



Research article

Statistical analysis of ^{222}Rn concentration in Zamzam and other water sources in the Kingdom of Saudi ArabiaKaltham B. Aljaloud^{a,*}, Mervette ElBatouti^b^a Department of Physics, College of Science, Qassim University, Kingdom of Saudi Arabia, Saudi Arabia^b Chemistry Department, Faculty of Science, Alexandria University, Egypt

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ABSTRACT

In the present study, six water samples were collected from different locations in the Kingdom of Saudi Arabia and another sample from the Zamzam site in Makkah city. The concentration of the radioactive isotope ^{222}Rn was measured using the electronic radon detector (RAD7). The comparative analysis study on these samples showed that the average concentration value in all samples was 0.504Bq/L. The data analysis showed that the concentration of ^{222}Rn was ranged from 0.43 ± 0.06 Bq/L to 0.57 ± 0.060 Bq/L for all samples. These levels are below the contamination threshold (11.1 Bq/L) recommended by the US Environmental Protection Agency (EPA). Interestingly, Radon radioactivity levels were lower than those harmful to human health. The principal component analysis (PCA) using (SPSS version 15) was used to reduce the four variables influencing the ^{222}Rn activity concentration to two variables: temperature (correlation coefficient, R^2 : 0.984) and the relative humidity (RH%) (R^2 : -0.987). The increase in temperature reduces the solubility of ^{222}Rn gas activity water and facilitates its detection, whereas increased the RH% increases its solubility and decreases the detection level of ^{222}Rn activity concentration. The interaction between temperature and RH% does not affect the concentration of ^{222}Rn .

1. Introduction

Radioactivity is a spontaneous process in which unstable atoms transform into new nuclides by the emission of excess energy in the form of alpha particles, beta particles, or gamma rays [1, 2]. Various radioisotopes are released into water from various industries, such as C-14, Pb-210 (up to 80 years layers of sand and soil), Caesium-137 (a radio-tracer for soil erosion and deposition and for low-intensity gamma sterilization), and ^{241}Am radioisotope (a smoke radioisotope detector) [3]. The radioactive isotopes are abundant in the air, soil, drinking water, and virtually every modern living area. Radioactive contamination is a serious problem throughout the world. The polluted water with radioactive isotopes can pose hazards to human health and the environment. The radioactive pollution changes water quality that becomes unsuited for the desired use and human consumption [4]. Radon gas (^{222}Rn) is a health hazard for individuals exposed to a long period of radiation. The exposure of ^{222}Rn comes mainly from buildings made of raw materials containing radioactive isotopes, and soils containing radioactive isotopes. The closed and less ventilated places enhanced the pollution by ^{222}Rn due to the little ^{222}Rn leakage. The infected people exposed to ^{222}Rn in closed places exceed by 5–10 folds the people in the aerated

places, especially in winter and cold countries where the doors and windows are closed for energy and warm air conservation. In that event, ^{222}Rn leakage decreases, which increases its concentration and the radiation dose to higher levels. Water and natural gas are other sources of ^{222}Rn in homes where this inert gas enters through the water body and is released into breathe air. Using ^{222}Rn -contaminated water for bathing or other household uses except drinking is not a problem because boiling water and using it in cooking remove ^{222}Rn . On the other hand, using cold water contaminated with ^{222}Rn causes many health problems [5]. The greater risk of ^{222}Rn from inhaling air containing ^{222}Rn is harming the respiratory system, which could lead to trachea, bronchioles, or lung cancer [1, 5]. The Kingdom of Saudi Arabia is a very important country for Muslims all over the world. In concurrence with the disruption caused by COVID-19, analysis of ^{222}Rn gas in water samples is a necessity, because a high level of ^{222}Rn in water decreases the immunity of the whole respiratory system and causes pneumonia [5]. The short-term inhalation of ^{222}Rn in the water while bathing can harm the lung cells and decreases the defense ability of these cells to defend against the acute infections by the COVID-19 virus, which disrupts the respiratory system [5].

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The ^{222}Rn radioactive decayed to the polonium element, yielding readily highly energetic alpha particles after a very short half lifetime of 3.83 days. The decay scheme of Thorium to Thallium yields ^{220}Rn radioactive isotope [6], while the decay scheme of Actinium produces ^{219}Rn radioactive isotope [7]. Each decay chain has the name of the parent radionuclide of a much longer half-life than other radioisotopes in the series. The secular equilibrium is achieved when the activity of the daughter isotope equals the activity of the parent isotope after nearly eight half-lives of the daughter. Hence, the concentration of daughter radioisotopes can be estimated by knowing the concentration of the parent radioisotope.

The change in the rate of decay of the N-parent nuclei decreases exponentially with time. Concerning half-life time, $t_{1/2}$ (the time required for the quantity of radioactive isotope to be reduced to one half of its original value), ^{222}Rn radioactive isotope produced from radioactive series of Uranium (U-238) present in nature with very long $t_{1/2}$. After several disintegrations of U-238, the produced radioactive Radium isotope (Ra-226) decayed giving Rn- 222 , and its decay series ended with a stable Pb-206 isotope.

This study aims to determine ^{222}Rn concentration in Zamzam water in comparison with that of other groundwater samples collected from different locations in the Saudi Arabia Kingdom to test its suitability for drinking across the world. In this context, we precisely determined in batch experiments the average concentration ^{222}Rn radioactive isotope in Zamzam Al-Taher water and compared it to different groundwater samples in Saudi Arabia.

Also, a comparative study was designed to compare the obtained average activity concentration of ^{222}Rn to those values reported of ^{222}Rn in different countries all over the world. Besides.

2. Methodology

2.1. Sample collection

A total of 7 water samples (one Zamzam water and six groundwater) were collected within the study area. The samples were collected in pre-cleaned and sterile 250 mL plastic containers by first purging water through pumping for 10 min, to ensure sample quality. The containers were tightly closed to ensure the minimum ^{222}Rn loss and no air contact.

The collected water samples during transporting were preserved in an icebox, and the collected water samples were stored and refrigerated at 5 °C [8]. Although the collected samples are few, they are still enough to represent that of the whole Kingdom. This is because the physicochemical properties of water within the study areas are nearly the same. The locations of the collected water samples, as illustrated in Figure 1, are Al-Qassim region (Sample one, S1), North Buraidah (Sample six, S6), Al-Basra Governorate located to the west of Buraidah (Sample two, S2), and the Hail region (Samples four and five, S4 and S5). In addition to sample three (S3), that was brought from the capital of Saudi Arabia, Riyadh, specifically from the wells of Hafr Al-Aish.

Figure 1 showed the Google map of the locations of these cities accurately [9].

All the samples were collected on the same day within 12 h of work using automatic samplers, and have been analyzed in the next day to sample collection. As soon as water samples were collected, all these water samples were acidified by 1.0 M HCl immediately to avoid wall adsorption on the collecting bottles. Generally, for the protection of any ^{222}Rn radioactivity, glass bottles of the specified chemical compositions prepared by RM El-Sharkawy [10], have been recommended for packing drinking water.

2.2. Sample processing

All the tested water samples were prepared or processed before the analysis as soon as reaching the Lab. The physicochemical parameters of the collected water samples were monitored as follows: The acidity scale, pH, of the collected water samples, was measured using an analytically calibrated pH meter (Multi-parameter analyzer, model ELJKEL KAMP 18.28, Belgium). Then, the pH of water samples was adjusted to 4 using 1.0M HCl. The temperature was measured using an analytical thermometer embedded in the electrical conductivity unit (Thermo Scientific, ORION 3 STAR conductivity Benchtop, U.S.A). This electronic thermometer is soaked carefully in the water sample. The temperature reading is taken after stabilization of the thermometer. The electrical conductivity was measured using a calibrated electrical conductivity unit (Thermo Scientific, ORION 3 STAR conductivity Benchtop, U.S.A). The turbidity was measured using a calibrated HACH Turbidimeter (2100N). The alkalinity of water samples was determined by the titration method [6].



Figure 1. Google map (GPS technology) of the different collection areas of water samples (<https://www.google.com/maps>).

2.3. The sample analysis

^{222}Rn activity concentration along with the standard errors of the coefficients was determined in the form of energy (eV) signals obtained from the calibrated MDA detector.

The detection and quantitative measurement of radiation emitted from ^{222}Rn radioisotope in water samples were carried out. The ^{222}Rn activity concentration was radioassayed using a computerized multi-channel radon detector (RAD7) connected to the silicon (Si) scintillation detector. Before the measurement, the detector was calibrated using appropriate sealed sources. The ^{222}Rn activity concentration at the peaks of the high applied voltage was recorded. The Si semiconductor is a very sensitive radioactive RAD7 Electronic Radon detector. It is an advanced, precise, and multi-purpose device used for measuring ^{222}Rn in water, continuously monitoring it in the air, especially inhaling air, soil, bull emissions from materials and surfaces. The external appearance for the multichannel RAD7 detector is operated by four main keys, according to the selected test [9].

The Si semiconducting material converted α -radiation energy from ^{222}Rn directly into an electrical signal amplified by an electronic circuit and converted to a digital format. The RAD7 is a small data processor, receives and stores the signal in the memory form spectral chart, has an energy range (0–10) MeV. The interest appears at 6–9 MeV where ^{222}Rn and thorium decay are located. The observed spectrum divided by 200 channels in eight windows, and each channel has an energy level 0.05 MeV, i.e., RAD7 detector can specify the isotope of the electronic energy distinction related to α -particles and hence distinguish ^{222}Rn isotope from (Po 218) by α -radiation (6 MeV) or Po-214 card (7.97 MeV). The spectrum is printed by RAD7 windows A, B, C, D, as shown in Figure 2 [8].

At the start of the measurement, the memory of the detector was empty. The number of the revolving of the last cycle must be less than 99 for 10 min, by connecting the drying unit in a closed loop with RAD7 detector, so the outside air passes through the dryer (Desiccant) and returns to the interior. The airflow of the same way is passed through the dryer (Durridge Co. Inc., 2015) to measure ^{222}Rn concentration in water samples. RAD7-H₂O, a supplement to RAD7, is designed to detect the ^{222}Rn in a water sample with high accuracy under a wide concentration range. The readings were taken within 1 h after collecting the sample, and after performing the cleaning of the detector probe, the moisture was observed. If the relative humidity (RH%) is less than (60%), the test started where the system set on the Grab (when measuring ^{222}Rn concentration in water sample the pump put on Grab, i.e. ^{222}Rn extracted from the sample). The pump operates for 5 min by which ^{222}Rn is drawn from the sample and delivered to the measurement room, then the detector stops and waits for more than 5 min to reach equilibrium and then repeats for four cycles by 5 min for one session, thus the total test duration is 30 min. At the end of each run, the RAD7 detector printed the included summary (average left Ra, standard deviation, humidity, and

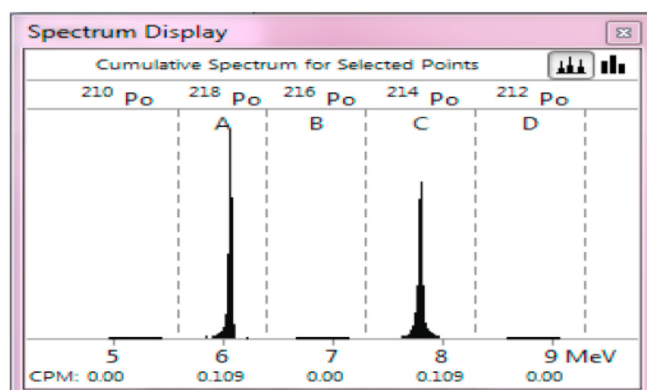


Figure 2. The display window of the alpha energy spectrum in RAD7 detector.

the temperature). The operation number, the number of cycles, the graph of the four cycles, and the accumulated spectrum. The ^{222}Rn removal rate of water in the air ring is very high 94% in a sample of 250 mL. The schematic output charts for the activity concentration of ^{222}Rn were precisely obtained and the minimum detection activity for the radionuclide ^{222}Rn has been measured within 0.07 Bq. L⁻¹.

The RAD7 detector connected to a water sample, along with monitoring the activity of ^{222}Rn in air based on using air inlet and air outlet with white and green color, respectively. The operation system of the RAD7 detector was previously illustrated [8]. A RAD7 detector is a machine accelerating ^{222}Rn at high voltage using an efficient filter and aerator.

The accurate electronic ^{222}Rn detector RAD7 continuously monitored ^{222}Rn level in water samples. Figure 3 showed the experimental setup for a connection of a water sample to the RAD7 detector until the equilibrium was established during the duration time during the radiometric assay of ^{222}Rn concentration [11].

The Sievert unit measures the biological effects of radiation on an organism, depending on the nature of radiation and the exposed organs. The Sievert unit is an equivalent or effective dose [12]. The most common unit is mL Sievert or 1000 Sievert. The effective exposure Sievert dose (Sv.y⁻¹) in water was calculated using Eq. (1).

$$D_w = C_w \cdot CR_w \cdot D_{CW} \quad (1)$$

Where C_w is the Radon concentration in a water sample (Bq.L⁻¹), CR_w is the general consumption rate of an individual (1095 L y⁻¹), D_{CW} illustrated in Eq. (2) is a conversion factor for conversion dose of radon [8].

$$D_{CW} = 5 \times 10^{-9} \text{ Sv. Bq}^{-1} = 0.504 \times 1095 \times 5 \times 10^{-9} = 2.80 \times 10^{-6} \text{ Sy.y}^{-1} \quad (2)$$

Different batch experiments were carried out under static conditions to determine the concentration of ^{222}Rn radioisotope in water samples [13]. The relative standard uncertainty for each determination of ^{222}Rn is less than 10%.

3. Results and discussions

Table 1 clarified the experimental results for the measured level of $^{222}\text{Rn} \pm$ standard error in the seven water samples at the specified conditions of temperature (°C), relative humidity (RH%), and the duration time. The standard deviation (\pm) in each reading of ^{222}Rn level which is the square root of the reading value of concentration decreases with an increasing concentration and an increase in the collection time. All standard deviation values (\pm) were recorded beside each concentration and showed variation in the seven tested samples as RAD7 depends on the Poisson distribution used to calculate the standard deviation [8]. The mechanism of transferring samples (aerating, type of water flow, travel time, and time of storage) is one of the critical reasons affecting the measured results [14, 15]. These factors are the controlling variables affecting the radioactivity of the ^{222}Rn isotope. The standard deviation and the standard error in the tested samples are all accepted. All the physical and chemical properties of the tested water samples lie within the normal range, such as pH (6.5–8); biological oxygen demand (BOD), 3–6 mg/L; chemical oxygen demand (COD), 30–34 mg/L.

Radon concentration in the tested groundwater samples (Zamzam water and the other six water samples collected from different areas within the Kingdom of Saudi Arabia) has been measured using RAD7-detector. Table 1 represents the radon concentration levels and their annual effective dose.

Table 1 summarized the specified experimental conditions (temperature (°C), relative humidity (RH%), and the duration time for measurement of ^{222}Rn concentration in the seven tested water samples):

It can be seen from Table 1 that the radon activity concentrations are in of 0.43 ± 0.06 to 0.57 ± 0.060 Bq/L with an average value of 0.504 ± 0.06563 Bq/L which is below the average value of 11.1 Bq/L set by the US Environmental Protection Agency (EPA) for drinking and bathing

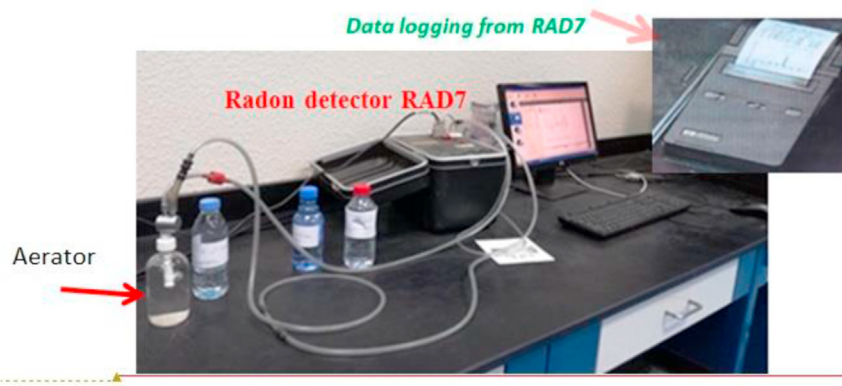


Figure 3. The overview of the experimental setup of water sample connection to RAD7 detector [current study].

Table 1. Temperature (T °C), relative humidity (RH%), and duration time of the tested water samples; collection areas [14]; and the statistical analysis of the measured ²²²Rn level concentration in the tested samples.

Sample	T(°C)	(RH%)	Duration time (d:h:min.)	Location area	Depth (m), Google map	²²² Rn concentration Bq/L	
S1	28.5	35.7	0:3:43	600	26° 25' 33.6" N 43° 52' 07.4" E	0.430	
S2	28.5	38.5	0:4:9	500	26° 17' 04.6" N 43° 50' 42.9" E	0.514	
S3	28.6	34.9	2:0:15	500	25° 57' 40.8" N 49° 29' 63.9" E	0.593	
S4	27.2	41.5	1:21:1	350	27° 34' 24.8" N 42° 08' 52.6" E	0.430	
S5	24.8	52.7	0:22:24	250	41° 39' 57.6" N 27° 31' 07.6" E	0.503	
S6	24.7	52.1	1:5:41	80	26° 30' 06.2" N 43° 43' 21.7" E	0.582	
S7 (Zamzam water)	24	53	1:0:20	30	21° 23' 24.5" N 39° 49' 22.1" E	0.582	
Mean	Sd±	Se±	Min.	(Max.)	Range	Sum	n
0.504	0.06563	0.0248	0.43	0.593	0.163	3.528	7

water. Notably, Radon concentrations measured in different areas within the Kingdom of Saudi Arabia along with Zamzam water were lower than those harmful to human health.

Table 1 that contained all the experimental results in this study also revealed that the activity concentration of ²²²Rn in each water sample is controlled by the combined effect of temperature, and relative humidity that affects the duration time taken by the sample to reach the steady-state equilibrium for recording ²²²Rn by the detector. The other controlling factors affect the concentration of ²²²Rn in water sample are other water pollutants, such as total dissolved solids, total suspended solids, heavy metals (e.g., Zn(II), Fe(II), Hg(II), etc.), organic matter, total hydrocarbons, anions (e.g., sulfate, nitrate, phosphate), total alkalinity, and nutrients [6].

The ²²²Rn level in the tested water samples was measured in terms of Bq unit, the number of disintegrations of radionuclides per second, where (1 Bq = 1 disintegration/sec.) [15]. It was found that the highest concentration of ²²²Rn was in sample S3, where the recorded value was (0.593 Bq/L). The lowest values found in the samples: S1 and S4 (0.430) brought from the El-Qassim region. While the Zamzam water sample has a moderate concentration level of ²²²Rn (0.476 Bq/L) between measured the samples.

The groundwater at different locations absorbs different amounts of radioactive ²²²Rn isotope when passing on the rock layers and soil. When water flow or temperature is elevated, ²²²Rn escape. The solubility of

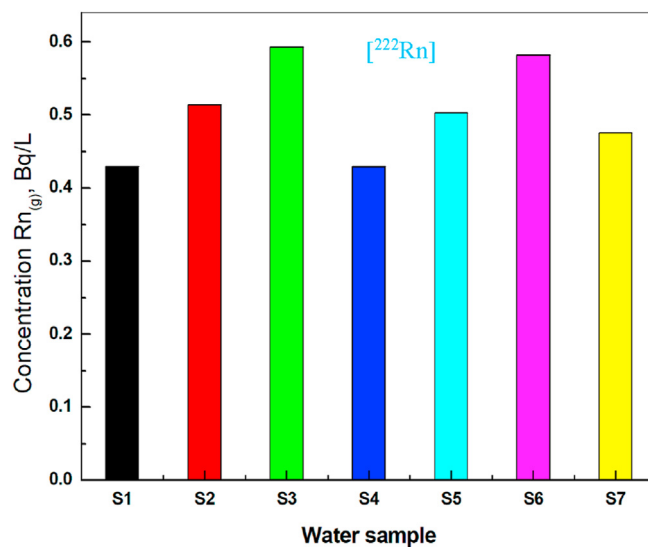


Figure 4. Histogram of ²²²Rn concentration in the various collected water samples.

Table 2. The average ^{222}Rn concentration in water for some countries [1] compared to the average value in the current study.

Country	^{222}Rn -concentration (Bq/L)
Iraq	1.133
Turkey	0.091
Kuwait	0.74
Syria	13
Iran	0.21
Jordan	3.9
Khartoum	14.13
Algeria	7
Brazil	0.95
Italy	1.8
The average value of ^{222}Rn concentration in the Saudi Arabia Kingdom (current study)	0.504

Table 3. Varimax rotated component loading matrix for average water analysis parameters.

Parameters	Component	
	PC1	PC2
RH%	-0.987	0.041
T	0.984	-0.108
Depth	0.943	-0.283
Duration time	0.044	0.904
C of Rn	-0.400	0.653
Eigenvalues	3.209	1.122
Variance%	64.172	22.444
Cumulative variance (CV%)	64.172	86.617

^{222}Rn at the atmospheric conditions follows Henry-law, where it is an exothermic process enhanced by lowering the temperature. Hence, the concentration of ^{222}Rn depends mainly on the following two factors: Geology characteristics of water resource, and the handling of groundwater (immediately or after a storage period). The water storage decreased the concentration of ^{222}Rn and there are various recommended permissible levels of ^{222}Rn in the drinking water [9].

Figure 4 showed histogram showing the comparative concentration of ^{222}Rn in the six tested samples in addition to the sample of Zamzam water (sample 7):

The trend of ^{222}Rn concentration [^{222}Rn] in the tested water samples follows the order: S3 (Riyadh from the wells of Hafr Al-Aish) > S6 (north Buraidah) > S2 (Al-Basra Governorate located to the west of Buraidah) > S5 (Hail region) > S7 (the sample of the King Abdullah project to Zamzam water) > S1 (north Buraidah) = S4 (Hail region).

All the studied regions have permissible concentrations of ^{222}Rn radioactive isotope, which referred to a low risk of lung cancer caused by ^{222}Rn in the Saudi Arabia Kingdom.

The statistical computer program (Micro-calculation origin, version 6) was used to investigate the statistical parameters of the concentration of ^{222}Rn in the seven water samples ($n = 7$), the mean, standard deviation ($Sd \pm$), standard error ($Se \pm$), minimum (min.), maximum (max.), and the range were calculated [15].

The results of the current study were compared to the recently reported ^{222}Rn levels in other countries. Table 2 contains the average of ^{222}Rn concentration in water samples from eleven countries: Newney-Iraq, Turkey, Kuwait, Syria, Iran, Jordan, Khartoum, Algeria, Brazil, and Italy, compared to the current study. The seven tested water samples gave the average concentration level of ^{222}Rn of 0.504 Bq/L.

A literature survey for the reported mean value of ^{222}Rn concentrations [16, 17, 18] showed that Tuyyeb et al. reported 4.69 Bq/L in Jeddah water (Saudi Arabia); El-Taher et al. reported 2.80 Bq/L in groundwater from Qassim Area, Saudi Arabia; and Garba et al. reported 7.30 Bq/L in groundwater from Zaria, Nigeria. The average value of ^{222}Rn concentration obtained in our current study was less than that reported in Iraq but more than that reported in Turkey, as shown in Table 2. As we mentioned earlier, the geological nature of the collection area affects the concentration of ^{222}Rn that differ according to the locations of the collected sample.

The concentration of ^{222}Rn radioactive isotope in different countries follows the order:

Khartoum > Syria > Algeria > Jordan, Italy > Iraq > Brazil > Kuwait > Zamzam water > Iran > Turkey.

The highest reported concentrations of ^{222}Rn in Khartoum (14.13 Bq/L) and Syria (13 Bq/L) is higher than the maximum permissible value (11.11 Bq.L^{-1}) recommended by US-EPA.

The factors that affect irradiative emission from ^{222}Rn radioactive isotope are the energy of neutrons, neutron flux, characteristics of water samples, water contaminants, and pH of water samples. All the other contaminants of water samples collected from different countries such as heavy metal ions, organic matter, biological activity, etc. affect the half-lives of the radioactive isotope, ^{222}Rn [1].

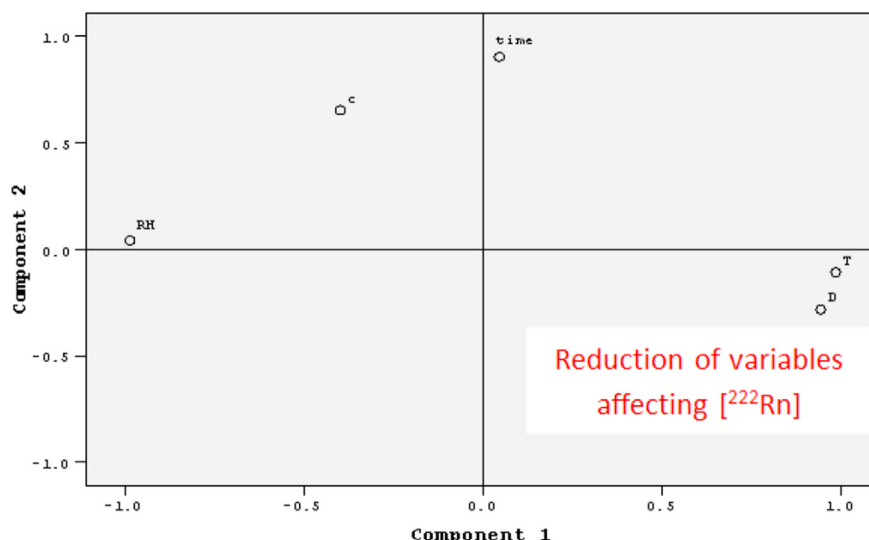


Figure 5. The principle analysis component plot in rotated space for the parameters affecting ^{222}Rn concentration in water samples.

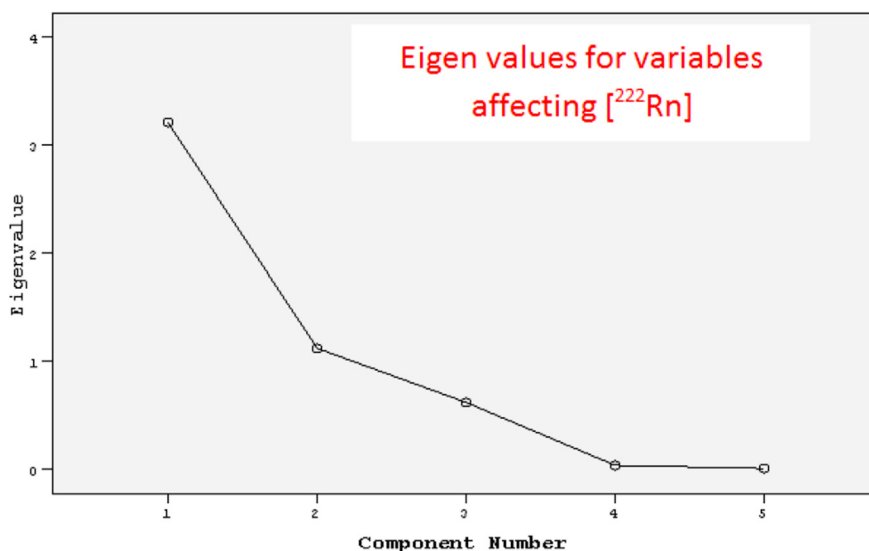


Figure 6. The variation of the Eigenvalues and the component number of average water parameters.

Table 4. Correlation matrix between the water parameters.

Parameters	T	RH	time	C	D
T	1.000				
RH%	-0.987	1.000			
Time	-0.103	0.038	1.000		
C	-0.393	0.360	0.301	1.000	
D	0.957	-0.934	-0.240	-0.513	1.000

The bold value shows strong correlation coefficient (R2) between any two different variables.

Fifty percent of the produced radioisotopes live longer than 25 min are dangerous to human health. The decay schemes of many radioactive isotopes showed that ²²²Rn isotope occupies an intermediate place in the radioactive series.

Different locations for the drinking water samples showed different concentrations of ²²²Rn radioactive isotope due to the different physical and chemical characteristics of these locations that affect the residence time of the radioactive pollutants and the transfer rate of these pollutants in the human body.

The novelty of the results obtained in the current study is that it is a commentary to the recent studies about radioactivity in Saudi Arabia Kingdom [19, 20, 21, 22, 23]. Where the building imparted some radiation dose to the human beings [21]; the average value of ²²²Rn

obtained in our current study agrees with that reported by Al-Ghamdi et al. [24].

3.1. Statistical analysis of the obtained results

The statistics of the measured ²²²Rn activity concentration in the analyzed water samples has been carried out following the method reported elsewhere [25]. The application of principal component analysis (PCA) reduces the variables affecting ²²²Rn concentration activity in water samples from four variables (temperature, relative humidity (RH %), the depth of the water sample, location region, and the residence time) into only two variables (Temperature (T) and RH% while preserving the relationships present in the original data. The eigenvalues (the resulting solution of the differential equations) on the four variables were

Two parameteric analysis for the factors affecting ²²²Rn activity concentration

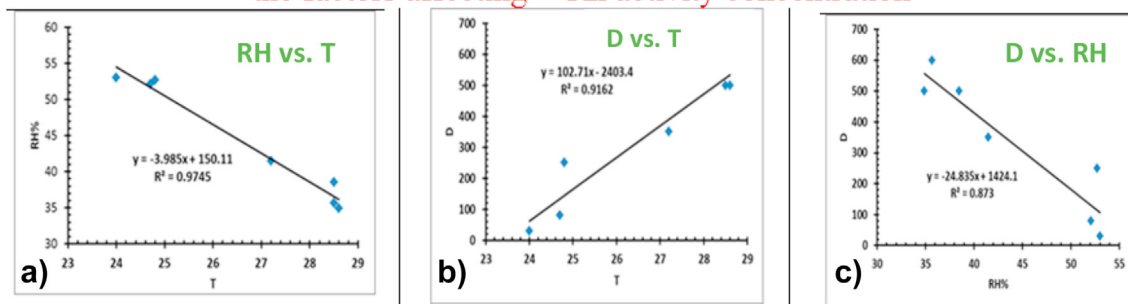


Figure 7. Some of the significant relationships between the studied parameters: a) Relative humidity (RH) versus temperature (T); b) Depth (D) versus temperature; c) Depth (D) versus temperature Relative humidity (RH).

computed for the standardized data using a specialized statistical software package (SPSS version 15). The data contain four variables, as shown in Table 3 and Figures 5 and 6. The eigenvalues obtained from PCA are significant only for (T) and RH%.

Hence the factor extraction was done with a minimum acceptable eigenvalue greater than one. The output data revealed that only two factors (PC1 and PC2) affected ^{222}Rn concentration in water samples with cumulative covariance of 86.617%, Table 3.

The cumulative covariance of the two-component factors is 64.172%, with the variance for PC1 and PC2 of 22.444%, and 21.916, respectively. The eigenvalues of PC1 and PC2 are 3.209 and 1.122. The PC1 represented positive loading for the temperature (0.984), duration time (0.943), while RH% (-0.987) is associated with negative loading. The PC2 represented positive loading for a duration time (0.904).

The correlation matrix between the different variables affecting ^{222}Rn activity concentration in water samples was determined (Table 4), which enabled the interpretation of the correlation of elements affecting ^{222}Rn concentration. The bold numbers indicate a good positive significant correlation in the four water samples and some of the significant relationships are shown in Figure 7. The temperature was significantly correlated with RH% ($r = 0.974$).

The tested PCA analysis for ^{222}Rn activity concentration in the tested water samples is a highly accurate method ($p = 0.0006$).

The tested PCA for the obtained results showed that the most significant factors that affect ^{222}Rn activity concentration are the temperature and RH%. These two factors act by affecting ^{222}Rn solubility in water. While the depth and the location of sample collection are not significant as these two parameters are related to the geology of rocks found in these regions not the solubility of this inert gas in water.

4. Conclusion

In this study, a sample of pure Zamzam water was analyzed in addition to another six water samples obtained from different geological locations in the Saudi Arabia Kingdom. The mean value of the concentration of dissolved ^{222}Rn gas representing radon radioactive isotope was 0.430Bq/L in the Zamzam water sample, which is less than the permissible concentration of ^{222}Rn in water as recommended by the Environmental Protection Agency. The ^{222}Rn level in all water samples collected from different locations in the Kingdom is less than 11 Bq/L: the maximum level of pollution recommended by US-EPA. The most significant variables affecting ^{222}Rn concentration are the temperature and the relative humidity (RH%) of the region of collecting water samples. Where the high level of RH% increases the concentration of ^{222}Rn in water, and the elevated temperature of water samples decreases ^{222}Rn activity concentration in water as the solubility of ^{222}Rn gas is an exothermic process.

Declarations

Author contribution statement

Kaltham B. Aljaloud: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mervette El Batouti: Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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