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Vertical Distribution of Air Particulate Matter (PM_1, $PM_{2.5}$, and PM_{10}) in Different Regions of Tehran

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ABSTRACT

Mass concentrations of particulate matter (PM_1, $PM_{2.5}$, and PM_{10}) were observed at different heights (1.5, 3, 9, 15, 18, and 290 m) in Tehran using affordable particulate matter sensors (Plantower PMS5003) to study their vertical distribution. In general, the results showed that the concentration of particulate matter increased with height. The mean concentrations of PM_1 at altitudes of 1–3, 9, and 15–18 m were 33.7 ± 22.4, 36.9 ± 24.7, and 38.2 ± 24.9 µg m^{-3}, respectively. Similarly, the mean concentrations of $PM_{2.5}$ were 62.9 ± 44.7, 64.4 ± 46.6, and 66.6 ± 45.8 µg m^{-3}, respectively. Furthermore, the mean concentrations of PM_{10} were 73.5 ± 51.2, 76.8 ± 53.4, and 79 ± 53.7 µg m^{-3}, respectively. Typically, as height increases, there is a general trend of the $PM_1/PM_{2.5}$ and PM_1/PM_{10} ratios increasing. In contrast, the $PM_{2.5}/PM_{10}$ ratio decreases. In addition, the disparity in particulate matter concentration with altitude was more statistically significant during periods when the atmosphere exhibited greater instability. Consequently, the alterations in particulate matter concentrations as altitude increased were statistically more significant during the daytime compared to night-time.

Keywords: Air pollution, Particulate matter, Vertical profile, Tehran

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1 INTRODUCTION

According to the Global Burden of Disease (GBD) study, air pollution emerged as the foremost environmental risk element, with ambient particulate matter ranking as the seventh major cause of global mortality in 2019 (2020). Fine particulate matter ($PM_{2.5}$) is considered one of the primary air pollutants responsible for various chronic and acute health consequences (Mitoma *et al.*, 2021). In 2019, approximately 3.8 million deaths were attributed to long-term exposure to ambient air $PM_{2.5}$ (McDuffie *et al.*, 2021). Particulate matter is not solely emitted from primary sources like vehicles and point sources; it can also be generated secondarily through chemical reactions between NO_x and SO_x pollutants in the atmosphere (Choomanee *et al.*, 2020).

Particulate matter is classified according to its particle size, with PM_{10} (particles with an aerodynamic diameter of ≤ 10 micrometers), $PM_{2.5}$ (particles with an aerodynamic diameter of ≤ 2.5 micrometers), and PM_1 (particles with an aerodynamic diameter of ≤ 1 micrometers) (Kelly and Fussell, 2012). The penetration of PM into the respiratory system is influenced by its size, with smaller particles having more destructive effects (Pope III and Dockery, 2006). $PM_{2.5}$ can penetrate deeper into the lower regions of the respiratory system, increasing the risk of developing heart and respiratory diseases (Sioutas *et al.*, 2005; Bell, 2012).

Numerous studies have focused on examining the spatial variation of PM (Naddafi *et al.*, 2012; Faridi *et al.*, 2018; Bayat *et al.*, 2019). In recent decades, apartment living has become more prevalent due to urbanization growth, and people live in multi-story buildings, so air pollution exposure varies across different vertical levels. Consequently, when assessing the extent of people's exposure to air pollution, it becomes imperative to consider the vertical distribution of pollutant concentration in addition to its spatial distribution (Gao *et al.*, 2017; Zhang *et al.*, 2021). However, the vertical distribution of PM has been studied less (Ding *et al.*, 2005; Zhang *et al.*, 2021; Frederickson *et al.*, 2024). Primary pollutants can vertically migrate and reach higher altitudes within the atmosphere. Vertical mixing can trigger chemical reactions, resulting in the formation of secondary pollutants. These secondary pollutants are not emitted directly but are generated through converting primary pollutants (Li *et al.*, 2021). The vertical movement and chemical transformations of pollutants substantially influence their distribution and impact on air quality (Liu *et al.*, 2018; Li *et al.*, 2021). Gaining insights into these processes is vital for understanding the intricate nature of air pollution and its consequences at both local and regional levels (Li *et al.*, 2018; Zhang *et al.*, 2021). The concentrations of PM can be influenced by various chemical reactions that take place at different altitudes within the atmosphere. It is crucial to study the vertical distribution of PM to understand better the intricate interactions between transport processes and changes in PM concentration. By observing the vertical distribution of PM, we can gain valuable insights into the complex dynamics of this pollutant and how it behaves in different layers of the atmosphere (Li *et al.*, 2021). This knowledge is essential for clarifying the complex interactions and processes that contribute to changes in PM concentration (Li *et al.*, 2021). However, varied and conflicting observations have been reported in the studies. In a study by Choomanee and his colleagues in Bangkok, at heights of 30, 70, and 110 m, it was observed that the concentration of $PM_{2.5}$ increases with increasing height both during the day and at night (Choomanee *et al.*, 2020). Another study found that under slightly unstable stratification, the concentration remained relatively constant with increments of the height for southwesterly and southerly winds. In contrast, in north, west, and northwest winds, an increase in concentration was observed in height. For other wind directions, the concentration decreased as height increased by approximately 40% to 50% (Frederickson *et al.*, 2024). Xiao *et al.* (2020) in the residential areas demonstrated a decreasing trend in the vertical distribution of $PM_{2.5}$ mass concentrations with increasing height. In the other study in which the concentration of $PM_{2.5}$ was monitored from a height of 1.5 to 89.1 m (from the 1^{st} to the 27^{th} floor), the trend of concentration changes with increasing height varied at different times and heights (Zhang *et al.*, 2021). The variations in observations can be ascribed to differences in measurement season, time of day and night, and each region's unique environmental and weather conditions. Therefore, given the controversies observed and since, up to our knowledge, no study has been conducted in Tehran, the present study aimed a) to investigate the concentration of PM at different heights, b) to determine the proportion of PM of varying sizes ($PM_1/PM_{2.5}$, PM_1/PM_{10}, and $PM_{2.5}/PM_{10}$) at different elevations, and c) to determine the temporal trend of the vertical distribution of PM concentration at different heights.

2 MATERIALS AND METHODS

2.1 Study Area, Sampling Sites, and Schedule

Tehran (35.6892°N, 51.3890°E), the capital city of Iran, is the most populous city in the country, with approximately 10 million residents (Farzad *et al.*, 2020). Fig. 1 illustrates the study area (Tehran City) and sampling sites.

People in Tehran city are mostly exposed to high levels of air pollution, especially $PM_{2.5}$. Poor air quality in Tehran is mainly the result of the old fleet as well as specific geographic conditions, with the Alborz Mountains in the north and a desert in the south (Faridi *et al.*, 2018). Tehran citizens have been exposed to concentrations of annual $PM_{2.5}$ exceeding the WHO air quality guideline (WHO AQG) (5 $\mu g\ m^{-3}$), U.S. EPA, and Iranian standard levels (12 $\mu g\ m^{-3}$) during the decades (Hassanvand *et al.*, 2014; Bayat *et al.*, 2019).

The measurements were conducted from September 2022 to December 2022. The measurements were conducted within a set of five buildings. Table 1 provides information regarding the measurement locations. Twenty-three measurements were performed to investigate the vertical distribution of PM mass concentrations. Three devices were placed (on the balconies or behind the windows of buildings) at specific heights (Table 1) to measure the vertical distribution of the PM concentration. Each measurement lasted from 6 to 12 hours. The devices sent particulate

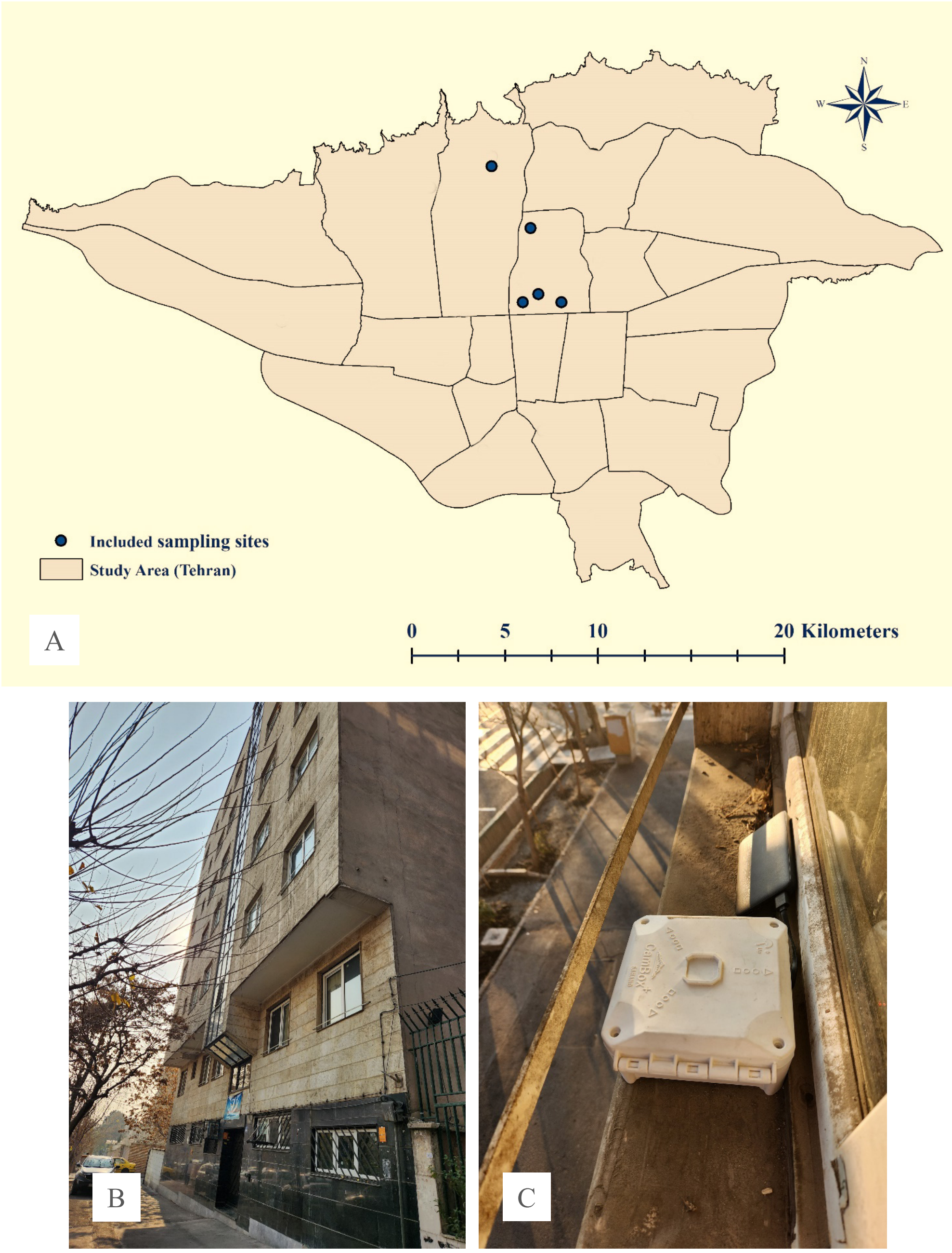

Fig. 1. (A) Study area (Tehran) and sampling sites, (B) Vesal dorm, (C) A low-cost sensor device that is located behind the window and is being measured.

Table 1. Measuring location specification.

Studied Buildings	Measurement Heights (m)	Zone Type	Number of Floors	Measurement Date	Distance from the Street (m)	Longitude	Latitude
School of Public Health	1.5, 9, 18	Residential	5	1/16/2023–2/5/2023	12	51.3957712	35.706809
School of Pharmacy	1.5, 9, 15	Residential	5	2/8/2023	35	51.3929347	35.7050456
Vesal dorm	3, 9, 15	Traffic	6	12/19/2022–1/2/2023	5	51.3981269	35.7065203
Koy dorm	3, 9, 15	Residential	5	2/21/2023	90	51.3861232	35.7315947
Milad Tower	1.5, 290	Commercial	–	2/13/2023–3/2/2023	220	51.3769951	35.7452503

matter concentrations to a website every 15 seconds and saved them in an Excel file. The average was reported on each date and location.

Fig. 2 illustrates the device placement and measurement methodology in the respective locations.

2.2 PM Measurement

We used low-cost PM sensors to measure PM. The devices consisted of a temperature and humidity sensor (BME680), a particulate matter sensor (Plantower PMS5003), and a GPS (NEO-6M) (Fig. 3). The Plantower PMS5003 is an instrument that detects particles (PM_1, $PM_{2.5}$, and PM_{10}) using light-scattering technology. The scattered light is converted into an electrical pulse by a photo-diode, which is further processed to determine the particle count. The manufacturer uses an undisclosed algorithm to assess the size of the particles. The PMS5003 has a laser that operates at 680 nm, and the fan blows air through it at 0.1 L m^{-1} (Sayahi *et al.*, 2019; Cowell *et al.*, 2022).

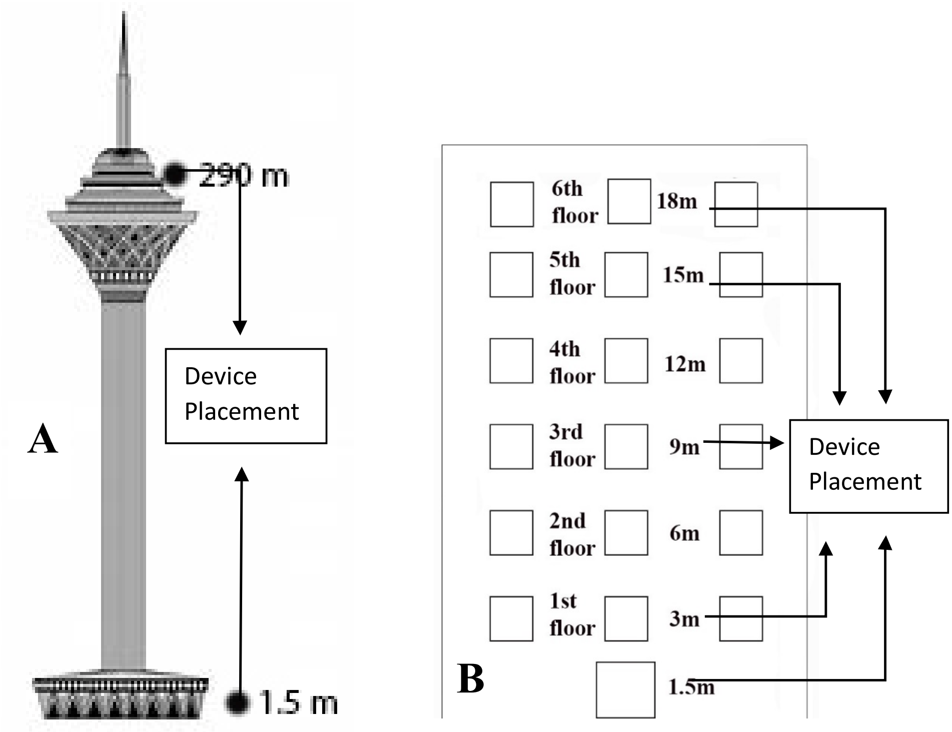

Fig. 2. Placement of devices in (A) Milad Tower and (B) the buildings.

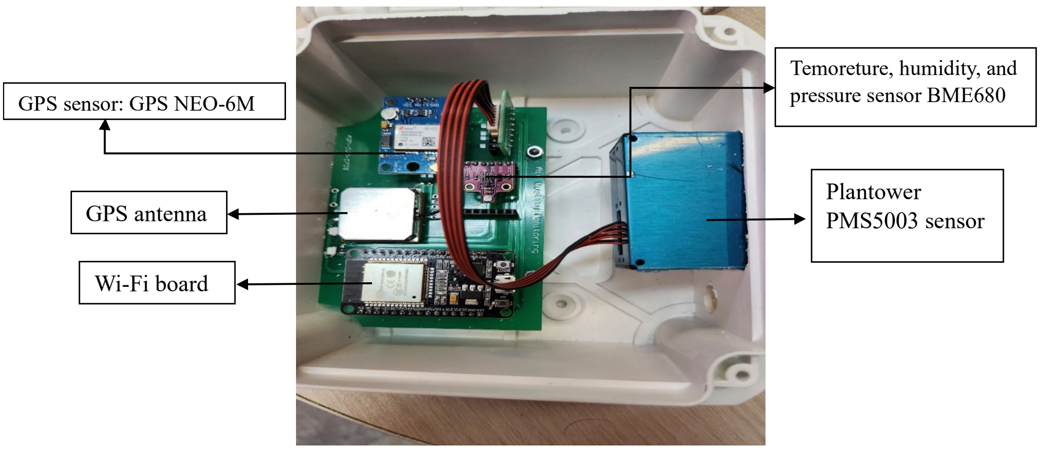

Fig. 3. Developed low-cost PM sensor device.

Table 2. Sensors performance evaluation.

Pollutant	Measurement Time	High Volume Samplers (μg m^{-3})	LCS (A) (μg m^{-3})	LCS (B) (μg m^{-3})	LCS (C) (μg m^{-3})	LCS MEAN	LCS SD	LCS CV (%)
$PM_{2.5}$	11/11/2023–11/12/2023	101.9	48.6	49.0	53.1	50.2	2.5	5.0
	11/14/2023–11/15/2023	141.6	76.3	83.6	87.8	82.6	5.8	7.1
	11/25/2023–11/26/2023	157.0	84.5	89.3	93.1	88.9	4.3	4.8
	12/02/2023–12/03/2023	163.0	94.5	101.7	105.3	100.5	5.5	5.4
	12/24/2023–12/25/2023	40.2	19.2	20.7	20.9	20.2	0.9	4.6
PM_{10}	11/11/2023–11/12/2023	142.6	60.8	62.6	66.0	63.1	2.7	4.2
	11/14/2023–11/15/2023	189.8	86.3	96.3	100.0	94.2	7.1	7.5
	11/25/2023–11/26/2023	189.2	95.1	103.4	105.6	101.4	5.6	5.5
	12/02/2023–12/03/2023	206.6	106.2	113.2	119.7	113.0	6.8	6.0
	12/24/2023–12/25/2023	55.7	21.1	24.0	23.3	22.8	1.5	6.6

Table 3. Results of sensor consistency and accuracy examination.

	$PM_{2.5}$	PM_{10}
	R	R
LCS A- LCS B	0.9984	0.9979
LCS A- LCS C	0.9990	0.9988
LCS B- LCS C	0.9995	0.9992
LCS A- HVAS	0.9926	0.9887
LCS B- HVAS	0.9868	0.9872
LCS C- HVAS	0.9909	0.9893

2.3 Low-cost Sensor Validation

The performance of low-cost sensors (LCS) was assessed to demonstrate their suitability for pollution monitoring and to validate their accuracy in detecting particulate matter concentration at various heights. This evaluation involved comparing three sensor-equipped devices, revealing their internal solid consistency and high precision. The examination was conducted by deploying three devices next to each other on the roof of the Faculty of Health of Tehran University of Medical Sciences, co-locating with two high-volume air samplers (HVAS) (Tisch TE-6070-2.5 $PM_{2.5}$ and Tisch TE-6070-10 PM_{10}, high volume ambient air sampler) for $PM_{2.5}$ and PM_{10} as reference devices for 24 hours over five days. Internal consistency was determined by comparing measurements from the sensors to ensure consistency, utilizing criteria such as standard deviation and coefficient of variation (Zimmerman, 2022). Pearson correlation among the sensors was also reported. The findings illustrated in Tables 2 and 3 indicate a high level of consistency among the sensors (Motlagh *et al.*, 2021; Zimmerman, 2022). To evaluate performance accuracy, measurements from the three devices were compared with concentrations derived from HVAS sampling. For particulate matter sampling by HVAS, first, four fiberglass filters (203 × 254 mm, Minipore Micro Products, India) were weighed with a scale; following that, two filters were situated within high-volume air samplers, and extra filters were positioned in the vicinity of low-cost sensors to quantify the weight of moisture absorbed by the filter. Finally, the moisture weight absorbed by the filter in the environment needs to be subtracted from the filter's weight inside the device (Khoshkam *et al.*, 2022).

Low-cost sensors and high-volume air samplers were operational for 24 hours. After that, the weight of the filter in the high-volume air samplers was calculated. The $PM_{2.5}$ and PM_{10} concentrations were determined based on the high-volume device's flow rate and the filter's weight. The results are shown in Table 2. Although the concentrations varied, a consistent ratio was observed across all measurements. The strong correlation between each device's readings and those from HVAS reinforces these findings.

2.4 Data Analysis

The PM concentrations were calculated in Excel (2019) and statistically processed in SPSS (version 26). The Kolmogorov-Smirnov test measured data distribution normality. ANOVA and Kruskal–Wallis tests were also conducted to assess and contrast the mean PM concentrations at three distinct elevations. The statistical significance level (*P*-value) was set at 0.05.

3 RESULTS AND DISCUSSION

3.1 Vertical Distribution of PM Concentration

Fig. 4 indicates the concentration of particulate matter (PM_1, $PM_{2.5}$, and PM_{10}) at various altitudes, regardless of sampling place. The mean concentrations of PM_1 increased at 3, 9, 15, and 18 m compared to the concentration at base height (1.5 m) by 13.3%, 25.3%, 27.3%, and 42.8%, respectively. The mean PM_1 concentration at 290 m decreased by 3% compared to the baseline height. Similarly, the mean concentrations of $PM_{2.5}$ at the exact altitudes compared to the concentration at base height increased by 22.8%, 25.1%, 28.7%, and 33%, respectively, and the mean $PM_{2.5}$ concentration at 290 m decreased by 9.8% compared to the baseline height. Finally, the mean concentrations of PM_{10} at the exact altitudes compared to the concentration at base height increased by 24.7%, 29.4%, 33.5%, and 31.1%, respectively, and the mean PM_{10} concentration at 290 m decreased by 9.6% compared to the baseline height.

As shown in Fig. 4, in general, as the height increased, the concentration of particulate matter also rose. This finding is consistent with the results of other studies in which PM concentration increased with altitude at levels similar to the current research (Choomanee *et al.*, 2020; Zhang *et al.*, 2021). At lower altitudes (1.5–18 m), tall buildings on both sides of the street can create wind vortex circulation, which traps particles and hinders their dispersion to higher altitudes (Liu *et al.*, 2021). Furthermore, roadside barriers like trees can act as obstacles, preventing particles from mixing with the air at higher altitudes. The result of the current study is further supported by Ezhilkumar *et al.* (2022), who observed an increase in PM concentration with an increase in height from 3 to 38 m in winter. The reason can also be attributed to the stable atmospheric conditions in winter that hold pollutants suspended for longer in the atmosphere (Ezhilkumar *et al.*, 2022). The association between PM concentration and height is a complex issue involving various factors, including the area's topography, wind direction, temperature, and urban shape (Chen *et al.*, 2020; Liao *et al.*, 2021). According to research, the spatial distribution pattern of buildings can affect the changes in the concentration of particulate matter with increasing height. Other essential factors include density, shape, orientation of buildings, and the ratio of height to width of streets (Ezhilkumar *et al.*, 2022; Kokkonen *et al.*, 2021). Nevertheless, some studies, like those of Liao *et al.* (2021) or Zheng *et al.* (2021), have identified an inverse correlation between PM concentration and elevation. This discrepancy could be linked to measurement sites, atmospheric circumstances, proximity to construction sites, and prevailing wind patterns, which may impact the connection between particulate matter concentrations and altitude.

Due to the morphology of buildings and the topography of the area affecting the vertical distribution of PM concentration (Kalaiarasan *et al.*, 2009; Li *et al.*, 2018; Liu *et al.*, 2018), we have shown the results of each site individually.

3.2 Vertical Distribution of PM Concentration at Each Location

The vertical distribution of the mean PM concentration in each measurement location is indicated in Fig. 5 (Table S1 (in supplementary data) presents the daily measurements conducted in the locations).

In the Vesal dorm, the lowest PM concentration was observed at 3 m (base height), while the highest concentration was at the tallest height (15 m). The average PM_1 concentrations increased by 11.6% and 14.8% at 9 and 15 m compared to the base height, respectively. Similarly, the average $PM_{2.5}$ concentrations at the exact altitudes rose by 4.7% and 7.1% compared to the base height. This finding corroborates the observations of Ezhil Kumar and Karthikeyan (2015), who demonstrated an increase in $PM_{2.5}$ concentrations with increasing height from 14.52 to 42.36 m. However, a concentration reduction was noted at higher altitudes (56.28). This was attributed to rapid dilution by the inflow of downwind from higher altitudes (Ezhil Kumar and Karthikeyan, 2015). The average PM_{10} concentrations at these heights also increased by 7% and 9.3%, respectively. This result contrasts

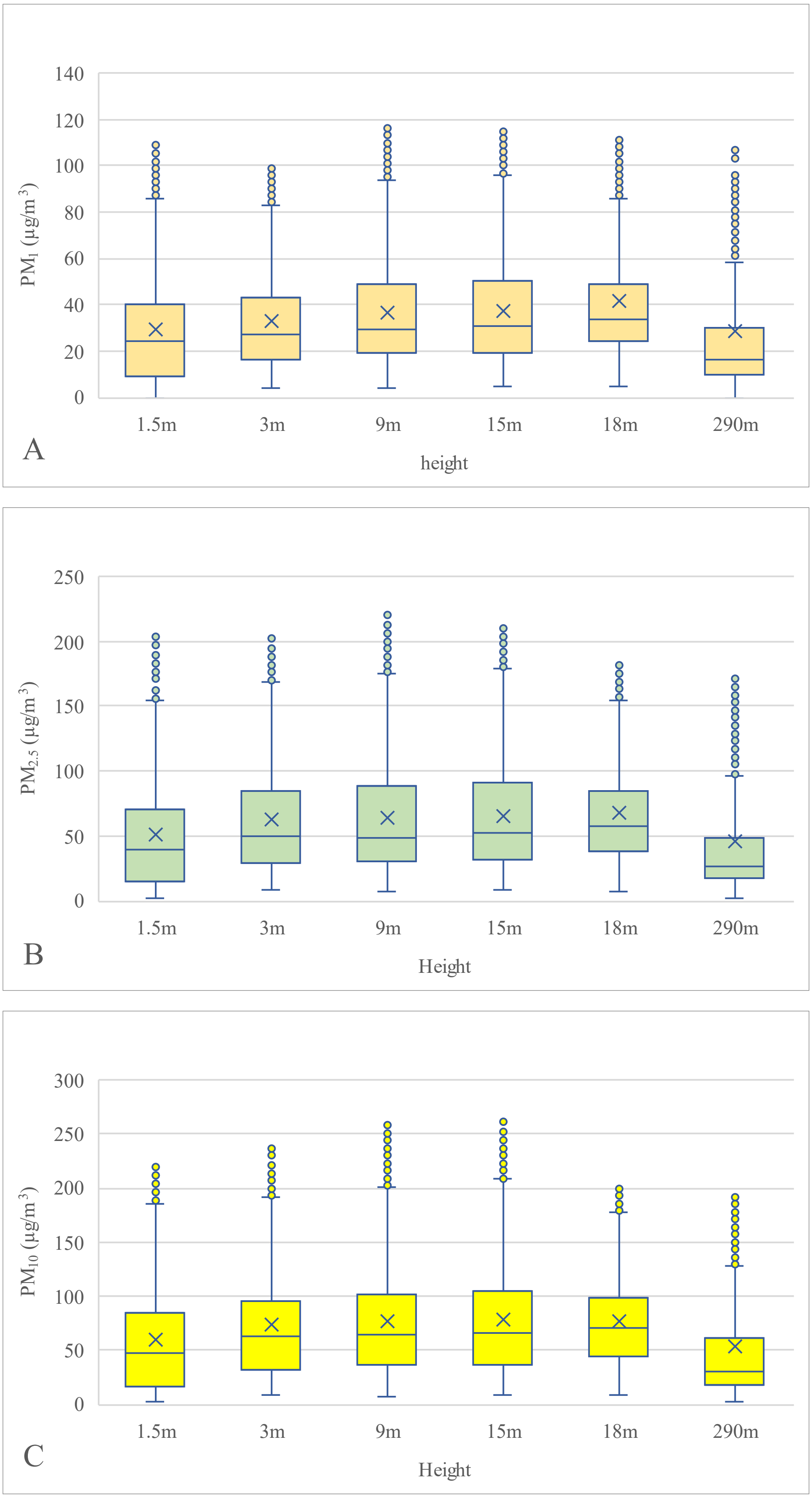

Fig. 4. Box plot graph of particulate matter concentration at different altitudes (the cross indicates the mean concentration), (A) concentration of PM_1, (B) concentration of $PM_{2.5}$, and (C) concentration of PM_{10}.

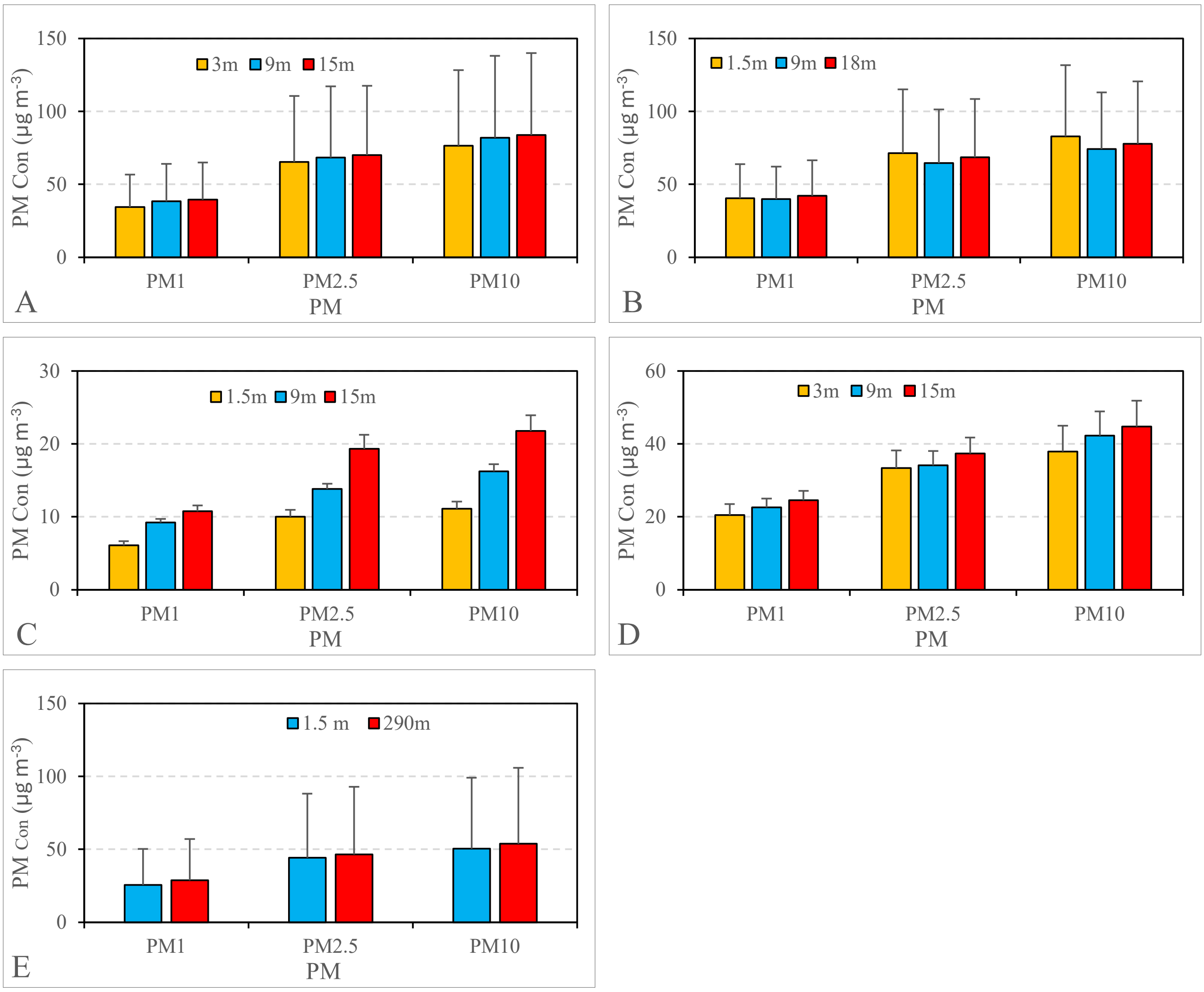

Fig. 5. Vertical distribution of the mean concentration of PM in each measurement location, (A) Vesal dorm, (B) School of Public Health, (C) School of Pharmacy, (D) Koy dorm, and (E) Milad Tower.

with the findings of Ezhil Kumar and Karthikeyan (2015), who showed a decrease in concentration with height. However, in another sampling site, a rise in PM_{10} concentration was observed by increasing the height from 6.8 to 19.08 and then decreasing (Ezhil Kumar and Karthikeyan, 2015). Statistical analysis revealed a significant variance in the particulate matter concentration at various altitudes (P-value < 0.05). Table S2 presents statistical analysis to compare the average PM concentration at different heights in the Vesal dorm.

In the School of Public Health (SPH), the lowest PM concentration was found at the mid-height (9 m). The PM_1 concentration peaked at 18 m, while $PM_{2.5}$ and PM_{10} concentrations were highest at the base height (1.5 m). The average PM_1 concentrations increased by 3.9% at 18 m and decreased by 1.3% at 9 m compared to base height. The average $PM_{2.5}$ concentrations decreased by 9.6% and 4.2% at these heights, respectively. Similarly, the average PM_{10} concentrations decreased by 10.4% and 6.2%, respectively. Previous studies observed similar results (Gao *et al.*, 2017; Liao *et al.*, 2023). Statistical analysis revealed significant differences in $PM_{2.5}$ concentrations between 9 m and 18 m, in PM_{10} concentrations between 1.5 m and 9 m, and between 1.5 m and 18 m (P-value < 0.05). Table S3 presents the statistical analysis comparing the mean PM concentration at different heights in SPH.

In the School of Pharmacy, the lowest PM concentration was observed at 1.5 m (base height), while the highest concentration was at the maximum height (15 m). The PM_1 mean concentrations increased by 50.8% and 77% at 9 and 15 m, respectively, compared to base height. The mean

$PM_{2.5}$ concentrations at these altitudes increased by 38% and 93% compared to the base height. Finally, the mean PM_{10} concentrations at these heights rose by 45.9% and 96.3%, respectively, compared to the base height. Statistical analysis indicated significant differences in the particulate matter concentrations at different elevations (P-value < 0.05). Table S4 presents a statistical analysis comparing the mean PM concentration at various heights in the School of Pharmacy.

In Koy dorm, the minimum PM concentration was observed at 3 m (base height), while the maximum concentration was at the highest height (15 m). The mean PM_1 concentrations increased by 10.2% and 19.5% at 9 and 15 m, respectively, compared to the base height. The mean $PM_{2.5}$ concentrations at the exact altitudes increased by 2% and 11.9%, respectively, compared to the base height. Similarly, the mean PM_{10} concentrations at these heights rose by 11.3% and 17.6%, respectively. Statistical analysis indicated a significant difference in the concentration of particulate matter at various altitudes, except for $PM_{2.5}$ between 3 and 9 m (P-value < 0.05). Table S5 presents a statistical analysis comparing the mean PM concentration at different heights in the Koy dorm.

In Milad Tower, the PM concentration was higher at 290 m compared to the base height (1.5 m), likely due to increased wind speed at elevated levels (Babaan *et al.*, 2018). Another possible reason for this rise could be the formation of secondary PM in the atmosphere (Chan *et al.*, 2005). Secondary PM is formed due to the chemical reactions between pollutants like NO_x and VOC in the presence of sunlight and moisture (Han *et al.*, 2015; Ho *et al.*, 2018). Some studies suggest that the increase in PM concentration is due to the inverse temperature layer at an altitude of 300 to 400 m (Lu *et al.*, 2019; Guan *et al.*, 2021). Also, PM rose to higher altitudes due to the expansion of the atmosphere mixing layer caused by increasing sunlight and human activities during noon measurements (12). Long-distance transportation may also contribute to the rise in $PM_{2.5}$ concentration (Sun *et al.*, 2013). The average PM_1 concentration increased by 12.9% at 290 m compared to the base height, while $PM_{2.5}$ and PM_{10} concentrations at the same altitude rose by 105.2% and 106.7%, respectively. Statistical analysis revealed a significant difference in the concentration of particulate matter at various altitudes (P-value < 0.05). Table S6 presents a statistical analysis comparing the mean PM concentration at different heights in Milad Tower.

3.3 Vertical Distribution of Particulate Matter Ratio

The $PM_1/PM_{2.5}$ and PM_1/PM_{10} ratio was typically highest at middle altitude (9 m) and lowest at lower altitudes (1.5–3 m). In contrast, the $PM_{2.5}/PM_{10}$ ratio was highest at lower altitudes and lowest at middle altitudes. Gravity has a significant impact on larger particles, causing them to settle, and their concentration is predicted to decrease as the altitude increases (Chan and Kwok, 2000). The ratio of PM at different heights in each location is indicated in Table 4.

In the Vesal dorm, the minimum $PM_1/PM_{2.5}$ and PM_1/PM_{10} ratios were observed at 3 m (base height), while the maximum ratio was observed at the middle height (9 m). On the other hand, the minimum ratio of $PM_{2.5}/PM_{10}$ was observed at the middle height, while the maximum ratio was observed at the base height. This finding is in contrast with the results of Zhang *et al.* (2021), who reported the maximum and minimum ratio at the highest middle altitude. The ratio of $PM_1/PM_{2.5}$ increased at 9 and 15 m compared to the ratio at base height by 7.4% and 5.5%, respectively. In the case of the ratio of PM_1/PM_{10} at the exact altitudes compared to the ratio at base height, both increased by 4.3%. Then, the ratio of $PM_{2.5}/PM_{10}$ at the exact altitudes compared to the ratio at base height decreased by 3.5% and 2.3%, respectively.

Statistical analysis revealed a significant difference in the ratio of particulate matter across various altitudes (P-value < 0.05). Table S2 presents statistical analysis to compare the ratio of PM at different heights in the Vesal dorm.

In the School of Public Health, the minimum ratio of $PM_1/PM_{2.5}$ and PM_1/PM_{10} was observed at a height of 1.5 m (base height), while the maximum ratio of $PM_1/PM_{2.5}$ was observed at the middle height (9 m) and the maximum ratio of PM_1/PM_{10} was observed high height (18 m). On the other hand, the minimum ratio of $PM_{2.5}/PM_{10}$ was observed at the middle height, while the maximum ratio was observed at the base height and high height. The ratio of $PM_1/PM_{2.5}$ increased at 9 and 18 m compared to the ratio at base height by 8.6% and 6.8%, respectively. The ratio of PM_1/PM_{10} at the exact altitudes compared to the ratio at base height increased by 5.8% and 7.8%, respectively. Then, the ratio of $PM_{2.5}/PM_{10}$ at 9 m compared to the ratio at base height decreased by 1.2%, and at 18 m, it was the same as the ratio at base height.

Table 4. The ratio of PM at different heights in each location.

Location	Height	$PM_1/PM_{2.5}$ (SD)	PM_1/PM_{10} (SD)	$PM_{2.5}/PM_{10}$ (SD)
Vesal dorm	3 m	0.54 (0.04)	0.46 (0.04)	0.86 (0.06)
	9 m	0.58 (0.04)	0.48 (0.04)	0.83 (0.06)
	15 m	0.57 (0.04)	0.48 (0.05)	0.84 (0.06)
School of Public Health	1.5 m	0.58 (0.05)	0.51 (0.06)	0.87 (0.06)
	9 m	0.63 (0.05)	0.54 (0.06)	0.86 (0.06)
	18 m	0.62 (0.05)	0.55 (0.06)	0.87 (0.05)
School of Pharmacy	1.5 m	0.61 (0.01)	0.55 (0.03)	0.90 (0.04)
	9 m	0.67 (0.01)	0.57 (0.02)	0.85 (0.02)
	15 m	0.56 (0.02)	0.50 (0.02)	0.89 (0.02)
Koy dorm	3 m	0.61 (0.04)	0.54 (0.04)	0.89 (0.05)
	9 m	0.66 (0.02)	0.54 (0.04)	0.81 (0.05)
	15 m	0.66 (0.03)	0.55 (0.04)	0.84 (0.05)
Milad Tower	1.5 m	0.58 (0.06)	0.51 (0.06)	0.88 (0.07)
	290 m	0.63 (0.06)	0.54 (0.07)	0.86 (0.07)
Total	Low altitude (1.5–3 m)	0.55 (0.05)	0.47 (0.05)	0.86 (0.06)
	middle altitude (9 m)	0.6 (0.08)	0.5 (0.08)	0.83 (0.06)
	high altitude (15–18 m)	0.59 (0.05)	0.5 (0.05)	0.85 (0.06)

Statistical analysis indicated a notable disparity in the ratio of particulate matter at different altitudes, except for $PM_1/PM_{2.5}$ and PM_1/PM_{10} between 9 m and 18 m, as well as $PM_{2.5}/PM_{10}$ between 1.5 m and 9 m, and 1.5 m and 18 m (P-value > 0.05). Table S3 presents statistical analysis to compare the ratio of PM at different heights in the School of Public Health.

In the School of Pharmacy, the minimum $PM_1/PM_{2.5}$ and PM_1/PM_{10} ratios were observed at 15 m (high height), while the maximum ratio was observed at the middle height (9 m). On the other hand, the minimum ratio of $PM_{2.5}/PM_{10}$ was observed at the middle height, while the maximum ratio was observed at the base height (1.5 m). The ratio of $PM_1/PM_{2.5}$ increased at 9 m compared to the ratio at base height by 9.8%, and the ratio at 15 m compared to the ratio at base height decreased by 8.2%. The ratio of PM_1/PM_{10} increased at 9 m compared to the ratio at base height by 3.6% and the ratio at 15 m compared to the ratio at base height decreased by 9.1%. Then, the ratio of $PM_{2.5}/PM_{10}$ at the exact altitudes compared to the ratio at base height decreased by 5.6% and 1.2%, respectively.

Statistical analysis revealed a significant difference in the ratio of particulate matter across various altitudes, except for $PM_{2.5}/PM_{10}$ between 9 m and 15 m (P-value < 0.05). Table S4 presents statistical analysis to compare the ratio of PM at different heights in the School of Pharmacy.

In Koy dorm, the minimum $PM_1/PM_{2.5}$ and PM_1/PM_{10} ratio were observed at 3 m (base height), while the maximum ratio was observed at the high height (15 m). On the other hand, the minimum ratio of $PM_{2.5}/PM_{10}$ was observed at the middle height (9 m), while the maximum ratio was observed at the base height. The ratio of $PM_1/PM_{2.5}$ increased at both 9 and 15 m compared to the ratio at base height by 8.1%. The ratio of PM_1/PM_{10} at 15 m compared to 3 and 9 m increased by 1.8%. Then, the ratio of $PM_{2.5}/PM_{10}$ at the exact altitudes compared to the ratio at base height decreased by 9% and 5.7%, respectively.

Statistical analysis indicated a notable disparity in the ratio of particulate matter at different altitudes, except for PM_1/PM_{10} between 3 m and 9 m, as well as $PM_{2.5}/PM_{10}$ between 3 m and 15 m, and 1.5 m and 18 m heights (P-value > 0.05). Table S5 presents statistical analysis to compare the ratio of PM at different heights in the Koy dorm.

In Milad Tower, the minimum $PM_1/PM_{2.5}$ and PM_1/PM_{10} ratios were observed at 1.5 m (base height), while the maximum ratio was observed at the high height (290 m). On the other hand, the minimum ratio of $PM_{2.5}/PM_{10}$ was observed at high height, while the maximum ratio was observed at the base height. The ratio of $PM_1/PM_{2.5}$ increased at 290 m compared to the ratio at base height by 8.6%. The ratio of PM_1/PM_{10} at the same altitude compared to the ratio at base height increased by 5.8%. Then, the ratio of $PM_{2.5}/PM_{10}$ at the same altitude compared to the ratio at base height decreased by 2.3%.

Statistical analysis revealed a significant difference in the ratio of particulate matter across various altitudes (P-value < 0.05). Table S6 presents statistical analysis to compare the ratio of PM at different heights in the Milad Tower.

3.4 Temporal Trend of the Vertical Distribution of PM Concentration at Different Heights

Fig. S1 shows the temporal trend of PM_1, $PM_{2.5}$, and PM_{10} concentrations at 3, 9, and 15 m throughout 24 hours. The trend is calculated based on the mean concentrations obtained each hour on different days.

Typically, the variation in particulate matter concentration during the daytime (from 7 A.M. to 10 P.M.) is higher than at nighttime. In contrast, the concentration of particulate matter at night exceeds that during the day. It could be because the atmosphere is more stable at night due to colder temperatures, while sunlight warms the earth during the day, so the mixing of the atmosphere is done better. PM rises to higher altitudes (Faridi *et al.*, 2018). Moreover, during nighttime, the mixing layer height (MLH) diminishes, leading to a decrease in the variation of PM concentrations across various altitudes (Taghvaee *et al.*, 2018). Despite the higher nighttime concentration of particulate matter, the difference in particulate matter concentration at various altitudes during the day is more pronounced due to the unstable atmosphere because particulate matter can go to higher altitudes more easily. The concentration of PM at multiple altitudes and hours is presented in Table S8.

4 CONCLUSION

Several factors, including wind speed and direction, temperature, building morphology, and topographic area, influence the vertical distribution of particulate matter concentration. At times when the atmosphere was more unstable (such as during the day), the concentration of particulate matter at different altitudes was more significant because particulate matter exhibits greater ease in reaching higher altitudes. The concentration of particulate matter increased with altitude in most of the places that were measured in this study. At low altitudes (under 18 m), the wind may be disrupted by buildings and barriers (such as trees), causing a wind vortex circulation that prevents the mixing of particulate matter produced at low altitudes with higher clean air. At a high altitude (290 m), secondary particle formation or transfer of particles from distant distances can result from increased particle concentration. Unfortunately, we could only take measurements at this altitude during daylight hours, when the production of secondary particulate matter and its dispersion across atmospheric layers are most pronounced. At the middle altitude (9 m), the ratio of $PM_1/PM_{2.5}$ and PM_1/PM_{10} is observed to be the highest at the middle altitude, while it is lowest at low altitude. Conversely, the ratio of $PM_{2.5}/PM_{10}$ is highest at low altitudes and lowest at the middle altitude, which shows that heavier particles settle more rapidly because of their greater weight and gravitational force. For future studies, further measurements can be done in other seasons (except winter) or at different altitudes. The effect of wind speed and direction on the vertical distribution of particle concentration can also be investigated.

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ADDITIONAL INFORMATION AND DECLARATIONS

Declaration of Competing Interest

The authors declare no conflict of interest.

Data Availability

The data used/analyzed during the present study are available from the corresponding author upon reasonable request.

Supplementary Material

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.240036

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