



Statistical Analysis for Understanding PM_{2.5} Air Quality and the Impacts of COVID-19 Social Distancing in Several Provinces and Cities in Vietnam

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Abstract Air pollution, especially in urban regions, is receiving increasing attention in Vietnam. Consequently, this work aimed to study and analyze the air quality in several provinces and cities in the country focusing on PM_{2.5}. Moreover, the impacts of COVID-19 social distancing on the PM_{2.5} level were investigated. For this purpose, descriptive statistic, Box and Whisker plot, correlation matrix, temporal variation, and trend analysis were conducted. R-based program and the R package “openair” were employed for the calculations. Hourly PM_{2.5} data were obtained from 8 national air quality monitoring sites. The study results indicated that provinces and cities in the North experienced more PM_{2.5} pollution compared to the Central and South. PM_{2.5} concentrations at each monitoring site varied significantly. Among monitoring sites, the northern sites showed high PM_{2.5} correlations

with each other than the other sites. Seasonal variation was observed with high PM_{2.5} concentration in the dry season and low PM_{2.5} concentration in the wet season. PM_{2.5} concentration variation during the week was not so different. Diurnal variation showed that PM_{2.5} concentration rose at peak traffic hours and dropped in the afternoon. There was mainly a decreasing trend in PM_{2.5} concentration over the studied period. The COVID-19 pandemic has contributed to PM_{2.5} reduction. In the months implemented social distancing for preventing the epidemic, PM_{2.5} concentration declined but it would mostly increase in the following months. This study provided updated and valuable assessments of recent PM_{2.5} air quality in Vietnam.

Keywords Fine particulate matter · Air pollution · Statistical analysis · COVID-19 · Statistical software R

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1 Introduction

Air pollution occurs when the presence of substances in the atmosphere reaches concentrations that are adverse to human health and the environment (Ivanova, 2020; Shaltami et al., 2020). Air pollutants can be in solid, liquid, or gas form, and originate both from natural processes and anthropogenic processes. Natural air pollution comes from forest fires, wind erosion, volcanic eruptions, organic compound

evaporation, pollen dispersal, and natural radioactivity while anthropogenic air pollution is mostly related to fossil fuel burning, industrial processes, transportation, urban activities, agricultural activities, and waste disposal. Air pollution is a significant risk to human health. Short-term exposure to air pollutants is associated with chronic obstructive pulmonary disease, cough, breath shortness, wheezing, asthma, respiratory disease, and high rates of hospitalization. Exposure to air pollutants in the long term is related to chronic asthma, pulmonary insufficiency, cardiovascular mortality, and cardiovascular diseases (Manisalidis et al., 2020). Air pollution is also harming the environment. The environment is impacted by decreasing visibility and intercepting sunlight; producing acid rain and ozone depletion; disserving forests, agriculture, and wildlife; and inducing climate change (Kumar et al., 2022a).

Of all the pollutants in the atmosphere, particulate matter (PM) affects human health more than any other pollutants (Gurjar et al., 2010). PM exists in a complex composite of liquid and solid particles formed from inorganic and organic substances that are suspended in the atmosphere. PM contains mainly sulfates, carbon, ammonia, nitrates, mineral dust, sodium chloride, and water. There are primary PM and secondary PM. Primary PM is released directly from sources into the atmosphere. Sources of primary PM include road dust, agricultural activities, vehicle exhaust, wood burning, forest fires, construction, and industrial activities. Secondary PM is produced from chemical reactions of gases in the atmosphere. PM precursors can be nitrogen oxides, ammonia, and sulfur dioxide. PM is classified by size. The major kinds are total suspended particulate matter (TSP), PM whose aerodynamic diameter is equal to or less than 10 μm (PM_{10}), and PM whose aerodynamic diameter is equal to or less than 2.5 μm ($\text{PM}_{2.5}$). $\text{PM}_{2.5}$ is lighter compared to the others, thus, in the atmosphere, it stays longer and travels farther. In terms of human health, $\text{PM}_{2.5}$ is considered more unfavorable because, when people inbreathe it, it can reach the bronchiole periphery regions and intervene in the gas exchange in the lung (Ambade et al., 2021b; Gurjar et al., 2010; Pénard-Morand and Annesi-Maesano, 2004).

Vietnam is suffering from $\text{PM}_{2.5}$ pollution as a result of local activities and long-range pollutant transport (Nguyen et al., 2018). In 2021, Vietnam

was the third most polluted Southeast Asia country; the capital of Vietnam, Ha Noi, ranked 15 out of 107 among the world's most polluted capital cities based on the $\text{PM}_{2.5}$ level (IQAir, 2022). Based on the report of the Viet Nam Ministry of Natural Resources and Environment (MONRE) (2021), $\text{PM}_{2.5}$ ambient concentration in Vietnam varied from city to city. $\text{PM}_{2.5}$ pollution occurs regularly in major cities. One of the significant sources of $\text{PM}_{2.5}$ in Vietnam along with emissions from vehicles and factories is electricity generation, half of which came from coal-fired power plants in 2020 (IQAir, 2022). In response to $\text{PM}_{2.5}$ pollution, governments, organizations, and individuals have made numerous efforts to improve air quality and obtained initial results (Nguyen et al., 2018).

Since air pollution has become a problem, air quality monitoring is essential. The monitoring should last for a long period to capture various atmospheric conditions. These monitoring data need to be comprehensively analyzed for a better understanding of air quality. This information then can provide useful information for further air quality studies and air pollution control. Vietnam has monitoring networks that supply monitoring data on air quality. However, there are still limited studies that fully evaluated the $\text{PM}_{2.5}$ air quality status in Vietnam currently. A useful tool for exploring a large dataset of environmental data is a statistical technique as well known. For analyzing big data, tools in the form of computer programming are available. FORTRAN, C++, and R are some computer programming languages that are frequently used for calculation in science. Typically, R is a statistical computing language that provides more in-depth analysis (Agustine et al., 2017). R offers a diversity of statistical and graphical techniques and it has been assessed to be highly extensible. One R package called "openair" was developed to consist of certain functions specifically designed to perform air quality monitoring analysis (Carslaw, 2019; Carslaw and Ropkins, 2012). This tool helps the analysis of big air quality data more efficiently.

In addition, in recent years, the COVID-19 (coronavirus disease 2019) pandemic occurred and has had a decreasing effect on air pollution in some countries (Ambade et al., 2021a; Kumar et al., 2022b; Srivastava et al., 2020; Varotsos et al., 2021). Adjacent to China, Vietnam was one of the first countries affected by the epidemic. The country reported its first case of COVID-19 on January 23, 2020. Responding to this

urgency, the Vietnam government had taken a series of measures to prevent coronavirus outbreaks. Social distancing was implemented as an effective measure to prevent the spread of the pandemic before vaccines were available (Ngo et al., 2021). During the social distancing periods, solutions including residential area quarantine; closing of schools, shopping malls, restaurants, and fitness centers; travel restrictions; and restrictions on public gatherings, etc., were properly applied (Dang and Trinh, 2022; Nguyen et al., 2022). With the transportation and socio-economic activities restricted to limit the spread of COVID-19, it is of interest to assess the COVID-19 pandemic's impact on $PM_{2.5}$ air quality in Vietnam to investigate the trade-off between socio-economic activities and air quality.

Therefore, this study aimed to statistically analyze the $PM_{2.5}$ monitoring data in several provinces and cities in Vietnam in order to comprehensively understand $PM_{2.5}$ air pollution characteristics. In addition, the impacts of the COVID-19 pandemic on $PM_{2.5}$ levels were quantitatively investigated. The analysis included statistical characteristics, Box and Whisker plot, correlation matrix, temporal variation, and trend of $PM_{2.5}$ concentrations. R-based program and the R package "openair" was utilized as computational tools. The study might play an important role in providing up-to-date and valuable assessments of recent $PM_{2.5}$ air quality characteristics and trends in Vietnam. Moreover, the findings can contribute to the literature on the impacts of COVID-19 on air quality. Till now, some studies were conducted to characterize the air quality in Vietnam including $PM_{2.5}$ using different methods (Hien et al., 2019; Lasko et al., 2018; Tran et al., 2020). Recently, several studies investigated the impact of COVID-19 social isolation on air pollution in the country (Dang and Trinh, 2022; Ngo et al., 2021; Nguyen et al., 2022). Most of these previous studies focused only on the two biggest cities of the country and/or a short interesting period. This study was carried out in 8 provinces and cities in the period from 2019 to 2021 depending on the data available at the monitoring sites.

2 Methodology

2.1 Description of the Study Area

Vietnam is situated in Southeast Asia, bordering China to the North; Cambodia, and Laos to the West;

and the Eastern Sea to the East (Fig. 1). The country has an area of 331,698 km² extending from 8°27'N, 102°8'E to 23°23'N, 109°27'E with a population of 96.5 million as of 2019 (Nguyen et al., 2018; United Nations (UN), 2019). It has three main regions: the North, the Central, and the South. The climate is subtropical in the North and tropical in the Center and the South, and it is influenced by the southwest monsoon which is from May to October and the northeast monsoon which is from November to April. The southwest monsoon brings heavy rainfall into the North and the South, while along the Central, due to the protection of the mountains, it brings relatively less rain. The northeast monsoon is commonly drier; however, it accompanies heavy rains along the East coast in the first months and light but frequent rains in the North. The annual rainfall ranges from 1200 to 3000 mm with the rainfall happening mostly from May to October in the North and the South and from September to January in the Central (Irish Aid, 2017; Nguyen et al., 2018).

2.2 Monitoring Data

Monitoring had been carried out by the Northern Center for Environmental Monitoring (NCEM), Environmental Pollution Control Department, MONRE, using automatic monitoring systems. $PM_{2.5}$ was

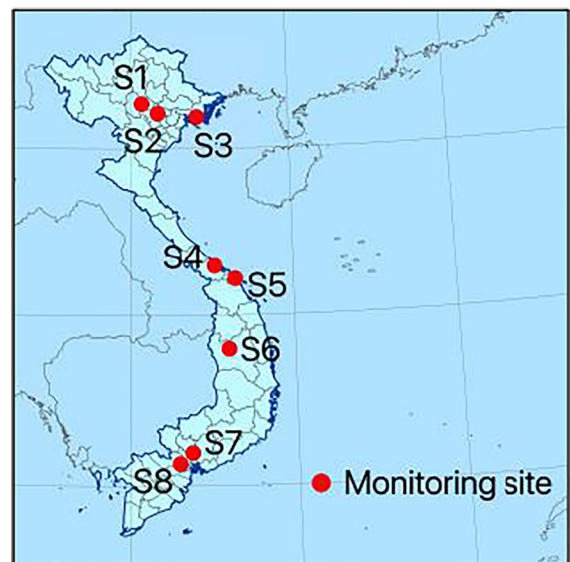


Fig. 1 Study area with monitoring site locations

measured by the GRIMM EDM 180. A measurable range is from 0.1 to above 1500 $\mu\text{g}/\text{m}^3$. The light-scattering technics is utilized for single-particle counts; hence, a semiconductor laser acts as the light source. The scattered signal from the particle transporting through the laser beam is gathered at about 90° by a mirror and conveyed to a receiving diode. After a comparable reinforcement, the signal of the diode crosses a multi-channel size classifier. After that, a pulse height analyzer categorizes the signal transferred in each channel. These counts can be displayed and are also stored in the data storage card (GRIMM, 2003). Hourly $\text{PM}_{2.5}$ concentration was computed from measurements taken each 5 min. Data from 8 mixed polluted urban NCEM sites were collected for the current study. Figure 1 presents the monitoring site locations. Three sites namely Phu Tho (S1), Ha Noi (S2), and Quang Ninh (S3) are located in the North. Hue (S4), Da Nang (S5), and Gia Lai (S6) are in the Central. The other two sites, Dong Nai (S7) and Long An (S8), belong to the South.

Quality control was applied to the raw monitoring data prior to further analysis in order to eliminate abnormal values caused during equipment calibrations, equipment failures, or other problems. Hourly values indicated as missing were set as invalid. Consecutive repeated values no less than 3 times were also set as invalid (Rohde and Muller, 2015). Unreasonable extreme values were removed using a variability check which was proposed by Fan et al. (2020). The method is as follows. For an observation (A) at time t over a monitoring site, the average (B) over the time window $[t - \Delta T/2, t + \Delta T/2]$ was calculated. If $A > 3B$ or $A < B/3$, observation A is set as an abnormal value and removed. Noted that ΔT is a time window width and was set as 4 h in this study. The method is similar to that employed by Rohde and Muller (2015) and Shi et al. (2018). The result of quality control excluded 1.11 % of the data. Table 1 shows the number of samples after the quality control together with the periods that the $\text{PM}_{2.5}$ data were available at each site.

2.3 Data Analysis

The statistical characteristic, spatio-temporal variation, and trend of the $\text{PM}_{2.5}$ concentrations at 8 monitoring sites were studied over a period that the data

Table 1 Information on monitoring sites

Site name	Site ID	Collected period	Number of sample
Phu Tho	S1	Jan 2019–Dec 2021	23,570
Ha Noi	S2	Jan 2019–Dec 2021	24,388
Quang Ninh	S3	May 2019–Mar 2021	15,365
Hue	S4	May 2019–Mar 2021	14,397
Da Nang	S5	Mar 2021–Dec 2021	5,696
Gia Lai	S6	Feb 2020–Dec 2021	15,483
Dong Nai	S7	Jul 2020–Dec 2021	7,579
Long An	S8	Jun 2021–Dec 2021	2,396

were available. For this purpose, several statistical analyses were utilized. Each is explained below.

Descriptive statistics which allow quantifying and describing a data set in an informative way were conducted. The lower quartile (25 %), median, average, and upper quartile (75 %) were calculated for characterizing the data. The coefficient of variation (CV) was used to estimate the dispersion in $\text{PM}_{2.5}$ concentrations around the average. CV is calculated by dividing the standard deviation by the average. Variation is classified as little variation if CV is lower than 20 %, moderate variation if CV is equal to or in between 20 and 50%, and high variation if CV is higher than 50 % (Ibe et al., 2020; Opara et al., 2016). Along with that, Box and Whisker plots were graphed to help in understanding the distribution of $\text{PM}_{2.5}$ concentration at each site. These calculations and Box and Whisker plots were conducted using a statistical R-based program.

A correlation matrix, which produces the relation between all data pairs, was carried out for detecting the associations of $\text{PM}_{2.5}$ concentration among monitoring sites. The correlation matrix is a row-by-column arrangement of a set of correlation coefficients. The correlation coefficients demonstrate the relationship between each pair of variables. In this study, Pearson product–moment correlation coefficient, the most popular correlation measure, was utilized. The coefficient is calculated using (Eq. (1)), where X_i and Y_i are values of two quantitative variables X and Y , \bar{X} and \bar{Y} are average values of X and Y , n is the number of pairs of observations, and the index i is over time series. The values of Pearson correlation coefficients are from -1 to $+1$. The larger the absolute

value shows the stronger association. The value of -1 or $+1$ describes a perfect correlation. The value of 0 means no relationship. A positive value indicates a positive or direct relationship while a negative value indicates a negative or inverse relationship (Hadd and Rodgers, 2021). The Pearson correlation coefficient is easy to compute; however, it can only reflect a linear correlation of variables and it is sensitive to outliers (Sobri et al., 2016).

$$R = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2 \sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (1)$$

The idea of a correlation matrix has been enhanced to help in visualizing correlations between variables by Friendly (2002) and Sarkar (2007). To obtain the visual correlation matrix, one function in the R package “openair” called “corPlot” was applied to hourly $PM_{2.5}$ data between the different monitoring sites. The input data was processed and then imported to the R program in the format of comma-separated value (csv). The data must include date-time and concentration data of $PM_{2.5}$. The function produces the plot which presents the relation coded by the number and the shape of ellipse or circle. The ellipse serves as a visual representation of a scatter plot. The circle indicates the zero relation. For a perfect positive relation, a line with a positive slope of 45 degrees is graphed. When there are a very large number of variables, the “corPlot” is a very valuable way to quickly obtain how variables are associated with each other.

Temporal variation, a variation in a time series, is one of the ways of describing air quality. In this study, variations of $PM_{2.5}$ concentrations by month, day of the week, and time of day were investigated. “TimeVariation” function included in the R package “openair” was utilized. The output of “TimeVariation” function shows graphs with the averages and the 95 % confidence intervals in the averages. The confidence interval was calculated through bootstrap resampling. The bootstrap is a data-based simulation method that involves plotting random samples from the original data repeatedly, with replacement. Sampling with replacement means that after an observation from the original sample is drawn randomly, it is placed back before drawing the next observation. The method provides better estimates than the application

of assumptions based on normality, particularly when there is a few data available. Furthermore, the monthly $PM_{2.5}$ variation graphs obtained from the “TimeVariation” function together with the monthly averages of $PM_{2.5}$ concentrations in each year at each monitoring site were employed to assess the impacts of COVID-19 social distancing on $PM_{2.5}$ air quality. The $PM_{2.5}$ concentration reductions in the context of COVID-19 social distancing were expressed as ratios of the monthly $PM_{2.5}$ concentration averages in months with COVID-19 social distancing to the monthly $PM_{2.5}$ concentration averages in the previous months or in the corresponding months of the previous years without COVID-19 social distancing. The $PM_{2.5}$ concentration returns after the context of COVID-19 social distancing were reflected as ratios of the monthly $PM_{2.5}$ concentration averages in the following months after the COVID-19 social distancing to the monthly $PM_{2.5}$ concentration averages in months with COVID-19 social distancing.

Trend analysis is a tool to understand the change in pollutant concentrations over time. In this study, $PM_{2.5}$ concentration trend was estimated using the Theil-Sen test (Sen, 1968; Theil, 1950). By employing this nonparametric test to a time series, any trend with significance can be found in the data. The method dates back to 1950 but needs the development of powerful computers to be feasible. The method is described as follows. Given a set of k pairs (M, N) , the slopes between all pairs of points (M, N) are calculated and the slope median (Eq. (2)) is chosen as Theil-Sen estimation.

$$\tilde{\beta}_k = \text{median}\{b_{u,v} = (N_u - N_v)/(M_u - M_v) : M_u \neq M_v, 1 \leq u < v \leq k\} \quad (2)$$

where (M_u, N_u) and (M_v, N_v) are two distinct points and $b_{u,v}$ is the slope between (M_u, N_u) and (M_v, N_v) . The advantages of the Theil-Sen method, as it is based on the median of the slopes, are its capacity in obtaining exact confidence intervals even with non-normal data and non-constant error variance and resisting outliers. These features can be significant in air pollution (Abdou, 2014; Carslaw, 2019). Theil-Sen slope was estimated by utilizing the “TheilSen” function contained in the “openair” package. In the package, the calculations can be more powerful through bootstrap resampling. Bootstrap resampling also produces p for the slope. The monthly average

PM_{2.5} values for the Theil-Sen test were calculated from collected hourly PM_{2.5} data. In addition, the study also examined how trends change with the wind direction because the effect of different sources is subjected to the wind direction. The Theil-Sen function divides the wind direction into 8 sectors namely, North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W), and Northwest (NW). The Theil-Sen slopes were then estimated for each direction alternately.

3 Results and Discussion

3.1 Spatial Variation of PM_{2.5} Concentrations

A statistical summary of PM_{2.5} concentrations recorded at 8 monitoring sites over the data collection period is shown in Table 2. Figure 2 presents the Box and Whisker plots together with average values of PM_{2.5} concentrations at each site by year. Overall, the average PM_{2.5} concentrations ranged from 2.48 to 28.73 µg/m³. It was in the order: Ha Noi (S2) >

Phu Tho (S1) > Dong Nai (S7) > Quang Ninh (S3) > Da Nang (S5) > Hue (S4) > Gia Lai (S6) > Long An (S8). It seemed that provinces and cities in the North have higher PM_{2.5} levels than those in the Central and the South in general. According to MONRE (2021), industrial zones in the North released more PM than those in the Central and South as indicated by PM levels measured around the industrial zones. In the North, there are still some old industrial zones with outdated technology, generating more pollutants. There are also many large-scale thermal power plants and cement manufacturers that consume a lot of fossil fuels, leading to large PM emissions in this region. Moreover, long-range transported PM_{2.5} contributed a larger amount to PM_{2.5} in the northern provinces, via the northeast monsoons, compared to the South (Hien et al., 2004; Nguyen et al., 2018).

The results also revealed that most monitoring sites had PM_{2.5} concentrations exceeding the World Health Organization (WHO) air quality guidelines for the annual PM_{2.5} level of 5 µg/m³ except Long An (S8). Noted that, PM_{2.5} concentration in Long An (S8) was captured mostly in the wet season (from May to

Table 2 Descriptive statistic parameters at monitoring sites

Site name	Site ID	25th, µg/m ³	Median, µg/m ³	Average, µg/m ³	75th, µg/m ³	CV, %
Phu Tho	S1	11.20	20.05	27.51	34.65	90.19
Ha Noi	S2	12.57	20.73	28.73	35.89	86.18
Quang Ninh	S3	9.45	16.45	20.37	26.59	74.93
Hue	S4	7.39	12.67	14.63	19.27	71.23
Da Nang	S5	9.42	14.98	18.04	23.86	67.67
Gia Lai	S6	5.22	9.07	12.76	15.64	101.57
Dong Nai	S7	13.37	20.78	21.53	27.24	49.55
Long An	S8	0.73	1.63	2.48	3.15	150.47

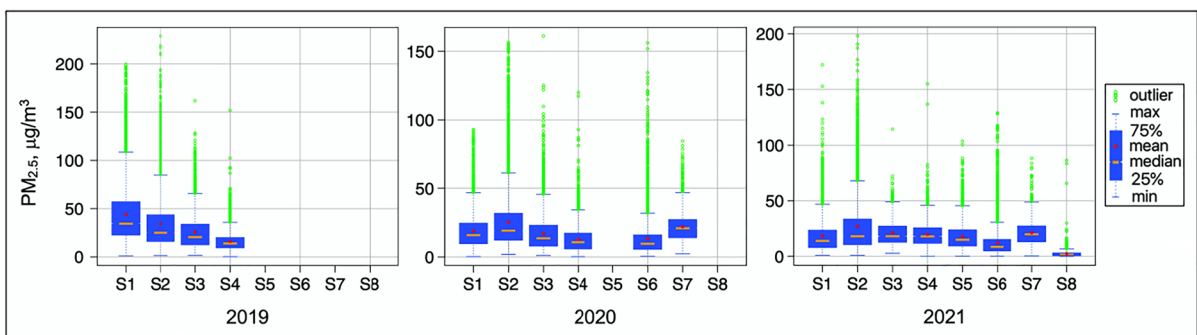


Fig. 2 Statistical characteristics of PM_{2.5} concentrations at the monitoring sites

October) when the $PM_{2.5}$ concentration is often low in the year. The exceeding of WHO air quality guidelines indicated the need for more effective policies to control $PM_{2.5}$ pollution in order to protect public health. Compared to the Viet Nam standard, in Ha Noi (S2), the annual $PM_{2.5}$ concentration was higher than the permitted limit of $25 \mu\text{g}/\text{m}^3$ by 1.36 times in 2019, and approximately equal to the limit in 2020 and 2021. The annual $PM_{2.5}$ concentration at Phu Tho (S1) was 1.72 times higher than the standard limit in 2019; however, it was lower than the standard limit in 2020 and 2021. Quang Ninh (S3) had the annual $PM_{2.5}$ concentration approximately equal to the standard limit in 2019 but lower than the standard limit in 2020 and 2021. The others had annual $PM_{2.5}$ concentrations lower than the national permitted limit.

Ha Noi (S2) suffered the highest $PM_{2.5}$ pollution among 8 monitoring sites. In Ha Noi, local $PM_{2.5}$ emissions mainly came from traffic, industry, construction, biomass burning, and coal combustion (Hai and Kim Oanh, 2013; Nguyen et al., 2018). The traditional farming practice of burning rice straws by farmers in suburban areas has also contributed to poor air quality. Nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) ($PM_{2.5}$ precursors) emissions from the industrial activities in Quang Ninh might have a significant impact on air quality in Ha Noi (Green Innovation and Development Centre (GreenID), 2018). In addition, Ha Noi has also been strongly affected by long-range transported pollution since it is located in the North as mentioned above. Hien et al. (2004) found that long-range transported $PM_{2.5}$ contributed 50, 34, and 33% to total $PM_{2.5}$ in Ha Noi with the northerly wind from October to December, the northeast monsoon over the East China Sea from January to March, and the southwest monsoon blowing through the Indochina Peninsula from May to July, respectively. Although overall $PM_{2.5}$ air quality in Ha Noi during 2019–2021 was considered unhealthy, there was some improvement when compared to 2017. As reported by GreenID (2018), the annual average $PM_{2.5}$ concentration in the city was $42.68 \mu\text{g}/\text{m}^3$ in 2017.

Dong Nai (S7) had a high $PM_{2.5}$ level among the monitoring sites located in the South. It was due to the rapid mechanical population increase and economic growth. Dong Nai ranked 5th in the population (3177.4 thousand persons) and 4th in monthly average income per capita (5621 thousand Viet Nam dong) in 2020 (General Statistics Office (GSO),

2021). The province is one of the leading industrial provinces with lots of industrial zones in the country. It is accompanied by a dense road system, often operating at high frequency, leading to large pollutants released into the environment (Nguyen et al., 2020).

The CV showed significant variations in $PM_{2.5}$ concentrations in all monitoring sites. The CV was in the order: Long An (S8) > Gia lai (S6) > Phu Tho (S1) > Ha Noi (S2) > Quang Ninh (S3) > Hue (S4) > Da Nang (S5) > Dong Nai (S7). These high variations implied the effects of diverse sources of $PM_{2.5}$ (Ibe et al., 2020). However, the complete assessments of $PM_{2.5}$ source contributions in these provinces and cities require more data and further research. Noted that the high variation of $PM_{2.5}$ concentrations at Long An (S8) should not be accounted for because of the low $PM_{2.5}$ values at this site.

Figure 3 provides the correlation coefficients of the hourly concentrations of $PM_{2.5}$ between all monitoring sites. The positive correlation coefficients between the sites namely, Phu Tho (S1), Ha Noi (S2), and Quang Ninh (S3), which are all situated in the North, were high compared to the others. This implied that meteorological conditions and emission sources, which were effectual across the regions, dominated the variations of $PM_{2.5}$ concentrations. The highest $PM_{2.5}$ correlation coefficient ($r = 0.66$) was between Ha Noi (S2) and Quang Ninh (S3).

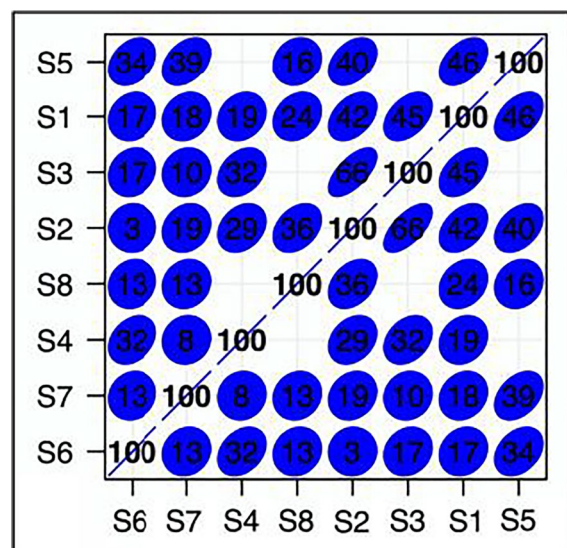
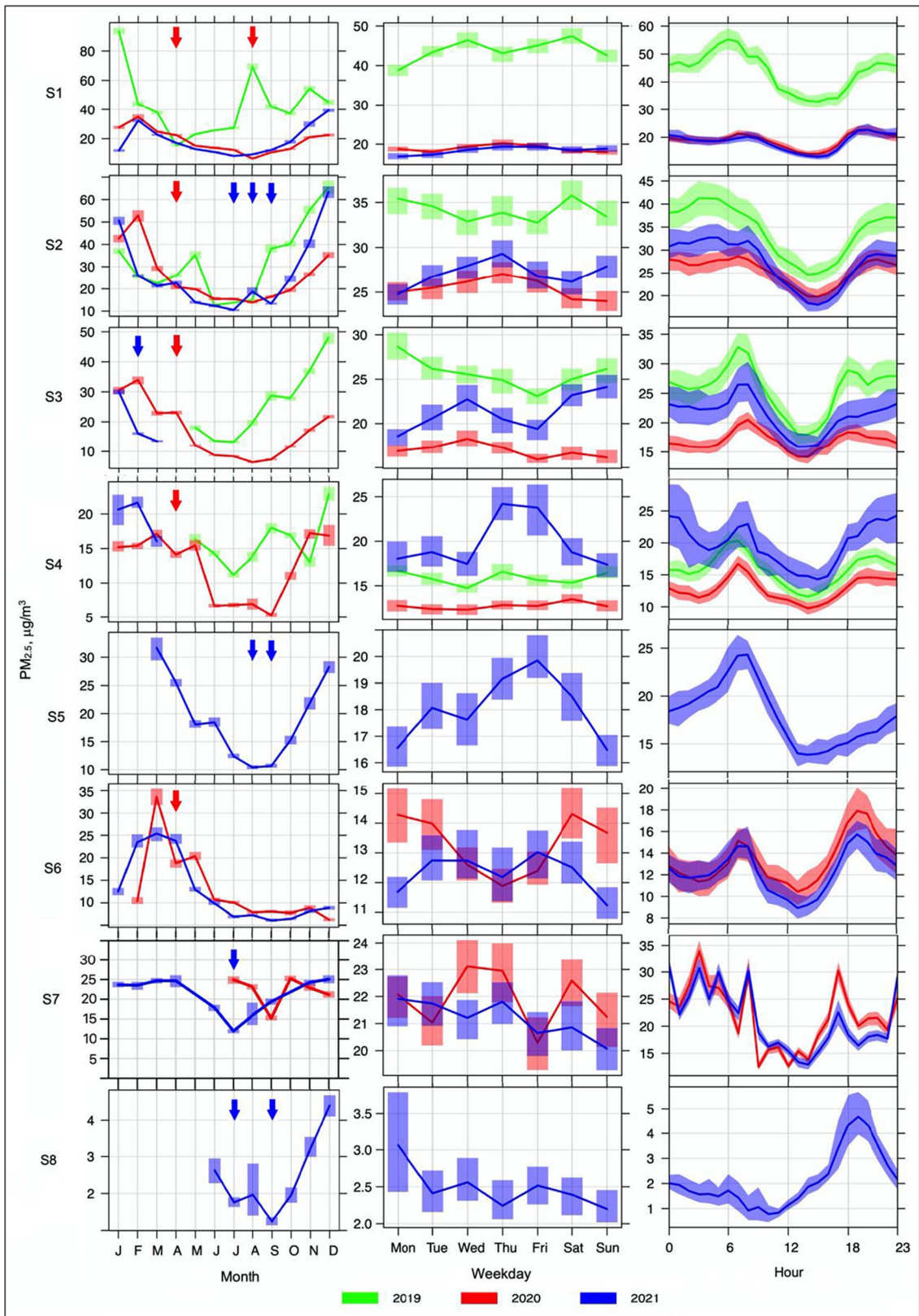


Fig. 3 Correlation matrix showing the $PM_{2.5}$ relationships among monitoring sites



◀**Fig. 4** Variation of $PM_{2.5}$ concentrations by month, day of the week, and time of day. Red arrows show months in which the social distancing was implemented in 2020; blue arrows show months in which the social distancing was implemented in 2021

Hue (S4) located in the Central was found to have positive $PM_{2.5}$ correlations with vicinity sites which were Ha Noi (S2), Quang Ninh (S3), and Gia Lai (S6). Da Nang is located nearby Hue but the $PM_{2.5}$ relationship could not exam due to the lack of corresponding monitoring data. Da Nang (S5) had positive $PM_{2.5}$ relations with most monitoring sites. Gia Lai (S6) had a higher positive $PM_{2.5}$ correlation with two neighboring sites, Hue (S4) and Da Nang (S5), in the North than those in the South. Dong Nai (S7) seemed to behave differently from most of the other sites. It showed the highest positive $PM_{2.5}$ relations with Da Nang (S5) located far away. Long An (S8) showed a $PM_{2.5}$ correlation with Ha Noi (S2) even though it is far from Ha Noi. These correlations might partly be contributed by the emission sources that have the same emission characteristics such as traffic.

3.2 Temporal Variation of $PM_{2.5}$ Concentrations

Temporal variations of $PM_{2.5}$ concentrations by month, day of the week, and time of day are presented in Fig. 4. The plots present the average lines and the shadings of the 95 % confidence intervals of the averages. The monthly $PM_{2.5}$ concentrations demonstrated seasonal variation in which $PM_{2.5}$ concentration was higher in the months of the dry season (from November to April), lower in the transition months, and lowest in the months of the wet season at monitoring sites located in the North and the Central. This variation in $PM_{2.5}$ concentrations was largely associated with the effect of meteorological factors. High precipitation during the wet season removed the particles producing low $PM_{2.5}$ concentration in the wet season. In addition, the low $PM_{2.5}$ level in the wet season was caused by the less long-range transported $PM_{2.5}$ from the North owing to the effect of the southwest monsoon in this season (Nguyen et al., 2018). The higher $PM_{2.5}$ concentration during the dry season was also attributed to the higher primary $PM_{2.5}$ emissions released from biomass burning in this season. Biomass burning was recognized as a significant emission source in the country (Nguyen et al., 2019).

Compared to monitoring sites in the North, monitoring sites in the Central showed less seasonal variation. Under the effect of the northeast monsoon, the Central received less long-range transported $PM_{2.5}$ than the North during the dry season. Moreover, the atmosphere got stagnant from October to March in the dry season contributing to high $PM_{2.5}$ concentration in the North (Nguyen et al., 2018). In the South, this seasonal trend was not observed in Dong Nai (S7) although southwesterly wind brought most of the total annual rainfall during the wet season. It suggested that the enhanced removal by the rainfall could not offset the high contribution of several emission sources. Rice straw biomass burning from the Mekong Delta area during this period was likely to largely contribute to $PM_{2.5}$ concentration in Dong Nai in the wet season. The Mekong Delta, located to the southwest of Dong Nai, is the largest hub for rice production in Viet Nam, contributing more than 50 % of the total production of the country. Biomass burning of crop residues is performed in June, September, and October in the delta, and the prevailing winds blow from the west and southwest in these periods (Hien et al., 2019). Besides, similar to the Central, the South receives less effect from the northeast monsoon than the North during the dry season, consequently, having less long-range transported $PM_{2.5}$ in this season. At the other southern site, Long An (S8), as monitoring data had only for the wet season, it was not enough for the assessment of seasonal variation.

Besides, in 2019, $PM_{2.5}$ concentration was particularly high in August at Phu Tho (S1) and in May at Ha Noi (S2) compared to the previous month and subsequent month. These results might be attributed to other influencing factors such as the local emission nearby the sites. High $PM_{2.5}$ concentration in May at Ha Noi also resulted from rice straw biomass burning in the areas surrounding Ha Noi. Ha Noi is situated in the center of the Red River Delta. The Delta is Vietnam's second largest rice-producing hub with over 35 % of the land dedicated to rice (Lasko et al., 2017). The two rice straw biomass burning periods in the delta were from May to June and from October to November. In September 2019, $PM_{2.5}$ concentration was strongly increased at Ha Noi (S2), Quang Ninh (S3), and Hue (S4) which indicated the same source that affected the $PM_{2.5}$ level at these sites. Further investigation is necessary for a deep understanding.

As indicated by Fig 4, $PM_{2.5}$ variation among weekdays was not much. The average CV showing differences in $PM_{2.5}$ concentrations among the days of the week was just only 4.91 %. The $PM_{2.5}$ level was mostly slightly high on Wednesday and slightly low on Sunday. Among monitoring sites, there were different variation patterns in $PM_{2.5}$ level by date which implied a difference in source contribution and source characteristics by date at each site. In addition, among the years, the weekly $PM_{2.5}$ patterns were also not similar within a monitoring site in general.

Diurnal variations of $PM_{2.5}$ concentrations showed that, in general, the $PM_{2.5}$ concentration increased and tended to get peak around 6:00–8:00, then reduced. The lowest $PM_{2.5}$ concentration was observed around 13:00–15:00. After that, it rose again, and the second peak was around 18:00–21:00. The pattern reflected the traffic impact. According to Nguyen et al. (2018), the $PM_{2.5}$ concentration increased during traffic rush hours in the morning (7:00–8:00) and afternoon (18:00–19:00) but was low at noon (13:00–14:00). Moreover, the peak in the morning was not only contributed by the traffic but also the increase in domestic activities. The $PM_{2.5}$ concentration decreased from the late morning partly due to the rise in the dilution and dispersion. The $PM_{2.5}$ concentration increased again in the late afternoon because vertical mixing became weak at this time and secondary $PM_{2.5}$ was formatted from its precursors. This diurnal variation pattern was not much different between weekdays and weekends; therefore, the plot separately for weekdays and weekends was not shown here.

This diurnal variation pattern was similar among monitoring sites since they were all highly impacted by traffic. Some notable points are discussed below. At Ha Noi (S2), higher $PM_{2.5}$ was clearly observed during the nighttime than that during the daytime. The reason might due to the stability of the atmosphere. It was also found by Zhang and Cao (2015). In the city, nocturnal radiation inversions and subsidence temperature inversions occur from October to December and January to March, respectively. During the inversions, $PM_{2.5}$ concentration was much enhanced at night (Hien et al., 2002; Nguyen et al., 2018). Long An (S8) had got an insignificant peak in the morning. One possibility can be given as follows. Besides the controls of temporal variation of emission and photochemical reactions, the diurnal variation of air pollutants is also impacted by vertical mixing

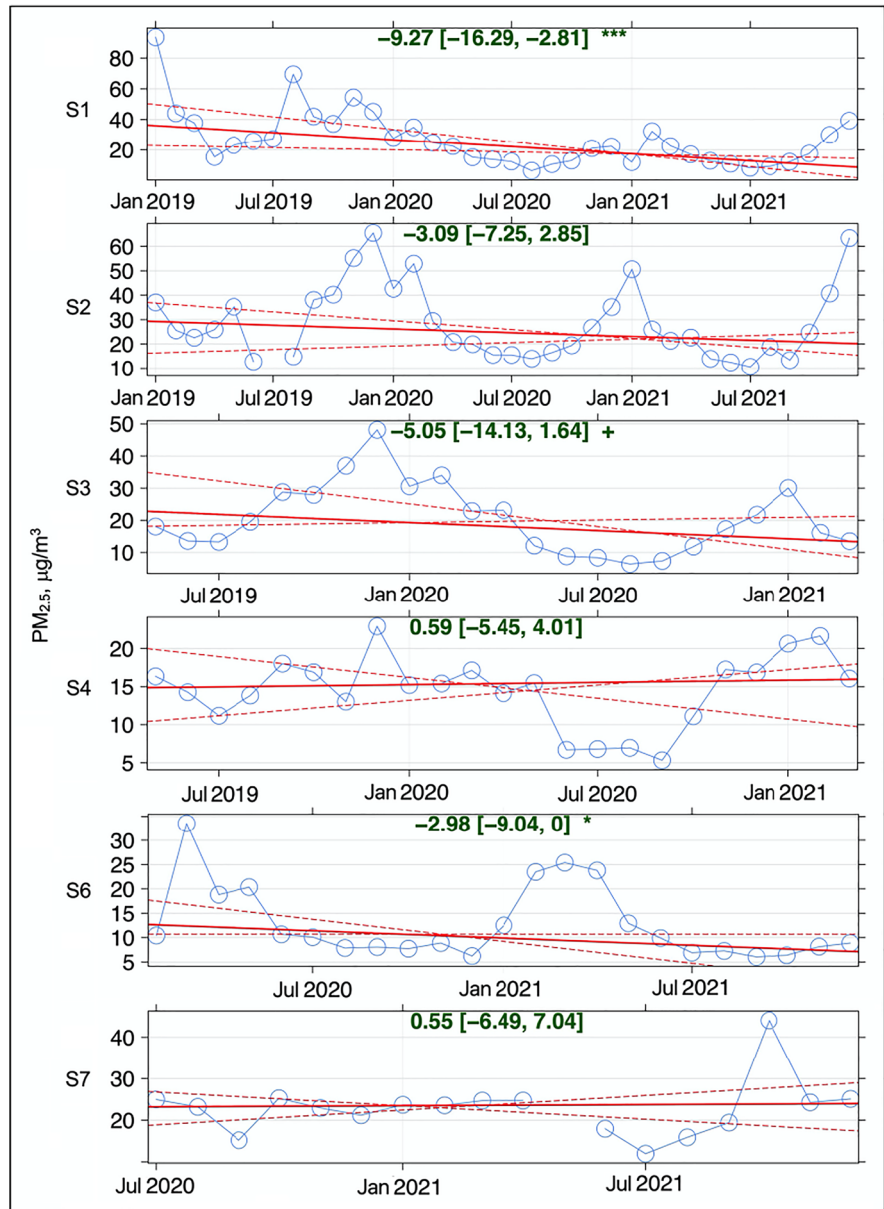
associated with the vertical temperature gradient and the mixing-layer height. The sudden growth of vertical mixing in the morning causes pollutant concentrations to decrease (Oleniacz and Gorzelnik, 2021).

3.3 Trend of $PM_{2.5}$ Concentrations

The plots together with the summary results of the $PM_{2.5}$ trend analysis at 8 monitoring sites are shown in Fig. 5. The monthly average concentrations of $PM_{2.5}$ are shown in blue circles. The solid red lines present the trend calculation and the dashed red lines present the 95 % confidence intervals for the trends derived from resampling methods. The overall trends and 95 % confidence intervals are shown in the green numbers at the top-middle expressed in $\mu\text{g}/\text{m}^3/\text{year}$. The symbols displayed next to each trend estimate number are associated with the statistical significance of the trend estimate: $p < 0.001 = ***$, $p < 0.01 = **$, $p < 0.05 = *$, and $p < 0.1 = +$. For example, the *** indicates that the trend is significant to the 0.001 level. It revealed that $PM_{2.5}$ concentration was reduced at all sites during the studied period except for Hue (S4) and Dong Nai (S7). The decreasing trend was in the order: Phu Tho (S1) > Quang Ninh (S3) > Ha Noi (S2) > Gia Lai (S6). Between two monitoring sites that had an increasing trend of $PM_{2.5}$, Hue (S4) showed a slightly higher increase in $PM_{2.5}$ concentration than Dong Nai (S7). Note that, the trends reported were calculated over a relatively short period and could be caused by a variety of different factors such as interannual variability in meteorology (Silver et al., 2018). Monitoring sites with collected data that were not enough for the whole year were excluded from this calculation.

For more understanding of the $PM_{2.5}$ trend, the output of trend analysis was split into 8 wind directions. The analysis indicated that $PM_{2.5}$ decrease at Phu Tho (S1) was captured for all wind directions but not for N and NE wind directions. In Ha Noi (S2), while the total $PM_{2.5}$ decreased, $PM_{2.5}$ for W and NE wind directions was found to increase. At Quang Ninh (S3), $PM_{2.5}$ reduced for the N wind direction but $PM_{2.5}$ increased in all other wind directions. In total, $PM_{2.5}$ decreased at this site. The $PM_{2.5}$ increasing trend in Hue (S4) and decreasing trend in Gia Lai (S6) were produced by all observed wind directions. Total $PM_{2.5}$ in Dong Nai (S7) was slightly increased as $PM_{2.5}$ increased in the E and SE wind directions.

Fig. 5 Trend of PM_{2.5} concentrations at monitoring sites



For the other wind directions, PM_{2.5} decreased. Further studies need to employ air quality models to completely evaluate the contribution of different drivers of the trends given here.

3.4 COVID-19 Social Distancing Impacts on PM_{2.5} Concentrations

Since 2020, the COVID-19 pandemic has begun to spread; socio-economic activities must be reduced or suspended to prevent the epidemic. Accordingly,

PM_{2.5} pollution was found to decrease. Compared to 2019, monthly average PM_{2.5} concentrations in the same months in 2020 and 2021 were mostly lower obviously (Fig. 4) at Phu Tho (S1), Ha Noi (S2), Quang Ninh (S3), and Hue (S4). At the other sites, the data for the year 2019 were not available so this comparison was not possible.

In January 2020, PM_{2.5} concentrations at Phu Tho (S1), Ha Noi (S2), Quang Ninh (S3), and Hue (S4) were lower than those in December 2019 and February 2020. As the COVID-19 epidemic first appeared

in Vietnam on January 23, 2020, the epidemic in the country was not one of the contribution to this decrease. However, at that time, in China, the first and major COVID-19 outbreak occurred. The reduction and suspension of socio-economic activities in China might contribute to a simultaneous decrease in long-range transported $PM_{2.5}$ at these northern sites. Compared to December 2019, the $PM_{2.5}$ concentrations in January 2020 decreased by 0.61, 0.65, 0.64, and 0.66 times; in February 2020, the concentration increased again by 1.26, 1.24, 1.11, and 1.01 times at Phu Tho (S1), Ha Noi (S2), Quang Ninh (S3), and Hue (S4), respectively.

From April 1 to April 22, 2020, national social distancing was implemented. Together, $PM_{2.5}$ concentrations dropped in this month and slightly increased again despite the decreasing trend caused by the influence of the season in May which was found at Hue (S4) and Gia Lai (S6). The $PM_{2.5}$ concentrations in April 2020 decreased by 0.82 and 0.56 times compared to March 2020 and increased again by 1.10 and 1.08 times in the next month at Hue (S4) and Gia Lai (S6), respectively. However, at the other sites, Phu Tho (S1), Ha Noi (S2), and Quang Ninh (S3), the $PM_{2.5}$ concentrations in April and May 2020 did not behave like that. The social distancing period did not show a significant decrease in these northern sites. It might be explained that the long-range transport mechanism has prevailed. In Ha Noi (S2), compared to April 2019, $PM_{2.5}$ concentration in April 2020 was lower by 0.8 times.

During other periods of social distancing at the regional, provincial or smaller scales, the $PM_{2.5}$ concentration changes were observed as follows. In Phu Tho, social distancing was implemented in two communes, Khai Xuan and Vo Lao, in August 2020. The $PM_{2.5}$ level in this month was low. It was lower than that in July 2020 by 0.52 times. In September 2020, $PM_{2.5}$ concentration increased again by 1.66 times. Compared to August 2019, it was lower by 0.09 times. Ha Noi implemented social distancing from July 24 to September 21, 2021, $PM_{2.5}$ concentration during this period was observed to be lower than that in the same month in 2019 and 2020 except August. Further investment needs to be carried out for understanding this high concentration in August 2021. $PM_{2.5}$ concentration in September 2021 was lower than those in September 2019 and September 2020 by 0.35 and 0.81 times,

respectively. After the social distancing period, the $PM_{2.5}$ concentration increased significantly. The $PM_{2.5}$ concentration during October – December 2021 was observed to be higher than that in 2020 by 1.59 times but this concentration was still lower than that in 2019 by 0.8 times. In Quang Ninh, from January 29 to February 23, 2021, there were social distancing and lockdown in several areas. $PM_{2.5}$ concentration was lower in February 2021 by 0.47 times compared to the same month in 2020 when no COVID-19 cases has been recorded in the province. Da Nang had social distancing started on July 31, 2021, and prolonged for almost 2 months. Together, $PM_{2.5}$ concentration in August and September 2021 was lower than that in July 2021 by 0.85 times. In October 2021, $PM_{2.5}$ concentration increased by 1.45 times compared to these 2 months. On July 19, 2021, 14-day social distancing was implemented in several southern provinces and cities including Dong Nai and Long An. Correspondingly, $PM_{2.5}$ concentrations in this month at Dong Nai (S6) and Long An (S7) were lower than those in June and August of 2021. $PM_{2.5}$ concentration was reduced by 0.67 and 0.67 times compared to June 2021 and increased by 1.33 and 1.12 times in August 2021 at Dong Nai (S7) and Long An (S8), respectively. In Dong Nai (S7), $PM_{2.5}$ concentration in July 2021 also decreased by 0.48 times compared to that in July 2020. At Long An (S8), $PM_{2.5}$ concentration was also low in September 2021. In this month, in Ben Luc district belonging to Long An, where the monitoring site is located, there was social distancing. The $PM_{2.5}$ concentration in this month was lower than that in August 2021 by 0.63 times; in October 2021, the concentration increased again by 1.57 times.

These results indicated that there were $PM_{2.5}$ concentration decreases during the periods of social distancing for preventing the COVID-19 epidemic. The social distancing provided researchers a chance to investigate the impacts of social-economic activities. Of course, there were many other factors related to emission and meteorology that affect $PM_{2.5}$ concentrations. After social distancing, in most cases, $PM_{2.5}$ concentration increased again. It was because people had been desperate to travel, and businesses tried to increase productivity to make up for losses. The results partly showed the impacts of the COVID-19 social distancing on $PM_{2.5}$ air pollution.

4 Conclusion

To enhance the understanding of $PM_{2.5}$ air quality feature in Viet Nam, the analysis of $PM_{2.5}$ monitoring data at 8 monitoring sites in 8 provinces and cities was carried out based on statistical methods and plots. Descriptive statistic, correlation matrix, temporal variation, and trend of $PM_{2.5}$ concentrations were studied by using R-based program and the R package “openair.” The study results provided updated knowledge about $PM_{2.5}$ air quality characteristics in Viet Nam. It provided a sound scientific basis for doing further air quality research and seeking appropriate solutions in air quality management.

As shown by the analysis, $PM_{2.5}$ pollution was generally high when compared to WHO air quality guidelines except for Long An (S8). Two out of eight monitoring sites had the annual $PM_{2.5}$ concentration excess Vietnam standard in 2019. In 2020 and 2021, the $PM_{2.5}$ concentrations at all monitoring sites were approximately equal to or lower than the standard limit value. Provinces and cities in the North mostly suffered higher $PM_{2.5}$ levels than those in the Central and the South attributed to higher industrial emissions and larger long-range $PM_{2.5}$ transportation from the North and Northeast via the northeast monsoons. Ha Noi (S2) was found to have the highest $PM_{2.5}$ pollution among 8 monitoring sites; however, this $PM_{2.5}$ level in the city was lower compared to 2017. Located in the South, Dong Nai (S7) had high $PM_{2.5}$ concentrations mostly coming from local industrial activities, transportation, and the dense population. Among the monitoring sites, the northern sites showed high correlations with each other; Dong Nai (S7) showed less correlation with the other sites.

Monthly $PM_{2.5}$ concentrations indicated a seasonal variation, with a lower $PM_{2.5}$ concentration in the wet season and a higher $PM_{2.5}$ concentration in the dry season mostly attributed to the decreasing effect of precipitation during the wet season and the increasing effect of long-range $PM_{2.5}$ transportation from the North and Northeast during the dry season. It was also because of the higher primary $PM_{2.5}$ emission from biomass burning in the dry season. Monitoring sites in the Central showed less seasonal variation than that in the North. In the South, this seasonal variation was not found in Dong Nai (S7). The variation of $PM_{2.5}$ concentrations by day of the week was not too much. Typically, Wednesday had higher $PM_{2.5}$

concentrations and Sunday had lower $PM_{2.5}$ concentrations within a week. Most diurnal variations of $PM_{2.5}$ concentrations showed $PM_{2.5}$ increases at rush hours and $PM_{2.5}$ decreases in the afternoon on both weekdays and weekends.

The Theil-Sen slope mostly indicated a reduction in $PM_{2.5}$ concentration except for Hue (S4) and Dong Nai (S7). Phu Tho (S1) was observed to have the strongest decline trend among monitoring sites. The $PM_{2.5}$ decrease reflected the success of Vietnam actions in air quality management. The $PM_{2.5}$ decrease was also owing to the COVID-19 pandemic. Compared to the year 2019, monthly $PM_{2.5}$ concentrations in the same month in the year 2020 and 2021 were mostly lower obviously. During social distancing, the limit of socio-economic activities took part in the $PM_{2.5}$ concentration decrease. However, after the social distancing periods, the $PM_{2.5}$ concentration increased. This increase in $PM_{2.5}$ level was more significant in big provinces and cities.

As shown by $PM_{2.5}$ characteristic analysis results, $PM_{2.5}$ pollution management still remains insufficient in Vietnam. Further measures for air pollution mitigation are required in order to obtain better air quality, especially in the North of Viet Nam. Stronger emission control actions are crucial for industries with a focus on high-emission manufacturing. Clean technologies should be promoted. Air pollution from biomass burning of crop residue is required to be controlled by appropriate solutions. In addition, currently, some monitoring sites provide incomplete data due to interrupted operations. Hence, additional funding and technical support are essential for the monitoring sites to operate properly. Besides, monitoring networks need to be installed widely. Having more and better data allows a comprehensive analysis of $PM_{2.5}$ status across the country.

With respect to future research, for effective air pollution control and management, it is necessary to have more studies to evaluate the contributions of individual emission sources to air quality and define the main pollution causes. A more detailed analysis of PM components and the use of receptor modeling for source apportionment is recommended. An adequate emission inventory should be developed in the near future. More research applying air quality models is needed to fully assess the air quality situation, forecast air pollution, and develop air pollution control plans. Moreover, the $PM_{2.5}$ seasonal variation found

by the study indicated the strong impact of meteorology on PM_{2.5} concentration. Therefore, research investing in the relation between PM_{2.5} concentration and meteorology should be conducted to deeply understand the PM_{2.5} in the atmosphere. Studies with multi-approaches would develop a greater scientific understanding and provide holistic information toward reasonable air quality management.

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Data Availability The authors do not have permission to share data.

Declarations

Competing Interests The authors declare no competing interests.

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