frontiers | Frontiers in Built Environment

TYPE Original Research
PUBLISHED 22 November 2023
DOI 10.3389/fbuil.2023.1297520

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OPEN ACCESS

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RECEIVED 20 September 2023
ACCEPTED 13 November 2023
PUBLISHED 22 November 2023

CITATION
Jung C and Abdelaziz Mahmoud NS (2023), Navigating dust storms and urban living: an analysis of particulate matter infiltration in Dubai's residences.
Front. Built Environ. 9:1297520.
doi: 10.3389/fbuil.2023.1297520

Navigating dust storms and urban living: an analysis of particulate matter infiltration in Dubai's residences

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In response to the growing concern of air pollution in Dubai, this study was undertaken to measure and analyze indoor and outdoor particulate matter (PM) concentrations in residential buildings during the spring dust storm period. The research focused on the infiltration of PM into indoor spaces and its impact on indoor air quality, exploring the relationship between PM particle diameter, building infiltration rates, and the indoor influence of outdoor PM. Conducted in a two-bedroom residential unit near a busy road, the study utilized particle size analysis and the indoor-outdoor (I/O) ratio for measurements. The findings revealed that smaller particles, particularly ultrafine $PM_{2.5}$, had a more substantial influence on indoor PM concentrations than larger particles. It was noted that buildings with higher infiltration rates, especially those with natural ventilation, were more susceptible to outdoor PM infiltration. Additionally, the study highlighted the significant role of occupant behavior, such as cooking and cleaning, in generating indoor PM. However, further research is necessary to better understand the correlation between architectural characteristics, infiltration rates, and the indoor influence of outdoor PM in residential buildings. The study underscores the importance of improved ventilation systems, raising awareness of indoor air quality, and implementing effective mitigation strategies to reduce indoor air pollution and enhance indoor air quality in urban environments like Dubai. These findings contribute significantly to our understanding of indoor and outdoor PM dynamics, emphasizing the urgent need to address indoor air pollution in urban areas.

KEYWORDS

particulate matter (PM), indoor air quality (IAQ), infiltration rate, indoor and outdoor concentration, residential buildings

1 Introduction

Dubai places considerable importance on environmental consciousness, particularly about air quality and pollution (Jung and Awad, 2021a; Awad and Jung, 2021; Awad and Jung, 2022; Jung and Al Qassimi, 2022). The Dubai Municipality actively undertakes initiatives and arranges events to enhance environmental awareness, which likely encompasses educating individuals about the risks associated with $PM_{2.5}$ and PM_{10} particles (Nasser et al., 2015; Benchrif et al., 2021a). To monitor and analyze air quality in real time, the UAE has implemented advanced tools such as the Air Quality Index (AQI) and the National Air Quality Platform (Jung et al., 2021a; Jung and Awad, 2021b). These platforms enable the public to assess the air quality in specific areas, comprehend the associated health hazards, and make informed decisions regarding visits based on air quality data (Arar and Jung, 2021; Mahmoud et al., 2023). Furthermore, the UAE has introduced the National Air Quality Agenda 2031, which establishes a comprehensive framework for monitoring and managing air quality while concurrently reducing air pollution (Abbas et al., 2021; Al-Dabbagh, 2021).

Despite these efforts, the $PM_{2.5}$ concentration in Dubai is currently reported to be 15 times more than the World Health Organization's (WHO) annual air quality guideline value, indicating that there is still a significant challenge to overcome in terms of air pollution in the city (Mushtaha and Helmy, 2017).

The sources of air pollution in the UAE are diverse, with industry accounting for just over two-thirds of $PM_{2.5}$ and road transport causing almost one-fifth (Mushtaha et al., 2021a). Power generation and desalination cause about 3% (Bani Mfarrej et al., 2020). Dust storms, carrying sand and sea salt, are another significant source of Particulate Matter (PM) in the UAE (Jung et al., 2021b).

Air pollution, particularly $PM_{2.5}$, is associated with serious health conditions such as lung cancer and cardiovascular disease (Chen et al., 2017; Al-Hemoud et al., 2019; Mushtaha et al., 2021b; González-Lezcano, 2023). Short-term exposure can increase the risk of asthma, chronic obstructive pulmonary disease, and respiratory infection (Amoatey et al., 2020). Reports have indicated that more than 120,000 people die prematurely each year in the Middle East and North Africa (MENA) region because of air pollution, equating to 7% of premature deaths (Benchrif et al., 2021b; Arar and Jung, 2022). Given the ongoing trajectory of sustained economic expansion and insufficient environmental safeguard measures, the expeditious resolution of the decline in atmospheric conditions caused by PM poses a formidable challenge (Arar et al., 2022).

The degradation of the atmospheric environment also contributes to the rise in indoor PM concentrations (Jung and El Samanoudy, 2023). The interior of a building undergoes a continuous exchange of air with the external environment through ventilation and infiltration (Abdelaziz Mahmoud and Jung, 2023). During this process, PM infiltrates the indoor spaces through crevices or openings in the building's structure and windows (Jung et al., 2022a). The extent of its impact within a room depends on the specific pathways these particulates penetrate (Al Qassimi and Jung, 2022).

In contrast to numerous commercial buildings where the air is filtered through air conditioning systems before being supplied to the indoor spaces during the introduction of outside air, residential buildings typically rely on infiltration and natural ventilation (Jung et al., 2021c; Jung et al., 2022b; Jung et al., 2022c). While there has been a recent surge in the construction of residential buildings equipped with mechanical ventilation systems, residents' reliance on such systems remains relatively low (Jung et al., 2022c). Of particular significance is the fact that elderly individuals and infants, who are more susceptible to respiratory ailments, often reside in residential buildings for extended periods (Kharrufa et al., 2022). Therefore, evaluating the indoor effects of outdoor PM in residential buildings can be deemed of utmost importance (Huang et al., 2018).

Prior research has predominantly concentrated on multi-purpose establishments like daycare centers, and there exists only a limited number of studies on measurement and simulation methodologies (Jung and Mahmoud, 2022). While a published study has examined the inflow of PM through the ventilation system in residential buildings, assessing its impact through infiltration remains constrained (Hussien et al., 2023a). Recently, there have been investigations into the penetration of PM via natural infiltration in office buildings (Elsayed et al., 2021). However, exploring PM penetration targeting residential buildings is still nascent (Stasiulaitiene et al., 2019a; Sultan et al., 2020).

Hence, this study aims to measure and analyze indoor and outdoor PM status during the spring dust storm period in residential buildings along roadways, where a substantial inflow of PM into indoor spaces is anticipated. Furthermore, it seeks to evaluate the extent of indoor influence caused by outdoor PM. To scrutinize the impact of outdoor PM on Indoor Air Quality (IAQ), a particle size analysis was conducted based on the indoor-outdoor concentration ratio, commonly referred to as the (I/O ratio).

2 Materials and methods

2.1 Example of PM I/O ratio measurement in residential buildings

As shown in Table 1, numerous researchers have conducted measurements of the indoor-outdoor (I/O) ratio to examine the correlation between outdoor and indoor PM (Hussien et al., 2023b). The results of these measurements have revealed a wide range of I/O ratios (Wang et al., 2016a).

In Dai et al. (2018) study, the I/O ratio of $PM_{2.5}$ was analyzed during winter and summer for 18 residential units. Bralewska et al. (2019) investigated the I/O ratio of $PM_{2.5}$ in high-traffic areas, distinguishing between residential dwellings' heating and non-heating periods. Gao et al. (2021) assessed pollutant levels, such as $PM_{2.5}$ concentration, where similar residential units were situated in the city center and suburbs, exhibiting significant traffic volume variations. The study examined the influence of pollution sources.

Nevertheless, it is worth noting that the I/O ratio varies depending on PM diameter (Jodeh et al., 2018). The studies above only present the I/O ratio for specific diameter groups of fine dust, thereby lacking information on the I/O ratios corresponding to various fine dust diameters (Wang et al., 2016b). Conversely, some studies have specifically analyzed the I/O ratio based on PM diameter (Ji et al., 2018). Tran et al. (2021) investigated PM_1, $PM_{2.5}$, and PM_{10} concentrations in 50 residential units. Faria et al. (2020) conducted monitoring of PM_1, $PM_{2.5}$, and PM_{10} in five dwellings near roadways and five urban dwellings. Ścibor et al. (2020) analyzed PM_1, $PM_{2.5}$, and PM_{10} concentrations in 19 city and suburban residential units.

However, it is important to note that the primary objective of these studies is to evaluate indoor PM while considering occupant behavior (Hodas et al., 2016). Moreover, these studies do not distinctly differentiate between residential and non-residential periods regarding the I/O ratio (Krstić et al., 2016). Consequently, there are limitations in determining the extent of influence of outdoor PM solely based on the provided measurement values (Jung and Awad, 2023).

2.2 Outdoor PM_{10} concentrations in Dubai

Figure 1 displays the concentration patterns of PM in the outdoor air of Dubai, where the designated residential location for the measurement experiment is situated (Taleb and Kayed, 2021). The data from the Dubai Municipality, encompassing the years

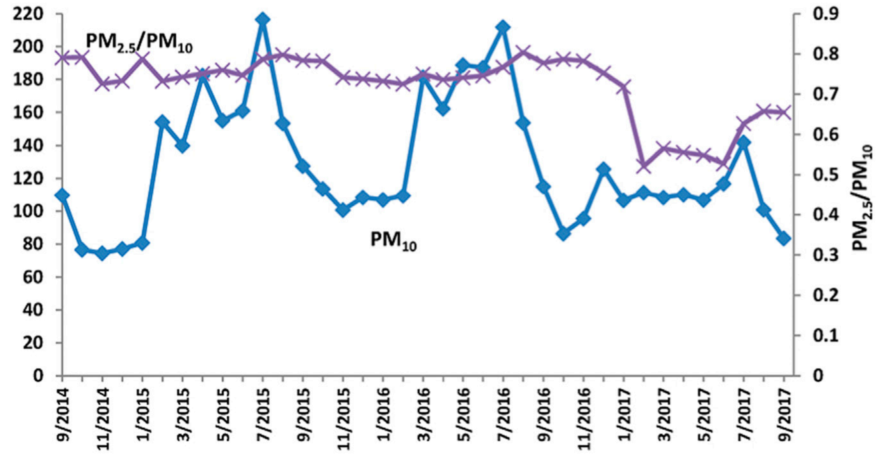

FIGURE 1
Annual variations in PM_{10} concentrations and $PM_{2.5}/PM_{10}$ ratio in Dubai between 2014 and 2017.

FIGURE 2
Noora, Al Habtoor City building in Business Bay, Dubai.

2014–2017, were analyzed to examine the concentrations of PM particles, temperature, and humidity (Klepeis et al., 2001). This analysis aimed to determine the suitable experimental period for data analysis in this study (Azimi et al., 2018a; Singer and Delp, 2018).

Given the specific attributes of the designated area, meticulous planning was undertaken for the experiment, with a concentrated focus on July, during which elevated levels of outdoor PM_{10} are anticipated (Jung et al., 2019).

2.3 Methodology for measurement of indoor and outdoor PM and indoor environment

2.3.1 Target building

The target is a 127 m^2 two-bedroom unit in Noora, Al Habtoor City building (Figure 2), in Business Bay, Dubai (Propsearch.ae. Al, 2021). The floor plan of the specific area to be measured is presented in Figure 3.

Architectural Layout Analysis: The residential unit under investigation boasts a strategic architectural layout integral to understanding potential PM infiltration dynamics. With two balconies, multiple windows, a lengthy entrance corridor, and three measurement locations near conceivable PM entry points (as depicted in the provided floor plan), the design and positioning of these elements could significantly influence PM infiltration rates. This is especially pertinent considering their proximity to potential outdoor PM sources and entry pathways. Balconies, particularly, can serve as primary ingress points if frequently left open. Additionally, the extended entrance corridor may channel outdoor PM, especially during recurrent door operations. The floor plan thus offers invaluable insights into the potential regions of PM concentration and its relation to architectural features Figure 3.

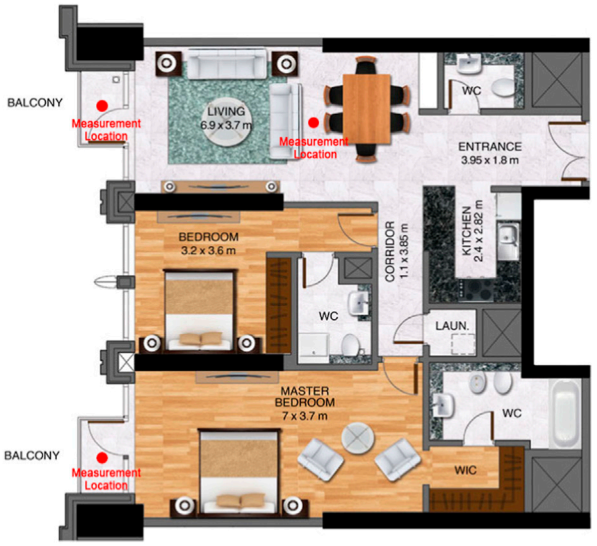

FIGURE 3
2 bedroom unit plan and measurement location at Noora, Al Habtoor city.

The targeted building is positioned adjacent to a bustling 14-lane Sheikh Zayed Road, implying that the exterior concentration of PM is expected to be substantial, owing to the continuous vehicular traffic outside commuting hours (Azimi et al., 2018b; Otuyo et al., 2023). The 14-lane thoroughfare runs parallel to the southern side of the apartment complex, with an approximate distance of 20 m separating the two. It was essential to consider the outdoor concentration levels to ensure that the evaluation of indoor penetration of outdoor PM is discernible (Tham et al., 2021). Hence, the measurement time and location were carefully selected (Fermo et al., 2021).

During the measurement periods, a log was maintained of various activities conducted by the occupants, including cooking, cleaning, smoking, and window/door usage. While comprehensive profiling of each family's habits and the number of occupants was not conducted in this study, we observed and noted predominant indoor activities.

2.3.2 Indoor and outdoor PM measurement methods and conditions

Measurements were conducted to assess the PM levels indoors, specifically in a central living room, and outdoors at a designated location (Raysoni et al., 2016). It should be noted that the extent of indoor penetration of outdoor PM varies depending on the diameter of the particles (Wang et al., 2016c).

To obtain accurate data, Particle Number Concentration (PNC) was measured using two Optical Particle Counters (TSI 9306-v2, United States) for different particle diameters: 0.3, 0.5, 1.0, 5.0, and 10.0 μm (Molho et al., 2019). Given the substantial fluctuations in the quantity and concentration of PM over time, a short collection interval of 5 min was set to capture these variations effectively (Etzion and Broday, 2018).

During the occupancy of the residential unit, occupants were allowed to engage in routine activities such as cooking, cleaning, and ventilation without any specific restrictions (Pietrogrande et al., 2021). Additionally, the duration of non-occupancy was recorded separately (Zhao et al., 2018). Based on the collected measurements, the indoor-outdoor (I/O) ratio was calculated for both the entire measurement period and the non-occupancy period (Silva et al., 2017). By considering the I/O ratio over the whole measurement period, which accounts for fine particulate matter generation from various sources, such as outdoor penetration and indoor generation, valuable insights into the overall trends of fine dust generation within the actual space can be obtained (Singer et al., 2020). Moreover, by analyzing the I/O ratio during the non-occupancy period, the impact of external fine dust penetration on the indoor fine dust concentration can be assessed and understood (Santin et al., 2021).

While the measurements account for indoor PM sources like cooking and cleaning, they also inherently consider PM from outdoor sources, thus providing an I/O ratio that simulates the combined effects of both ventilation (intentional introduction of outdoor air) and infiltration (unintentional leakage of outdoor air into a building). This dynamic evaluation ensures that the concentrations recorded are representative of both active ventilation processes and passive infiltration processes.

2.3.3 Infiltration rate estimation

The indoor-outdoor (I/O) ratio of PM in the measured household can be influenced by the infiltration rate during the measurement period (Stasiulaitiene et al., 2019b). To estimate the infiltration rate of the target unit during the PM period, the infiltration rate using carbon monoxide (CO) gas generated by occupants was employed (Peng et al., 2017). Previous studies have proposed a correlation between the detailed methods and procedures of the occupant-generated CO_2 gas method and other tracer gas methods (Remion et al., 2019). This study used the same way as previous studies suggested to estimate the infiltration rate. The carbon dioxide (CO_2) concentration within the unit was measured using a CO_2 monitor (TSI 7545, United States) placed at the center of the household (Savdie et al., 2020). These measurements were recorded every minute. The collected CO_2 data served not only to estimate the infiltration rate but also to verify the occupancy and non-occupancy periods of the residents (Asif and Zeeshan, 2020).

Carbon dioxide emissions based on the number of occupants in the target space were calculated using Formula 1 (Zhong et al., 2019).

$$V_{02} = \frac{0.00276 A_D M}{0.23RQ + 0.77}$$

V_{O2}: Oxygen Consumption Rate (*L/s*).
RQ: Respiratory Coefficient (–)
M: Amount of Activity (*met*).
A_D: DuBois Body Surface Area (m^2).

During the estimation of the infiltration rate for the target unit, it was assumed that the occupants resided in the space for a sufficient duration, allowing for the complete diffusion of CO gas indoors (Militello-Hourigan and Miller, 2018). The air exchange rate was determined by calculating the minimal difference between the indoor CO_2 concentration value measured using the least square method and the indoor CO_2 concentration value estimated using the mass conservation equation (Zhu et al., 2019). This calculated air exchange rate represents the infiltration rate of the unit (Formula 2).

$$V \frac{\partial C}{\partial t} = QC_0 - QC_i + G$$

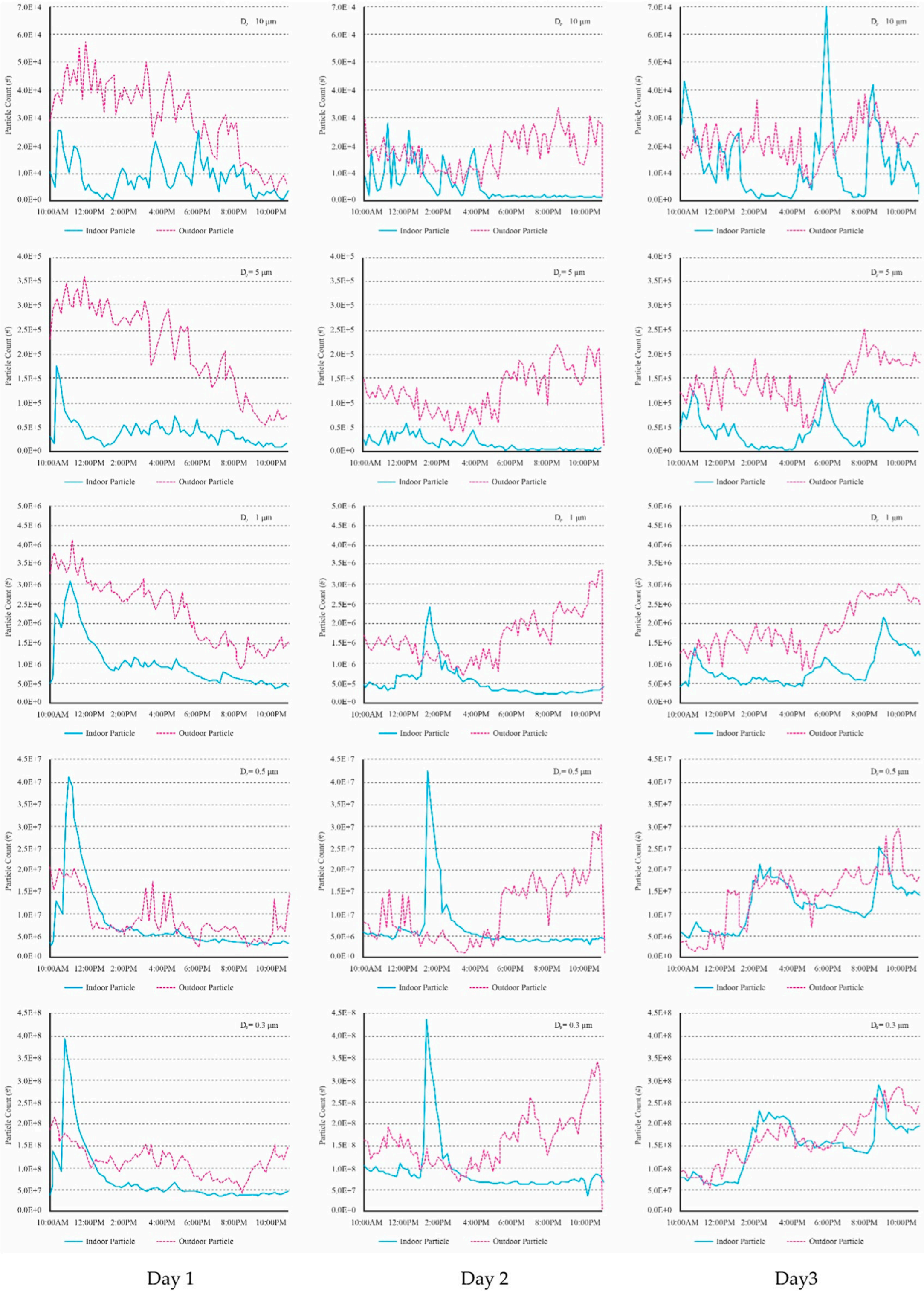

FIGURE 4
Particle size-resolved indoor and outdoor concentrations in target unit.

V: Room Volume (m^3).
t: Time (h).
Q: Air Exchange Rate (m^3/h).
C: CO_2 Concentration (g/m^3).
C_0: Outdoor CO_2 Concentration (g/m^3).
C_i: Indoor CO_2 Concentration (g/m^3).
G: Amount of Tracer Gas (g/h).

In our attempt to simulate real-world conditions, the infiltration rate is a pivotal factor, representing the unintended air exchange between indoor and outdoor environments. Using occupant-

TABLE 1 Previous research on I/O ratio in residential buildings.

Previous research	Location	Area	Season	I/O ratio
Dai et al. (2018)	Shanghai, China	City Center	winter, summer	0.88 ($PM_{2.5}$)
Bralewska et al. (2019)	Warsaw, Poland	High Traffic Area	4 Seansons	1.64 ($PM_{2.5}$)
Gao et al. (2021)	Beijing, China	Urban, Suburban	4 Seasons	2.1 (PM_1), 1.6 ($PM_{2.5}$), 1.4 (PM_{10})
Tran et al. (2021)	Kaunas, Lithuania	Urban Area	winter	0.68 (PM_1), 0.71 ($PM_{2.5}$), 0.98 (PM_{10})
Faria et al. (2020)	Lisbon, Portugal	Urban Area	winter, summer, Monsoon	1.00 (PM_1), 0.92 ($PM_{2.5}$), 1.07 (PM_{10})
Ścibor et al. (2020)	Kraków, Poland	High Traffic Area	winter, summer	0.74 ($PM_{2.5}$), 0.60 (PM_{10})

generated CO_2 as a tracer reflects the building's actual conditions, incorporating both natural ventilation and the effects of building envelope integrity. The calculated air exchange rate, thus, does not just consider the mechanical or active introduction of fresh air but also the inherent building characteristics that allow air to infiltrate. In combining both the I/O PM measurements and the infiltration rate estimations, our methodology captures a multi-faceted view of air quality dynamics within residential units, accounting for both intentional ventilation processes and unintentional infiltration events. This ensures a comprehensive representation of air quality in real-life living scenarios.

3 Results

3.1 Concentration measurement result by indoor and outdoor diameter

Figure 4 illustrates the days (Day 1–18 July 2022, Day 2 - 22 July 2022, and Day 3 - 26 July 2022) during the measurement period when the concentration of PM in the outdoor air was notably high, thereby revealing its impact on indoor fine particulate matter concentration. The figure showcases the number of outdoor and indoor PM particles categorized by diameter. The characteristics of these 3 days are segmented based on variations in the outdoor air concentration of PM. Day 1 observed a high outdoor air concentration in the morning, followed by a gradual decrease over time. Conversely, Day 2 and Day 3 experienced low outdoor air concentrations in the morning, which progressively increased as the day unfolded. Day 2 and Day 3 displayed differences in infiltration rates.

As presented in Table 2, the infiltration rate on July 22 was recorded as 0.11 times per hour, a lower value than Day 3's 0.19 times per hour. For Day 1 and Day 3, when the infiltration rates were 0.20 times per hour and 0.19 times per hour, respectively, the indoor PM concentration generally tended to follow the fluctuations in outdoor concentration. However, on Day 2, with an infiltration rate of 0.11 times per hour, this correlation was more evident, indicating a clear relationship. Furthermore, it can be observed that the disparity between outdoor and indoor number concentrations of PM diminishes as the particle size decreases from larger-sized fine particles to smaller ones.

TABLE 2 Estimated infiltration rate at target unit by CO_2 method.

Experiment day	Infiltration rate (*1/h*)
Day 1–18 July 2022	0.21
Day 2–22 July 2022	0.12
Day 3–26 July 2022	0.19

3.2 Indoor/outdoor PM concentration ratio

For a quantitative comparison of the variation in the number and concentration of delicate particulate matter between indoor and outdoor environments, the indoor-outdoor (I/O) ratio was analyzed, as demonstrated in Figure 5 and Figure 6. Figure 5 presents the I/O ratio encompassing both occupancy and non-occupancy periods, while Figure 6 exclusively showcases the I/O ratio during non-occupancy periods. As depicted in Figure 5, the I/O ratio occasionally exceeds 1.0. This is attributed to the influence of PM generated indoors due to occupants' indoor activities. These findings indicate that individuals tend to seal windows during high outdoor dust concentrations, inadvertently causing an increase in indoor PM concentration. Consequently, the indoor air quality may be poorer than the outdoor environment. It is worth noting that due to the experimental design lacking systematic control over occupants' activities, it is challenging to quantitatively analyze the individual impact of the I/O ratio resulting from each occupant's behavior. However, the analysis reveals that the I/O ratio is notably high for PM with a diameter smaller than 0.5 μm.

Figure 6 illustrates the analysis of the indoor-outdoor (I/O) ratio during the non-occupancy period, excluding occupant behavior's influence. The I/O ratio is consistently below 1.0 for all fine dust diameter groups. As explained earlier, the results shown in Figure 6 primarily reflect the impact of indoor penetration of fine dust from the outdoor environment. It can be observed that the effect on the indoor climate varies depending on the diameter of the PM. Some of the external fine dust infiltrates the room through gaps in the building, while some accumulates on the surface of these gaps. The experimental findings analyzed a higher I/O ratio for smaller dust diameters, indicating that smaller particles tend to deposit less on the gap surfaces and penetrate more into the room. On Day 3, the average I/O ratios for the diameters of 0.3, 0.5, and 1.0 μm were

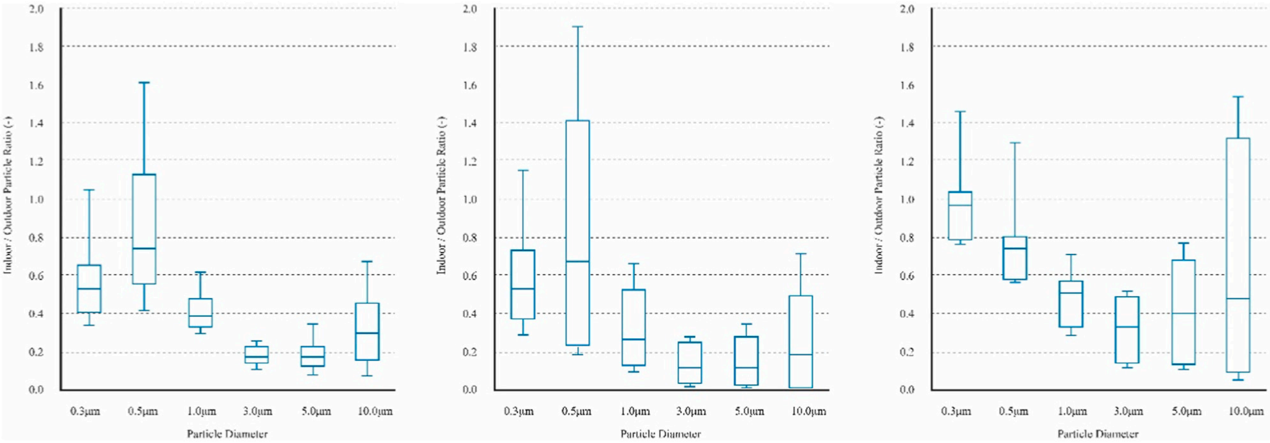

FIGURE 5
Particle size-resolved indoor and outdoor ratio during the experiment.

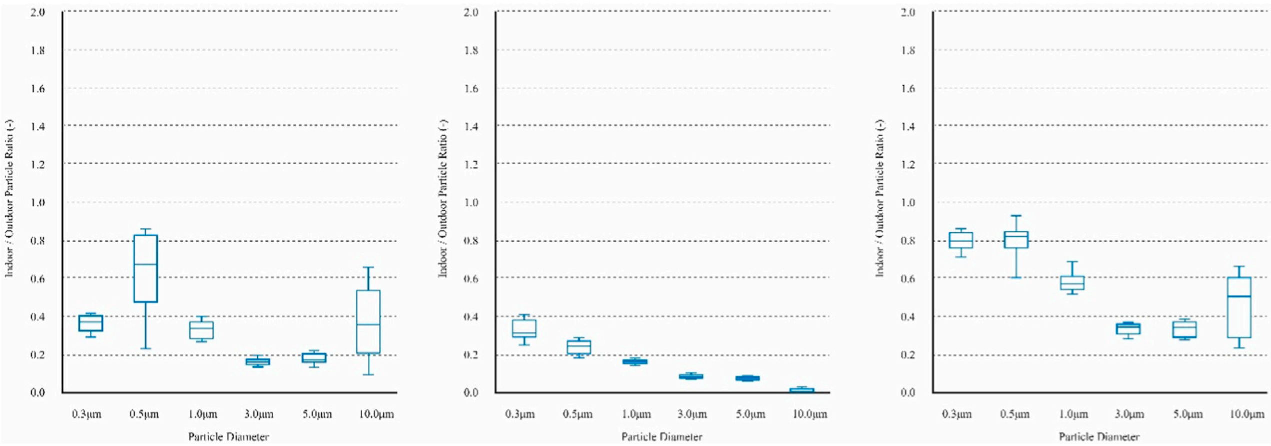

FIGURE 6
Particle size-resolved indoor and outdoor ratio only during unoccupied period.

notably high at 0.77, 0.80, and 0.53, respectively. In contrast, larger dust particles with diameters of 3.0, 5.0, and 10.0 µm exhibited lower average I/O ratios of 0.30, 0.30, and 0.47, respectively.

This suggests a more significant concern for indoor air pollution due to the indoor infiltration of outdoor fine dust, particularly fine dust with diameters classified as $PM_{2.5}$ or smaller, which falls under ultrafine dust.

On Day 2, when the infiltration rate was low, the I/O ratio was lower for all diameter groups than Day 3. The average I/O ratios for the diameters of 0.3, 0.5, 1.0, 3.0, 5.0, and 10.0 µm were 0.26, 0.19, 0.11, 0.03, 0.02, and 0.00, respectively. These findings demonstrate that the degree of indoor influence due to the infiltration of external fine dust is significantly affected by fluctuations in the infiltration rate.

Based on these findings, it can be concluded that the indoor penetration of outdoor PM in residential buildings is influenced by the diameter of the particles and the infiltration rate of the target unit. Notably, in the ultrafine dust category, which includes particles classified as $PM_{2.5}$, the impact of outdoor PM indoors was significant. This emphasizes the importance of conducting further comprehensive research in this area. Moreover, the study revealed that outdoor PM's indoor influence is linked to residential building infiltration rate. Consequently, it is recommended that future investigations be conducted to elucidate the correlation between architectural characteristics, which affect the infiltration rate, and the indoor influence of outdoor PM.

4 Discussion

The study results indicate significant penetration of outdoor PM into residential buildings in Dubai, particularly during periods of high outdoor PM concentrations. The indoor-outdoor (I/O) ratio analysis showed that the I/O ratio occasionally exceeds 1.0, indicating that indoor PM concentration can be higher than outdoor levels. This is attributed to PM generated indoors due to occupants' activities, such as cooking, cleaning, and window sealing during high outdoor PM concentrations.

Compared to prior research, our findings are consistent with those observed in urban environments where indoor PM concentrations often exceeded outdoor levels due to specific indoor activities (Wang et al., 2016a; Dai et al., 2018; Hussien et al., 2023b).

The study also found that the indoor penetration of outdoor PM is influenced by the diameter of the particles and the infiltration rate of the building. Smaller particles, classified as ultrafine dust ($PM_{2.5}$ or smaller), tend to penetrate more into the indoor environment than larger particles. Previous research has similarly highlighted the differential penetration of PM based on particle size (Jodeh et al., 2018; Bralewska et al., 2019; Gao et al., 2021). The infiltration rate, influenced by factors such as building design and ventilation, also plays a significant role in the indoor influence of outdoor PM.

Our observations from the measurement periods for the influence of ultrafine $PM_{2.5}$ on indoor concentrations underline the pronounced influence of ultrafine $PM_{2.5}$ in indoor environments, particularly in a residential unit near a traffic-dense street. In alignment with earlier studies, vehicular emissions, especially from diesel vehicles, are identified as a significant contributor to indoor $PM_{2.5}$ concentrations (Wang et al., 2016b). Several factors may account for this notable influence.

Firstly, the proximity of the residential unit to a bustling street exposes it to increased concentrations of vehicular emissions. Diesel vehicles, particularly, are renowned for emitting significant quantities of ultrafine $PM_{2.5}$. These minute particles can stay airborne for prolonged durations, thus leading to their sustained presence indoors.

The ultrafine nature of $PM_{2.5}$ particles facilitates their more efficient penetration into indoor spaces. Their capability to navigate through gaps and cracks has also been emphasized in previous research (Taleb and Kayed, 2021). They can navigate through gaps, cracks, and even conventional ventilation systems that might not be equipped to trap these smaller-sized particles efficiently. In addition, certain indoor activities, such as cooking, can be a source of ultrafine particle generation, further elevating indoor concentrations. Additionally, our study reaffirms the findings from other studies that indoor activities, such as cooking, play a vital role in generating ultrafine particles (Wang et al., 2016c).

This observed trend highlights the critical importance of devising effective mitigation measures, especially for residences near high-traffic zones. Enhanced filtration systems and awareness about indoor activities that contribute to ultrafine $PM_{2.5}$ generation can be key strategies to maintain healthier indoor air quality.

Our findings on indoor PM concentrations are influenced not just by outdoor sources but also by various indoor activities and the profile of occupants. Cooking, cleaning, and smoking can significantly alter indoor PM levels. The number and demographics of the occupants, their habits, and lifestyle choices play a pivotal role in determining indoor air quality. Our findings on indoor PM concentrations, though unique in Dubai, share parallels with global observations on the influence of both outdoor sources and indoor activities. As echoed in earlier research, the demographics and habits of occupants are instrumental in shaping indoor air quality (Etzion and Broday, 2018).

While our study provides insights into the influence of some of these factors, a more detailed analysis based on individual family profiles and habits would provide a clearer picture. Such an analysis could be valuable for future research to devise effective mitigation strategies for indoor air pollution.

Based on these findings, it is recommended that further research be conducted to explore the correlation between architectural characteristics, infiltration rates, and the indoor influence of outdoor PM in residential buildings. Understanding how building design and ventilation systems affect the infiltration of outdoor PM can help develop strategies to mitigate indoor air pollution and improve indoor air quality. Additionally, future studies should consider different seasons and locations to account for variations in outdoor PM concentrations and sources.

The results of this study contribute to the understanding of the indoor-outdoor relationship of PM in residential buildings and highlight the need for measures to address indoor air pollution in Dubai. Given the high levels of $PM_{2.5}$ concentration in the city and its associated health risks, efforts should be made to improve ventilation systems, promote awareness among residents about indoor air quality, and implement effective mitigation strategies to reduce the penetration of outdoor PM into indoor environments.

5 Conclusion

This study aimed to assess the impact of outdoor particulate matter (PM) on indoor PM concentrations in residential buildings in Dubai and explore the relationship between the infiltration rate and the indoor influence of external PM based on particle diameter. The findings of this study have significant implications for understanding and addressing indoor air pollution in Dubai. The study's results revealed that smaller particles, particularly ultrafine dust such as $PM_{2.5}$, had a more pronounced influence on indoor PM levels than larger particles. This suggests that the indoor penetration of outdoor PM is size-dependent, with smaller particles being more likely to infiltrate indoor spaces. The higher degree of indoor impact observed for ultrafine dust emphasizes the importance of addressing $PM_{2.5}$ concentrations, which are associated with adverse health effects such as respiratory ailments and cardiovascular diseases.

Furthermore, the study demonstrated that the infiltration rate, influenced by architectural characteristics such as building design and ventilation systems, played a significant role in the indoor influence of outdoor PM. Residential buildings, particularly those relying on natural ventilation rather than mechanical ventilation systems, are more susceptible to outdoor PM infiltration.

The implications of this study extend beyond the specific context of Dubai. Indoor air pollution is a global concern, and residential buildings are often overlooked in air quality studies compared to commercial or industrial settings. This study fills the knowledge gap by shedding light on indoor and outdoor PM dynamics in residential buildings. It emphasizes the need to address indoor air pollution in various urban environments.

In urban environments, effectively mitigating indoor air pollution requires a multifaceted approach. Source control stands out as the premier method; by eliminating or managing pollutant sources, such as choosing low-emission construction materials and household products and ensuring proper maintenance of heating and cooking equipment, significant strides can be made. Enhancing the influx of fresh air through improved ventilation—be it by frequently opening windows, utilizing exhaust fans, or deploying mechanical air supply systems—can drastically lower indoor pollutants. For targeted pollutant removal, various air cleaners are available, from compact table-top versions to expansive whole-house systems; their efficacy lies in their ability to filter out specific particles and gaseous contaminants when used correctly. Regular maintenance and cleaning of HVAC systems, complemented by routine dusting and vacuuming with HEPA filters, curtails indoor pollution accumulation. Additionally, integrating certain indoor plants, such as spider or rubber plants, can act as natural purifiers by reducing contaminants like benzene and formaldehyde. However, the bedrock of any successful mitigation strategy remains awareness and education. By keeping residents informed about the origins of indoor pollution, its detrimental effects, and potential countermeasures, they can make informed decisions about indoor practices and product choices.

To further validate and expand upon the findings of this study, future research should investigate various types of residential buildings, considering different architectural characteristics and geographical locations. A more comprehensive understanding of the indoor-outdoor relationship of PM can be achieved by considering variations in outdoor PM concentrations and sources across seasons and regions. Based on the results of this study, several recommendations can be made to mitigate indoor air pollution in residential buildings.

1. Improving ventilation systems in existing and new residential constructions can help reduce the infiltration of outdoor PM. This can involve installing adequate air filtration systems, promoting mechanical ventilation systems, or adopting energy-efficient building designs that balance ventilation and energy consumption.
2. Raising awareness among residents about indoor air quality and the potential health risks associated with PM exposure is crucial. Education campaigns and informational materials can guide indoor air quality management, including proper ventilation practices, regular cleaning, and air purifiers or filters. Encouraging residents to seal windows and doors during periods of high outdoor PM concentrations can also minimize the infiltration of PM into indoor spaces.
3. Implementing effective mitigation strategies at a broader scale is essential. This includes developing and enforcing air quality regulations and policies targeting outdoor and indoor PM pollution sources. Collaborative efforts involving government agencies, urban planners, architects, and building developers can lead to the design and construction of more sustainable and healthy residential buildings.
4. The findings underscore the importance of revisiting and enhancing ventilation systems in residential settings. Effective ventilation not only mitigates the incursion of outdoor pollutants but also plays an essential role in promoting better indoor air quality, which is imperative for residents' health and wellbeing.

This study contributes to our understanding of the impact of outdoor PM on indoor PM concentrations in residential buildings. The findings emphasize the importance of addressing indoor air pollution, particularly in urban environments like Dubai, where high levels of $PM_{2.5}$ concentration pose significant health risks. By considering the infiltration rate and architectural characteristics, future research can further explore strategies to mitigate the penetration of outdoor PM and improve indoor air quality. Implementing these measures can contribute to creating healthier and more sustainable living environments for residents in residential buildings worldwide.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

CJ: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Writing–original draft. NA: Conceptualization, Investigation, Resources, Software, Supervision, Validation, Visualization, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

The authors would like to express their gratitude to University of Sharjah and Ajman University for APC support and providing great research environment.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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