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RETRIEVAL OF $PM_{2.5}$ CONCENTRATIONS USING MODIS-DERIVED AEROSOL OPTICAL DEPTH IN HO CHI MINH CITY, VIETNAM

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Abstract. Air pollution characterized by fine particulate matter ($PM_{2.5}$) has emerged as a critical environmental problem in Vietnam, particularly within densely populated metropolitan areas like Ho Chi Minh city. The integration of remote sensing (RS) and geographical information systems (GIS) offers a robust framework for monitoring $PM_{2.5}$ due to its extensive spatial coverage, high temporal resolution, and cost-effectiveness. This study estimates ground-level $PM_{2.5}$ concentrations by establishing a correlation between in-situ measurements from six monitoring stations and Aerosol Optical Depth (AOD) values retrieved from MODIS satellite imagery. The spatial, temporal, and seasonal dynamics of $PM_{2.5}$ in Ho Chi Minh city during the 2020 – 2025 period. Results indicate that the highest concentrations are concentrated in central urban districts, averaging 24.0 µg/m³. During the rainy season, the average of $PM_{2.5}$ concentration drops to 14.4 µg/m³. This seasonal reduction is primarily attributed to enhanced atmospheric dispersion and the wet deposition (rainwash). Overall, the study demonstrates that utilizing satellite-derived AOD provides a more comprehensive spatial understanding of $PM_{2.5}$ distribution, thereby supporting evidence-based air quality management and sustainable urban planning.

Keywords: $PM_{2.5}$, Aerosol Optical Depth (AOD), Ho Chi Minh city, MODIS, GIS, Remote Sensing.

1. Introduction

Fine particulate matter ($PM_{2.5}$) refers to microscopic airbone particles with an aerodynamic diameter equal to or smaller than 2.5 micrometers (µm) [1]. According to the World Health Organization (WHO), approximately 90% of the global population resides in environments where air quality fails to meet established safety guidelines [2]. In South Asia, the $PM_{2.5}$ concentrations in 2017 ranged from 58.3 to 99.7 µg/m³, manifold higher than the WHO Air Quality Guidelines (AQG) [3]. In Vietnam, rapid industrialization and unplanned urbanization have exacerbated fine dust pollution in megacities like Hanoi and Ho Chi Minh city. Specifically, between 2013 and 2017, the average $PM_{2.5}$ concentration in Ho Chi Minh reached 28.0 ± 18.1 µg/m³, consistently exceeding national standards and frequently ranking it among the most polluted cities globally [4]. This environmental crisis poses grave risks to public health, driving a surge in respiratory morbidities and lung cancer. Furthermore, the economic burden is staggering; in 2018 alone, the health-related economic losses in Ho Chi Minh city were estimated at nearly 3,000 billion VND [5].

Numerous global studies have employed spatial analysis techniques to model and predict $PM_{2.5}$ concentrations. For instance, Kazhal Masroor et al. conducted a study in Tehran using the Inverse Distance Weighting (IDW) interpolation method based on ground monitoring data. While this approach achieved a mean squared error (MSE) of 12.3 µg/m³ and demonstrated high efficacy in areas with a dense monitoring network, its predictive accuracy significantly diminished in regions with sparse monitoring distributions [6]. In contrast, Qianqian Yang et al. applied a Geographically Weighted Regression (GWR) model in China, achieving a high coefficient of determination (R^2) of 0.89 and a Mean Absolute Error (MAE) of 5.8 µg/m³. While interpolation and GWR-based regression offer substantial potential for spatial characterization, these methods often demand an extensive input dataset and entail significant computational overhead [7].

In Vietnam, several studies have leveraged GIS and remote sensing (RS) technologies to evaluate $PM_{2.5}$ pollution dynamics. A comprehensive study by Duong Huu Huy et al, analyzing monitoring data from 2013 - 2017, reported that the average $PM_{2.5}$ concentration in Ho Chi Minh city reached 28.0 ± 18.1 µg/m³. This research identified a distinct seasonal oscillation, with elevated concentrations during the dry season and a marked reduction, primarily attributed to the wet deposition (scavenging) effect [4]. Furthermore, Tran Quang Tra et al. utilized LANDSAT-8 OLI satellite imagery integrated with ground-level monitoring data to develop $PM_{2.5}$ distribution maps for the 2015 – 2020 period. The model yielded robust results, with a coefficient of determination (R^2) > 0.79 and a Root Mean Square Error (RMSE) of 2.37 µg/m³. The finding clearly illustrated the spatio-temporal heterogeneity of $PM_{2.5}$, confirming that densely populated urban centers consistently exhibit higher pollution levels compared to peri-urban and suburban areas [8].

The integration of advanced technologies, such as remote sensing and Geographic Information Systems (GIS), into air quality assessment is pivotal for effective urban environmental management. Although previous research has addressed this issue, several limitations persist, such as the reliance on outdated data, insufficient monitoring networks, or the use of traditional interpolation methods that fail to accurately capture the spatial heterogeneity of $PM_{2.5}$. To address these gaps, the present study leverages aerosol optical depth (AOD) data from MODIS satellite imagery to monitor $PM_{2.5}$ dynamics in Ho Chi Minh city. The main objective is to establish a quantitative relationship between satellite-derived AOD data and in-situ $PM_{2.5}$ concentrations recorded at monitoring stations, thereby generating high-resolution maps of $PM_{2.5}$ distribution across spatial, temporal, and seasonal scales. The results aim to provide a robust analytical tool to support environmental management and the formation of sustainable urban development policies. The remainder of this paper is organized as follows: Section 2 describes the study area and research methods; Section 3 discusses the results and analysis, and Section 4 summarizes the main conclusions.

2. Content

2.1. Study area

The study was conducted prior to the administrative merger under Resolution No. 202/2025/QH15, selecting Ho Chi Minh city (Latitude: 10°10'-10°38' N; Longitude: 106°22'- 106°54' E) as the study area (Figure 1). Ho Chi Minh city is situated at the transitional interface between the Southeast region and the Mekong Delta, with an average population of approximately 9.46 million in 2023 [9], [10]. The city experiences a tropical monsoon climate characterized by two distinct seasons: the rainy season extending from May to October, and the dry season spanning from November to April. Parallel with rapid urbanization and population growth, the city faces serious environmental challenges, particularly air pollution driven by fine particulate matter ($PM_{2.5}$). According to the 2021 National State of Environment Report, transportation activities are the primary source of $PM_{2.5}$ emissions within the city. In addition, industrial activities, construction, and biomass burning from surrounding areas are also major emission sources [11].

2.2. Research data

2.2.1. $PM_{2.5}$ concentration data

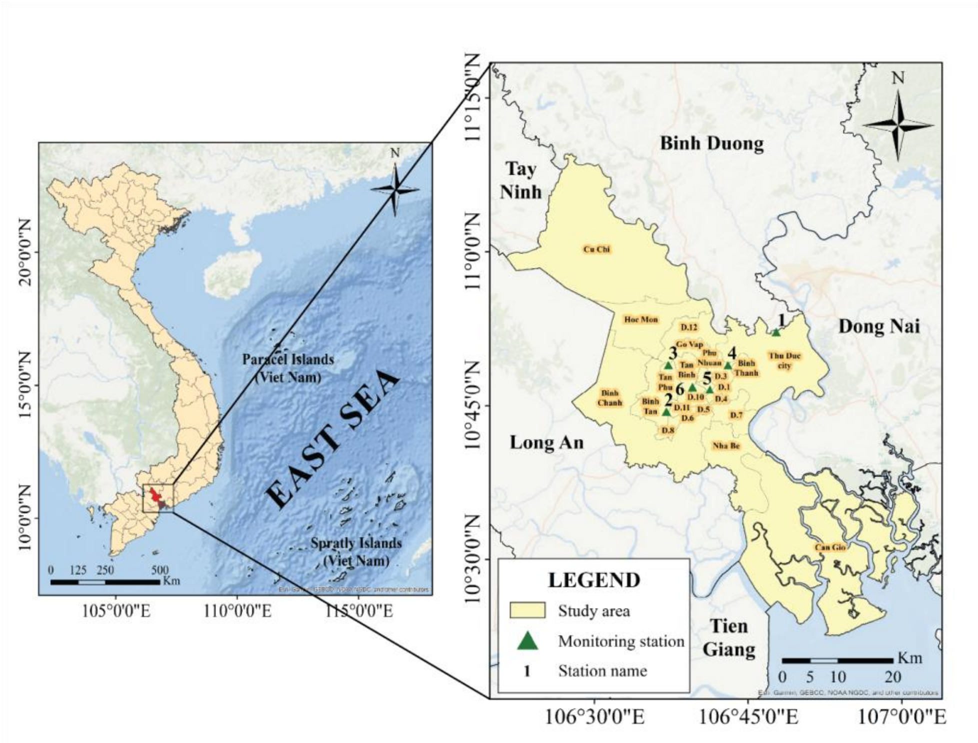

Figure 1. Study area and locations of $PM_{2.5}$ monitoring stations in Ho Chi Minh city (before the administrative merger under Resolution No. 202/2025/QH15)

The $PM_{2.5}$ dataset was continuously collected from April 2021 to March 2022 across six $PM_{2.5}$ monitoring stations distributed in different sectors of Ho Chi Minh city, as shown in Figure 1 [12]. The stations were strategically positioned at locations representing diverse urban characteristics, including residential areas, industrial zones, and major traffic corridors. This configuration ensured comprehensive spatial coverage, reflecting the heterogeneity in environmental conditions and anthropogenic emission sources across the metropolitan area.

Table 1 presents detailed information on geographical coordinates, site characteristics, and ground-level $PM_{2.5}$ concentrations at each station during the study period. These data provide a robust basis for quantitative analysis, spatiotemporal comparison, and evaluating the impacts of anthropogenic and meteorological factors on the variability of fine particulate matter within the study area.

Table 1. The locations of six stations and statistical descriptions of measured $PM_{2.5}$ concentrations in Ho Chi Minh city between April 2021 and March 2022

Station	Longitude	Latitude	$PM_{2.5}$ conc. (µg/m³)			Station locations
			Max	Min	Mean	
1	10°52'11"	106°47'45"	32.2	10.1	23.5	Industry, Traffic, Residential
2	10°44'27"	106°37'01"				Traffic
3	10°48'58"	106°37'13"				Industry
4	10°48'57"	106°43'02"				Residential
5	10°46'34"	106°41'16"				Traffic
6	10°46'49"	106°39'34"				Traffic, Residential

2.2.2. Aerosol optical depth (AOD) data

Aerosol Optical Depth (AOD) quantifies the extent to which aerosol particles in the atmosphere absorb and scatter sunlight [13]. In this study, satellite-based AOD serves as a critical dataset for $PM_{2.5}$ estimation. The AOD data were derived from the MODIS/Terra + Aqua Land Aerosol Optical Depth Daily L2G Global 1 km SIN Grid V061 (MCD19A2) product, provided by NASA via the Earthdata Search portal (https://search.earthdata.nasa.gov). This product is generated utilizing the Multi-Angle Implementation of Atmospheric Correction (MAIAC) algorithm, with AOD values retrieved at a wavelength of $\lambda \approx 0{,}55$ µm - this wavelength is highly sensitive to aerosol loading and exhibits a strong correlation with ground-level $PM_{2.5}$ concentration. With a spatial resolution of 1 km, the dataset allows for detailed observation of AOD variations with high reliability [14]. Throughout the study period from January 1, 2020, to May 23, 2025, a total of 1,939 MODIS scenes were processed. Images were collected daily between 07:00 and 13:00 (UTC+7), a representative time frame for monitoring diurnal air quality dynamics. Specifically, 23 cloud-free MODIS scenes were selected for the dry season and 6 for the rainy season to develop the core models. This dataset forms the basis for analyzing spatial and seasonal $PM_{2.5}$ patterns and improving the accuracy of urban air quality assessment in Ho Chi Minh city.

2.3. Methods

In this study, the following methodological approaches were employed: systematic data collection and reprocessing, statistical regression analysis, and advanced cartographic and Geographic Information System (GIS) techniques to visualize the spatial distribution of $PM_{2.5}$ concentrations. The comprehensive research procedure is illustrated in the methodological framework (Figure 2) below.

The authors integrated two primary data sources: in-situ $PM_{2.5}$ concentration and satellite-derived Aerosol Optical Depth (AOD). $PM_{2.5}$ data were monitored hourly across six ground-based monitoring stations, while AOD data were extracted from the MCD19A2 daily remote sensing product. To synchronize the datasets, $PM_{2.5}$ concentrations were matched within +/- 3-hour window centered on the satellite overpass time. Due to cloud contamination preventing AOD retrieval and satellite gaps in the $PM_{2.5}$ monitoring records, the final synchronized dataset comprised 76 valid observation pairs. For model construction and validation, the dataset was partitioned into a training set (n = 60) and a testing set (n = 16), based on the standard 80:20 ratio. The training set was utilized to calibrate the model, while the testing set served to independently evaluate predictive accuracy.

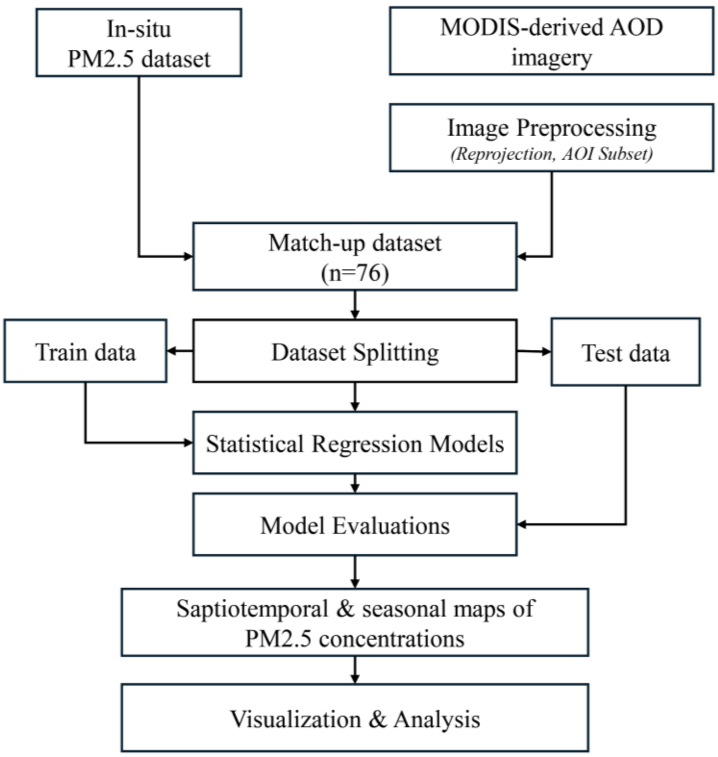

Figure 2. Flowchart of the research process

Linear regression is a widely adopted statistical method for modeling the relationship between a target dependent variable and one or more independent predictors [15]. In this study, the linear relationship between ground-level $PM_{2.5}$ and satellite-derived AOD is expressed as:

$$PM2.5 = \beta_0 + \beta_1 AOD + \varepsilon \quad (1)$$

where

- $PM2.5$ is the predicted concentration of fine particulate matter.

- AOD is the output Aerosol Optical Depth value (dimensionless).- β_0 is the intercept coefficient, representing the baseline $PM_{2.5}$ level when AOD is zero.

- β_1 is the slope coefficient, indicating the rate of change in $PM_{2.5}$ per unit increase in AOD

- ε is the random error term (residual), accounting for the variability in $PM_{2.5}$ not explained by the model.

The primary objective of the model is to estimate the optimal values of these coefficients such that the residual error between the predicted $PM_{2.5}$ values and the observed in-situ measurements is minimized. This is achieved through the Ordinary Least Squares (OLS) criterion, which minimizes the Sum of Squared Errors (SSE) to ensure the best fit across the 76 synchronized data points.

Once the regression model is established, its predictive accuracy and performance are evaluated by the estimated $PM_{2.5}$ values against the in-situ observations at monitoring sites. Key statistical indicators, including the Pearson correlation coefficient (R) and the root mean square error (RMSE), are employed to assess the model's reliability and goodness-of-fit. Specifically, the Pearson correlation coefficient [15] which measures the linear strength between satellite-derived and ground-based data, is calculated as follows:

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}} \quad (2)$$

where

- x_i, y_i are the individual values of the two variables (observed and predicted $PM_{2.5}$, respectively).

- $\bar{x}, \bar{y}$ are the arithmetic mean values of the corresponding variables.

The root mean square error (RMSE) is further employed to measure the average magnitude of the deviation between the predicted $PM_{2.5}$ values and the observed in-situ data [15]. Unlike the correlation coefficient, RMSE provides an absolute measure of fit in the same units as the target variable. The formula is defined as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \quad (3)$$

where

- y_i is the observed in-situ value at the i-th observation point.

- $\hat{y}_i$ is the predicted $PM_{2.5}$ concentration at the i-th observation point.

- n is the total number of valid observations (n=76).

2.4. Results

2.4.1. The establishment of $PM_{2.5}$ retrieval models

To ensure methodological objectivity and maximize the accuracy of $PM_{2.5}$ estimation from remote sensing data, three distinct linear regression models corresponding to three temporal periods: the full year (annual), the rainy season, and the dry season. This stratified approach allows for an in-depth examination of the variability in the relationship between the aerosol optical depth (AOD) and $PM_{2.5}$ concentrations, accounting for the specific hydro-meteorological conditions of each period. The resulting linear regression equations for each timeframe are presented in Table 2, illustrating the unique correlation coefficients for each model and facilitating a comparative assessment of predictive performance across different seasonal contexts.

Table 2. Linear regression equations for estimating $PM_{2.5}$ concentrations for each study period

Period	Equation	
Entire year	$PM2.5 = 15.02 + 25.98 AOD$	(4)
Rainy season	$PM2.5 = 12.81 + 6.79 AOD$	(5)
Dry season	$PM2.5 = 13.49 + 37.68 AOD$	(6)

To evaluate the goodness-of-fit of the developed linear regression models, the research team conducted a comparative analysis between the observed $PM_{2.5}$ concentrations and the estimated values derived from the AOD index. This validation process was performed for the entire study duration as well as independently for the dry and rainy seasons. By cross-referencing in-situ measurements with model outputs, the study identifies the predictive capability and seasonal sensitivity of the $PM_{2.5}$-AOD relationship in the specific context of Ho Chi Minh city.

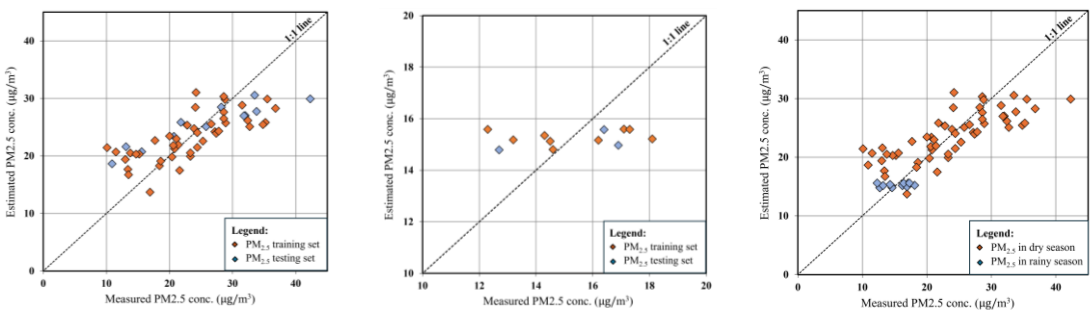

Figure 3. The scatter plot between observed and predicted $PM_{2.5}$ concentrations in the dry season (left), the rainy season (middle), and the entire year (right)

The results demonstrate that the linear regression model for the dry season achieved the highest predictive performance, with a Pearson correlation coefficient of 0.782 and an RMSE of 6.231 µg/m³. Furthermore, the correlations for the rainy season and the annual dataset also showed statistically significant results, with R values of 0.591 and 0.531, respectively.

Notably, while the dry season exhibited a stronger linear relationship, the prediction error was significantly lower during the rainy season, reaching a minimum RMSE of 1.712 µg/m³. This suggests that while AOD is a more robust predictor during the dry season, the absolute variability of $PM_{2.5}$ is more constrained during the rainy period.

Table 3. Accuracy Assessment of $PM_{2.5}$ retrieval models using the test dataset

Statistical indices	Dry season	Rainy season	Entire year
Pearson's r	0.78	0.59	0.53
RMSE (µg/m^3)	6.23	1.71	7.84

2.4.2. The spatial-temporal distributions of $PM_{2.5}$ during a period 2020 - 2025

From 2020 to 2025, $PM_{2.5}$ concentrations in Ho Chi Minh city exhibited significant fluctuations. During the 2020 - 2021 period, the study area recorded relatively high $PM_{2.5}$ levels, reaching 22.0 µg/m³, with elevated pollution attributed to dense traffic, rapid industrial expansion, and construction activities, coupled with dry weather conditions and low precipitation. However, in the 2022 - 2023 period, a marked decrease in $PM_{2.5}$ concentrations was observed, ranging from 19.5 to 20.5 µg/m³, due to social distancing measures implemented during the COVID-19 pandemic, which reduced traffic and industrial activities, along with emission control policies and increased public awareness. In the following years, $PM_{2.5}$ levels rebounded, ranging from 20.5 to 21.5 µg/m³, as economic activities gradually recovered, the number of personal vehicles increased rapidly, urban construction expanded, and temperature inversions hindered the dispersion of particulate matter into the atmosphere [10], [16], [17]. This trend indicates that air quality can improve in the short term if emission sources are strictly controlled, but long-term improvement requires comprehensive and sustainable management solutions to mitigate increasing urbanization pressures.

From the $PM_{2.5}$ distribution maps (Figures 4 and 5), it is evident that the central urban core, including Districts 1, 3, 5, 10, Binh Tan, and Binh Chanh Districts, exhibits the highest $PM_{2.5}$ concentrations, ranging from 22 to 24 µg/m³. These elevated levels are attributed to high traffic intensity, concentrated commercial activities, and ongoing urban construction [12]. Mobile source emissions, particularly from approximately 9 million motorbikes, many of which are outdated and lack efficient exhaust filtration systems, respresents the primary emission source [12]. Additionally, industrial clusters such as Vinh Loc, Le Minh Xuan, and Tan Tao, along with fossil fuel combustion in manufacturing processes, significantly contribute to the ambient pollution load. Fugitive dust from construction activities, especially under arid conditions, further exacerbates $PM_{2.5}$ levels [12], [18]. Furthermore, nocturnal and early-morning temperature inversions during the dry season trap pollutants within the planetary boundary layer, hindering vertical dispersion. This synergistic effect of high population density and a deficit of green infrastructure and blue spaces in central areas also reduces the natural urban scavenging capacity. This indicates that the urban core of Ho Chi Minh city is under dual pressure from both prolific internal emission sources and adverse meteorological conditions. Without stringent traffic regulations, construction oversight, and the expansion of nature-based solutions, the pollution trend in these hotspots is projected to intensify.

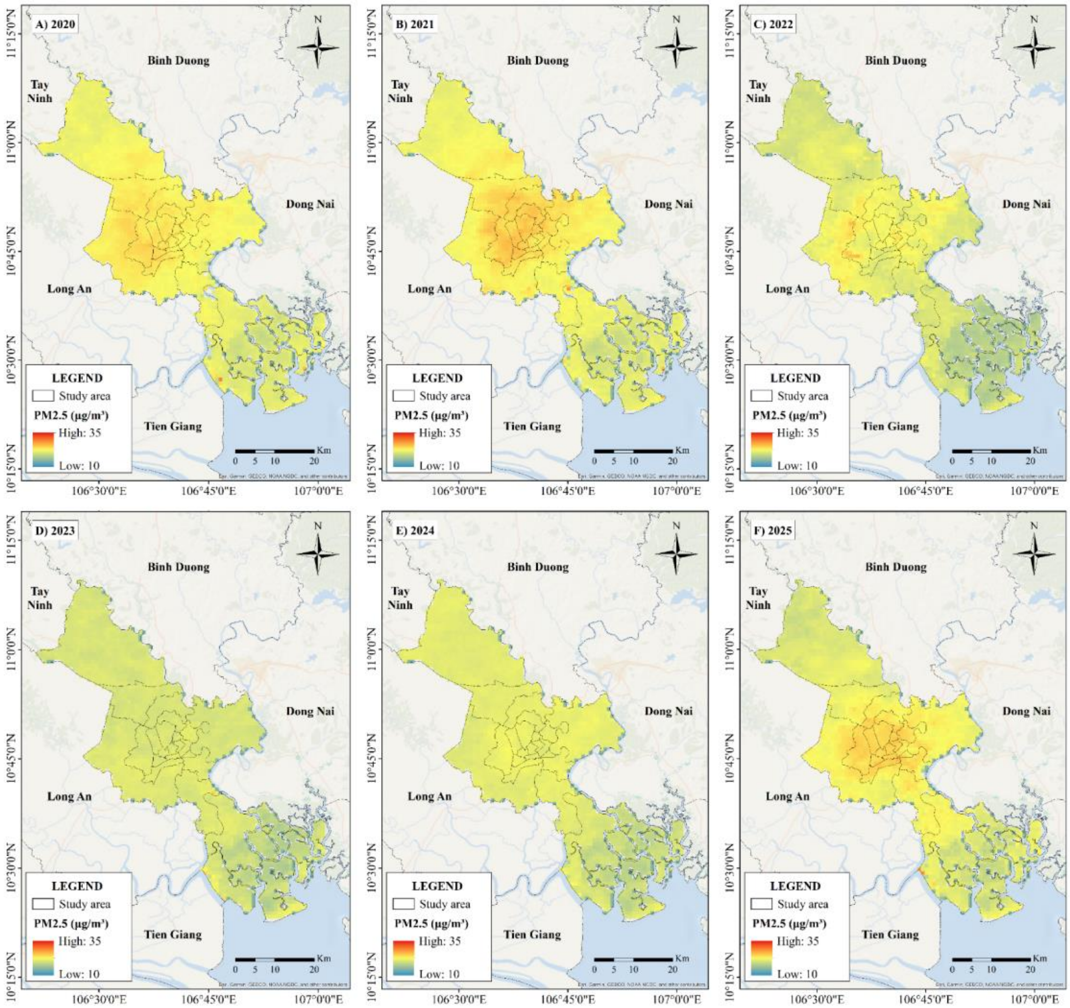

Figure 4. Distribution of $PM_{2.5}$ for each year during the 2020 - 2025 period

Areas with moderate pollution levels include District 12, Go Vap, Tan Phu, Hoc Mon, and portions of Thu Duc city, with $PM_{2.5}$ concentrations ranging from 18 to 22 µg/m³. Pollution in these suburban and transitional zones originates from traffic, light industry, and rapid urbanization, while also being influenced by transboundary transport of dust from industrial zones in Binh Duong province, driven by northeast winds [12], [18]. However, owing to the wide open spaces, abundant vegetation, and water surfaces, the air quality in these regions remains superior compared to the city center. This highlights the critical role of urban spatial structure and greenery coverage in mitigating $PM_{2.5}$ concentrations, despite the presence of significant emission sources.

The southeastern part of Ho Chi Minh city (Can Gio, Nha Be, District 7) records the lowest $PM_{2.5}$ concentrations, ranging from 15 to 18 µg/m³, due to lower population density, limited industrial activity, and fewer construction projects [12]. Can Gio District exhibits the cleanest air, as its extensive mangrove forest ecosystem acts as a natural sink to absorb particulate matter, while the dense river network and onshore sea breezes effectively facilitate dust dispersion. It should be noted that the $PM_{2.5}$ estimates in peripheral areas such as Cu Chi and Can Gio could not be directly validated due to the lack of ground monitoring stations. However, the spatial gradient, showing decreasing $PM_{2.5}$ concentrations from the urban core toward the outskirts, is consistent with the expected emission patterns where traffic density and industrial activities diminish. Additionally, the relatively homogeneous land-use characteristics in these areas - dominated by agriculture in Cu Chi; mangrove ecosystems in Can Gio - suggest lower spatial heterogeneity of $PM_{2.5}$ compared to the complex urban center.

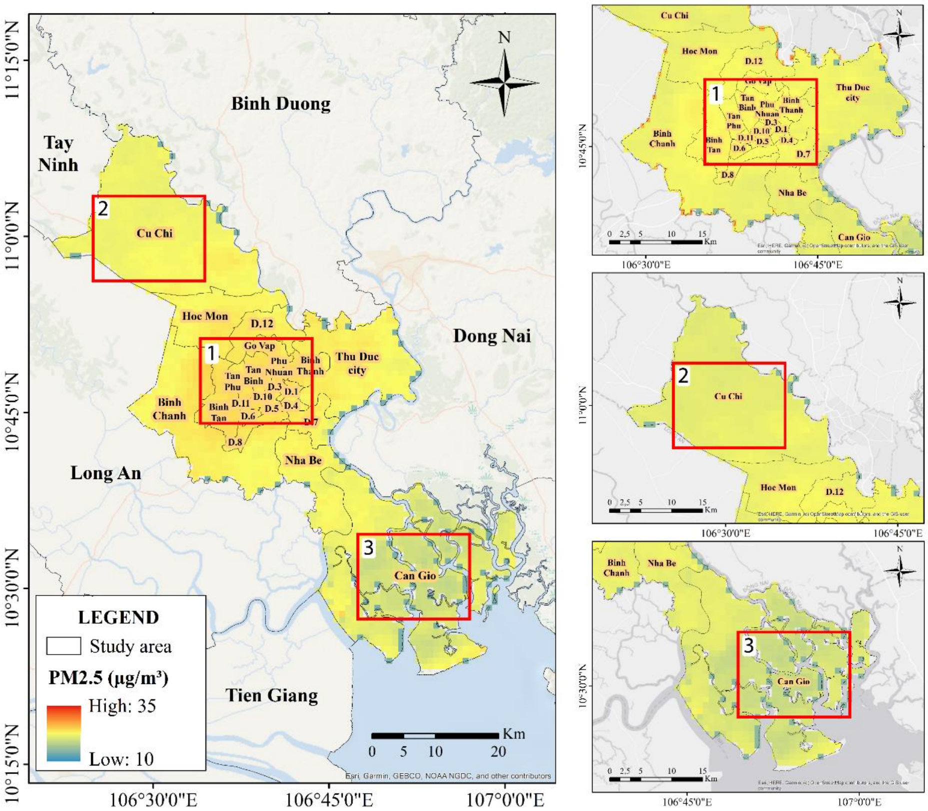

Figure 5. Spatial distribution of average $PM_{2.5}$ for the entire 2020 - 2025 period

2.4.3. The seasonal variations in $PM_{2.5}$ concentrations

The study results (Figure 6) indicate that $PM_{2.5}$ concentrations in Ho Chi Minh city are higher during the dry season, averaging 22.2 µg/m³, compared to 14.4 µg/m³ in the rainy season. The primary drivers for seasonal disparity stem from the interplay between meteorological factors and emission activities. Specifically, during the rainy season, frequent and heavy precipitation facilitates the removal of particulate matter through wet deposition. Additionally, high relative humidity and the prevailing southwest monsoon enhance the dilution and vertical dispersion of dust in the atmosphere [19], [20]. In contrast, the dry season is characterized by frequent nocturnal and early-morning temperature inversions, including atmospheric stability in the lower troposphere, which traps fine particles and prevents them from dispersing. Low relative humidity and stagnant wind speeds also prolong the residence time of $PM_{2.5}$ in the air. Beyond natural factors, the dry season coincides with intensified anthropogenic activities, such as biomass burning (crop residues and agricultural waste) in surrounding areas. Furthermore, traffic and construction activities are typically at their peak due to favorable weather conditions, further elevating $PM_{2.5}$ loading in the urban environment [21]. This demonstrates that the synergistic impact of adverse meteorological conditions and increased emission sources is the fundamental cause for the significant seasonal fluctuations in $PM_{2.5}$ concentrations in Ho Chi Minh city.

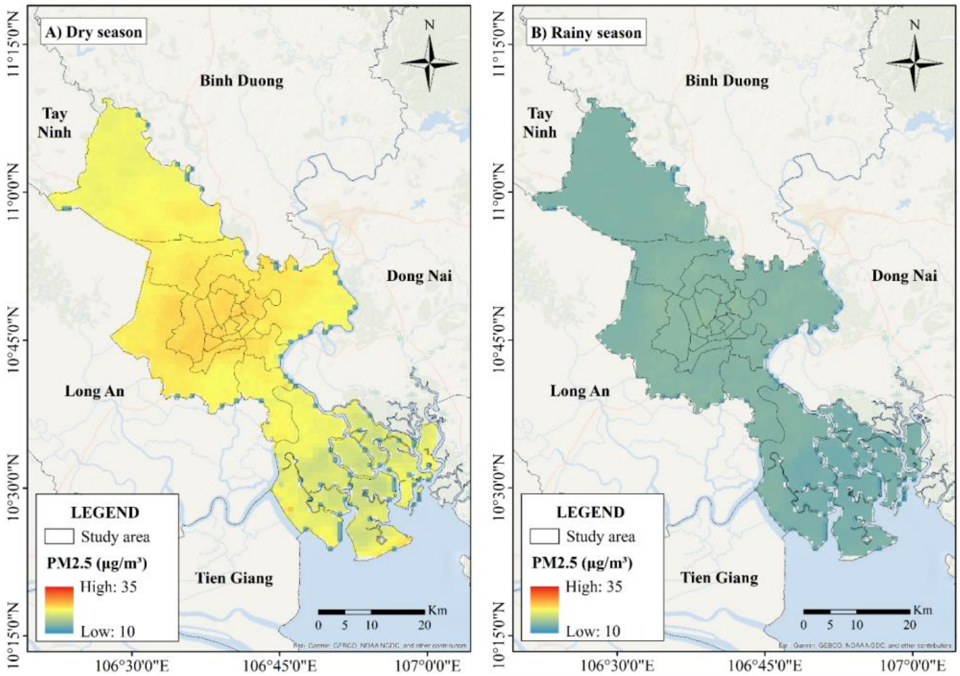

Figure 6. Spatial distribution of seasonally averaged $PM_{2.5}$ concentrations for the dry and rainy seasons over the period between 2020 and 2025

Observational data indicate that $PM_{2.5}$ concentrations in Ho Chi Minh city vary significantly by season, reflecting the typical characteristics of the region's tropical monsoon climate. Specifically, $PM_{2.5}$ levels reach their peak during the dry season and decrease markedly with the onset of the rainy season [18]. The primary drivers for this pattern stem from variations in meteorological and hydro-climatic factors such as precipitation, relative humidity, wind direction, and wind speed - coupled with the influence of socio-economic activities specific to each period.

Notably, the highest average monthly $PM_{2.5}$ concentration of 24.15 µg/m³ was recorded in April. This period coincides with the peak of the dry season, characterized by arid conditions , low precipitation, and high temperatures, which constrain vertical atmospheric mixing and hinder the dispersion of fine particulate matter. In addition, construction and infrastructure retrofitting activities typically intensify before the onset of the rainy season, generating significant fugitive dust from construction sites [18]. The months of January, February, March, and November, and December also record elevated $PM_{2.5}$ levels, primarily due to persistent dry climate conditions, low humidity, and high-volume traffic in the central urban areas. Furthermore, nocturnal and early-morning temperature inversion during the dry season causes the near-surface atmospheric layer to become "stable" or "trapped," preventing pollutant venting and leading to the localized accumulation of fine dust in the lower troposphere.

In contrast, the annual minimum $PM_{2.5}$ levels occur in June - the middle of the rainy season -with a concentration of 14.29 µg/m³. During this period, abundant precipitation promotes wet deposition, effectively scavenging fine particles from the atmosphere. Strong southwest monsoon winds also facilitate dispersion and dilution of particulate matter away from the urban area, significantly improving air quality [18]. Overall, the period from May to October, coinciding with the rainy season, records a marked decrease in $PM_{2.5}$ concentrations, highlighting the pivotal regulatory role of meteorological factors in modulating urban air quality [21]. This relationship underscores the importance of integrating meteorological variables into air pollution forecasting models and suggests that $PM_{2.5}$ mitigation policies should be dynamically designed to account for seasonal variations to achieve optimal effectiveness.

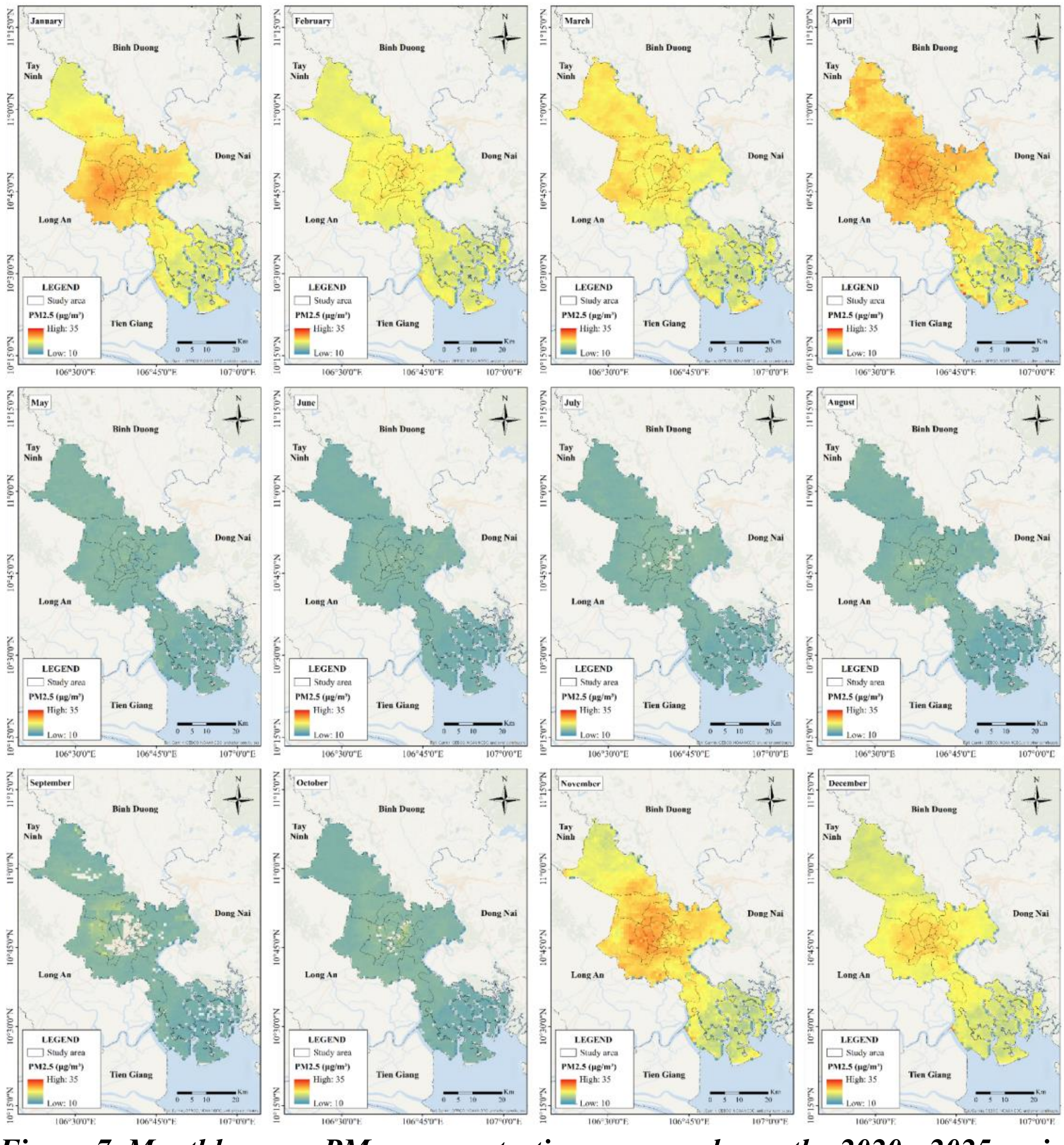

Figure 7. Monthly mean $PM_{2.5}$ concentrations averaged over the 2020 - 2025 period in Ho Chi Minh city

3. Conclusions

This study successfully established seasonal linear regression models between AOD and $PM_{2.5}$ concentrations for Ho Chi Minh city. The models achieved Pearson correlation (r) values of 0.78, 0.59, and 0.53, with corresponding RMSE values of 6.23, 1.71, and 7.84 µg/m³ for the dry season, rainy season, and annual period, respectively. The $PM_{2.5}$ spatial distribution maps revealed that $PM_{2.5}$ concentrations were highest in the central urban districts, ranging from 22 to 24 µg/m³, followed by northern peri-urban areas with moderate concentrations of 18 to 22 µg/m³, while the southern coastal region recorded the lowest levels of 15 to 18 µg/m³. Regarding seasonal variation, the average $PM_{2.5}$ concentration during the dry season reached 22.2 µg/m³, significantly higher than 14.4 µg/m³ observed in the rainy season. Monthly temporal analysis further indicated that April recorded the annual peak at 24.15 µg/m³, whereas June exhibited the annual minimum at 14.29 µg/m³.

Several limitations should be acknowledged in this study. First, the ground monitoring stations are disproportionately distributed, concentrated primarily in central urban areas. This spatial bias makes it challenging to directly validate $PM_{2.5}$ estimates in peripheral suburban regions such as Cu Chi and Can Gio. Although the observed spatial patterns aligned with expected emission characteristics, the absolute accuracy in these areas remains unverified without in-situ measurements. Second, persistent cloud contamination significantly constrained satellite data availability during the rainy season, which may affect the statistical robustness of the seasonal analysis. Third, the moderate correlation coefficients suggest that AOD data as a single predictor may not fully capture the complex spatio-temporal variability of $PM_{2.5}$.

Despite these limitations, this study demonstrates the potential of integrating MODIS-derived AOD data for $PM_{2.5}$ monitoring in data-scarce regions. Future research should incorporate auxiliary meteorological variables - such as relative humidity, boundary layer, and wind speed - as well as advanced machine algorithms to improve model predictive power. Additionally, expanding the ground monitoring network to suburban and rural sectors would enable more rigorous validation of satellite-derived $PM_{2.5}$ estimates. Overall, the findings provide a scientific foundation to support air quality management and sustainable urban environmental planning in Ho Chi Minh city.

REFERENCES

[1] Environmental Protection Agency (April 4, 2025), *Particulate Matter (PM) Basics*. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics.

[2] World Health Organization, (April 4, 2025), *More than 60 000 deaths in Viet Nam each year linked to air pollution*. https://www.who.int/vietnam/news/detail/02-05-2018-more-than-60-000-deaths-in-viet-nam-each-year-linked-to-air-pollution.

[3] Jabbar SA, Qadar LT, Ghafoor S, Rasheed L, Sarfraz Z, Sarfraz A, Sarfraz M, Felix M & Ojeda IC, (2022). Air quality, pollution and sustainability trends in South Asia: A population-based study. *Environmental Research and Public Health*, 19(12), 7534. DOI: 10.3390/ijerph19127534.

[4] Duong HH, Nguyen DTC, Nguyen LSP & To TH, (2018). Fine particulate matter ($PM_{2.5}$) in Ho Chi Minh city: Analysis of the status and the temporal variation based on the continuous data from 2013-2017. *Journal of Science and Technology Development*, 2(5), 130-137. DOI: 10.32508/stdjns.v2i5.788 (in Vietnamese).

[5] Tran ND, Nguyen NNT, Nguyen TV, Phan HTD, Nguyen DTA, Truong TTD & Dinh TG, (2021). Mortality and economic burden of $PM_{2.5}$ on cardiovascular disease in Ho Chi Minh city in 2018. *Vietnam Journal of Preventive Medicine*, 3(6), 9-18. DOI: 10.51403/0868-2836/2021/369 (in Vietnamese).

[6] Masroor K, Fanaei F, Yousefi S, Raeesi M, Abbaslou H, Shahsavani A & Hadei M, (2020). Spatial modelling of $PM_{2.5}$ concentrations in Tehran using Kriging and inverse distance weighting (IDW) methods. *Journal of Air Pollution and Health*, 5(2), 89-96. DOI: 10.18502/japh.v5i2.4237.

[7] Yang Q, Yuan Q, Yue L, Li T, Shen H & Zhang L, (2020). Mapping $PM_{2.5}$ concentration at sub-km level resolution: a dual-scale retrieval method. *ISPRS Journal of Photogrammetry and Remote Sensing*, 165, 140-151. DOI: 10.48550/arXiv.1907.03095.

[8] Tran QT, Nguyen PH & Dao NK, (2021). Evaluating the distribution of $PM_{2.5}$ in Ho Chi Minh city using remote sensing technology–some initial results. *Journal of Hydro-Meteorology*, 721, 80-91. DOI: 10.36335/VNJHM.2021(721).80-91 (in Vietnamese).

[9] The National Assembly Standing Committee, (2025). *Regarding the Arrangement of Provincial-Level Administrative Units,* p. 1-5 (in Vietnamese).

[10] Ho Chi Minh city Statistics Department, (April 4, 2025), *Socio-Economic Overview of Ho Chi Minh city in 2023*. https://thongkehochiminh.gso.gov.vn/Niengiam/2023/TONG%20QUAN%20KINH%20TE%20XA%20HOI.pdf (in Vietnamese).

[11] HCMC Central for Natural Resources and Environmental Monitoring, (April 4, 2025), *Current Status of Air Quality in Ho Chi Minh city*. http://hoiyhoctphcm.org.vn/wp-content/uploads/2018/10/NCL.pdf. (in Vietnamese).

[12] Rakholia R, Le Q, Vu HNK, Ho QB & Carbajo SR, (2022). AI-based air quality $PM_{2.5}$ forecasting models for developing countries: A case study of Ho Chi Minh city, Vietnam. *Urban Climate*, 46, 101315. DOI: 10.1016/j.uclim.2022.101315.

[13] National Aeronautics and Space Administration, (April 4, 2025), *Aerosol Optical Depth*. https://aeronet.gsfc.nasa.gov/new_web/Documents/Aerosol_Optical_Depth.pdf#:~:text=Aerosol%20Optical%20Depth%20%28AOD%29%20is%20the%20measure%20of,%28Earth%27s%20surface%29%20to%20the%20top%20of%20the%20atmosphere.

[14] Lyapustin A & Wang Y, (April 4, 2025), *MODIS Multi-Angle Implementation of Atmospheric Correct (MAIAC) Data User's Guide*. https://lpdaac.usgs.gov/documents/1500/MCD19_User_Guide_V61.pdf.

[15] Wilks DS, (2011). *Statistical Methods in the Atmospheric Sciences* (3rd ed.). Academic Press, p. 359.

[16] General Statistics Office, (2021). *Statistical yearbook of Vietnam 2021* Statistical Publishing House, p. 20. (in Vietnamese).

[17] Nguyen NL, (2022). Recovery and sustainable development of Vietnam's economy after COVID-19 from logistics viewpoints. *Hoa Binh University Journal of Science and Technology*, 6, 30-35 (in Vietnamese).

[18] Nguyen TH, (2023). Concentration evaluation of fine particulate matter ($PM_{2.5}$) in Ho Chi Minh city in 2021. *Journal of Hydro-Meteorology*, 751, 68-77. DOI: 10.36335/VNJHM.2023(751).68-77 (in Vietnamese).

[19] Pham DH, Pham DL & Nguyen VD, (2011). Air pollution episodes associated with East Asian winter monsoons. *Science of The Total Environment*, 409(23), 5063-5068. DOI: 10.1016/j.scitotenv.2011.08.049.

[20] Ly BT, Matsumi Y, Nakayama T, Sakamoto Y, Kajii Y & Nghiem TD, (2024). Characterizing $PM_{2.5}$ in Hanoi with New High Temporal Resolution Sensor. *Aerosol and Air Quality Research*, 18(9), 2487-2497. DOI: 10.4209/aaqr.2017.10.0435.

[21] Pham DH, Vuong TB, Ho CT, Dang DN & Le DV, (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(21), 3473-3484. DOI: 10.1016/S1352-2310(02)00295-9.