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Original Article

Evaluation of Radon Pollution in Underground Parking Lots by Discomfort Index

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Abstract

Introduction
Recent studies of public underground parking lots showed the influence of radon concentration and the probable discomfort caused by parking cars.
Materials and Methods
Radon concentration was measured in semi-closed public parking lots in the six governorates of Kuwait, using Durridge RAD7radon detector (USA).
Results
The peak radon concentration in the parking lots of Kuwait governorates was relatively higher during winter (63.15Bq/m^3) compared to summer (41.73 Bq/m^3). Radon in the evaluated parking lots revealed a mean annual absorbed dose (D_{Rn}: 0.02mSv/y) and annual effective dose (H_E: 0.06mSv/y).
Conclusion
This study validated the influence of relative humidity and temperature as the major components of discomfort index (DI). The mean annual absorbed and effective dose of radon in the evaluated parking lots were found below the permissible limits. However, high radon D_{Rn} and H_E were reported when the assessment included the parking lots, the surrounding residential apartments, and office premises. Furthermore, the time-series analysis indicated significant variations of the seasonal and site-wise distribution of radon concentrations in the indoor evaluated parking lots of the six Kuwait governorates.

Keywords: Air pollution Humidity, Radon, Temperature

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1. Introduction

Radon is a colorless, odorless, radioactive gas, which can contribute to respiratory disorders and lung cancer. The risk of lung cancer is said to rise 16% per 100 Bq/m^3 increase in human exposure to radon [1]. In fact, radon enters the basement floors through cracks in the walls and other openings in rock or soil and can be detected in different regions [2-4].

Unlike radon concentrations detected outdoors, radon becomes trapped in the indoor environment and may accumulate over time, causing respiratory diseases in humans [5,6]. On the other hand, ceiling cracks and openings, as well as appropriate ventilation systems, can significantly reduce the radon level [3].

According to statistics, 50% of the radiated radon is accumulated in humans due to the radioactive decay of ^{238}U in the environment [7]. Radon level is normally higher in confined places, old buildings, and structural areas in contact with soil [8]. Radon is speculated to reach high concentrations, depending on the geological location, ventilation rate, temperature, and relative humidity (RH)[9,10]. In fact, radon concentration in buildings varies with time, both diurnally and seasonally. These variations are primarily due to the effects of meteorological changes on radon level in soil gas and ventilation systems in buildings [11, 12].

Earlier investigations in Arab countries have indicated lower radon concentrations in most residential areas above the ground level, compared to basements and areas involved in industrial activities [13, 15]. In the previous studies, the mean indoor radon concentration ranged from 29 to 58Bq/m^3 with the exception of few radon concentrations (150-242Bq/m^3) emanating from the basements of certain buildings [13-15]. On the other hand, a previous study revealed high indoor radon accumulation due to poor radon exhalation and improper building design [16].

The above mentioned findings highlight the need for preventive measures. In Kuwait, rocks contain neither traces of volcanic activities nor mineral constituents; consequently, dispersion of radon in soil is very low. In a previous study, evaluation of the seasonal impact showed higher radon concentrations during winter, compared to summer [17].

Moreover, earlier studies revealed higher radon concentrations in the basement of buildings (58Bq/m^3), compared to the first and second floors (29and 15Bq/m^3, respectively)[15,18-20]. On the contrary, [21] reported a lower radon concentration in the first floor(16Bq/m^3), compared to the second floor(23.8Bq/m^3)of schools in Kuwait, which can be attributed to improper heating, ventilation, air-conditioning systems, and poor building maintenance in the second floor.

The mentioned investigations correlated high radon concentration with environmental factors in a given urban area. The high rate of pollution in urban regions has been found to cause the urban heat island effect, which is indicative of thermal comfort variations. The importance of thermal comfort standards for occupants of buildings or enclosures has been highlighted in the literature [22-24].

People residing in large metropolitan areas are subjected to a greater risk of morbidity and mortality due to higher temperature, compared to the surrounding countryside. Overall, major factors causing thermal discomfort in humans include temperature and RH, which can be calculated by Thom's formula for Discomfort Index (DI)[25]. Furthermore, wind action, chemical pollutants, noise, and social load can influence the comfort of indoor occupants [26].

Innumerable studies have been performed on radon concentration and DI in urban areas. The recent surge in Kuwait's population has also led to the increased use of automobiles [27], which in turn results in the increased number of cars and traffic congestion on the roads and parking lots in this country. In addition, poor maintenance of parking lots have been observed in Kuwait in the recent years.

So far, in Kuwait, no studies on spatial and temporal variations were assessed to relate the inadequate basic amenities of car parking lots. Therefore, the present study, aimed to determine radon concentration time-series (24h) in public underground parking lots in the six governorates of Kuwait. Moreover, varying radon concentrations were evaluated during winter and summer, and the combined effects of radon concentration and DI components, i.e., temperature and RH of the sampled regions were studied.

2. Materials and Methods

Evaluation of the combined effects of radon concentration and environmental variables was conducted in random public underground parking lots in six governorate areas (GI-GVI; Figure 1). These areas included Al-Jahra (GI), Al-Asimah (GII), Al-Hawalli (GIII), Farwaniya (GIV), Mubarak Al-Kabeer (GV), and Al-Ahmadi (GVI).

Al-Jahra (29.343°N, 47.673°E) encompasses open areas in the north of Kuwait and is mostly influenced by Northwesterly winds. Small-scale industries, along with thermal and water treatment plants, are housed in this region.

Al-Asimah (Kuwait City) (29.3697°N, 47.9783°E) is one of the six governorates of Kuwait. This populated region includes residential areas, commercial centers, and small-scale industries, which cater to the needs of Kuwait's population.

Al-Hawalli (29.333°N, 48.033°E) is known for commercial activities in Kuwait with thickly populated residential apartments and recreational centers.

Farwaniya (29^o16’37.2”N, 47^o57’32.4”E) is dominated by the thickly populated expatriate community of Kuwait and is polluted with domestic wastes. Mubarak Al-Kabeer (29^o15’25.2”N, 48^o03’25.2”E) is moderately populated and noted for several recreational centers.

Al-Ahmadi (29^o4’37.2”N, 48^o05’2.4”E) is a district located in the south of Kuwait. The northern part of this town is dominated by oil industries, whereas the southern region (thinly populated)mainly encompasses open farming and greenhouse gardening. Overall, Kuwait has a hot and dry climate with occasional and unpredictable mild-to-moderate dust storms.

A Kestrel-4500 (Nielsen-Kellerman Company, US) weather monitor was used to record the ambient air temperature ($^{\circ}$C) and RH (%) in six semi-closed public underground parking lots in the six Kuwait governorates(Figure 1). Simultaneously, a radon detector (RAD7, Durridge, USA) was used to detect and measure radon concentrations (Bq/m^3) in the parking lots. These measurements were recorded every hour from 8:00a.m.to 8:00p.m. (24h) at an approximate height of 1.5±0.3m every month from October2013 to July2015. This was based on the possible human breathing exposure to radon after parking the cars. Non-smoking respondents, who parked their cars at least three times a day in the parking lots and spent more than 10 min in the basement (±2min), were evaluated in the present study. The mean monthly data were recorded by using the DI formula [25]:

DI = T-(0.55-0.0055xRH) (T-14.5) (Equation 1)

Wherein DI denotes discomfort index, T refers to mean monthly dry-bulb temperature ($^{\circ}$C), and RH is the mean RH of air (%).

The mean seasonal radon concentrations from six public underground parking lots were plotted along DI and validated for Kuwait. The standard DI value (Table 1) was compared with the obtained DI values to determine the percentage of residents who might have experienced discomfort while parking their cars in the parking lots at different time intervals. DI was compared with different radon concentrations to determine the seasonal and site-wise effects of radon concentrations in the sampled area.

Table 1. Discomfort index (DI)

Discomfort conditions	*DI ($^{\circ}$C)
No discomfort	<21
Less than 50% of the population feels discomfort.	21-24
More than 50% of the population feels discomfort.	24-27
The majority of the population suffers from discomfort.	27-29
Everyone feels severe stress.	29-32
State of medical emergency	>32

*DI: Discomfort index (Thom, 1959)

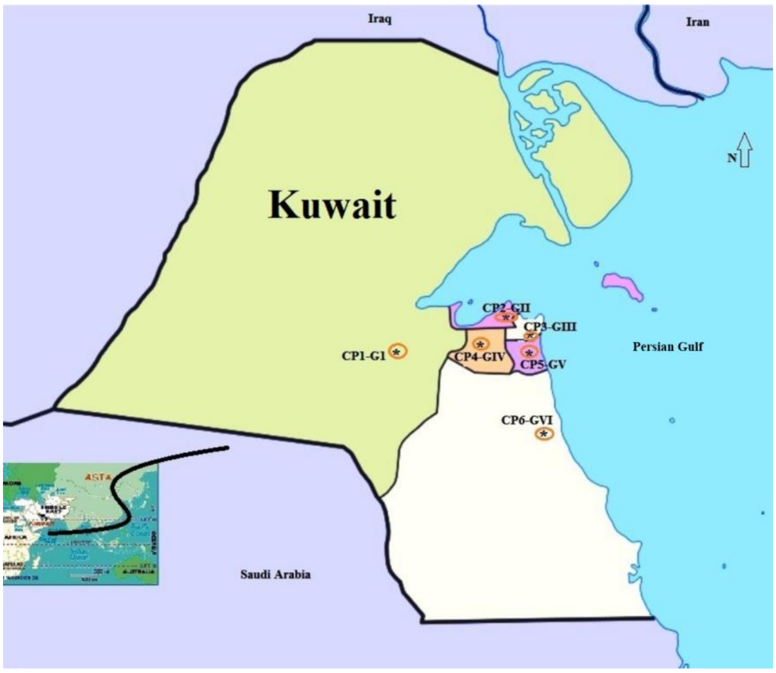

Figure 1. Kuwait map locating theparking lotsfor radon concentration measurements

Quality assurance of radon concentration measurements (by RAD7 meter) was achieved by using the standard reference material (SRM 4968), introduced by the National Institute of Standards and Technology (NIST). A certified volume of ^{222}Rn was allowed to accumulate in a container at very high atmospheric humidity, using an alpha pump. This container was connected to RAD7 meter, and radon concentration released by the standard material was measured.

In the present study, quality assurance was validated to those samples that attained 95% (±2.0%) recovery to that of the standard reference material (SRM). In addition, the annual absorbed dose of radon (D_{Rn}) in each parking lot was calculated, using the following equation:

$D_{Rn} = C_X \times D \times H \times F \times t$ (2)

Where D_{Rn} is the annual absorbed dose, C_X is the indoor radon concentration, D is the dose conversion factor (9×10^{-6}mSv.m^3/h. Bq.), H denotes the indoor occupancy factor (0.4), and t is the indoor occupancy time (10min,three times a day in the parking lot, 8h in the office, 10h in the residential area, and 6h roaming at random for 365d in a year).

Also, the effective dose of radon (H_E) was measured, using Equation3:

$H_E = D_{Rn} \times WR \times WT$ (3)

Where H_E is the annual effective dose of radon, D_{Rn} is the annual absorbed dose, WR is the radiation weighting factor (WR= 20), and WT denotes the tissue weighting factor (WT= 0.12), according to the International Commission on Radiological Protection (ICRP)[28]. Furthermore, the total annual dose of radon in an individual (influenced by radon exposure in the parking lot) from the residential area or office was estimated by calculating the total effective dose rate of radon (ΣH_E).

3. Results

Kuwait houses innumerable semi-closed parking lots of varying capacities in the six governorates. The 24-h monitoring of parking lots using RAD7 meter revealed the peak radon concentrations at 8:00a.m.(62.39Bq/m^3) and 8:00p.m. (62.12Bq/m^3) during December and January (Figure 2). In summer, the peak radon concentrations were reported at 8:00a.m. (42.93 Bq/m^3) and 8:00p.m.(39.65 Bq/m^3) (Figure 3).

Interestingly, the highest radon concentrations were observed at specific hours of the day (8:00 a.m. and 8:00 p.m.), irrespective of the season. Radon concentration was moderately high during November and February (early and late winter) and comparatively low in October and March (early and late winter) (Figure 2). However, the overall radon concentrations was found to be lower during summer (Figure 3), compared to winter (Figure 2).

RH was found to be higher (60.75-86.5%) during winter, compared to summer (27.25-55.42%). Moreover, RH was reported to be high between 7:00p.m. and 9:00a.m. and low between 11:00a.m. and 2:00p.m. The season-wise analysis revealed significant differences in RH between summer and winter. Moreover, time-series (24h) and season-wise analyses by ANOVA test revealed significant differences between radon concentration and RH (Tables 2A& 2C).

The mean temperature in the parking lots was within the range of17-26°C and 33.4-42.96°C during winter and summer, respectively. The radon concentrations in the underground parking lots were found to increase with decreasing temperature, irrespective of the season. The present study indicated higher radon concentrations in underground parking lots in winter, early morning, and late evening, compared to summer and day time (until dusk).

Furthermore, the time-wise analysis by ANOVA test showed no significant difference between radon concentration and temperature especially between 8:00 a.m. and 5:00 p.m. during the day time (Tables 2B&2D). However, ANOVA test results indicated a significant association between the seasons and radon concentrations (Tables 2B&2D).

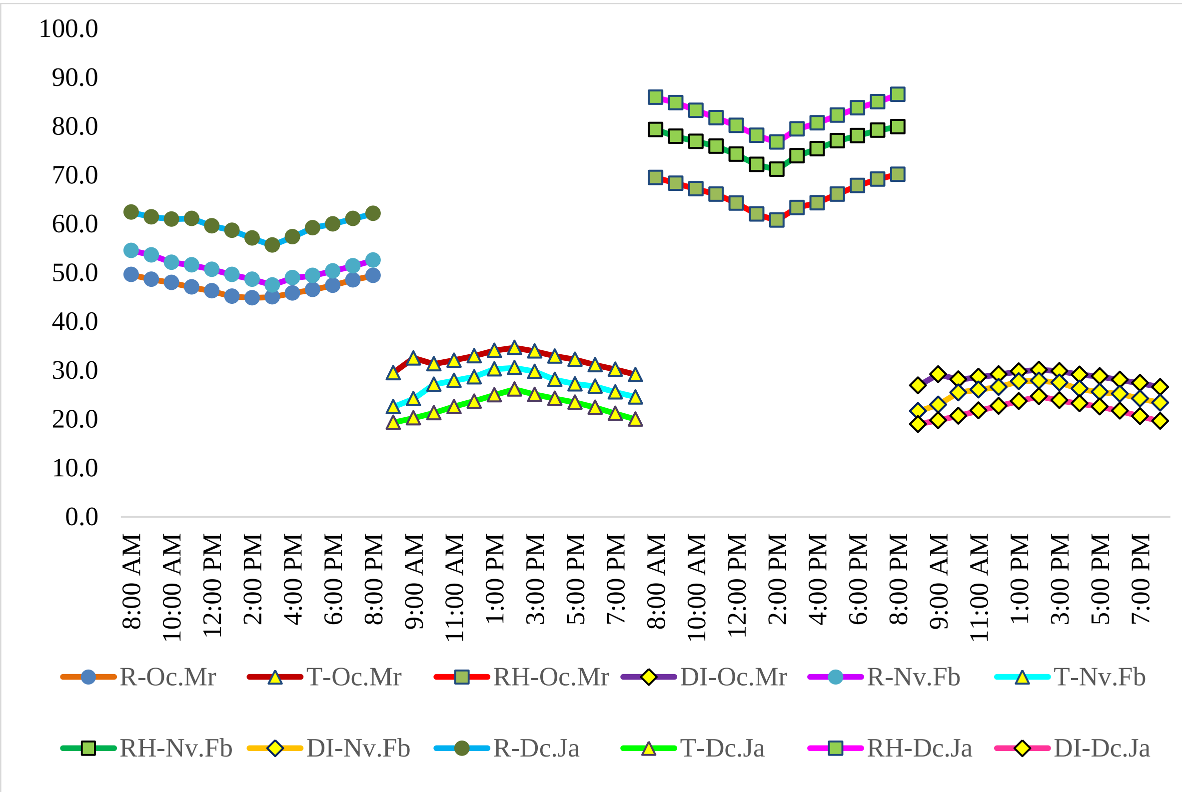

Figure 2. Time-series radon concentrations, indoor variables, and discomfort index (DI) during winter

R: Radon, T: Temperature, RH: Relative humidity, DI: Discomfort index, Oct: October, Mar: March, Nov: November, Feb: February, Dec: December, Jan: January

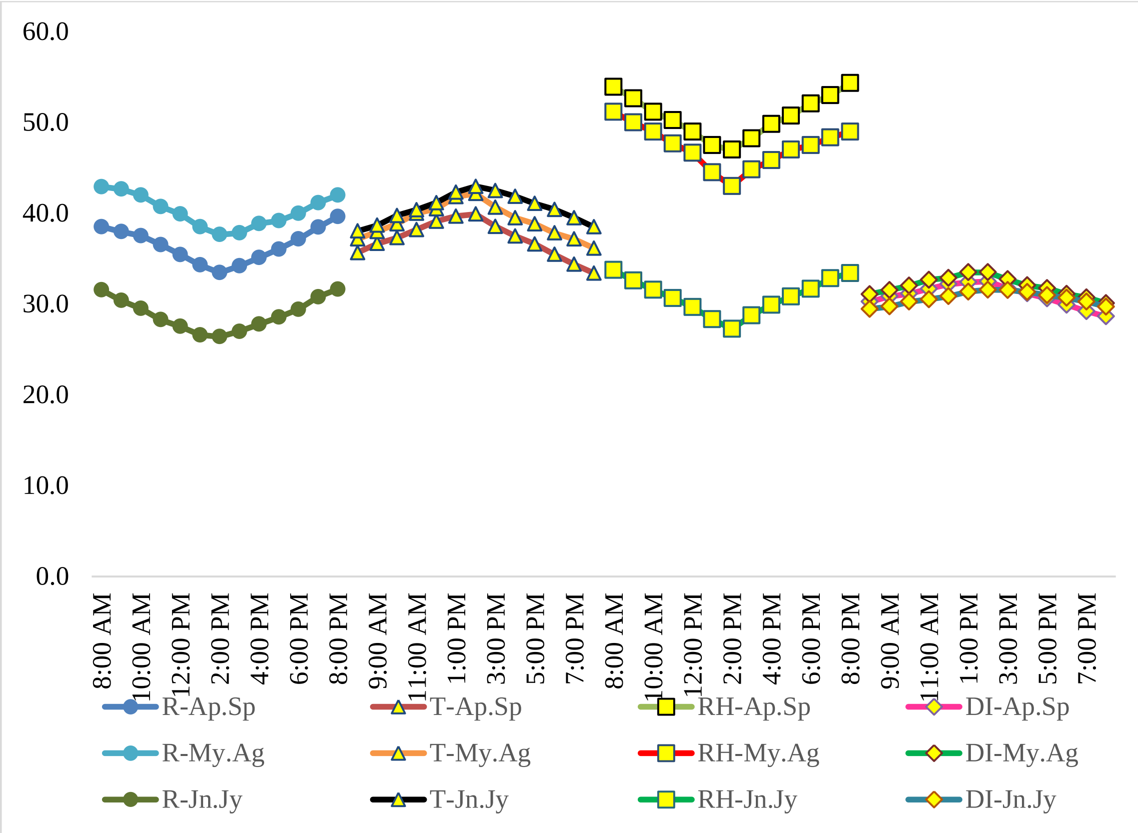

Figure 3. Time-series analysis of radon concentrations, indoor variables, and discomfort index (DI) during summer
R: Radon, T: Temperature, RH: Relative humidity, DI: Discomfort index, Apr: April, Sep: September, May: May, Aug: August, Jun: June, Jul: July

Table 2. ANOVA test results on radon concentration and environmental factors in the evaluated parking lots

Source of variation	SS	df	F	P-value	F-ratio	Significance
A. Radon concentration Vs relative humidity (RH) during winter						
Radon Vs. RH (time)	387.25	12	34.18	0.00025	1.91	*
Radon Vs. RH (season-winter)	12491.03	5	2646.59	0.00056	2.36	*
Error	56.63	60				
Total	12934.92	77				
B. Radon concentration Vs temperature during winter						
Radon Vs. temp. (time)	9.45	12	0.163	0.9992	1.91	**
Radon Vs. temp. (winter)	14118.75	5	585.96	0.00052	2.36	*
Error	289.13	60				
Total	14417.34	77				
C. Radon concentration Vs RH during summer						
Radon Vs. RH (time)	28683.76	12	79.14059	0.0004	1.91	*
Radon Vs. RH (summer)	4975.42	5	3294.612	0.0008	2.36	*
Error	18.12	60				
Total	5280.38	77				
D. Radon concentration Vs temperature during summer						
Radon Vs. temp. (time)	5.75	12	0.1208	0.99	1.91	**
Radon Vs. temp. (summer)	1220.60	5	61.5916	0.0002	2.36	*
Error	237.81	60				
Total	1464.15	77				
E. Site-wise radon concentration Vs environmental variables during winter and summer						
Radon Vs. parking lots	37.18347	5	23.61	0.0002	2.48	*
Variables in winter and summer	11119.99	7	5044.23	0.0001	2.28	*
Error	11.02	35				
Total	11168.19	47				

SS: Sum of squares, df: Degree of freedom, *Significant, **Insignificant

Moreover, in the present study, the season-wise analysis revealed a high DI value at high RH and low temperature in the evaluated underground parking lots. However, DI was not found to be correlated with radon concentration, as temperature varied during daytime. The DI value was also high in regions with more traffic congestion and high population density.

The site-wise analysis revealed higher radon concentrations in parking lots in GVI region (followed by GIV and GII) in comparison with radon concentrations from the parking lots of other governorates (Figures4a-4d). Also, Statistical analysis by ANOVA test revealed a significant difference between site-wise radon concentrations and DI that is calculated using RH and temperature during summer and winter (Table 2E).

Table 3. Site-wise annual doses of radon in the evaluated parking lots and the surrounding premises

Site	D_{Rn}	H_E	ΣH_E
G-I:Office	0.09	0.21	
G-I:Residence	0.35	0.84	
G-I:Parking lot	0.02	0.06	1.1081
G-II:Office	0.10	0.24	
G-II:Residence	0.38	0.91	
G-II:Parking lot	0.02	0.06	1.2059
G-IIII:Office	0.08	0.20	
G-III:Residence	0.34	0.82	
G-III:Parking lot	0.02	0.06	1.0722
G-IV:Office	0.11	0.27	
G-IV:Residence	0.40	0.95	
G-IV:Parking lot	0.02	0.06	1.2806
G-V:Office	0.08	0.18	
G-V:Residence	0.32	0.77	
G-V:Parking lot	0.02	0.06	1.0106
G-VI:Office	0.09	0.23	
G-VI:Residence	0.41	0.99	
G-VI:Parking lot	0.03	0.06	1.2807
Mean: Office	0.09	0.22	1.33
Mean: Residence	0.37	0.88	5.88
Mean: Parking lot	0.02	0.06	0.35

D_{Rn}: Annual absorbed dose, H_E: Annual effective dose, ΣH_E: Collective effective dose

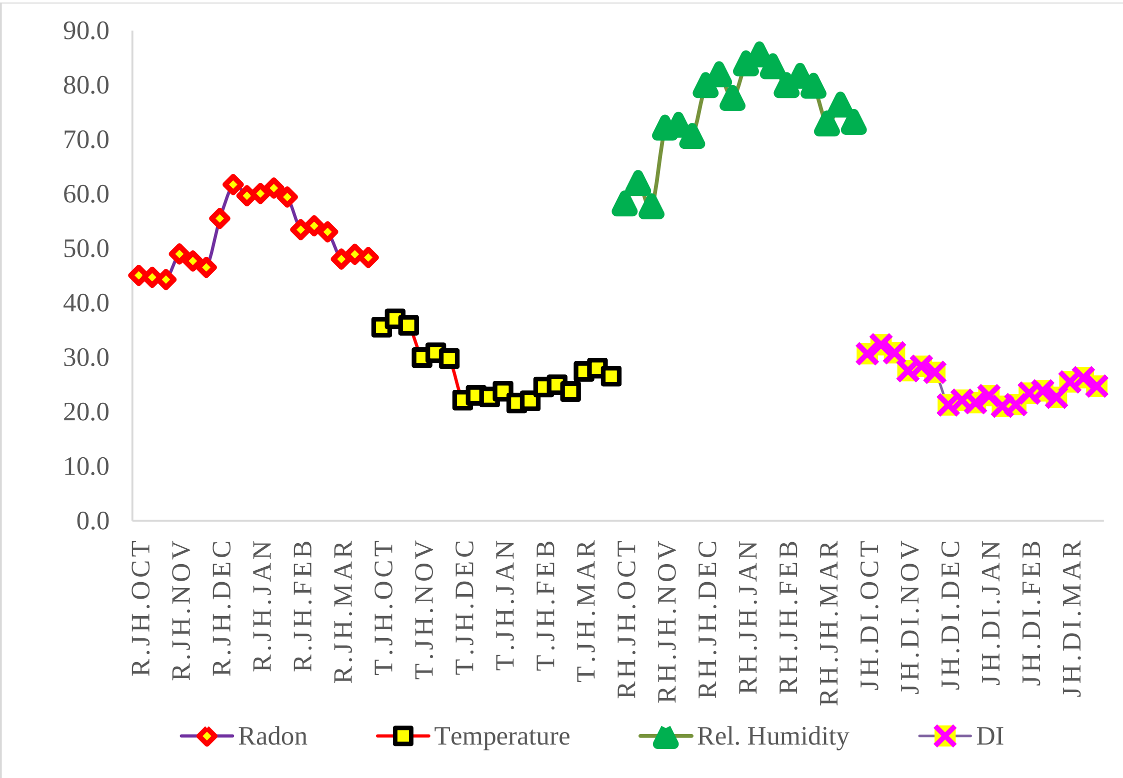

Figure 4a. Site-wise analysis of radon concentrations, indoor variables, and discomfort index (DI) in northern Kuwait during winter

R: Radon, T: Temperature, RH: Relative humidity, DI: Discomfort index, Oct: October, Mar: March, Nov: November,Feb: February, Dec: December,Jan: January, JH: Al-Jahra (Governorate I), HW: Al-Hawally(Governorate III), KC: Kuwait City (Governorate II)

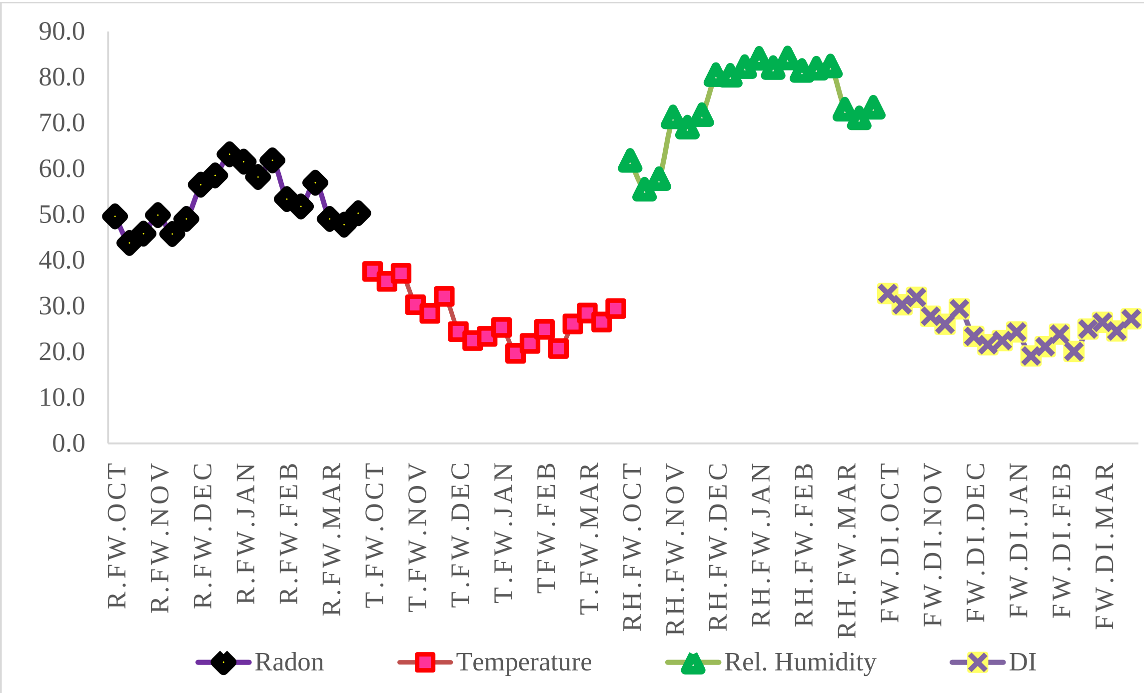

Figure 4b. Site-wise analysis of radon concentrations, indoor variables, and discomfort index (DI) in southern Kuwait during winter

R: Radon, T: Temperature, RH: Relative humidity, DI: Discomfort index, Oct: October, Mar: March, Nov: November,Feb: February, Dec: December,Jan: January, FW: Farwaniya (Governorate IV), AM: Al-Ahmadi (Governorate VI), MK: Mubarak Al-Kabeer (Governorate V)

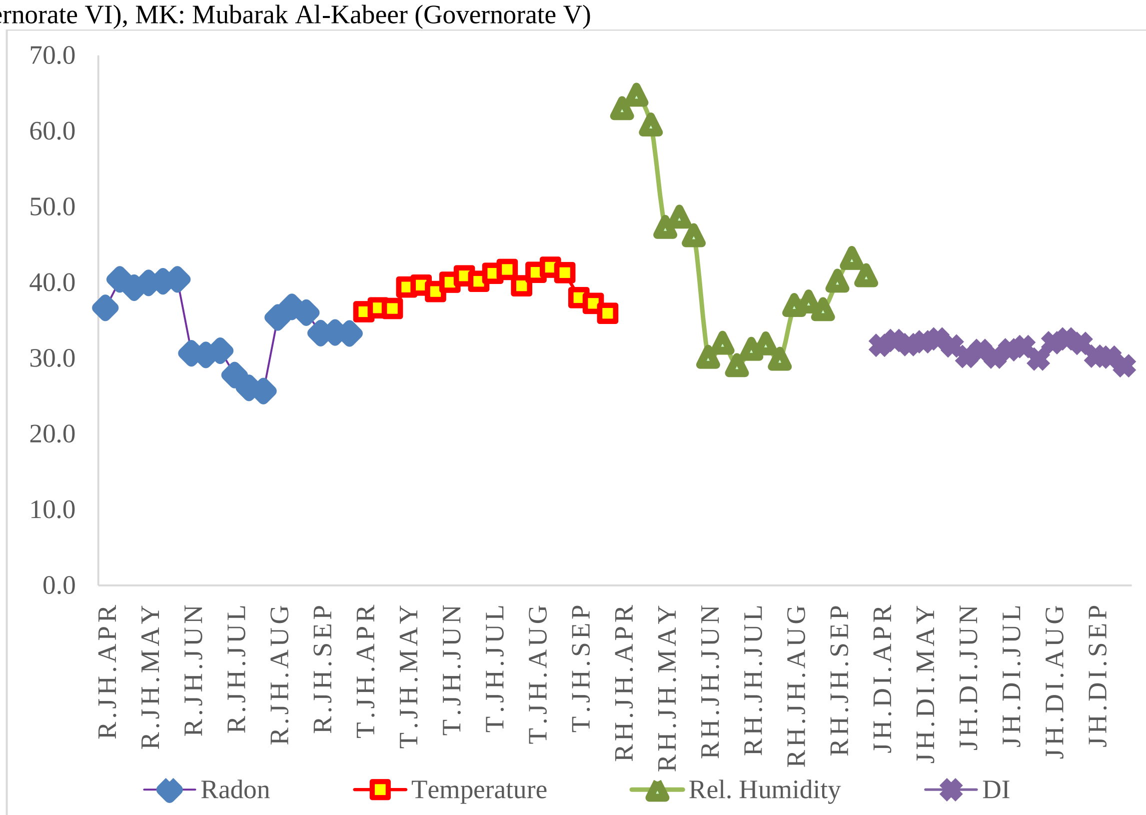

Figure 4c. Site-wise analysis of radon concentrations, indoor variables, and discomfort index (DI) innorthern Kuwait during summer

R: Radon, T: Temperature, RH: Relative humidity, DI: Discomfort index, Apr: April, Sep: September, May: May, Aug: August, Jun: June, Jul: July, JH:Al-Jahra (Governorate I), HW: Al-Hawally(Governorate III), KC: Kuwait City (Governorate II)

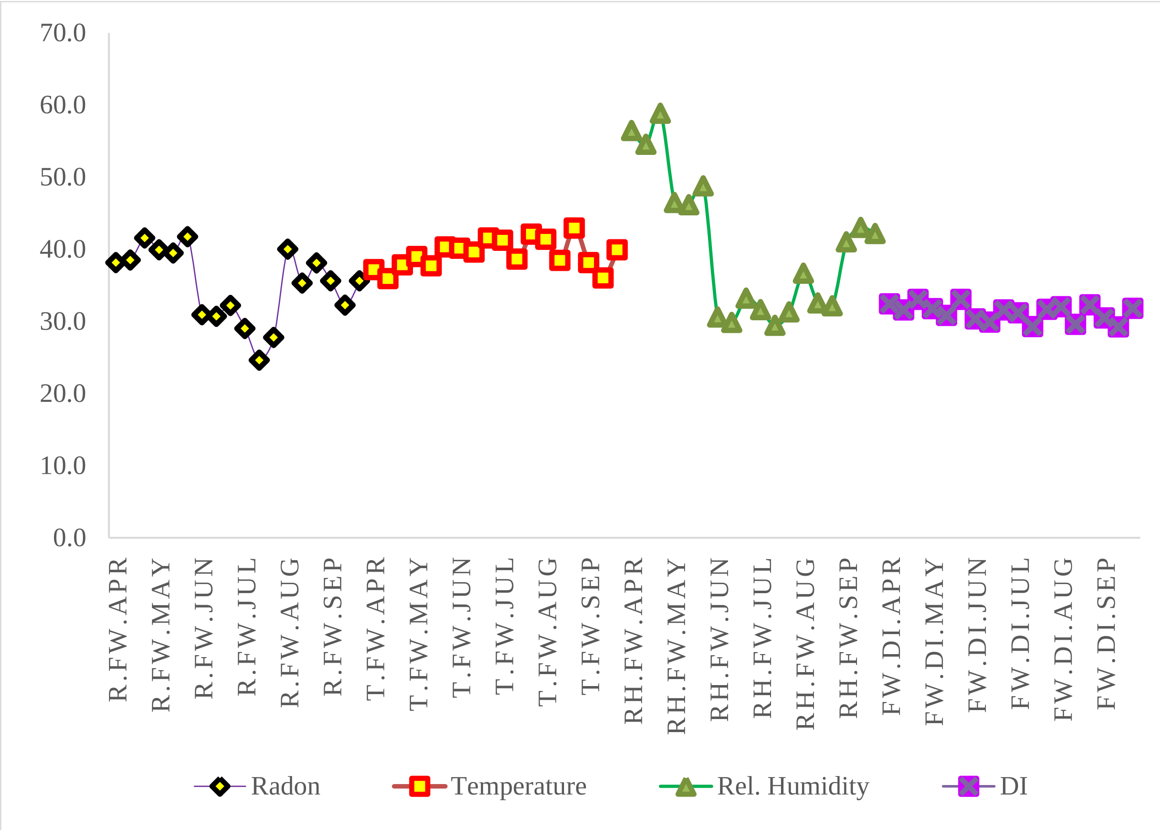

Figure 4d. Site-wise analysis of radon concentrations, indoor variables, and discomfort index (DI) in southern Kuwait during summer
R: Radon, T: Temperature, RH: Relative humidity, DI: Discomfort index, Apr: April, Sep: September, May: May, Aug: August, Jun: June, Jul: July, FW: Farwaniya (Governorate IV), AM: Al-Ahmadi (Governorate VI), MK: Mubarak Al-Kabeer (Governorate V)

The annual absorbed dose of radon (D_{Rn}) in the parking lots was found to be high in the GVI region, followed by GII, GI, GIII, and GV (Table 3). The overall mean D_{Rn} in the parking lots (0.02mSv/y) was comparatively lower than D_{Rn} in residential apartments (0.37mSv/y) and offices (0.09mSv/y) surrounding the parking areas (Table 3).

The mean annual effective dose (H_E) of radon for an individual near the parking lots was 0.06mSv/y, whereas the H_E values of radon were0.22and 0.88mSv/y in the residential apartments and offices within a 0.2km radius distance from the parking lots, respectively. The collective dose of radon concentration (ΣH_E) from the parking lots, offices, and residential apartments of the six governorates (GI-GVI) ranged between 1.01and1.28mSv/y (Table 3).

4. Discussion

According to statistics, more than 1.7 million vehicles were registered in2014 in Kuwait. In fact, more than 1.5 million cars were registered by the residents of Kuwait for domestic and public purposes [27]. The present findings revealed spacing capacity of each parking lot ranged between 2500 and 3000 cars, with few exceptions ranging between 4000 and 12,000 cars in certain private shopping malls.

The present study, conducted in the years 2013-2015 showed high radon concentrations in the parking lots when compared to the radon concentrations from automobiles that ply on roads. Besides the above factors, radon pollution was found high as a result of the recent increase in the population of Kuwait with corresponding increase of automobiles.

However, the effects of radon concentrations in the indoor and the outdoor environment was seldom evidenced in Kuwait [13, 17, 21]. Limitations of these studies are attributed to difficult technicalities involved in their assessments, inaccessibility of sampling strategies in the public, and unawareness of respiratory disorders, caused by radon and its progeny.

In line with earlier investigations regarding respiratory disorders among residents [1,5,10,15,19,20], the present study determined radon concentrations in the parking lots of six Kuwait governorates and evaluated the frequency and number of cars parked in these semi-closed underground parking spaces and also assessed the thermal discomfort endured by the residents of Kuwait. Regardless of the season, high radon concentrations in the parking lots can be attributed to the entry of radon through cracks or crevices of basements from the surrounding soil, low temperature, and high RH from outdoor environments. Therefore, temperature inversion conditions might trap radon closer to the ground [7,12,14,16].

In the present study, RH was found to be correspondingly high with increasing radon concentration, regardless of the season. These findings suggested RH as one of the dependent factors for the increase in radon concentration. This study indicated the increasing trend of radon concentration with RH, which was in line with earlier findings [9,18,23,26]; however, it should be noted that RH was comparatively low in the present study.

Researchers in earlier studies have hypothesized the influence of radon concentration from the outdoor environment [4,7,9,11]. Limited vertical mixing of air, especially in the early morning and late evening during winter, leads to the low diffusion rate of radon into the atmosphere and high radon concentrations near the ground.

Another factor influencing radon concentration was the high temperature in dry regions due to the increased vertical mixing of air from the outdoor environment. This enabled radon to dissipate from the underground parking lots to the outdoor environment through ventilation; this process in fact resulted in the reduced radon concentration in the basement during summer.

The high DI at low temperature and high RH, leading to increased radon concentrations, can be attributed to the provision of ventilation, soil permeability (mobilizing radon into the structure), and the space in basements. This finding was in agreement with the observations of previous studies and within the standard permissible limits [2, 3, 6, 8-9, 22, 24-26].

The high radon concentrations in the parking lots of GVI and GIV regions could be attributed to the influence of external soil sources, poor parking lot maintenance, and the exhaust smoke emanated from the cars due to frequent parking by residents in such populated areas. Furthermore, the high annual effective dose (H_E) of radon could be related to the longer exposure period (10 to14h) of an individual in his/her residential apartment, compared to the workplace and parking lots.

The collective dose of radon concentration (ΣH_E) was found to be high in the present study. This value was reported to be within the action level of 3-10mSv/y, as recommended by ICRP [28], but higher than the global average (1.15mSv/y), proposed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [7], especially in the parking lots of GVI, GIV, and GII regions. Therefore, the present findings indicated the necessity of preventive measures for reducing radon concentrations, especially in parking lots.

5. Conclusion

In the present study, we performed time-wise, season-wise, and site-wise assessments on indoor radon concentrations in the parking lots of six Kuwait governorates. The radon concentrations were measured from June 2013 to May 2015. The observations showed radon concentrations of 24.62-63.15Bq/m^3 in different seasons. The mean radon concentrations during winter were found to be higher than the global average (40 Bq/m^3). This study reported high radon concentrations and high DI values as a result of high humidity and low temperature, especially in thickly populated regions with highly frequented underground parking lots. The mean annual absorbed dose (D_{Rn}) and the mean annual effective dose (H_E) assessed in the parking lots were lower than the standard limits. However, the annual effective dose (H_E) from indoor residential areas and offices surrounding the parking lots was found to be higher than the standard limits, indicating the need for radon amelioration in near future.

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