

Analysis on Temporal Pattern of Fine Particulate Matter (PM_{2.5}) in Hanoi, Vietnam and the Impact of Meteorological Conditions

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Abstract

Air quality is one of key issues to be addressed in the Vietnam environmental security strategy. As part of the strategy, this study investigates the temporal patterns of PM_{2.5} variations in Hanoi using data measured from January 2017 to December 2018. The loglinear regression is used to analyze how the meteorological factors affect the PM2.5 variations. The analysis indicates the seasonal, monthly and diurnal variations of PM_{2.5} concentrations. The lowest concentration level is found in the summer due to hot climatic conditions with strong winds and high solar radiation. The highest PM_{2.5} concentration is observed in winter as a result of stagnation. The concentration levels from 2:00 AM to 8:00 AM tend to be higher than other hours of the day while the downtrend is recorded from 11:00 AM to 7:00 PM and reaches the lowest levels of the day at 2:00 PM to 3:00 PM. The study results provide important information for government authorities, international and civil society organizations on when and why the PM2.5 concentration levels increase. This predictive analysis would be useful to develop early warning systems and to minimize the negative impacts of air pollution on public health.

Keywords

 $\mathrm{PM}_{2.5}$ Variations, Wind Speed, Temperature, Solar Radiation and Air Pressure

1. Introduction

Air pollution has been considered as the world's biggest environmental health

risk and the major cause of environmentally related deaths [1] [2]. The health impacts of air pollution are serious. The World Health Organization (WHO) found that the majority of air pollution related deaths are due to increased risks of stroke, heart disease, lung cancer, acute respiratory infections and chronic obstructive pulmonary diseases [1] [2]. WHO reported a total of around 7 million air pollution related premature deaths in 2012. Low and middle income countries in the South-East Asia and Western Pacific Regions are the worst affected countries [2].

Vietnam is among the top countries with the worst air pollution in the world, according to the annual Environmental Performance Index (EPI) report [3]. The air pollution was reported to reach unhealthy levels in major cities, especially the Capital city of Hanoi and Ho Chi Minh City [4]. It was pointed out that increased number of vehicles might have been the main contribution to the increased concentration levels [5]. Increased PM_{2.5} concentration level was thought to associate with the rise in the numbers of construction projects dust, vehicle emissions, smoke from manufacturing plants and factories [4] [6] [7] [8] [9]. Another reason is the problem of biomass burning in surrounding suburban area, especially dried rice stem burning during rice harvest seasons. Biomass burning events may have caused the rise in PM2.5 concentrations at some point in time [10] [11] [12].

Once the air pollutants are released, they are either suspended or dispersed in the air. Previous studies found seasonal, weekly and diurnal patterns of $PM_{2.5}$ concentration [11] [13] [14]. The concentration levels were found to be lower in summer and higher in winter [5] [11] [15] [16]. Ly *et al.* (2018) noted that June, 2016 and July 2017 had lower concentration levels as compared to December 2016. The PM_{2.5} concentration was also found higher around midnight than other times of the days [11].

Meteorological factors were considered to play an important role in increasing or decreasing $PM_{2.5}$ concentration. Although the impacts of between meteorological factors on the $PM_{2.5}$ levels have been studied in several countries, especially in China [17]-[24], there has been little research conducted to determine the impacts of meteorological factors on the atmospheric $PM_{2.5}$ levels in Hanoi, Vietnam. Hien *et al.*, (2002) pointed out that meteorological contributed to 60% - 70% of day-to-day variations of $PM_{2.5}$ levels during the moonsoon season. Thuy *et al.*, (2018) indicated the relationship between wind speed, wind direction, temperature, relative humidity, surface pressure, radiation and precipitation and mass concentration of $PM_{0.1}$, $PM_{2.5}$ and PM_{10} during the rice straw opens burning episode in 2015. However, these studies were conducted in a short period and focused on specific events during a year. The long-term effects of meteorological factors on the atmospheric $PM_{2.5}$ levels were not examined. The level of contribution of each meteorological factor to the variation of $PM_{2.5}$ concentration has not been explained.

Our research further studies the temporal patterns of $PM_{2.5}$ concentration; examines the relationship between meteorological factors and the variation of

 $PM_{2.5}$ concentration levels in Hanoi, Vietnam; and investigates the influence of these factors on the diurnal, monthly and seasonal variation of $PM_{2.5}$ concentration. The study seeks to provide governmental authorities with valuable information in order to develop early warning systems and to minimize the negative impacts of air pollution on public health.

2. Materials and Methods

Data used in this study was collected from the automatic monitoring stations (HORIBA) located on 556 Nguyen Van Cu street, Long Bien district, Hanoi of the Center for Environmental Monitoring (CEM), Vietnam Environment Administration (VEA). This is the only one out of seven stations providing real-time data with public access via <u>http://enviinfo.cem.gov.vn/</u> [25]. This monitoring station aims to monitor air quality on Nguyen Van Cu street, one of the busiest streets and the entrance to the Hanoi center with heavy traffic flow every day. The monitoring data is updated hourly. Data includes hourly measurement of $PM_{2.5}$ (µg/m³), wind speed (m/s), temperature (°C), air pressure (hPa) and solar radiation (W/m²). This is time series of hourly data collected from January 01, 2017 to December 31, 2018.

Regression models are used to examine temporal patterns of PM_{2.5} variation and identify factors that affect these patterns. The histogram by transformation was performed to determine appropriate regression models. The log transformation is the most suitable as it forms normal distribution and thus increases validity of the statistical analyses. This is a well-known method to deal with skewed data [26] [27].

The $PM_{2.5}$ variable is transformed using logarithmic transformation and used as the dependent variables in the Loglinear regression models. The Loglinear regression model is presented in the Equation (1):

$$\log Y = \infty + \beta X_i + \varepsilon_i \tag{1}$$

where *Y* is the PM_{2.5} concentration and X_i is the set of explanatory variables. The terms ∞, β and ε_i are constant, coefficients and error terms. The explanation for the relationship between response variable *Y* and an explanatory variable *x* is based on the elasticity or marginal effects estimated directly form the loglinear model.

If an explanatory variable is a continuous variable, an elasticity presents the percentage change in the response variable Y due to 1% change in that explanatory variable and a marginal effect measures change in the response variable Y due to a unit change in the explanatory variable x. Equations (2) and (3) show the calculation of elasticity and marginal effect for continuous variables.

Elasticity
$$(x_i) = \beta_i * \overline{x_i}$$
 (2)

Marginal effect
$$(x_i) = \beta_i * \overline{Y}$$
 (3)

In the case the explanatory variable is a dummy variable, an elasticity and a marginal effect respectively measure the percentage and absolute difference in $PM_{2.5}$ concentration level between subgroups of the explanatory variable *x* (see calculation in Equations (4) and (5)).

Elasticity
$$(x_i) = \exp(\beta_i) - 1$$
 (4)

Marginal effect
$$(x_i) = Y * \text{Elasticity}(x_i)$$
 (5)

All the statistical and regression models are performed by using the Stata software version 12 (StataCorp LP., College Station, TX, USA). The calculation of elasticity and marginal effect are performed by using Microsoft Excel 365 (Microsoft, Redmond, Washinton, USA).

3. Results and Discussions

3.1. Yearly, Seasonal, Monthly and Diurnal PM_{2.5} Variations

The regression results as presented in **Table 1** suggest that there exist yearly, seasonal and monthly variations. The analytical results in **Table 1** suggest that there was statistically different in PM_{2.5} concentration between 2017 and 2018. The mean PM_{2.5} was found 14.52% or 3.38 μ g/m³ lower in 2017 as compared to 2018. Given the stable settlement with little construction activities in Nguyen Van Cu street, this increasing trend is expected to be caused by increased number of vehicles on this street over the years as this is one of the main corridors entering the Hanoi center. Cohen *et al.* (2010) pointed out that automobiles and transport are major contributors to PM_{2.5} concentration in Hanoi.

Variables	Coef.	Elasticity	Marginal effects			
a: compared to 2018						
Year 2017	-0.1569***	-14.52	-3.83			
b: compared to Winter						
Spring	-0.2683***	-23.53	-7.65			
Summer	-0.4474***	-36.07	-11.73			
Autumn	-0.1714***	-15.75	-5.12			
c: compared to January						
February	-0.3615***	-30.33	-11.43			
March	-0.1478***	-13.74	-5.18			
April	-0.6096***	-45.64	-17.20			
May	-0.8760***	-58.36	-21.99			
June	-0.3739***	-31.19	-11.75			
July	-0.3898***	-32.28	-12.16			
August	-0.2531***	-22.36	-8.43			
September	-0.3071***	-26.44	-9.96			
October	-0.2821***	-24.58	-9.26			
November	-0.3051***	-26.29	-9.91			
December	-0.0177	-1.75	-0.66			

Table 1. Yearly, seasonal and monthly variations of PM_{2.5} concentration level.

The concentration level in Spring, Summer and Autumn is statistically different from the concentration level in Winter. Negative coefficients indicate that the concentration levels in these seasons are statistically lower than in Winter. This means that the concentration level is reported highest in Winter. The elasticity calculation indicates that summer has the lowest concentration level and is measured at 36.07% lower than Winter. It is followed by Spring and Autumn with the mean concentration level at 23.53% and 15.75% lower, respectively. This result agrees with observations from other studies [10] [11]. Ly *et al.* (2018) noted that there was seasonal variation in PM_{2.5} concentration with lower concentration found in summer by observing 2017 data monitored at the University of Science and Technology, Hanoi, Vietnam [11]. The study by Lasko *et al.* (2018) found severe air pollution in Winter period, during December 2013 and January 2014 [10].

The monthly analysis of $PM_{2.5}$ concentration shows that except December, all other months have statistically lower concentration levels as compared to January. This means that January and December are the months with highest $PM_{2.5}$ level. The concentration is found to be the lowest in May with 58.36% lower than in January. It is followed by April, July, June and February with 45.64%, 32.28%, 31.19% and 30.33% lower, respectively. The analyses on seasonal and monthly variations show the similar trend when Summer which includes June, July and August has lowest $PM_{2.5}$ level, followed by Spring which is characterized by March, April and May and then Autumn which contains September, October and November. These seasonal and monthly variations were also confirmed in studies in different areas in South East Asia and East Asia [5] [10] [11] [14] [28] [29].

The diurnal analysis suggests the variation of $PM_{2.5}$ concentration across different time of the day. Figure 1 indicates the concentration trend of $PM_{2.5}$ level from 0:00 to 11:00 PM. Higher concentration is found early in the morning from 0:00 AM till 8:00 AM before starting to decline until it reaches the lowest peak around 2:00 PM. The concentration then starts to increase again.



Figure 1. Diurnal variation of PM_{2.5} concentration levels.

By comparing the concentration level between different hours of the day and the level at 0:00 AM, the regression result in **Table 2** show that: 1) concentration at the time from 8:00 PM-11:00 PM, at 1:00 AM and from 9:00 AM-10:00 AM are not statistically significant difference from the concentration at 0:00 AM; 2) concentrations between 2:00 AM-8:00 AM tends to be higher than at 0:00 AM; and 3) concentrations between 11:00 AM and 6:00 PM appears to be lower than at 0:00 AM.

Taking the sample mean concentration of $PM_{2.5}$ at 0:00 AM as a benchmark, **Figure 2** shows the higher $PM_{2.5}$ concentration occurs between 2:00 AM and 8:00 AM and reaches the highest levels at 5:00 AM-6: 00 AM with measurements of 13.05% and 13.61% higher than the measurements at 0:00 AM. The calculation of marginal effects indicates that mean $PM_{2.5}$ at 6:00 AM is 3.65 µg/m³ higher than at 0:00 AM. The downtrend is recorded from 11:00 AM and reaches the lowest levels of the day at 2:00 PM-3:00 PM with 34.97% and 34.64% lower figures than at 0:00 AM. The lowest level of $PM_{2.5}$ is 11.28 µg/m³ less than it is at 0:00 AM. Although the concentration level from 4:00 PM-7:00 PM is still lower

Table 2. Diurnal variations of PM_{2.5} concentration level.

Variables	Coefficient	Elasticity (%)	Marginal effects (µg/m³)				
Compared to 0:00 AM							
1:00 AM	0.0706	7.31	2.36				
2:00 AM	0.0849*	8.86	2.86				
3:00 AM	0.0783*	8.14	2.63				
4:00 AM	0.0858*	8.96	2.89				
5:00 AM	0.1227**	13.05	4.21				
6:00 AM	0.1276***	13.61	4.39				
7:00 AM	0.0984**	10.34	3.34				
8:00 AM	0.1072**	11.31	3.65				
9:00 AM	0.0401	4.09	1.32				
10:00 AM	-0.0712	-6.87	-2.22				
11:00 AM	-0.1594***	-14.74	-4.75				
12:00 PM	-0.2611***	-22.98	-7.41				
1:00 PM	-0.3701***	-30.93	-9.98				
2:00 PM	-0.4303***	-34.97	-11.28				
3:00 PM	-0.4253***	-34.64	-11.18				
4:00 PM	-0.3822***	-31.76	-10.25				
5:00 PM	-0.3125***	-26.83	-8.66				
6:00 PM	-0.1985***	-18.00	-5.81				
7:00 PM	-0.0945*	-9.01	-2.91				
8:00 PM	-0.0566	-5.51	-1.78				
9:00 PM	-0.0468	-4.57	-1.47				
10:00 PM	-0.0324	-3.19	-1.03				
11:00 PM	-0.0388	-3.81	-1.23				



Figure 2. Statistical variations of PM_{2.5} concentrations at different hours as compared to at 0:00 am.

at 0:00 AM, it tends to increase gradually and is only 9.01% higher at 7:00 PM than at 0:00 AM. The concentration level was recorded with no statistical difference from 8:00 PM-1:00 AM.

The above analysis provided interesting information into the temporal patterns of PM2.5 concentration levels over time. It was pointed out that the increasing number of vehicles might have been the main contribution to the increased concentration levels, accounting for $40\% \pm 10\%$ [5]. Other sources included windblown soil windblown soil $(3.4 \pm 2)\%$, secondary sulfates (7.8 \pm 10)%, smoke from biomass burning (13 \pm 6)%, ferrous and cement industries (19 \pm 8)%, and coal combustion (17 \pm 7)% [5]. This study result is consistent with the study findings by Hai and Oanh (2013) [13]. They found peaks of PM mass in Hanoi during morning and evening rush hours by analyzing 4 h-samples. The rush hours start from 6:00 AM to 8:00 AM and from 5:00 PM to 7:00 PM that sees more vehicles on roads which cause traffic congestion.

The variation is also affected by long-range transport of particulate matter from other geographical areas due to rainfall and wind direction [30]. Heavy duty trucks transporting construction wastes and materials may also cause serious problems. Tran and Yanagida (2019) found operations of heavy-duty trucks generate higher dust emission and considered as a major stationary source of fugitive dust pollution [31]. Although there is unclear how emissions from cement plants, coal power plants, industrial zones and handicraft villages, etc. located within or surrounding Hanoi areas affect air quality in Hanoi. These activities are releasing paricles into the air every day. Meteorological factors have been found to play an essential role in affecting PM_{2.5} variation

3.2. Correlations between PM_{2.5} Concentrations and Meteorological Factors

The log-linear regression model is performed to examine the relationship between PM2.5 concentration level and meteorological factors, including air pressure, wind speed, temperature and solar radiation using hourly data of 2017 and 2018.

The regression results show statistical relationship between all the meteorological factors and $PM_{2.5}$ concentration level (**Table 3**). These factors, however, have different effects on the trend and magnitude of concentration. The results indicate positive relationship between air pressure and the concentration level, meaning that when air pressure increases, $PM_{2.5}$ tends to increase. Other three factors, including windspeed, temperature and solar radiation, show negative trend. This means $PM_{2.5}$ level increases when wind speed, temperature and solar radiation decrease and vice versa. The negative association between wind speed and $PM_{2.5}$ concentration levels was also found in the study by Thuy *et al.* (2018) [14]. It was pointed out that strong wind contributed to the dilution of pollution and therefore it reduced PM2.5 concentration in the air.

The turbulence of air as the result of interactions between these factors directly affects dispersion of air pollutants into the atmospheric boundary layer horizontally and vertically and become mixed with this layer [32]. This refers to mixing layer height which is also one of the key characterizing air polltution together with emission source, meteorological influences [32] [33]. Low wind speed and low mixing layer height were considered as the dominant factors contributing to high concentration of particulate matter in the air [34]. As noted by Haagenson (1979), mixing depth, ventilation, and the degree of stability significantly contribute to the daily variation of particles. Of which, pollutant diversion mostly depends on mixing depth and ventilation which are largely affected by meteorological conditions [35]. Week turbulence and radiative cooling at night lead contribute to the formation of stable boundary layer near the ground which results in higher PM_{2.5} concentration [32] [36] [37].

The results of elasticity and marginal effects estimates measured at the sample mean indicate how the meteorological factors affect the levels of $PM_{2.5}$ concentration. The elasticity results suggest that the $PM_{2.5}$ level will increase by 6.16% if air pressure increases by 1% (other factors remain constant). Also, for each 1% increase in one of the factors, wind speed, temperature and solar radiation (other factors remain constant), $PM_{2.5}$ concentration will decrease by 0.39%, 0.17% and 0.06%, respectively.

Table 3. Diurnal variations of PM_{2.5} concentration level.

Variables	Coefficient	Elasticity (%)	Mean	Min	Max	Marginal effects (µg/m³)
Air pressure (hPa)	0.0061***	6.16	1010.27	993.69	1032.10	0.18
Wind speed (m/s)	-0.2726***	-0.39	1.43	0.02	4.88	-8.19
Temperature (°C)	-0.0068***	-0.17	25.20	8.22	42.35	-0.20
Solar radiation (W/m ²)	-0.0005***	-0.06	125.20	0.90	985.65	-0.02

The marginal effects indicate that each unit increase in air pressure would result in 0.18 μ g/m³ increase of PM_{2.5} (other factors held constant). In case the air pressure increases from the mean value of 1010.27 to the max value of 1032.10, the PM_{2.5} level goes up by 3.93 μ g/m³. If wind speed increases by 1 m/s, the concentration level will decrease by 8.19 μ g/m³. In the case that wind reaches highest average speed of 4.88 m/s, PM_{2.5} can decrease by 28.26 μ g/m³. The decrease levels of 3.43 μ g/m³ and 17.21 μ g/m³ are reached when temperature and solar radiation go up to their max value of 42.35 Celsius degree and 985.65 W/m², respectively (other factors held constant). These factors have been determined to play important role in altering mixing layer height which lead to changes in particles concentration [38]. Increase in these factors results in increase mixing layer height and therefore reduce PM_{2.5} concentration on the ground level.

Table 4 presents analysis on the cross-correlations between meteorological factors. The result reveals that wind speed, temperature, solar radiation and air pressure are statistically related. Wind speed, temperature and solar radiation have a positive relationship with each other and that all three factors have an inverse relationship with air pressure. **Table 4** indicates strongest inverse relationship between air temperature and pressure with R = -0.8064 and followed by the positive relationship between temperature and solar radiation with R = 0.4228. Third is the relationship between wind and temperature with R = 0.3226.

The positive long-term cross-correlations between wind speed and solar radiation was also found in studies by Dos Anjos *et al.* (2015) [39] using 2004-2013 temporal series from Fernando de Noronha Island, Brazil and Jerez *et al.* (2013) [40] using hourly series data for the period 1959-2007 in the Iberian Peninsula. Solar radiation affects wind speed by heating soil and ocean which creates pressure and air convection movement. Wind speed, on the other hand, affects cloud coverage which has an impact on solar radiation [39]. High correlation between surface temperature, wind speed and air pressure was also found in the study by Wooten (2011) [41].

Combinations of meteorological conditions have different impacts to variations of $PM_{2.5}$ concentration. The positive relationship between wind speed, temperature and solar radiation means that higher temperature leads to higher wind speed and solar radiation. This phenomenon also leads to reduced air pressure. **Figure 3** shows the hourly measurements of wind speed, temperature,

 Table 4. Correlation between surface air pressure, wind speed, temperature and solar radiation.

	Air pressure	Wind speed	Temperature	Solar radiation
Air pressure (hPa)	1			
Wind speed (m/s)	-0.2673*	1		
Temperature (°C)	-0.8064*	0.3226*	1	
Solar radiation (W/m ²)	-0.1193*	0.1286*	0.4228*	1



Figure 3. Average hourly measurements of wind speed, temperature, air pressure and solar radiation in 2017-2018.

air pressure and solar radiation in 2017-2018. Declining wind speed from 0:00 AM to 7:0 AM in combination with low radiation and temperature mainly contributes to higher levels of $PM_{2.5}$ during this time period due to their negative correlations as analyzed in **Table 3**. Although the increasing trend in air pressure occurs during this time frames, its effect on $PM_{2.5}$ concentration is small as compared to other factors, especially wind speed and solar radiation. As a result, the concentration level often stays high in early morning. The rising trend of wind speed, solar radiation and temperature which starts from the morning and reaches the peak around 1:00 PM-3:00 PM is also consistent with the downward trend of $PM_{2.5}$ concentration (see **Figure 2**).

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3.3. Four Seasons and PM_{2.5} Variations

The Capital city of Hanoi, Vietnam is characterized by four seasons: Winter, Spring, Summer and Autumn. Each season has its own meteorological characteristics that make it distinguished from others. **Figure 4** describes the meteorological conditions in each season measured at data point location. It is noticeable that average wind speed, temperature and solar radiation are high during Summer. This condition probably leads to higher mixing layer height, resulting in low particle concentration in Summer. The positive relationship between wind speed and temperature and mixing layer height is also confirmed in the study by Soni *et al.* (2014). High solar radiation and wind speed may cause dust to spread widely in the air and be blown away by the wind which results in low suspended PM_{2.5}. Winter is characterized by low wind speed, temperature and solar and high air pressure as compared to other months. This combination of weather factors may keep fine particulate matter suspended in the air which leads to high concentration in low mixing layer height near the ground.



Figure 4. Average (a) Air pressure; (b) Wind speed; (c) Temperature; (d) Solar radiation by season.

This type of climate confirms the close relationship between meteorological factors and $PM_{2.5}$ concentration as analyzed in **Table 1** and **Table 3**. Hot climatic conditions with strong winds and solar radiation make $PM_{2.5}$ concentration during the Summer fall sharply compared to other seasons. The highest $PM_{2.5}$ level is reported in Winter. This season is characterized by higher air pressure but low temperature, wind speed and radiation. This combination of meteorological factors may keep fine particulate matter suspended in the air which lead to high concentration level.

Given distinguished meteorological conditions in each season, changes in meteorological factors can have different effects on $PM_{2.5}$ concentrations in each season. Table 5 present regression results about the correlation between meteorological conditions and $PM_{2.5}$ concentration in each season. The analytical results indicate statistically consistent negative effects of wind speed over all four seasons. Solar radiation also shows consistent trend in Winter, Summer and Autumn, except Spring where there is no statistical significance found. Air pressure is found to have positive relationship with $PM_{2.5}$ concentration in Winter, Spring and Autumn, but negative effects in Summer. Increasing temperatures tend to increase $PM_{2.5}$ levels in Winter and Autumn but the trend is opposite in Spring and Summer.

4. Conclusions

This study investigates the temporal patterns of $PM_{2.5}$ variations and how the meteorological factors, including wind speed, surface temperature, solar radiation and air pressure, affect these temporal patterns. The time series of hourly data was collected from the automatic monitoring stations (HORIBA) located on 556 Nguyen Van Cu street, Long Bien district, Hanoi of the Center for Environmental Monitoring (CEM), Vietnam Environment Administration (VEA) from January 01, 2017 to December 31, 2018. Loglinear regression models were performed for the analysis.

Variables	Winter	Spring	Summer	Autumn		
Air pressure						
Coef.	0.0351***	0.0126***	-0.0613***	0.0042		
Elasticity (%)	35.6334	12.7967	-61.4696	4.2664		
Marginal effect (µg/m ³)	1.2480	0.3383	-1.5434	0.1367		
Wind speed						
Coef.	-0.2613***	-0.1452***	-0.2343***	-0.2871***		
Elasticity (%)	-0.3220	-0.2402	-0.3841	-0.3522		
Marginal effect (µg/m ³)	-9.3045	-3.8905	-5.9034	-9.2697		
Temperature						
Coef.	0.0363***	-0.0265***	-0.0564***	0.0181***		
Elasticity (%)	0.7482	-0.5910	-1.6884	0.5102		
Marginal effect (µg/m³)	1.2941	-0.7101	-1.4203	0.5857		
Solar radiation						
Coef.	-0.0009***	0.0000	-0.0002**	-0.0007***		
Elasticity (%)	-0.0777	0.0018	-0.0319	-0.0996		
Marginal effect (µg/m ³)	-0.0317	0.0005	-0.0047	-0.0218		

Table 5. Correlation between meteorological factors to seasonal variations of PM_{2.5} level.

Note: * p < 0.05, ** p < 0.01, *** p < 0.001.

The regression results suggest that there were seasonal, monthly and diurnal variations of $PM_{2.5}$ concentrations. The seasonal analysis indicates that the concentration levels in Spring, Summer and Autumn were statistically negative correlated with the concentration levels in Winter. Summer has the lowest concentration level and is measured at 36.07% lower than Winter. The monthly analysis suggests that January and December are the months with highest $PM_{2.5}$ levels. The concentration was found the lowest in May with 58.36% lower than in January. It was followed by April, August, July and March respectively. The diurnal analysis finds that the concentration reaches the highest level around 5:00 AM-6: 00 AM and the lowest levels around 2:00 PM-3:00 PM.

Meteorological factors are found to statistically affect $PM_{2.5}$ concentration. Positive relationship is found between air pressure and the concentration level, meaning that when air pressure increases, $PM_{2.5}$ tends to increase. Other three factors, including windspeed, temperature and solar radiation, show negative trend. This means $PM_{2.5}$ level increases when wind speed, temperature and solar radiation decrease and vice versa. Analysis on the cross-correlations between meteorological factors and $PM_{2.5}$ variations reveals hot conditions with strong winds and solar radiation lead to low particulate matter while low wind speed in combination with low temperature, low solar radiation and high air pressure contributes to high concentration.

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Conflicts of Interest

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

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