

Investigation on the Outdoor-Indoor Interactions of PM 2.5 Concentrations via Vertical In-situ Monitoring

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This study investigates the vertical distribution and outdoor-indoor interactions of PM 2.5 concentrations in a four-story school building in Taguig City, Metro Manila. A 12-day monitoring campaign was conducted from November 12 to 23, 2024, using low-cost, cloud-based monitors measuring PM 2.5, temperature, and relative humidity across all floors. Results revealed that outdoor PM 2.5 concentrations exhibited an increasing then decreasing trend with height, while indoor concentrations were highest on the third floor, where indoor sources such as more frequent room use and higher occupancy are present. Strong positive correlations between outdoor and indoor PM 2.5 were observed ($r = 0.92 - 0.94$). Infiltration factors ranged from 0.79 to 0.90, with estimated indoor emissions evident in linear regression intercepts. Temporal and diurnal variations indicated peak PM 2.5 concentrations during early morning in both indoor areas (6:00 - 8:00 AM) and outdoor areas (5:00 - 7:00 AM). Moreover, both environments also show elevated concentrations in the evening (6:00 - 8:00 PM). These elevated levels are due to increased vehicular activity and reduced atmospheric dispersion during these periods. Findings emphasize the importance of vertical and outdoor-indoor PM 2.5 monitoring for effective air quality management in urban buildings.

1. Introduction

Urbanization and vertical expansion have become defining features of cities like Metro Manila, where space limitations have driven the construction of multi-story buildings for residential, commercial, and institutional use. Among these, schools are often built as mid-rise structures located near busy roadways, exposing students and staff to various air pollutants. Fine particulate matter (PM 2.5), defined as airborne particles with a diameter of 2.5 micrometers or less, poses serious health risks due to its ability to penetrate deep into the lungs and enter the bloodstream. Common sources include vehicle emissions, industrial activities, and combustion of fuels. While the general impacts of PM 2.5 on health are well known, there is limited research on how PM 2.5 disperses vertically in urban environments and how it influences indoor air quality across multiple floors, particularly in educational settings in the Philippines. Previous studies that conducted indoor-outdoor monitoring of PM 2.5 in buildings did not assess floor-level differences, such as the study by Peng et al. (2017) in a school building in China and the hospital-based investigation by Rosales et al. (2025) in the Philippines, further underscoring this research gap.

Several studies have investigated the vertical distribution of PM 2.5 concentrations in urban environments. Li et al. (2018) investigated the vertical distribution of PM 2.5 in urban water, green space, and roads during the heavy pollution period in Xi'an, China. Kalaiarasan et al. (2009) examined PM 2.5 concentrations in a multi-story residential building in Singapore and found that concentrations peaked at middle floors due to building design and airflow patterns. Roostaei et al. (2024) studied vertical PM 2.5 profiles in mid-rise dormitories in Tehran, showing how meteorological factors influenced pollutant dispersion. Frederickson et al. (2024) conducted similar vertical profiling in Denmark, observing no significant variations in PM 2.5 concentrations across floor levels. However, these studies primarily focused on outdoor measurements, with limited research addressing how outdoor PM 2.5 infiltrates indoor environments across multiple floors. In the Philippines, studies investigating the vertical distribution of PM 2.5 concentrations are limited, both for outdoor and indoor settings across building floors, particularly in typical mid-rise school buildings.

The health impacts of PM 2.5 exposure have been well documented. Pope et al. (2006) linked increases in PM 2.5 concentrations to higher mortality rates. Dominici et al. (2006) highlighted its adverse effects on lung function and respiratory health. Cohen et al. (2017) estimated that PM 2.5 contributed to over 4 million premature deaths worldwide. More recently, Garcia et al. (2023) summarized how PM 2.5 induces oxidative stress, inflammation, and DNA damage, affecting various organ systems.

This study aims to investigate the vertical distribution and outdoor-indoor interactions of PM 2.5 concentrations in a four-story school building in Taguig City, Metro Manila. Specifically, it seeks to (1) analyze variations in PM 2.5 concentrations across different floor levels, (2) determine infiltration factors and estimate indoor emission contributions, and (3) assess the influence of temperature and relative humidity on PM 2.5 concentrations. The findings are expected to provide valuable insights into air quality management in mid-rise educational buildings and contribute to local air pollution studies in the Philippines.

2. Methodology

Monitoring campaign was conducted in a four-story school building located along a service road in Taguig City, Metro Manila. Indoor and outdoor PM 2.5 concentrations, temperature and relative humidity were measured simultaneously across floor levels using low-cost monitors over a twelve (12) day period from Nov 12 - 23, 2024. Selected indoor locations are composed of two typical classrooms, a computer laboratory, and a conference hall. The 1st floor classroom, equipped with 50 chairs, operated for 36 hours and 15 minutes per week, while the 2nd floor classroom, also with 50 chairs, was used for 30 hours per week. The 3rd floor housed a computer laboratory with 75 seats, operating for 40 hours per week. The 4th floor featured a conference hall with a seating capacity of approximately 100 but did not follow a fixed schedule. All rooms were fully air-conditioned with closed ventilation and had no mechanical ventilation systems.

Low-cost air quality monitors were deployed for real-time measurements. Outdoor monitors (O-1SPT, AirGradient Open Air) and indoor monitors (I-9PSL, 9th Generation) used in the study utilized Plantower PMS5003T and PMS5003 sensors, respectively, based on the laser scattering principle with a 60-second resolution. Accuracy of these sensors are at $\pm 10\%$ @100~500 $\mu\text{g}/\text{m}^3$, ± 10 $\mu\text{g}/\text{m}^3$ @0~100 $\mu\text{g}/\text{m}^3$. Both devices also measured temperature and relative humidity. PMS5003 sensors have been validated in previous studies of Bulot et al. (2019).

Outdoor monitors were mounted at approximate heights of 2.5 m, 5.0 m, 8.0 m, and 11.0 m above ground level, corresponding to the 1st through 4th floors. Indoor monitors were installed between 1.5 - 2.5 m above floor level, following AirGradient's recommended sensor placement for representative breathing height. Data were continuously transmitted to the AirGradient dashboard for centralized collection.

Data processing involved aligning indoor and outdoor measurements based on hourly timestamps. To ensure data consistency, any time period where a single monitor failed to report data was excluded from the dataset across all devices. Hourly averages of PM 2.5 concentrations, temperature, and relative humidity were computed for subsequent analysis.

Indoor PM 2.5 concentrations were considered to result from both outdoor infiltration and indoor emissions. The contributions were estimated using a linear regression model, as proposed by Rojano et al. (2023), as expressed in Eq(1):

$$C_{PM2.5_{ind}} = C_{PM2.5_{ein}} + F_{in} * C_{PM2.5_{out}} \quad (1)$$

$C_{PM2.5_{ind}}$ ($\mu\text{g}/\text{m}^3$) is the total indoor PM 2.5 concentration; $C_{PM2.5_{ein}}$ ($\mu\text{g}/\text{m}^3$) is the generated PM 2.5 concentration indoors; F_{in} is the PM 2.5 infiltration factor; and $C_{PM2.5_{out}}$ ($\mu\text{g}/\text{m}^3$) is the total outdoor PM 2.5 concentration. The model assumes a near steady-state condition and relatively constant infiltration factor. However, this model is limited to a single predictor, which is the outdoor PM 2.5 concentration, and does not account for other factors such as temperature or seasonal changes that may influence infiltration dynamics.

3. Results and Discussion

Figure 1 presents the hourly average PM 2.5 concentrations for outdoor and indoor environments across four floor levels, based on the 12-day monitoring period. This representation highlights the typical diurnal variations observed during the study, with data aggregated to reflect consistent daily patterns. Outdoor PM 2.5 concentrations showed distinct peaks during morning (5:00–7:00 AM) for outdoors and (6:00- 8:00 AM) for indoors and both peaks at evening (6:00–8:00 PM), corresponding to rush hour traffic emissions. The combination of increased vehicular activity and reduced atmospheric dispersion during these periods contributed to elevated PM 2.5 concentrations outdoors. Indoor PM 2.5 concentrations followed a similar diurnal trend but remained consistently lower than outdoor levels. This is primarily due to the protective effect of the building enclosure and its closed ventilation system, which limits the direct entry of outdoor pollutants. While

outdoor fluctuations still influence indoor air quality, the building structure reduces the immediate impact of traffic-related emissions, resulting in lower indoor concentrations.

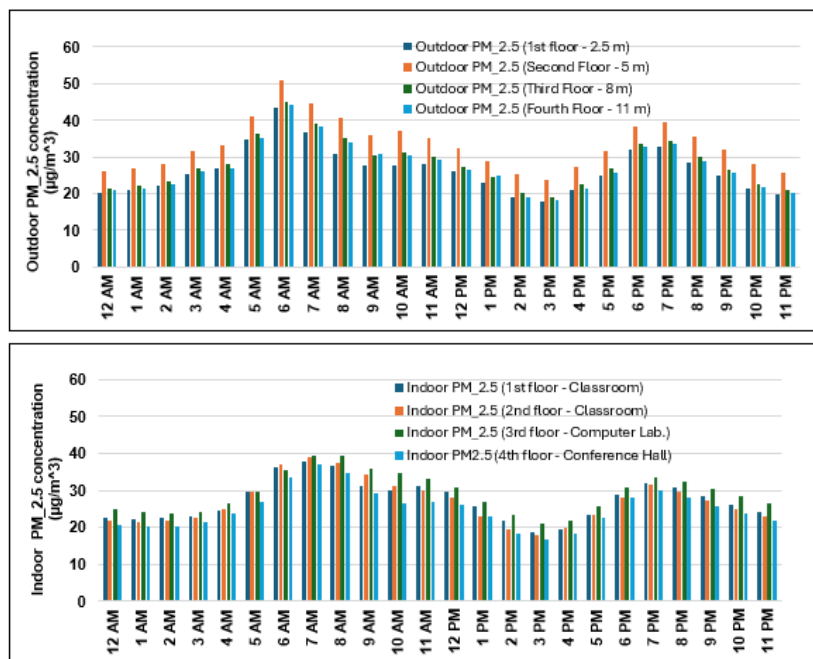


Figure 1: Hourly average of outdoor PM 2.5 concentrations (above) and indoor PM 2.5 concentrations (below) across floor levels from November 12–23, 2024.

The lowest PM 2.5 concentrations in Figure 1 are observed at midday (3:00 PM), which are due to reduced traffic activity and enhanced atmospheric boundary layer. Hao et al. (2020) emphasized how boundary layer dynamics reduce PM 2.5 concentrations during the afternoon. Frederickson (2024) also observed similar diurnal variation trends in urban monitoring, noting midday reductions following morning peaks, which aligns with the findings of Zhang et al. (2020), who reported time-dependent PM patterns in high-rise outdoor environments, with midday dips driven by atmospheric mixing and solar radiation.

Indoor PM 2.5 variations are influenced by room function and usage. Floors with higher occupancy and more frequent equipment use, such as the 3rd floor computer laboratory, exhibited more pronounced indoor PM 2.5 concentrations.

Figure 2 shows the vertical distribution of PM 2.5 concentrations in outdoor and indoor environments across four floor levels of the building. Low-cost monitors were installed at heights of 2.5 m (1st floor), 5 m (2nd floor), 8 m (3rd floor), and 11 m (4th floor), with values averaged from hourly data collected during the 12-day monitoring period. Elevated outdoor PM 2.5 concentrations were observed on the 2nd floor, corresponding to the height of the nearby skyway, which served as a direct source of emissions. Shading from adjacent trees contributed to localized drops in temperature and increased humidity, creating favorable conditions for particle accumulation. This decline at higher floors is influenced by the reduced proximity to emission sources and effective particle capture by tree foliage, as similarly observed in Indonesia (Yuniati et al., 2024). Indoor PM 2.5 concentrations peaked on the 3rd floor (8 m), where the computer laboratory is located. This elevated level is attributed to both outdoor particle infiltration and indoor sources, such as high occupancy, prolonged equipment usage, and limited ventilation. Similar observations were reported by Yulinawati et al. (2021), who highlighted the influence of room functions on indoor PM 2.5 accumulation in hospital environments.

The outdoor vertical distribution observed aligns with the study of Zhang et al. (2020), who noted fluctuating PM 2.5 concentrations with height driven by local dispersion dynamics. A similar observation was reported by Zalakeviciute et al. (2018) in Quito, Ecuador, where high relative humidity was associated with elevated PM 2.5 concentrations.

Figure 3 presents the correlation plots between outdoor and indoor PM 2.5 concentrations for each monitored floor level. Across all four floors, strong positive correlations were observed, with Pearson's r values ranging from 0.90 to 0.94. These r values were obtained as the square roots of the R^2 values shown in the regression plots, indicating a consistent relationship between outdoor and indoor PM 2.5 concentrations.

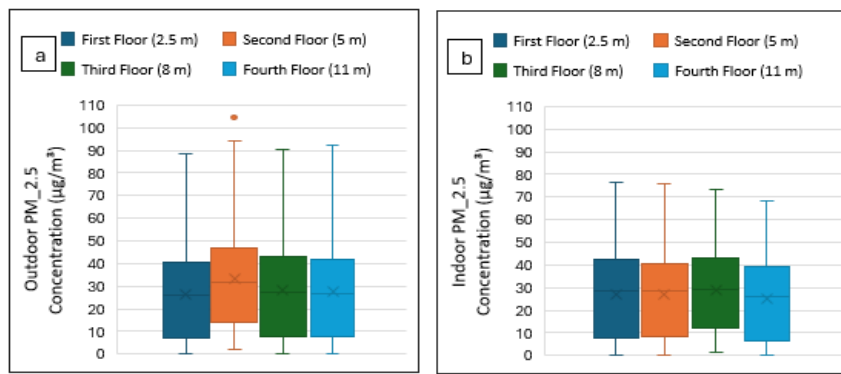


Figure 2: Vertical Distribution of total hourly average PM 2.5 Concentrations from November 12–23, 2024 in the (a) outdoor and (b) indoor environments across floor levels.

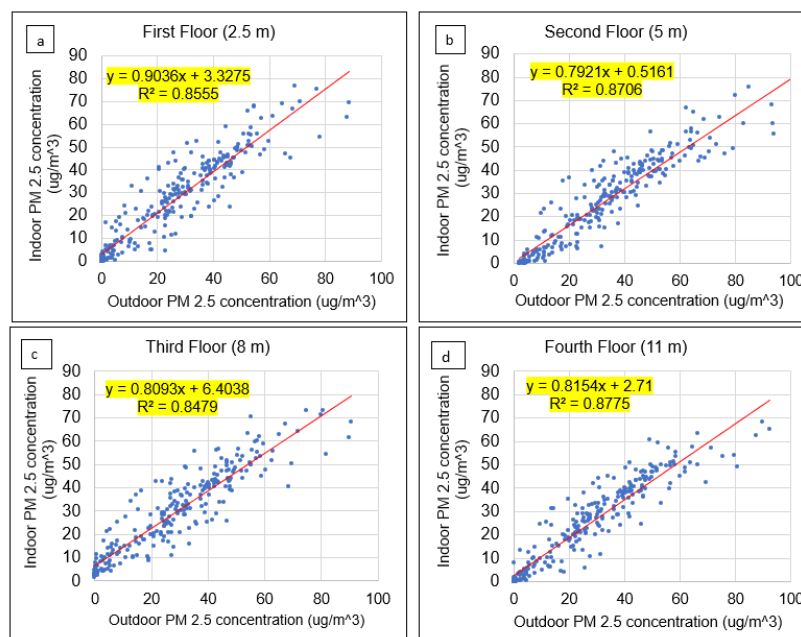


Figure 3: Correlation plots of Indoor vs. Outdoor PM 2.5 Concentrations per floor level (Nov. 12–23, 2024): (a) 1st Floor (2.5 m), (b) 2nd Floor (5 m), (c) 3rd Floor (8 m), and (d) 4th Floor (11 m).

The 1st floor (2.5 m) exhibited a high correlation ($r = 0.93$, $R^2 = 0.8555$) with a substantial infiltration factor of 0.903 ± 0.05 , reflecting a strong outdoor influence. The indoor contribution is indicated by an intercept of $3.33 \pm 1.51 \mu\text{g}/\text{m}^3$, suggesting moderate indoor sources. Similarly, the 2nd floor (5 m) recorded a high correlation ($r = 0.93$, $R^2 = 0.8706$), but with the lowest infiltration factor (0.792 ± 0.04) and intercept ($0.52 \pm 1.49 \mu\text{g}/\text{m}^3$), indicating minimal indoor PM 2.5 contributions. In contrast, the 3rd floor (8 m), which functions as a computer laboratory, demonstrated the lowest correlation ($r = 0.92$, $R^2 = 0.8479$) and the highest intercept value ($6.40 \pm 1.47 \mu\text{g}/\text{m}^3$), indicating a significant contribution from indoor sources despite maintaining a substantial infiltration factor of 0.809 ± 0.04 . This is attributed to high occupancy and prolonged room usage. Meanwhile, the 4th floor (11 m) recorded the highest correlation ($r = 0.94$, $R^2 = 0.8775$), with an infiltration factor of 0.815 ± 0.04 and an indoor contribution reflected by an intercept of $2.71 \pm 1.28 \mu\text{g}/\text{m}^3$, suggesting substantial infiltration of outside PM 2.5.

These findings highlight that while outdoor infiltration is the dominant factor influencing indoor PM 2.5 across all floors, indoor contributions vary significantly based on room function and occupancy patterns. The elevated indoor-generated PM 2.5 on the 3rd floor highlights the influence of frequent room usage (approximately 40 hours per week) and high occupancy (around 75 students), despite the presence of lower infiltration. Fu et al. (2022) similarly emphasized that indoor PM 2.5 concentrations are strongly shaped by both infiltration rates and indoor sources, reinforcing the importance of space usage in indoor air quality assessments.

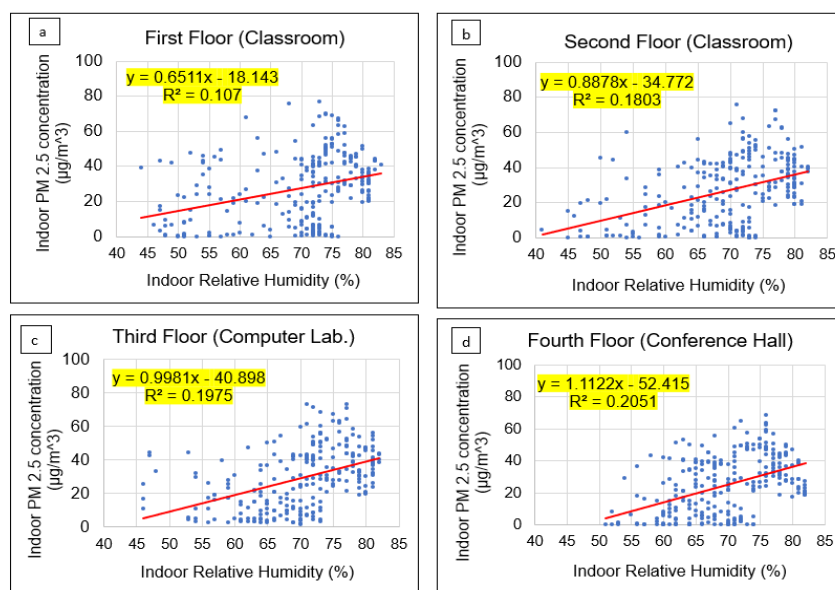


Figure 4: Correlation plots of Indoor PM 2.5 concentrations versus Indoor Relative Humidity (%) for each floor level measured from November 12-23, 2024: (a) 1st Floor (2.5 m), (b) 2nd Floor (5 m), (c) 3rd Floor (8 m), and (d) 4th Floor (11 m).

Figure 4 shows linear regression scatter plots correlating indoor relative humidity (RH) with indoor PM 2.5 concentrations for each floor. The analysis yielded moderate positive correlations, with correlation coefficients (r) ranging from 0.33 on the 1st floor to 0.45 on the 4th floor, indicating that RH moderately influences indoor PM 2.5 concentrations across all levels. This positive correlation suggests that higher indoor RH levels are associated with elevated PM 2.5 concentrations.

The results indicate that while infiltration of outdoor particles remains a primary source of indoor PM 2.5, indoor RH plays a secondary role by affecting particle size and suspension duration. Zhang et al. (2019) reported that at RH levels 70 - 80 %, particles ranging from 1 to 2.5 μm become more prevalent into particle distribution size due to hygroscopic growth. Given the fully enclosed and air-conditioned nature of the study rooms, fluctuations in indoor RH are primarily influenced by internal occupancy and air conditioning efficiency. Thus, even moderate variations in RH can amplify indoor PM 2.5 concentrations by promoting particle hygroscopic growth. In contrast, outdoor RH showed weak positive correlations across all floors with values ranging from $R^2 = 0.0285$ to 0.077 and $r = 0.17$ to 0.27 .

For temperature, both outdoor and indoor temperatures showed weak positive correlations with outdoor PM 2.5 concentrations, with $R^2 = 0.0009$ to 0.0204 and $r = 0.03$ to 0.14 . Similarly, indoor temperatures also exhibited weak positive correlations with indoor PM 2.5 concentrations, with values of $R^2 = 0.0495$ to 0.0652 and $r = 0.22$ to 0.25 , indicating a consistently low association between temperature and PM 2.5 across all floor levels.

4. Conclusions

The 12-day sampling campaign revealed that outdoor PM 2.5 infiltration is the main contributor to indoor PM 2.5 concentrations across all floor levels of a mid-rise school building. However, indoor concentrations are also significantly affected by room function, especially in high-occupancy and frequently used spaces such as computer laboratories, where indoor activities further elevate PM 2.5 concentrations.

Moderate correlations between indoor relative humidity and PM 2.5 further emphasized the role of micro-environmental factors in shaping indoor air quality. Additionally, outdoor PM 2.5 reduction with height was attributed to the presence of nearby trees, which can intercept and accumulate airborne particles, limiting their dispersion at higher elevations. Given these findings, school administrators are encouraged to prioritize air filtration systems in high-occupancy rooms and implement continuous air quality monitoring using low-cost monitors. Further studies focusing on indoor exposure levels, occupant activity, and the effectiveness of mitigation strategies are essential to ensure healthier indoor environments in educational institutions. The use of HEPA filters may be explored for comparative assessment of their effectiveness. Extended seasonal monitoring is also recommended to better understand outdoor - indoor PM 2.5 dynamics, including vertical distribution and infiltration behavior.

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References

- Bulot F.M., Johnston S.J., Basford P.J., Easton N.H., Apetroaie-Cristea M., Foster G.L., Morris A.K., Cox S.J., Loxham M., 2019, Long-term field comparison of multiple low-cost particulate matter sensors in an outdoor urban environment. *Scientific Reports*, 9(1), 7497.
- Cohen A.J., Brauer M., Burnett R., Anderson H.R., Frostad J., Estep K., Balakrishnan K., Brunekreef B., Dandona L., Dandona R., Feigin V., Freedman G., Hubbell B., Jobling A., Kan H., Knibbs L., Liu Y., Martin R., Morawska L., Pope C.A. III, Shin H., Straif K., Shaddick G., Thomas M., van Dingenen R., van Donkelaar A., Vos T., Murray C.J.L., Forouzanfar M.H., 2017, Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*, 389(10082), 1907–1918.
- Dominici F., Peng R.D., Bell M.L., Pham L., McDermott A., Zeger S.L., Samet J.M., 2006, Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. *JAMA*, 295(10), 1127–1134.
- Frederickson L.B., Russell H.S., Raasch S., Zhang Z., Schmidt J.A., Johnson M.S., Hertel O., 2024, Urban vertical air pollution gradient and dynamics investigated with low-cost sensors and large-eddy simulations. *Atmospheric Environment*, 316, 120162.
- Fu N., Kim M.K., Huang L., Liu J., Chen B., Sharples, S., 2022, Experimental and numerical analysis of indoor air quality affected by outdoor air particulate levels (PM 1.0, PM 2.5 and PM 10), room infiltration rate, and occupants' behaviour. *Science of The Total Environment*, 851, 158026.
- Garcia A., Santa-Helena E., De Falco A., de Paula Ribeiro J., Gioda A., Gioda C.R., 2023, Toxicological effects of fine particulate matter (PM 2.5): health risks and associated systemic injuries—systematic review. *Water, Air, & Soil Pollution*, 234(6), 346.
- Hao Y., Luo B., Simayi M., Zhang W., Jiang Y., He J., Xie, S., 2020, Spatiotemporal patterns of PM 2.5 elemental composition over China and associated health risks. *Environmental Pollution*, 265, 114910.
- Kalaiarasan M., Balasubramanian R., Cheong K.W.D., Tham, K.W., 2009, Traffic-generated airborne particles in naturally ventilated multi-storey residential buildings of Singapore: Vertical distribution and potential health risks. *Building and Environment*, 44(7), 1493-1500.
- Li H., Zhao J., Zhang J., Gao Y., Xin K., 2018, Vertical distribution of urban near-surface pollutant PM 2.5 based on UAV monitoring platform. *Chemical Engineering Transactions*, 71, 25-30.
- Peng Z., Deng W., Tenorio R., 2017, Investigation of indoor air quality and the identification of influential factors at primary schools in the north of China. *Sustainability*, 9(7), 1180.
- Pope C.A. III, Dockery, D.W., 2006, Health effects of fine particulate air pollution: lines that connect. *Journal of the Air & Waste Management Association*, 56(6), 709–742.
- Rojano R., Vengoechea A.M., Arregocés H.A., 2023, Indoor/outdoor relationship of particulate matter (PM 10) and its chemical composition in a coastal region of Colombia. *Case Studies in Chemical and Environmental Engineering*, 8, 100397.
- Roostaei V., Abbasi A., Gharibzadeh F., Faridi S., Naddafi K., Yunesian M. and Hassanvand M.S., 2024, Vertical distribution of air particulate matter (PM 1, PM 2.5, and PM 10) in different regions of Tehran. *Aerosol and Air Quality Research*, 24(10), 240036.
- Rosales C.M.F., Tamayo E.G., Babela D.L., Benjamin M.P., 2025, Indoor penetration of ambient particulate pollution in a hospital maternity ward in Manila, Philippines: perspectives towards holistic city-level air quality management. *Environmental Science: Atmospheres*, 5(5), 563-573.
- Yulinawati H., Khairani T., Siami L., 2021, Analysis of indoor and outdoor particulate (PM 2.5) at a women and children's hospital in West Jakarta. *IOP Conference Series: Earth and Environmental Science*, 737(1), 012067.
- Yuniati R., Handayani W., Nugrahani L., Khoerunnisa I., Halimah, Putrika A., Hemelda N.M., 2024, The capacity of trees to remove particulate matter and lead and its impact on tree health. *Biodiversitas*, 25(8), 2541-2551.
- Zalakeviciute R., López-Villada J., Rybarczyk Y., 2018, Contrasted effects of relative humidity and precipitation on urban PM 2.5 pollution in high elevation urban areas. *Sustainability*, 10(6), 2064.
- Zhang J., Zhou Z., Wang C., Xue K., Liu Y., Fang M., Zuo J., Sheng Y., 2019, Research on the influence of indoor relative humidity on PM 2.5 concentration in residential buildings. *IOP Conference Series: Materials Science and Engineering*, 585(1), 012086.
- Zhang L., An J., Liu M., Li Z., Liu Y., Tao L., Liu X., Zhang F., Zheng D., Gao Q., Guo X., 2020, Spatiotemporal variations and influencing factors of PM 2.5 concentrations in Beijing, China. *Environmental Pollution*, 262, 114276.