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The effect of particle size, meteorological parameters, and building airtightness on particulate matters infiltration

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ABSTRACT

Introduction: The present study analyzed the infiltration behavior of size-fractionated particles and the influencing parameters.

Materials and methods: The studies were carried out in two apartments under varying conditions of airtightness, utilizing real-time surveillance of Particulate Matters ($PM_{0.3}$, $PM_{1.0}$, $PM_{2.5}$, PM_{10}), along with air exchange rates and meteorological factors. The seasonal variations of the indoor dissemination of particulate matters have been also discussed.

Results: The analysis of correlations indicated a strong dependency of indoor Particulate Matter (PM) concentrations on outdoor levels. However, the penetration patterns varied across different particle sizes. The highest contribution to outdoor PM_{10} was observed for $PM_{2.5-10}$ while indoors, the predominant particle size was among the finer categories, $PM_{0.3-1.0}$. Moreover, window air-tightening appeared to decrease the overall effective leakage area of the building envelope, which in turn slightly lowered the ratio of indoor to outdoor PMs as well as the infiltrability for particles of all sizes. However, this intervention did not alter the distribution of particles within indoor environments.

The most penetrated particles were observed in the size range 0.3-1.0 µm and then $PM<0.3$ µm, and the least in the size range 2.5-10 µm.

Conclusion: Particle dimensions and external sources primarily influenced the degree of particle infiltration, significantly overshading the impact of weather-related factors. The relationship between indoor and outdoor particulate matter was diminished by the airtightness of windows, particularly for larger particles. No notable difference was observed in the infiltrability and indoor distribution of particles of varying sizes between the winter and fall seasons.

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Introduction

The importance of indoor air quality lies in that people, specifically certain groups, such as housewives and individuals of specific age groups, tend to spend up to 90% of their time in closed spaces [1-6].

World Health Organization (WHO) reports that fatalities related to non-communicable diseases including cardiovascular, respiratory conditions, and the incidence of lung cancer attributed to indoor air pollution significantly exceeds that associated with outdoor air pollution [7]. Prior investigations have indicated that particle accumulation varies across different regions of the respiratory tract and is directly related to particle size [8], Additionally, researches have indicated that particles originating from outdoor environments pose a greater risk to human health. [9, 10].

Since particles of different sizes impact health with different mechanisms, examining the outdoor distribution of various particle sizes and their ability to penetrate the building envelope under different weather conditions is vital for predicting their total exposure and how they harm human health [11]. Positive values of the correlation coefficient between indoor and outdoor particles in residential buildings indicate the high dependence of indoor particles on the ambient environment [12].

The indoor concentration of particulate pollutants depends on various factors such as production, and deposition in the indoor environment as well as outdoor penetration, which is affected by the meteorological parameters and permeability of buildings (airtightness) [11,13-15]. Under natural ventilation, particles penetrate the building through adventitious air leaks in the building envelope, window gaps, and openings [16].

Numerous research efforts have focused on analyzing the correlation between particles of varying sizes found both indoors and outdoors. [17-19]. Some investigations have examined the infiltrability of various particle sizes [20]–[23], while others have focused on the physical characteristics of the constructions, such as air-permeability, and their influence on short-term indoor particle concentrations [24-27]. Nonetheless, there has been limited research on the combined impact of building permeability (including airtightness and ACH), meteorological conditions, and particle size on the infiltration and indoor dispersion of particles across different size fractions, particularly through continuesly tracking all involved variables in real-time [28].

On the other hand, the quality of indoor air differs across various countries and even among different cities within a single nation, influenced by elements like local climate, external sources of pollution, construction technology, and the behaviors of inhabitants.

At the local level, due to the significant air pollution of Tehran city in terms of particulate matter, especially in the cold seasons of the year, there is a possibility of high levels of pollution in the indoor environment. Currently, Tehran lacks monitoring facilities for fine particulate matter, specifically $PM_{0.3}$ and $PM_{1.0}$, and there are rarely studies related to the estimation of indoor exposure to such pollutants, especially for winter and under seasonal inversion conditions.

To the best of our knowledge, few studies on the distribution of particles in the indoor environment are available in open databases. Some investigated the impact of PM size on its distribution in the indoor environment [29, 30] but did not consider other effective parameters such as ACH, envelope airtightness, and meteorological variables.

Additionally, a comparable study examined how various factors, including particle size, building airtightness, and air exchange rates, influence the distribution of PMs across indoor and outdoor settings [28], but only the data of the fall season were involved. This article complements the results of the previous study by studying the data of the winter season. In this study, we want to know how and in what direction the change of season affects the infiltration of size-fractionated particles and their relative indoor distribution.

Although, the effect of seasonal changes (comparison of summer and winter) on the concentration of size-fractionated particles indoors has been studied previously [31], however, the effect of seasonal variations on the PM infiltration, indoor-outdoor particles correlation, as well as changes in the dispersion of indoor particulate matters with the outdoor origin under different envelope airtightness conditions remains as a research gap, which has been covered in this study.

The nonexistence of an intrinsic particle source (Absence of resident presence and activity) and natural ventilation of apartments were significant assumptions in the study.

The outcome of this research enhances our comprehension of seasonal variations in the penetration of particles of varying dimensions in airtight and non-airtight buildings, thereby helping to manage the risks associated with exposure.

Materials and methods

Description of the measurement location

Two residential apartments, characteristic of older structures in Tehran, the largest city and capital of Iran, and featuring poorly sealed windows, were chosen for the study. These units were situated within the same building complex (Fig. 1), and displayed comparable physical characteristics with the exception of window air-permeability. In one site, no airtightness intervention was made in the existing window (Site A), and for the other, to reduce envelope leakage, the window gaps were sealed by airtight strips (site B). Site A (bedroom 1 in Fig. 1) and site B (bedroom 2 in Fig. 1) were located on the third and fourth floors, respectively.

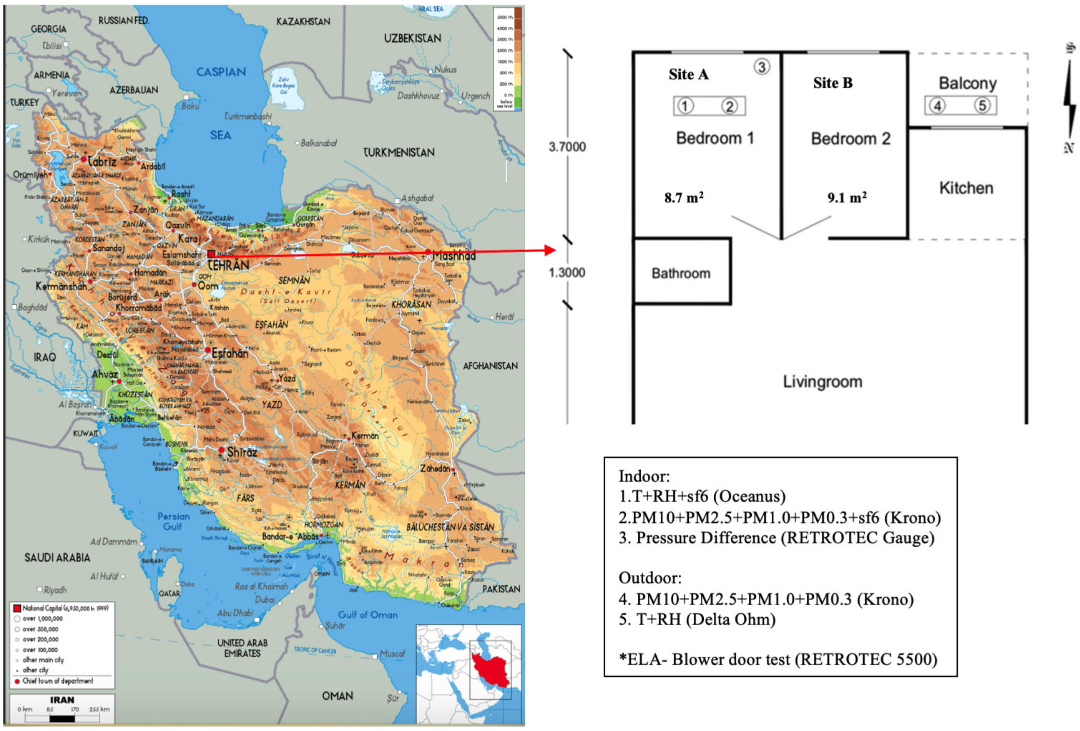


Fig. 1. Diagram of the research zone and layout of the apartments (located on the third and fourth floors) indicating the positioning of the instruments

Measurements were performed in the bedroom of each apartment under natural ventilation through the gaps of the closed windows. Aside from the infrequent visits by the operator to monitor the instruments and gather data, there were no indoor activities generating particulate matter during the experiment, and the building remained unoccupied to reduce disturbances from internal sources. Due to the lack of sampling equipment and due to the test method, which was continuous monitoring for at least one week with one-minute resolution, it was not possible to simultaneously monitor sites A and B. Therefore, the measurements were carried out in two sites alternately and under relatively similar outdoor conditions in terms of meteorological parameters.

The data collection period at site A spanned from January 22 to February 2 (about 247 h) and the period for site B was from 20 to 28 February (about 202 h).

To minimize the impact of internal variables like particle resuspension due to operator movements, the room's door was sealed for eight hours prior to each experiment. This protocol was established to equalize particle concentrations between indoor and outdoor environments before beginning the tests. Moreover, during the test, the air conditioner duct and door gaps were sealed to diminish the interference of internal sources.

The Tehran Air Quality Control Company reported that in 2021 and the first months of 2022, Tehran had polluted air on about 30% of the days. On 60% of these days, $PM_{2.5}$ was the primary pollutant. Measurements performed in the winter (January and February 2022) sometimes, overlapped with intense PM pollution brought on by seasonal inversion, with hourly and daily concentrations exceeding the allowable limit. Therefore, the study results cover seasonal inversion conditions.

Study arrangement

Assessments of particle levels, ventilation rates, and meteorological variables

In this research, the focus was on examining the infiltration behavior of particles in different size fractions. So, real-time concentrations of PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and $PM_{0.3}$ along with weather related factors, including temperature, Relative Humidity (RH), and the pressure difference between indoor and outdoor environments, were recorded every minute at locations A and B, which resulted in 8325 data sets for site A and 11881 data sets for site B. Also, the air change rate was continuously monitored using the SF6 decay technique, and the building airtightness in terms of Effective Leakage Area (ELA) for each site was also measured using the blower door.

Fluctuations in indoor and outdoor particle levels on an hourly and daily basis, along with the indoor/outdoor (I/O) ratio for four specific particle size fractions ($PM_{0.3}$, $PM_{1.0}$, $PM_{2.5}$, PM_{10}) and three size-resolved categories ($PM_{2.5-10}$, $PM_{1.0-2.5}$, $PM_{0.3-1.0}$), were examined at each location.

The infiltration factors for $PM_{0.3}$, $PM_{1.0}$, $PM_{2.5}$, and PM_{10} were estimated for both airtightness cases, using data series for indoor-outdoor concentrations and ACH.

The correlations between indoor and outdoor concentrations of different particle sizes were analyzed under airtight (site A) and non-airtight (site B) window conditions, using the Pearson correlation method. Also, multivariate regression models for indoor PM as a dependent variable and outdoor concentration, meteorological factors, and ACH as independent variables were developed to investigate the effect of influencing factors on the infiltration of different size fractions. The field measurement equipment utilized is as follows:

Real-time measurements of $PM_{0.3}$, $PM_{1.0}$, $PM_{2.5}$, and PM_{10} particles were conducted using two gas and particle detectors (KORNO-GT1000 series) that employ light scattering photometric technology. Prior to the experiment, these devices were calibrated by a well-established representative company. The indoor monitoring unit was positioned 1.1 m above the floor and centrally located at least 1.5 meters away from any doors and walls. Meanwhile, the outdoor unit was situated on a balcony of the building's facade within a shelter designed to protect the apparatus from direct exposure to sunlight and precipitation. Calibration of particle measurement devices for both indoor and outdoor environments was conducted during various intervals by positioning them alongside each other and in conjunction with the Tehran Air Quality Reference Station, where they exhibited an average discrepancy of 10%. This facilitated the adjustment of the preliminary data output. Furthermore, to verify the uniformity of the deviations observed between the two devices, an analysis of the real-time data correlation for the paired devices was undertaken. This analysis demonstrated a substantial and meaningful correlation between the datasets (R^2=0.92,P-Value≅0).

Indoor RH and temperature levels were tracked using the Oceanus (model:OC-1000), which includes a data logger, while the external conditions were recorded with the Delta OHM device (model: HD206-2).

The ACH indicates the number of times that the volume of indoor air changes occurs per hour, including various forms of exchange through the building shell (gaps), door and window openings, and any active or non-active ventilation. The ACH was measured using the SF6 detector, through gas decay technique (ISO 125669). This technique can be employed even while the residents are in the building. It has sufficient accuracy at a wide range of concentrations. Although its density is about five times that of air, this difference has no systematic effect on the results of air exchange measurements at concentrations usually applied in practice [33]. SF6 gas was injected at a concentration of 300 ppm intermittently every 3 to 6 hours. Decay levels were monitored minutely using a pair of electrochemical sensors, specifically the Oceanus (model: OC-1000) and the KORNO (model: GT-1000), which have accuracies of 1 ppm and 0.1 ppm, respectively. The function describing the concentration decay is given by Eq. 1:

$$C(t) = C_0 * e^{-\lambda * t} \tag{1}$$

WhereC_0 is the SF6 gas level at time injected t = 0, and λ is the air change per hour (h^{-1}).

To ensure accuracy in measuring RH and temperature, the instruments were adjusted using the reference equipment from the Energy Laboratory of BHRC (Testo 177H1-RH and Temp. Logger). The deviation found when compared to the reference instrument was around -0.4°C for temperature and -8% for RH. These discrepancies were accounted for in the adjustments made to the output data.

The instantaneous pressure differential (ΔP) was recorded using the Retrotec-5500 Blower Door gauge with the fan deactivated. To facilitate this measurement, one hose of the gauge was positioned within the interior space, while its counterpart was extended outside the building through a securely sealed aperture in the wall. This setup enabled continuous monitoring of the pressure variance between the indoor and outdoor settings by the gauge, which possesses a precision of 0.1 Pascals. The data was systematically logged at one-minute intervals by the associated data logging software.

Air permeability test

To examine the characteristics of air leakage, the area of leakage was quantified using a blower door system (RETROTEC model: 5000 with DM32), adhering to the EN13829 testing protocol. The error margin in measuring air volume was approximately -3%. This system was set up at the main entrance of the room. The fundamental principle of this apparatus involves determining a correlation between the airflow generated by the fan and the pressure differential between the indoor and outdoor environments, typically assessed through a 3-point or 5-point test. From this setup, the C and n coefficients were derived as per Eq. 2 [11].

$$Q = C\,\Delta P^{n} \tag{2}$$

In this expression, Q represents the rate of airflow through the envelope, ΔP denotes the pressure differential between the interior and exterior, C is the coefficient of flow, and n refers to the exponent, which is dimensionless. The flow coefficient, denoted as C, has a direct correlation with the overall leakage area of the structure. The n value ranges from 0.5 to 1.0, and in typical buildings, this coefficient commonly approaches 0.65 for the usual aggregate of leakage pathways in houses [34]. The permeability of a building is represented by the Effective Leakage Area (ELA), measured in square meters. It represents an orifice area that would have the same airflow rate at a specified pressure difference. It is calculated from Eq. 3 [11, 20].

$$\text{ELA}= C\,\Delta P_{ref}^{n-0.5}\sqrt{\frac{\rho}{2}} \tag{3}$$

Δ_{Pref} represents the reference pressure differential, set at 4 Pa, while ρ denotes the density of air, which is presumed to be 1.2 kg/m^3. Furthermore, the specific effective leakage area (specific ELA), defined as the ELA normalized by the floor area or envelope area, was determined to evaluate the level of airtightness relative to each unit area of the floor and envelope.

Analysis

Infiltration factor

The infiltration factor (F_{inf}) served as a measure representing the proportion of outdoor particles that penetrate and stay suspended indoors, utilized to adjust the exposure estimates. This factor is determined by the particle penetration factor (P), the deposition rate (K), and the air change rate per hour (ACH) Eq. 4 [35].

$$F_{inf} = (P.ACH)/(ACH + k) \tag{4}$$

P is a dimensionless quantity ranging from 0 to 1, while ACH and k share identical dimensional characteristics (inverse time). Consequently, the infiltration factor remains a dimensionless figure, varying between 0 and P.

Assuming that the air within the indoor environment is uniformly mixed and by combining the mentioned factors (P, K, and ACH) in a mass conservation model, Eq. 5 indicates the dynamic concentration of indoor particles:

$$\frac{dC_{in}}{dt} = P.ACH.C_{out} - (ACH + k)C_{in} \tag{5}$$

Over short periods (Δt = 1 minute), Eq. (5) is written as a difference equation (Eq. 6). From the nonlinear solution of this equation, the unknown coefficients P and k can be obtained [36]:

$$C_{in_{t+1}} = P.ACH.\Delta t\, C_{out_{t+1}} + (1 - (ACH + k)\Delta t)C_{in_t} \tag{6}$$

Where, C_{in} is the indoor level (µg/m^3), C_{out} is the outdoor level (µg/m^3), and Δt is the time difference (one minute). Given that the above equation does not consider any internal source, the impact of the internal source should be censored, if any.

We employed the Solver plugin, an optimization algorithm in Microsoft Excel, to derive optimal estimates for the parameters p and K for each particle size in each time series (approximately

11,400-minute data for site A and 12,000-minute data for site B) by minimizing the absolute relative discrepancy between the observed and predicted concentrations as shown in Eq. 6.

The infiltration factor of each particle size was calculated by substituting the estimated values of p and k in Eq. (4). The voids in ACH data were completed by averaging the values measured before and after each gap. In contrast, missing data on temperature and RH were not subjected to interpolation and were instead excluded from the dataset.

2.32. Regression and Correlation Analysis

The association between the indoor and outdoor concentration of particles in different size fractions was determined using Pearson correlation analysis (Eq. 7). The correlation coefficient, r, varied between -1 to 1.

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})\,(Y_i - \bar{Y})}{(n-1)\,S_x\,S_y} \tag{7}$$

In this expression, r represents the correlation coefficient, $\bar{X}$ and $\bar{Y}$ denote the means of the samples x and y respectively. S_x and S_y indicate the standard deviations of the samples x and y, and n stands for the sample size. A correlation coefficient exceeding 0.7 suggests a robust relationship between the two variables [37], and when the P-value is less than 0.05, the result is statistically significant.

In order to investigate the factors affecting the indoor levels of PMs, all available predictor variables, including meteorological variables and air change rate, were evaluated. Parameters that showed a significant correlation with indoor particulate matter (p-value <0.05) were chosen for inclusion in multivariate models. The efficacy of multivariate models was evaluated through the modification of variables, guided by the coefficient of determination (R^2) and P-value. Parameters exhibiting a P-value exceeding 0.05 were excluded from the models.

Results and discussion

Data analysis

Air change rate and permeability test

The average hourly air change rate at site A varied between 0.61 to 1.98 h^{-1} (1.02±0.2) which represents (mean ± Sd) from now on. At location B, which featured sealed windows, the air change per hour (ACH) varied between 0.25 to 0.96 (0.52±0.18). Reduced air exchange rates at site B may be due to the sealing of window openings.

The mean ACH in both locations showed almost 25% higher values for winter compared to values reported by the authors for the fall season (October and November) [28], probably due to higher wind speed and indoor-outdoor pressure difference during winter.

As expected, the leakage test results showed that at site B, where the window gaps were sealed, the ELA was reduced by about 25% compared to site A. The specific ELA measurements for envelope areas at sites A and B were recorded as 26.6 cm^2/m^2 and 20.2 cm^2/m^2, respectively

Indoor-outdoor concentrations and I/O ratio

Table 1 summarizes the findings on particle concentrations both indoors and outdoors, as well as the indoor/outdoor (I/O) ratios for various particle sizes. These include fractionated particles ($PM_{0.3}$, $PM_{1.0}$, $PM_{2.5}$, and PM_{10}) and size-resolved particles ($PM_{0.3-1.0}$, $PM_{1.0-2.5}$, $PM_{2.5-10}$).

Table. 1. Results of indoor and outdoor particle concentrations and I/O ratio for size-fractionated (PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and $PM_{0.3}$) and size-resolved ($PM_{2.5-10}$, $PM_{1.0-2.5}$, $PM_{0.3-1.0}$) particles

Monitoring Site	No. of Samples		PM_{10}		$PM_{2.5}$		$PM_{1.0}$		$PM_{0.3}$	
			Mean±SD	Min Max	Mean±SD	Min-Max	Mean±SD	Min-Max	Mean±SD	Min-Max
Site A	247	In	17.9±16.4	0.4 66.3	15.6±13.7	0.35 53.1	11.5±9.2	0.3 37.1	3.5±3.1	0 12
		Out	46.2±34.2	1.6 148.7	37.8±28.5	1.1 129.6	24.7±17.0	0.9 83.9	7.9±5.7	0 27.6
		In/Out	0.37±0.2	0.025 2.5	0.4±0.2	0.3 3.0	0.47±0.21	0.05 4.0	0.46±0.23	0 2
			$PM_{0.3-1.0}$		$PM_{1.0-2.5}$		$PM_{2.5-10}$			
			Mean±SD	Min Max	Mean±SD	Min-Max	Mean±SD	Min-Max		
		In	7.98±6.15	0.3 25.1	4.08±4.6	0 16.7	2.37±2.8	0.05 13.3		
		Out	16.8±11.4	0.85 56.3	13.1±11.6	0.25 45.9	8.4±6.1	0.36 20.3		
		In/Out	0.46±0.3	0.09 4.56	0.25±0.26	0 3.7	0.27±0.18	0.03 1.18		
Site B	202		PM_{10}		$PM_{2.5}$		$PM_{1.0}$		$PM_{0.3}$	
		In	12.1±7.76	3.05 48.7	10.8±6.79	2.3 39.75	8.56±4.58	1.85 26.5	2.52±1.52	2.7 6.1
		Out	35.7±18.3	6.12 98.87	28.8±14.2	4.3 83.02	19.2±8.26	3.03 51.5	6.05±2.8	0.73 16.8
		In/Out	0.36±0.15	0.12 0.7	0.39±0.16	0.14 0.69	0.46±0.17	0.16 0.53	0.42±0.18	0.11 0.49
			$PM_{0.3-1.0}$		$PM_{1.0-2.5}$		$PM_{2.5-10}$			
		In	6.04±3.06	1.68 17.98	2.26±2.2	0.17 13.22	1.29±1.12	0.2 8.95		
		Out	13.15±5.5	2.3 34.73	9.62±6.07	1.0 33.83	6.92±4.36	0.67 18.1		
		In/Out	0.48±0.17	0.18 0.55	0.24±0.14	0.04 0.48	0.23±0.15	0.05 0.5		

At both locations, the pattern of Particulate Matter (PM) indoors mirrored that observed outdoors, suggesting a notable influence of external PM on indoor concentrations when there are no internal sources present (Fig. 2 and Fig. 3).

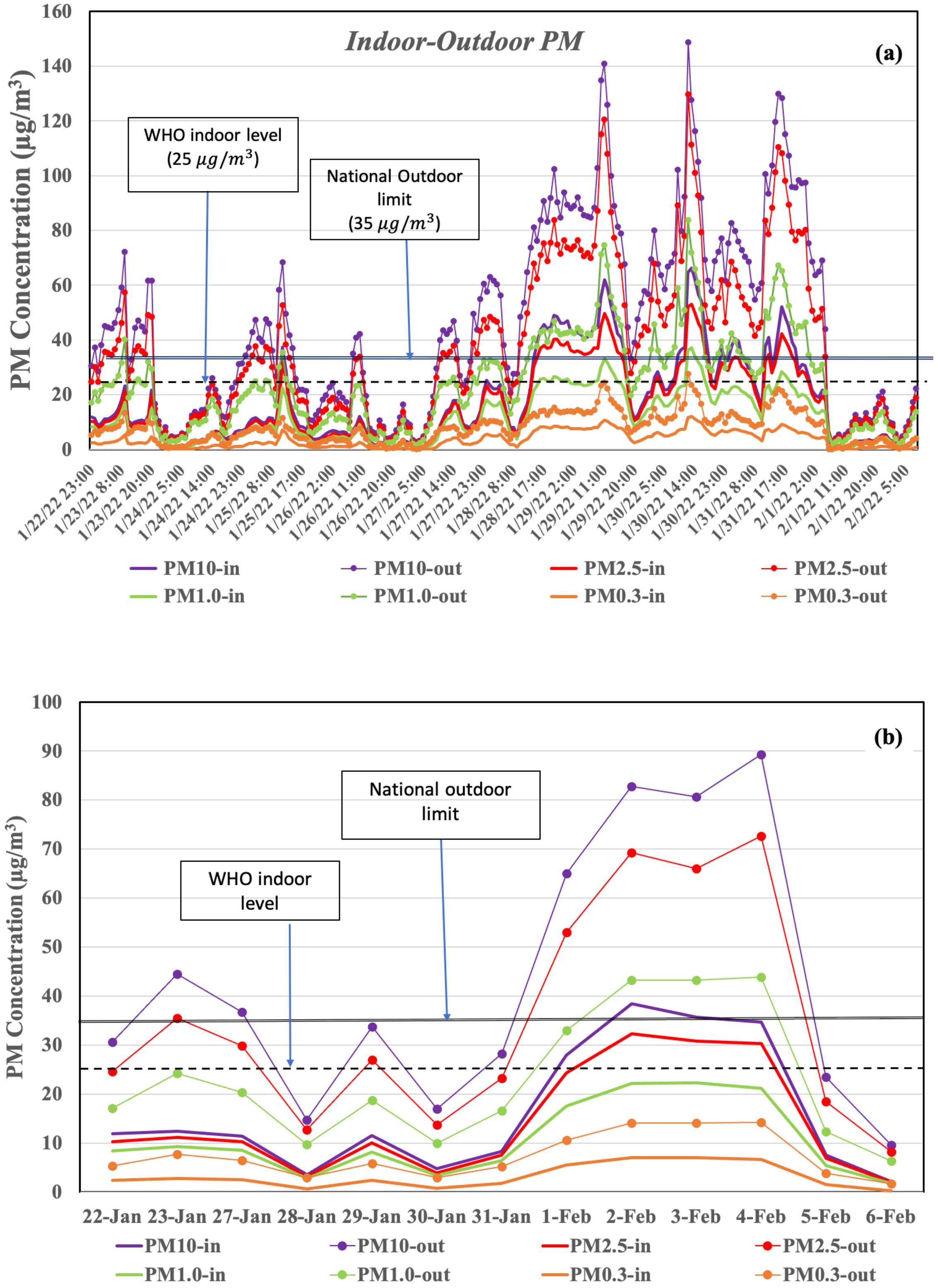


Fig. 2. Indoor and outdoor PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and $PM_{0.3}$ mass concentrations a) Hourly trend and b) daily average variations in site A

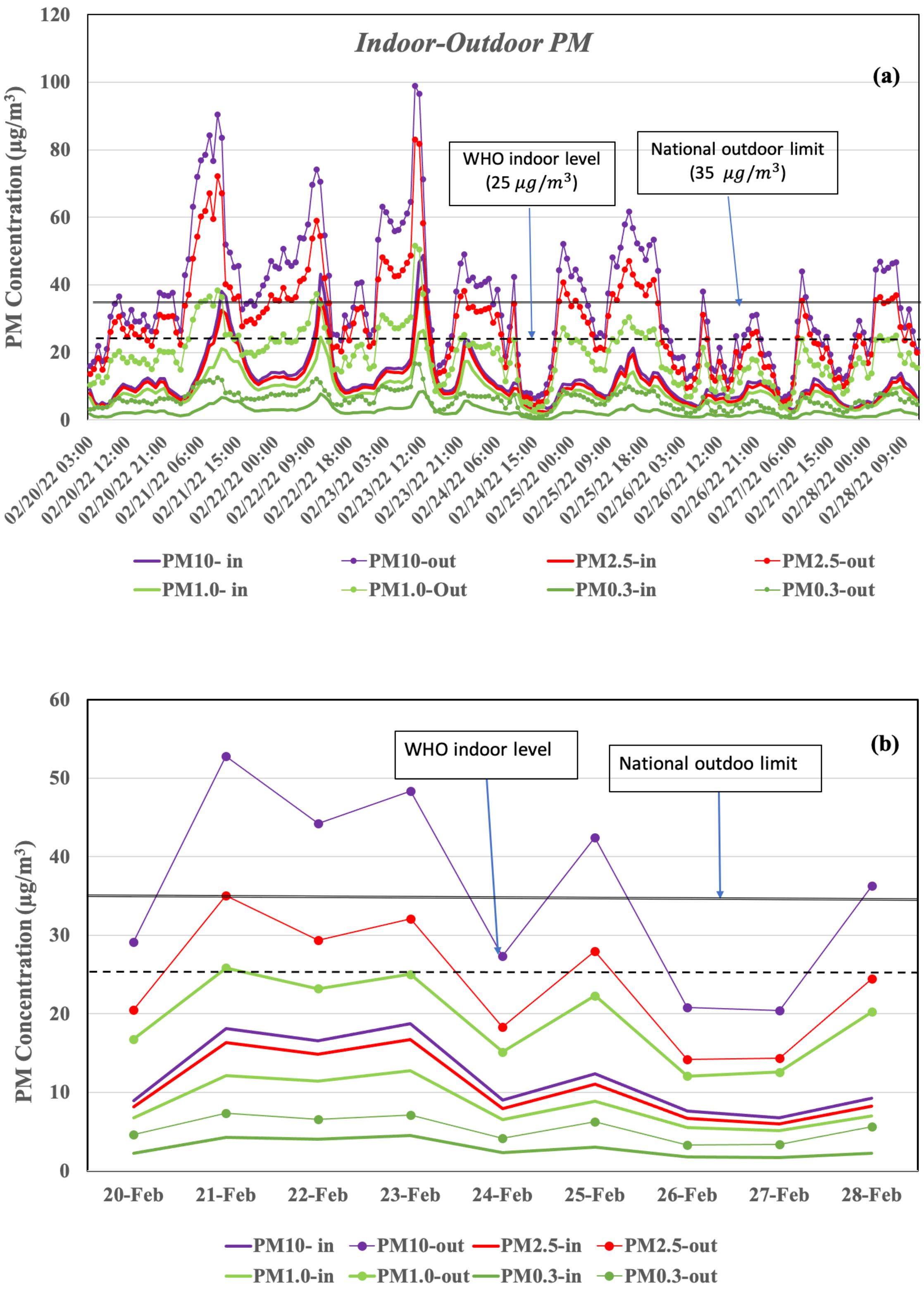


Fig. 3. Indoor and outdoor PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and $PM_{0.3}$ mass concentrations a) Hourly trend and b) daily average variations in site B

For site A, from January 31 to February 4, the average daily concentration of outdoor PM, especially for $PM_{2.5}$, was dramatically higher than the permissible limit (about two times) due to seasonal inversion. Similar results were obtained for the indoor environment from February 1 to 4, when the average daily $PM_{2.5}$ exceeded the WHO recommended limit (25 µg/m^3).

In site A, the hourly mean concentration of outdoor PM_{10} and $PM_{2.5}$ exceeded WHO guidelines in 40% and 60% of the sampled times, respectively, while the corresponding exceedance for the indoor PM_{10} and $PM_{2.5}$ levels were 4% and 26% of the monitored duration, respectively.

At site B, the average hourly concentration of outdoor PM_{10} exceeded the WHO guideline in 19% of the sampling times. PM_{10} was below the allowable limit indoors during the study. For $PM_{2.5}$, the indoor and outdoor exceedance was 5% and 57%, respectively; indicating similar to site A, $PM_{2.5}$ was the primary pollutant.

So, window air tightening significantly reduced indoor exposure to polluted air. Although in case B similar to case A in 57% of the sampled time the outdoor $PM_{2.5}$ surpassed the WHO permissible limit, indoor exposure time with contaminated air showed an 80% reduction compared to the leaky building.

High values of PM concentration in Tehran are possibly associated with heavy traffic and emissions from close sources, which can be of traffic origin for the sampled locations due to proximity to the highway.

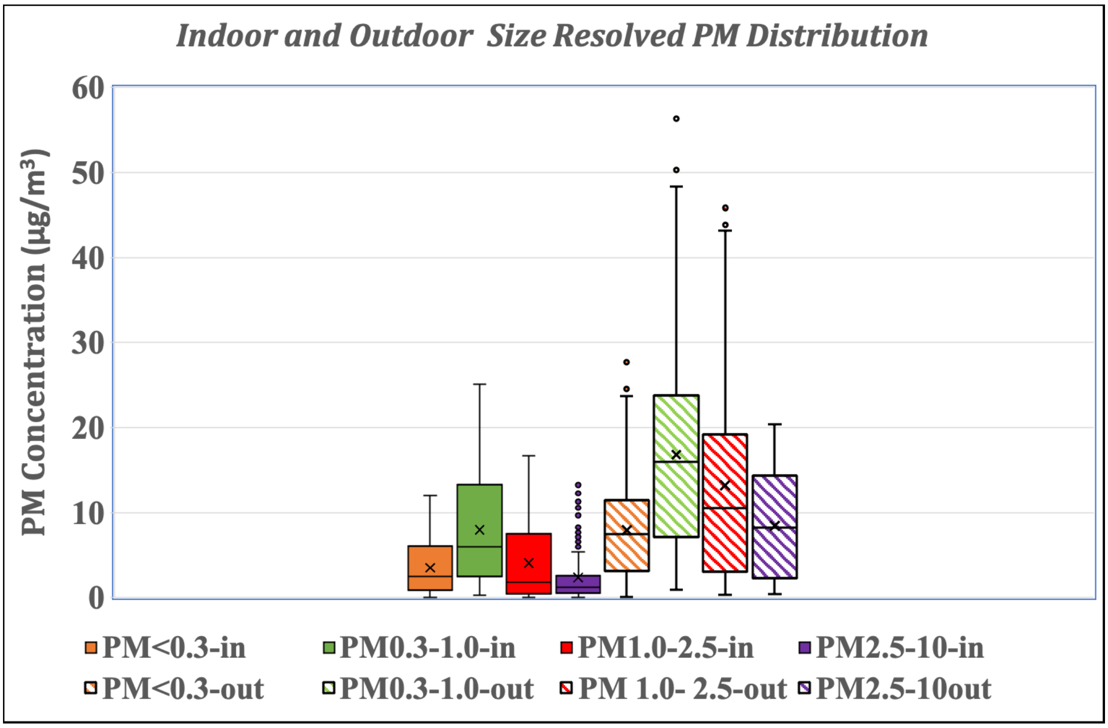
No guidelines or national standard levels are currently recommended for $PM_{1.0}$ and $PM_{0.3}$, so it was impossible to compare their concentration levels with the standard.

The distribution of particles by size, both indoors and outdoors (PM<0.3, $PM_{0.3-1.0}$, $PM_{1.0-2.5}$, and $PM_{2.5-10}$), is illustrated in Fig. 4a for site A and Fig. 5a for site B. For both sites, the highest outdoor levels of particles were observed for $PM_{0.3-1.0}$ and $PM_{1.0-2.5}$, and the lowest one for $PM_{2.5-10}$ particles. The indoor environment experienced a similar distribution of PMs. These results are in agreement with the previous study for the fall season, which showed that the highest frequency of particles in the indoor was pertinent to particles in the size range of 0.3 to 2.5 µm and the lowest concentration in the indoor environment was related to particles in the range of 2.5 to 10 µm, confirming that seasonal variations did not influence the indoor distribution of particles categorized by size.

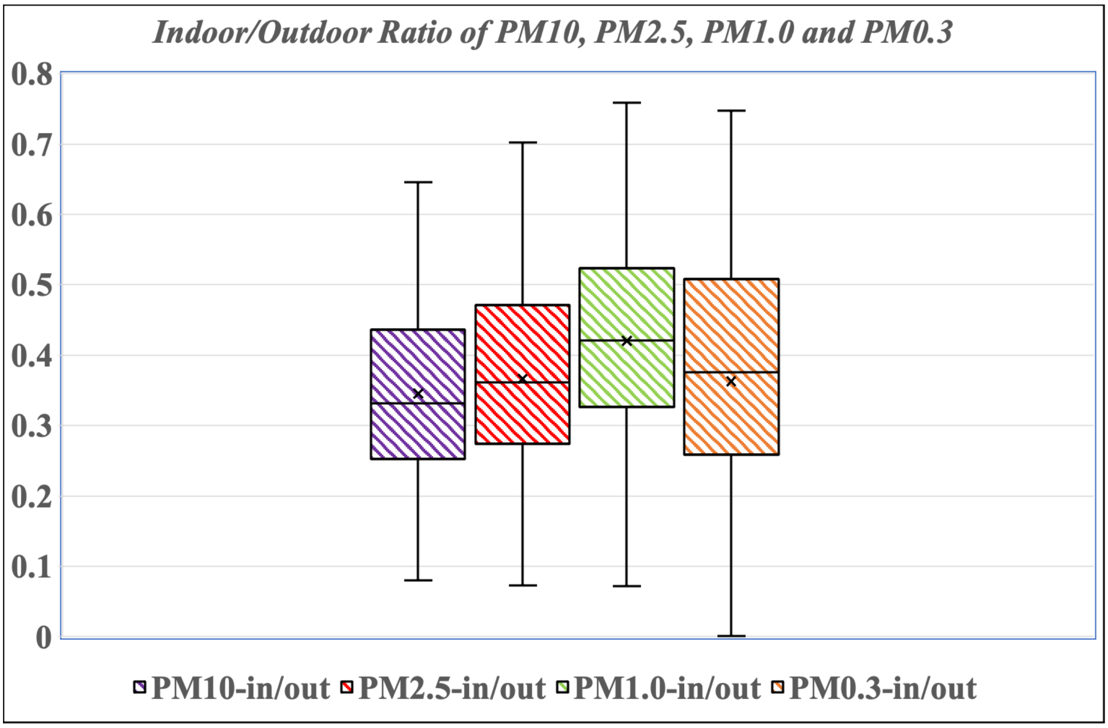
As depicted in Fig. 4b, at site A, the highest hourly I/O recorded for $PM_{1.0}$ was 0.47, while the lowest was for PM_{10} at 0.37. This difference can be explained by the higher penetration capabilities of $PM_{1.0}$ compared to the lower permeability of PM_{10}, consistent with the literature [38]. For site B, the mean I/O ratio varied between 0.36 and 0.46, in which case also the I/O ratio was maximum for fine particles ($PM_{1.0}$) and minimum for coarse particles (PM_{10}) (Fig. 5b). Regarding seasonal changes, a comparison with the results of the previous study [28], shows that the I/O ratio for different particles increased by less than 10% (7 to 9.5%) in the winter season compared to the fall season, indicating negligible effects of the season variation on the infiltration of particles into the indoor setting.

Analyses of the indoor/outdoor ratios for particulate matter of various size ranges ($PM_{2.5-10}$, $PM_{1.0-2.5}$, $PM_{0.3-1.0}$, and PM<0.3) were conducted as well (Fig.4c and Fig. 5c). For both leaky and airtight windows, the greatest I/O ratio was observed for $PM_{0.3-1.0}$ and particles smaller than 0.3 µm and the lowest for $PM_{2.5-10}$, endorsing the pre-mentioned findings of penetration behavior of fine and coarse particles. Sealing the gaps around windows at site B led to a reduction in the indoor/outdoor ratio by an average of 17% across all particle sizes.

This slight difference is justifiable with envelope-specific ELA, which was not significantly different for leaky and airtight window a)


Indoor and Outdoor Size Resolved PM Distribution
PM Concentration (µg/m³)
60
50
40
30
20
10
0
PM<0.3-in
PM0.3-1.0-in
PM1.0-2.5-in
PM2.5-10-in
PM<0.3-out
PM0.3-1.0-out
PM 1.0- 2.5-out
PM2.5-10out

b)


Indoor/Outdoor Ratio of PM10, PM2.5, PM1.0 and PM0.3
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
PM10-in/out
PM2.5-in/out
PM1.0-in/out
PM0.3-in/out

c)

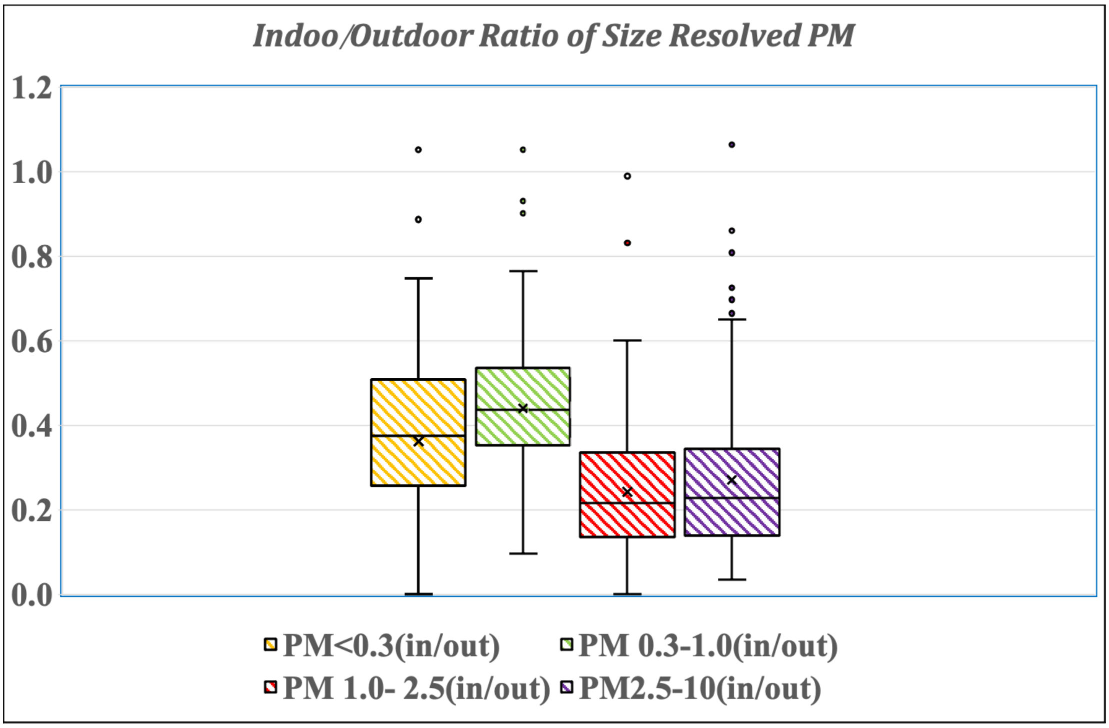
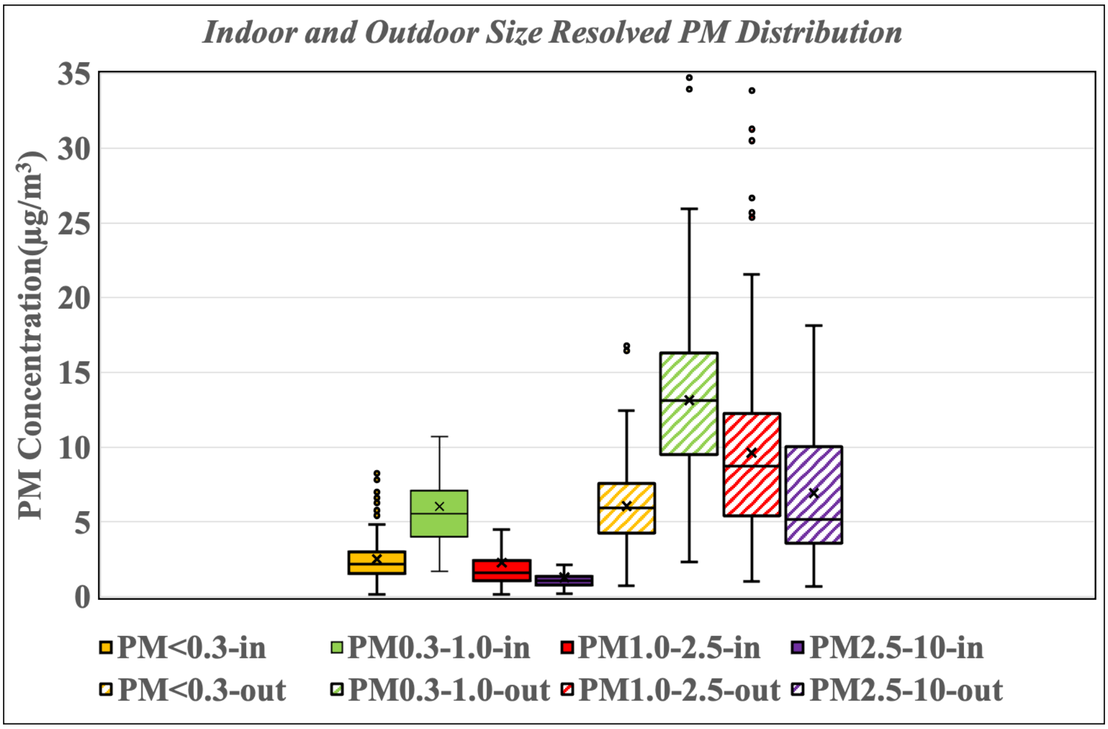
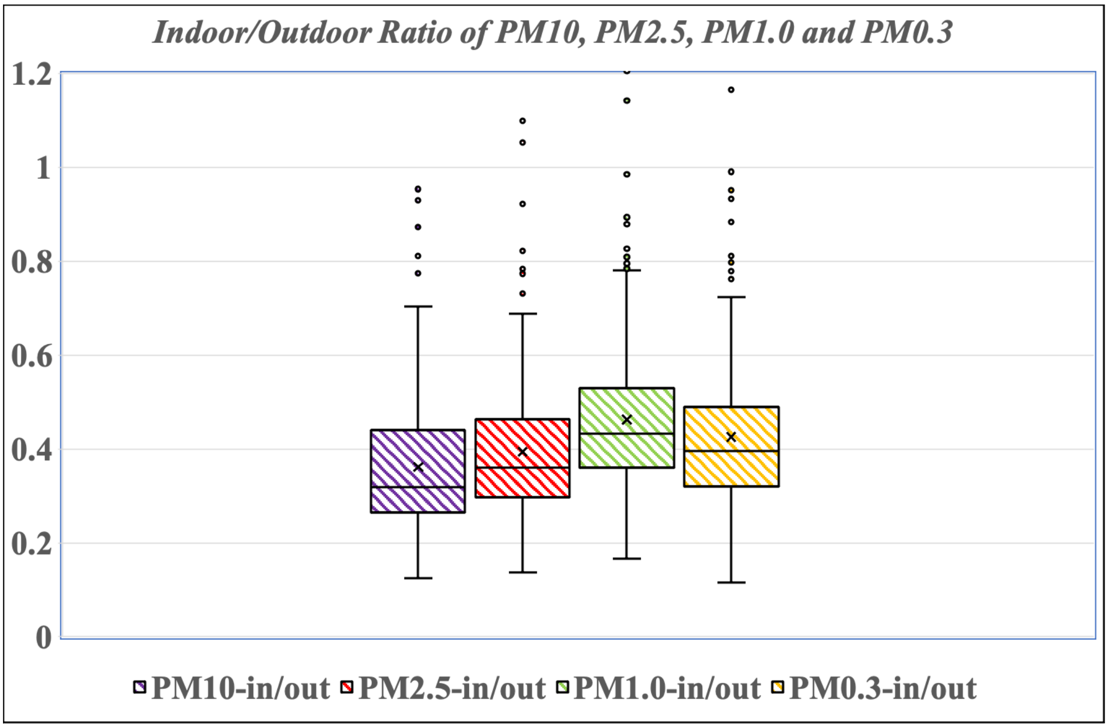


Fig. 4. Box plot for a) indoor-outdoor, b) I/O distribution of size-fractionated (PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and $PM_{0.3}$), c) I/O distribution of size-resolved ($PM_{2.5-10}$, $PM_{1.0-2.5}$, $PM_{0.3-1}$ and PM<0.3) particles for site A

a)



b)



c)

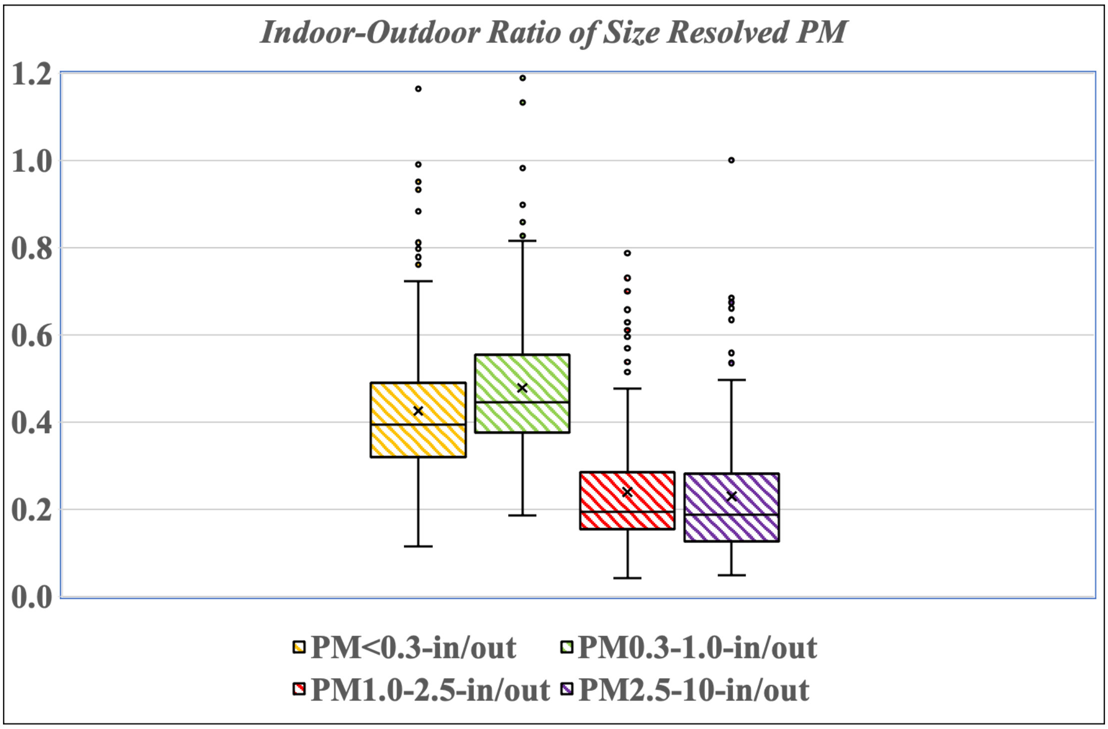


Fig. 5. Box plot for a) indoor-outdoor, b) I/O distribution of size-fractionated (PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and $PM_{0.3}$), c) I/O distribution of size-resolved ($PM_{2.5\text{-}10}$, $PM_{1.0\text{-}2.5}$, $PM0_{.3\text{-}1}$ and PM<0.3) particles for site B

We also investigated indoor and outdoor PM_{10} content (Fig. 6). Although the outdoor contribution of $PM_{0.3-1.0}$ was on average 40%, it reached 52% in the indoor environment. For particles less than 0.3 µm in size, while their contribution to outdoor PM_{10} levels was negligible, they were the predominant type of particle found indoors following those in the $PM_{0.3-1.0}$ range.

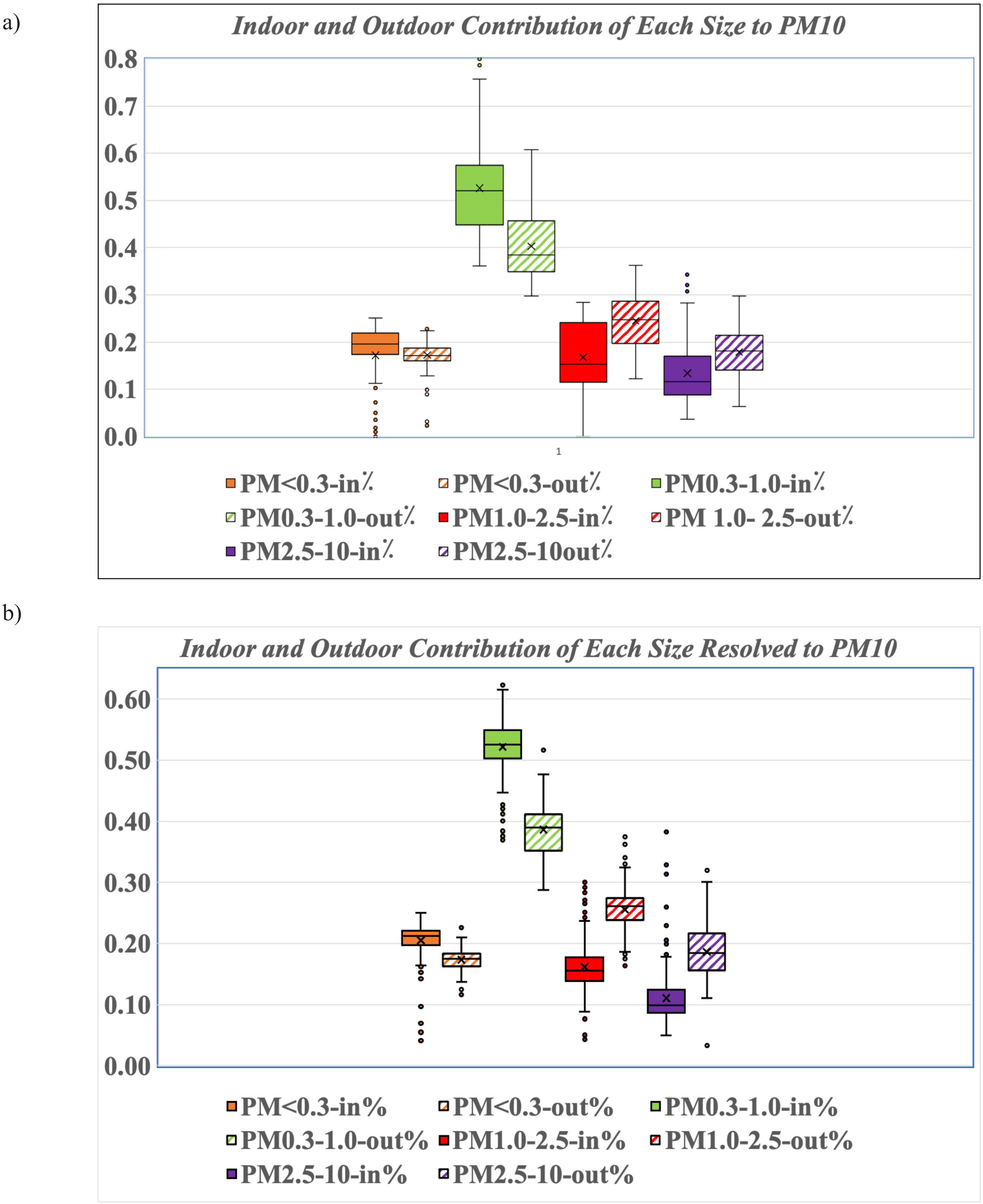


Fig. 6. Box plot for the contribution of each size-resolved particle to PM_{10} in a) Site A and b) Site B

For particles measuring between 2.5 to 10 µm, their presence indoors was found to be less significant compared to outdoor environments. This finding is consistent with a previous study, which showed that finer particles exhibit greater penetration capabilities, whereas larger particles tend to have reduced penetration [35]. These outcomes are consistent with the findings of the previous study [28], confirming that although the season change and the temperature reduction, especially when coincided with seasonal inversion conditions, increased the concentration of particles both in the outdoor and indoor environments, however, had no considerable effect on the infiltrability of different particle sizes. In both seasons, particles smaller than 1µm had the greatest penetration strength, and particles greater than 2.5 µm had the least infiltrability.

At location B, the proportional distribution of particles between outdoor and indoor settings was similar to that observed at location A, indicating window airtightness did not affect the indoor physical content of PM_{10}.

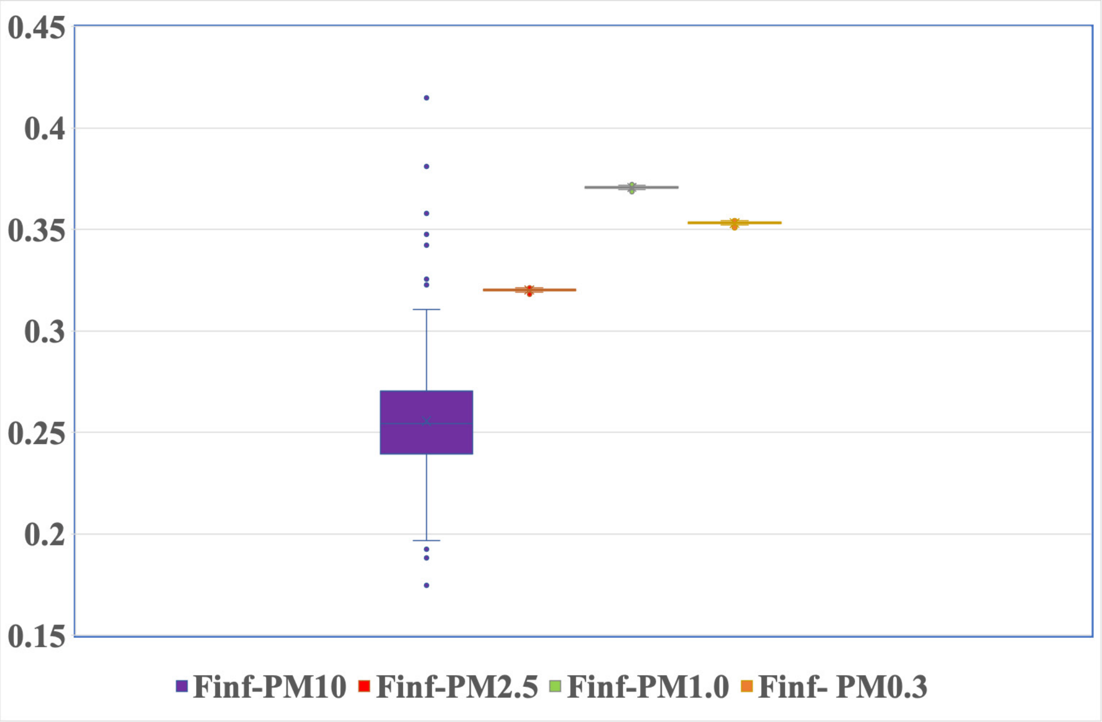
PM infiltration

To enhance the precision of our study on indoor exposure to particulate matter of respiratory origin, we determined the infiltration factor across a time series of particle concentrations (refer to Fig. 7). Consistent with the indoor/outdoor (I/O) ratios observed, the infiltration factor was highest for $PM_{1.0}$, succeeded by $PM_{0.3}$, with PM_{10} showing the lowest factor. Furthermore, window sealing was found to decrease the average infiltration factor by approximately 20%.

A previous study for the fall season has resulted in a similar trend for infiltration of particles with different sizes, which indicates that this trend is independent of the seasonal changes.

Additionally, the hourly infiltration factor for various particle sizes exhibited minimal variation from the average, and the hourly F_{inf} data was slightly scattered (Fig. 7).

a)



b)

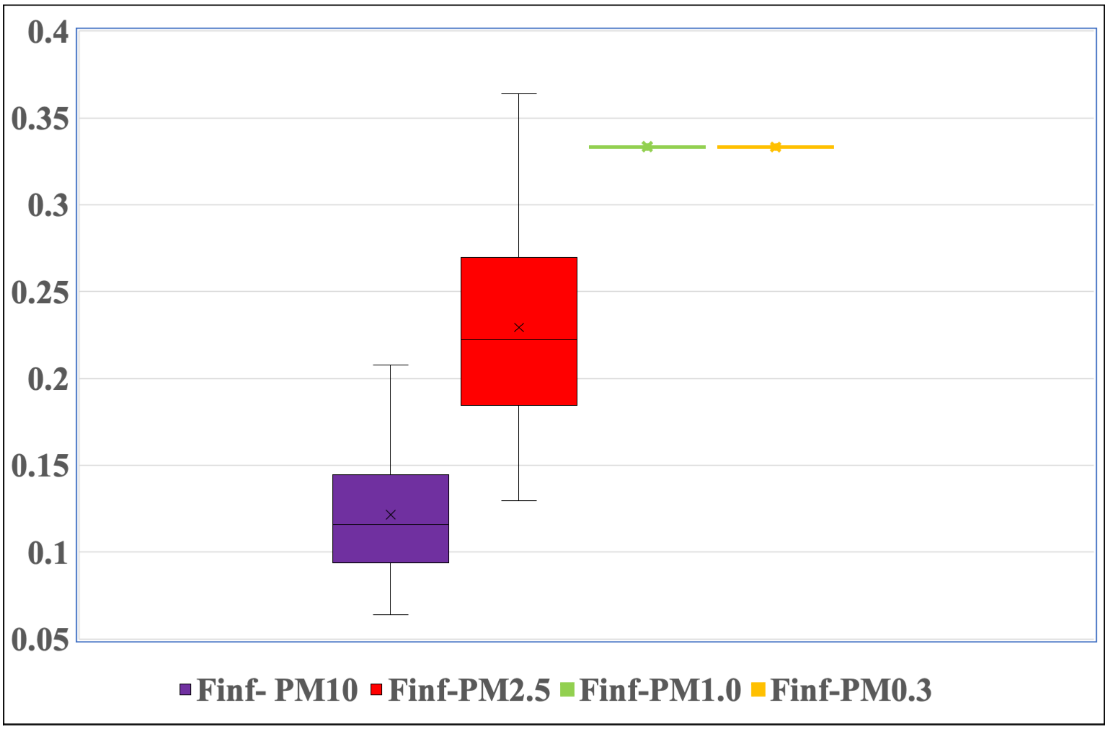


Fig. 7. Infiltration factor of PM_{10}, $PM_{2.5}$, $PM_{1.0}$, and $PM_{0.3}$ for a) Site A b) Site B

Therefore, in long-term exposure studies, the fluctuations in the infiltration factor on an hourly basis can be disregarded, allowing for the utilization of daily or weekly infiltration rates instead.

Regression and correlation analysis

The analysis of hourly measurements of both indoor and outdoor particles indicated a strong correlation at site A between indoor particulate matter and outdoor PM across all particle sizes ($R^2 \cong 0.9$), with the exception of particles ranging from 2.5 to 10µm, where the correlation was notably weaker (Fig. 8). This reduced correlation for coarser particles may be attributed to their lower penetration capabilities and greater losses through cracks in the building envelope. These results are consistent with previous studies on the lower correlation of coarse particles [12].

At location B, the integrity of the airtightness appeared to diminish the association between indoor and outdoor hourly measurements across all particle dimensions, particularly for particles ranging in size $PM_{2.5\text{-}10}$, showing that window air-sealing reduced the dependence of indoor PM concentrations on outdoor PM levels (Fig. 9).

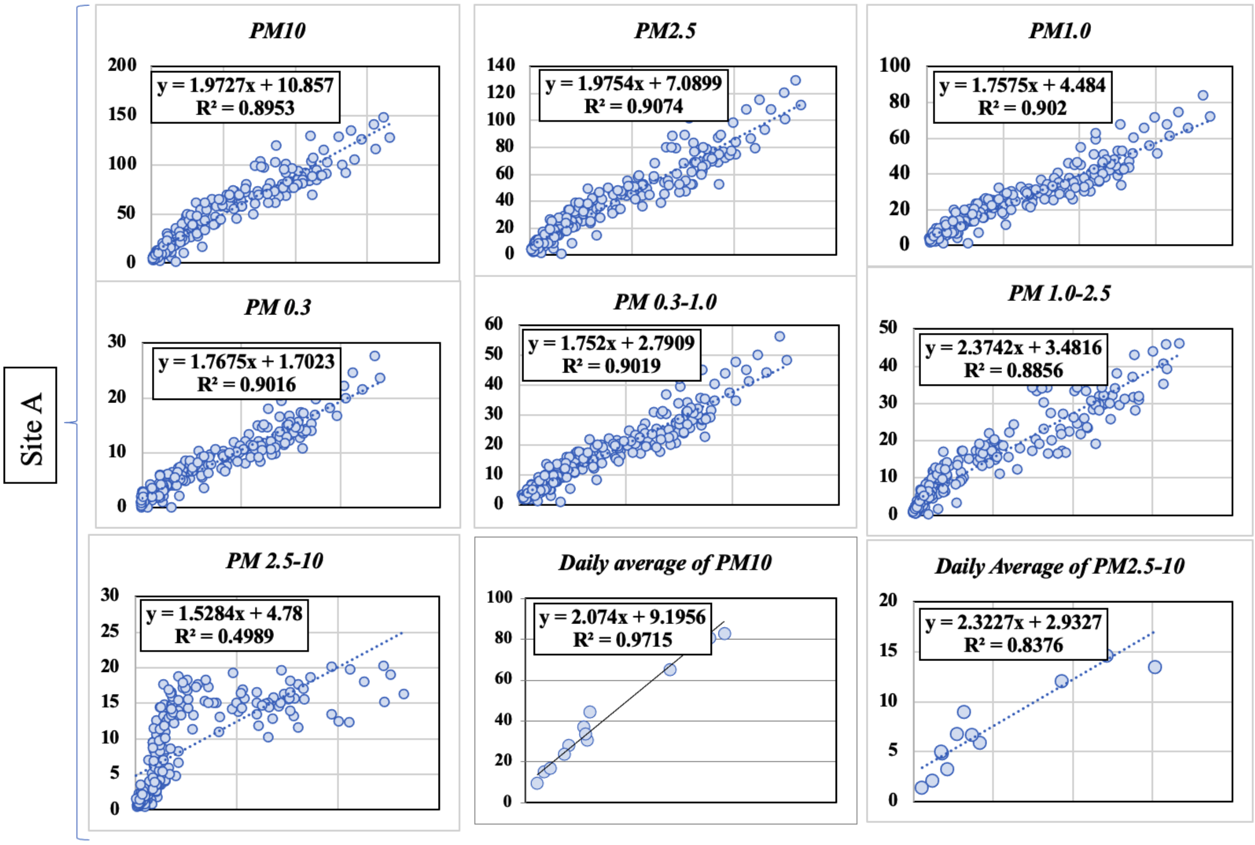


Fig. 8. Correlation between indoor and outdoor particles for hourly and daily data in site A

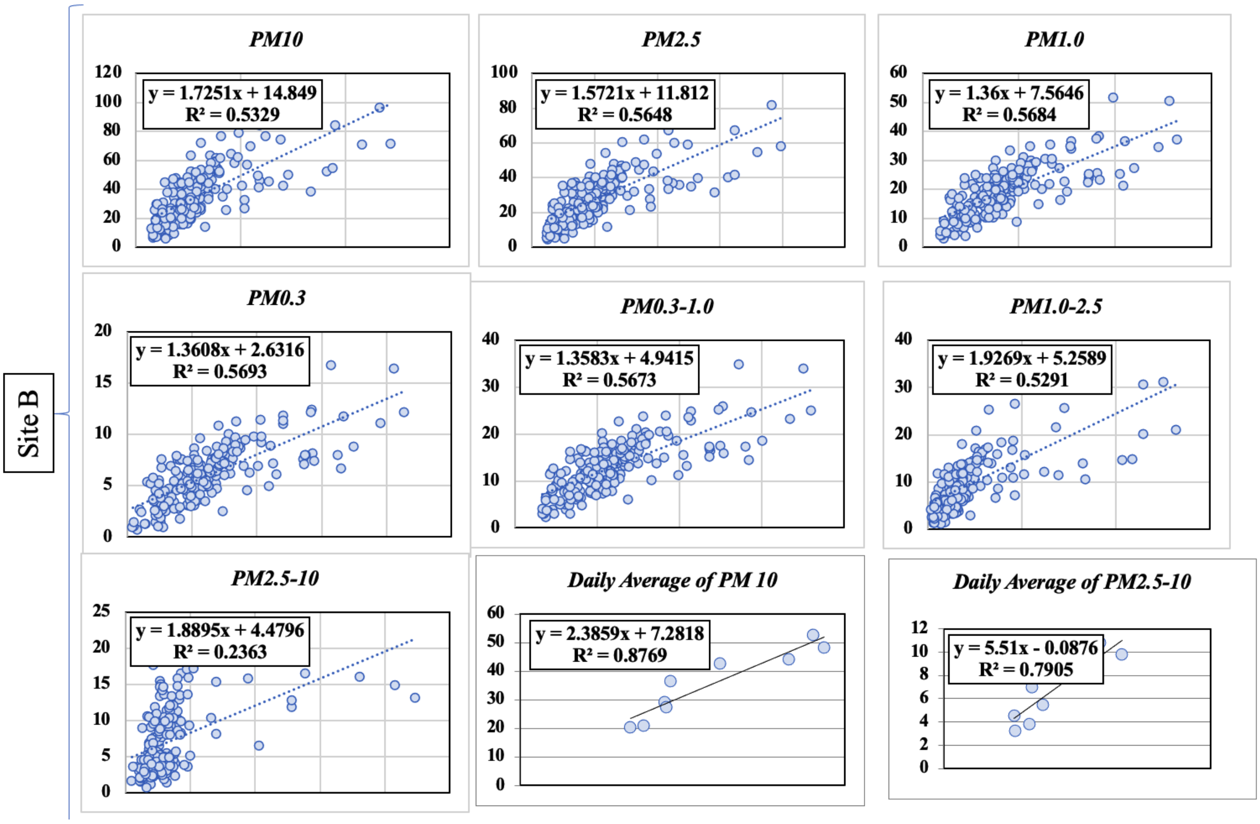


Fig. 9. Correlation between indoor and outdoor particles for hourly and daily data in site B

The results of previous studies[39, 28], also emphasize that regardless of the status of envelope airtightness, in the absence of internal sources, the trend of indoor PM is mainly dependent on the outdoor concentration variations, leading to a strong association between indoor and outdoor patterns, particularly concerning fine particles. Therefore, seasonal changes had no meaningful effect on this correlation.

The previous sections discussed the effect of external sources and building physics, particularly window airtightness, on the indoor concentration of particles in different sizes. In this section, in order to examine the simultaneous impact of the mentioned factors along with weather related parameters, including T, RH, and ΔP, some regression models were developed (Table 2). Moreover, since ACH depended on meteorological parameters, they could not be used simultaneously in one model. ACH was omitted from the regression analyses due to its weak correlation coefficient (R^2=0.1) and a p-value greater than 0.05 (P-value=0.27).

The outcomes from the stepwise multivariate regression analyses (refer to Table 2) indicate that across all particle sizes and within both non-airtight and sealed structures, the predominant independent variable influencing the model was the outdoor concentration, accounting for over 70% of the variation in indoor particulate matter (PM) concentrations, particularly with respect to smaller particles.

Additionally, the analysis of the association between the dependent variable (C_{in}) and the weather related factors ΔT, ΔRH, and ΔP revealed that meteorological factors have no significant influence on indoor particle levels, consistent with the previous studies [40], and with the abovementioned findings which indicated that the change of season had no significant effect on the indoor PM trend.

Table. 2. Results of regression models between indoor PM and predictor variables, including outdoor concentrations and meteorological parameters, determination coefficients (R^2), and Root Mean Square Error (RMSE) for sites A & B

Site	Model	R^2	RMSE	P-Value
Site A	$PM_{10\text{-Indoor}}$ [µg/m^3] = (0.41 $PM_{10\text{-Outdoor}}$)+(0.111 ΔT) + (0.137 ΔRH)+(0.36 ΔP)-2.84 (N=8325)	0.85	5.03	~0
	$PM_{2.5\text{-Indoor}}$ [µg/m^3] = (0.445 $PM_{2.5\text{-Outdoor}}$)+(0.073 ΔT) +(0.094 ΔRH)+(0.271 ΔP)-2.52 (N=8325)	0.87	3.94	<0.01
	$PM_{1.0\text{-Indoor}}$ [µg/m^3] = (0.514 $PM_{1.0\text{-Outdoor}}$)+(0.044 ΔT) +(0.072 ΔRH)+(0.204 ΔP)-2.22 (N=8325)	0.86	2.76	<<0. 01
	$PM_{0.3\text{-Indoor}}$ [µg/m^3] = (0.46 $PM_{0.3\text{-Outdoor}}$)+(0.030 ΔT) + (0.027 ΔRH)+(0.074 ΔP)-0.09 (N=8325)	0.81	0.99	<<0.001
	$PM_{0.3\text{-}1.0\text{-Indoor}}$ [µg/m^3] = (0.54 $PM_{0.3\text{-}1.0\text{-Outdoor}}$) +(0.045 ΔRH)+(0.129 ΔP)-2.4 (N=8325)	0.87	1.89	<<0.001
Site B	$PM_{10\text{-Indoor}}$ [µg/m^3] = (0.32 $PM_{10\text{-Outdoor}}$)+(0.47 ΔT) - (0.076 ΔRH)+(0.69 ΔP)+8.39 (N=11881)	0.59	5.13	~0
	$PM_{2.5\text{-Indoor}}$ [µg/m^3] = (0.38 $PM_{2.5\text{-Outdoor}}$)+(0.368 ΔT) – (0.07 ΔRH)+(0.615 ΔP)+6.21 (N=11881)	0.63	4.25	~0
	$PM_{1.0\text{-Indoor}}$ [µg/m^3] = (0.43 $PM_{1.0\text{-Outdoor}}$)+(0.22 ΔT) – (0.043 ΔRH)+(0.433 ΔP)+3.97 (N=11881)	0.61	2.95	~0
	$PM_{0.3\text{-Indoor}}$ [µg/m^3] = (0.41 $PM_{0.3\text{-Outdoor}}$)+(0.071 ΔT) - (0.015 ΔRH)+(0.15 ΔP)+1.28 (N=11881)	0.59	0.99	<<0.001
	$PM_{0.3\text{-}1.0\text{-Indoor}}$ [µg/m^3] = (0.44 $PM_{0.3\text{-}1.0\text{-Outdoor}}$)+(0.15 ΔT) - (0.027 ΔRH)+(0.28 ΔP)+2.74 (N=11881)	0.6	2.03	<<0.001

Consequently, besides the airtightness of the building envelope, the levels of pollutants outdoors emerged as the most significant determinant of indoor pollutant levels, surpassing the influence of weather-related factors.

Conclusion

The impact of particle size, seal integrity, and weather-related variables on particle infiltration patterns was analyzed by continuously observing these influencing elements for the winter season and in two similar apartments, with and without window airtightness intervention.

Also, we investigated the effect of seasonal variations on the PM infiltration, indoor-outdoor particle correlation, as well as indoor distribution of particles with the outdoor origin under different envelope airtightness status.

The trend of hourly and daily changes in indoor concentration for all particle sizes and at both locations followed the trend of outdoor, suggesting the outdoor PM as the most important factor influencing particle concentrations indoors when no internal sources are present.

While indoor PM was predominantly influenced by outdoor sources, the composition of PM_{10} indoors differed from that outdoors, indicating a greater proportion of finer particles inside than outside. Conversely, larger particle sizes were more prevalent outdoors than indoors.

Based on the indoor and outdoor profiles of $PM_{2.5}$ particles, window sealing reduced the exposure time to polluted air ($PM_{2.5}$ over the WHO limit) by 80% compared to the leaky building.

The findings on the distribution of size-specific particles between indoor and outdoor environments showed that within the PM<2.5 μm category, particles smaller than 1.0 μm, specifically those in the 0.3-1.0 μm range and those smaller than 0.3 μm, exhibited higher concentrations than their larger counterparts in the 1.0-2.5 μm range, especially in the indoor environment, which due to the more detrimental health impacts of ultrafine particles, it is essential to develop national guidelines to limit their exposure.

Research on leakage tests indicates that enhancing the airtightness of building envelopes by sealing gaps around windows decreases the effective leakage area of the envelope by 25%. This reduction lowers both the indoor/outdoor ratio and the infiltration factor. Nevertheless, it does not influence the comparative penetration rates of various particle sizes.

According to the I/O and infiltration factor results, in both cases of window airtightness, the levels of indoor particles of ambient origin, from more to less, were observed for $PM_{0.3\text{-}1.0}$, $PM_{0.3}$, $PM_{1.0\text{-}2.5}$, and $PM_{2.5\text{-}10}$, respectively.

Comparable discoveries were observed for particles sorted by size, showing the greatest presence of particles originating from outdoor sources in indoor $PM_{1.0}$ (particle size range 0.3-1.0μm), with the smallest presence observed in PM_{10}.

Similar findings for the fall season for previously published work admitted that season change did not considerably affect indoor PM in terms of the distribution of size-resolved and size-fractionated particles.

The research established a robust correlation between indoor and outdoor particulate matter across all particle sizes, with the exception of $PM_{2.5\text{-}10}$. This deviation is likely attributed to the reduced infiltrability or greater loss of coarse particles as they traverse through envelope cracks and gaps.

The analysis of the results between the two seasons showed that although in the winter season, with the prevailing seasonal inversion, the I/O ratio increased slightly (below 10%) compared to the fall season, it did not affect the infiltrability of particles of different sizes.

Regarding multivariate regression models, in case of no mechanical ventilation and the absence of indoor sources, the primary independent variable in the model was the outdoor concentration, which accounted for over 70% of the variability in indoor PM concentrations, overshadowing the impact of meteorological parameters.

In the study conditions, under relatively stable weather conditions, meteorological variables and Seasonal variations did not markedly influence the concentrations indoors, in both airtightness conditions. It is suggested that the present study be repeated under severe atmospheric events such as storms or in hot seasons to understand whether the obtained results can be generalized to all seasons or not.

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Competing interests

The authors declare they have no conflicts of interest or competing interests.

Authors' contributions

The contributors to this paper have delineated their roles as follows: Fatemeh Zahed was responsible for preparing the initial draft of the manuscript, collecting data, and conducting analytical procedures. Alireza Pardakhti took charge of conceptualizing and designing the study, managing the project, and interpreting the findings. Majid Shafiepour Motlagh contributed through critical revisions and editorial oversight, in addition to supervising the project. Behrouz Mohammad Kari provided essential resources, developed the methodology, and curated the data. Azadeh Tavakoli assisted in reviewing and editing the manuscript.

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Ethical considerations

“Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, redundancy, etc) have been completely observed by the authors.”

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