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The effect of climatic elements on the spatial and temporal variation of radon gas concentrations in Maytham Al-Tammar district, Al-Kufa city, Iraq

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Abstract

Radon gas (^{222}Rn) is a naturally occurring radioactive noble gas that is predominantly generated as a decay product of the radioactive decay of radium-226 in the uranium-238 decay series. Radon can move through the soil and enter homes. The amount of radon in indoor air can vary a lot depending on the environment, weather and the building. The present study aimed to study the spatial and temporal variation of indoor radon concentrations and to investigate their relationship with indoor temperature in Maytham Al-Tammar District, Al-Kufa City, Najaf Governorate, Iraq. A random sample of fifty residential houses was selected as sampling locations to provide representative spatial coverage of the study area. Indoor radon and temperature were measured with an Airthings Wave Plus Radon and Indoor Air Quality Monitor (Model 2930). Measurements were grouped by the six months studied from January to June. The geographical locations of the selected houses were incorporated into a Geographic Information System (GIS) to facilitate spatial representation and interpretation of the measurements. Results indicate a significant temporal variation of the two variables under consideration. The mean indoor temperature increased progressively from 20.0 °C in January to 22.0 °C in February, 25.1 °C in March, 29.0 °C in April, 33.0 °C in May and 41.0 °C in June. Conversely, the mean radon concentration decreased from 90.0 Bq/m³ in January to 82.0 Bq/m³ in February, 70.5 Bq/m³ in March, 59.0 Bq/m³ in April, 45.0 Bq/m³ in May and 25.2 Bq/m³ in June. In addition, the single measurements showed a high spatial variability among the 50 houses, suggesting that the response of radon to changing climatic conditions may be modulated by house characteristics. Overall, the results show a clear inverse temporal relationship between indoor temperature and radon concentration over the study period. The rise in temperature was accompanied by a sharp decrease in radon levels, suggesting that temperature and the associated change in ventilation and air exchange may influence the observed seasonal behavior. However, the spatial differences between the houses studied suggest that temperature should not be considered as the sole controlling factor. Other local environmental factors such as building characteristics, ventilation conditions, soil properties and pressure differences may also affect indoor radon accumulation. Thus, the study emphasizes the need to consider climatic, environmental and building-related factors in the assessment of the spatial and temporal distribution of indoor radon in residential areas.

Keywords: Radon gas, ^{222}Rn , indoor air, temperature, climatic elements, spatial variation, temporal variation, GIS, Maytham Al-Tammar, Al-Kufa

1. Introduction

Radon (^{222}Rn) is a naturally occurring radioactive noble gas, resulting predominantly from the radioactive decay of radium-226 (^{226}Ra) in the uranium-238 (^{238}U) decay chain. It is able to travel through the pores of the soil and reach the near-surface atmosphere, where its concentration is governed by the interaction of geological, soil, atmospheric, and climatic conditions. Long-term exposure to high concentrations of radon is of considerable environmental and public health importance because it has been linked to an increased risk of lung cancer ^[1]. While the presence and release of radon are closely related to the radioactive and physical properties of soil and geological materials, the movement and atmospheric concentration of radon are strongly influenced by climatic elements. Temperature, atmospheric pressure, relative humidity, precipitation, wind speed and wind direction can affect radon exhalation from soil, atmospheric dispersion and near-surface accumulation ^[2].

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Thus, radon concentrations can be highly variable in space and time even in relatively small geographical areas. The air temperature is an important factor in determining the radon behavior since changes in the temperature of soil and air can alter the movement of gas, the stability of the atmosphere and the vertical mixing. Variations in near-surface radon concentrations can arise from daily heating and cooling at night^[3]. The atmospheric pressure might also be one of the factors influencing the migration of soil gas and radon transport from the subsurface to the atmosphere, especially when pressure variations are developed over a short period of time^[2, 4]. Precipitation and soil moisture are other controls on radon transport. Soil moisture variations can change the permeability of soils as well as the movement of gasses through pore spaces. Rain can affect the physical and moisture conditions of the near-surface soil. The relation between moisture and radon is complicated and depends on the nature of the soil and the amount of water present^[2]. Wind speed and atmospheric stability are also very important factors in the dispersion of radon. Weak winds and stable atmospheric conditions may cause accumulation near the surface, while stronger winds improve atmospheric mixing and dispersion^[4, 5]. Differences in the properties of the soil, land use, surface cover, building density and urban structure also affect the spatial distribution of radon. In cities, roads, buildings, paved surfaces and soil compaction can affect the natural exchange of natural gas between the soil and the atmosphere. Also, meteorological conditions can interact with these urban characteristics and lead to local variations in radon concentrations^[6]. The temporal behavior of radon is therefore closely associated with the diurnal and seasonal variations of climatic conditions. Fluctuations in temperature, pressure, humidity, precipitation and wind patterns can lead to hourly, daily and seasonal variations in radon levels^[3, 5]. Moreover, the possible effect of climate change on environmental radioactivity has recently attracted increasing attention, particularly via changes in temperature, precipitation, soil moisture and atmospheric circulation^[7]. In this context, Maytham Al-Tammar District in Al-Kufa City offers a good local location to study the correlation between climatic factors and radon fluctuations. The present study aims to analyze the spatial and temporal variation of radon concentrations and their relation with the main climatic elements, especially temperature, atmospheric pressure, relative humidity, precipitation and wind characteristics. A clearer climatological interpretation of the radon behavior and contributions to the environmental assessment and the future monitoring of natural radioactivity in the study area can be obtained from the understanding of these relationships.

2. Study Area

The district of Maytham al-Tammar is located in the city of al-Kufa in the province of Najaf in central Iraq. The study area is a part of Al-Kufa City as a broader geographical setting of the study area which is a part of the Najaf Governorate. The fact that it is situated on the Euphrates River system provides a very important environmental and climatic setting for the study of the spatial and temporal variation of radon gas concentrations. District is predominantly urban land-use, with residential buildings, streets, paved areas and areas with different surface and soil characteristics. The geographical location of the study area is presented progressively in Figure (1), starting from the

location of Iraq in the regional setting, then Najaf Governorate, Al-Kufa City and finally Maytham Al-Tammar District. The detailed map of the district showing the distribution of the 50 selected residential houses, used for radon measurements. The sampling locations were distributed in different parts of the district to ensure a spatial representation of radon concentrations and to facilitate the analysis of their relation with local climatic conditions. The location and distribution of the sampling sites are especially important because radon concentrations may vary spatially with variations in soil properties, surface conditions, building characteristics, ventilation and local atmospheric circulation. The spatial distribution of the 50 houses is suitable for the investigation of the geographical variation of radon in the district and for the comparison of the measured concentrations with climatic elements such as air temperature, relative humidity, atmospheric pressure, wind speed, wind direction and precipitation. The study area map was prepared using a Geographic Information System (GIS) for spatial analysis, so as to ensure that the sampled houses were accurately represented and spatially distributed within Maytham Al-Tammar District. The GIS approach is an effective instrument for visualizing the geographical pattern of radon concentrations and for delineating zones of relatively high and low concentrations. Furthermore, it allows the combination of radon measurements with climatic and environmental variables, thus enabling a more comprehensive interpretation of the spatial and temporal behavior of radon in the study area.

3. Field Measurements and Experimental Procedure

The practical part of this study was conducted to investigate the spatial and temporal variation of indoor radon concentrations and their relationship with the temperature in Maytham Al-Tammar District, Al-Kufa City, Najaf Governorate, Iraq. Fifty (50) residential houses were selected as the sampling points and spatially distributed to have a representative coverage for the district. All the selected houses were geolocated and imported in a Geographic Information System (GIS). Each house was assigned a unique ID from 1 to 50. The Airthings Wave Plus Radon and Indoor Air Quality Monitor (Model 2930) was used to measure indoor radon concentrations and temperature. The device was installed inside each selected home under normal residential conditions and operated continuously throughout the monitoring period specified. The instrument was located indoors, away from direct sunlight, heating and cooling sources, windows, doors, and areas of high air movement to ensure consistency between sampling locations. All houses were kept as similar as possible concerning installation conditions. The measurements were grouped according to the months of the study period to investigate the temporal variation of temperature and radon concentrations. The instrument continuously logged indoor environmental conditions, in particular temperature, and at the same time radon concentrations were measured. Temperature measurements were expressed in degrees Celsius (°C) and radon concentrations in becquerels per cubic meter (Bq/m³). The observations from each house were grouped by month, to allow temporal comparisons of the measurements over the duration of the study. The recorded measurements were related to the geographical coordinates and the house identification number of each sampling location. The

monthly data were assembled into a structured database containing the location of each house, month of monitoring, temperature observations, and radon measurements. This process created a homogenous data set to investigate spatial inequities across 50 houses and temporal differences month on month. In the practical work, the GIS part was used to show the geographical distribution of the 50 residential sampling sites in Maytham Al-Tammar district. The spatial database was built in a way that the radon and temperature observations can be later associated with their respective locations. With such an approach, it is possible to obtain a suitable framework for the production of maps of spatial distribution and for the study of the geographical pattern of

radon concentration during the different months of monitoring. A monthly monitoring procedure was specifically established to characterize the thermal variability of the study area and to provide a temporal framework for the evaluation of radon behavior under different thermal conditions. The field measurements thus provided a combined spatial and temporal data set of 50 residential locations, which was subsequently used for the statistical analysis, graphical representation and interpretation of the relationship between temperature and radon concentration presented separately in the Results and Discussion section. [12-8].

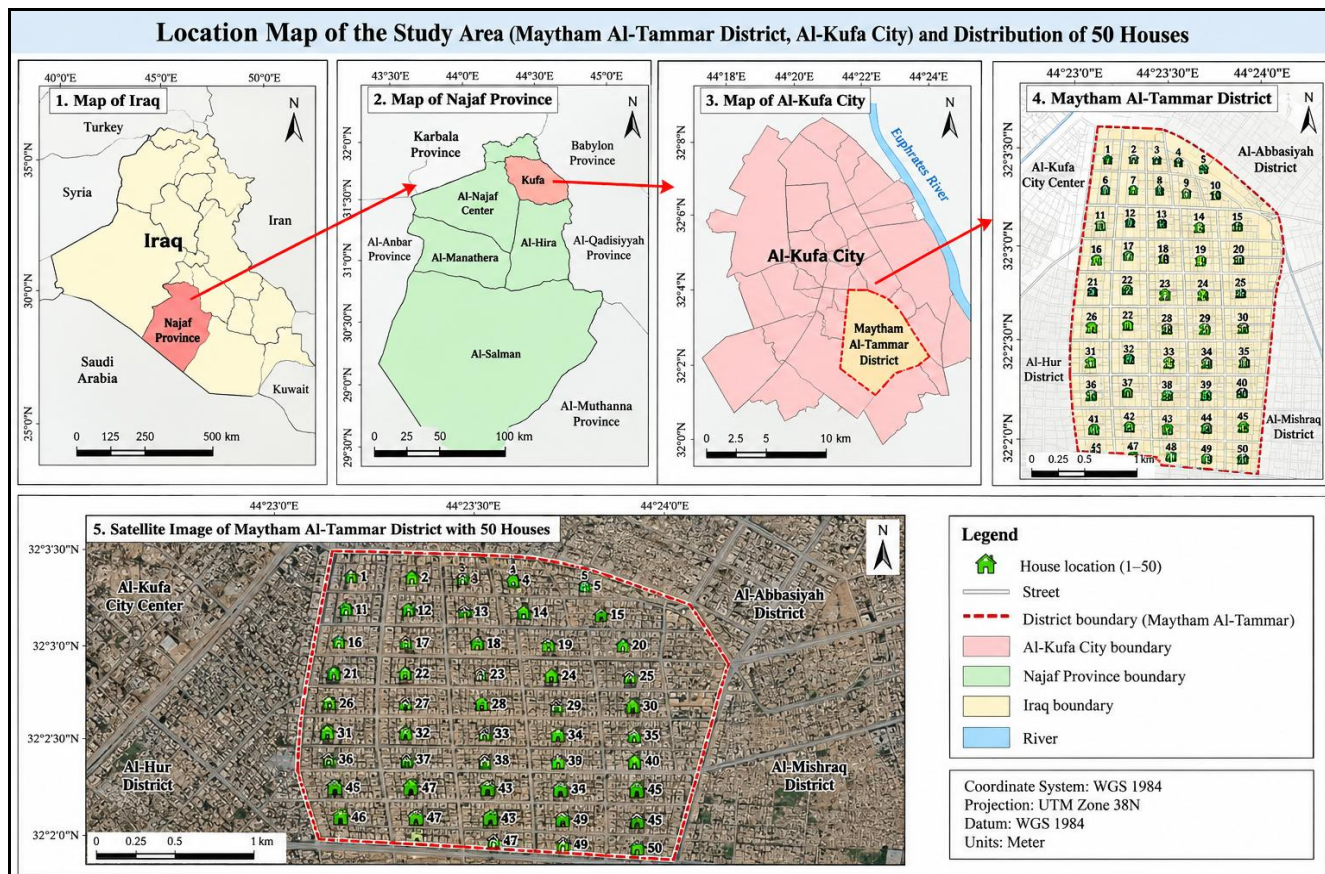


Fig 1: Location of the study area and spatial distribution of the 50 selected houses in Maytham Al-Tammar District, Al-Kufa City, Najaf Governorate, Iraq.



Fig 2: Airthings Wave Plus (Model 2930) used for measuring indoor radon concentration and temperature in the selected residential houses of Maytham Al-Tammar District, Al-Kufa City.

4. Results and Discussion

The results from the 50 residential houses investigated showed a clear temporal variation in both the indoor temperature and the radon concentration during the study period. The values measured for each residential house are shown in Table 1 and they are distinguished by a strong spatial variability but also a common temporal pattern for the 6 months under study. In each cell of Table 1 the corresponding indoor temperature (°C) and radon concentration (Bq/m³) are reported. This allows the simultaneous evaluation of the two variables for all the 50 houses. Table 1 shows that the mean indoor temperature gradually increased from 20.0 °C in January to 22.0 °C in February, 25.1 °C in March, 29.0 °C in April, 33.0 °C in May and 41.0 °C in June. In contrast, the average radon concentration decreased from 90.0 Bq/m³ in January to 82.0 Bq/m³ in February, 70.5 Bq/m³ in March, 59.0 Bq/m³ in April, 45.0 Bq/m³ in May and 25.2 Bq/m³ in June. This opposite behavior points to a strong inverse temporal association of indoor temperature and radon concentration throughout the entire monitoring period. Table 1 provides detailed house-by-house observations and further underlines that the 50 homes did not present similar radon concentrations under similar monthly temperature conditions. For example, some houses had relatively high concentrations in January, e.g. House 8 and House 41 with 109 and 106 Bq/m³ respectively, while other houses had much lower values. This spatial variation suggests that temperature may be influencing the general timing, but that radon accumulation may be influenced by other factors related to individual houses. Table 2 gives the monthly averages, which better represent the seasonal behavior. The table shows a steady increase in mean temperature and a steady decrease in mean radon concentration from January to June. The lowest mean temperature was recorded in January with the highest mean radon concentration, while the highest mean temperature was recorded in June with the lowest mean radon concentration. This regular monthly pattern is consistent with the view that the residential setting studied exhibited an inverse seasonal relationship between temperature and indoor radon. This is shown in Table 2, where the average radon level fell from 90.0 Bq/m³ in January to 25.2 Bq/m³ in June. This is a large decrease of the radon concentration during the period of the sharp increase of the indoor temperature. The observed pattern is in general agreement with previous studies reporting seasonal variation of indoor radon concentrations with higher concentrations often during the colder seasons due to less ventilation and increased radon accumulation inside buildings [12-14]. Warmer conditions could change air

exchange and ventilation, which could reduce radon. Warmer times can also allow for more natural ventilation by opening windows and doors, and a rise in temperature can change the relationship between indoor and outdoor pressures and air flows. This allows for faster radon ingress into a building and a reduction of its accumulation inside [15-16]. But this explanation should be seen in relation to other environmental and structural factors, not just temperature. This is supported by the house-to-house differences in Table 1. The amount of radon reduction was different for each of the 50 houses, but the same seasonal pattern was observed in all houses. Such variability might be related to changes in building construction, ventilation characteristics, floor level, foundation properties, soil permeability, cracks or openings and the presence of pathways for radon to enter residential buildings [17-18]. Therefore, temperature should be considered one of the components of a larger system that controls indoor radon behavior. The monthly trend as shown in Table 2 is in line with observations made in other climatic environments such as desert and semi-arid regions where seasonal trends of indoor radon have been related to temperature, ventilation, soil conditions and building characteristics [19]. But other studies have also shown that the seasonal behavior of radon is not the same in all buildings and geographical settings. In some cases local geology, architecture and climate may alter or even reverse the expected seasonal pattern [20]. This underscores the significance of considering Maytham Al-Tammar's accomplishments within the specific climate and housing conditions. To summarize, Tables 1 and 2 show that the houses studied were influenced by spatial heterogeneity and temporal variability of indoor radon concentration. Table 1 shows the differences between the 50 individual residences and Table 2 shows the overall monthly trend. Overall, the interpretation suggests that radon concentrations were generally higher in the cooler months and gradually lower in the warmer months, with the differences between individual houses indicating the additional effect of local residential characteristics. Tables 1 and 2 summarize the results. There is a clear seasonal inverse relationship between indoor temperature and radon concentration in the study area. The mean radon concentration in January was 90.0 Bq/m³ and decreased to 25.2 Bq/m³ in June where the temperature increased from 20.0 ° to 41.0 °C. Therefore, the results obtained emphasize the importance of considering the climatic conditions with the building properties, ventilation and other environmental factors when studying the spatial and temporal distribution of indoor radon in Maytham Al-Tammar District.

Table 1: Monthly Temperature and Radon Concentration for the 50 Residential Houses Each cell is presented as: Temperature (°C)/Radon (Bq/m³).

Houses No.	January	February	March	April	May	June
1	20.0/94	22.4/84	26.3/76	29.1/62	34.1/52	0.6/35
2	19.9/92	22.0/91	23.2/81	28.3/67	32.7/56	39.8/29
3	20.4/72	22.7/81	26.1/57	30.1/58	33.2/38	42.4/24
4	21.2/87	23.1/77	25.6/74	29.5/68	32.9/56	41.4/22
5	17.9/88	19.2/79	23.4/74	27.8/57	29.7/44	39.1/27
6	18.8/96	20.9/83	23.3/68	27.8/56	31.6/41	40.3/25
7	19.5/90	21.6/84	24.9/71	29.0/63	34.6/42	41.6/23
8	19.5/109	21.0/94	25.5/85	29.2/68	33.0/55	41.0/36
9	20.5/83	21.5/76	25.3/61	27.8/55	32.7/35	40.0/26
10	18.3/94	21.1/85	25.4/79	27.5/68	32.6/51	40.6/31
11	21.0/74	23.3/69	26.4/58	28.8/48	32.8/34	41.1/12
12	20.8/86	21.8/80	25.9/71	28.2/53	33.4/47	41.8/25
13	19.7/104	22.1/86	26.1/78	28.6/53	33.1/50	40.2/25
14	20.0/93	22.6/86	26.2/71	30.4/54	33.9/49	42.2/28
15	20.4/102	22.2/92	25.9/77	29.2/60	33.8/58	40.9/30
16	19.0/94	21.9/95	24.1/86	28.4/64	32.5/58	39.5/26
17	20.4/94	22.6/82	25.3/65	29.9/56	33.7/44	41.7/20
18	19.2/90	22.0/82	23.8/64	29.0/66	31.8/41	40.4/26
19	21.7/98	22.6/91	26.3/80	29.7/72	34.2/58	41.3/29
20	19.8/90	21.5/82	24.3/75	29.8/54	33.9/47	41.8/17
21	19.2/79	21.7/70	25.3/62	28.9/52	32.3/31	40.6/22
22	19.6/85	21.6/77	24.3/70	28.0/49	31.9/39	40.5/21
23	21.1/82	23.1/76	26.7/69	29.6/51	34.8/42	42.1/19
24	20.7/90	21.2/98	25.3/80	28.0/65	32.8/47	40.5/25
25	20.2/87	21.7/93	25.7/76	28.1/64	33.5/50	40.9/30
26	19.9/98	21.9/91	25.2/89	28.5/64	32.5/46	40.4/32
27	21.3/96	23.9/77	24.5/68	29.9/62	34.3/51	41.2/33
28	19.6/94	23.4/80	25.3/63	30.3/56	33.4/56	42.1/29
29	19.9/96	21.8/95	24.6/85	28.5/65	33.5/52	40.7/31
30	19.8/91	22.2/83	25.0/67	29.6/71	34.3/47	39.9/24
31	21.5/102	22.8/90	27.6/76	30.1/65	34.5/40	43.7/32
32	18.8/88	21.3/70	25.1/73	29.0/62	32.1/37	42.2/26
33	20.0/87	21.8/86	24.2/61	28.5/58	32.3/44	40.3/29
34	19.2/94	22.1/83	23.7/63	27.3/60	32.6/40	39.2/23
35	19.6/85	22.1/69	25.5/54	30.0/50	32.6/42	41.3/18
36	20.3/104	22.5/86	25.2/72	29.5/63	34.3/62	41.7/28
37	20.1/89	20.6/82	24.5/70	28.6/52	32.6/38	40.8/27
38	19.8/86	21.2/84	24.5/75	27.7/62	33.0/44	39.7/31
39	20.5/89	20.7/86	25.0/77	27.9/60	30.9/53	40.7/28
40	22.3/104	22.2/87	25.9/69	29.8/67	33.0/60	41.8/27
41	20.8/106	22.1/88	24.2/66	29.5/71	32.6/47	40.7/31
42	19.8/90	22.4/84	25.6/71	29.6/61	32.9/48	41.9/25
43	18.2/87	20.4/88	24.5/66	28.7/55	32.6/54	41.7/27
44	20.3/99	21.3/71	25.4/74	30.0/62	33.1/39	41.3/18
45	19.6/73	23.4/69	26.1/62	28.9/45	32.9/28	40.9/14
46	19.9/76	21.4/73	23.9/61	28.3/53	33.1/34	41.1/16
47	20.3/85	22.0/75	25.3/65	30.3/40	33.8/35	42.1/12
48	20.1/82	23.3/74	25.5/65	29.0/50	32.6/44	40.1/17
49	21.2/95	24.3/78	24.6/78	30.2/53	34.0/52	41.6/26
50	20.1/84	21.4/78	25.9/61	29.3/45	33.5/32	40.8/21
Mean	20.0/90.0	22.0/82.0	25.1/70.5	29.0/59.0	33.0/45.0	41.0/25.2

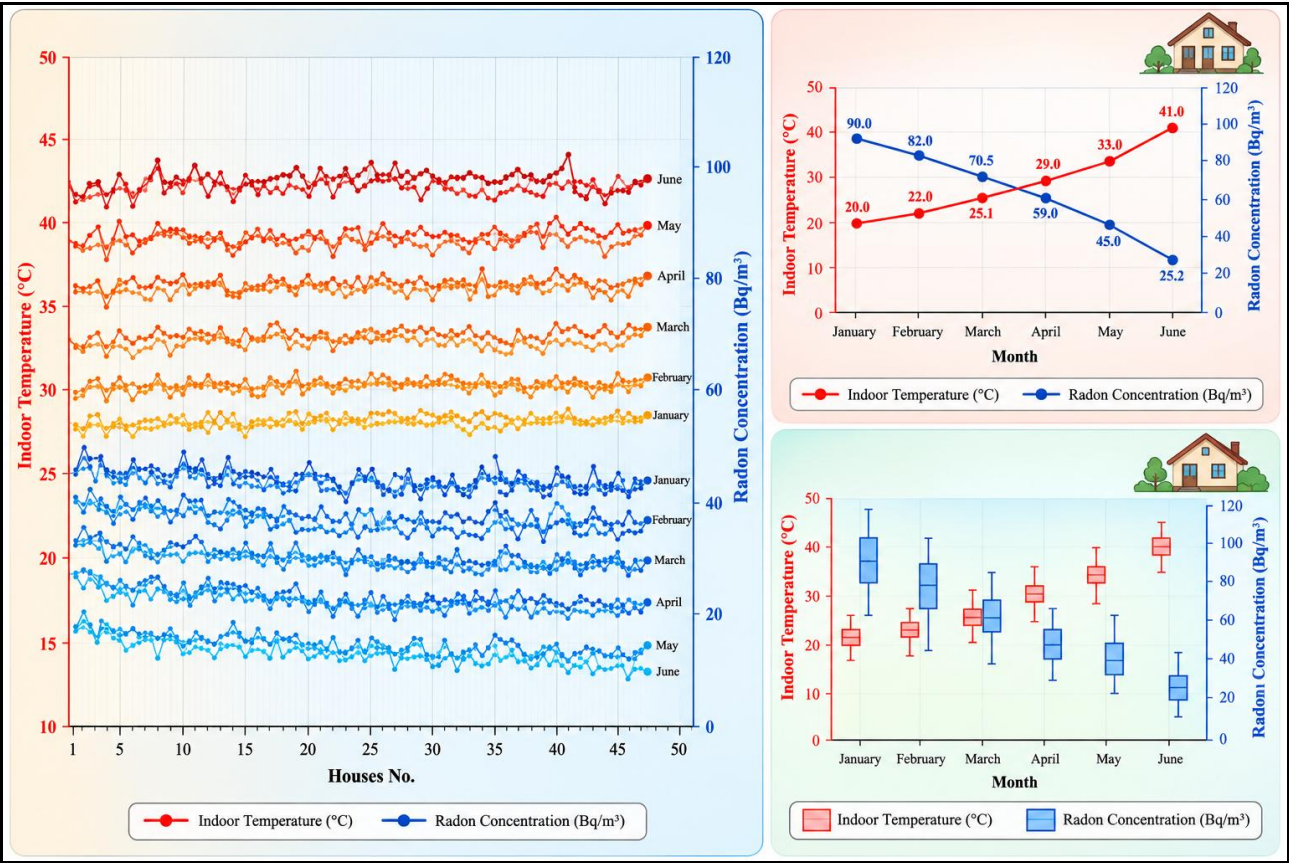


Fig 3: Monthly Variation of Indoor Temperature and Radon Concentration in the 50 Residential Houses in Maytham Al-Tammar District, Al-Kufa City

Table 2: Monthly Mean Variation of Indoor Temperature and Radon Concentrations

Month	Mean Temperature (°C)	Mean Radon (Bq/m³)	Temperature Trend	Radon Trend
January	20.0	90.0	Low	High
February	22.0	82.0	↑	↓
March	25.1	70.5	↑	↓
April	29.0	59.0	↑	↓
May	33.0	45.0	↑	↓
June	41.0	25.2	↑	↓

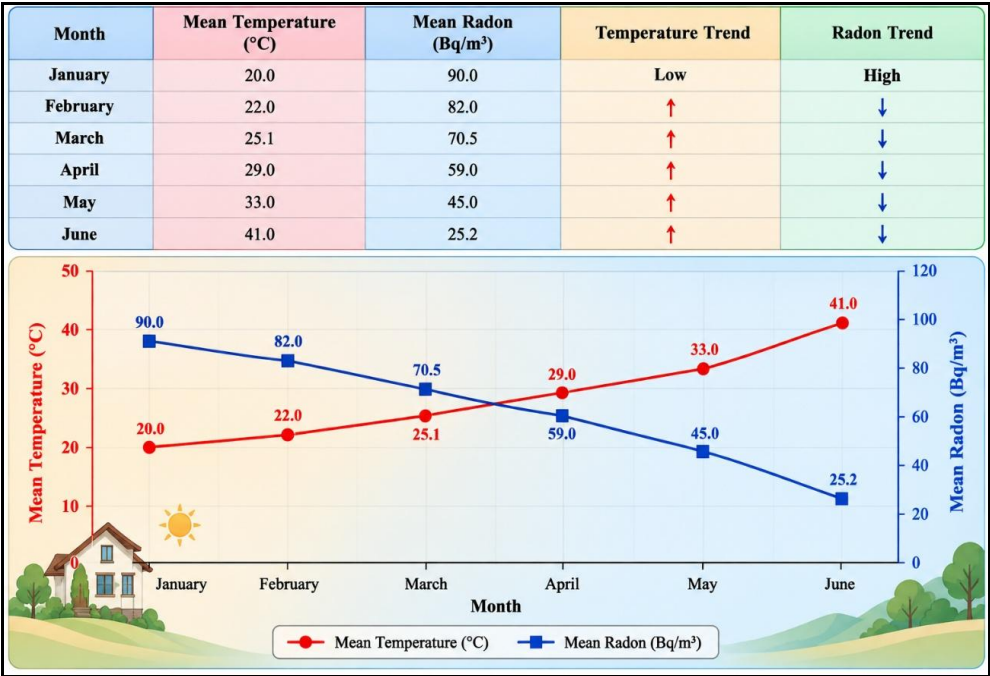


Fig 4: Monthly Mean Variation of Indoor Temperature and Radon Concentration in the 50 Residential Houses

Table 3 presents the monthly variation of the mean indoor temperature and radon concentration measured in the 50 residential houses investigated. The results indicate that the average temperature increased progressively and significantly during the study period, ranging from 20.0 °C in January to 41.0 °C in June. The increase in monthly temperature change from +2.0 °C in February to +8.0 °C in June showed a distinct warming trend toward the end of the observation period. In contrast, the mean radon concentration showed a continuous decreasing pattern, decreasing from 90.0 Bq/m³ in January to 25.2 Bq/m³ in June. The decrease was more and more pronounced during

the warmer months, in June it was −19.8 Bq/m³ compared with the previous month. Thus, the table indicates an apparent inverse temporal pattern between the two variables. The mean radon concentration reduced with the increase in indoor temperature. The overall results show a significant decrease in indoor radon concentrations with the increase in temperature during the season. This pattern indicates that temperature could have a significant role in the temporal variability of indoor radon in the study area. But the table describes only temporal variation and does not in itself establish that temperature is the sole cause of the observed radon changes,

Table 3: Monthly Variation in Mean Temperature and Radon Concentration

Month	Mean Temperature (°C)	Mean Radon (Bq/m ³)	Temperature Change (°C)	Radon Change (Bq/m ³)
January	20.0	90.0	0.0	0.0
February	22.0	82.0	+2.0	−8.0
March	25.1	70.5	+3.1	−11.5
April	29.0	59.0	+3.9	−11.5
May	33.0	45.0	+4.0	−14.0

5. Conclusion

The study has shown that there are clear spatial and temporal variations of the indoor radon concentrations in 50 residential houses in the Maytham Al-Tammar District. During the course of the study a clear inverse relationship was observed between indoor temperature and radon concentration. The temperature gradually increased from the cold to the warm months and radon concentrations decreased. This pattern indicates that climatic conditions, especially temperature, may have a significant impact on indoor radon behavior. The differences observed between individual houses, however, suggest that temperature is not the only controlling factor and that factors such as ventilation, building characteristics, soil conditions, pressure differences and other local environmental factors may also contribute to variations in radon levels. In general, results highlight the relevance of a simultaneous consideration of climatic, environmental and building-related factors in the analysis of the spatial and temporal distribution of indoor radon concentrations in residential environments.

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