egypt | - | The mean 209.94 | The mean 30.04 | The mean 41.1 | The mean 490.21 | [45] |
| Türkiye | 0 - 0.140 with mean 0.029 | 0 - 0.060 with mean 0.005 | 0 - 1.497 with mean 0.095 | 0 - 30.058 with mean 1.598 | - | [29] |
| Malaysia | - | 0.07 - 2.22 with mean 0.49 | 0.03 - 4.35 with mean 0.84 | - | <0.17 below the detection limit—118.97 with mean 5.51 | [30] |
| Current study | - | - | - | <LOQ—0.34 with mean 0.24 | - | - |

## 3.4. Pearson Correlation between Radon ($^{222}Rn$) and Each of pH, TDS, EC and Nickel

Correlation gives the degree and direction of relationship between the two variables, a correlation has direction, and correlation coefficient (r) can be either positive or negative [46]. Zero indicates no relationship between the two variables, and $r = 1$ or $r = -1$ indicate a perfect relationship [46]. The strength can be anywhere between 0 and ±1 [46]. In this study, the Pearson correlation coefficient was determined following the methodology outlined in reference [46].

The Pearson correlation coefficient between radon concentration ($Rn^{222}$) and pH was calculated directly using Excel, and the value was 0.28416. This indicates a weak positive relationship between the two variables. A positive relationship means that as pH increases, radon concentration tends to increase, as in Figure 10.

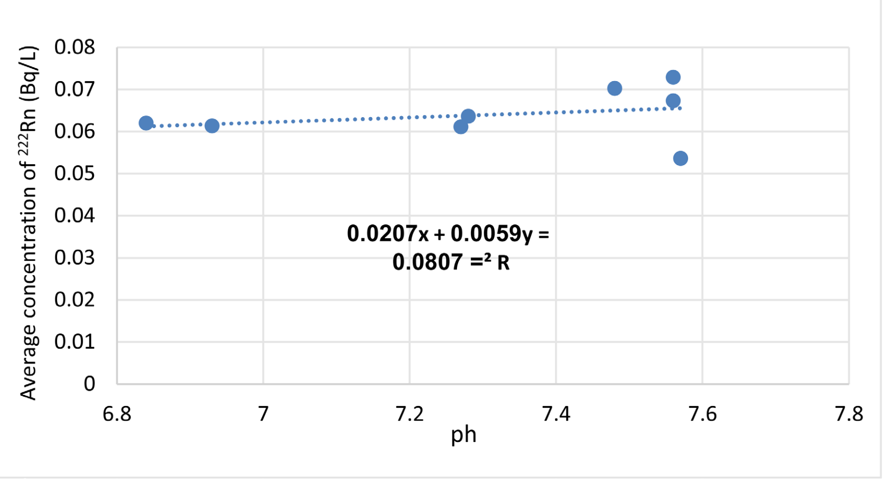


Figure 10. The relationship between $^{222}$Rn concentration and pH.

The Pearson correlation coefficient between radon concentration ($Rn^{222}$) and total dissolved solids (TDS) was calculated directly using Excel and was −0.6506, indicating a fairly strong negative correlation. A negative correlation means that as the TDS value increases, the radon concentration tends to decrease, as shown in Figure 11.

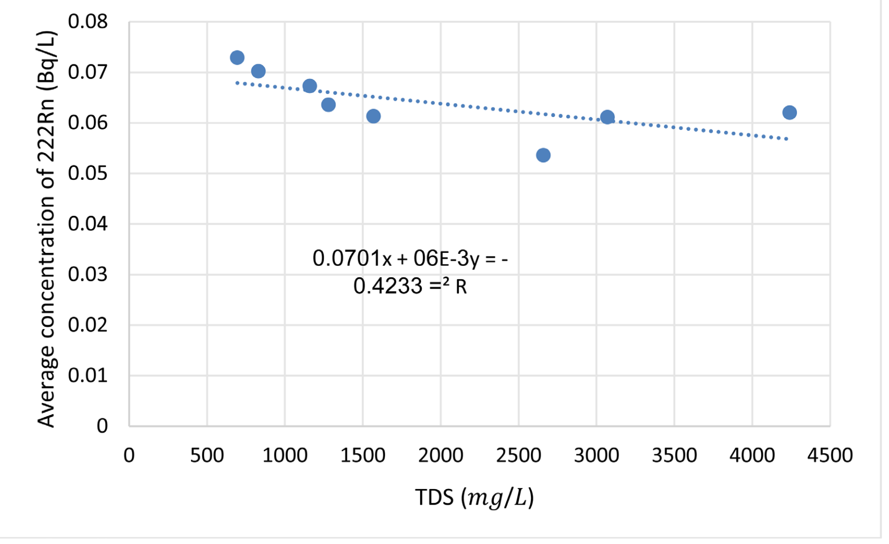


Figure 11. Relationship between $^{222}$Rn concentration and total dissolved solids (TDS).

The Pearson correlation coefficient between radon concentration and electrical conductivity (EC) was calculated directly using Excel, and the value of the coefficient was −0.6521, indicating a medium-strength negative correlation, meaning that as the total dissolved solids (TDS) value increases, the radon concentration tends to decrease, as shown in Figure 12.

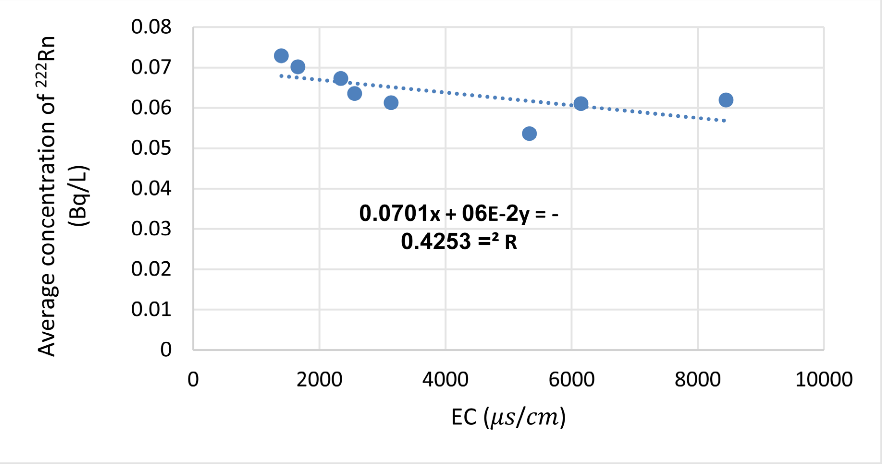


**Figure 12.** The relationship between $^{222}$Rn concentration and electrical conductivity (EC).

The Pearson correlation coefficient between radon concentration ($Rn^{222}$) and nickel concentration (Ni) was calculated directly using Excel, based on data from three samples. The coefficient value was 0.9969, indicating a very strong positive relationship, approaching a perfect correlation. This means that as nickel concentration increases in water samples, radon concentration increases almost proportionally, as shown in Figure 13.

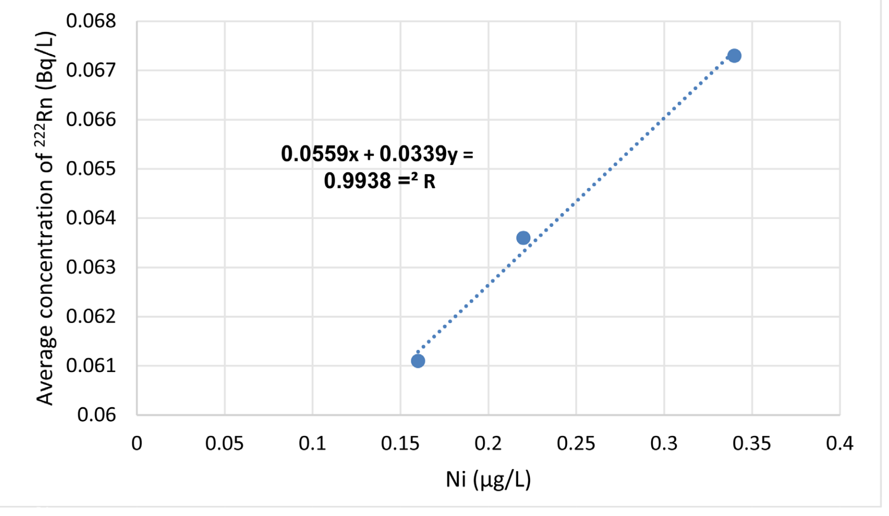


**Figure 13.** The relationship between $^{222}$Rn concentration and nickel (Ni).

## 4. Conclusion

In this work, the groundwater quality in a selected area of Saudi Arabia—the Qassim region—was studied by measuring radon gas concentrations and physical and chemical parameters, including pH, total dissolved solids (TDS), and electrical conductivity (EC), along with measurements of heavy metals (mercury, copper, lead, nickel, and zinc). Radon concentrations remained below standard limits, and annual effective doses, whether by ingestion or inhalation, did not pose any radiological health risks. According to the chemical and physical parameters, pH values were within acceptable limits, while some samples exceeded the recommended limits for total dissolved solids and electrical conductivity, requiring periodic monitoring. Regarding heavy metals, all samples were within permissible limits and showed no serious signs of contamination, reflecting the quality of the groundwater. These results indicate that the groundwater in the studied area is safe for human consumption. Pearson correlation analysis revealed varying degrees of correlation between radon concentration and water quality parameters. While the correlation with pH was weak and positive, both total dissolved solids (TDS) and electrical conductivity (EC) showed a fairly strong negative correlation with radon, suggesting that dissolved metal content may be reducing radon levels. The very strong positive correlation with nickel suggests a significant link between the presence of radon and heavy metal contamination in some samples. However, ongoing monitoring and periodic reassessment are essential to ensuring long-term water safety, as outlined in Saudi Arabia's Vision 2030.

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## Conflicts of Interest

The authors declare no conflicts of interest.

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