Impact of Particulate Matter 2.5 During Covid-19 in Bangkok, Thailand

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Abstract

Bangkok is a large city with severe Particulate Matter 2.5 (PM2.5) and traffic congestion problem. In past decades, traffic was the main cause of PM2.5. Due to the Covid-19 pandemic in 2020, Bangkok was in lockdown which substantially decreased traffic volume during that period. In this research, the author studied how this change in Bangkok's traffic volume affected the concentration of pollution, especially PM2.5. Data were collected from 63 points in Bangkok and on 4 highways during January 2018 to December 2023. The analysis showed that during the lockdown period, the concentrations of PM2.5, NOX, NO2, NO and CO decreased by 14.38%, 12.93%, 18.43%, 2.65% and 5.66%, respectively, while traffic volume decreased by about 40%. However, there was no significant relationship between the concentration of PM2.5 and the decreased traffic volume. Therefore, the results indicated that while the Covid-19 pandemic might have influenced the change in traffic volume, it was not the main cause because the effect of season on PM2.5 outweighed the impact of traffic volume.

Keywords: Traffic; PM2.5; Covid-19 pandemic; Bangkok; Thailand

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1. Introduction

The US EPA (United States Environmental Protection Agency) [1] has set a standard for small particles which are harmful to human health based on a particulate matter (PM) rating. For example, PM10 or coarse particles defines the small particles found in dust and smoke, which have a diameter in the range 2.5–10 microns that can be clearly seen. However, PM2.5, or fine particles, are tiny, having a diameter of 2.5 microns and below.

There is substantial evidence and many studies all over the world that have shown that traffic is the main factor contributing to PM2.5 [2]–[7]. Currently, PM2.5 pollution has become a severe problem in Thailand, especially in metropolitan areas, such as Bangkok, Chiangmai, Chiang Rai and Lampang [8], [9]. In addition, extreme traffic congestion in Thailand is still a concern, with Bangkok having consistently bad traffic jams over a long period [10], [11]. From the beginning of 2020, the Covid-19 pandemic changed people's behavior. In many countries, cities were locked down to reduce the opportunities for the virus to spread, which catalyzed online learning and working from home. This lockdown policy not only had economic impacts but also restricted activities in communities, such as major reductions in traveling and changing the mode of transportation in many countries [12]–[14]. In particular, on Bangkok's highway, during the worst of the Covid-19 period, traffic volume decreased by about 40% and the number of people using public transportation fell by 50% [15], [16]. Authors questioned the relationship between the decrease in traveling and air pollution.

The current research separated statistical data 2015 and 2021 into 2 periods, with the first set the Covid-19 pandemic (from 2015 to 2019) and second during the pandemic (2020 to 2021) [17]. Statistical methods were was applied to compare the data in same the period range [16] as well as to study how traffic volume and air pollution were related, especially the impact of the PM2.5 concentration level on changing traffic volume.

2. Other Studies

Particulate matter is made up of particles (tiny pieces) of solids or liquids that are in the air. It may include dust, dirt, soot, smoke and drops of liquid (aerosols). It may occur from natural sources, such as dust and pollen, but also can arise from human activities, such as industrial processes, working machinery (including internal combustion engines), electrical generation processes, and construction, mining and agricultural activity [18]–[20], lead to the release of PM2.5 material into the atmosphere that is sourced from releasing elementary particles and changes in initial substances, such as SO2, NOX, VOCs and NH3 in the primary releasing stage [21]–[24]. In addition, PM2.5 material can include not only toxic but also long-lasting components that continue to pollute the environment. Furthermore, PM2.5 can travel long distances due to atmospheric circulation. In summary, the combination of these factors makes PM2.5 material extremely harmful to human health [25], [26].

2.1 PM2.5 in Thailand

The Pollution Control Department has estimated that the number of deaths in Thailand caused by PM2.5 may have reached 22,000 in 2021 [27] as the Thailand air quality index (AQI) from the beginning of 2021 [28], including the concentration level of PM2.5 was exceedingly high. Main factors influencing the level of PM2.5 are human activities especially from transportation—smoke from exhaust pipes and emissions from the incomplete combustion of gases in the engine—which were the main sources of PM2.5 in Bangkok, Chiang Mai and Khon Kaen [9].

In addition, high density traffic results in high PM2.5 levels. Thailand was ranked fifth in the Asian region after Indonesia, Myanmar, Vietnam, and Laos, respectively [8]. In 2021, Lampang had the highest level of PM2.5 in Thailand. PM2.5 levels in Thailand are heavily influenced by dust and air pollution related to seasonal activities, especially in the Chiang Mai river basin due to particles from burning agricultural waste to prepare for the next rice harvest in the subsequent rainy season. These agricultural areas are in valleys where the landscape is suitable for PM2.5 accumulation [29]. The PM2.5 problem is especially bad during the dry season in northern rural areas, such as Chiang Mai, Lampang and Nan provinces, where the [pollution seems to have become increasingly severe in recent times [30], [31]. Research studies on the causes of PM 2.5 in community areas, such as Bangkok, found there were higher levels of PM2.5 in the dry season compared to the wet season. The most common sources of PM2.5 emissions in Bangkok are biomass combustion and traffic, and industrial activities, with varying concentrations based on seasonal factors [32]–[34]. A study on pollutant concentrations for O3, NOX, CO and SO2 from 1996 to 2009 in Bangkok reported that for residential area and roadside locations, the winter air pollution concentrations were higher than in summer and rainy seasons, with the roadside areas having higher levels than the residential areas in Bangkok [35].

2.2 Transportation and PM2.5

Road transportation is a source of pollutants, such as O3 CO, NOX, and NMVOC, along with the greenhouse gases (CO2, CH4 and N2O), acidic substances (NH3 and SO2) and carcinogens (polycyclic aromatic hydrocarbons (PAHs) and Persistent organic pollutants (POPs)) as well as toxic heavy metals [36]. Over past period, transportation and travel-related activity were the main cause of PM 2.5 in urban areas. A study in China on the impacts of freight transport on PM2.5 concentrations showed that switching the mode of goods transportation from road freight to sea freight helped to significantly reduce the PM2.5 level in rural areas [37]. Another research study on alternative transport options in Adelaide, South Australia using modeling found that the PM2.5 level was directly proportional to Vehicle-Kilometers Traveled (VKT), with a decrease of 40% decreasing the PM2.5 level by 0.4 µg./m3. In other words, shifting transportation modes from road to other forms could help in reducing the PM2.5

level [38]. A study in in Pittsburgh, USA on trace elements found that the concentration of pollutants, such as As and Se, during rush hours was higher than during other periods in the week [39]. The above research results show that in the transport sector, especially road transport, the higher the traffic density, the more it affects the occurrence of PM2.5.

2.3 Transportation and PM2.5 during Covid-19 pandemic

In Wuhan, China on December 2020, the WHO China Country office reported cases of pneumonia of unknown etiology [40] that was later confirmed by WHO as an emerging infectious disease defined as coronavirus disease 2019 (COVID-19) [41]. Thailand declared a state of emergency on 26th March 2021, leading to a partial lockdown of Bangkok and surrounding areas. Although the number of infected cases in other areas continuously increased as a result of worker immigration, the number of confirmed cases never exceeded 200 per day. The Covid-19 situation in Thailand remains under control; however, there are uncertain factors and there is the risk of outbreaks. Therefore, the government issued prevention measures and continues to closely monitor the situation [9]. Throughout the Covid-19 pandemic (January 2019 to August 2022), Thailand took preventive and proactive measures as the situation unfolded. Then, Covid-19 was declared endemic, and Thailand has reopened its borders to tourists after a long period of closure. Countermeasures applied, from the first infection until 2021 (when the situation unfolded), are provided in **Table 1.**

Table 1 Preventive measure for handling Covid-19 in Thailand.

Measure	Wave				
	1st	2nd	3rd	4th	5th
Restriction on entering high-risk infected areas	•	•	•	•	
Curfew 9.00pm–04.00am				•	
Working from home and online learning	•	•	•	•	
Restriction on opening times for shopping malls and markets	•	•	•	•	
Parks and entertainment places closed	•	•	•	•	
Border closed	•				
14 days quarantine on international arrival		•	•	•	•
Availability of 1st dose of vaccine (Aug. 2021)				•	
Availability of 2nd dose of vaccine					•

1st wave, Mar 2020–Jun 2020; 2nd wave, Dec 2020–Jan 2021; 3rd wave, Apr 2021–May 2021; 4th wave Jun 2021–Dec 2021; and 5th wave, Jan 2022–May 2022.

Fig. 1 shows the number of infected cases from January 2020 to June 2021. During the 1st and 2nd waves of Covid-19, there were low numbers of new infected cases per day because of the quarantine policy when Covid-19 was an emerging disease, with no developed vaccine. However, after some people had received a vaccination and retuned to living a normal life, they became familiar with the Covid-19 situation and were less careful and ignored some of the preventative measures. This led to new waves (3rd and 4th) of Covid-19, resulting in increased numbers of infected cases over a short period. Concurrently, Covid-19 had evolved to produce mutations that were more severe and more rapidly transmitted.

Therefore, during the 4th and 5th waves, the numbers of infected cases increased to 10,000 per day before continuously declining. Finally in July 2022, the Ministry of Public Health, Thailand declared the Covid-19 situation to be fully controlled and Covid-19 was downgraded from pandemic to endemic status. However, the Covid-19 pandemic changed the travel behavior of people globally. In Europe, research in Spain (Mobility Patterns: The First Wave's Results) [42], provided evidence of changing travel behavior.

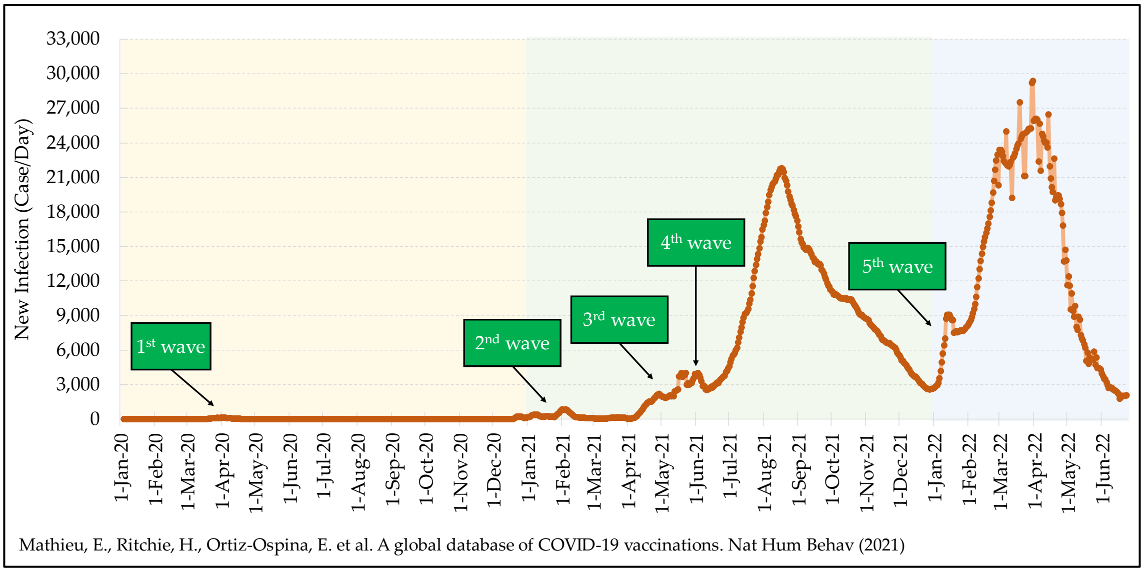


Fig. 1 Overview of number of Covid-19 infections (cases/day) in Thailand January 2020–June 2021

3. Methodology and Motivation

The meteorological dataset used in this research contained air pollution and statistical data of expressway traffic volumes in Bangkok. These data were used to identify the correlation between traffic volume and the PM2.5 level during the Covid-19 pandemic. Daily data were obtained from the Bangkok Pollution Control Department and the Expressway Authority, from January 2015 to December 2021.

3.1. Statistical data of meteorology and air pollution

In this research, the meteorological and pollution data of Bangkok areas were collected at the points shown in **Fig. 2** based on 2 sources totaling 66 stations: 12 stations from the Pollution Control Department (green points in **Fig. 2**) and 50 stations from the Environment Bureau Bangkok (red points in **Fig. 2**). These inspection tools are aligned to the announcements of the Pollution Control Department [43] (Measuring Instruments and Methods for Measuring Average Gases or Particulates in the Atmosphere in General Other Systems or other Methods Approved). The instruments are permanently installed 2 meters above ground level.

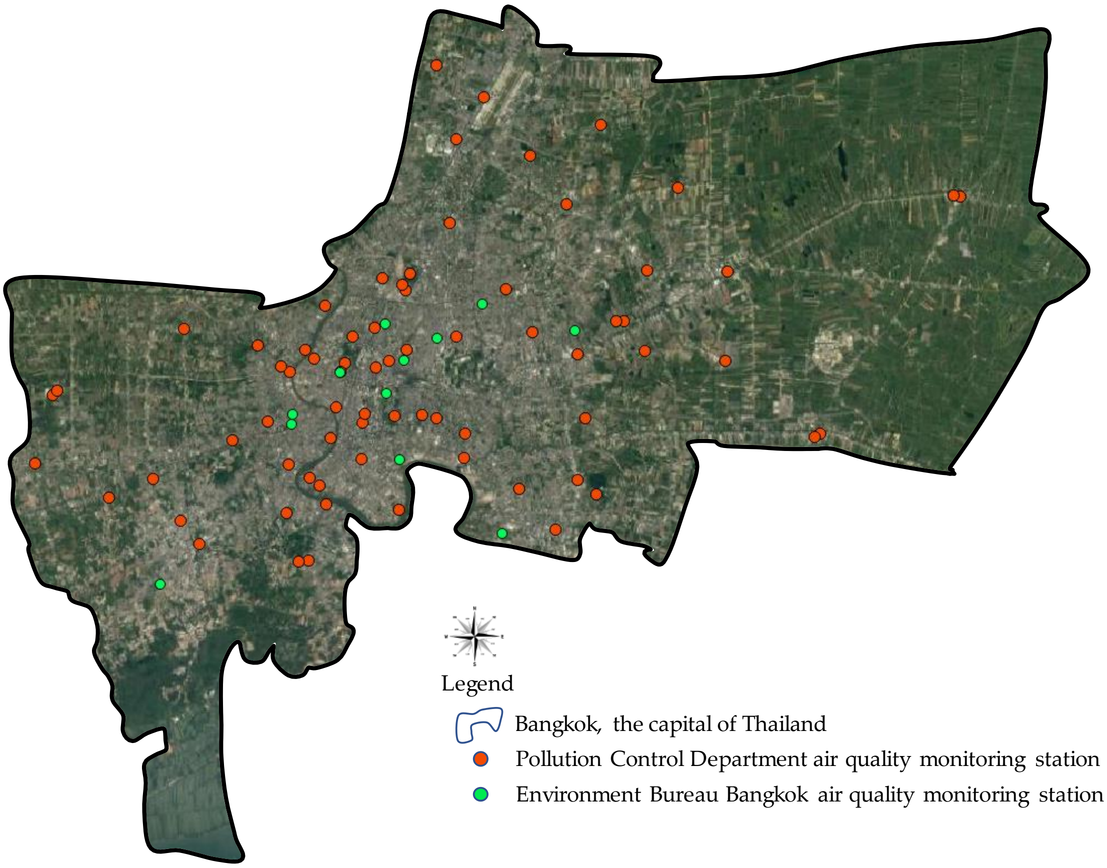


Fig. 2 Air monitoring stations of Pollution Control Department (50 red points) and Environment Bureau Bangkok (13 green points)

The meteorological dataset consisted of more than 2.3 million measured values for PM2.5 (fine dust particles with a size less than 2.5 microns), coarse particles (PM10), nitrogen oxide (NOx), nitrogen dioxide (NO2), nitric oxide (NO), carbon monoxide (CO), wind speed (WS), wind direction (WD), temperature (Temp), barometric pressure (BP), relative humidity (RH%), and ozone (O3) from 1 January 2015 to 31 December 2021. Hourly measurements were taken using appropriate instrumentation and the results were reported according to standard values. For example, PM2.5 values were collected every hour and then averaged to provide a 24-hour average that was compared with standard values. The measurement and sampling methods followed the Federal Equivalent Method standards. **Fig. 3** shows an example of some of the dataset used in this study. **Table 2** provides a summary of the raw data obtained from various organization during the study period.

Key_mth	Hour	WS(m/s)	WD(Deg)	Temp(Deg.C)	RH(%)	BP(mBar)	CO(ppm)	NO(ppb)	NO2(ppb)	NOX(ppb)	O3(ppb)	PM10(ug/m3)	PM2.5(ug/m3)
20210101.0	1.0	1.2	81.0	22.8	57.0	763.0	0.85	7.0	20.0	27.0	22.0	43.0	15.0
20210101.0	2.0	0.8	78.0	22.2	59.0	762.0	0.99	14.0	22.0	36.0	18.0	45.0	23.0
20210101.0	3.0	0.6	83.0	21.6	62.0	762.0	0.98	9.0	21.0	30.0	18.0	45.0	21.0
20210101.0	5.0	0.6	32.0	20.9	62.0	762.0	0.92	11.0	21.0	32.0	15.0	46.0	33.0
20210101.0	6.0	1.2	342.0	20.2	61.0	762.0	0.86	18.0	24.0	42.0	13.0	42.0	32.0
20210101.0	7.0	0.5	8.0	19.9	63.0	763.0	1.01	40.0	33.0	73.0	7.0	38.0	28.0
20210101.0	8.0	0.6	6.0	20.0	64.0	764.0	1.06	59.0	33.0	91.0	6.0	41.0	27.0
20210101.0	9.0	0.8	46.0	20.5	64.0	765.0	1.04	49.0	33.0	80.0	10.0	47.0	28.0
20210101.0	10.0	0.9	13.0	21.8	60.0	765.0	1.02	44.0	28.0	71.0	14.0	52.0	33.0
20210101.0	11.0	1.1	22.0	23.3	56.0	765.0	1.01	32.0	28.0	60.0	18.0	52.0	33.0

Fig. 3 Example of dataset used in this study

Table 2 Summary of data sources

Data Source	Number of stations	Data records (2015–2021)
Pollution Control Department air quality monitoring station	13	787,550
Environment Bureau Bangkok air quality monitoring station	50	1,516,342
Total	**63**	**2,303,892**

Then, a data cleansing process was conducted to obtain the final data used in the analysis. Data within the 99^{th} percentile were used. This meteorological dataset was used to help not only identify influential factors of pollution sources regarding air quality but also to help directly reduce pollution from the origin source [44], [45].

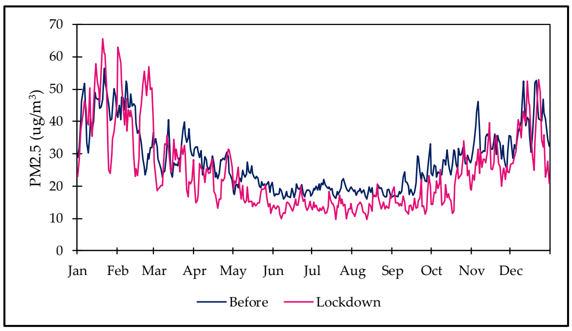
The meteorological data were separated into 2 datasets: 1) before the Covid-19 pandemic (2015–2019); and 2) during the Covid-19 lockdown. (2020–2021) **Table 3** provides an overview of the various pollution concentrations before the Covid-19 outbreak and during the lockdown. The authors compared the hourly average pollution concentration data from the 63 monitoring stations in Bangkok. There were differences and trends in the air pollution concentrations before the Covid-19 epidemic and during the lockdown. During the Covid-19 outbreak, the average values for PM2.5, NOx, NO2, NO and CO were lower than before the Covid-19 outbreak, while the average PM10 and O3 values increased during the Covid-19 outbreak.

During the lockdown period, there were fewer cars on roads. Mobility was restricted and most people stayed at home. During this time, the concentrations of PM2.5, NOX, NO2, NO and CO decreased by 14.38, 12.93, 18.4, 2.65 and 5.66%, respectively. In addition, we compared the average hourly concentration of air pollution before the pandemic and during the lockdown period.

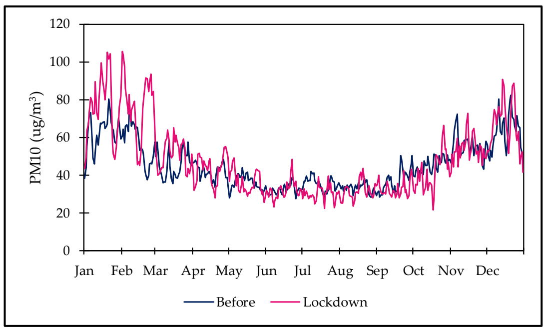
Fig. 4 (a) PM2.5, (b) PM10, (c) NOX, (d) NO2, (e) NO, (f) CO and (g) O3 show the concentration values of each parameter after analysis and compared with the concentration of pollution in the dry season, from November to March for both before the pandemic and during lock down period; the concentration levels of pollution in both periods were in the same direction.

Table 3 Statistical data on air pollution used in this study

Factor	Before Covid-19 pandemic		During lockdown period		Difference (%)
	Mean	SD	Mean	SD	
PM2.5 (ug/m^3)	27.93	18.94	23.92	16.21	-14.38
PM10 (ug/m^3)	44.97	26.19	47.45	27.94	5.51
NO_X (ppb)	42.15	40.88	36.70	41.32	-12.93
NO_2 (ppb)	22.15	15.10	18.07	14.35	-18.43
NO (ppb)	23.00	32.96	22.39	33.93	-2.65
CO (ppm)	0.85	0.55	0.80	0.55	-5.66
WS (m/s)	0.84	0.66	0.65	0.52	-23.40
WD (°)	188.56	92.74	186.22	97.33	-1.24
Temp (°C)	29.42	2.92	29.18	3.09	-0.82
BP (mBar)	869.66	59.13	978.40	83.61	12.50



(a)



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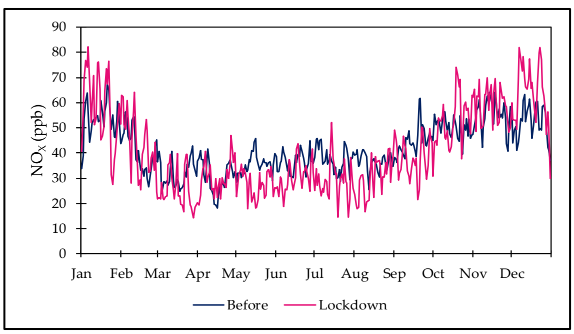

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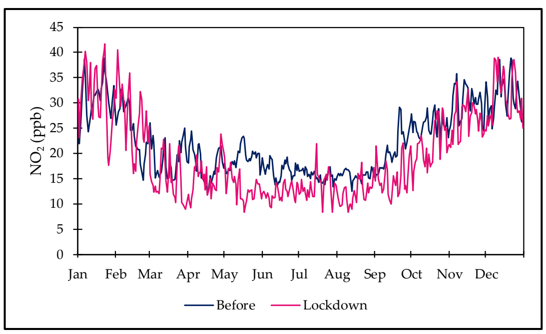

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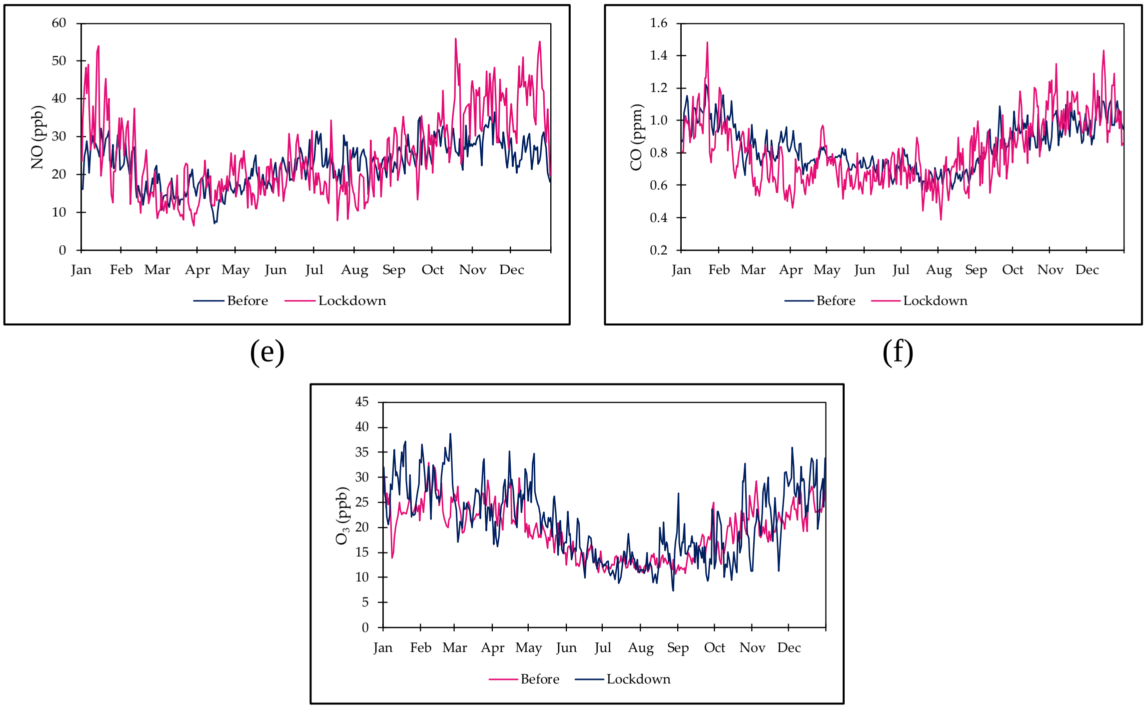

(e) (f)

(g)

Fig. 4 Hourly average concentration levels of each parameter before period of Covid-19 pandemic and during period of lockdown: (a) PM2.5; (b) PM10; (c) NO_X; (d) NO_2; (e) NO; (f) CO; (g) O_3

3.2. Kruskal-Wallis test

The Kruskal-wallis one-way analysis of variance method was used to identify the characteristics of the distribution of the time series data [46], [47]. The Kruskal-Wallis method is commonly used for identifying the distribution of air pollution data and has been proven effective at monitoring seasonal distribution data of air quality and dominant air pollutants [48], [49]. Initially in the characteristic distribution testing, the pollution data characteristic was assumed to be seasonal using the hypotheses:

H0: Median value of each pollution parameter is equal every month.

H1: Median value of each pollution parameter differs for at least 1 month.

H was calculated using equation (1):

$$H = \left[\frac{12}{n(n+1)}\sum_{j=1}^{c}\frac{T_j^2}{n_j}\right] - 3(n+1) \qquad (1)$$

based on the sum of sample sizes for all samples (n), the number of samples (c), the sum of ranks in the j^{th} sample ($\boldsymbol{T_j}$) and the size of the j^{th} sample ($\boldsymbol{n_j}$).

Table 4 shows the results, indicating that the median of each pollution parameter differed in at least 1 pair in each monthly result, with a P-value lower than 0.05. Therefore, hypothesis H1 was accepted that pollution parameters each month before the pandemic and during the lockdown period were significantly different.

Table 4 Results of Kruskal-Wallis test on pollution parameters (January 2015 to December 2021)

Parameter	Statistic	
	H statistic	Asymp. Sig.
PM2.5 (ug/m^3)	48.57	0.000
PM10 (ug/m^3)	49.37	0.000
NO_X (ppb)	28.62	0.000
NO_2 (ppb)	28.94	0.000
NO (ppb)	44.48	0.000
CO (ppm)	36.69	0.000
O_3 (ppb)	48.47	0.000

In summary, the concentration of PM2.5 was significantly influenced by seasonal factors.

Some research has shown that decreasing road traffic volume is not the major cause of decreasing air pollution, with general human activity more directly related to the pollution level [50]. Nonetheless, research in Italy [51], studying the correlation between road traffic and air pollution, indicated the effect of traffic on the concentration of air pollution; however, the research focus was on NO, NO2 and NOx (PM2.5 was not mentioned). Therefore, it was not possible to utilize that study to determine conclusively the relationship between traffic and the concentration of PM2.5.

3.3. Relationship between traffic density and PM2.5

The daily traffic data in the metropolitan area, shown in **Fig. 5**, covered the Chalerm Maha Nakhon Expressway, the Si Rat Expressway, Chalong Rat Expressway and the Burapha Withi Expressway. The travel data showed that under normal conditions, the traffic volume on these expressways reached 1.78 million vehicles per day. However, during the lockdown period (2020–2021), the traffic volume on expressways dropped to 1.36 million vehicles per day.

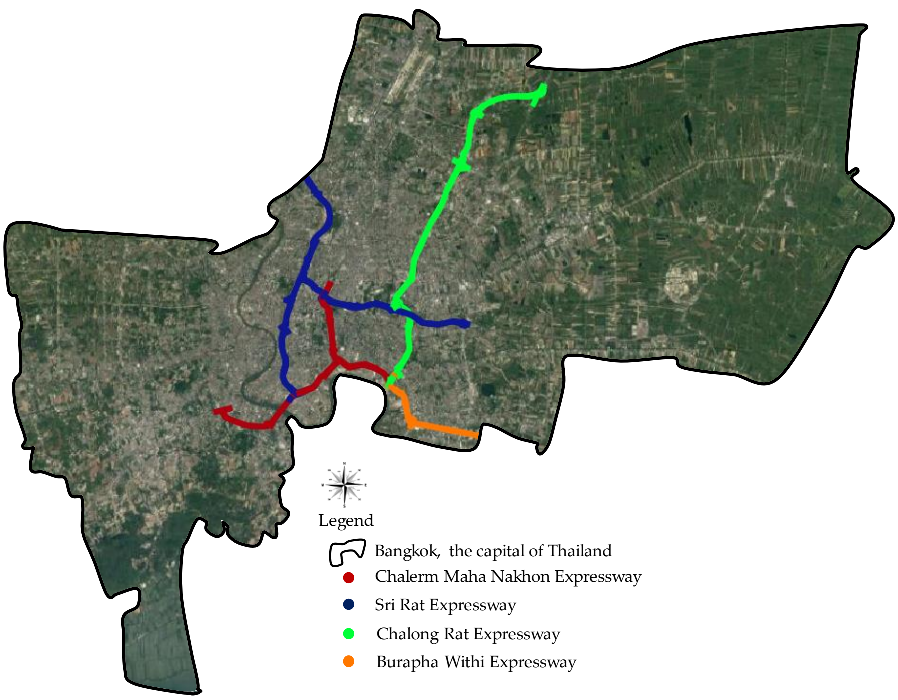

Fig. 5 Overview of 4 urban expressways in Bangkok

In **Fig. 6,** the daily volume of vehicles is separated into 2 periods: before the Covid-19 pandemic (January 2015 to December 2019), and during the Covid-19 outbreak (January 2020 to December 2021). In Thailand, the Covid-19 pandemic began in January 2020, with the lockdown that prohibited people from going out for non-essential activities being implemented from April to June 2020 and was considered to be most effective as indicated by the approximately 40% reduction in travel volume that occurred during this time.

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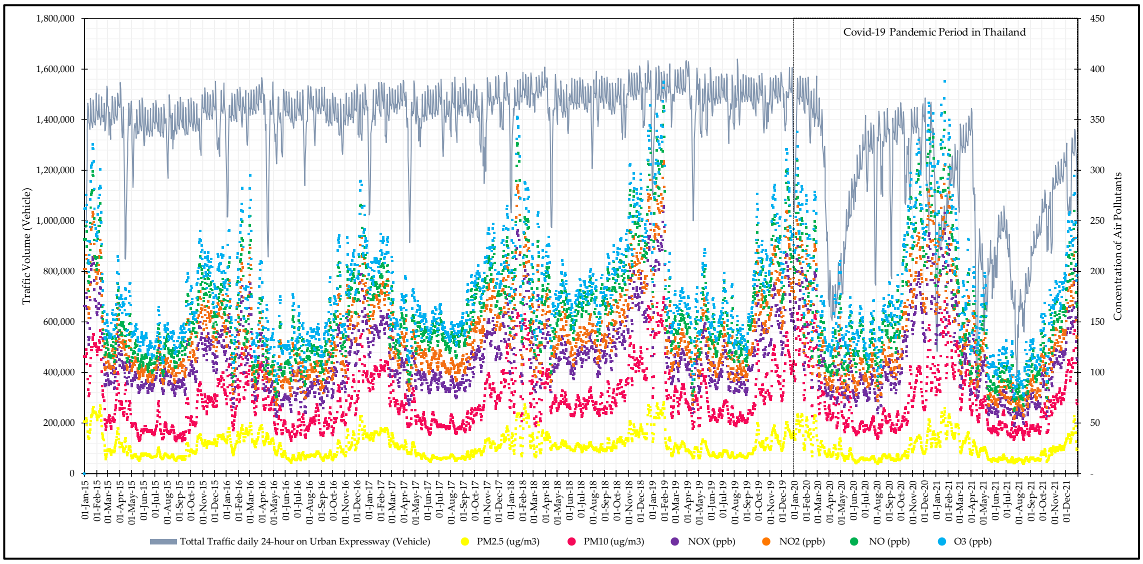

Fig. 6 Daily traffic volume and concentration of air pollution during 2 periods: before Covid-19 pandemic (January 2015 to December 2019) and during Covid-19 outbreak (January 2020 to December 2021)

4. Results and Discussion

Considering relationship between traffic volume and PM2.5 in Figure 7, before the Covid-19 pandemic (January 2015 to December 2019), the traffic volume each day was generally within the same range, while the PM2.5 concentration level depended on seasonal factors. In every year, PM2.5 was the highest in the dry season (November to March).

During the Covid-19 pandemic, the implementation of a lockdown caused the traffic volume to rapidly decrease (from March 2020). Considering only the data before March 2020, the data is misleading, suggesting that PM2.5 and traffic volume are strongly related. However, considering all the data in this research (from 2015 to January 2021), it was during the dry season that there was a 5th wave of Covid-19 which reduced the traffic volume again. The analysis showed that when the PM2.5 level was highest it resulted in an inverse effect on the traffic volume, especially during the dry season (January) when traffic volumes were reduced but the PM.5 level was noticeably higher (square box highlighted in yellow in **Fig. 7**).

In addition, the statistical data showed that the correlation coefficient between traffic volume and the concentration of PM2.5 was 0.206.

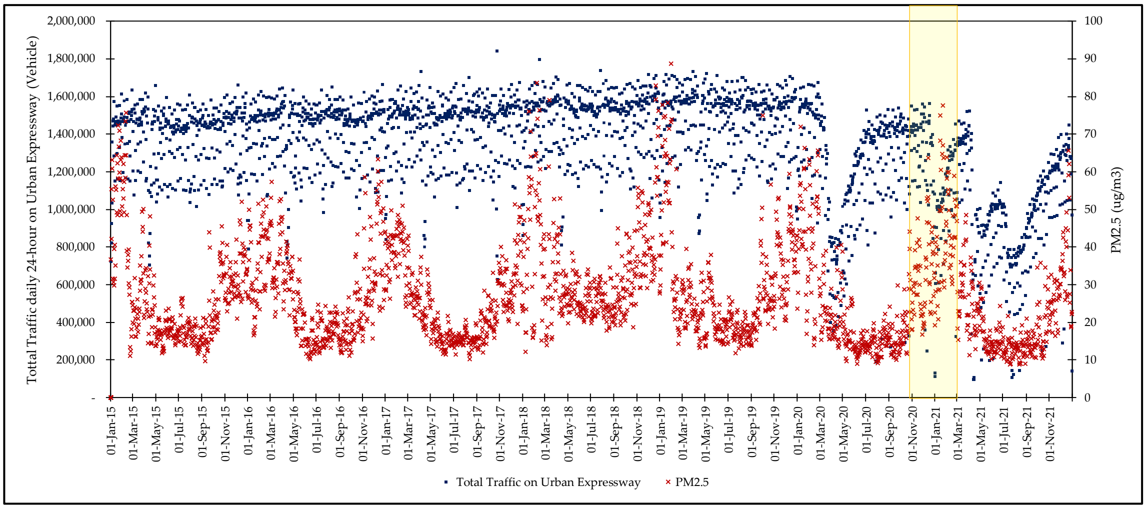

Fig. 7 Daily traffic volume and concentration of PM2.5 in 2 periods: before Covid-19 pandemic (January 2020 to December 2019), and during the Covid-19 outbreak (January 2020 to December 2021)

5. Conclusions

This study examined the changes in PM2.5 levels as a result of the Covid-19 outbreak. The researchers used data on the levels of PM2.5 and other air pollution parameters gathered at 63 points in addition to traffic volume data on 4 expressways from January 2015 to December 2021.

The results showed that during the city lockdown due to the Covid-19 pandemic, the percentage of concentration of the air pollution parameters PM2.5 NOX NO2 NO and CO, decreased by 14.38, 12.93, 18.43, 2.65, and 5.66%, respectively. In addition, testing the time series air pollution dataset using the Kruskal-Wallis method indicated that the data directly related to seasonal distribution, with the concentrations of pollution being highest during the dry season every year.

In addition, the city lockdown forced people to stay at home and to work and learn online. This directly reduced the traffic volume by 40%. The average monthly PM2.5 level dropped by 21 percent from before the Covid-19 outbreak compared to during the lockdown period. This indicated that during the outbreak, the lockdown had a direct impact on human behavior, particularly transportation, which decreased by 40%. These changes played a substantial role in the reduction of PM2.5 concentrations.

While it was not possible to clearly determine which factors (traffic or seasonal) had the greater impact on the PM2.5 concentration, the current research provided evidence that human activities, specifically traffic in urban regions, had a notable effect on PM2.5 levels.

The PM2.5 problem has been of concern in Thailand, with government and academic studies attributing the main cause of increased PM2.5 levels to traffic. The cur-rent research results showed that decreasing the traffic volume significantly reduced PM2.5 levels. The authors believe that this research can contribute to policy and stake-holder reviews on how to sustainably solve the PM2.5 problem in Thailand in a more appropriate way. However, the data collected represent only a sample from a part of Thailand.

6. Acknowledgement

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7. References

[1] US EPA, "Criteria Air Pollutants," Encycl. Immunotoxicol., pp. 218–218, October. 2016.

[2] V. Ratanavaraha and S. Jomnonkwao, "Trends in Thailand CO2 emissions in the transportation sector and policy mitigation," Transp. Policy, vol. 41, pp. 136–146, 2015.

[3] C. Li and S. Managi, "Contribution of on-road transportation to PM2.5," Sci. Rep., vol. 11, no. 1, pp. 1–12, 2021.

[4] S. Heydari, M. Tainio, J. Woodcock, and A. de Nazelle, "Estimating traffic contribution to particulate matter concentration in urban areas using a multilevel Bayesian meta-regression approach," Environ. Int., vol. 141, no. December 2019, p. 105800, 2020.

[5] W. M. Hodan and W. R. Barnard, "Evaluating the Contribution of PM2. 5 Precursor Gases and Re-entrained Road Emissions to Mobile Source PM2. 5 Particulate Matter Emissions. MACTEC Under Contract to the Federal Highway Administration," MACTEC Fed. Programs, Res. Triangle Park. NC, p. 58 pp, 2004, Available: https://www3.epa.gov/ttnchie1/conference/ei13/mobile/hodan.pdf

[6] R. Sun, Y. Zhou, J. Wu, and Z. Gong, "Influencing factors of PM2.5 pollution: Disaster points of meteorological factors," Int. J. Environ. Res. Public Health, vol. 16, no. 20, 2019.

[7] R. Li, X. Mei, L. Wei, X. Han, M. Zhang, and Y. Jing, "Study on the contribution of transport to PM2.5 in typical regions of China using the regional air quality model RAMS-CMAQ," Atmos. Environ., vol. 214, no. 40, p. 116856, 2019.

[8] Engel, "World air quality report 2021," Pap. Knowl. Towar. a Media Hist. Doc., 2014.

[9] M. Station, K. Findings, K. Kaen, C. Mai, and C. Mai, "Greenpeace's City Rankings for PM2.5 in Thailand," no. 2013, pp. 1–6, 2016.

[10] Tomtom Traffic Index, "Traffic Index Traffic Index results 2018 - 2021," Www.Tomtom.Com, p. 21, 2021, Available: https://www.tomtom.com/traffic-index/ranking/

[11] B. Pishue and T. Trepanier, "2020 INRIX Global Traffic Scorecard and

latest travel trends," Mar. 2021.

[12] A. König and A. Dreßler, "A mixed-methods analysis of mobility behavior changes in the COVID-19 era in a rural case study," Eur. Transp. Res. Rev., vol. 13, no. 1, 2021.

[13] M. Hasselwander, T. Tamagusko, J. F. Bigotte, A. Ferreira, A. Mejia, and E. J. S. Ferranti, "Building back better: The COVID-19 pandemic and transport policy implications for a developing megacity," Sustain. Cities Soc., vol. 69, October 2020, 2021.

[14] Q. Cui et al., "The impacts of COVID-19 pandemic on China's transport sectors based on the CGE model coupled with a decomposition analysis approach," Transp. Policy, vol. 103, January, pp. 103–115, 2021.

[15] "People's travel during the COVID-19 viral epidemic - dataset - MOT Data Catalog." https://datagov.mot.go.th/dataset/greenhouse-emissions-in-the-road-transport-sector

[16] "Annual Traffic Report 2021, EXAT.". Available: https://www.exat.co.th/statistics/.

[17] "Air quality and noise statistics, Pollution Control Department.". Available: http://air4thai.pcd.go.th/webV3/#/History

[18] J. D. Sacks et al., "Particulate matter-induced health effects: who is susceptible?" Environ. Health Perspect., vol. 119, no. 4, pp. 446–454, Apr. 2011.

[19] M. Rosenlund, F. Forastiere, D. Porta, M. De Sario, C. Badaloni, and C. A. Perucci, "Traffic-related air pollution in relation to respiratory symptoms, allergic sensitisation and lung function in schoolchildren," Thorax, vol. 64, no. 7, pp. 573–580, 2009.

[20] G. Chen et al., "Short-term effects of ambient gaseous pollutants and particulate matter on daily mortality in Shanghai, China.," J. Occup. Health, vol. 50, no. 1, pp. 41–47, 2008.

[21] J. Cao, J. C. Chow, F. S. C. Lee, and J. G. Watson, "Evolution of PM2.5 measurements and standards in the U.S. And future perspectives for China," Aerosol Air Qual. Res., vol. 13, no. 4, pp. 1197–1211, 2013.

[22] M. Kanakidou et al., "Organic aerosol and global climate modelling: A review," Atmos. Chem. Phys., vol. 5, no. 4, pp. 1053–1123, 2005.

[23] M. Hallquist et al., "The formation, properties and impact of secondary organic aerosol: Current and emerging issues," Atmos. Chem. Phys., vol. 9, no. 14, pp. 5155–5236, 2009.

[24] X. Liu et al., "Secondary formation of sulfate and nitrate during a haze episode in megacity Beijing, China," Aerosol Air Qual. Res., vol. 15, no. 6, pp. 2246–2257, 2015.

[25] R. M. Harrison and J. Yin, "Particulate matter in the atmosphere: Which particle properties are important for its effects on health?" Sci. Total Environ., vol. 249, no. 1–3, pp. 85–101, 2000.

[26] U. Pöschl, "Atmospheric aerosols: Composition, transformation, climate and health effects," Angew. Chemie - Int. Ed., vol. 44, no. 46, pp. 7520–7540, 2005.

[27] A. Farrow and E. Newport, "The Burden of Air Pollution in Thailand 2021 The Burden of Air Pollution in Thailand 2021," May, 2022.

[28] P. C. Department, "Bangkok Air Pollution: Real-time Air Quality Index (AQI)." pp. 1–5, 2021. Available: https://aqicn.org/city/bangkok

[29] T. Amnuaylojaroen and J. Kreasuwun, "Investigation of fine and coarse particulate matter from burning areas in Chiang Mai, Thailand using the WRF/CALPUFF," Chiang Mai J. Sci., vol. 39, no. 2, pp. 311–326, 2012.

[30] S. Khodmanee and T. Amnuaylojaroen, "Impact of Biomass Burning on Ozone, Carbon Monoxide, and Nitrogen Dioxide in Northern Thailand," Front. Environ. Sci., vol. 9, , pp. 1–6, April 2021.

[31] T. Amnuaylojaroen, "Prediction of PM2.5 in an Urban Area of Northern Thailand Using Multivariate Linear Regression Model," Adv. Meteorol., vol. 2022, p. 3190484, 2022.

[32] S. Chirasophon and P. Pochanart, "The long-term characteristics of PM10 and PM2.5 in Bangkok, Thailand," Asian J. Atmos. Environ., vol. 14, no. 1, pp. 73–83, 2020.

[33] D. Narita et al., "Pollution characteristics and policy actions on fine particulate matter in a growing Asian economy: The case of Bangkok Metropolitan Region," Atmosphere (Basel)., vol. 10, no. 5, pp. 1–18, 2019.

[34] P. Uttamang, V. P. Aneja, and A. F. Hanna, "Assessment of gaseous criteria pollutants in the Bangkok Metropolitan Region, Thailand," Atmos. Chem. Phys., vol. 18, no. 16, pp. 12581–12593, 2018.

[35] P. Watcharavitoon, C. P. Chio, and C. C. Chan, "Temporal and spatial variations in ambient air quality during 1996-2009 in Bangkok, Thailand," Aerosol Air Qual. Res., vol. 13, no. 6, pp. 1741–1754, 2013.

[36] EEA, "EMEP/EEA air pollutant emission inventory guidebook 2013: Technical guidance to prepare national emission inventories," EEA Tech. Rep., no. 12/2013, p. 23, 2013. Available: http://www.eea.europa.eu/publications/emep-eea-guidebook-2013

[37] Y. Wang and D. Yang, "Impacts of freight transport on PM2.5 concentrations in China: A spatial dynamic panel analysis," Sustain., vol. 10, no. 8, 2018.

[38] T. Xia, M. Nitschke, Y. Zhang, P. Shah, S. Crabb, and A. Hansen, "Traffic-related air pollution and health co-benefits of alternative transport in Adelaide, South Australia," Environ. Int., vol. 74, pp. 281–290, 2015.

[39] B. J. Tunno et al., "Spatial patterns in

rush-hour vs. Work-week diesel-related pollution across a downtown core," Int. J. Environ. Res. Public Health, vol. 15, no. 9, 2018.

[40] D. S. Hui et al., "The continuing 2019-nCoV epidemic threat of novel coronaviruses to global health — The latest 2019 novel coronavirus outbreak in Wuhan, China," Int. J. Infect. Dis., vol. 91, pp. 264–266, 2020.

[41] L. Pérez-Campos Mayoral, M. T. Hernández-Huerta, G. Mayoral-Andrade, E. Pérez-Campos Mayoral, and E. Pérez-Campos, "World Health Organization declares global emergency: A review of the 2019 novel Coronavirus (COVID-19)," Int. J. Surg., vol. 79, pp. 163–164, Feb. 2020.

[42] A. E. Dingil and D. Esztergár-Kiss, "The Influence of the Covid-19 Pandemic on Mobility Patterns: The First Wave's Results," Transp. Lett., pp. 1–13, Mar. 2021.

[43] "Instruments and methods for measuring the average value of gas or dust in the atmosphere in general - Pollution Control Department." Available: https://www.pcd.go.th/publication/5420/

[44] P. Wetchayont, "Investigation on the impacts of covid-19 lockdown and influencing factors on air quality in greater Bangkok, Thailand," Adv. Meteorol., vol. 2021, no. 2, 2021.

[45] Y. Miao, S. Liu, L. Sheng, S. Huang, and J. Li, "Influence of boundary layer structure and low-level jet on pm2.5 pollution in Beijing: A Case Study," Int. J. Environ. Res. Public Health, vol. 16, no. 4, 2019.

[46] W. H. Kruskal and W. A. Wallis, "Use of ranks in one-criterion variance analysis," J. Am. Stat. Assoc., vol. 47, no. 260, pp. 583–621, 1952.

[47] T. W. MacFarland and J. M. Yates, Introduction to Nonparametric Statistics for the Biological Sciences Using R, 1st ed. Springer Publishing Company, Incorporated, 2018.

[48] X. Zhao et al., "Statistical analysis of spatiotemporal heterogeneity of the distribution of air quality and dominant air pollutants and the effect factors in Qingdao Urban Zones," Atmosphere (Basel)., vol. 9, no. 4, pp. 12–16, 2018.

[49] K. Webel, "A data driven selection of an appropriate seasonal adjustment approach," SSRN Electron. J., no. 07, 2021.

[50] S. Dursun, M. Sagdic, and H. Toros, "The impact of COVID-19 measures on air quality in Turkey," Environ. Forensics, vol. 23, no. 1–2, pp. 47–59, 2022.

[51] R. Rossi, R. Ceccato, and M. Gastaldi, "Effect of road traffic on air pollution. experimental evidence from covid-19 lockdown," Sustainability, vol. 12, no. 21, 2020.