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Article

Assessing Indoor and Outdoor Particulate Matter Dynamics in Daycare Center: A Case Study in Dubai, United Arab Emirates

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Abstract: This study examines the dynamics of indoor and outdoor particulate matter concentrations in childcare facilities in Dubai, UAE, with a focus on particle size-specific behavior under varying occupancy conditions. Measurements were conducted in a daycare room for three-year-olds over five consecutive days, capturing real-world activity scenarios. The study employed an Optical Particle Counter to measure particulate matter concentrations for six particle sizes (0.3 µm, 0.5 µm, 1 µm, 3 µm, 5 µm, and 10 µm), along with indoor carbon dioxide (CO_2) levels as an indicator of source intensity. The findings reveal a strong correlation between indoor and outdoor concentrations for smaller particles (0.3 µm, 0.5 µm, and 1 µm), regardless of occupancy, indicating the dominance of outdoor sources. Conversely, larger particles (3 µm, 5 µm, and 10 µm) displayed significant variability in Indoor/Outdoor (I/O) ratios, with indoor activities such as movement and bedding preparation contributing to elevated concentrations during occupancy. For particles measuring 10 µm, no correlation with outdoor sources was observed under either condition, emphasizing the predominance of indoor factors. Additionally, the positive correlation between CO_2 levels and concentrations of larger particles (3 µm, 5 µm, and 10 µm) confirms that occupant activities significantly contribute to their generation and resuspension. These results underscore the importance of targeted strategies for air quality management, including the implementation of enhanced filtration systems for smaller particles and design interventions to minimize resuspension for larger particles. This research provides actionable insights for creating healthier childcare environments, addressing the unique challenges posed by Dubai's environmental conditions.

Keywords: indoor air quality (IAQ); particulate matter particles; childcare facilities; indoor/outdoor correlation; occupancy and airborne pollutants

1. Introduction

The increased time spent indoors and enhanced building airtightness have heightened concerns about indoor air quality (IAQ) (Kempton et al. 2022; Jung et al. 2021; Razak et al. 2025). Ventilation can effectively reduce concentrations of pollutants originating indoors by expelling them outside (Elsaid & Ahmed 2021; Al-Rikabi et al. 2024). However, in cases where pollutants originate outdoors, ventilation may inadvertently introduce contaminants into the indoor environment (Goldstein et al. 2020; Arar & Jung 2022). Therefore, improving IAQ requires accurately identifying the source of indoor or outdoor pollutants and implementing effective management strategies to mitigate their concentration (Jung & Mahmoud 2022; Awad & Jung 2021). Particulate matter, a critical air pollutant, is particularly problematic in Dubai due to construction activities, regional air pollution, and frequent sandstorms (Akasha et al. 2023). Particulate matter particles in the air vary in size from 0.005 to 500 µm, with particles smaller than 10 µm referred to as respirable particulate matter (Liu et al. 2019; Jung & Abdelaziz Mahmoud 2023). Prolonged exposure to particulate matter is associated with respiratory and cardiovascular diseases and, in severe cases, can result in mortality (Kutlu et al. 2025). Smaller particulate matter particles carry higher concentrations of toxic components, such as heavy metals (Ogundele et al. 2017; Zeng et al. 2020). These particles bypass the body's natural filtration mechanisms, such as the mouth and nose, and penetrate deep into the respiratory system, increasing health risks (Nozza et al. 2021). Indoor particulate matter originates primarily from cooking, smoking, printing activities, and occupant movements (Tapia-Brito & Riffat 2025; Maung et al. 2022; Jung et al. 2024). Additionally, particulate matter from outdoors can settle on surfaces and be resuspended due to changes in air currents (Yuan et al. 2023). Outdoor particulate matter infiltrates buildings through structural gaps and ventilation systems (Bo et al. 2017). Consequently, indoor particulate matter is comprised of both internally generated, including resuspended particles, and externally introduced particulate matter (Bousiotis et al. 2023). Analyzing indoor particulate matter sources according to particle size is crucial for developing targeted management strategies, given the differences in penetration, resuspension, and deposition behaviors (Li et al. 2023).

Several studies have investigated the sources and behavior of indoor particulate matter particles of varying sizes. For instance, Garbarienė et al. (2022) examined the sources of indoor and outdoor particulate matter in residential buildings, focusing on particle sizes ranging from 0.02 to 10 µm. Their findings revealed that outdoor sources significantly influenced particles sized 0.02–2 µm, while indoor sources, including cooking, predominantly contributed to particulate matter sized 2–10 µm (Garbarienė et al. 2022). Similarly, Sánchez-Soberón et al. (2019) and Yuhe et al. (2021) analyzed particulate matter concentrations in classrooms, categorized as PM10, PM2.5, and PM1. Their research demonstrated a strong correlation between outdoor sources and particles sized 1–2.5 µm, while particles sized 2.5–10 µm increased during periods of high student activity (Sánchez-Soberón et al. 2019; Yuhe et al. 2021). Additionally, Godini et al. (2021) identified cooking and smoking as the primary sources of ultra-fine particles (0.014–0.552 µm) indoors (Godini et al. 2021). The literature underscores that particulate matter sources vary by particle size and building type (Fang et al. 2024). Yet, most existing studies focus on environments with intermittent pollutant sources or adult occupants (Sherzad & Jung 2022). In contrast, this study examines childcare facilities where infants and young children—particularly vulnerable due to their developing immune systems—spend extended periods (Arar & Jung 2021). Managing indoor particulate matter in such facilities is crucial to safeguarding children's health (Kumar et al. 2023). Unlike previous research, which has primarily been conducted in residential buildings and educational facilities such as schools, this study targets childcare centers in Dubai, a region characterized by unique environmental and climatic challenges, including frequent sandstorms, extensive construction activities, and extreme temperatures. The distinct urban layout, building practices, and climatic conditions of Dubai necessitate a focused analysis of particulate matter dynamics in childcare environments, thereby addressing a significant gap in existing literature.

This study aims to evaluate the impact of indoor and outdoor particulate matter sources on indoor concentrations across particle sizes within childcare facilities in Dubai. Over five days, the concentrations of indoor and outdoor particulate matter were measured in daycare rooms where daily activities took place. The study analyzed correlations between indoor and outdoor concentrations during occupancy and variations in the indoor/outdoor (I/O) ratio based on occupancy. Additionally, it assessed the relationship between the intensity of indoor sources and indoor particulate matter concentrations to determine the extent of indoor source contributions. This research offers actionable insights into particulate matter management strategies specifically designed for childcare environments, thereby contributing to improved air quality and healthier living conditions for society's youngest and most vulnerable members.

2. Materials and Methods

2.1. Previous Research of PM I/O Ratio Measurements in Buildings

Numerous studies have examined the indoor–outdoor (I/O) ratio of particulate matter (PM) to assess the relationship between outdoor and indoor PM concentrations (Martins et al. 2020). These investigations have reported a wide range of I/O ratios across different contexts. For instance, Huang et al. (2022) analyzed the I/O ratio of PM2.5 during winter and summer in 18 residential units, providing insights into seasonal variations (Huang et al. 2022). Similarly, Alves et al. (2020) studied the I/O ratio of PM2.5 in high-traffic areas, distinguishing between heating and non-heating periods in residential dwellings (Alves et al. 2020). Guo et al. (2023) evaluated PM2.5 concentrations in residential units in city and suburban areas with varying traffic volumes, emphasizing the impact of pollution sources on IAQ (Guo et al. 2023). It is crucial to note that the I/O ratio varies significantly with PM particle size (Martins et al. 2020). While the aforementioned studies primarily focused on specific PM size groups, such as PM2.5, they lacked comprehensive data on I/O ratios for a broader range of fine dust particle sizes (Martins & Da Graca 2018). However, some studies have addressed the I/O ratio across various PM diameters. For example, Nadali et al. (2020) investigated PM1, PM2.5, and PM10 concentrations in

50 residential units (Nadali et al. 2020). Jodeh et al. (2018) monitored PM1, PM2.5, and PM10 levels in five dwellings near roadways and five urban dwellings (Jodeh et al. 2018). Cichowicz et al. (2021) analyzed PM1, PM2.5, and PM10 concentrations in 19 residential units across city and suburban areas (Cichowicz & Dobrzański 2021).

It is also essential to consider that many of these studies primarily aimed to evaluate indoor PM concentrations while accounting for occupant behavior. However, they often did not distinctly differentiate between residential and non-residential periods when analyzing I/O ratios. This limitation complicates the assessment of the extent to which outdoor PM influences indoor concentrations based solely on the reported measurement values, See Table 1.

Table 1. Previous Research on I/O Ratio in Buildings

Previous Research	Location	Area	Season	I/O Ratio
Huang et al. (2022)	Shanghai, China	City Center	Winter, Summer	0.88 ($PM_{2.5}$)
Alves et al. (2020)	Warsaw, Poland	High Traffic Area	4 Seansons	1.64 ($PM_{2.5}$)
Guo et al. (2023)	Beijing, China	Urban, Suburban	4 Seasons	2.1 (PM_1), 1.6 ($PM_{2.5}$), 1.4 (PM_{10})
Nadali et al. (2020)	Kaunas, Lithuania	Urban Area	Winter	0.68 (PM_1), 0.71 ($PM_{2.5}$), 0.98 (PM_{10})
Jodeh et al. (2018)	Lisbon, Portugal	Urban Area	Winter, Summer, Monsoon	1.00 (PM_1), 0.92 ($PM_{2.5}$), 1.07 (PM_{10})
Cichowicz et al. (2021)	Kraków, Poland	High Traffic Area	Winter, Summer	0.74 ($PM_{2.5}$) 0.60 (PM_{10})

2.2. Research Method

2.2.1. Overview of the Sampling Room and Daycare Center

The measurement site for this study was a daycare center in Umm Suqeim, Dubai (Jung et al. 2021). The facility is a two-story structure with a basement adjacent to a two-lane road. It comprises eight daycare rooms—four on each floor—an activity room, and a library on each level. The kitchen and dining areas are situated in the basement. Measurements were conducted explicitly in a daycare room designated for three-year-olds on the first floor (Jung et al. 2022). The room features east-facing pull-in windows and a west-facing door that opens into the hallway. Adjacent daycare rooms are located north and south of the measured room. The location of the building and detailed information about the daycare room used for measurements are presented in Figure 1 and Table 2.

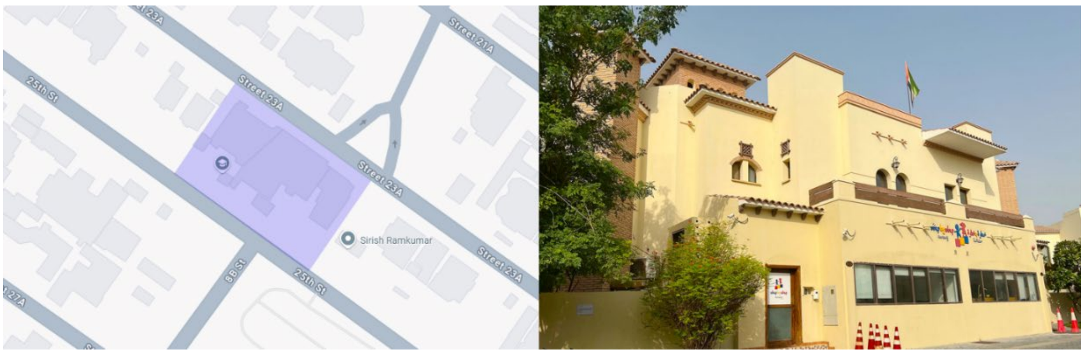


Figure 1. Urban Context and Building Photograph of Daycare Center.

Table 2. Description of the daycare center and sampling room characteristics. Information includes location, floor area, volume, occupancy details, and finishing materials.

Daycare Center Information	Location	Umm Suqeim, Dubai
	Total Floor	3 (Basement + 2 floors)
	Use	Daycare rooms, Cafeteria(B1), Staff room, Special activity rooms
	GFA (Gross Floor Area)	2,529 m^2
	Build-up Area	1,082 m^2
Sampling Room Information	Location	1st Floor (East Side)
	Sampling Room Area	44.02 m^2
	Sampling Room Volume	162.40 m^3
	Number of Occupants	15 Infants and 1 Teacher
	Finishing Materials	Wall: Water Paint / Floor: Wood Flooring

2.2.2. Observation of the Daily Routine of Children

The daily activities at the childcare facility are broadly categorized into free play, naptime, meals, educational sessions, and other activities (Thorpe et al. 2020). While free play, nap time, and meals occur daily, educational and other activities vary on a weekly basis (Razak et al. 2018; Dev et al. 2018). At this childcare facility in Al Barsha, Dubai, the facility's large size and the availability of dedicated activity rooms allow specialized activities to occur outside the childcare rooms (Jung et al. 2022). Meals are also conducted in a cafeteria located in the basement. In the childcare room where measurements were conducted, natural ventilation was irregularly implemented during daily activities using east-facing pull-in windows, as no mechanical ventilation systems were installed (Zheng et al. 2023; Park et al. 2022). During most activities conducted in the childcare room, except during naptime, infants and young children engaged in continuous movement, which significantly influenced the generation and resuspension of particulate matter within the room (Kim et al. 2019). Detailed observations were made during the measurement period to provide a comprehensive analysis of particulate matter concentration changes, including the presence or absence of children, the number of individuals in the room, and the nature of the activities being carried out (Zhai et al. 2019). These observations served as critical reference points for understanding the variations in particulate matter concentration throughout the day.

2.2.3. Measurement Method

The measurements were conducted in October 2024 over five consecutive days, capturing the weekly recurring patterns of activities and operations at the childcare facility (Jung et al. 2022). To ensure authentic data collection, the measurements were taken during routine activities in a daycare room without the researcher's intentional intervention or control (Salimifard et al. 2020).

An Optical Particle Counter (AEROTRAK, TSI 9306-V2) was employed to measure particulate matter particle sizes during various activities. Before conducting measurements, the Optical Particle Counter (AEROTRAK, TSI 9306-V2) was calibrated according to the manufacturer's recommended procedure. The calibration involved verifying particle-count accuracy using monodisperse polystyrene latex spheres under controlled laboratory conditions. This ensured accurate particle-size discrimination and concentration measurement during the experiment.

This device estimates particle size and concentration by analyzing the intensity of light scattered by particles as they pass through its light-scattering chamber (Hussein et al. 2017). In this study, six particle size categories—0.3 µm, 0.5 µm, 1 µm, 3 µm, 5 µm, and 10 µm—were measured both indoors and outdoors to facilitate particle size-specific analysis of particulate matter (Morawska et al. 2017). Outdoor measurement locations were carefully selected based on criteria designed to represent typical outdoor air quality conditions affecting the childcare facility. Specifically, measurements were performed approximately 2 meters from the building façade, at a location representative of air intake zones for natural ventilation, while avoiding immediate interference from direct building exhausts or mechanical ventilation units. A proximity to vehicular traffic was considered, ensuring that outdoor sampling points were sufficiently distant (more than 10 meters) from the adjacent two-lane road to minimize the influence of direct traffic emissions

Additionally, indoor and outdoor temperature, relative humidity (RH), and CO_2 concentrations were recorded (Li et al. 2018). During data collection, environmental variables such as ambient wind speed and direction, as well as general weather conditions, were recorded from a nearby meteorological station. Wind speed during measurement periods typically ranged between 1 and 3 m/s, with predominant wind directions noted for each measurement day. These variables were monitored to confirm that outdoor particulate measurements reliably represented general ambient conditions and were not significantly influenced by localized anomalies or extreme weather events. Measurements were taken at a height of 0.9 m, corresponding to the respiratory zone of three-year-old children, in a location that did not interfere with their activities. A detailed summary of the measurement conditions is provided in Table 3.

***Table* 3.** Measurement equipment, locations, and sampling intervals used in the study. Instruments include the Optical Particle Counter (AEROTRAK, TSI 9306 - V2) and CO_2/Temperature/RH Data Logger (Lutron MCH-383SD).

Parameter	Details
Location	Daycare Room (90 cm above the floor and Outdoor)
Particulate Matter Equipment	Optical Particle Counter (AEROTRAK, TSI 9306 - V2)
CO_2, Temperature, RH Equipment	Data Logger (Lutron MCH-383SD)
Sampling Interval	10 minutes

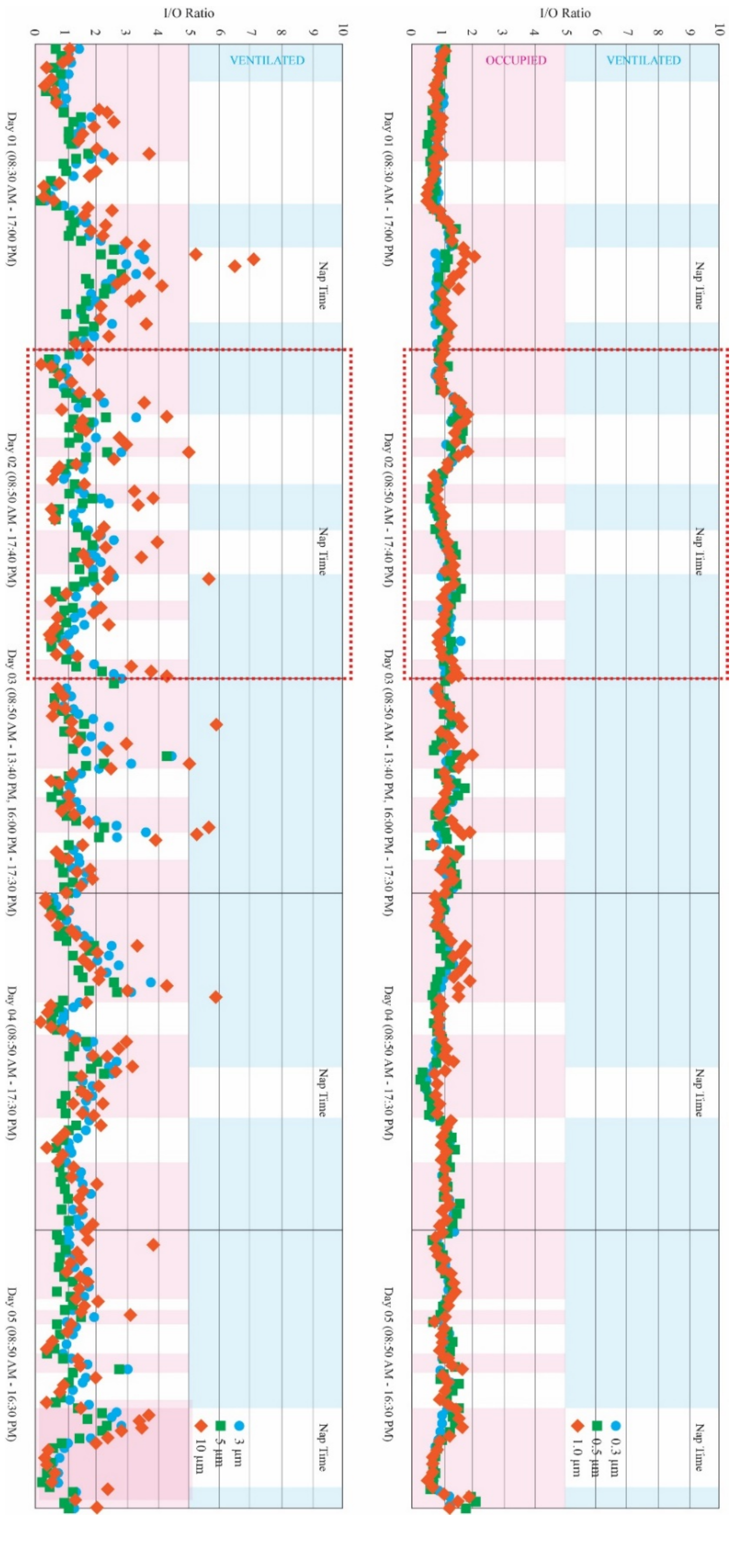
The following three-step analysis was conducted to ascertain whether the primary source of particulate matter within the daycare room originated indoors or outdoors (Lee et al. 2024). First, to evaluate the impact of outdoor particulate matter on indoor concentrations, a linear regression model was used to analyze the correlation between indoor and outdoor particulate matter measurements (Yuchi et al. 2019). A slope and R^2 value close to 1 in the regression model indicate a strong correlation, suggesting that outdoor sources significantly influence indoor particulate matter concentrations. Additionally, the data were categorized into two conditions for analysis: occupancy, when infants and toddlers were present and activities identified as potential indoor particulate matter sources were observed, and non-occupancy, when the daycare room was unoccupied, with only outdoor sources influencing indoor particulate matter concentrations (Um et al. 2022). Second, to further examine the influence of children's activities—considered a source of indoor particulate matter—on indoor concentrations, the I/O ratio of particulate matter concentrations was analyzed (Oliveira et al. 2019). The analysis was conducted separately for occupancy and non-occupancy periods, with particle size-specific comparisons (Jung et al. 2023). Third, an indicator representing the intensity of indoor sources was selected to establish a clear link between children's activities and particulate matter generation (Jan et al. 2017). The correlation between this source intensity indicator and indoor particulate matter concentrations was then analyzed using a linear regression model (Garbarienė et al. 2022). A strong positive correlation would confirm that children's activities are a significant source of indoor particulate matter (Niu et al. 2021). This comprehensive approach ensures a nuanced understanding of the interplay between indoor and outdoor sources, enabling precise identification of dominant contributors to particulate matter concentrations in childcare environments (Ferguson et al. 2017; Abdelaziz Mahmoud & Jung 2023).

Linear regression analysis, including slopes and R^2 values, was selected to identify correlations between indoor and outdoor particulate matter concentrations due to its interpretability and common application in IAQ studies. To enhance statistical robustness, p-values and 95% confidence intervals were calculated to evaluate the statistical significance of observed relationships. Furthermore, the Durbin-Watson statistics were employed to assess potential autocorrelation within the time-series data, ensuring that regression assumptions were adequately met.

3. Results

The variation in particulate matter concentration throughout the measurement period at the childcare facility was analyzed using the Indoor/Outdoor (I/O) ratio, defined as the ratio of indoor concentration to outdoor concentration. The results of the I/O ratio measurements over the five days are presented in Figure 2.

The analysis revealed distinct patterns in the I/O ratio based on particle size. For particulate matter particles measuring 0.3 µm, 0.5 µm, and 1 µm, the I/O ratio remained consistently close to 1 throughout daily activity, indicating a balanced relationship between indoor and outdoor concentrations. In contrast, for particles measuring 3 µm, 5 µm, and 10 µm, the I/O ratio exhibited noticeable increases during specific indoor activities. These increases were particularly pronounced during tasks such as preparing and organizing bedding, which appeared to contribute significantly to the resuspension of larger particles indoors. This differentiation in I/O ratio patterns highlights the influence of activity type and particle size on the dynamics of particulate matter concentration within the childcare environment.



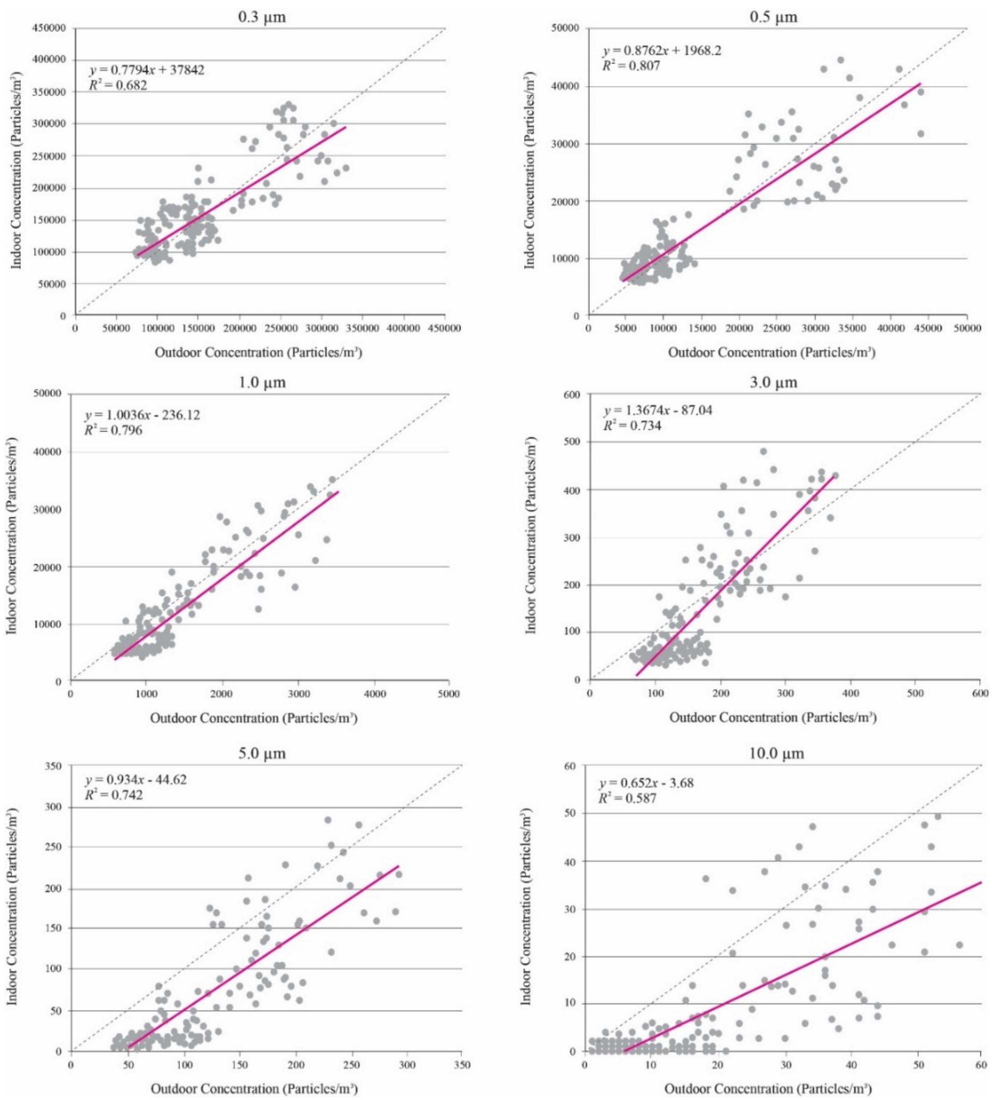
X-axis: Particle Size (µm), Y-axis: Indoor/Outdoor (I/O) Ratio

Figure 2. Indoor/Outdoor (I/O) ratio for particulate matter concentrations measured over five consecutive days. Each box plot represents the distribution of I/O ratios for particle sizes (0.3 µm to 10 µm). Boxes indicate interquartile ranges (25th–75th percentile), horizontal lines within boxes represent median values, and whiskers extend to the minimum and maximum observed ratios.

3.1. Correlation between Indoor/Outdoor Particulate Matter Concentration

The correlation between indoor and outdoor particulate matter concentrations was analyzed under both occupancy and non-occupancy conditions to assess the influence of indoor sources. Figure 3 illustrates the correlation during non-occupancy conditions, where no indoor sources were active. The R^2 values of the linear regression model for particle sizes, excluding 10 µm, indicate a strong correlation between indoor and outdoor concentrations: 0.68 for 0.3 µm, 0.81 for 0.5 µm, 0.80 for 1.0 µm, 0.74 for 3.0 µm, and 0.74 for 5.0 µm. Additionally, the slopes of the regression lines are close to 1, suggesting that indoor particulate matter concentrations closely reflect outdoor concentrations under non-occupancy conditions. These findings demonstrate that, in the absence of indoor sources, particulate matter concentrations indoors are primarily influenced by outdoor sources across most particle sizes. This highlights the significant role of outdoor air quality in determining indoor particulate matter levels when indoor activities are minimal.

The linear regression analysis confirmed these correlations as statistically significant ($p < 0.01$), with 95% confidence intervals for regression slopes consistently excluding zero (0.3 µm: CI [0.62, 0.83]; 0.5 µm: CI [0.74, 0.92]; 1.0 µm: CI [0.71, 0.89]; 3.0 µm: CI [0.66, 0.85]; 5.0 µm: CI [0.67, 0.86]). The Durbin-Watson test (ranging between 1.85 to 2.10 across particle sizes) indicated negligible autocorrelation, validating the independence of observations within this analysis.



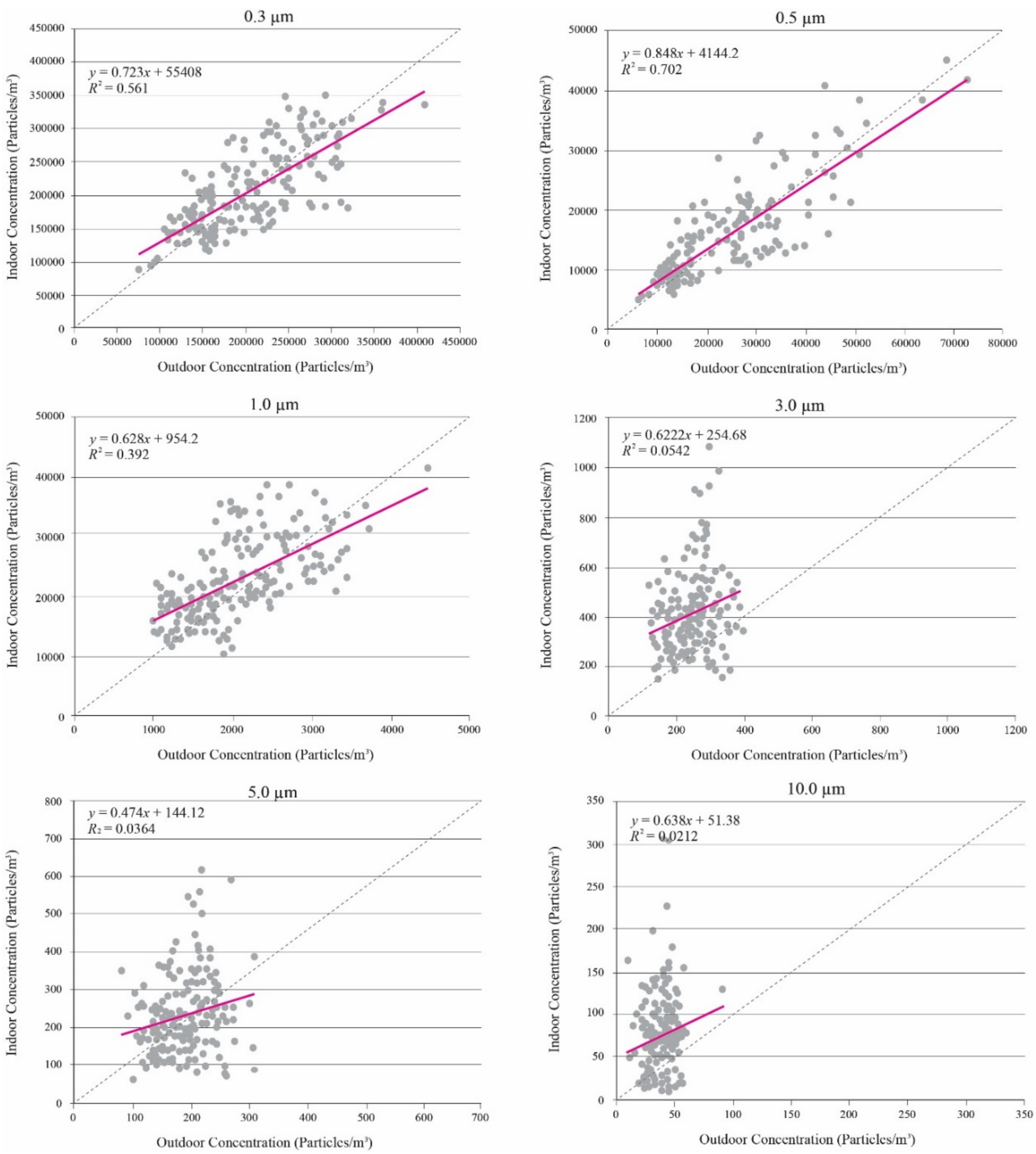
X-axis: Outdoor PM Concentration (particles/cm³), Y-axis: Indoor PM Concentration (particles/cm³)

Figure 3. Correlation between indoor and outdoor particulate matter concentrations under non-occupancy conditions. Scatter plots include linear regression lines with corresponding equations, R^2

values, and statistical significance (p-values). Axes represent particulate matter concentration (particles/cm³), with clearly marked units for indoor (y-axis) and outdoor (x-axis) measurements.

Figure 4 illustrates the correlation between indoor and outdoor particulate matter concentrations during the experiment. For particle sizes of 0.3 µm and 0.5 µm, the slopes of the linear regression models are 0.72 and 0.85, respectively, with R^2 values of 0.56 and 0.70. These results indicate a moderate correlation between indoor and outdoor particulate matter concentrations for these smaller particle sizes.

For particle sizes of 1 µm, the slope of the linear regression model is 0.63, and the R^2 value is 0.39, suggesting a weaker correlation compared to the smaller particles (0.3 µm and 0.5 µm). However, the correlation is still notable when compared to larger particles, such as 3 µm ($R^2 = 0.05$), 5 µm ($R^2 = 0.03$), and 10 µm ($R^2 = 0.02$). Additionally, the data reveal a trend where indoor concentrations increase as outdoor concentrations rise, particularly for smaller particle sizes.



X-axis: Outdoor PM Concentration (particles/cm³), Y-axis: Indoor PM Concentration (particles/cm³)

Figure 4. Correlation between indoor and outdoor particulate matter concentrations during occupied periods. Scatter plots present linear regression fits with clearly labeled equations, R^2 values, and p-values. Axes clearly show particle concentrations (particles/cm³), differentiating between indoor (y-axis) and outdoor (x-axis) environments.

For particles measuring 3 µm, 5 µm, and 10 µm, the points on the graph are not evenly distributed around the regression line, and the R^2 values are below 0.05. This indicates a negligible correlation between indoor and outdoor concentrations for these larger particles. Furthermore, the variability in indoor concentrations for these particle sizes appears to exceed that of outdoor concentrations, suggesting that indoor factors play a more significant role in influencing the concentrations of larger particles.

These findings demonstrate that the influence of outdoor particulate matter concentrations on indoor levels is more pronounced for smaller particle sizes (0.3 µm, 0.5 µm, and 1 µm) than for larger particles (3 µm, 5 µm, and 10 µm), where indoor sources and resuspension may have a more significant impact.

The following findings distinctly demonstrate how Dubai's climatic conditions and urban activities uniquely influence particulate matter dynamics within childcare environments, differentiating this study from previous research conducted in less extreme climatic regions or more commonly studied building types.

The regression results for smaller particles during occupied conditions were statistically significant ($p < 0.05$), with confidence intervals for slopes distinctly greater than zero (0.3 µm: CI [0.59, 0.85]; 0.5 µm: CI [0.72, 0.98]; 1 µm: CI [0.49, 0.77]). Conversely, larger particles (3 µm, 5 µm, and 10 µm) exhibited non-significant relationships ($p > 0.05$), further emphasizing the predominant role of indoor activities for these particle sizes. The Durbin-Watson statistic (1.92–2.12) again indicated minimal autocorrelation, confirming the reliability of the regression model.

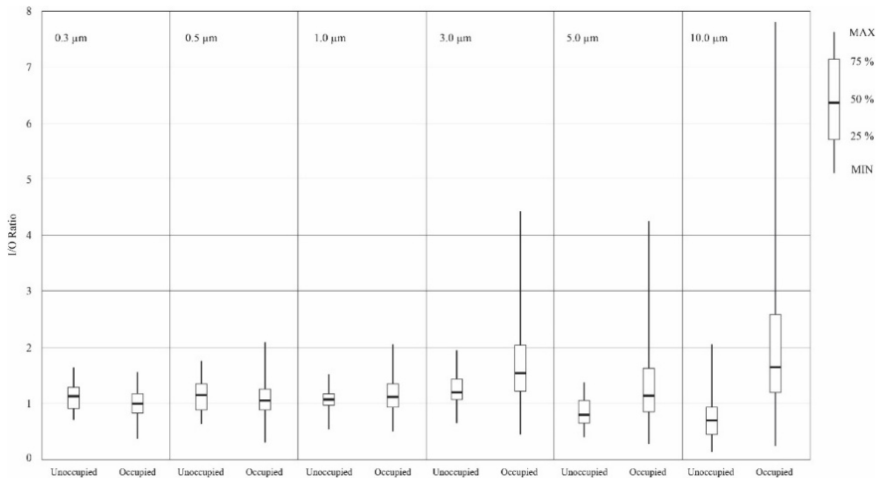
The experiment confirmed that particulate matter particles measuring 0.3 µm, 0.5 µm, and 1 µm are influenced by outdoor concentrations under non-occupied and occupied conditions. For particle sizes of 3 µm and 5 µm, a correlation between indoor and outdoor concentrations was observed in non-occupied conditions; however, for particle sizes of 3 µm, 5 µm, and 10 µm, it was established that outdoor concentrations have negligible influence under occupied conditions.

3.2. Comparison of I/O Ratios during Occupied and Unoccupied Conditions

To evaluate the impact of the presence of infants and young children on indoor particulate matter concentrations by particle size, the Indoor/Outdoor (I/O) ratio under non-occupied (I/O ratio - Unoccupied) and occupied (I/O ratio - Occupied) conditions was compared for different particle sizes of particulate matter (Figure 5).

For particulate matter particles measuring 0.3 µm, 0.5 µm, and 1 µm, the I/O ratios were consistently close to 1 in both occupied and non-occupied conditions. Furthermore, the variation in the I/O ratios for these particle sizes was minimal compared to particles measuring 3 µm, 5 µm, and 10 µm. This indicates that the presence or absence of occupants has a negligible impact on the I/O ratio for smaller particle sizes.

In contrast, particulate matter particles with sizes of 3 µm, 5 µm, and 10 µm exhibited significant deviations in the I/O ratio depending on occupancy. For particles measuring 5 µm and 10 µm, the median I/O ratio in non-occupied conditions was below 1, suggesting that indoor concentrations were generally lower than outdoor concentrations. However, during occupied conditions, the I/O ratios for particles measuring 3 µm, 5 µm, and 10 µm increased markedly. The difference between the maximum and minimum I/O ratios was approximately 10 times for 3 µm, 16 times for 5 µm, and 34 times for 10 µm, indicating a substantial variation in particulate matter concentration under occupied conditions. These findings highlight the pronounced influence of occupant activity on the concentration of larger particulate matter particles, while smaller particles are less affected by occupancy.



X-axis: Particle Size (µm), Y-axis: Indoor/Outdoor (I/O) Ratio

Figure 5. Comparison of Indoor/Outdoor (I/O) ratios under unoccupied and occupied conditions for different particle sizes (0.3 µm to 10 µm). Each box plot clearly differentiates occupancy status, with medians, interquartile ranges, and minimum/maximum values labeled. Axes are clearly defined with consistent notation.

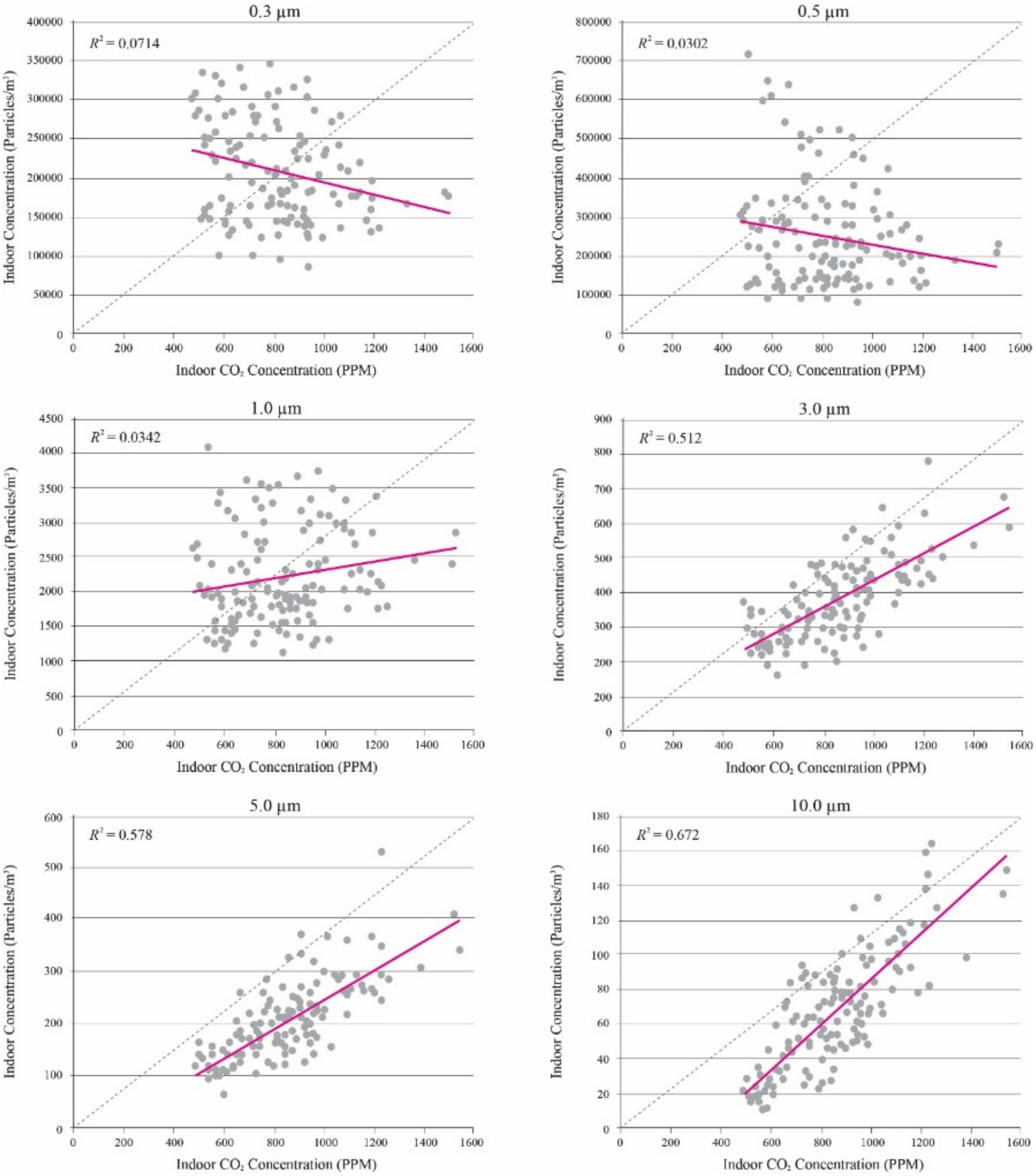
3.3. Correlation between Particulate matter Concentration and CO_2 Concentration

To investigate the causes of increased indoor particulate matter concentrations during occupancy, the relationship between indoor particulate matter levels and the intensity of indoor sources was analyzed. In a study by Son (2023), the number of students present indicated indoor source intensity, and its correlation with indoor particulate matter concentration was examined (Son 2023). However, observations and recordings of activities at the targeted daycare center revealed that the arrival times of infants and toddlers and the number of occupants were highly irregular and fluctuated significantly within short periods. These inconsistencies made it impractical to use occupant numbers as a reliable indicator of source intensity. Additionally, because ventilation was irregular and varied throughout the day, selecting an indicator that accounted for both source intensity and ventilation was necessary. This study chose indoor CO_2 concentration - produced by human respiration and diluted through ventilation - as a comprehensive indicator that reflects both factors.

During nap times, when infants and toddlers were inactive and particulate matter generation ceased, CO_2 continued to be produced through respiration. This made CO_2 an unsuitable indicator during these periods, and data from nap times were excluded from the analysis. The correlation between indoor particulate matter concentrations and indoor CO_2 levels is shown in Figure 6. The data points were widely scattered for particulate matter particles with sizes of 0.3 µm, 0.5 µm, and 1 µm, and the R^2 value was less than 0.1. This indicates no meaningful correlation between indoor particulate matter concentrations and indoor sources for these smaller particle sizes, confirming that indoor sources had minimal influence.

In contrast, for particles measuring 3 µm, 5 µm, and 10 µm, the data points were consistently aligned along a positive trend, with R^2 values of 0.51 (3 µm), 0.58 (5 µm), and 0.67 (10 µm). These results confirm a positive correlation between indoor particulate matter concentrations of larger particle sizes and indoor CO_2 levels, suggesting that indoor sources play a significant role in generating and resuspending larger particulate matter particles during occupancy.

Statistical analysis confirmed significant correlations ($p < 0.01$) between indoor CO_2 and larger particle concentrations, with slopes having confidence intervals clearly above zero (3 µm: CI [0.44, 0.58]; 5 µm: CI [0.49, 0.66]; 10 µm: CI [0.61, 0.73]). The Durbin-Watson statistics ranged from 1.90 to 2.05, indicating minimal autocorrelation and validating the assumption of independence in the data analyzed points.



X-axis: Indoor CO_2 Concentration (ppm), Y-axis: Indoor PM Concentration (particles/cm³)

Figure 6. Correlation between indoor CO_2 concentrations (ppm) and particulate matter concentrations (particles/cm³) excluding nap times. Scatter plots display linear regression models, including equations, R^2 values, and p-values, clearly illustrating the relationships between different particle sizes.

3.4. Analysis of Major Sources of Indoor Particulate Matter by Particle Size

The analysis of the correlation between indoor and outdoor particulate matter concentrations under both occupancy and non-occupancy conditions, using a linear regression model, revealed the following insights. A correlation was observed between indoor and outdoor concentrations, regardless of occupancy, for particulate matter particles with sizes of 0.3 µm, 0.5 µm, and 1 µm. However, for particle sizes of 3 µm and 5 µm, a correlation between indoor and outdoor concentrations was confirmed only under non-occupancy conditions, while no such correlation was observed during occupancy. For particles measuring 10 µm, there was no correlation between indoor and outdoor concentrations under either condition.

These results suggest that particulate matter with smaller particle sizes (0.3 µm, 0.5 µm, and 1 µm) is predominantly influenced by outdoor sources, irrespective of occupancy. In contrast, larger particles

(3 µm, 5 µm, and 10 µm) are minimally affected by outdoor sources during occupancy, likely due to the influence of indoor activities.

To further investigate the impact of infants' and toddlers' activities on indoor particulate matter concentrations, the Indoor/Outdoor (I/O) ratios were compared between occupancy and non-occupancy conditions. For particles measuring 0.3 µm, 0.5 µm, and 1 µm, the I/O ratios remained close to 1 across both conditions, confirming that outdoor particulate matter concentrations exert a more significant influence than occupancy. Conversely, for particle sizes of 3 µm, 5 µm, and 10 µm, the I/O ratios showed significant variation between occupancy and non-occupancy. This indicates that the activities of infants and toddlers substantially contribute to the increase in indoor concentrations of larger particles.

To validate whether the activities of infants and young children serve as an indoor source of large particulate matter particles (3 µm, 5 µm, and 10 µm), the relationship between indoor particulate matter concentrations and indoor source intensity was analyzed. Indoor CO_2 concentrations, generated through human respiration and influenced by ventilation, indicated source intensity. The analysis revealed no significant correlation between source intensity and particulate matter concentrations for smaller particles (0.3 µm, 0.5 µm, and 1 µm). However, a positive correlation was observed for larger particles (3 µm, 5 µm, and 10 µm), with the R^2 values indicating a meaningful relationship between CO_2 levels and indoor particulate matter concentrations.

These findings confirm that outdoor sources of small particle sizes primarily influence particulate matter concentrations in childcare facilities, but indoor sources of larger particles drive them mainly.

4. Discussion

This study presents novel insights into the behavior and impact of particulate matter specifically within childcare facilities in Dubai, UAE, an underrepresented research context characterized by severe climatic events, intense construction activities, and unique urban characteristics that significantly influence particulate dynamics. The results underscore the importance of understanding particle size-specific dynamics in developing effective air quality management strategies tailored to such sensitive environments (Bani Mfarrej et al. 2020; Jung & El Samanoudy 2023).

Particulate matter particles of smaller sizes (0.3 µm, 0.5 µm, and 1 µm) showed strong correlations between indoor and outdoor concentrations under both occupied and unoccupied conditions (Zhao et al. 2020). This indicates that smaller particles are primarily influenced by outdoor air quality, irrespective of indoor human activity (Von Schneidemesser et al. 2019; Śmiełowska et al. 2017). In the context of Dubai, where regional factors such as transboundary air pollution, construction dust, and sandstorms are prevalent, the findings emphasize the need to improve building filtration systems and mitigate outdoor pollution sources to safeguard indoor air quality, particularly for smaller particle sizes (Akasha et al. 2024).

In contrast, larger particles (3 µm, 5 µm, and 10 µm) exhibited minimal correlation between indoor and outdoor concentrations during occupancy, with significant increases in indoor levels directly linked to occupant activities (Liao et al. 2021; Dris et al. 2017). Children's movements, bedding preparations, and routine activities significantly resuspend settled dust, elevating concentrations of larger particles (Liu 2022). This aligns with the observed variability in Indoor/Outdoor (I/O) ratios, which showed substantial increases for larger particles during occupancy compared to non-occupancy periods. These findings underscore the crucial role of indoor source control, particularly in facilities serving young children whose respiratory systems are still developing and are more susceptible to airborne pollutants (Ali et al. 2021).

Using CO_2 concentrations to indicate indoor source intensity provided additional insights (Blocken et al. 2021). Smaller particles showed little correlation with indoor CO_2, whereas larger particles correlated positively, confirming the significant role of human activities in their resuspension and generation (Stratigou et al. 2020). This finding highlights the significance of understanding indoor activity patterns and their impact on air quality degradation.

Given Dubai's unique environmental and climatic conditions, strategies for improving air quality in childcare facilities must address both outdoor and indoor sources. Managing smaller particles requires enhanced building envelopes, high-efficiency filtration (HEPA), and control of outdoor sources. Reducing larger particles requires careful material selection, optimized ventilation, and spatial design to minimize resuspension.

This study underscores the importance of adopting a comprehensive approach to air quality management in childcare facilities, which involves integrating robust architectural and operational measures to create healthier indoor environments. These efforts are particularly crucial in Dubai, where environmental conditions and urban development factors pose unique challenges to maintaining IAQ, especially for vulnerable populations such as young children. Contrary to existing literature, which predominantly examines indoor air quality (IAQ) within residential or educational facilities in temperate or controlled climates, the originality of this research lies in its contextual focus on Dubai's environmental extremes. Such conditions pose distinctive challenges to managing indoor particulate matter, particularly in childcare facilities, thus underscoring the critical contribution of this study to the field of IAQ research. Future research could expand on these findings by further exploring innovative design solutions and real-time monitoring systems to enhance air quality in similar settings.

Despite the valuable insights provided, this study has several limitations that warrant careful consideration. Firstly, the measurement period was limited to five consecutive days, which may not fully capture long-term or seasonal variability in particulate matter concentrations. Extending the sampling duration would enhance the robustness of the findings. Secondly, measurements were conducted exclusively in a single daycare room, which may have limited the generalizability of the results to other rooms or daycare centers with varying spatial layouts and ventilation characteristics. Furthermore, the study period (October) reflects specific climatic conditions in Dubai. It thus may not represent particulate matter dynamics during other seasons, such as the intense summer months or periods of higher frequency sandstorms. Lastly, while proximity to traffic was considered in selecting outdoor sampling locations, potential transient impacts from nearby traffic congestion or sporadic sandstorm events could influence particulate matter concentrations and were not explicitly accounted for in the modeling. Future research should address these limitations by conducting longitudinal studies across multiple rooms and seasons, explicitly accounting for external episodic events to provide comprehensive air quality management strategies.

5. Conclusions

This study investigated the primary sources of indoor particulate matter in childcare facilities in Dubai, UAE, by measuring and analyzing the concentrations of particulate matter indoors and outdoors. The research focused on a daycare room for three-year-old children, capturing real-world activity conditions over a five-day period. The findings offer critical insights into the interplay between indoor and outdoor sources of particulate matter and their implications for managing air quality in childcare environments.

First, the correlation analysis between indoor and outdoor particulate matter concentrations revealed that particulate matter particles with smaller sizes (0.3 µm, 0.5 µm, and 1 µm) are significantly influenced by outdoor sources, regardless of occupancy. This underscores that outdoor air quality plays a pivotal role in determining the indoor concentrations of these smaller particles, suggesting that effective outdoor filtration strategies are essential for reducing their presence indoors. In contrast, for larger particles (3 µm and 5 µm), a correlation with outdoor concentrations was only observed during non-occupancy periods, while no correlation was evident during occupancy. No correlation was observed under either condition for the largest particles (10 µm), indicating that indoor factors dominate their concentration levels.

Second, an analysis of the Indoor/Outdoor (I/O) ratios during occupancy and non-occupancy revealed distinct trends. The I/O ratios for smaller particles (0.3 µm, 0.5 µm, and 1 µm) remained close to 1 regardless of occupancy, indicating limited influence from indoor activities. However, larger particles (3 µm, 5 µm, and 10 µm) exhibited substantial variation in I/O ratios, with occupancy leading to marked increases. This suggests that indoor activities, particularly those involving movement, are the primary contributors to the elevated concentrations of larger particles.

Third, the study utilized CO_2 concentration as a proxy for indoor source intensity to examine its correlation with indoor particulate matter levels. While no significant correlation was found for smaller particles, a positive correlation was observed for larger particles (3 µm, 5 µm, and 10 µm). This confirms that indoor activities, such as the movement of infants and young children, are major contributors to the generation and resuspension of larger particulate matter particles.

These findings highlight the dual influence of outdoor and indoor sources on particulate matter concentrations, with smaller particles predominantly affected by outdoor conditions and larger particles by indoor activities. The results underscore the importance of implementing tailored strategies for air quality management in childcare facilities. Efforts should focus on enhancing building envelope integrity and outdoor air filtration to capture smaller particles. For larger particles, strategies should include selecting materials that minimize dust accumulation, optimizing ventilation to reduce resuspension, and carefully designing indoor spaces to limit disturbances during activities.

To enhance the practical applicability of these findings, specific actionable recommendations are provided for key stakeholders in Dubai. Policymakers should implement regulatory guidelines mandating high-efficiency particulate air (HEPA) filtration systems and regular IAQ assessments in childcare centers, especially during high-risk periods such as sandstorms and construction activities. Daycare managers are advised to adopt daily protocols, including regular wet-cleaning routines and controlled natural ventilation schedules, minimizing dust resuspension from indoor surfaces. Additionally, educational sessions for staff on effective indoor pollutant management are recommended. Building designers should incorporate air-lock vestibules, airtight building envelopes, and smooth, low-dust-accumulating interior finishes to mitigate particulate infiltration and resuspension. Incorporating these strategies will significantly enhance air quality, creating healthier environments specifically tailored for childcare facilities in Dubai's unique climatic and urban context.

This study contributes valuable data and insights to the field of indoor air quality management, particularly in Dubai's unique environmental context. Addressing indoor and outdoor sources, the research provides a foundation for creating healthier and safer environments for vulnerable populations, such as young children in childcare facilities. Furthermore, by situating this investigation in Dubai's specific climatic and urban environment, this study makes a unique contribution to the literature by providing data and strategies tailored explicitly to managing indoor air quality within childcare facilities under such challenging environmental conditions. Future research should further explore real-time monitoring and adaptive approaches to enhance air quality in similar settings.

Author Contributions

Conceptualization, C.J.; methodology, C.J.; software, C.J.; validation, C.J.; formal analysis, C.J.; investigation, C.J.; resources, C.J.; data curation, C.J.; writing—original draft preparation, C.J.; writing—review and editing, C.J.; visualization, C.J.; supervision, C.J.; project administration, C.J. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

New data were created or analyzed in this study. Data will be shared upon request, provided that consideration is given to the authors.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Abdelaziz Mahmoud, N. S., & Jung, C. (2023). Analyzing the bake-out effect in winter for the enhancement of indoor air quality at new apartments in UAE. *Buildings*, *13*(4), 846. https://doi.org/10.3390/buildings13040846

Akasha, H., Ghaffarpasand, O., & Pope, F. D. (2023). Climate change, air pollution and the associated burden of disease in the Arabian peninsula and neighbouring regions: A critical review of the literature. *Sustainability*, *15*(4), 3766. https://doi.org/10.3390/su15043766

Akasha, H., Ghaffarpasand, O., & Pope, F. D. (2024). Air pollution and economic growth in Dubai a fast-growing Middle Eastern city. *Atmospheric Environment: X*, *21*, 100246. https://doi.org/10.1016/j.aeaoa.2024.100246

Ali, M. U., Yu, Y., Yousaf, B., Munir, M. A. M., Ullah, S., Zheng, C., ... & Wong, M. H. (2021). Health impacts of indoor air pollution from household solid fuel on children and women. *Journal of hazardous materials*, *416*, 126127. https://doi.org/10.1016/j.jhazmat.2021.126127

Al-Rikabi, I. J., Karam, J., Alsaad, H., Ghali, K., Ghaddar, N., & Voelker, C. (2024). The impact of mechanical and natural ventilation modes on the spread of indoor airborne contaminants: A review. *Journal of Building Engineering*, 108715. https://doi.org/10.1016/j.jobe.2024.108715

Alves, C., Vicente, A., Oliveira, A. R., Candeias, C., Vicente, E., Nunes, T., ... & Almeida, S. M. (2020). Fine particulate matter and gaseous compounds in kitchens and outdoor air of different dwellings. *International Journal of Environmental Research and Public Health*, *17*(14), 5256. https://doi.org/10.3390/ijerph17145256

Arar, M., & Jung, C. (2021). Improving the indoor air quality in nursery buildings in United Arab Emirates. *International Journal of Environmental Research and Public Health*, *18*(22), 12091. https://doi.org/10.3390/ijerph182212091

Arar, M., & Jung, C. (2022). Analyzing the perception of indoor air quality (IAQ) from a survey of new townhouse residents in Dubai. *Sustainability*, *14*(22), 15042. https://doi.org/10.3390/su142215042

Awad, J., & Jung, C. (2021). Evaluating the indoor air quality after renovation at the Greens in Dubai, United Arab Emirates. *Buildings*, *11*(8), 353. https://doi.org/10.3390/buildings11080353

Bani Mfarrej, M. F., Qafisheh, N. A., & Bahloul, M. M. (2020). Investigation of indoor air quality inside houses from UAE. *Air, Soil and Water Research*, *13*, 1178622120928912. https://doi.org/10.1177/117862212092891

Blocken, B., Van Druenen, T., Ricci, A., Kang, L., Van Hooff, T., Qin, P., ... & Brombacher, A. C. (2021). Ventilation and air cleaning to limit aerosol particle concentrations in a gym during the COVID-19 pandemic. *Building and Environment*, *193*, 107659. https://doi.org/10.1016/j.buildenv.2021.107659

Bo, M., Salizzoni, P., Clerico, M., & Buccolieri, R. (2017). Assessment of indoor-outdoor particulate matter air pollution: A review. *Atmosphere*, *8*(8), 136. https://doi.org/10.3390/atmos8080136

Bousiotis, D., Alconcel, L. N. S., Beddows, D. C., Harrison, R. M., & Pope, F. D. (2023). Monitoring and apportioning sources of indoor air quality using low-cost particulate matter sensors. *Environment International*, *174*, 107907. https://doi.org/10.1016/j.envint.2023.107907

Cheriyan, D., & Choi, J. H. (2020). A review of research on particulate matter pollution in the construction industry. *Journal of Cleaner Production*, 254, 120077. https://doi.org/10.1016/j.jclepro.2020.120077

Cichowicz, R., & Dobrzański, M. (2021). Spatial analysis (measurements at heights of 10 m and 20 m above ground level) of the concentrations of particulate matter (PM10, PM2. 5, and PM1. 0) and gaseous pollutants (H2S) on the university campus: a case study. *Atmosphere*, *12*(1), 62. https://doi.org/10.3390/atmos12010062

Dev, D. A., Williams, N., Iruka, I., Garcia, A. S., Guo, Y., Patwardhan, I., ... & Sedani, A. (2018). Improving the nutrition and screen time environment through self-assessment in family childcare homes in Nebraska. *Public health nutrition*, *21*(13), 2351-2359. https://doi.org/10.1017/S1368980018001416

Dris, R., Gasperi, J., Mirande, C., Mandin, C., Guerrouache, M., Langlois, V., & Tassin, B. (2017). A first overview of textile fibers, including microplastics, in indoor and outdoor environments. *Environmental pollution*, *221*, 453-458. https://doi.org/10.1016/j.envpol.2016.12.013

Elsaid, A. M., & Ahmed, M. S. (2021). Indoor air quality strategies for air-conditioning and ventilation systems with the spread of the global coronavirus (COVID-19) epidemic: Improvements and recommendations. *Environmental Research*, *199*, 111314. https://doi.org/10.1016/j.envres.2021.111314

Ferguson, A., Penney, R., & Solo-Gabriele, H. (2017). A review of the field on children's exposure to environmental contaminants: A risk assessment approach. *International journal of environmental research and public health*, *14*(3), 265. https://doi.org/10.3390/ijerph14030265

Garbarienė, I., Pauraitė, J., Pashneva, D., Minderytė, A., Sarka, K., Dudoitis, V., ... & Byčenkienė, S. (2022). Indoor-outdoor relationship of submicron particulate matter in mechanically ventilated building: chemical composition, sources and infiltration factor. *Building and Environment*, *222*, 109429. https://doi.org/10.1016/j.buildenv.2022.109429
Garbarienė, I., Pauraitė, J., Pashneva, D., Minderytė, A., Sarka, K., Dudoitis, V., ... & Byčenkienė, S. (2022). Indoor-outdoor relationship of submicron particulate matter in mechanically ventilated building: chemical composition, sources and infiltration factor. *Building and Environment*, *222*, 109429. https://doi.org/10.1016/j.buildenv.2022.109429
Goldstein, A. H., Nazaroff, W. W., Weschler, C. J., & Williams, J. (2020). How do indoor environments affect air pollution exposure?. *Environmental science & technology*, *55*(1), 100-108. https://doi.org/10.1021/acs.est.0c05727

Guo, X., Zhang, M., Gao, Z., Zhang, J., & Buccolieri, R. (2023). Neighborhood-scale dispersion of traffic-related PM2. 5: Simulations of nine typical residential cases from Nanjing. *Sustainable Cities and Society*, *90*, 104393. https://doi.org/10.1016/j.scs.2023.104393

Huang, Y., Wang, J., Chen, Y., Chen, L., Chen, Y., Du, W., & Liu, M. (2022). Household PM2. 5 pollution in rural Chinese homes: levels, dynamic characteristics and seasonal variations. *Science of The Total Environment*, *817*, 153085. https://doi.org/10.1016/j.scitotenv.2022.153085

Hussein, T., Boor, B. E., dos Santos, V. N., Kangasluoma, J., Petäjä, T., & Lihavainen, H. (2017). Mobile aerosol measurement in the eastern Mediterranean–a utilization of portable instruments. *Aerosol and air quality research*, *17*(7), 1875-1886. https://doi.org/10.4209/aaqr.2016.11.0479

Jan, R., Roy, R., Yadav, S., & Satsangi, P. G. (2017). Exposure assessment of children to particulate matter and gaseous species in school environments of Pune, India. *Building and Environment*, *111*, 207-217. https://doi.org/10.1016/j.buildenv.2016.11.008

Jodeh, S., Hasan, A. R., Amarah, J., Judeh, F., Salghi, R., Lgaz, H., & Jodeh, W. (2018). Indoor and outdoor air quality analysis for the city of Nablus in Palestine: Seasonal trends of PM 10, PM 5.0, PM 2.5, and PM 1.0 of residential homes. *Air Quality, Atmosphere & Health*, *11*, 229-237. https://doi.org/10.1007/s11869-017-0533-5

Jones, N. C., Thornton, C. A., Mark, D., & Harrison, R. M. (2000). Indoor/outdoor relationships of particulate matter in domestic homes with roadside, urban and rural locations. *Atmospheric environment*, 34(16), 2603-2612. https://doi.org/10.1016/S1352-2310(99)00489-6

Jung, C., & Abdelaziz Mahmoud, N. S. (2023). Navigating dust storms and urban living: an analysis of particulate matter infiltration in Dubai's residences. *Frontiers in Built Environment*, *9*, 1297520. https://doi.org/10.3389/fbuil.2023.1297520

Jung, C., & El Samanoudy, G. (2023). Mitigating indoor air pollution in university dormitory: the need for better ventilation and resident awareness. *Buildings*, *13*(5), 1144. https://doi.org/10.3390/buildings13051144

Jung, C., & Mahmoud, N. S. A. (2022). Extracting the critical points of formaldehyde (HCHO) emission model in hot desert climate. *Air, Soil and Water Research*, *15*, 11786221221105082. https://doi.org/10.1177/11786221221105082

Jung, C., Abdelaziz Mahmoud, N. S., Al Qassimi, N., & Elsamanoudy, G. (2023). Preliminary study on the emission dynamics of TVOC and formaldehyde in homes with eco-friendly materials: beyond green building. *Buildings*, *13*(11), 2847. https://doi.org/10.3390/buildings13112847

Jung, C., Al Qassimi, N., Arar, M., & Awad, J. (2021). The analysis of indoor air pollutants from finishing material of new apartments at business Bay, Dubai. *Frontiers in Built Environment*, *7*, 765689. https://doi.org/10.3389/fbuil.2021.765689

Jung, C., Al Qassimi, N., Arar, M., & Awad, J. (2022). The improvement of user satisfaction for two urban parks in dubai, UAE: bay avenue park and Al ittihad park. *Sustainability*, *14*(6), 3460. https://doi.org/10.3390/su14063460

Jung, C., Alqassimi, N., & El Samanoudy, G. (2022). The comparative analysis of the indoor air pollutants in occupied apartments at residential area and industrial area in Dubai, United Arab Emirates. *Frontiers in Built Environment*, *8*, 998858. https://doi.org/10.3389/fbuil.2022.998858

Jung, C., Awad, J., & Al Qassimi, N. (2021). Evaluation of residents' comfort in high-rise residential buildings in Dubai, United Arab Emirates. *Frontiers in Built Environment*, *7*, 766057. https://doi.org/10.3389/fbuil.2021.766057

Jung, C., Ismail, M. A., Arar, M., & AlQassimi, N. (2024). Mitigating indoor air pollution in UAE's high-rise apartment buildings: a study on eco-friendly materials and adsorbents. *Smart and Sustainable Built Environment*. https://doi.org/10.1108/SASBE-09-2023-0269

Jung, C., Mahmoud, N. S. A., El Samanoudy, G., & Al Qassimi, N. (2022). Evaluating the color preferences for elderly depression in the United Arab Emirates. *Buildings*, *12*(2), 234. https://doi.org/10.3390/buildings12020234

Kempton, L., Daly, D., Kokogiannakis, G., & Dewsbury, M. (2022). A rapid review of the impact of increasing airtightness on indoor air quality. *Journal of Building Engineering*, *57*, 104798. https://doi.org/10.1016/j.jobe.2022.104798

Kim, J., Park, S., Kim, H., & Yeo, M. S. (2019). Emission characterization of size-resolved particles in a pre-school classroom in relation to children's activities. *Indoor and Built Environment*, *28*(5), 659-676. https://doi.org/10.1177/1420326X17707565

Kumar, P., Singh, A. B., Arora, T., Singh, S., & Singh, R. (2023). Critical review on emerging health effects associated with the indoor air quality and its sustainable management. *Science of The Total Environment*, *872*, 162163. https://doi.org/10.1016/j.scitotenv.2023.162163

Kutlu, C., Erdinc, M. T., Ehtiwesh, A., Bottarelli, M., Su, Y., & Riffat, S. (2025). Evaluation of operation control parameters of a residential solar organic Rankine cycle with effects of expander-generator coupling. *Global Decarbonisation*, *2025*, 1–19. https://doi.org/10.17184/eac.9437

Lee, H., Lee, B. G., Kim, Y. J., Shim, J. E., & Yeo, M. K. (2024). Assessment of airborne bacteria in the indoor of public-use facilities concentrated on influencing factors and opportunistic pathogenic bacteria. *Air Quality, Atmosphere & Health*, 1-14. https://doi.org/10.1007/s11869-024-01540-3

Li, J., Fan, G., Ou, Y., & Deng, Q. (2023). Characteristics and control strategies of indoor particles: An updated review. *Energy and Buildings*, *294*, 113232. https://doi.org/10.1016/j.enbuild.2023.113232

Li, Y., Yuan, Y., Li, C., Han, X., & Zhang, X. (2018). Human responses to high air temperature, relative humidity and carbon dioxide concentration in underground refuge chamber. *Building and Environment*, *131*, 53-62. https://doi.org/10.1016/j.buildenv.2017.12.038

Li, Z., Wen, Q., & Zhang, R. (2017). Sources, health effects and control strategies of indoor fine particulate matter (PM2. 5): A review. *Science of the Total Environment*, 586, 610-622. https://doi.org/10.1016/j.scitotenv.2017.02.029

Liao, Z., Ji, X., Ma, Y., Lv, B., Huang, W., Zhu, X., ... & Shang, X. (2021). Airborne microplastics in indoor and outdoor environments of a coastal city in Eastern China. Journal of Hazardous Materials, 417, 126007. https://doi.org/10.1016/j.jhazmat.2021.126007

Liu, X. (2022). Understanding semi-volatile organic compounds in indoor dust. *Indoor and Built Environment*, *31*(2), 291-298. https://doi.org/10.1177/1420326X211070859

Liu, X., Nie, D., Zhang, K., Wang, Z., Li, X., Shi, Z., ... & Hu, J. (2019). Evaluation of particulate matter deposition in the human respiratory tract during winter in Nanjing using size and chemically resolved ambient measurements. *Air Quality, Atmosphere & Health*, *12*, 529-538. https://doi.org/10.1007/s11869-019-00663-2

Martins, N. R., & Da Graca, G. C. (2018). Impact of PM2. 5 in indoor urban environments: A review. *Sustainable Cities and Society*, *42*, 259-275. https://doi.org/10.1016/j.scs.2018.07.011

Martins, V., Faria, T., Diapouli, E., Manousakas, M. I., Eleftheriadis, K., Viana, M., & Almeida, S. M. (2020). Relationship between indoor and outdoor size-fractionated particulate matter in urban microenvironments: Levels, chemical composition and sources. *Environmental research*, *183*, 109203. https://doi.org/10.1016/j.envres.2020.109203
Martins, V., Faria, T., Diapouli, E., Manousakas, M. I., Eleftheriadis, K., Viana, M., & Almeida, S. M. (2020). Relationship between indoor and outdoor size-fractionated particulate matter in urban microenvironments: Levels, chemical composition and sources. *Environmental research*, *183*, 109203. https://doi.org/10.1016/j.envres.2020.109203
Maung, T. Z., Bishop, J. E., Holt, E., Turner, A. M., & Pfrang, C. (2022). Indoor air pollution and the health of vulnerable groups: a systematic review focused on particulate matter (PM), volatile organic compounds (VOCs) and their effects on children and people with pre-existing lung disease. *International journal of environmental research and public health*, *19*(14), 8752. https://doi.org/10.3390/ijerph19148752

Morawska, L., Ayoko, G. A., Bae, G. N., Buonanno, G., Chao, C. Y. H., Clifford, S., ... & Wierzbicka, A. (2017). Airborne particles in indoor environment of homes, schools, offices and aged care facilities: The main routes of exposure. *Environment international*, *108*, 75-83. https://doi.org/10.1016/j.envint.2017.07.025

Nadali, A., Arfaeinia, H., Asadgol, Z., & Fahiminia, M. (2020). Indoor and outdoor concentration of PM10, PM2. 5 and PM1 in residential building and evaluation of negative air ions (NAIs) in indoor PM removal. *Environmental Pollutants and Bioavailability*, *32*(1), 47-55. https://doi.org/10.1080/26395940.2020.1728198

Niu, X., Jones, T., BéruBé, K., Chuang, H. C., Sun, J., & Ho, K. F. (2021). The oxidative capacity of indoor source combustion derived particulate matter and resulting respiratory toxicity. *Science of the Total Environment*, *767*, 144391. https://doi.org/10.1016/j.scitotenv.2020.144391

Nozza, E., Valentini, S., Melzi, G., Vecchi, R., & Corsini, E. (2021). Advances on the immunotoxicity of outdoor particulate matter: A focus on physical and chemical properties and respiratory defence mechanisms. *Science of The Total Environment*, *780*, 146391. https://doi.org/10.1016/j.scitotenv.2021.146391

Ogundele, L. T., Owoade, O. K., Hopke, P. K., & Olise, F. S. (2017). Heavy metals in industrially emitted particulate matter in Ile-Ife, Nigeria. *Environmental research*, *156*, 320-325. https://doi.org/10.1016/j.envres.2017.03.051

Oliveira, M., Slezakova, K., Delerue-Matos, C., Pereira, M. C., & Morais, S. (2019). Children environmental exposure to particulate matter and polycyclic aromatic hydrocarbons and biomonitoring in school environments: A review on indoor and outdoor exposure levels, major sources and health impacts. *Environment international*, *124*, 180-204. https://doi.org/10.1016/j.envint.2018.12.052

Park, J., Yoo, J., & Jeong, J. W. (2022). Impact of ventilation methods on indoor particle concentrations in a daycare center. *Indoor air*, *32*(11), e13150. https://doi.org/10.1111/ina.13150

Razak, L. A., Yoong, S. L., Wiggers, J., Morgan, P. J., Jones, J., Finch, M., ... & Wolfenden, L. (2018). Impact of scheduling multiple outdoor free-play periods in childcare on child moderate-to-vigorous physical activity: a cluster randomised trial. *International Journal of Behavioral Nutrition and Physical Activity*, *15*, 1-12. https://doi.org/10.1186/s12966-018-0665-5

Razak, T. R., Ismail, M. H., Jarimi, H., Nadzir, M. S. M., Zheng, T., Yanan, Z., Ahmad, E. Z., Syafiq, U., Ludin, N. A., Rahman, N. M. A., Jamaludin, M. H., & Riffat, S. (2025). Machine learning-based predictive models for indoor air quality and thermal comfort: Bridging sensor data and human perception in healthcare facilities. *Energy Catalyst*, *1*(1), Article 003. https://doi.org/10.61552/EC.2025.01.003

Salimifard, P., Rim, D., & Freihaut, J. D. (2020). Evaluation of low-cost optical particle counters for monitoring individual indoor aerosol sources. *Aerosol Science and Technology*, *54*(2), 217-231. https://doi.org/10.1080/02786826.2019.1697423

Sánchez-Soberón, F., Rovira, J., Sierra, J., Mari, M., Domingo, J. L., & Schuhmacher, M. (2019). Seasonal characterization and dosimetry-assisted risk assessment of indoor particulate matter (PM10-2.5, PM2. 5-0.25, and PM0. 25) collected in different schools. *Environmental research*, *175*, 287-296. https://doi.org/10.1016/j.envres.2019.05.035

Sherzad, M., & Jung, C. (2022). Evaluating the emission of VOCs and HCHO from furniture based on the surface finish methods and retention periods. *Frontiers in Built Environment*, *8*, 1062255. https://doi.org/10.3389/fbuil.2022.1062255

Śmiełowska, M., Marć, M., & Zabiegała, B. (2017). Indoor air quality in public utility environments—A review. *Environmental Science and Pollution Research*, *24*, 11166-11176. https://doi.org/10.1007/s11356-017-8567-7

Son, Y. S. (2023). A review on indoor and outdoor factors affecting the level of particulate matter in classrooms of elementary schools. *Journal of Building Engineering*, *75*, 106957. https://doi.org/10.1016/j.jobe.2023.106957

Stratigou, E., Dusanter, S., Brito, J., & Riffault, V. (2020). Investigation of PM10, PM2. 5, PM1 in an unoccupied airflow-controlled room: How reliable to neglect resuspension and assume unreactive particles?. *Building and Environment*, *186*, 107357. https://doi.org/10.1016/j.buildenv.2020.107357

Tapia-Brito, E., & Riffat, S. (2025). Design and performance analysis of a MopFan-based multi-stage air purification system for indoor pollution control. *Green Technology & Innovation* (online first), Article 7100. https://doi.org/10.36922/gti.7100

Thorpe, K., Irvine, S., Pattinson, C., & Staton, S. (2020). Insider perspectives: the 'tricky business' of providing for children's sleep and rest needs in the context of early childhood education and care. *Early Years*, *40*(2), 221-236. https://doi.org/10.1080/09575146.2018.1443434

Um, C. Y., Zhang, N., Kang, K., Na, H., Choi, H., & Kim, T. (2022). Occupant behavior and indoor particulate concentrations in daycare centers. *Science of the Total Environment*, *824*, 153206. https://doi.org/10.1016/j.scitotenv.2022.153206

Von Schneidemesser, E., Steinmar, K., Weatherhead, E. C., Bonn, B., Gerwig, H., & Quedenau, J. (2019). Air pollution at human scales in an urban environment: Impact of local environment and vehicles on particle number concentrations. *Science of the Total Environment*, *688*, 691-700. https://doi.org/10.1016/j.scitotenv.2019.06.309

Yuan, F., Yao, R., Yu, W., Sadrizadeh, S., Awbi, H., & Kumar, P. (2023). Dynamic characteristics of particulate matter resuspension due to human activities in indoor environments: a comprehensive review. *Journal of Building Engineering*, *79*, 107914. https://doi.org/10.1016/j.jobe.2023.107914

Yuchi, W., Gombojav, E., Boldbaatar, B., Galsuren, J., Enkhmaa, S., Beejin, B., ... & Allen, R. W. (2019). Evaluation of random forest regression and multiple linear regression for predicting indoor fine particulate matter concentrations in a highly polluted city. *Environmental pollution*, *245*, 746-753. https://doi.org/10.1016/j.envpol.2018.11.034

Yuhe, Z., Guangfei, Y., & Xianneng, L. (2021). Indoor PM2. 5 concentrations and students' behavior in primary school classrooms. *Journal of Cleaner Production*, *318*, 128460. https://doi.org/10.1016/j.jclepro.2021.128460

Zeng, J., Han, G., & Yang, K. (2020). Assessment and sources of heavy metals in suspended particulate matter in a tropical catchment, northeast Thailand. *Journal of Cleaner Production*, *265*, 121898. https://doi.org/10.1016/j.jclepro.2020.121898

Zhao, J., Birmili, W., Wehner, B., Daniels, A., Weinhold, K., Wang, L., ... & Wiedensohler, A. (2020). Particle mass concentrations and number size distributions in 40 homes in Germany: indoor-to-outdoor relationships, diurnal and seasonal variation. *Aerosol and Air Quality Research*, *20*(3), 576-589. https://doi.org/10.4209/aaqr.2019.09.0444

Zheng, H., Wang, Z., Loomans, M., Walker, S., & Zeiler, W. (2023). Bedroom ventilation performance in daycare centers under three typical ventilation strategies. *Building and Environment*, *243*, 110634. https://doi.org/10.1016/j.buildenv.2023.110634