

Assessment of PM_{2.5} Distribution at Different Heights in Hanoi, Vietnam

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Abstract

Monitoring of PM₁₀ and PM_{2.5} concentrations frequently is essential for assessing air quality and informing pollution control strategies. This study examines the effect of height on PM_{2.5} distribution in Hanoi using EPA-standard methods at five rooftop locations on high-rise buildings. Results from Phase 1 (pre-pollution period) indicate a nearly 50% reduction in PM_{2.5} concentration, decreasing from 34.76 µg/m³ at 40 m to 13.95 µg/m³ at 336 m. In contrast, Phase 2 (pollution wave) showed relatively stable PM_{2.5} concentrations across heights, likely influenced by cold air masses and wind speed. MLR and MNLN analyses reveal the significant impact of meteorological factors and PM₁₀ on PM_{2.5} levels, with the MNLN model accounting for 80% - 94% of the variance, outperforming the MLR model's 50% - 80%. Employing UAVs, Lidar, and synchronized meteorological data is proposed as an advanced approach to enhance the accuracy of height-based dust concentration assessments.

Keywords

Lidar, PM_{2.5}, PM₁₀, Air Monitoring

1. Introduction

The accelerated urban expansion and intensifying urbanization have imposed substantial environmental pressures, especially air quality, leading to a marked increase in PM_{2.5} concentrations (Zhou et al., 2023). These fine matter particulates, predominantly derived from transportation, industrial activities, and biomass combustion, are also transported across regions. PM_{2.5} denotes particles with an aerodynamic diameter of less than 2.5 µm, which are harmful to human health and ecosystems

(Wang et al., 2021; Gao et al., 2017; Chen & Chen, 2021). Exposure to fine particulate matter is associated with reduced lung function and an increase in respiratory symptoms, including airway irritation, coughing, and breathing difficulties, and it may exacerbate COVID-19 symptoms (Carretero-Peña et al., 2019). According to a 2012 report by the United States Environmental Protection Agency (EPA), air pollution is responsible for 1.8% to 6.4% of child mortality (ages 0 to 4) across Europe, resulting in an estimated 100,000 annual deaths in urban areas (EPA, 2012). Additionally, in 2015, exposure to ambient $PM_{2.5}$ was estimated to contribute to approximately 4.2 million premature deaths worldwide (Cohen et al., 2017).

The swift expansion of urban areas and the construction of towering skyscrapers, serving as both residential and commercial spaces, have resulted in human exposure to air pollution at various heights. Recently, numerous studies have focused on the vertical distribution of air pollution, with particular attention to $PM_{2.5}$ levels in urban settings. These studies have employed diverse methodologies, including Lidar technology (Tao et al., 2016; Lyu et al., 2018; Liu et al., 2019; Wang et al., 2016), UAV-based measurements (Zhao et al., 2021; Qu et al., 2022; Wu et al., 2021), high-rise building observations (Yang et al., 2009; Liu et al., 2018; Ding et al., 2005), and computational modeling techniques (Liu et al., 2021; Lee et al., 2017; Yang et al., 2020).

Hanoi, the capital and most populous city of Vietnam had an estimated population of 8.6 million in 2023 (Statistical Publishing House, 2023). The city's rapid socio-economic growth and urbanization have exacerbated severe air pollution, particularly concerning $PM_{2.5}$ levels. From 2015 to 2021, the annual average $PM_{2.5}$ concentration in Hanoi surpassed the QCVN 05:2013/BTNMT standard by over 1.3 times (MONRE, 2023), highlighting persistent pollution challenges. This has led to extensive research on $PM_{2.5}$, including emission sources (Bang, 2022; Amann et al., 2019; Le et al., 2022), composition (Vo et al., 2022; Hai & Oanh, 2013; Makkonen et al., 2023), spatial distribution (Vuong et al., 2023), meteorological impacts (Luong et al., 2021; Ly et al., 2021; Hien et al., 2002; Tham et al., 2018; Ngo et al., 2012) and health consequences (Nguyen et al., 2022; Nhung et al., 2022). However, studies addressing the vertical distribution of $PM_{2.5}$ in Vietnam remain relatively scarce.

Therefore, it is necessary to conduct a study evaluating the vertical distribution of air pollution in Hanoi. In this research, $PM_{2.5}$ concentrations were measured at different heights across the city, adhering to EPA reference standards. The findings from the assessment of $PM_{2.5}$ distribution will offer a more detailed understanding of its spatial patterns and the magnitude of its impact at various heights within the urban environment in Hanoi.

2. Materials and Methods

2.1. Methods

The primary methodology employed in this study involved measuring meteorological parameters and $PM_{2.5}$ concentrations on the rooftops of high-rise

buildings. Due to the absence of meteorological or television towers of approximately 200 meters in height in Hanoi, the research team opted for tall building rooftops to conduct simultaneous measurements. This approach enabled the study to effectively capture $PM_{2.5}$ data at various elevations within urban areas.

In this study, sampling was conducted at two urban locations within the inner city of Hanoi, with each site having simultaneous measurements taken at five distinct points situated on the rooftops of buildings at varying elevations as shown in **Figure 1**. Vertical distribution data for the examined parameters were obtained by sampling at the highest floors of buildings, with elevations ranging from 40 meters to over 300 meters (**Table 1**). Wind speed, humidity, and temperature were directly measured at different heights using a microclimate measuring device. At the same time, $PM_{2.5}$ concentrations were sampled using the Instrumex dust sampler and analyzed with an AD-421D-32 analytical balance.

Five Instrumex samplers, designed to concurrently collect $PM_{2.5}$ and PM_{10} particles in compliance with U.S. EPA reference standards, were employed simultaneously for sampling. Each sample was collected over 6 hours, with two samples taken daily between 8 AM and 8 PM.

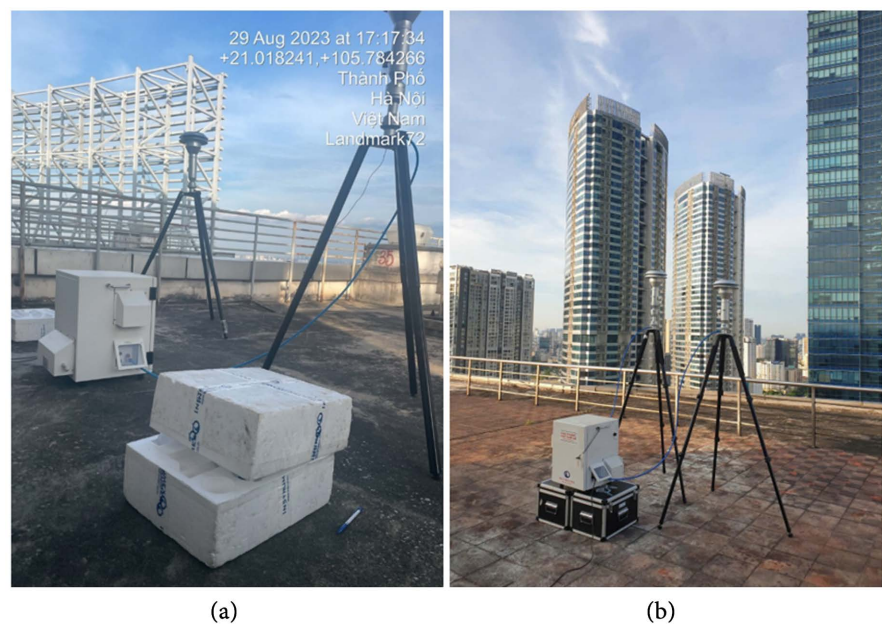


Figure 1. Collecting sample images. (a) KengNam 49; (b) CEO Tower.

Table 1. Parameters considered for correlation assessment.

Independent variables	Elements
X_0	Height
X_1	Temperature
X_2	Wind speed
X_3	Humidity
X_4	PM_{10} Concentration

2.2. Analysis of the Relationship between PM_{2.5} and Other Factors

There are multiple approaches for analyzing the relationship between PM_{2.5} concentrations and meteorological variables, with Multivariable Linear Regression (MLR) and Multivariable Nonlinear Regression (MNLN) being the most commonly employed techniques (Liu et al., 2023; Li et al., 2017; Hao et al., 2022). In this study, both MLR and MNLN models were utilized to assess the relationship between PM_{2.5} concentrations and key variables, including elevation, PM₁₀ concentrations, and various meteorological conditions.

Multivariable Linear Regression (MLR), an extension of simple linear regression, is utilized to predict a response variable based on multiple explanatory variables. This study employed a MLR to assess the extent to which fine dust concentration can be estimated using meteorological factors. The regression function was accordingly adjusted to incorporate several predictor variables as follows:

$$Y = \beta_0 * X_0 + \beta_1 * X_1 + \beta_2 * X_2 + \dots + \beta_n * X_n + \varepsilon \quad (1)$$

In this statistical model, Y is designated as the dependent variable, with X_0 , X_1 and additional terms representing the explanatory variables, also referred to as independent regressors. The term ε notes the stochastic error component. It is observed that as the quantity of predictor variables escalates, the corresponding constants β exhibit a proportional increase.

Multivariable Nonlinear Regression (MNLN) is a sophisticated statistical technique that enables the modeling of relationships between a dependent variable and one or more independent variables when linear representations cannot adequately capture such relationships. In this study, the regression model is formulated as a nonlinear function of the parameters in conjunction with one or more independent variables, allowing for greater flexibility and accuracy in representing complex data patterns.

Informed by the comprehensive analysis of MNLN in the studied (Yin et al., 2016), the model proposed in this study is delineated as follows:

$$Y = a + \sum_{i=0}^n b_i * X_i + \sum_{j<i} b_{ij} * X_{ij} + \sum_{i=0}^n b_{ii} * X_{ii} \quad (2)$$

where Y represents the dependent variable (PM_{2.5} dust), a is the constant, and b_i , b_{ij} , b_{ii} are the coefficients associated with the independent variables X_i , which include PM₁₀ dust, temperature, wind speed, rainfall, humidity, and other relevant factors.

It is crucial to note that the considerations for interpreting the results of the nonlinear regression model are analogous to those applicable in the context of multivariate linear regression models.

2.3. Data

This study collected observational data during two distinct periods across two separate areas, with five concurrent samples obtained at each location. **Table 2** describes the geographic coordinates and sampling heights for each sampling point.

The collected data encompassed wind speed, humidity, temperature, and concentrations of PM₁₀ and PM_{2.5}. Additionally, surface data were gathered from the Environmental Protection Agency's air quality monitoring station located at 105.799°E, 21.015°N.

Table 2. Information about PM_{2.5} sampling locations.

	Name	Height (m)	Coordinates	Time
Area 1	CT 3-1 Me Tri Ha	40	21°00'56"N 105°46'55"E	Period 1: 25-31/08/2023. Period 2: 09-15/10/2023
	CEO Tower	102	21°00'56"N 105°46'58"E	
	Vinhome Skylake	151	21°01'11"N 105°46'53"E	
	Keangnam	212	21°01'06"N 105°47'04"E	
	Keangnam	336	21°01'00"N 105°47'03"E	
Surface	The Sub-department of Environment Protection Hà Nội		21°00'54"N 105°47'59"E	Automatic Station
Area 2	Sunny Hotel	40	21°01'40"N 105°48'46"E	Period 1: 04-10/09/2023. Period 2: 16-22/10/2023.
	VIT Tower	80	21°01'46"N 105°48'42"E	
	Lieu Giai Tower	122	21°02'07"N 105°48'50"E	
	Vinhome Metropolis	160	21°01'52"N 105°48'55"E	
	Lotte Center	272	21°01'56"N 105°48'45"E	

3. Results

3.1. Trends in PM_{2.5} Concentrations

The trends in PM_{2.5} concentrations were analyzed for two investigation periods: from August 25, 2023, to September 10, 2023, and from October 4, 2023, to October 22, 2023. These periods fall within the autumn season in Northern Vietnam and align with the pre-harvest and post-harvest phases of the summer-fall rice crop in the surrounding areas of Hanoi. PM_{2.5} concentrations during these periods ranged from 9 to 109 µg/m³. The average concentration for the first period was 22.33 µg/m³ in Area 1 and 31.07 µg/m³ in Area 2, while for the second period, it increased to 33.39 µg/m³ and 31.93 µg/m³ for Area 1 and Area 2, respectively. These findings indicate higher fine particulate matter concentrations during the second period, likely due to the impact of agricultural residue burning, consistent with previous studies in Hanoi (Le et al., 2022; Vuong et al., 2023; Pham et al., 2024; Pham et al., 2021).

In this study, the majority of PM_{2.5} concentrations were within the lower range of the daily limit of 50 µg/m³ specified by QCVN 05:2013/BTNMT. However, these values exceeded the recommended 15 µg/m³ threshold established by the World Health Organization (WHO).

3.2. Distribution of PM_{2.5} Concentrations by Heights

Figure 2 shows the variations in meteorological factors, along with PM₁₀ and PM_{2.5} concentrations by Height during two measurement periods in Area 1. In the first measurement, PM_{2.5} concentrations were observed to increase at a height of 40 m

before decreasing sharply with further increases in height. This trend is attributed to the significant rise in wind speed at higher heights. At 40 m, the $PM_{2.5}$ concentration was approximately $34.76 \pm 2.38 \mu\text{g}/\text{m}^3$, which declined to $13.95 \pm 1.7 \mu\text{g}/\text{m}^3$ at 336 m, representing a reduction by a factor of two.

A similar pattern was observed in Area 2 during the first measurement period, where $PM_{2.5}$ concentrations also peaked at 40 m and then gradually decreased with increasing height (Figure 3). At 40 m, the concentration was approximately $33.92 \pm 2.98 \mu\text{g}/\text{m}^3$, decreasing to $23.99 \pm 4.53 \mu\text{g}/\text{m}^3$ at 272 m, a reduction of about 1.4 times. Differences in the ground-level measurement location and the $PM_{2.5}$ monitoring methods can explain the concentration increase at 40 m. This trend of decreasing $PM_{2.5}$ concentration with height aligns with findings from several other studies worldwide (Liu et al., 2018; Chan et al., 2005).

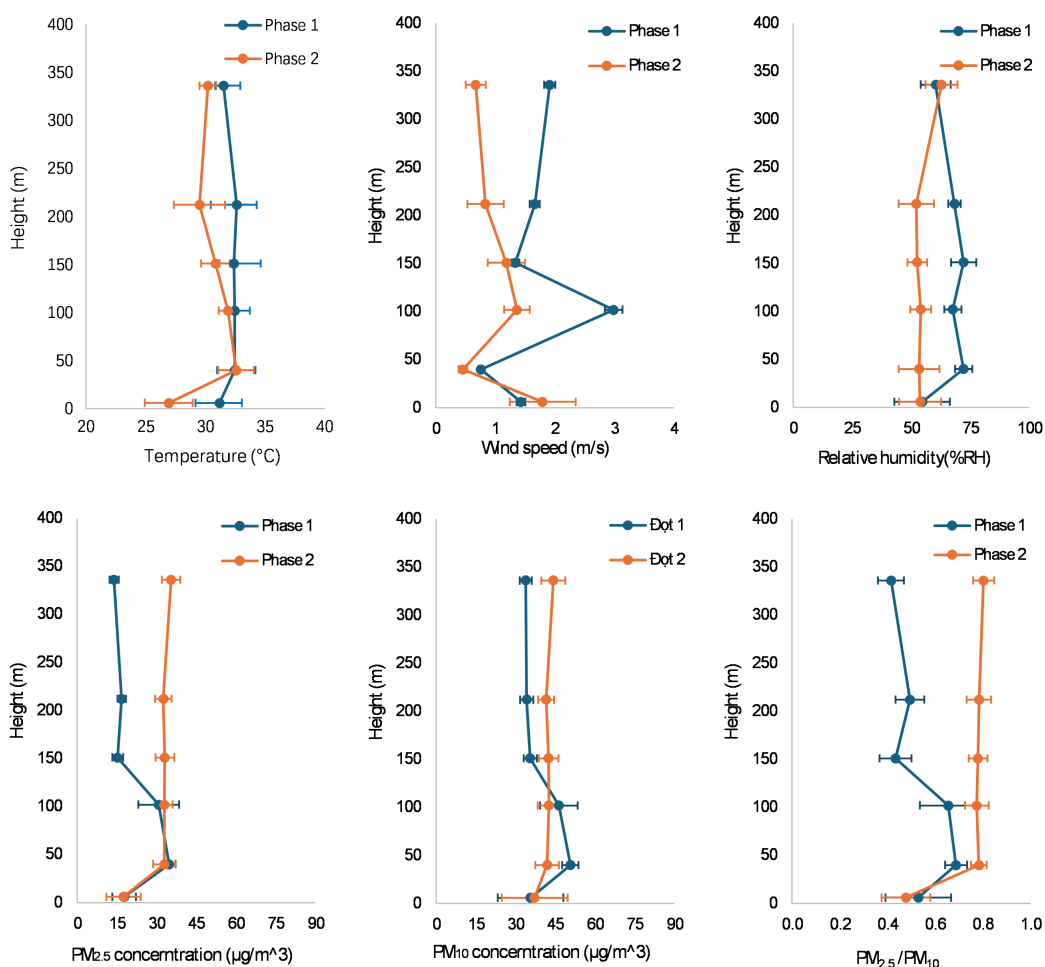


Figure 2. Measurement data and analysis in area 1.

PM_{10} and $PM_{2.5}$ concentrations decreased with increasing height during the first period; however, the second period did not show significant variations in these values. Despite these differences, fine particulate matter concentrations in both periods consistently remained within the permissible environmental

limits.

Similarly, **Figure 3** presents the results for meteorological factors and fine dust concentrations by Height in Area 2. As observed in Area 1, discrepancies were noted between ground-level measurements and those at 40 m. Temperature, wind speed, and humidity varied at different heights, showing consistent trends across both periods. $PM_{2.5}$ and PM_{10} concentrations in Area 2 were comparable to those in Area 1, with no significant differences in concentration levels.

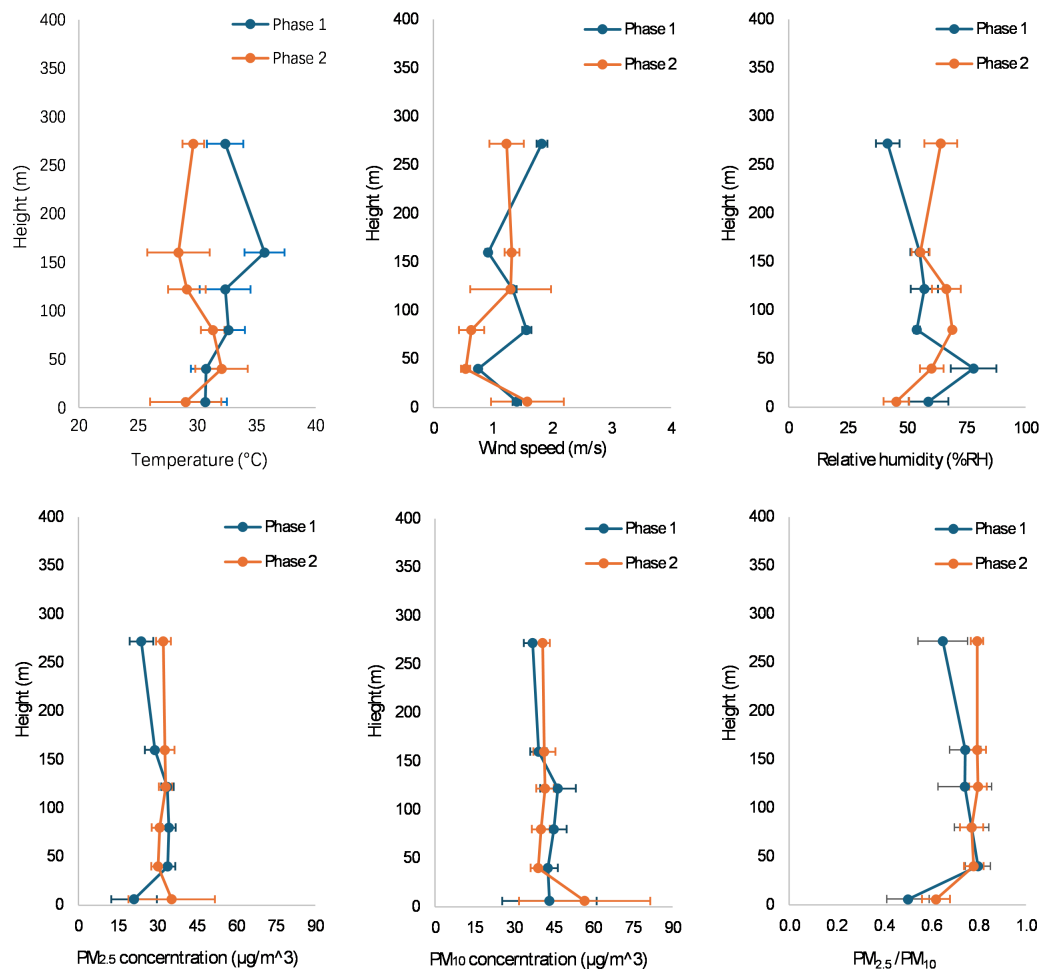


Figure 3. Measurement data and analysis in area 2.

Meteorological factors are vital in influencing the distribution of PM_{10} and $PM_{2.5}$ concentrations. Lower wind speeds contribute to poor dust dispersion in the air, and activities such as traffic and construction at ground level lead to higher dust concentrations. At greater heights, the influence of topographical obstructions diminishes, resulting in a gradual decrease in dust concentrations.

The measurements were conducted during a transitional period affected by light cold air masses, which emit higher dust values in the second period compared to the first. This pattern aligns with Hanoi's climatic characteristics, as cold air masses hinder the dispersion of air layers, causing dust particles to remain

stagnant.

A comparison of $PM_{2.5}$ values with those from published studies shows variations across regions. For instance, in the research by Zauli-Sajani et al. (2018), $PM_{2.5}$ concentrations at height during warm conditions were measured at $15 \mu\text{g}/\text{m}^3$, while cold conditions yielded $22 \mu\text{g}/\text{m}^3$. Similarly, the research by C.Y. Chan (Chan et al., 2005) in Beijing, which measured air quality at heights ranging from 8 to 325 m, found an average $PM_{2.5}$ concentration of $65 \mu\text{g}/\text{m}^3$ and PM_{10} concentration of $150 \mu\text{g}/\text{m}^3$. These studies also demonstrate a similar trend of minimal concentration changes with height, consistent with the results observed in Hanoi.

3.3. Correlation between $PM_{2.5}$ Concentrations and Factors

MLR and MNLR analyses were employed to assess the influence of variables such as height, temperature, wind speed, humidity, and PM_{10} concentration on $PM_{2.5}$ levels. The detailed results of the MLR model are presented in Table 3, while the MNLR model results are shown in Table 4. The MLR analysis reveals that the selected factors account for approximately 50% to 80% of the variance in $PM_{2.5}$ concentrations. In comparison, the MNLR model explains between 80% and 94% of the variance in $PM_{2.5}$ concentrations. These findings demonstrate a clear influence of meteorological variables and PM_{10} concentrations on $PM_{2.5}$ levels. Wind speed emerged as the most significant factor affecting $PM_{2.5}$ concentrations, aligning with the findings of several previous studies (Vuong et al., 2023; Luong et al., 2021).

Table 3. The results of MLR model.

Coefficients of the MLR	Area 1		Area 2	
	Period 1	Period 2	Period 1	Period 2
ε	-17	-34	-23	-0.60
β_0	-0.02	0.02	0.02	0.02
β_1	0.12	1.23	0.56	0.08
β_2	0.64	-1.43	-0.49	-1.47
β_3	0.12	0.06	0.20	0.07
β_4	0.72	0.54	0.49	0.61

Table 4. The results of MNLR model.

Coefficients of the MNLR	Area 1		Area 2	
	Period 1	Period 2	Period 1	Period 2
a	-128	-32	3.47	-123
b_0	0.23	0.06	1.58	-0.07
b_1	11	1.45	-7.12	4.16
b_2	12	4	-49	16
b_3	-0.29	-0.04	3	1.76
b_4	-3	0.25	-1.34	0.84

Continued

b_{10}	0.00	0.00	-0.02	0.00
b_{20}	0.00	0.00	-0.01	0.02
b_{30}	0.00	0.00	-0.01	0.00
b_{40}	0.00	0.00	0.00	0.00
b_{21}	0.07	-0.11	1.16	-0.31
b_{31}	-0.01	0.00	-0.02	-0.02
b_{41}	0.06	0.00	0.03	-0.01
b_{32}	-0.05	-0.01	0.13	0.02
b_{42}	-0.03	0.00	0.02	-0.17
b_{43}	0.02	0.01	0.01	0.00
b_{00}	0.00	0.00	0.00	0.00
b_{11}	-0.18	-0.02	0.14	-0.03
b_{22}	-1.80	-0.21	1.75	-1.04
b_{33}	0.00	0.00	-0.02	-0.01
b_{44}	0.01	0.00	0.00	0.00

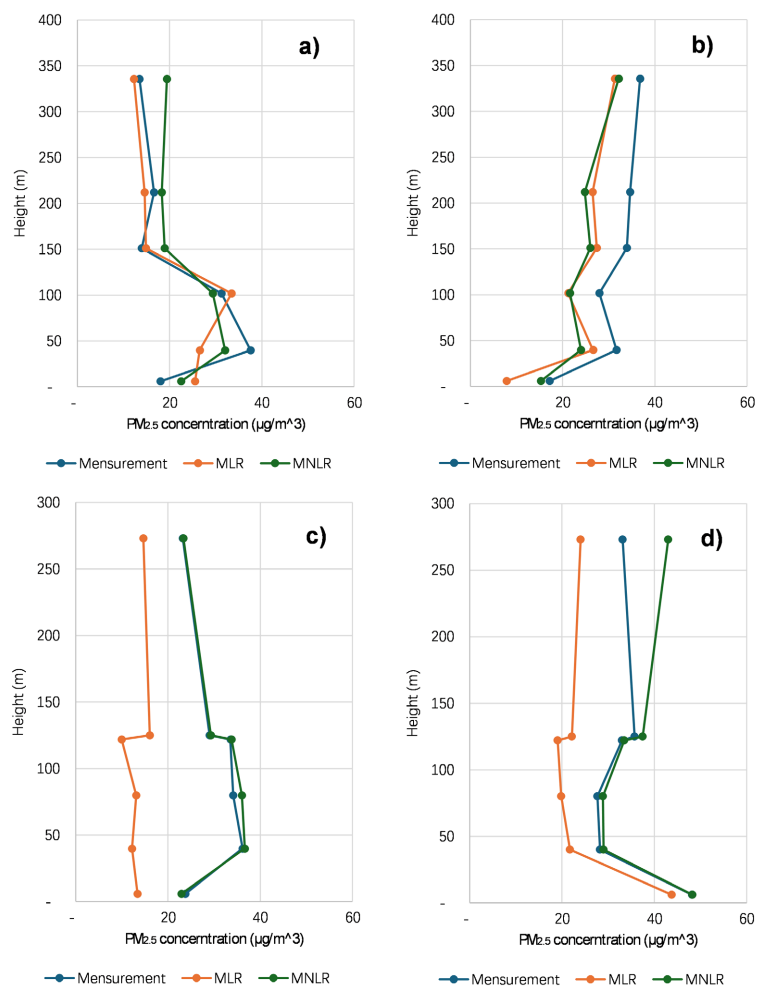


Figure 4. MAPE of the models. a) Area 1—Period 1; b) Area 1—Period 2; c) Area 2—Period 1; d) Area 2—Period 2.

Table 5. Comparison of the results from the linear regression model (MLR) and the non-linear regression model (MNLr).

Area	Phase	R ²		MAPE (error)	
		MLR	MNLr	MLR	MNLr
1	1	0.795	0.892	21%	26%
	2	0.787	0.923	24%	21%
2	1	0.517	0.815	53%	16%
	2	0.883	0.942	28%	9%

Since PM_{2.5} is a subset of PM₁₀, numerous researchers in previous studies have posited that PM_{2.5} concentration has a linear relationship with PM₁₀ concentration (Makkonen et al., 2023). As a result, they have employed Multivariable Linear Regression (MLR) to estimate PM_{2.5} concentrations based solely on PM₁₀ levels. However, as observed in Table 3 and Table 4, meteorological factors such as temperature, wind speed, and humidity also significantly influence PM_{2.5} concentrations with a proportional relationship with PM₁₀. Given that meteorological conditions vary by season, their impact on PM concentrations fluctuates accordingly. Multivariable Nonlinear Regression (MNLr) was applied for each survey period. Table 5 presents a comparison between the MLR and MNLr models. The results indicate that through all periods, the adjusted R² values for each area and survey period using MNLr are consistently higher than those obtained with MLR. Except for the first period in Area 1, the MNLr model also yields substantially better Mean Absolute Percentage Error (MAPE) values compared to the MLR model. Thus, MNLr proves to be a more reliable approach for estimating PM_{2.5} concentrations. Figure 4 shows a comparison between the estimated PM_{2.5} concentrations from both models and the observed values at different heights, under corresponding meteorological conditions.

4. Conclusion

This study provided an overview of PM_{2.5} distribution by height across Hanoi, measured at multiple high-rise buildings following EPA standards. Most PM_{2.5} concentrations ranged between 30 and 38 µg/m³, lower than QCVN 05:2023 but more than double the WHO limit of 15 µg/m³.

PM_{2.5} distribution by height was uneven, with notable differences from ground level to over 300 m. In the first monitoring period, concentrations peaked at 40 m and decreased twofold from 34.76 µg/m³ at 40 m to 13.95 µg/m³ at 336 m. During the second period, there was less variation, likely due to cold air masses and reduced wind speeds.

MLR and MNLr models identified wind speed as the most significant factor influencing PM_{2.5} concentrations, explaining the minimal height variation in the second period.

The synchronization of meteorological conditions, along with the adjustment of corresponding height values across experimental phases, will more accurately

elucidate the distribution of PM_{2.5} and PM₁₀ concentrations as influenced by height variations.

Due to logistical constraints, measurements were taken simultaneously at five high-rise locations, which may have been affected by local meteorological conditions and building proximity. Future studies will aim to use technologies such as UAVs and Lidar for more accurate height-based assessments.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- Amann, M., Klimont, Z., An Ha, T., Rafaj, P., Kiesewetter, G., Gomez Sanabria, A., et al. (2019). *Future Air Quality in Ha Noi and Northern Vietnam*.
- Bang, H. Q. (2023). *Research on Developing an Emission Map of Air Pollutants for Forecasting and Controlling Air Pollution in the Key Economic Region of Northern Vietnam*.
- Carretero-Peña, S., Calvo Blázquez, L., & Pinilla-Gil, E. (2019). Estimation of PM₁₀ Levels and Sources in Air Quality Networks by Digital Analysis of Smartphone Camera Images Taken from Samples Deposited on Filters. *Sensors, 19*, Article 4791. <https://doi.org/10.3390/s19214791>
- Chan, C. Y., Xu, X. D., Li, Y. S., Wong, K. H., Ding, G. A., Chan, L. Y., et al. (2005). Characteristics of Vertical Profiles and Sources of PM_{2.5}, PM₁₀ and Carbonaceous Species in Beijing. *Atmospheric Environment, 39*, 5113-5124. <https://doi.org/10.1016/j.atmosenv.2005.05.009>
- Chen, F., & Chen, Z. (2021). Cost of Economic Growth: Air Pollution and Health Expenditure. *Science of The Total Environment, 755*, Article 142543. <https://doi.org/10.1016/j.scitotenv.2020.142543>
- Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., et al. (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*, 1907-1918. [https://doi.org/10.1016/s0140-6736\(17\)30505-6](https://doi.org/10.1016/s0140-6736(17)30505-6)
- Ding, G. A., Chan, C., Gao, Z., Yao, W., Li, Y., Cheng, X., et al. (2005). Vertical Structures of PM₁₀ and PM_{2.5} and Their Dynamical Character in Low Atmosphere in Beijing Urban Areas. *Science in China, 48*, 38-54.
- EPA (2012). *Overview of Particle Air Pollution (PM_{2.5} and PM₁₀)*. <https://www.epa.gov/sites/default/files/2014-05/documents/huff-particle.pdf>
- Gao, S., Yang, L., Dong, S., Sun, W., Zha, K., & Zhao, J. (2017). A Study on Spatial-Temporal Distribution Characteristics of PM_{2.5} Concentrations in Nanjing during 2012-2016. *IOP Conference Series: Earth and Environmental Science, 81*, Article 012070. <https://doi.org/10.1088/1755-1315/81/1/012070>
- Hai, C. D., & Oanh, N. T. K. (2013). Effects of Local, Regional Meteorology and Emission Sources on Mass and Compositions of Particulate Matter in Hanoi. *Atmospheric Environment, 78*, 105-112. <https://doi.org/10.1016/j.atmosenv.2012.05.006>
- Hao, X., Hu, X., Liu, T., Wang, C., & Wang, L. (2022). Estimating Urban PM_{2.5} Concentration: An Analysis on the Nonlinear Effects of Explanatory Variables Based on Gradient Boosted Regression Tree. *Urban Climate, 44*, Article 101172. <https://doi.org/10.1016/j.uclim.2022.101172>
- Hien, P. D., Bac, V. T., Tham, H. C., Nhan, D. D., & Vinh, L. D. (2002). Influence of

- Meteorological Conditions on PM_{2.5} and PM_{2.5-10} Concentrations during the Monsoon Season in Hanoi, Vietnam. *Atmospheric Environment*, 36, 3473-3484. [https://doi.org/10.1016/s1352-2310\(02\)00295-9](https://doi.org/10.1016/s1352-2310(02)00295-9)
- Le, H. A., Khoi, N. Q., & Mallick, J. (2022). Integrated Emission Inventory and Modelling to Assess the Distribution of Particulate Matters from Rice Straw Open Burning in Hanoi, Vietnam. *Atmospheric Pollution Research*, 13, Article 101416. <https://doi.org/10.1016/j.apr.2022.101416>
- Lee, P., McQueen, J., Stajner, I., Huang, J., Pan, L., Tong, D., et al. (2017). NAQFC Developmental Forecast Guidance for Fine Particulate Matter (PM_{2.5}). *Weather and Forecasting*, 32, 343-360. <https://doi.org/10.1175/waf-d-15-0163.1>
- Li, X., Feng, Y. J., & Liang, H. Y. (2017). The Impact of Meteorological Factors on PM_{2.5} Variations in Hong Kong. *IOP Conference Series: Earth and Environmental Science*, 78, Article 012003. <https://doi.org/10.1088/1755-1315/78/1/012003>
- Liu, B., Ma, Y., Guo, J., Gong, W., Zhang, Y., Mao, F., et al. (2019). Boundary Layer Heights as Derived from Ground-Based Radar Wind Profiler in Beijing. *IEEE Transactions on Geoscience and Remote Sensing*, 57, 8095-8104. <https://doi.org/10.1109/tgrs.2019.2918301>
- Liu, C., Huang, J., Hu, X., Hu, C., Wang, Y., Fang, X. et al. (2021). Evaluation of WRF-Chem Simulations on Vertical Profiles of PM_{2.5} with UAV Observations during a Haze Pollution Event. *Atmospheric Environment*, 252, Article 118332. <https://doi.org/10.1016/j.atmosenv.2021.118332>
- Liu, F., Zheng, X., & Qian, H. (2018). Comparison of Particle Concentration Vertical Profiles between Downtown and Urban Forest Park in Nanjing (China). *Atmospheric Pollution Research*, 9, 829-839. <https://doi.org/10.1016/j.apr.2018.02.001>
- Liu, L., He, H., Zhu, Y., Liu, J., Wu, J., Tan, Z., et al. (2023). Spatiotemporal Distribution Characteristics and Multi-Factor Analysis of Near-Surface PM_{2.5} Concentration in Local-Scale Urban Areas. *Atmosphere*, 14, Article 1583. <https://doi.org/10.3390/atmos14101583>
- Luong, N. D., Hieu, B. T., & Hiep, N. H. (2021). Contrasting Seasonal Pattern between Ground-Based PM_{2.5} and MODIS Satellite-Based Aerosol Optical Depth (AOD) at an Urban Site in Hanoi, Vietnam. *Environmental Science and Pollution Research*, 29, 41971-41982. <https://doi.org/10.1007/s11356-021-16464-z>
- Ly, B., Matsumi, Y., Vu, T. V., Sekiguchi, K., Nguyen, T., Pham, C., et al. (2021). The Effects of Meteorological Conditions and Long-Range Transport on PM_{2.5} Levels in Hanoi Revealed from Multi-Site Measurement Using Compact Sensors and Machine Learning Approach. *Journal of Aerosol Science*, 152, Article 105716. <https://doi.org/10.1016/j.jaerosci.2020.105716>
- Lyu, L., Dong, Y., Zhang, T., Liu, C., Liu, W., Xie, Z., et al. (2018). Vertical Distribution Characteristics of PM_{2.5} Observed by a Mobile Vehicle Lidar in Tianjin, China in 2016. *Journal of Meteorological Research*, 32, 60-68. <https://doi.org/10.1007/s13351-018-7068-z>
- Makkonen, U., Vestenius, M., Huy, L. N., Anh, N. T. N., Linh, P. T. V., Thuy, P. T., et al. (2023). Chemical Composition and Potential Sources of PM_{2.5} in Hanoi. *Atmospheric Environment*, 299, Article 119650. <https://doi.org/10.1016/j.atmosenv.2023.119650>
- Ministry of Natural Resources and Environment (MONRE) (2023). *National Environmental Status Report 2021*.
- Ngo, T. X., Pham, H. V., Phan, H. D. T., Nguyen, A. T. N., To, H. T., & Nguyen, T. T. N. (2012). A Daily and Complete PM_{2.5} Dataset Derived from Space Observations for

- Vietnam from 2012 to 2020. *Science of The Total Environment*, 857, Article 159537. <https://doi.org/10.1016/j.scitotenv.2022.159537>
- Nguyen, T. P. M., Bui, T. H., Nguyen, M. K., Ta, T. N., Tran, T. M. H., Nguyen, Y. N., et al. (2022). Assessing Pollution Characteristics and Human Health Risk of Exposure to PM_{2.5}-Bound Trace Metals in a Suburban Area in Hanoi, Vietnam. *Human and Ecological Risk Assessment: An International Journal*, 28, 433-454. <https://doi.org/10.1080/10807039.2022.2056872>
- Nhung, N. T. T., Jegasothy, E., Ngan, N. T. K., Truong, N. X., Thanh, N. T. N., Marks, G. B., et al. (2022). Mortality Burden Due to Exposure to Outdoor Fine Particulate Matter in Hanoi, Vietnam: Health Impact Assessment. *International Journal of Public Health*, 67, Article 1604331. <https://doi.org/10.3389/ijph.2022.1604331>
- Pham, C.-T., Ly, B.-T., Nghiem, T.-D., Pham, T. H.-P., Minh, N.-T., Tang, N., et al. (2021). Emission Factors of Selected Air Pollutants from Rice Straw Burning in Hanoi, Vietnam. *Air Quality, Atmosphere & Health*, 14, 1757-1771. <https://doi.org/10.1007/s11869-021-01050-6>
- Pham, C.-T., Nghiem, T.-D., Le, H.-T., Chu, H. D., Tran Viet, T., Sekiguchi, K., et al. (2024). Size Distribution of Airborne Particle-Bound Polycyclic Aromatic Hydrocarbons during Rice Straw Open Burning in Hanoi, Vietnam. *Atmospheric Pollution Research*, 15, Article 102115. <https://doi.org/10.1016/j.apr.2024.102115>
- Qu, Y., Zhao, M., Wang, T., Li, S., Li, M., Xie, M., et al. (2022). Lidar- and UAV-Based Vertical Observation of Spring Ozone and Particulate Matter in Nanjing, China. *Remote Sensing*, 14, Article 3051. <https://doi.org/10.3390/rs14133051>
- Statistical Publishing House (2023). *Report on the Socio-Economic Situation for the Fourth Quarter and Year 2023*.
- Tao, Z., Wang, Z., Yang, S., Shan, H., Ma, X., Zhang, H., et al. (2016). Profiling the PM_{2.5} Mass Concentration Vertical Distribution in the Boundary Layer. *Atmospheric Measurement Techniques*, 9, 1369-1376. <https://doi.org/10.5194/amt-9-1369-2016>
- Tham, T. T., Hanh, N. T. D., Thu, N. T. A., & Thuy, T. T. (2018). Research on Effects of Temperature Inversions to Concentration of Particulate Matter (PM_{2.5}) in the Atmosphere in Hanoi. *VNU Journal of Science: Earth and Environmental Sciences*, 34, 1-9. <https://doi.org/10.25073/2588-1094/vnuees.4289>
- Vo, L. T., Yoneda, M., Nghiem, T., Shimada, Y., Van, D., Nguyen, T. T., et al. (2022). Indoor PM_{0.1} and PM_{2.5} in Hanoi: Chemical Characterization, Source Identification, and Health Risk Assessment. *Atmospheric Pollution Research*, 13, Article 101324. <https://doi.org/10.1016/j.apr.2022.101324>
- Vuong, T. B., Ha, L. A., Mai, D. K., & Nguyen, H. T. (2023). Characteristics of Fine Dust Pollution PM_{2.5} in Hanoi in 2021. *Nuclear Science and Technology*, 13, 1-10. <https://doi.org/10.53747/nst.v13i4.450>
- Wang, H., Wang, S., Zhang, J., & Li, H. (2021). Characteristics of PM_{2.5} Pollution with Comparative Analysis of O₃ in Autumn-Winter Seasons of Xingtai, China. *Atmosphere*, 12, Article 569. <https://doi.org/10.3390/atmos12050569>
- Wang, W., Mao, F., Gong, W., Pan, Z., & Du, L. (2016). Evaluating the Governing Factors of Variability in Nocturnal Boundary Layer Height Based on Elastic Lidar in Wuhan. *International Journal of Environmental Research and Public Health*, 13, Article 1071. <https://doi.org/10.3390/ijerph13111071>
- Wu, C., Liu, B., Wu, D., Yang, H., Mao, X., Tan, J., et al. (2021). Vertical Profiling of Black Carbon and Ozone Using a Multicopter Unmanned Aerial Vehicle (UAV) in Urban Shenzhen of South China. *Science of The Total Environment*, 801, Article 149689. <https://doi.org/10.1016/j.scitotenv.2021.149689>

- Yang, J., Kang, S., Ji, Z., Tripathee, L., Yin, X., & Yang, R. (2020). Investigation of Variations, Causes and Component Distributions of PM_{2.5} Mass in China Using a Coupled Regional Climate-Chemistry Model. *Atmospheric Pollution Research*, 11, 319-331. <https://doi.org/10.1016/j.apr.2019.11.005>
- Yang, S., Yuesi, W., & Changchun, Z. (2009). Measurement of the Vertical Profile of Atmospheric SO₂ during the Heating Period in Beijing on Days of High Air Pollution. *Atmospheric Environment*, 43, 468-472. <https://doi.org/10.1016/j.atmosenv.2008.09.057>
- Yin, Q., Wang, J., Hu, M., & Wong, H. (2016). Estimation of Daily PM_{2.5} Concentration and Its Relationship with Meteorological Conditions in Beijing. *Journal of Environmental Sciences*, 48, 161-168. <https://doi.org/10.1016/j.jes.2016.03.024>
- Zauli-Sajani, S., Rovelli, S., Trentini, A., Bacco, D., Marchesi, S., Scotto, F. et al. (2018). Higher Health Effects of Ambient Particles during the Warm Season: The Role of Infiltration Factors. *Science of the Total Environment*, 627, 67-77. <https://doi.org/10.1016/j.scitotenv.2018.01.217>
- Zhao, M., Fang, Z., Yang, H., Cheng, L., Chen, J., & Xie, C. (2021). UAVC: A New Method for Correcting Lidar Overlap Factors Based on Unmanned Aerial Vehicle Vertical Detection. *Applied Sciences*, 12, Article 184. <https://doi.org/10.3390/app12010184>
- Zhou, Q., Nizamani, M. M., Zhang, H., & Zhang, H. (2023). The Air We Breathe: An in-Depth Analysis of PM_{2.5} Pollution in 1312 Cities from 2000 to 2020. *Environmental Science and Pollution Research*, 30, 93900-93915. <https://doi.org/10.1007/s11356-023-29043-1>