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Regional Case Study

Fluctuations of PM2.5 and NOx Concentration and Their Relationship with Meteorological Factors in the Rural Area (Case Study: Puncak Bogor)

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Abstract

Rural areas are generally synonymous with better air quality than urban areas. However, if there is an agricultural activity, it has the potential to release nitrogen from the soil, be oxidized and form NO and NO2 in the air. These two gases encourage the formation of secondary PM2.5 particulates in the air of rural areas. This study aims to analyze fluctuations in PM2.5 concentration in rural areas, the effect of its precursor NOx, and the influence of meteorological factors. The location used as a case study is the Cibeureum area, Puncak, Bogor Regency. The data used are PM2.5, NO, NO2, NOx concentration data (per 3 hours), rainfall, air temperature, wind speed and direction in 2019 and 2020, which were analyzed using correlation and linear regression and the open-air package provided by RStudio. The results showed that the concentration of PM2.5 with NOx as a precursor had a significant positive correlation in 2019 (r = 0.68) and 2020 (r = 0.63). Cumulative precipitation affects the concentration of PM2.5 and NOx in the air. Meteorological factors have a small correlation value to fluctuations in PM2.5 concentration and NOx concentration except for air temperature (r = 0.3).

Keywords: Correlation; meteorogical factors; PM2.5; Puncak Bogor; precursor NOx

1. Introduction

Air pollution is one of the environmental problems that have a severe impact on health. One of the essential air pollutants is PM2.5, a fine particle with a diameter of < 2.5 m. PM2.5 can pass through the filtration of nasal hairs until it reaches the end of the respiratory tract with airflow and can accumulate by diffusion, damaging other body parts through air exchange in the lungs (Xing et al., 2016). PM2.5 may contain hazardous substances, for example, heavy metals. PM2.5 organic components can cause DNA damage and suppress DNA repair; it can also encourage the replication of damaged DNA fragments, triggering carcinogenesis or the process of cancer formation (Xing et al., 2016).

The concentration of PM2.5 in the atmosphere was influenced by anthropogenic sources, natural sources, meteorological factors, and chemical processes. In rural areas, anthropogenic emissions are not as much as in urban areas, so particulate fluctuations are more influenced by natural sources, meteorological factors, and chemical reactions to form secondary particulates. According to Almaraz et al. (2018), NOx is the primary pollutant in agricultural areas. Nitrogen oxide (NOx) is one of the secondary particulate precursors for PM2.5. According to Leibensperger et al. (2011), anthropogenic NOx emission can affect PM concentration in a complex manner depending on the chemical environment of the receptor area. Research Wang et al. (2020) in China found a significant positive correlation between NOx concentration and PM2.5 concentration due to NOx conversion affecting PM2.5 formation. In Indonesia, research on particulate precursors is still rare due to the limited data available. In addition to NOx, ammonia (NH3), VOCs, and sulfur oxides (SOx) are PM2.5 precursor compounds (Hodan & Barnard, 2004).

The time required for the precursor compounds to react and form particulates varies greatly and depends on the precursor chemistry and meteorological conditions. According to Hodan and Barnard (2004), the contribution of NOx to the formation of PM2.5 differs greatly depending on atmospheric conditions, including humidity and temperature. According to Wang-Li (2015), most inorganic PM2.5 in the atmosphere is secondary and is formed through an acid or base neutralization process involving NOx and NH3 as precursors. NOx reacts with OH to form HNO3, which then reacts with NH3 available in the rural atmosphere to form ammonium nitrate (NH4NO3). This chemical reaction is highly dependent on temperature, humidity, and the concentration of the precursor. When the temperature is high and the humidity is low, the equilibrium will shift to the gas phase NH3 and HNO3. Vice versa, when the temperature is low and the humidity is high, the equilibrium will move to the NH4NO3 particle phase. The chemical equation for the formation of secondary particulates involving NOx is as follows:

$NO_2 + OH \rightarrow HNO_3(g)$ (1)

$NH_3(g) + HNO_3(g) \rightarrow NH_4NO_3$ (particle) (2)

The increase in PM2.5 concentration in the afternoon and evening can be influenced by local factors, altitude, and weather patterns in the region, including temperature and humidity. The decrease in temperature, especially when there is an inversion of temperature at night, will inhibit particle diffusion and the accumulation of particles on the surface, thereby increasing the PM2.5 concentration. Condensation due to high humidity can also increase PM2.5 concentrations (Hernandez et al., 2017). In general, air pollution is mainly analyzed in urban areas. In contrast, rural areas are considered clean areas, indicated by pollutant concentrations that do not exceed the applicable ambient air quality standards. However, the air quality in rural areas can also be polluted by certain pollutants related to the potential for emissions from agricultural activities. According to Majra (2011), López-Aparicio (2013), and Wang-Li (2015), the primary pollutant produced by agrarian movements is ammonia (NH3), which will contribute to the formation of secondary particulates as a result of the chemical reaction shown in equation 1): According to the research of Chang et al. (2020), the concentration of NH3 in rural areas is around 4.6, 8.3 g/m3, and about 7-8 g/m3 according to Wang et al. (2015b) in rural China.

Puncak area (Bogor Regency) is one of the rural areas in Indonesia which considered to have clean air. However, the Puncak Bogor area is not only agricultural but also a tourist destination that is very busy with tourists, especially during holidays. This will affect the number of motorized vehicles heading to the Puncak area so that they can contribute to sources of NOx and PM2.5 emissions in the region. Based on data from Jasa Marga (2019), the average number of motorized vehicles passing through the Gadog toll gate towards Puncak was 31467 vehicles per working day and 33206 vehicles per holiday during the pre-pandemic period. This study aims to analyze the fluctuation of PM2.5 concentrations and precursor pollutant concentrations (NOx) in the Puncak Bogor area in 2019 and 2020 and to analyze the influence of meteorological factors that contribute to their fluctuations.

2. Methods

This study examines the Puncak area (Bogor Regency) as one of the rural areas in Indonesia. The data used are PM2.5, NO, NO2, and NOx, as well as meteorological data in air temperature, humidity, wind direction, speed, and precipitation, with a study period of 2019 and 2020. The 2019 and 2020 periods are used, taking into account the influence of large-scale social restrictions (PSBB) during the COVID-19 pandemic, which is expected to affect fluctuations in vehicles entering the Puncak area, as well as affect air pollutant emissions. The data above is sourced from the BMKG Cibeureum Air Pollution Observatory, a collaboration between the Meteorology, Climatology and Geophysics Agency (BMKG) and the National Institute for Environmental Studies (NIES) Japan. The system continuously monitors many air quality parameters consisting of GHGs and air pollutants (CO2, CH4, O3, CO, NOx, SO2, aerosol concentrations PM2.5, PM10, Black Carbon, chemical components and flask sampling of air) [2]. Measurement of CO2 and CH4 uses G2301 from Picarro, CO using CO-30r from Los Gatos Research, NOx using Model 42i-TL from Thermo, SO2 using Model 43i-TLE from Thermo, O3 using OA-787 from Kimoto Electric, aerosol concentrations (PM2.5, PM10, BC) and chemical components using ACSA- 14 from Kimoto Electric, and automatic flask sampler of air from Koshin-RS (Immanuel et al. 2019). The map of the study location is shown in Figure 1. The monitoring location is located in geographical coordinates 06°34'22.5" South Latitude, 106°44'48.8" East Longitude, and at an altitude of 1130 masl. The area around Cibeureum is related to tourism activities, in the form of villas for staying, agricultural areas, as well as tourist attractions, especially in the North and East directions, conditions are more open, and there are many buildings. The inn (villa) location is around 35-800 m. Meanwhile, in the South and Southeast directions, there are mixed green areas between agricultural areas, including tea plantations and Taman Safari Indonesia, as well as mountains that are denser in vegetation, with a higher topography (800 masl). Mount Gede-Pangrango is about 7 km away in this direction, affecting the wind patterns around it by sea breeze and land breeze mechanism.

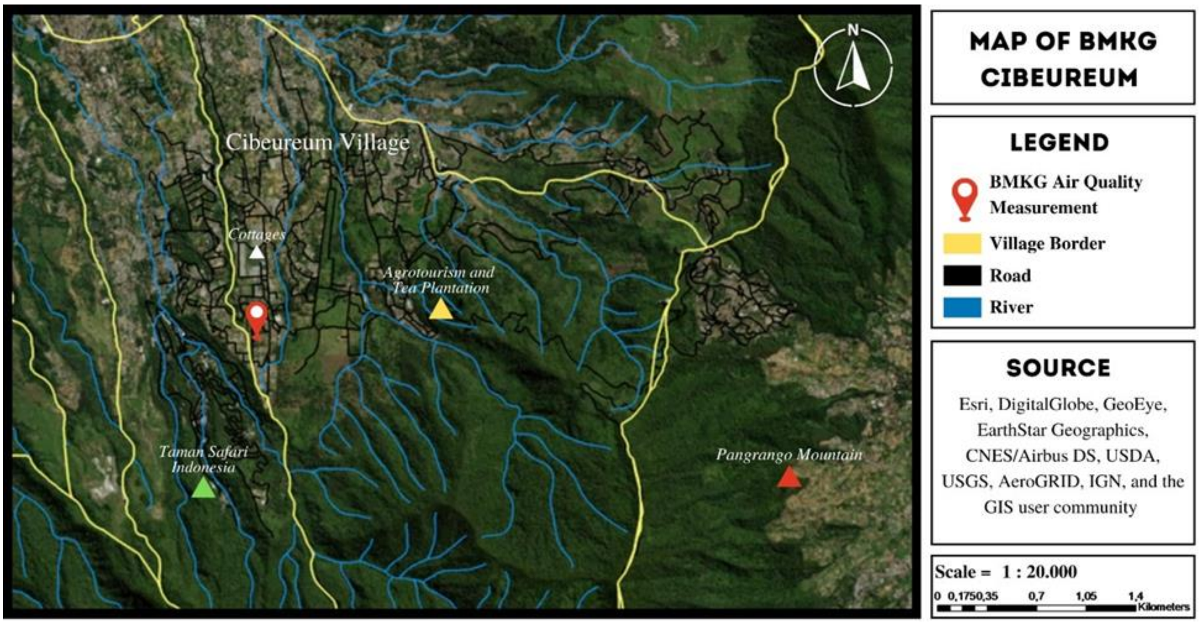


Figure 1. Map of Cibeureum BMKG air quality measurement locations (Source: Google Maps

The relationship between PM2.5 and its precursor, in this case. NOx was carried out by analyzing the fluctuations in the concentration of the two pollutants and NOx-related compounds, NO and NO2. Data fluctuations are displayed through diurnal, daily, and monthly graphs. The effect of precipitation is analyzed through PM2.5 and NOx data plots in real-time in the week with the highest and lowest rainfall. This is done to see the impact of accumulated precipitation conditions on fluctuations in pollutant concentrations. The effect of the wind was analyzed using a polar plot diagram.

Analysis of wind direction and speed was carried out to see the dominant wind direction and wind speed blowing in the Puncak Bogor area and associated with fluctuations in pollutant concentrations. The data is divided into two periods: during the day (07:00-19:00 GMT +7) and night (20:00-06:00 GMT +7). This time separation is to see the influence of mountain and valley winds because of the presence of mountains around the location. Based on Hasanah's research (2018), at night, Cibeureum/Citeko gets influenced by local winds. Namely, the wind blows from the Southeast (mountain direction) towards the Northwest (lower plains). Data processing using Microsoft Excel and Rstudio application. Fluctuations in pollutant concentration (PM2.5, NOx, NO, and NO2) were analyzed statistically concerning meteorological factors (air temperature, relative humidity, precipitation, wind direction, and speed). Statistical analysis was carried out to see the close relationship between the variables used and to pay attention to the presence or absence of a causal relationship between these variables. Calculations of correlation and regression tests were performed using the Minitab 18 software. The correlation test used in this study was Pearson Correlation.

3. Result and Discussion

3.1. PM2.5 and NOx. Concentration Fluctuations

The annual average PM2.5 concentration in 2019 (20.8 $\mu g/m^3$) was higher than in 2020 (14.8 $\mu g/m^3$). The average concentration of PM2.5 in 2019 exceeded the one-year National Ambient Air Quality Standard of 15 $\mu g/m^3$, by Government Regulation of the Republic of Indonesia No. 22/2021 concerning the National Ambient Air Quality Standard. In 2020, Large-Scale Social Restrictions (PSBB) were imposed in connection with the COVID-19 pandemic so that the number of motorized vehicles passing through the Puncak Bogor area was reduced and reduced particulate emissions into the air. This condition is following the observations of Wang et al. (2020) in Hangzhou, China which showed a decrease in the average concentration of PM2.5 in urban and rural areas of Hangzhou, China, during the implementation of the lockdown.

The diurna pattern of PM2.5 concentration in 2019 and 2020 in the Puncak Bogor area has a similar movement pattern, but the magnitude is different (Figure 2). This is indicated by the two lines having a unimodal pattern. Namely, one peak concentration at 19:00 WIB of 29.6 $\mu g/m^3$ in 2019 and 22.5 ug/m3 in 2020, while the lowest concentration was measured at 07: 00 WIB with a value of 12.6 $\mu g/m^3$ in 2019 and 8.7 $\mu g/m^3$ in 2020. This pattern is similar to the results of research conducted by Zhao et al. (2009) in the rural area of Beijing, which shows that PM2.5 concentration has a unimodal pattern, with the peak concentration occurring at night and the lowest concentration occurring in the morning. Seasonal and diurnal wind patterns heavily influence the fluctuations in PM2.5 concentration in rural areas.

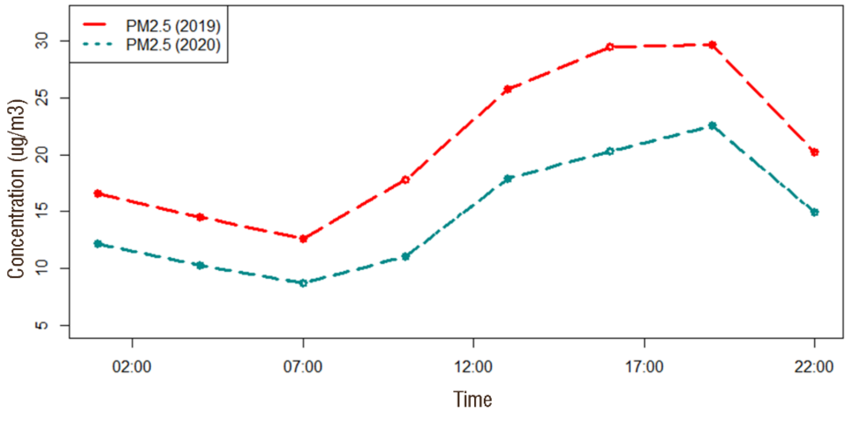


Figure 2. The diurnal average concentration of PM2.5 in 2019 and 2020

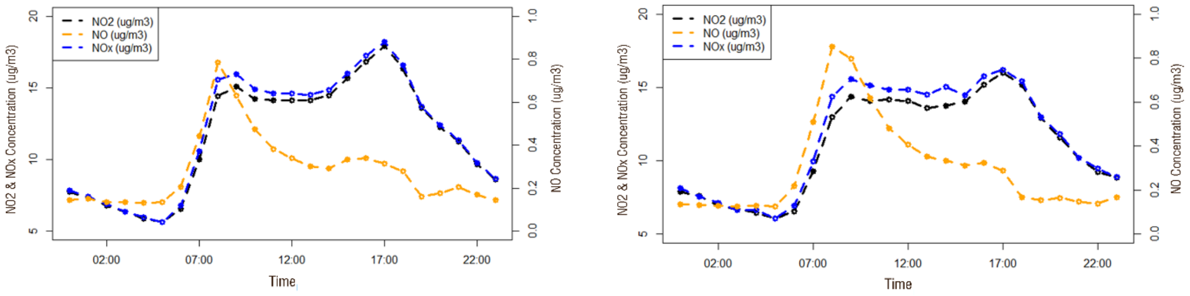
The average annual concentration of NO2 in the Puncak Bogor area in 2019 was 11.6 mg/m3, and in 2020 it was 11.1m g/m3. Both values do not exceed the one-year National Ambient Air Quality Standard value of 50 mg/m3. The pattern of diurnal fluctuations in NO2, NO, and NOx concentrations in 2019 and 2020 in the Puncak Bogor area looks similar but has different values, especially since the maximum concentration value in 2019 is higher than in 2020 (Figure 3). This difference is caused by restrictions on community activities when entering the COVID-19 pandemic. Around the location of the Cibeureum monitoring station, there are many tourism-related activities, such as hotels or villas and Taman Safari Indonesia, which experienced a decrease in visitors during the pandemic, so the number of transportation needed entering the area is also affected, while also reducing pollutant emissions. According to analysis results in several cities such as China, India, and California, NO2 and NOx concentrations decreased during the COVID-19 pandemic in 2020 (Zhang et al., 2021; Liu et al., 2021; Misra et al., 20221; He et al., 2021; Gough & Anderson 2022). The three concentrations started to increase at 05:00 WIB, with the concentration of NO reaching its peak first at 08:00 WIB, while the concentration of NO2 and NOx at 09:00 WIB. Then the NO concentration decreased, and around 16:00 WIB experienced a slight increase but not more significant than the first peak. NOx diurnal fluctuations have a pattern of 2 peak concentrations, morning and evening.

Meanwhile, the concentration of NO2 and NOx still has a high value during the day and has a second peak at 17:00 WIB with a higher value. This diurnal pattern is similar to the results of a study conducted by Bassani et al. (2021) and Pancholi et al. (2018), which showed that NO2 and NO concentrations in rural Italy and Jodhpur India had two concentration peaks occurring in the morning and evening, with the second peak of NO being lower. The concentration of NOx that increases earlier in the morning can be produced by vehicle emissions from the wind and using fertilizers on agricultural land, especially N-fertilizer (Almaraz et al. 2018). Then, the NO available in the atmosphere reacts with ozone to form NO2 (equation 5). This causes the time lag at the peak of NO and NO2 concentrations in the morning Gasmi et al. (2017).

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad (3)$$

During the day, ozone is still available in the atmosphere because solar radiation assisted its formation, so the NO2 formation reaction still occurs. Therefore, the concentration of NO2 and NOx still has a high value during the day, while the concentration of NO decreases. The higher concentrations of NO2 and NOx at the second peak resulted from the gradual accumulation of the reaction products between NO and O3 to form NO2, even though the radiation began to decrease (Song et al., 2011). At night, when ozone is unavailable in the atmosphere, the concentrations of NO2 and NOx decrease drastically. This happens because at night, the formation of O3 does not occur, and the source of NO emission is also reduced so that the appearance of secondary NO2 also decreases (Han et al. 2011). The fluctuation of PM2.5 concentration compared to its precursor indicates a time lag when the attention of the two pollutants increases and decreases. Figures 4 and 5 show that the NOx concentration increased first around 05:00 WIB, while the PM2.5 concentration increased at 07:00 WIB. Likewise, when the NOx concentration decreased first around 17:00 WIB, the PM2.5 concentration also decreased at 19:00 WIB.

According to Manning et al. (2018), the diurnal PM2.5 cycle is driven by the influence of local emissions, meteorological conditions, and secondary PM2.5 production. The concentration of PM2.5 increases during the day due to the formation of secondary PM2.5 that occurs through the chemical reaction of the precursor gas with solar radiation (Li et al., 2015).



(a) (b)

Figure 3. Diurnal average concentrations of NO_2, NO, and NO_x (a) in 2019 (b) in 2020

According to Svoboda et al. (2000), $NO + HO_2 \; NO_2 + OH$, then NO_2 decomposes in the presence of solar radiation into NO and O, and O reacts with O_2 to produce O_3. Data from Cibeureum shows that the diurnal concentration of NO_x will be closely related to NO and Ozone. As result of data analysis at Puncak in 2020, the concentration of $PM_{2.5}$ has decreased, while the concentration of NO_x is not different from 2019.

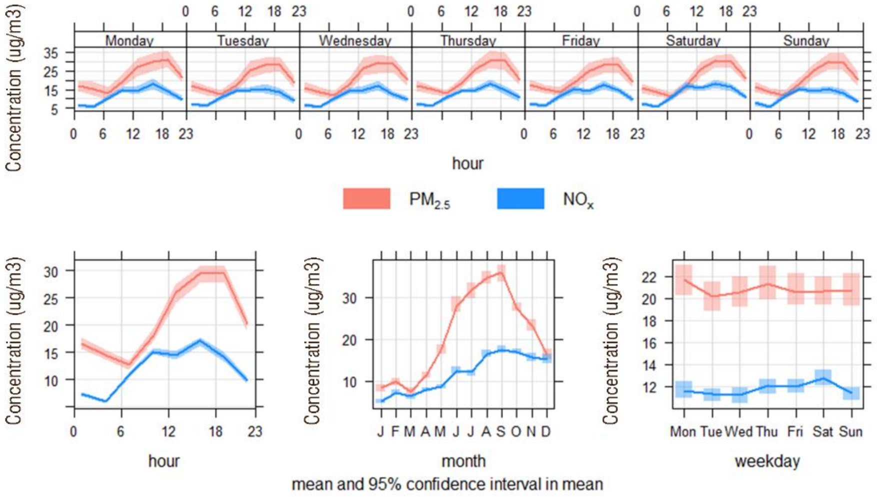


Figure 4. Fluctuations in average daily, diurnal, and monthly $PM_{2.5}$ and NO_x concentrations in 2019

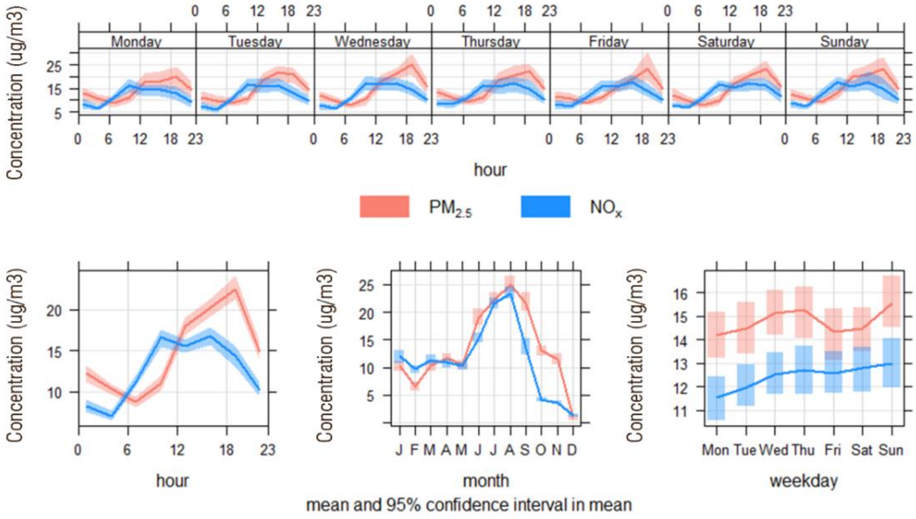
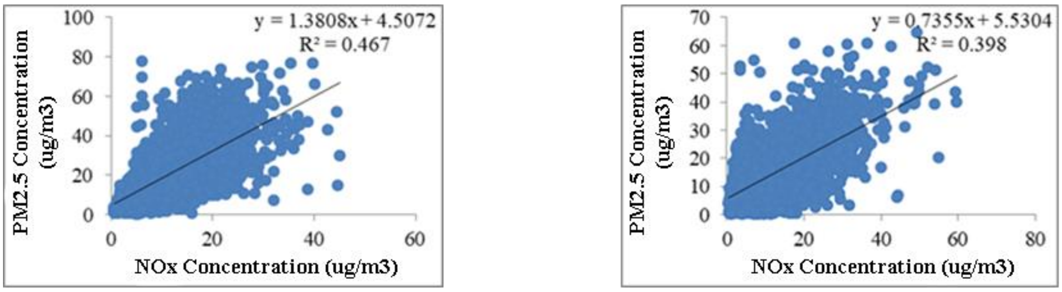


Figure 5. Fluctuations in average daily, diurnal, and monthly average concentrations of $PM_{2.5}$ and NO_x in 2020

The average daily and monthly NOx concentrations showed an increase in 2020; this is a different condition from the general conditions during the pandemic, namely a decrease in pollutant concentrations, including NOx (Misra et al., 2021; He et al., 2021; Bartonova et al., 2022). The conditions around the Cibeureum monitoring station are very close to community agricultural activities, so there is a possibility of increased agricultural activities during the lockdown period, which affects N emissions from the fertilizers used, and contributes to the formation of NOx in the air. However, there is a need for further identification regarding this matter. However, there is a significant difference in the diurnal average hourly PM2.5 concentration in 2019 and 2020. Based on this, the decrease in PM2.5 concentration in 2020 could be due to a reduction in the primary PM2.5 emission source in the Puncak Bogor area. As a result of the implementation of the large-scale social restriction. The daily concentration pattern of PM2.5 and NOx tends to increase on weekends; this is related to the characteristics of the Puncak Bogor area as a tourist destination so that the emission of transportation modes of visitors who come every day contributes to the pollutants found in the Puncak Bogor area. Monthly fluctuations in PM2.5 and NOx concentrations in 2019 and 2020 showed a similar pattern, namely when the NOx concentration increased, accompanied by an increase in PM2.5 concentration, and vice versa when the concentration decreased. Both pollutants tend to grow in the dry season and drop in the rainy season; according to Mukhtar et al. (2013), when it rains, the pollutants floating in the air will be carried away along with the rain.

Based on the results of the correlation analysis, the diurnal average concentration of PM2.5 with its precursor concentration had a significant positive correlation in 2019 ($r = 0.68$) and 2020 ($r = 0.63$). These results are similar to those of Wang et al. (2020). They found a significant positive correlation between the concentration of PM2.5 and the concentration of NOx in China due to the second conversion of NOx affecting the formation of PM2.5 in China. The p-value generated in 2019 and 2020 is < 0.05; it can be said that the diurnal average concentration of NOx significantly affects the diurnal average concentration of PM2.5 in 2019 (Figure 6).



(a) (b)

Figure 6. Scatter plot diagram of the diurnal average concentration of PM2.5 with NOx (a) 2019 (b) 2020

3.2. Analysis of the Effect of Meteorological Factors on PM2.5 and NOx. Concentrations

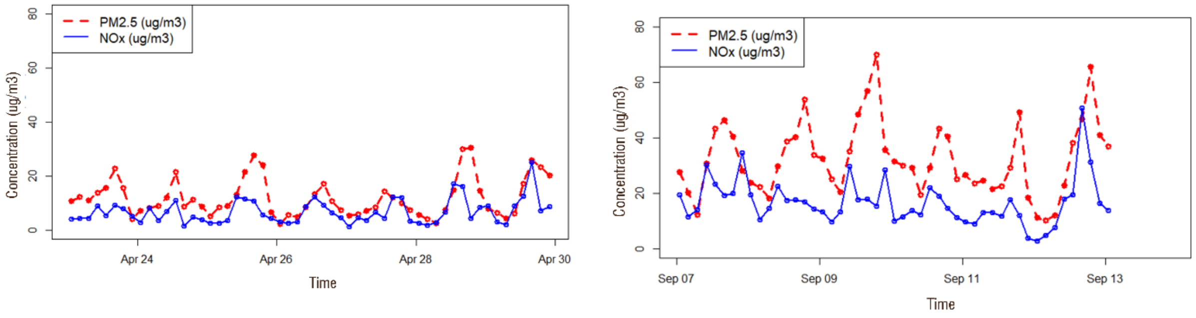
According to Manning et al. (2018), the diurnal PM2.5 cycle is driven by the influence of local emissions, meteorological conditions, and secondary PM2.5 production. The results of the correlation analysis of pollutant concentrations with meteorological factors resulting in a relatively low correlation coefficient (r), the highest for NOx with temperature ($r = 0.36$), are shown in Table 1. Common r values for PM2.5 per 3 hours and NOx concentrations per minute in the Cibeureum Puncak Bogor area show that meteorological factors are not the dominant factor in influencing fluctuations in the concentration of these pollutants. PM2.5 and NOx were positively correlated with air temperature in 2019 and 2020. According to the research of Wang and Ogawa (2015), An increasing temperature can support the reaction of secondary pollutant formation and increase PM2.5. Increasing humidity encourages particles to grow more prominent and become too heavy so that deposition occurs to the surface so that the measured particulate concentration decreases.

NOx concentration has small negative correlation with relative humidity (RH) in 2019 and 2020. This is related to ozone which plays a role in the oxidation reaction process of NO2 formation. Ozone concentration will increase as temperature increases and humidity decreases. The increased ozone concentration triggers a reaction to the formation of NO2. .

Table 1. Correlation coefficient (r) of PM2.5 and NOx concentrations with meteorological parameters

Pollutant	Air Temperature		Relative Humidity		Precipitation		Wind Velocity	
	2019	2020	2019	2020	2019	2020	2019	2020
PM2.5	0.15	0.10	-0.16	0.03	-0.03	0.00	-0.08	-0.15
NOx	0.36	0.31	-0.17	-0.12	-0.02	-0.04	-0.10	-0.15

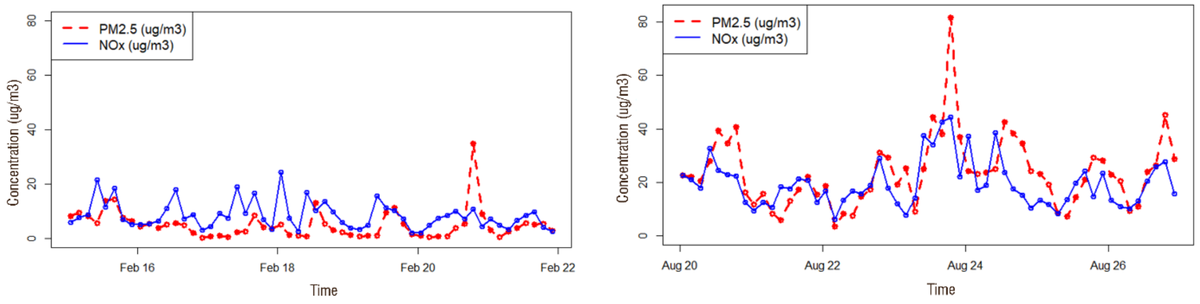
The effect of precipitation for real-time data does not show a significant correlation in Cibeureum. According to Zhao et al. (2020), rainfall has a washing effect depending on the intensity and the mass of pollutants. High rainfall is more effective at cleaning large particles than small particles. Therefore, an analysis was carried out using the period of the highest and lowest precipitation and a study of monthly rainfall.



(a) (b)

Figure 7. Fluctuations in PM2.5 and NOx concentrations for one week (a) high rainfall (b) low rainfall in 2019

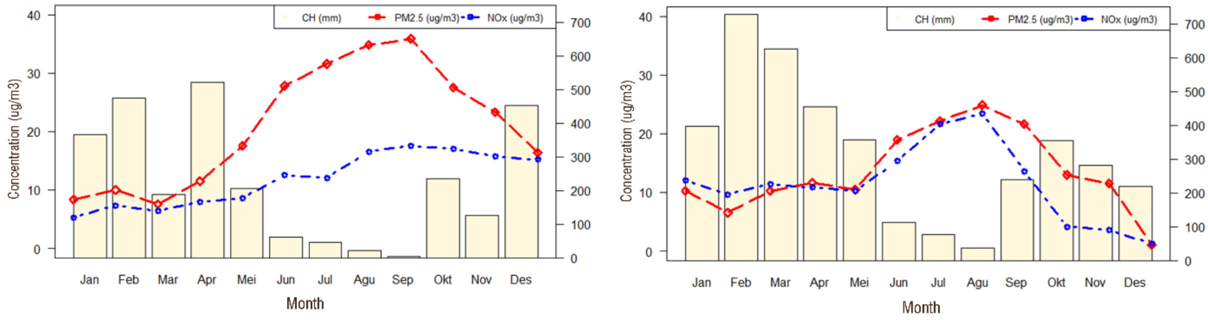
PM2.5 and NOx concentration data were analyzed in two time periods, namely 23-29 April 2019 (highest precipitation) and 7-13 September 2019 (lowest precipitation) and 15-21 February 2020 (highest precipitation) and 20-26 August 2020 (lowest precipitation) to see real-time fluctuations in PM2.5 concentration and its precursor concentration (Figure 7 and Figure 8). The analysis results show that in periods of high precipitation, the attention of PM2.5 and NOx is lower than in periods of low precipitation, both in 2019 and 2020. Fluctuations in the concentrations of PM2.5 and NOx appear large in the dry season, while changes in concentration are minor in the rainy season. In the rainy season, rainfall effectively reduces pollutant concentrations, which is indicated by the low concentration values in the rainy season in both 2019 and 2020. In 2020, the pollutant concentration decreased, and the decrease in PM2.5 was more significant than NOx. This is because the formation of NO2 continues to occur with the help of sunlight and ozone. Also, around the monitoring location, there are agricultural areas that are active and have the potential to contribute to N emissions that trigger NOx formation. PM2.5 concentration fluctuations, which are very close to NOx fluctuations in the dry season of 2020, show that in that year, even though it was dry, the concentration was not as high as in 2019 because it was supported by reduced primary particulate emissions from motor vehicles and community activities in tourist areas. According to Arunanta (2020), the number of cars crossing the Puncak Bogor area in 2020 has decreased by 70-80% as a result of the implementation of Large-Scale Social Restrictions in the Jakarta area and its surroundings. Therefore, it can be indicated that the decrease in PM2.5 concentration in 2020 is more due to reduced vehicle emissions as the primary source of PM2.5 in the Puncak Bogor area. Although the monitoring station location is in a higher place and not directly adjacent to the main highway, activities in the surrounding tourist sites also contribute.



(a) (b)

Figure 8. Fluctuations in PM2.5 and NOx concentrations (a) high rainfall (b) low rainfall in 2020

Monthly rainfall in the Puncak Bogor area in 2019 and 2020 has a monsoon pattern, namely high rainfall at the beginning and end of the year (Figure 10). Based on monthly data, in the dry season, there is an increase in pollutant concentrations and vice versa. Rain has a role in washing the air (rainwash) and dissolving pollutant particles and other gases in the air. The higher the rainfall, the greater its ability to dissolve gas and pollutant particles in the air (Prabowo & Muslim, 2018). Based on the correlation results, the monthly PM2.5 concentration and rainfall have a significant negative correlation in 2019 (r = -0.80) and 2020 (r = -0.63). The monthly concentration of NOx also has a negative correlation with rainfall in 2019 (r = -0.53) and 2020 (r = -0.43). The resulting p-value shows that monthly rainfall significantly negatively affects the average concentration of PM2.5 with an R2 value of 63.58% in 2019 and 39.60% in 2020, while the NOx concentration has no significant effect (p-value > 0.05) both in 2019 and 2020. It is estimated that other factors influence NOx fluctuations around Cibeureum and require further research.



(a) (b)

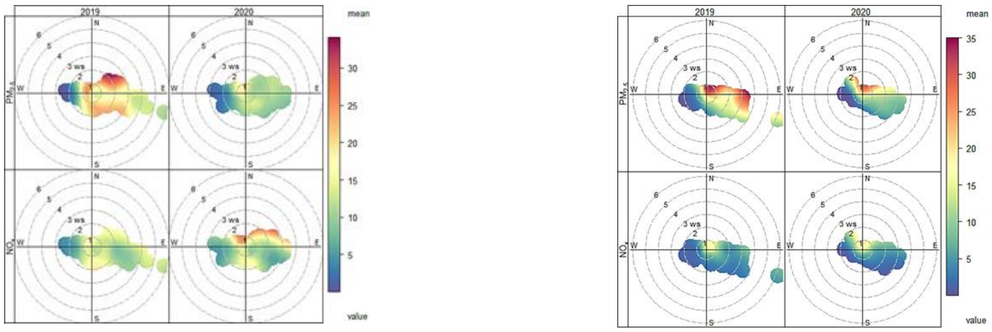
Figure 9. Monthly fluctuations of PM2.5 concentration, NOx concentration, and rainfall (a) in 2019 (b) in 2020 in Puncak Bogor

3.3. The influence of Wind Direction and Speed on PM2.5 and NOx Concentrations at Bogor Peak

Wind can significantly affect pollutant concentrations. In general, high wind speeds can reduce pollutant concentrations. Wind speed accelerates the spread of pollutants and can also dilute pollutants (Godish, 1977). Figure 11 shows the distribution of PM2.5 and NOx concentrations along with the wind direction that blows during the day (Figure 11a) and at night (Figure 11b). This polar plot chart is analyzed based on two time periods: daytime (07:00 to 16:00) and night (19:00 to 04:00) in 2019 and 2020.

At noon in 2019, the maximum concentration of PM2.5 was measured along with winds from the Northeast (2-3 m/s) (Figure 11a). This is related to settlements and lodging places such as guesthouses, villas, and other tourist destinations in the Northeast Cibeureum area. In addition, there are activities engaged in agriculture that have the potential to produce emissions. In addition, the measured PM2.5 and NOx concentrations were lower when the wind was blowing from the west than the east wind. This can be presumed as a result of the western part of the Cibeureum area, which is less densely populated.

In 2020, it was seen that the value of PM2.5 concentration during the day decreased (Figure 10b). Due to the existence of Large-Scale Social Restrictions *Pembatasan Sosial Berskala Besar (PSBB)* reducing additional sources of pollutants in the Puncak Bogor area, the activities of the surrounding community only influence those pollutant concentrations. The concentration of NOx increased along with the wind from the North and Northeast (speed 2-3 m/s).



(a) (b)

Figure 10. Polar plot of PM2.5 and NOx concentrations in 2019 and 2020 (a) during the day (b) at night

At night in 2019, the maximum concentration of PM2.5 was measured along with winds from the north with low speed (1 m/s), Northeast, and the East (3.5 m/s). This is related to several lodging places and community activities compared to other directions. In addition, Liu et al. (2020) stated that under certain geographical conditions and dominant wind directions, an increase in wind speed can increase the concentration of PM2.5. The dominant wind direction at night comes from the Southeast, which coincides with the position of Mount Gede-Pangrango, so the wind that blows is a mountain wind. Wind characteristics from the mountains are cleaner, so the polar plot is bluer, indicating low pollutant concentrations.

4. Conclusions

The annual average PM2.5 concentration in 2019 (20.8 mg/m3) was higher than in 2020 (14.8 mg/m3), and also the concentration of NO2 in 2019 was 11.6 g/m3, higher than in 2020 (11.1 g/m3) The diurnal fluctuations of PM2.5 concentration in 2019 and 2020 have a unimodal pattern, with peak concentrations occurring at night. Meanwhile, fluxes in NO2, NO, and NOx concentrations in 2019 and 2020 have a bimodal pattern, with peak concentrations occurring in the morning and evening.

The fluctuation of diurnal PM2.5 concentration had a significant positive correlation with NOx concentration as precursor (r2019 = 0.68; r2020 = 0.63). The meteorological factors such as air temperature, relative humidity, and wind speed had little correlations to PM2.5 and NOx concentrations, whether in 2019 or 2020, except for air temperature to NOx concentration, which had a correlation coefficient value r = 0.36. The influence of precipitation was analyzed in specific periods, mainly high precipitation periods and lower precipitation periods. It showed that the concentrations of PM2.5 and NOx are lower in periods with high precipitation, both in 2019 and 2020. The fluctuation of both pollutants concentrations is higher when precipitation is lower, and vice versa.

Influence of wind analyses showed that the dominant wind that blows during the day in the Puncak Bogor area comes from the West and coincides with lower concentrations of PM2.5 and NOx. Concentrations are higher during the day as winds blow from the North, Northeast to East directions, which is associated with valley breezes, carrying pollutants from residential areas and tourist attractions. While at night, the dominant wind is from the Southeast, along with low concentrations of PM2.5 and NOx. This is related to the Southeast Gede Pangrango Mountains, so the wind from the Southeast is assumed to bring clean air masses from the top of the mountain. However, at night the PM2.5 concentration is high along with the wind blowing from the Northeast at low speed and East at the higher rate, which is thought to carry pollutants from around the residential areas (resorts and agriculture).

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