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Impact of microclimatic parameters on radon concentration in preschool institutions in Sarajevo Canton

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ABSTRACT

Introduction: Radon (^{222}Rn), a radioactive gas produced by uranium decay, is the second leading cause of lung cancer after smoking. Indoor environments, especially preschool institutions, present increased risks due to children's vulnerability and extended occupancy. Microclimatic parameters such as air temperature, relative humidity, and airflow are known to affect radon dynamics, but their impact in preschool settings remains insufficiently studied. This research aimed to assess the seasonal variability of radon concentrations and their association with microclimatic conditions in preschool institutions in Sarajevo Canton.

Methods: A prospective longitudinal observational study was conducted from January to October 2025 across 38 preschool institutions. Radon concentrations were continuously measured with EcoQube dosimeters, and air temperature, relative humidity, and airflow velocity were recorded with a TSI multifunctional instrument. Measurements were conducted for 7 days per institution in rooms occupied by children. Statistical analyses included Wilcoxon signed-rank tests, Chi-square tests, and Spearman's correlation.

Results: Average radon levels were significantly higher in winter (166.35 Bq/m^3) than in summer (84.45 Bq/m^3; $z = 2.074$, $p = 0.038$). Radon concentrations exceeding 300 Bq/m^3 occurred more frequently in winter (10.8%) than in summer (2.7%), although this difference was not statistically significant ($\chi^2 = 2.173$, $p = 0.337$). A significant inverse relationship between radon and temperature was observed in summer ($\rho = -0.338$, $p = 0.015$). No significant associations were found between radon and relative humidity or airflow. The seasonal variation in microclimatic factors supports their influence on radon fluctuations.

Conclusion: Radon concentrations in preschool institutions show marked seasonal variation, with significantly higher values in winter. Temperature was associated with radon concentration indirectly through ventilation dynamics, while relative humidity and airflow had limited effects. Continuous monitoring and optimization of ventilation, especially during colder months, are essential to reduce radon exposure risks in preschool environments.

Keywords: Child; preschool; radiation dosimeters; radon

INTRODUCTION

Radon (^{222}Rn) is a naturally occurring radioactive noble gas produced by the decay of uranium found in soil, rocks, and building materials. It is the most significant isotope in the uranium (^{238}U) decay chain and is continuously generated within the Earth's crust. Radon is considered the most important natural source of ionizing radiation for the general population, with the greatest contribution to total exposure coming from indoor environments (1,2). Short-lived radon progeny emit alpha particles that, when inhaled, can damage the epithelial cells of the respiratory tract. Numerous epidemiological studies have confirmed that radon is the second leading cause of lung cancer after smoking (2,3).

International regulatory frameworks have clearly defined reference levels and protective measures. The World

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Health Organization recommends a reference level of 100 Bq/m^3, while the International Commission on Radiological Protection suggests a range of 100-300 Bq/m^3 (2,4). According to the International Basic Safety Standards developed by the International Atomic Energy Agency and the European Union, Member States are required to establish national reference levels (≤300 Bq/m^3) and implement systematic monitoring and protective measures, particularly in public facilities such as schools and preschool institutions (5). Preschool institutions are a particularly sensitive category of buildings, as they accommodate young children whose respiratory systems are still developing. Children have limited control over their environment and spend a substantial proportion of their time indoors, where radon concentrations may be elevated, especially in poorly ventilated or ground-level rooms (1,2,6). Their increased vulnerability is due to higher respiratory rates, ongoing lung development, and longer life expectancy, allowing a prolonged period for the manifestation of long-term effects of ionizing radiation (7).

Because it is a gas, radon moves freely through pores and fissures in the soil, migrating from geological formations into the atmosphere and indoor spaces. Radon enters buildings from the ground through diffusion and convection (1), passing through structural imperfections such as cracks in foundations, joints between walls and floors, gaps around service pipes, and porous construction materials (8,9). Indoor radon concentration results from a complex interaction of geological characteristics, building properties, and microclimatic parameters. The most important indoor factors include air temperature, relative humidity, atmospheric pressure, and airflow velocity (ventilation), all of which influence radon entry, accumulation, and distribution (10). In addition, radon concentrations show seasonal variability, typically higher in winter and lower in summer, due to differences in ventilation patterns and indoor environmental conditions (11). Temperature affects radon dynamics by changing air density and pressure differentials between indoor and outdoor environments, potentially increasing radon infiltration under colder conditions or reducing it under others (2). Relative humidity influences aerosol behavior and the attachment of short-lived radon progeny, thereby altering their distribution and potential inhalation dose (6). Airflow velocity is a key control mechanism: increased air exchange reduces radon concentration, while limited ventilation promotes its accumulation (2,6). Since no safe threshold for radon exposure exists, the principle of optimization of radiation protection (As Low As Reasonably Achievable [ALARA]) is applied (2,4). The principle of ALARA is widely used in radiation protection to minimize exposure to ionizing radiation (2,4).

Although many studies have confirmed the presence of radon in indoor environments and its public health significance, the extent to which microclimatic parameters influence variations in radon concentration under real-life conditions in preschool settings remains insufficiently understood. A particular challenge is the limited evidence regarding the relationship between air temperature, relative humidity, and airflow velocity, as well as their individual and combined effects on indoor radon levels. While these factors are recognized as important determinants of radon entry, accumulation, and distribution (9), their interactions and relative contributions have not been adequately clarified within the specific context of preschool institutions. Furthermore, in Sarajevo Canton, there is a lack of systematic research quantifying the impact of microclimatic parameters on radon concentrations in facilities occupied by this particularly vulnerable population. Considering the seasonal variability of radon and the influence of ventilation and indoor environmental conditions (10), there is a clear need for local research to improve understanding of risk factors and optimize protective measures.

This study aimed to assess the impact of microclimatic parameters – specifically air temperature, relative humidity, and airflow velocity – on radon concentration in indoor environments of preschool institutions in Sarajevo Canton. In addition, the study aimed to evaluate differences in radon concentrations between winter and summer periods and their association with microclimatic conditions.

METHODS

This study was designed as a prospective observational longitudinal study in which radon concentrations and microclimatic parameters (air temperature, relative humidity, and airflow velocity) were measured during both winter and summer seasons to assess their influence on variability in indoor radon levels. The winter season covered measurements from January 07 to April 27, while the summer season extended from July 02 to October 20, 2025. In each preschool institution, measurements were conducted continuously for seven days. According to official data, 99 public and private preschool institutions were registered at the beginning of the study. The sample was formed using proportional stratified selection of preschool institutions across all nine municipalities of the Sarajevo Canton, with an initial selection of 47 institutions. Following the consent procedure for participation, the study was ultimately conducted in 38 preschool institutions, while 9 declined participation. The non-participation of a subset of the initially selected institutions (9 out of 47) is unlikely to have introduced significant selection bias, as the analysis included key preschool institutions representing different facility types, locations, and environmental conditions within the Sarajevo Canton, thereby supporting the representativeness of the sample. Radon concentration was measured using an active dosimeter, the EcoQube dosimeter (Ecosense Inc., San Jose, USA), based on pulse ionization chamber technology that enables continuous real-time indoor air monitoring, with factory calibration and uninterrupted measurement throughout the monitoring period. Devices were positioned approximately 50 cm above floor level, at appropriate distances from windows, doors, and heat sources, while avoiding areas of high humidity. Measurements were conducted in rooms where children spent more than 2 h/day, using a 7-day continuous monitoring protocol in both the summer and winter seasons; in both cases, measurements were performed in the same rooms and at identical positions, ensuring methodological consistency and reproducibility of the results. Simultaneously with the measurement of radon concentration, microclimatic parameters were continuously monitored using a portable multifunctional instrument, the TSI Incorporated VelociCalc (Shoreview, Minnesota, USA), a factory-calibrated device for measuring air temperature, relative humidity, and air velocity for assessment of ventilation characteristics and indoor air quality, with the probe positioned in the breathing zone (1.0-1.5 m above the floor) in the direction of airflow. All data were continuously recorded and, on completion of measurements, transferred to a computer for further processing and statistical analysis.

Ethical approval and institutional permissions were obtained from the Ministry of Education of Sarajevo Canton, the Ethics Committee of the Faculty of Health Studies at the University of Sarajevo, and the administrations of all participating preschool institutions.

Descriptive statistics were used to summarize the characteristics of preschool institutions and the measured environmental parameters. Continuous variables were presented as mean ± standard deviation or median with interquartile range (IQR), depending on the data distribution, while categorical variables were expressed as frequencies and percentages. Seasonal differences in radon concentrations were assessed using the Wilcoxon signed-rank test for paired samples due to the non-normal distribution of the data. Differences in the distribution of radon concentration categories between seasons were analyzed using the Chi-square (χ^2) test. Correlation analysis was performed to evaluate the relationship between radon concentration and microclimatic parameters. Given the non-normal distribution of the variables, Spearman's rank correlation coefficient (ρ) was used to assess the strength and direction of associations. A $p < 0.05$ was considered statistically significant. All statistical analyses were performed using R (3.6.0 or later) in RStudio (Version 2026.01.2+418) and JASP software (Version 0.96.0).

RESULTS

A total of 38 preschool institutions in Sarajevo Canton were included in the study, where active radon measurements were conducted during both the winter and summer seasons.

Table 1 presents the general characteristics of the 38 analyzed preschool institutions. The mean number of children per institution was 91.87 ± 64.28, indicating substantial variability in institutional size. The total floor area had a median of 405.5 m^2, with an IQR of 182.5-664.0 m^2, suggesting heterogeneity in spatial capacity across facilities. Nearly half of the institutions (47.4%) were organized as ground-floor buildings with one additional story. Most were located in residential areas (76.31%), which may have implications for exposure to environmental factors such as air quality and noise.

TABLE 1. General characteristics of the included preschool institutions

Variable	Value
Number of institutions	38
Number of children (mean±standard deviation)	91.87±64.28
Total area (median, IQR), m2	405.5 (182.5-664.0)
Building type – ground floor and one storey	18 (47.4%)
Located in residential area, n (%)	29 (76.31)
Ventilation type – combined, n (%)	24 (63.2)
Ventilation type – natural, n (%)	13 (34.2)
Ventilation operating during working hours, n (%)	18 (47.36)
Air purification filters present, n (%)	27 (71.1)

IQR: Interquartile range

Combined ventilation systems were the most common (63.2%), while natural ventilation was present in 34.2% of institutions. However, ventilation systems were operational during working hours in less than half of the facilities (47.36%), which may represent a potential risk factor for indoor air quality. Air purification filters were installed in 71.1% of institutions, representing a positive aspect in terms of pollution control. Microclimatic parameters were considered important determinants of indoor radon accumulation and were therefore included in the interpretation of measured radon concentrations.

Table 2 demonstrates that active radon measurements revealed a clear seasonal variability in indoor radon concentrations in preschool institutions. Because of the skewed distribution of values and the influence of higher measurements on the mean, median values more accurately represent typical radon concentrations. In winter, the median radon concentration was 70.87 Bq/m^3 (IQR: 31.43-213.50 Bq/m^3), compared with 51.93 Bq/m^3 (IQR: 33.16-105.90 Bq/m^3) in summer, indicating higher typical exposure levels during winter. Mean values were also higher in winter (166.35 Bq/m^3) than in summer (84.45 Bq/m^3), but this difference is affected by greater variability and higher individual measurements, as shown by a higher coefficient of variation (CV) in winter (1.622 vs. 1.099). Paired comparisons using the Wilcoxon signed-rank test showed a statistically significant difference between seasons ($z = 2.074$, $p = 0.038$), confirming that radon concentrations were significantly higher in winter than in summer. These findings align with expected seasonal patterns, where reduced ventilation and increased indoor confinement during colder months contribute to radon accumulation. For further assessment of seasonal differences, radon concentrations were categorized into three levels: low (<100 Bq/m^3), moderate (100-300 Bq/m^3), and high (>300 Bq/m^3). In winter, low radon concentrations were observed in 62.2% of institutions, while moderate and high concentrations were present in 27.0% and 10.8%, respectively. In summer, the proportion of low concentrations increased to 73.0%, with moderate concentrations in 24.3% and high concentrations in only 2.7% of institutions.

Although a higher proportion of elevated radon levels was observed in winter, especially in the high-concentration category, the difference in distribution between seasons was not statistically significant ($\chi^2 = 2.173$, $p = 0.337$).

Microclimatic conditions varied between seasons, with higher air temperature and relative humidity observed during the summer, while airflow values remained relatively consistent across seasons. During the summer, a statistically significant negative correlation was found between radon concentration and air temperature ($\rho = -0.338$, $p = 0.015$), indicating that higher temperatures were associated with lower radon concentrations (Figure 1). Consistent with the findings in Table 3, Figure 1 graphically illustrates the relationship between radon concentration and air temperature during the summer, facilitating clearer interpretation of the observed correlation.

TABLE 2. Seasonal comparison of indoor radon concentrations and distribution of radon levels (active measurements)

Parameter	Winter season	Summer season	Test statistics	p-value
Radon concentration (Bq/m^3)				
Mean value	166.35	84.45	z=2.074	0.038
Median value	70.87	51.93		
IQR	31.43-213.50	33.16-105.90		
Coefficient of variation	1.622	1.099		
Radon level classification	%	%		
Low (<100 Bq/m^3)	62.2	73.0	x^2=2.173	0.337
Moderate (100-300 Bq/m^3)	27.0	24.3		
High	10.8	2.7		

IQR: Interquartile range

TABLE 3. Correlation between microclimatic parameters and radon concentration by season (active measurements)

Parameter	Winter median (IQR)	Summer median (IQR)	Correlation with radon (Winter ρ, p)	Correlation with radon (Summer ρ, p)
Temperature (°C)	21.93 (20.84-23.09)	25.00 (23.87-25.45)	$\rho=0.011$, $p=0.947$	$\rho=-0.338$, $p=0.015$
Relative humidity (%)	37.04 (29.39-47.03)	52.08 (48.81-55.77)	$\rho=0.065$, $p=0.702$	$\rho=0.062$, $p=0.709$
Airflow (m/s)	0.135 (0.124-0.140)	0.126 (0.115-0.137)	$\rho=-0.199$, $p=0.237$	$\rho=0.288$, $p=0.080$

IQR: Interquartile range

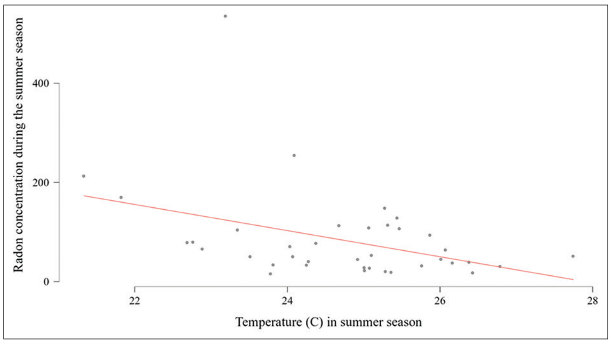

FIGURE 1. Relationship between indoor radon concentration (Bq/m^3) and air temperature (°C) during the summer season in preschool institutions. Each point represents a single measurement, while the red line indicates the fitted linear regression trend, demonstrating a negative association between temperature and radon concentration.

No statistically significant correlations were found between radon concentration and relative humidity in either season (winter: $\rho = 0.065$, $p = 0.702$; summer: $\rho = 0.062$, $p = 0.709$). Similarly, airflow did not show a statistically significant association with radon concentration, although a positive trend was observed during the summer ($\rho = 0.288$, $p = 0.080$).

DISCUSSION

The results of this study show pronounced seasonal variability in indoor radon concentrations in preschool institutions, with significantly higher values during winter (166.35 Bq/m^3) compared to summer (84.45 Bq/m^3). Greater variability was also observed in winter (CV = 1.622) than in summer (CV = 1.099). The difference between seasons was statistically significant (Wilcoxon z = 2.074; $p = 0.038$), confirming a seasonal association with radon accumulation.

Categorization of radon concentrations (low <100 Bq/m^3, moderate 100-300 Bq/m^3, high >300 Bq/m^3) revealed a higher proportion of elevated values during winter, although the difference in distribution between seasons was not statistically significant ($\chi^2 = 2.173$; $p = 0.337$). This may indicate variability within the sample and an association with local factors such as ventilation and building characteristics. These findings align with established mechanisms of seasonal radon variation, where reduced ventilation and greater temperature differences between indoor and outdoor environments during winter contribute to radon accumulation in enclosed spaces. Similar observations have been reported by the World Health Organization, which states that indoor radon concentrations are higher during winter due to reduced ventilation (2). More recent studies indicate that the winter-to-summer concentration ratio typically ranges from 1.2 to 2.5, depending on regional characteristics and building properties (12). European studies conducted in schools and preschool institutions indicate that winter radon concentrations commonly range from 150 to 800 Bq/m^3, while summer values are considerably lower (13). Preschool settings are particularly sensitive environments due to prolonged occupancy and increased susceptibility of children to ionizing radiation. Consequently, continuous monitoring and improvement of ventilation, especially during winter, are strongly recommended (2). In this study, the findings clearly indicate both seasonal and microclimatic associations with indoor radon concentrations, with air temperature, relative humidity, and airflow identified as key determinants of variability. During the summer, a statistically significant negative correlation was observed between radon concentration and air temperature ($\rho = -0.338$; $p = 0.015$), indicating that higher temperatures are associated with lower radon concentrations. These findings are consistent with those reported by Chung et al. (2020) (14) and Xie et al. (2016) (15), who also identified negative correlations in the range of $r \approx -0.14$–-0.30 and $R \approx -0.3$–-0.6. This relationship is most commonly explained by the indirect effect of temperature through increased ventilation and reduced radon accumulation under warmer conditions. No statistically significant association was observed between relative humidity and radon concentration ($\rho = 0.062$; $p = 0.709$), although a weak positive trend was noted. This finding is partially consistent with Chung et al. (14), who reported a weak but consistent positive association with humidity, as well as with computational fluid dynamics results by Adelikhah et al. (16), which showed that relative humidity may influence radon distribution, albeit to a lesser extent than ventilation. Airflow showed a positive correlation with radon concentration ($\rho = 0.288$; $p = 0.080$), which did not reach statistical significance but suggests a potential trend. This finding differs from the predominant evidence in the literature, where ventilation is consistently identified as a key factor in reducing radon concentrations. For example, Kashkinbayev et al. (17) and Akbari et al. (10) emphasize the importance of ventilation, reporting significant seasonal differences ($p < 0.001$) and reductions in radon concentrations of up to approximately 80% with increased air exchange rates (Air changes per hour [ACH]). The discrepancy observed in this study may be due to the limited range of measured airflow values or specific characteristics of the investigated indoor environments. Analysis of interrelationships among microclimatic parameters revealed a statistically significant negative correlation between temperature and relative humidity ($\rho = -0.455$; $p = 0.004$), consistent with expected physical relationships and further confirming the seasonal dependence of indoor environmental conditions. A combined interpretation of the results suggests that the highest radon concentrations occur under conditions of lower temperature and increased relative humidity, indicating a potential synergistic effect in the process of radon accumulation. This pattern is consistent with findings reported by Kashkinbayev et al. (17), who also observed higher radon concentrations during winter and statistically significant seasonal differences ($p < 0.001$) associated with reduced ventilation. Numerous studies further confirm the dominant role of ventilation in controlling radon concentrations. Xie et al. (15) reported substantial differences between ventilated and non-ventilated spaces (approximately 1083 ± 6 Bq/m^3 vs. 29 ± 21 Bq/m^3), while Adelikhah et al. (16) demonstrated reductions from 66 to 70 Bq/m^3 at 1 ACH to approximately 20 Bq/m^3 at higher air exchange rates. These findings clearly indicate that increased ventilation is the most effective mechanism for reducing radon levels. Overall, the results of our study confirm that ventilation is the primary regulator of indoor radon concentration, while temperature exerts an indirect effect mainly through its association with air exchange dynamics. Relative humidity appears to have a secondary but potentially consistent role. Although airflow did not reach statistical significance in this study ($\rho = 0.288$; $p = 0.080$), its importance in radon dynamics remains well established within the broader scientific literature.

Study limitation

The limitations of this study include the absence of passive dosimetry, which will be implemented in future phases of the research to enable a longer-term assessment of radon concentrations. Active dosimetric measurements were limited to 7 days per institution, which may not capture longer-term variations. In addition, the study covered only the summer and winter seasons, while transitional periods (spring and autumn) were not included in the analysis. Furthermore, building characteristics of preschool institutions (age of the building, construction materials, number of floors, insulation level, ventilation systems, and occupancy regime), as well as the geological characteristics of the study area, were not analyzed in detail, although they may represent important influencing factors on radon concentrations and potential confounding variables.

CONCLUSION

This study confirmed pronounced seasonal variability in indoor radon concentrations, with significantly higher values and greater variability observed during winter. Although a higher proportion of elevated radon concentrations was detected in winter, differences in their distribution across categories were not statistically significant. Air temperature showed a statistically significant negative association with radon concentration during summer, while relative humidity and airflow did not show significant relationships. The findings indicate that seasonal conditions and ventilation are key factors in regulating indoor radon concentrations. These results highlight the importance of continuous monitoring and optimizing ventilation strategies, particularly during winter, to reduce potential health risks in preschool environments.

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DECLARATION OF INTERESTS

Authors declare no conflict of interests.

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