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ARTICLE

Mapping Radon Concentrations in Aerosols, Water, and Soil in Dhi Qar Governorate Using CR-39 Nuclear Track Detectors

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Abstract: The concentration of Rn-222 was measured in environmental samples from several areas of Dhi Qar Governorate, Iraq, by counting alpha particle tracks in CR-39 nuclear track detectors. The sampling campaign extended over a period of twenty days, during which aerosol, water, and soil samples were systematically collected to ensure temporal consistency and minimize short-term environmental fluctuations. Radon concentrations in aerosol samples from ten regions of the governorate ranged between 90.01 Bq/m³ and 16.21 Bq/m³, with an average concentration of 47.29 Bq/m³. Radon concentrations in ten water samples obtained from rivers, wells, irrigation canals, and ponds ranged between 2.11 and 0.21 Bq/L, with an average value of 1.06 Bq/L. Soil samples from ten regions of Dhi Qar exhibited concentrations between 358.11 Bq/m³ and 104.73 Bq/m³, with an average of 248.56 Bq/m³. The concentrations of radon in aerosols, water, and soil were mapped using a Geographic Information System (GIS). This integration offers a novel and more accurate approach to radon assessment in Iraq, a field rarely studied in a multi-environmental context. By combining ground-based data with GIS, the study delineates spatial variations with higher resolution and provides a comprehensive visualization of radon risk, thereby improving environmental health assessments and establishing a baseline for future research.

Keywords: Environment, Rn-222, Radioactive materials, CR-39, Dhi Qar Governorate.

1. Introduction

Through various mechanisms, radioactive elements move between the air, water, soil, and living things as part of a natural cycle. Their duration and ability to reach people depend on the physical and chemical characteristics of the environments through which they move. For instance, radioactive pollutants travel slowly in surface and groundwater systems but quickly via the atmosphere [1, 2]. On the other hand, because soil is a relatively stable environment, radioactive pollutants may accumulate there over time. Because soil is a long-term storage for radioactive elements and a source of continuous contamination of air, water, and organisms, it is significant in this context [3, 4].

The radioactivity and wide-spreading potential of Rn-222 gas make it dangerous. Furthermore, radon decays with a half-life of 3.83 days into polonium, releasing alpha particles and putting the local population at risk as polonium deposits on buildings and vegetation [5]. Radioactivity is a persistent environmental factor influencing soil, air, and water quality. Radionuclides can also pollute plants and animal feed [6]. Pollution is defined as the presence of a substance at a concentration higher than that permitted by local and international environmental standards, which causes harm to the environment in general and to humans in particular [7–9].

This work focuses on radioactive pollution in the air, water, and soil of Dhi Qar city. Our interest in Dhi Qar city stems from, first, the environmental effects of radioactivity in the city; second, the city's exposure to heavy bombardment during the war; third, the environmental neglect it has suffered; and fourth, its high population density.

With an atomic number of 86, radon is a radioactive noble gas. It is one of the heaviest

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known gases that occur naturally [10]. It was discovered in radium salts by Dorn in 1900. It is colorless and odorless, and enters the atmosphere by molecular diffusion from the soil [11].

Because radon can travel easily through the atmosphere, many people are at risk of exposure. Research shows that when soil porosity is low, particles are tightly packed, making it difficult for released Rn atoms to escape; when particle spacing is greater, they spread to the surface more readily [12, 13].

According to a 1982 UNSCEAR assessment of natural radiation sources, natural radon gas accounts for more than half of the overall radiation dose people receive [14–16]. Exposure to radon-222 (Rn-222) poses a significant public health hazard, with well-documented correlations between inhalation of alpha-emitting radionuclides and increased lung cancer incidence [17]. Upon inhalation, Rn-222-laden air deposits substantial quantities of radioactive isotopes on the epithelial surfaces of the respiratory tract, particularly within bronchial tissues. Epidemiological studies estimate an annual mortality rate of approximately 200 cases per 100,000 individuals attributable solely to background radiation exposure from radon and its decay radionuclides [18, 19].

Nuclear track detection technology has emerged as a critical tool for quantifying radioactive substances because of its accessibility, precision, and operational simplicity. These detectors consist of electrically insulating materials (resistivity: 10^6–10^{20} Ω·cm) that retain microscopic radiation-damage pathways, termed latent tracks, when charged particles penetrate them [20–22].

The aim of this work is to spatially map the radon concentrations in aerosols, water, and soil samples from Dhi Qar Governorate, to assess environmental radon pollution levels and evaluate their compliance with international safety standards.

2. Study Area

Dhi Qar is one of the governorates of the Republic of Iraq. It is a significant historical and cultural area in the southeast of the country, 370 km south of the capital, Baghdad, between latitudes 33.30° and 32° N and longitudes 45.37° and 47.12° E (Fig. 1). It is famous for its location on the Euphrates River, making it a fertile agricultural area. It includes important archaeological sites. It has about 2 million residents, most of whom are Arabs.

FIG. 1. Dhi Qar Governorate is indicated in orange on the map of Iraq.

3. Materials and Methods

A one-month exposure time was chosen for CR-39 detectors, as this duration represents a scientific and practical compromise: it is sufficient to accumulate countable tracks while preventing detector saturation or damage, ensuring accurate results comparable with international standards [23].

GIS data were processed and integrated in ArcGIS 10.8, including preprocessing to standardize coordinate systems and spatial resolutions. The selected resolution depended on the study's objectives [24]. The process involved data collection, preprocessing and correction, dataset integration, and production of maps and tables for analysis. Radon concentration values were interpolated using the Inverse Distance Weighting (IDW) method, chosen for its effectiveness in spatial prediction and its common application in environmental studies [25].

3.1. Calibration Procedure and Uncertainty

Radon concentrations were determined using CR-39 detectors calibrated with standard radon sources. The calibration factor (CF) relating track density to radon concentration was calculated as [26]:

$$C_{Rn} = CF \times D \quad (1)$$

where C_{Rn} is the radon concentration (Bq/L or Bq/m³) and D is the measured track density (track/mm²). The combined uncertainty accounted for counting statistics, source activity (±5%), and environmental factors, resulting in an expanded uncertainty of ±10–15% at a 95% confidence level [27]. Calibration was validated with reference samples, confirming accuracy within the uncertainty range.

3.2. Measuring Radon in Air

For seven days, samples of air aerosols that contain suspended liquid and solid particles were taken with an air extractor set at 2500 rpm and 165 cm in height, the average height of an Iraqi. A seven-day period was selected for collecting airborne particulate matter samples, as this duration is sufficient to represent daily and weekly variations in suspended particle concentrations resulting from human activities and meteorological conditions. It also provides an adequate sample volume for statistical analysis without overloading the filters and is consistent with practices followed in similar studies. The aerosols were collected from various areas of Dhi Qar and sieved using a 75-µm sieve.

Each aerosol sample (20 g) was placed in a tightly sealed plastic cup with the CR-39 nuclear trace detector (1 × 1 cm^2) attached to the inside of the lid with adhesive tape (Fig. 2) and left for one month. Given that the half-lives of Rn-222 and thoron (Rd-220) are 3.8 days and 55 seconds, respectively, and that the emission from the aerosol sample to the detector takes longer than the half-life of thoron, it is ideal for the cup's height to be at least 10 cm [28].

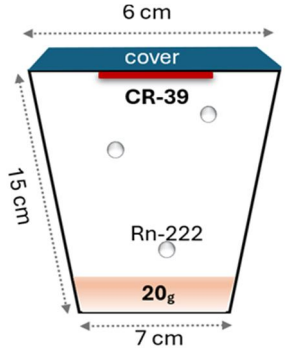

FIG. 2. Radioactivity detection of aerosol samples.

3.3. Measuring Radon in Water

Water samples were collected from several locations in Dhi Qar. For each sample, 0.25 liters of water were placed in a plastic container, as shown in Fig. 3. A CR-39 nuclear trace detector, measuring 2 × 2 cm^2, was attached to the inside of the container lid for a month. Water samples were collected from a depth of 20–30 cm below the surface to avoid surface layers and bottom sediments. The collection time was kept consistent daily (typically between 8:00 and 10:00 a.m.) to ensure homogeneous representation and enable accurate comparison of results.

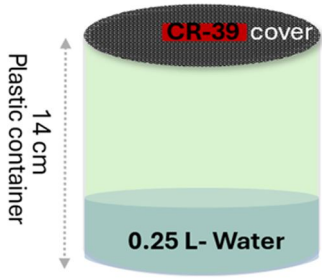

FIG. 3. Radioactivity detection of water samples.

3.4. Measuring Radon in Soil

Soil samples were collected from several locations in Dhi Qar Governorate, then dried and sieved. A sample of 25 g of dried and sieved soil was placed in a plastic cup, and a CR-39 nuclear trace detector (1 × 1 cm^2) was attached to the inside of the cup lid using adhesive tape (Fig. 4). Soil samples were collected from a standard depth of 20–30 cm below the surface, a depth commonly used in field studies for measuring radon exhalation. This depth minimizes the influence of surface fluctuations (such as ventilation and weather conditions) and more

accurately represents the gas concentration within the soil.

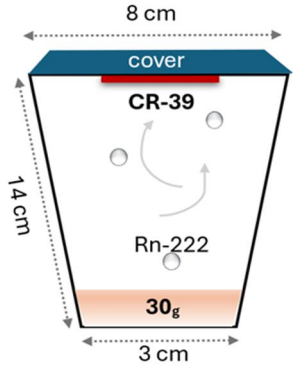

FIG. 4. Radioactivity detection of soil samples.

Correlation Analysis: Radon concentrations in soil and air are generally correlated, as soil serves as the primary source of radon emission into the atmosphere [29]. However, the strength of this correlation is influenced by local factors such as soil type, moisture content, permeability, and ventilation, which can result in relative differences between concentrations measured in the two media [30].

Spatial Analysis: The spatial distribution maps were generated using the Inverse Distance Weighting (IDW) interpolation method [31]. IDW estimates values at unsampled locations as a weighted average of nearby measured points, with closer points having greater influence. While IDW is simple and widely used, its accuracy can be limited in areas with sparse or unevenly distributed sampling points, and it does not account for spatial trends or anisotropy in the data [32].

3.5. Calculating Radon Concentrations

After irradiation, the detector was removed from the container and subjected to chemical scraping with a 6.25 M NaOH solution at 70 °C for four hours. Soil standards with known uranium contents produced by the International Atomic Energy Agency and certified globally were used to calibrate the detector. The trace densities, T_x of each sample and T_s of the standard soil formed on the detector, were determined using an optical microscope [33].

The relationship between the known concentration E_s of the standard sample and the standard trace density T_s for the study samples was plotted in Figs. 5, 6, and 7 for air, water, and soil, respectively. The relationship was linear in each case. The radon concentration E_x of each unknown sample was calculated from this relationship [34, 35]:

$$E_X = \left[\frac{E_S}{T_S}\right] \times T_X = \frac{T_S}{Slope} \quad (2)$$

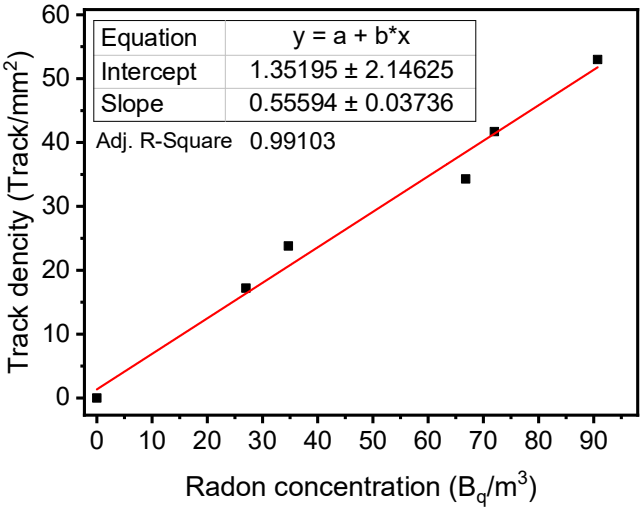

FIG. 5. Track density as a function of radon concentrations in standard air aerosol models.

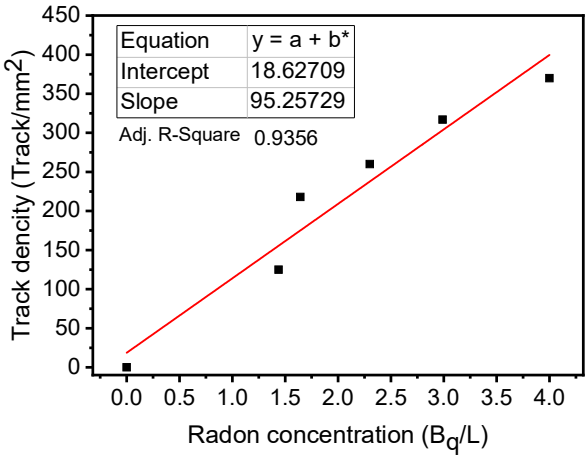

FIG. 6. Track density as a function of radon concentrations in standard water samples.

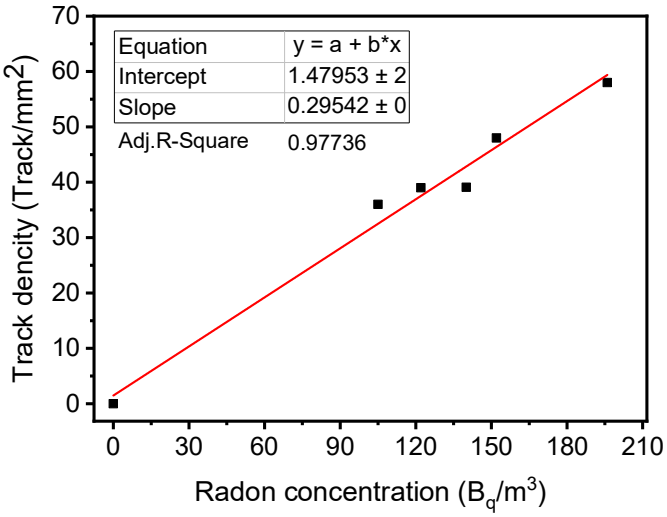

FIG. 7. Track density as a function of radon concentrations in standard soil samples.

4. Results and Discussion

Using CR-39 nuclear track detectors to count the traces of radon-emitted alpha particles, the radon gas concentrations in the samples from several locations in Dhi Qar were ascertained. In Ur District, samples were collected from the following locations: Al-Refai, Qulat Sikar, Al-Shatra, Al-Fajr, Suq-Al-Shuyukh, Al-Fuhud, Al-Nasir, Al-Dwaya, Al-Garraf, and Al-Nasiriyah.

As indicated in Table 1, air aerosol samples were gathered from 10 distinct locations throughout Dhi Qar Governorate. With an average concentration of 47.29 Bq/m^3, the Al-Refai region had the greatest radon concentration in air (90.01 Bq/m^3), while the Nasiriyah (Ur District) region had the lowest concentration (16.21 Bq/m^3).

TABLE 1. Radon concentrations in air aerosols in different areas in Dhi Qar.

Model number	Study area	Track density (track/mm^2)	Radon concentrations (Bq/m^3)
1	AL-Refai	50 ± 13.0	90.01 ± 23.9
2	Qulat Sikar	41 ± 13.0	73.0 ± 23.9
3	AL-Shatra	36 ± 13.0	64.84 ± 23.9
4	AL-Fajr	32 ± 13.0	57.65 ± 23.9
5	Suq-AL-Shuyukh	23 ± 13.0	41.44 ± 23.9
6	AL-Fuhud	21 ± 13.0	37.83 ± 23.9
7	AL- Nasir	20 ± 13.0	36.03 ± 23.9
8	AL- Dwaya	18 ± 13.0	32.42 ± 23.9
9	AL- Garraf	13 ± 13.0	23.42 ± 23.9
10	AL- Nasiriyah (Ur District)	9 ± 13.0	16.21 ± 23.9
Average		26.3 ± 13.0	47.29 ± 23.9

Water samples were systematically collected from multiple sources, including ponds, irrigation canals, wells, and the Tigris and Euphrates rivers, across different regions of Dhi Qar Governorate to evaluate radon contamination. The analysis indicated considerable spatial variation in radon concentrations among the sampling sites. The Al-Refai area recorded the highest concentration, reaching 2.11 Bq/L (0.17 ppm), whereas the lowest level was measured in the Nasiriyah (Ur District) area at 0.21 Bq/L (0.017 ppm). As summarized in Table 2, the overall mean concentration of radon in the examined water samples was 1.06 Bq/L. Although these values remain below the maximum permissible levels recommended by the World Health Organization (0.3996 Bq/L) and the U.S. Environmental Protection Agency (0.148 Bq/L), continuous monitoring is advised.

TABLE 2. Radon concentrations in water in different areas in Dhi Qar.

Model number	Study area	Track density (track/mm^2)	Radon concentrations (Bq/L)
1	AL-Refai	201 ± 65.8	2.11 ± 0.65
2	Qulat Sikar	178 ± 65.8	1.87 ± 0.65
3	AL-Shatra	157 ± 65.8	1.65 ± 0.65
4	AL-Fajr	116 ± 65.8	1.22 ± 0.65
5	Suq-AL-Shuyukh	90 ± 65.8	0.94 ± 0.65
6	AL-Fuhud	88 ± 65.8	0.92 ± 0.65
7	AL- Nasir	68 ± 65.8	0.71 ± 0.65
8	AL- Dwaya	64 ± 65.8	0.67 ± 0.65
9	AL- Garraf	28 ± 65.8	0.29 ± 0.65
10	AL- Nasiriyah (Ur District)	20 ± 65.8	0.21 ± 0.65
Average		101 ± 65.8	1.06 ± 0.65

Samples of soil were collected from several locations throughout the Dhi Qar Governorate. Table 3 shows that the average radon concentration in the soil was 248.56 Bq/m^3, with the greatest concentration in Al-Rifai (358.11 Bq/m^3) and the lowest in Al-Nasiriya (Ur District) (104.73 Bq/m^3). Moreover, the rates of radon pollution in the soil vary from one area to another, as the study areas have different terrains, some of which are agricultural or residential. The differences in soil radon gas concentrations between the study regions could be attributed to underlying bedrock and geological differences. Bedrock type beneath the soil may be the most important factor influencing radon gas concentration [36]. It was discovered that the variety of rocks containing radioactive concentrations influences radon concentration. In most cases, rocks with high ^{226}Ra concentrations produce soils with high radon levels. Bedrock type influences a soil's gas permeability, which determines the migration distance, in addition to its ^{238}U or ^{226}Ra concentrations [37]. While the radon exhalation rate increases as soil porosity increases, the variation in radon exhalation rate values may be related to soil porosity differences [38].

TABLE 3. Radon concentrations in soil in different areas in Dhi Qar.

Model number	Study area	Track density (track/mm^2)	Radon concentrations (Bq/m^3)
1	AL-Refai	106 ± 25.1	358.11 ± 93.1
2	Qulat Sikar	95 ± 25.1	320.95 ± 93.1
3	AL-Shatra	94 ± 25.1	317.57 ± 93.1
4	AL-Fajr	83 ± 25.1	280.41 ± 93.1
5	Suq-AL-Shuyukh	86 ± 25.1	290.54 ± 93.1
6	AL-Fuhud	72 ± 25.1	243.24 ± 93.1
7	AL- Nasir	64 ± 25.1	216.22 ± 93.1
8	AL- Dwaya	62 ± 25.1	209.46 ± 93.1
9	AL- Garraf	43 ± 25.1	145.27 ± 93.1
10	AL- Nasiriyah (Ur District)	31 ± 25.1	104.73 ± 93.1
Average		73.6 ± 25.1	248.56 ± 93.1

TABLE 4. Comparison of the present study results for water and soil samples with previously reported data.

	Country	C_{Rn} (Bq/L)	Reference
Water Samples	Iraq (Anbar)	8.02–11.7	[39]
	Iraq (Waset)	0.11–0.174	[39]
	Iraq (Babylon)	0.117–0.18	[39]
	Iraq (Salahaddin)	0.106–0.153	[39]
	Iraq (Falluja)	0.065–0.195	[40]
	Iraq (Baghdad)	0.144–0.180	[40]
	Iraq (Thi-Qar)	0.21–2.11	Present work
Soil Samples	Iraq (Basrah)	1721–25142	[41]
	Iraq (Anbar)	136.9–176.8	[40]
	Iraq (Waset)	84.26–1123.6	[39]
	Iraq (Babylon)	88–123.4	[39]
	Iraq (Salahaddin)	61.2–99	[39]
	Iraq (Falluja)	205.24–400.5	[21]
	Iraq (Baghdad)	113.82–169.1	[40]
	Iraq (Thi-Qar)	104.73–358.11	Present work

From Table 4, radon concentrations in water samples in the present study (0.21–2.11 Bq/L) are generally higher than those reported in several other Iraqi governorates, such as Wasit (0.11–0.174 Bq/L), Babylon (0.117–0.18 Bq/L), Salahaddin (0.106–0.153 Bq/L), Fallujah (0.065–0.195 Bq/L), and Baghdad (0.144–0.180 Bq/L), but lower than the exceptionally high levels reported in Anbar (8.02–11.7 Bq/L) [39, 40]. The elevated radon levels observed in Thi-Qar water may indicate local contamination sources, including upstream sewage discharge and residual pollutants from military activities during the Gulf War and subsequent conflicts. When compared with international standards, some measured concentrations exceed recommended limits: the US Environmental Protection Agency (0.148 Bq/L), the International Commission on Radiation Protection (0.5994 Bq/L), the World Health Organization (0.3996 Bq/L), and the US National Council on Radiation Protection (0.296 Bq/L) [41]. This suggests potential health risks for local populations relying on these water sources.

Similarly, radon concentrations in soil samples from Thi-Qar (104.73–358.11 Bq/m³) are higher than those reported in Salahaddin (61.2–99 Bq/m³) and Babylon (88–123.4 Bq/m³) [39] but lower than the extremely high values observed in Basrah (1,721–25,142 Bq/m³) [42]. These variations highlight the significant spatial heterogeneity of radon levels across Iraq, influenced by geological formations, soil composition, and human activities [42]. The relatively elevated soil radon in Thi-Qar may contribute to higher radon concentrations in water through leaching and infiltration. Overall, these findings underscore the importance of continuous monitoring and the implementation of mitigation strategies, particularly in areas where water radon levels exceed internationally recognized safety thresholds [43].

Nevertheless, the study has several limitations. Measurements were performed during a single season, and seasonal fluctuations in temperature, precipitation, and groundwater dynamics may affect radon concentrations in both water and soil [44]. Furthermore, the relatively small sample size may limit the representativeness of the results for the entire governorate. Future investigations with larger, seasonally distributed samples would allow a more comprehensive evaluation of radon exposure risks and provide stronger guidance for effective mitigation strategies [45].

Radium-222 activity distribution maps were generated for the three types of environmental samples collected within the study area through the application of geographic information system (GIS) techniques. These spatial maps provide a clear visualization of the variability in radionuclide activity across different locations and enable the identification of potential hotspots of elevated concentrations. Figs. 8, 9, and 10 illustrate results for aerosols, water, and soil, respectively, highlighting spatial patterns critical for assessing environmental safety and compliance with radiological standards.

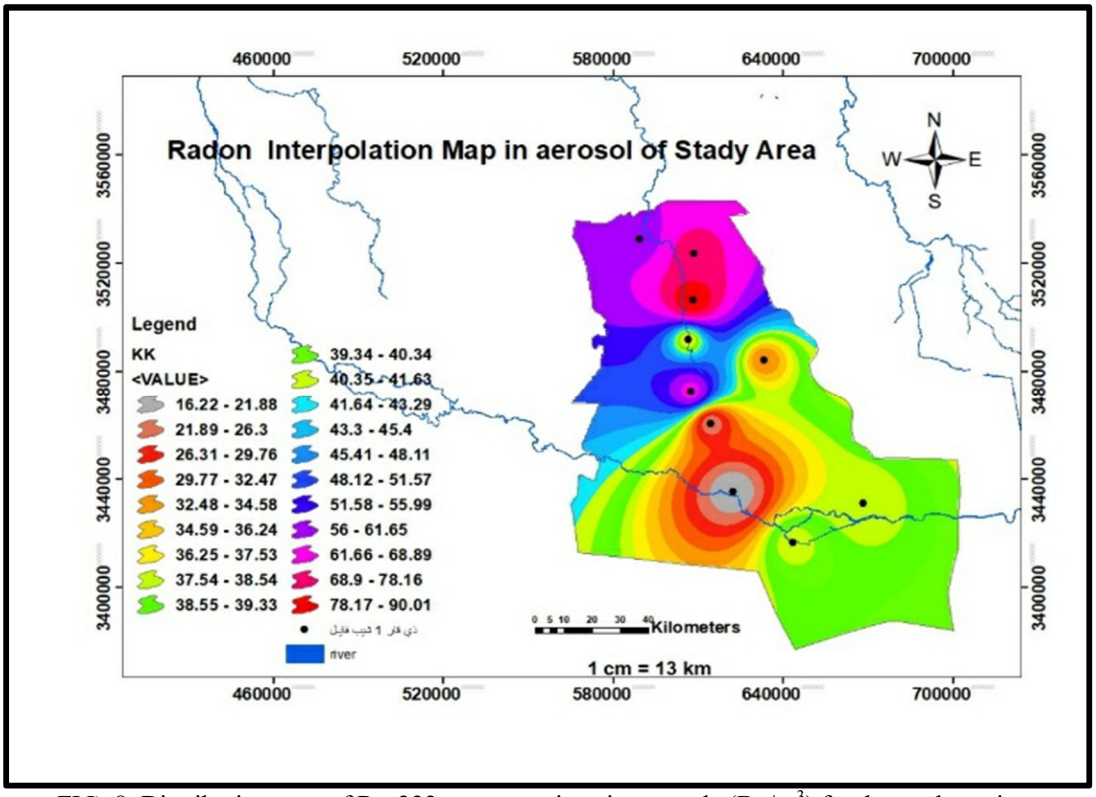

FIG. 8. Distribution map of Rn-222 concentrations in aerosols (Bq/m^3) for the study region.

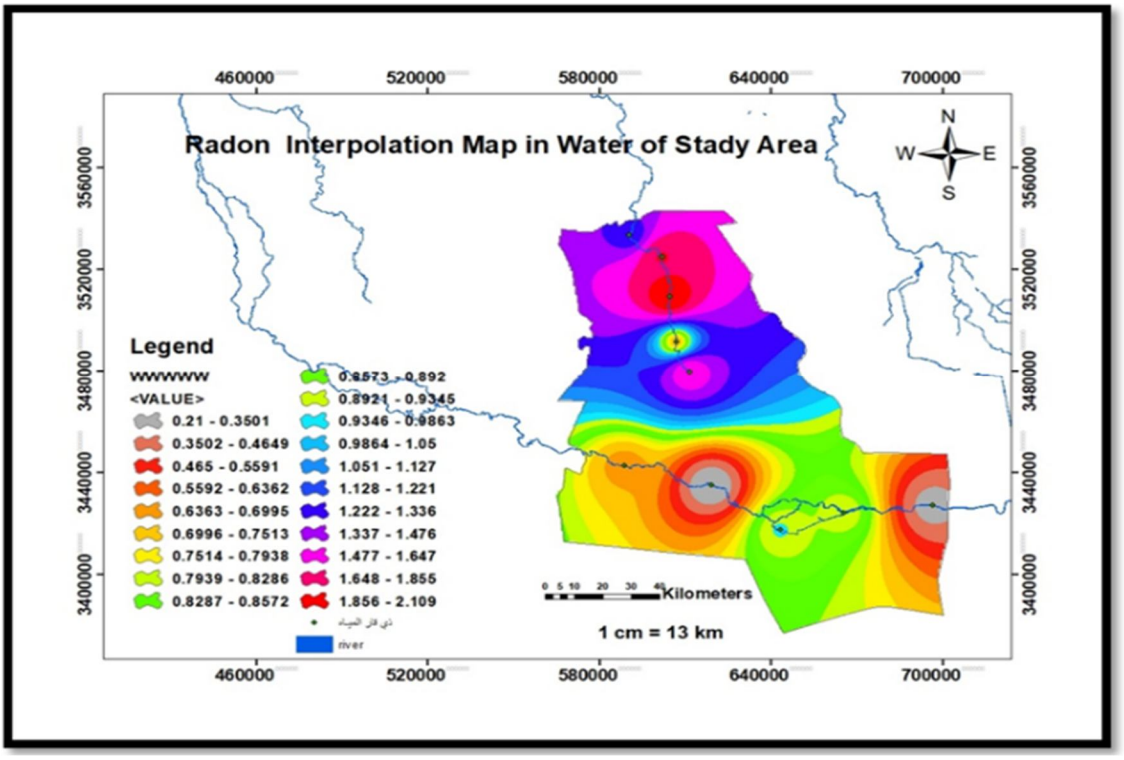

FIG. 9. Distribution map of Rn-222 concentrations in water (Bq/L) for the study region.

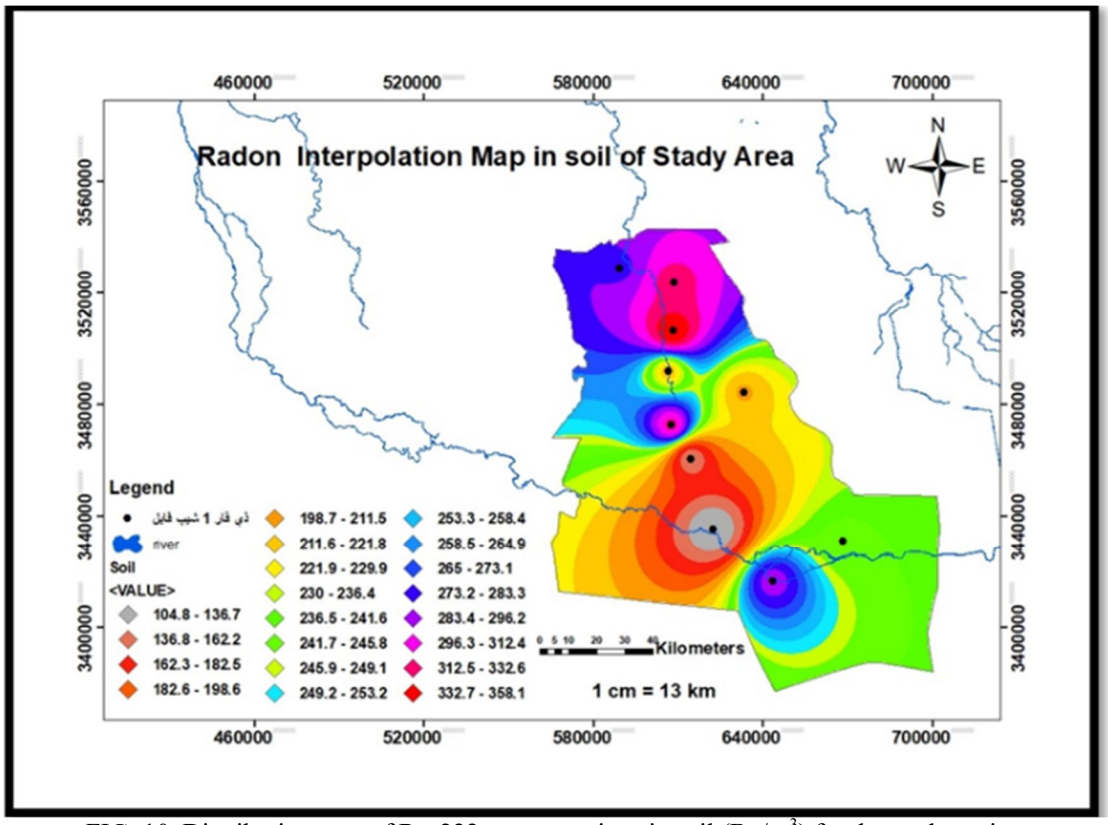

FIG. 10. Distribution map of Rn-222 concentrations in soil (Bq/m^3) for the study region.

5. Conclusions

Extensive studies were conducted in Dhi Qar Governorate to assess the geographical distribution of natural radioactivity levels of radon in airborne particles, water, and soil. The results revealed that radon concentrations in aerosols for all samples were below the global average and did not exceed the permissible limits set by international bodies such as the International Commission on Radiological Protection (ICRP) and the World Health Organization (WHO). In contrast, water samples recorded levels above normal limits, indicating a significant radioactive risk to the population, particularly in areas showing rising pollution indicators, thus requiring urgent water treatment, such as in Al-Refal and other affected localities.

Soil radon concentrations varied considerably; some regions showed high and potentially hazardous levels, while others remained within safe limits. The attached maps provide a preliminary visualization of the spatial distribution of radon concentrations and represent an initial step toward developing a comprehensive radon risk map for Dhi Qar Governorate. This mapping incorporates spatial analysis of radon gas levels along with geological factors such as soil permeability and rock composition, which influence radon accumulation.

Recommendations and Future Work:

- Urgently treat water sources in areas exceeding radon limits, prioritizing high-risk zones.
- Conduct seasonal monitoring to capture temporal variations in radon levels.
- Expand sampling to increase coverage and representativeness across the governorate.
- Assess health impacts by linking radon levels with local epidemiological data.
- Align findings with international guidelines (ICRP, WHO, EPA) to inform policy and enhance public health protection.

These actions will strengthen local safety measures and support broader environmental health management.

Author Contribution Statement

Imad Hameed Ahmed was solely responsible for all aspects of this study, including the conceptualization and design, development of the methodology, execution of the experimental work, data collection and analysis, as well as the

writing, review, and final approval of the manuscript.

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Data Availability Statement

Some or all data that support the findings of this study are available from the corresponding author upon reasonable request.

Statements and Declarations

This manuscript presents a comprehensive analysis of radon concentration mapping in aerosols, water, and soil across Dhi Qar Governorate using CR-39 nuclear track detectors.

Competing interests

The author declares no conflict of interest.

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