TEMPORAL ANALYSIS OF INDOOR RADON DYNAMICS USING HIGH-RESOLUTION MONITORING DATA

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Abstract

This study investigates short-term indoor radon variability using high-resolution hourly monitoring data collected from five indoor environments with different ventilation conditions, occupancy patterns, and structural characteristics. Indoor radon concentrations were continuously measured using RadonEye RD200 detectors, yielding approximately 3,300 hourly observations during the monitoring period from November to December 2025. Indoor temperature was simultaneously monitored to support environmental interpretation. The monitored environments included storage rooms, office spaces, technical infrastructure areas, and continuously occupied working rooms distributed across different floor levels. Hourly radon concentrations ranged from approximately 1 to 265 Bq m³, with the highest average concentrations observed in the working room and the lowest in the archive room. Short-term radon accumulation events were most evident during periods of reduced ventilation and limited room occupancy, while rapid concentration declines were consistently observed following natural ventilation or routine human activity. The dataset was analysed using exploratory time-series analysis, heatmaps, diurnal profiling, and stratified comparisons. The results revealed reproducible daily radon patterns and substantial room-specific variability strongly influenced by ventilation *behaviour and occupancy conditions. The findings highlight the importance of high-resolution monitoring for understanding short-term indoor radon dynamics that may remain hidden when relying solely on long-term average measurements and demonstrate a practical framework for applied indoor environmental analysis.*

Key words: *Indoor radon, time-series analysis, radonEye RD200, data visualisation, temporal dynamics.*

Përmbledhje

Ky studim analizon ndryshimet afatshkurtra të radonit në ambiente të brendshme duke përdorur të dhëna monitorimi orë pas ore me rezolucion të lartë, të mbledhura nga pesë ambiente të ndryshme me kushte të ndryshme ventilimi, shfrytëzimi dhe karakteristika strukturore. Përqendrimet e radonit janë matur vazhdimisht me detektorë RadonEye RD200, duke gjeneruar rreth 3,300 orë matjesh gjatë periudhës nga nëntori deri në dhjetor 2025. Njëkohësisht është monitoruar edhe temperatura e brendshme për të ndihmuar në interpretimin e rezultateve. Ambientet e monitoruara përfshinin depo, zyra, zona teknike dhe hapësira pune të shfrytëzuara vazhdimisht, të vendosura në kate të ndryshme të ndërtesës. Përqendrimet e radonit varionin nga rreth 1 deri në 265 Bq m $^{-3}$, ku vlerat më të larta mesatare u regjistruan në dhomën e punës, ndërsa më të ulëtat në dhomën e arkivit. Rritjet afatshkurtra të radonit u vunë re kryesisht gjatë periudhave me ventilim të kufizuar dhe prani të reduktuar të njerëzve, ndërsa ulje të shpejta të përqendrimit u vërejtën pas ventilimit natyror ose aktivitetit të zakonshëm njerëzor. Të dhënat u analizuan përmes analizës së serive kohore, heatmap-eve, analizës së ndryshimeve ditore dhe krahasimeve sipas kushteve të ventilimit. Rezultatet treguan modele të përsëritshme ditore të radonit dhe ndryshime të dukshme ndërmjet hapësirave të ndryshme, të ndikuara kryesisht nga ventilimi dhe mënyra e shfrytëzimit të ambienteve. Gjetjet tregojnë rëndësinë e monitorimit me rezolucion të lartë për të kuptuar ndryshimet afatshkurtra të radonit, të cilat mund të mos vërehen në matjet afatgjata mesatare, dhe paraqesin një qasje praktike për analizën e mjediseve të brendshme.

Fjalë kyçe: *Radoni në ambiente të brendshme, analiza e serive kohore, monitorimi me rezolucion të lartë, vizualizimi i të dhënave, dinamika kohore.*

Introduction

Indoor environmental monitoring has changed rapidly with the spread of compact, low-cost sensors capable of producing continuous, high-resolution datasets. Despite these advances, many studies and regulatory frameworks still rely mainly on long-term averages to describe indoor environmental quality. While such averages are useful for compliance assessment, they often hide short-term variability caused by human behaviour, operational schedules, and ventilation practices (Abulibdeh, 2022; Laukkarinen & Vinha, 2024).

Indoor radon is a particularly informative parameter for studying these dynamics. As a naturally occurring radioactive gas, its concentration is influenced by building characteristics, floor level, air exchange rates, and occupancy behaviour. Long-term passive techniques, such as CR-39 detectors, provide reliable spatial averages but cannot capture daily or hourly fluctuations. Recent high-resolution studies have reported pronounced diurnal cycles and episodic accumulation events strongly modulated by ventilation and occupancy, yet such temporal structures remain rarely quantified in routine radon assessments, which are still dominated by long-term integrated measurements (Kashkinbayev et al., 2024; Bossew et al., 2024; Bossew, 2025; Mphaga et al., 2024). From both health-protection and building-performance perspectives, this gap raises important questions about exposure characterisation and mitigation strategies.

Beyond its role as a health-related indicator, radon is increasingly used as a tracer for indoor air exchange and environmental dynamics (World Health Organization [WHO], 2009). Parallel progress in exploratory time-series analysis and environmental data visualisation has expanded the tools available for interpreting such datasets (Abulibdeh, 2022; Chatfield, 2004), allowing researchers to move from static indicators towards dynamic interpretations grounded in real operational conditions.

The present study treats indoor radon measurements as a methodological case study rather than focusing only on radiological risk assessment. The aim is to show how moderate-sized, high-resolution datasets, examined through exploratory time-series analysis, diurnal profiling, heatmap visualisation, correlation analysis, and a targeted behavioural case report, can reveal short-term radon dynamics linked to ventilation and occupancy that remain hidden in long-term averages. The novelty lies in the integrated use of accessible and transparent analytical tools to expose these temporal structures, rather than in new sensing hardware or complex predictive models. The proposed approach provides a practical and replicable framework for applied indoor environmental monitoring and short-term radon variability assessment.

Materials and methods

a) Study Design and Measurement Setup

The monitoring campaign was designed to capture realistic variability across indoor environments with differing structural and operational characteristics. Five locations were selected to reflect contrasts in ventilation potential, occupancy frequency, and floor level, factors widely recognised as influential drivers of indoor radon behaviour [WHO], 2009; International Atomic Energy Agency [IAEA], 2019). The selected spaces included windowed and windowless rooms, offices on the ground and second floors, and a rarely accessed technical room, encompassing storage areas, continuously occupied workspaces, and infrastructure zones distributed across multiple floor levels.

Hourly indoor radon concentrations were recorded throughout the campaign using five RadonEye RD200 electronic detectors.

These instruments rely on a pulsed ion chamber detection principle and are designed for high-resolution monitoring of short-term variability. All units were factory calibrated, with certification valid through 2027. Each detector was placed on a stable surface approximately 1-1.5 m above floor level and 40-50 cm from the nearest wall, as shown in Figure 1.

Indoor temperature was measured in parallel using portable digital temperature data loggers placed next to each radon detector, ensuring temporal alignment between environmental and radiometric measurements and supporting subsequent exploratory correlation and stratified analyses.

Figure 1. RadonEye RD200 radon detector deployed in situ in one of the monitored indoor environments during the measurement campaign.

Detailed characteristics of the monitored spaces and accompanying environmental conditions are summarised in Table 1.

Table 1. Characteristics of the monitored indoor environments and summary of environmental conditions during the monitoring campaign

Room	Floor Level	Area (m^2)	Windows	Ventilation	Occupancy	Mean Temp (°C)	Temp Range (°C)
Archive Room	Second floor	9	No	None	Low	23.4	20.0–27.0
Pharmacy	Basement	5	No	Mechanical	Low	21.7	18.0–27.0
Working Room	Ground floor	16	No	Mechanical	High	24.2	23.0–27.0

Technical Room	Basement	24	No	Mechanical	Very low	22.2	21.0–31.8
Office Room	Ground floor	20	3 windows	Natural	Moderate–high	23.7	20.0–28.3

b) Dataset Characteristics and Preprocessing

The monitoring period extended from November to December 2025, yielding approximately 3,300 hourly observations across the five locations. The resulting dataset constitutes a multivariable time series of moderate size but high informational value, suitable for exploratory and comparative analysis. A summary of the descriptive statistics for each monitored environment, including the number of hourly observations, mean, median, minimum, maximum, and standard deviation of indoor radon concentrations, is presented in Table 2.

Data preprocessing was performed using Python and Microsoft Excel. Initial steps included time alignment, verification of data continuity, and inspection for missing values. Rather than excluding short-term peaks or apparent anomalies, these events were examined in relation to known occupancy patterns and ventilation conditions. This approach aligns with recommended practices in environmental time-series analysis, where preserving physically meaningful variability is essential for interpretation.

Table 2. Descriptive statistics of hourly indoor radon concentrations measured during the monitoring campaign.

Monitoring Location	N (hours)	Mean (Bq m^{-3})	Median (Bq m^{-3})	Min (Bq m^{-3})	Max (Bq m^{-3})	Std (Bq m^{-3})
Archive Room	626	23.3	22.0	1.0	75.4	11.4
Pharmacy	614	75.6	69.0	1.0	216.0	32.2

Working Room	626	94.3	92.0	26.4	205.4	27.7
Technical Room	686	49.4	45.0	11.0	152.1	22.7
Office Room	789	55.3	39.0	20.0	265.2	36.1

c) Exploratory Time-Series Analysis

Exploratory data analysis formed the foundation of the analytical approach. Hourly radon time-series plots were constructed to identify trends, episodic peaks, and subsequent concentration decline phases. Visual inspection revealed pronounced short-term variability, with accumulation events often occurring during periods of reduced ventilation and rapid declines following room access or window opening, as shown in Figure 2.

Time-series decomposition techniques were applied to separate long-term trends, diurnal components, and residual variability. Seasonal decomposition and moving-average smoothing approaches were used for exploratory interpretation of temporal patterns. These methods facilitated clearer interpretation of recurring temporal patterns and reduced the risk of misattributing systematic behaviour to random noise (Chatfield, 2004).

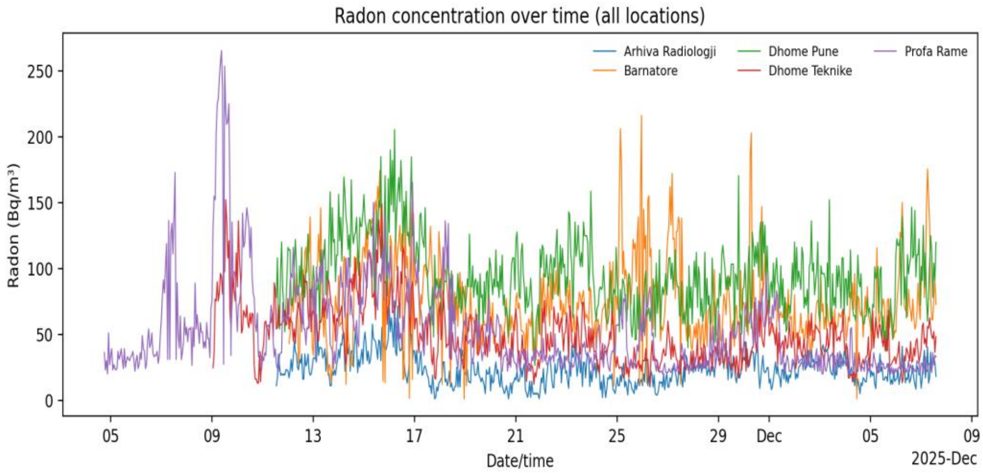

Figure 2. Representative hourly radon concentration time series illustrating episodic accumulation events and rapid decay following ventilation

d) Diurnal Patterns and Heatmap Visualisation

To further explore temporal structure, radon concentrations were aggregated by hour of day to generate diurnal profiles. These profiles revealed consistent daily rhythms, as shown in Figure 3, characterised by radon accumulation during periods of low activity and reduced ventilation, followed by decay during working hours when ventilation increased. Such patterns underscore the limitations of long-term averaging, as predictable exposure dynamics are effectively smoothed out when temporal resolution is reduced.

Heatmap representations of radon concentration as a function of hour and day were then constructed, as shown in Figure 4, to identify systematic peak periods. The resulting visualisations demonstrated recurrent high-radon intervals, confirming that observed peaks were not random but followed reproducible temporal structures.

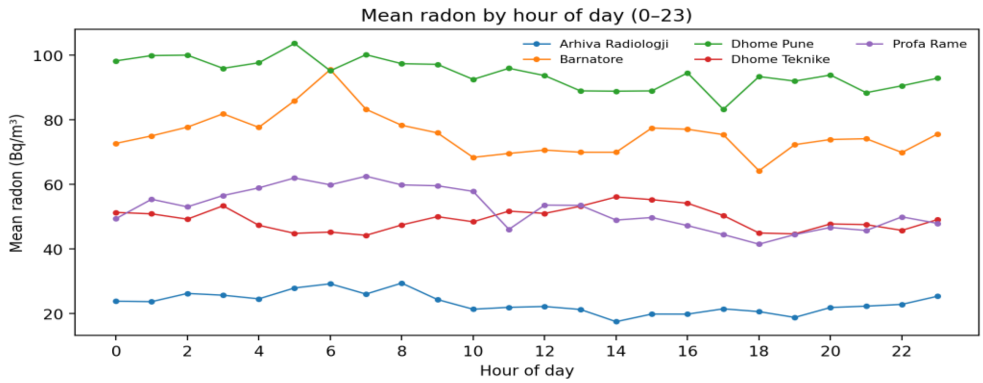

Figure 3. Average hourly radon concentration profile highlighting hidden daily rhythms.

e) Correlation and Stratified Analysis

Pearson correlation coefficients were calculated between hourly radon concentration and indoor temperature for each monitored room to assess the strength and direction of their association. The analysis revealed substantial variability in correlation strength across environments, as shown in Figure 5, with stronger correlations typically observed in poorly ventilated spaces and weak or negligible correlations in well-ventilated rooms. These findings indicate that radon-temperature relationships are highly room-specific and strongly modulated by ventilation and occupancy behaviour rather than by temperature alone.

To isolate the effect of ventilation, the dataset was stratified into ventilation ON and ventilation OFF conditions. Scatter plots and comparative statistics demonstrated that radon accumulation increased markedly when ventilation was absent, as shown in Figure 6, while correlations weakened once ventilation resumed.

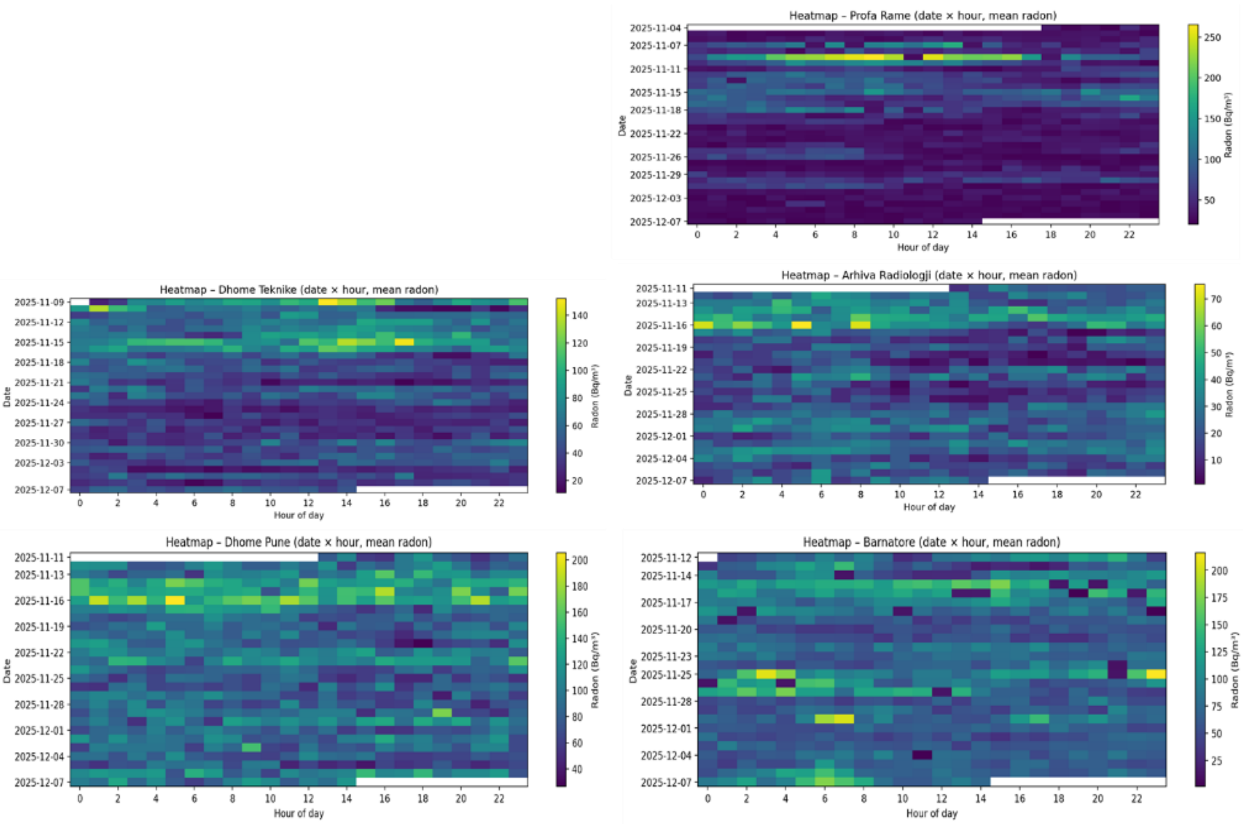

Figure 4. Hour-by-day heatmap of indoor radon concentrations illustrating recurrent peak periods

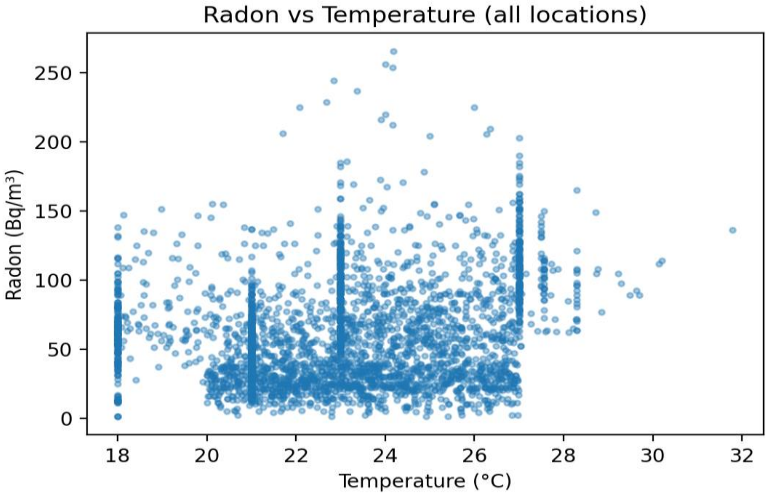

Figure 5. Overall radon–temperature relationship across monitored locations.

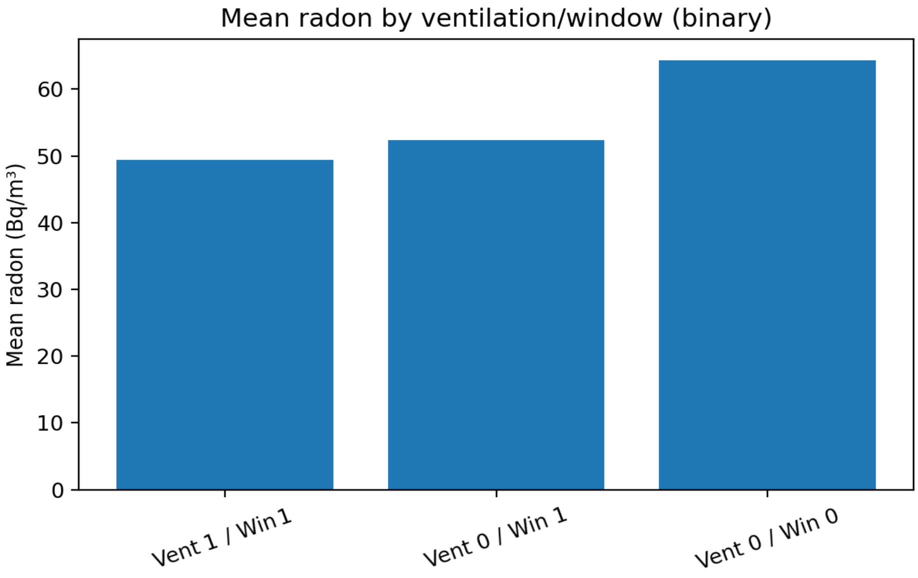

Figure 6. Stratified analysis comparing radon behaviour under ventilation OFF and ON conditions.

f) Case Study: Behavioural Intervention in an Office Environment

A focused case study was conducted in an office environment where occupant behaviour changed during the monitoring period. The intervention consisted of maintaining windows and natural ventilation continuously open during working hours. This change resulted in a clear and immediate reduction in indoor radon concentration, as shown in Figure 7, accompanied by a noticeable weakening of the radon-temperature correlation.

This case report provides empirical evidence that human behaviour can override physical correlations and serves as a natural experiment validating the broader analytical findings (WHO, 2009; IAEA, 2024). Unlike purely descriptive analysis, the case study demonstrates a cause-effect relationship between behavioural intervention and radon dynamics, supporting the interpretation of the observed ventilation-related dynamics.

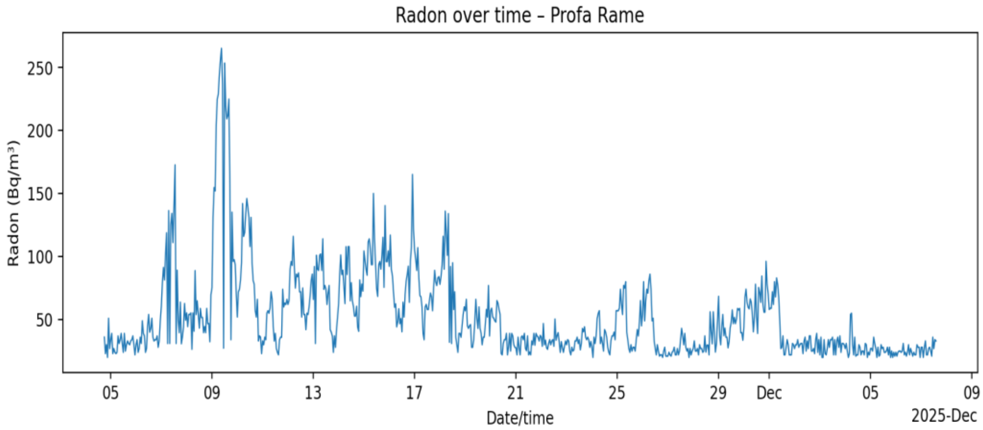

Figure 7. Case study results showing radon concentration before and after behavioural intervention in the office environment

From an applied perspective, the case study highlights how behavioural interventions can be as effective as structural mitigation measures, particularly in office environments where ventilation practices are flexible. This observation reinforces the role of continuous monitoring not only as a diagnostic tool, but also as a feedback mechanism capable of informing occupants and facility managers in near real time. Such feedback-driven mitigation strategies may represent a cost-effective complement to conventional radon control measures, especially in existing buildings where structural modification is not practical.

Results and discussion

Hourly radon concentrations across the monitored environments ranged from approximately 1 to 265 Bq m^{-3}, with the highest variability recorded in the office and working room. Short-term accumulation events were most frequent during weekends and periods of reduced room access, in agreement with recent high-resolution radon studies (Mao et al., 2023). These peaks were typically followed by rapid declines once ventilation resumed, confirming the dominant role of air exchange compared with slower environmental drivers. Rooms with limited ventilation and low occupancy showed more stable but persistently elevated radon levels than naturally ventilated spaces.

The stratified and correlation analyses indicated that temperature effects were secondary and largely context-dependent, while ventilation and occupancy behaviour exerted a much stronger influence on short-term radon variability.

The office case study reinforced this conclusion by providing direct evidence of a behavioural effect, moving the interpretation beyond statistical association towards a causal explanation.

Some limitations should be noted. The study covered a limited number of rooms, which restricts direct generalisation to wider building stocks; however, the aim was methodological rather than population-based, and the selected rooms were deliberately diverse in floor level, ventilation, and occupancy. Long-term passive measurements were not included, as the focus was on short-term dynamics that such techniques cannot capture. Finally, the analytical methods were intentionally simple and exploratory, favouring clarity and interpretability over predictive modelling. Future work may extend this framework by including pressure differences, indoor-outdoor temperature gradients, and hybrid modelling approaches to improve short-term exposure assessment.

Conclusions

This study demonstrated substantial short-term variability in indoor radon concentrations across the monitored environments using high-resolution hourly monitoring (Mao et al., 2023). Hourly values ranged from approximately 1 to 265 Bq m^{-3}, with the highest average concentration recorded in the working room (94.3 Bq m^{-3}) and the lowest in the archive room (23.3 Bq m^{-3}). Marked accumulation events were observed during periods of reduced ventilation and low occupancy, while rapid declines consistently followed natural ventilation or routine human activity.

Reproducible daily patterns and room-specific radon-temperature relationships were identified, although ventilation and occupancy emerged as stronger drivers of short-term radon dynamics than temperature alone. The office case study further showed that simple behavioural actions, such as keeping windows open during working hours, can effectively reduce indoor radon levels under real operational conditions. Beyond radiological interpretation, the work highlights the practical value of combining continuous monitoring with accessible analytical tools such as time-series analysis, heatmaps, and stratified comparisons. The proposed framework offers a simple and replicable approach for studying indoor environmental dynamics and shows how high-resolution monitoring supports a more realistic understanding of indoor radon behaviour in occupied spaces.

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