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Regional Case Study

Determination of Fine Particulate Matter Episode Periods in Jakarta by Incorporating Meteorological Conditions

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Abstract

The analysis of observed fine particulate matter (PM2.5) in Jakarta, Indonesia, was conducted from January 2021 to October 2023 using hourly monitoring data from AirNow, managed by the U.S. Environmental Protection Agency. Data were collected from two air quality monitoring stations in Central and South Jakarta. Meteorological data, including wind speed, temperature, humidity, and rainfall, were obtained from NASA's global forecasting database. The objective was to understand the correlation between PM2.5 formation and meteorological conditions to identify favorable meteorology during high air pollution episodes. During the dry season (May to August), there was a notable increase in PM2.5, linked to higher temperatures, lower humidity, slower wind speeds, and minimal rainfall. The results showed that meteorological conditions significantly affected PM2.5 concentrations, influenced by seasonal changes. In contrast, the rainy season had lower PM2.5 concentrations due to higher rainfall, humidity, and wind speed, and lower temperatures. Further modeling studies are required to assess the combined impacts of emission build-up and meteorology on recurring PM2.5 episodes in Jakarta.

Keywords: PM2.5; meteorology; episode; air quality; Jakarta

1. Introduction

In 2022, Jakarta had a population density of 16,084 individuals per square kilometer, making it one of the most densely populated cities in Indonesia.. High population density will trigger an increase in the sectoral intensity such as industrialization, transportation, and others in the effort to strengthen the economic growth . The negative impact of this increasing anthropogenic activities is the increased consumption of fossil fuel which in turn causing the deteriorated air quality in the city (Tiarani et al., 2016; Yunita and Kiswandono; Permadi and Oanh, 2008). In the absence of control measures, this air pollution problem can have a severe impact on human health (Amalia et al., 2022).

One of the critical pollutants that often exceeds the National Ambient Air Quality Standards set in the Ministry of Environment and Forestry Number 22 of 2021 is fine particulate matter which has aerodynamic diameter of less than 2.5 micronmeter (PM2.5). The elevated level of emissions in urban areas, particularly during periods of heavy traffic congestion, is a result of the massive increase of motorization in Jakarta. PM2.5 pollutant was reported by Amalia et al., (2022) to be the main pollutant that causes air quality in Jakarta to fall into the unhealthy category with an air quality index value of 156. This was partly due to the the total primary PM2.5 emission burden in Jakarta for the year of 2015 of 7,842 tons/year (Lestari et al., 2020).

PM2.5 has become a concern in the world because it has a small size (smaller than PM10) which in turn the particles possess significant potential for adverse effects on human health as they can easily enter the respiratory system, penetrate deep into the lungs, irritate and corrode the alveoli, ultimately causing damage to lung function (Narita et al., 2019). According to research published by the Health

Effects Institute in Cambridge, MA, increased PM2.5 concentrations in the atmosphere may result in an increased number of premature deaths and increase the number of elderly people requiring hospitalization due to chronic heart and lung diseases (Samet et al., 2000). In addition to direct human impacts, PM2.5 also has environmental impacts that include reduced visibility, cloud formation, modification of heat flow in the atmosphere which results in increased surface temperatures, and thus contributes to climate change (Santoso et al., 2020). To address these issues, particularly the elevated levels of PM2.5 pollutants in Jakarta, it is crucial to comprehend the processes involved in the formation and accumulation of PM2.5 within a specific region. Air quality monitoring and modeling applications are one of the tools that can be used to understand this process (Permadi and Oanh, 2008) In general, the PM2.5 formation process is always influenced by regional meteorological conditions. Several research studies have consistently shown a significant correlation between PM2.5 and meteorological conditions, with a particular emphasis on seasonal variations (Driejana et al., 2020).

A previous study on PM2.5 concentration analysis using the gravimetric method taken in 2011 (Muliane and Lestari, 2011) indicated a lack of PM2.5 monitoring data could be a barrier to understanding the condition of pollutants in an area. PM2.5 monitoring data in Jakarta has just started in 2019 at the limited number of governmental air quality monitoring stations and full measurements were only available in 2021 from all stations (Nelvidawati, 2022). Data summary from those stations are publicly shown in the website but episode analysis has been never done before. This is important to understand the role of meteorological conditions on the PM2.5 pollution build up in Jakarta. Impact of primary PM2.5 emissions can be done using integrated emission inventory and modeling study. The simulation can be initially focused on the suggested episode periods investigated in this research to formulate mitigation options.

2. Methods

2.1 Location of Study

We focused our study in the capital city of Indonesia, Jakarta, which is centered at -6.22 (latitude) and 106.81 (longitude). Jakarta is considered as province which consists of 6 cities and it is located in the western part of Java Island (see Figure 1). Population of the province was reported of nearly 10.6 million people in 2022 with total number of registered vehicle of nearly 22 million unit. With several industrial estates located inside and outside of the province, air pollutant emission burden is significant hence air quality deterioration was reported especially for PM2.5 (Santoso et al., 2020; Santoso et al., 2021).

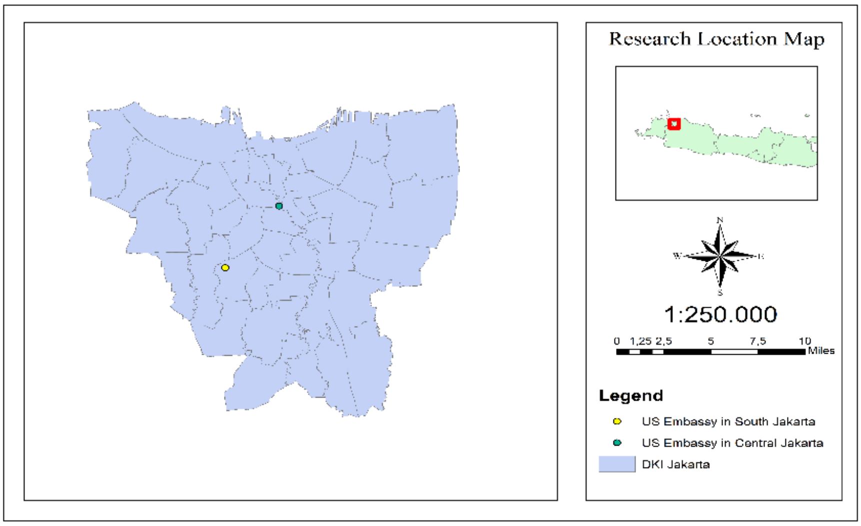


Figure 1. Research Location Map

2.2 Data Collection

The information gathered for this research comprises secondary data encompassing air quality data (specifically PM2.5) and meteorological data, including temperature, humidity, wind speed, and rainfall. Air quality data (PM2.5) were taken from the U.S. Department of State Indonesia's air quality monitoring system located in Central Jakarta and South Jakarta with a 24-hour continuous monitoring system that can be accessed through the website https://www.airnow.gov/?city=&country=IDN (see Figure 1 for the location of the stations). These air quality data are provided under the global initiative of AirNow which conducts ambient monitoring for the United States (US) embassies and consulates around the world and managed by the US Environmental Protection Agency (EPA). Note that there are other automatic air quality monitoring stations (AQMs) managed by the Jakarta provincial EPA however the raw data are not published which further prevents in-depth analysis.

In addition, the meteorological data used were obtained from the Prediction of Worldwide Energy Resources (POWER) database from the National Aeronautics and Space Administration (NASA) of the United States which was accessed at https://power.larc.nasa.gov/data-access-viewer/. The data provided world-wide meteorological fields generated by global circulation model including wind speed, temperature, relative humidity, and precipitation.

2.3 Data Analysis and Visualization

Data analysis using PM2.5 concentrations per day survived one year (2021-2023) which will be compared with Government Regulation of the Republic of Indonesia Number 22 of 2021 concerning the Implementation of Environmental Protection and Management per day for the PM2.5 parameter of 15 μg/m^3. PM2.5 and meteorological conditions also will be correlated using simple linear regression which will be analyzed through the constant b (slope) value obtained with a sig value <0.05 if the sig value $>$ 0.05 then the slope is declared not significantly different from 0 or it can be said that at that time meteorological conditions have no effect on PM2.5. Subsequently, the analysis is conducted by contrasting the daily PM2.5 concentrations over a year with the established quality standards. Episodes are then identified based on the daily maximum PM2.5 concentration exceeding the Ministry of Environment and Forestry (MoEF) No 22 of 2021 national ambient air quality standard for two consecutive days are recommended. Meteorological conditions were analyzed under episodic (maximum PM2.5) conditions and simple linear regression analysis was performed (Permadi and Oanh, 2008). Visualization of the data was done using the Origin software version 10.1.0.170.

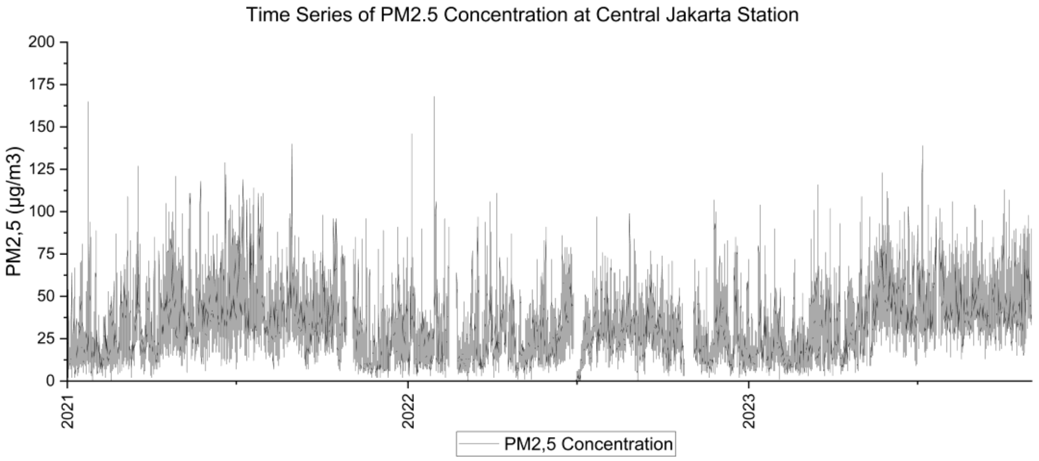
AirNow data quality assurance / quality control (QA/QC) is reported to follow the EPA's regulatory database - the Air Quality System (AQS). We also conducted outlier analysis prior to data presentation to ensure the data are in the common sense of magnitude. Error marked data from the website were considered as no data rather than zero concentration. POWER NASA meteorological data are used for global forecasting nowadays which means that carefull evaluation against the global observation has been conducted regularly.

3. Result and Discussion

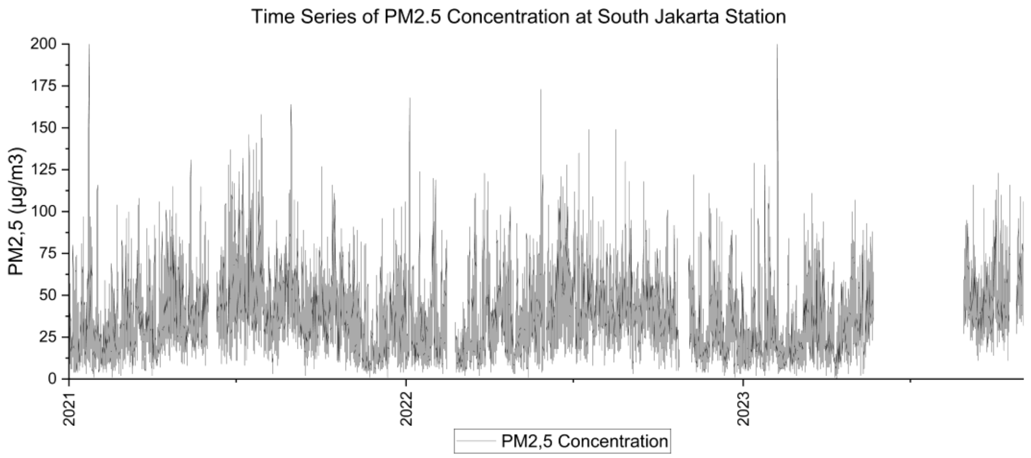
3.1 Time Series Particulate Matter 2,5

We analyzed of three years period (2021-2023) of observed PM2.5 data obtained from AirNow. We intend to analyze the most recent conditions hence these years period were chosen. AirNOW presents data from only two existing stations located in Central Jakarta and South Jakarta (see Figure 1). In Central Jakarta, the highest PM2.5 hourly measured concentrations for 2021 and 2022 coincided in January with observed value of 189 μg/m^3. However, in 2023, the highest PM2.5 hourly measured concentration occurred in July of 139 μg/m^3 (Figure 2. a). The data completeness at the Central Jakarta station for 2021, 2022, and 2023 were 98.08%, 93.29%, and 82.25%, respectively. In South Jakarta, the highest PM2.5 concentration in 2021 was recorded in January of 202 μg/m^3, followed by May in 2022 with a concentration of 173 μg/m^3. In 2023, the peak PM2.5 concentration took place in February, reaching 204 μg/m^3 (Fig 2.

b). Data completeness for the years 2021, 2022, and 2023 in South Jakarta were calculated of 97.29%, 93.93%, and 53.94%, respectively. Elevated PM2.5 concentrations during the middle of the year may be attributed to meteorological factors such as temperature, humidity, rainfall, and wind speed. For instance, a study by Hutauruk et al. (2020) indicated that PM2.5 concentrations in Jakarta from 2016 to 2019 exhibited higher values during the dry season in June-August. Similarly, Driejana et al. (2020) reported lower PM2.5 concentrations during the rainy season and higher concentrations during the dry season.



(a)

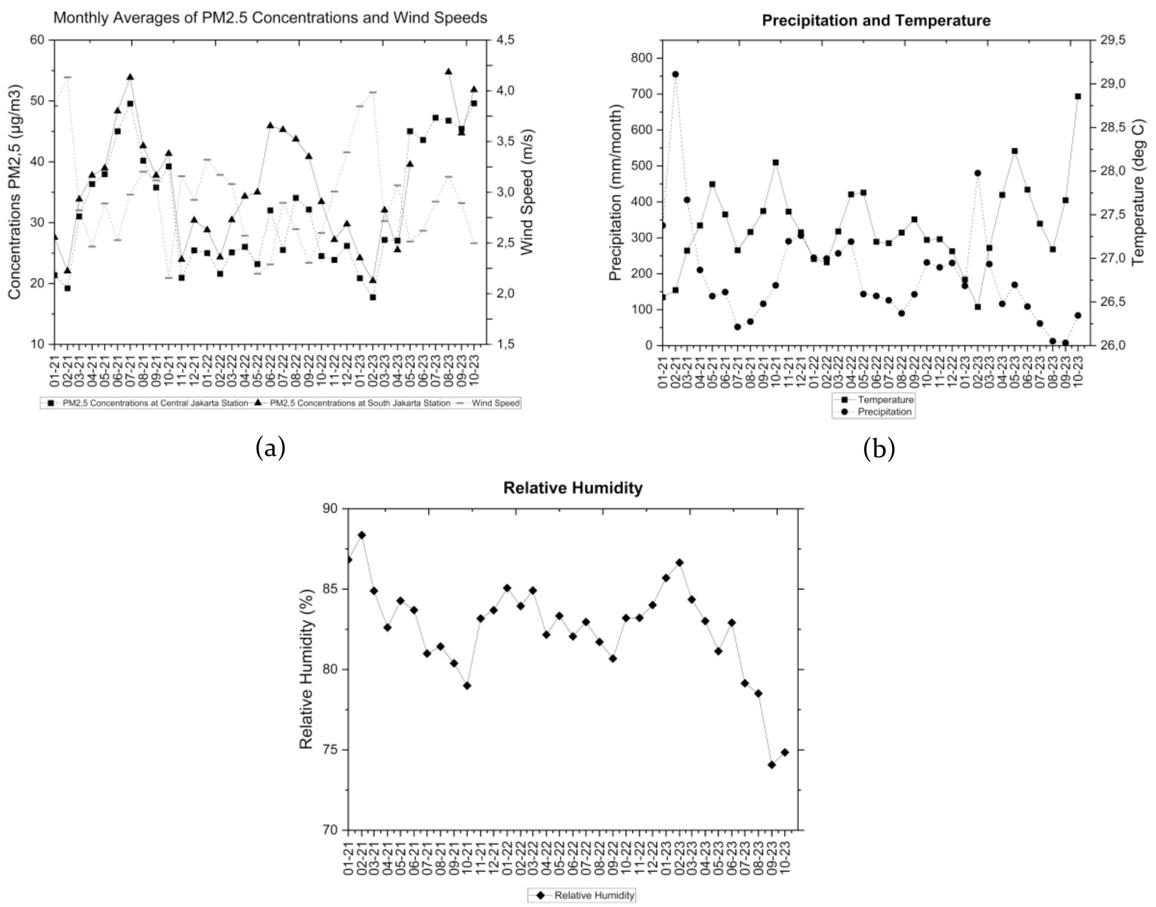


(b)

Figure 2. Time series of PM2.5 Concentration per hour in jakarta 2021-2023 (a) at north jakarta station (b) at south jakarta station

3.2 Monthly Variation of Particulate Matter 2.5 in DKI Jakarta and Meteorological Conditions

In (Figure 3) it is evident that the monthly average hourly PM2.5 concentration is significantly impacted by meteorological conditions. The rise in PM2.5 concentration from 2021-2023 is predominantly observed during the dry season months, specifically from May to August. The peak PM2.5 concentration occurred in July, averaging 53.86 µg/m3 in 2021. In 2022, the highest PM2.5 concentration took place in June with an average value of 45.9 µg/m3, while in 2023, it was observed in August with an average value of 54.75 µg/m3. This phenomenon is attributed to the dry season conditions characterized by lower wind speeds (2.20-3.20 m/s), higher temperatures (27-28 °C), lower relative humidity (79-81%), and reduced rainfall (12-169 mm/month), which collectively contribute to elevated PM2.5 concentrations in the atmosphere (Chen et al., 2016; Driejana et al., 2020; Yang et al., 2011). This aligns with findings by Driejana et al. (2020), indicating that PM2.5 concentrations tend to escalate at the onset of the dry season, specifically in May-June, and decline with the advent of the rainy season.



(a) (b)

(c)

Figure 3. (a) Monthly average variation of PM2.5 concentration and wind speed, (b) precipitation, temperature, (c) relative humidity conditions in Jakarta during January 2021-October 2023

3.3 Diurnal Variation of Particulate Matter 2.5

The yearly average hourly PM2.5 concentration displays a consistent pattern, characterized by a morning peak occurring between 07:00-09:00 and an evening peak between 21:00-23:00, while the lowest PM2.5 concentration transpires between 16:00-18:00 (Fig 4.). This trend aligns with the findings of Driejana et al. (2020), who reported higher morning PM2.5 concentrations compared to the afternoon in their research. This phenomenon is attributed to the prevailing weather conditions in Jakarta and is in accordance with the observations made by Manning et al. (2018), indicating a similar PM2.5 concentration pattern across diverse regions.

The morning elevation in PM2.5 concentrations is influenced by the lower hourly average temperatures in Jakarta, rendering the air mass or aerosols in the lower atmosphere denser, hindering their ascent. In contrast, higher temperatures in the afternoon result in the heating of the dense air mass, making it lighter and conducive to upward movement (Driejana et al., 2020). This explanation is supported by the findings of J. Guo et al. (2017) in China, revealing that half of the observed sites exhibited morning peaks in PM2.5, likely due to intense solar radiation in the afternoon, promoting the rapid dispersion of aerosol particles and reduced mass concentrations. A similar trend was observed in a study by Chen et al. (2016) in China, where PM2.5 values consistently decreased from noon to late afternoon/early evening.

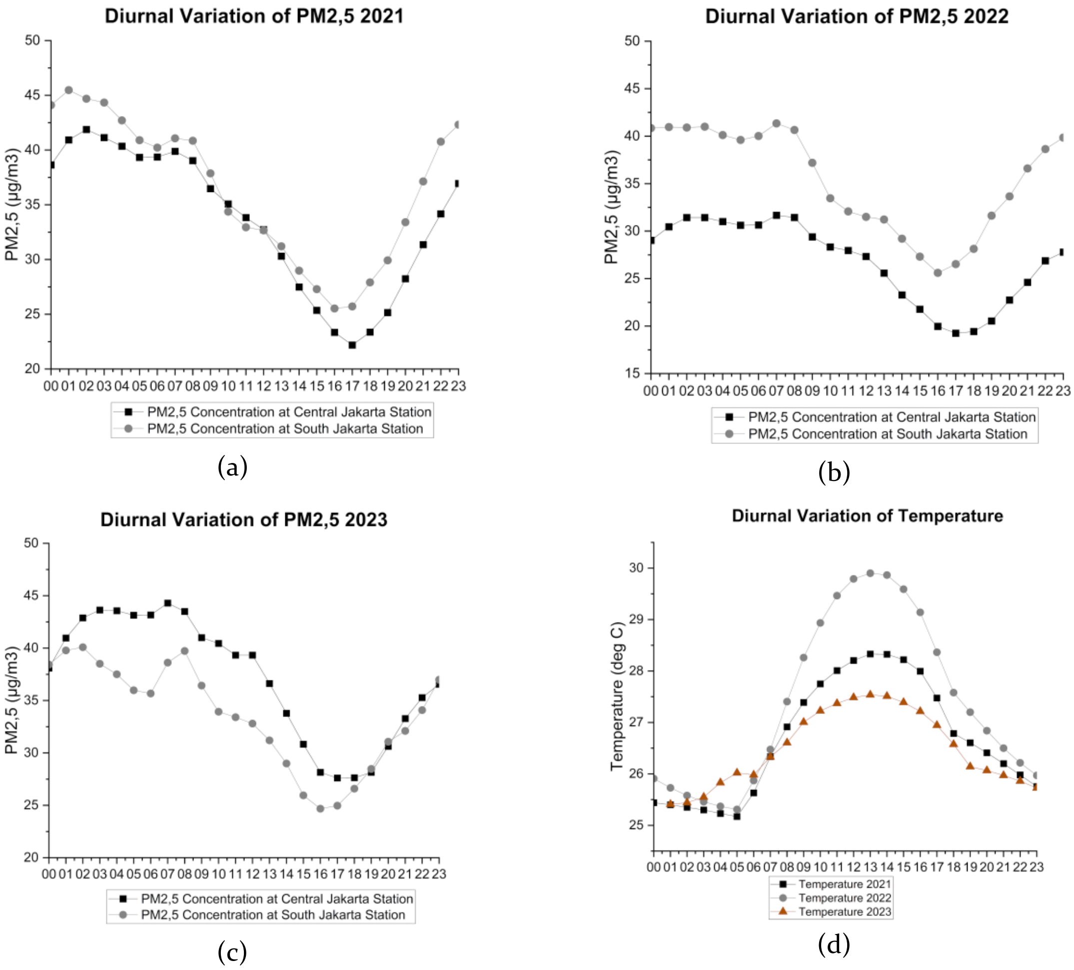


Figure 4. Diurnal variation of PM2.5 concentration in (a) 2021, (b) 2022, (c) 2023 and (c) temperature at two monitoring stations.

3.4 Annual Average Concentration of Particulate Matter 2.5

The yearly average PM2.5 concentration in Jakarta consistently surpasses the quality standards outlined in Government Regulation of the Republic of Indonesia Number 22 of 2021 concerning the Implementation of Environmental Protection and Management, as detailed in (Table 1.). In Central Jakarta, the highest PM2.5 concentration was recorded in 2023, reaching 37.16 µg/m3, while at the South Jakarta station, the highest PM2.5 concentration occurred in 2021, measuring at 36.36 µg/m3.

Table 1. Annual average PM2.5 concentration

Year	PM2.5 Concentration		Standard *	Unit
	Central Jakarta Station	South Jakarta Station		
2021	33.60	36.36	15	µg/m³
2022	26.77	35.34	15	µg/m³
2023	37.16	33.59	15	µg/m³

*Government Regulation of the Republic of Indonesia Number 22 of 2021.

3.5 Correlation between PM2.5 and meteorological conditions

Table 2 illustrates the correlation between daily PM2.5 concentrations and meteorological factors (temperature, humidity, rainfall, and wind speed) at the monitoring stations in Central Jakarta (JP) and

South Jakarta (JS) using simple linear regression. Among all the parameters, it is evident that temperature exhibits a robust positive correlation with PM2.5, indicating that elevated temperatures correspond to increased PM2.5 levels in the air. This association is attributed to the heightened photochemical activity in the atmosphere under high temperatures, leading to the production of more PM2.5 secondary particulates (Chen et al., 2016). Notably, for the temperature parameter, there are nine months with significance values exceeding 0.05, suggesting that during these months, temperature does not significantly impact PM2.5. Conversely, wind speed demonstrates a substantial negative correlation with PM2.5, signifying that higher wind speeds result in decreased PM2.5 levels in the air. This effect is due to the increased diffusion and mixing processes in the air when wind speed rises (Yang et al., 2011). However, there are months within the wind speed parameter where significance values exceed 0.05. Similar to wind speed, rainfall and humidity also exhibit negative correlations with PM2.5, although not as strong as wind speed. In the rainfall parameter, there are eight months with significance values exceeding 0.05, while in the humidity parameter, only three months show significance values above 0.05. Despite the negative correlation between temperature and PM2.5 and the positive correlation between wind speed, humidity, rainfall, and PM2.5 throughout the entire period, it is noteworthy that some of these correlations have significance values exceeding 0.05. This indicates that during those periods, meteorological conditions may not significantly influence PM2.5 values. In summary, the analysis suggests that meteorological conditions exert a complex influence on PM2.5 concentrations.

Table 2. Constant b (slope) of daily PM2,5 related with meteorogical parameters

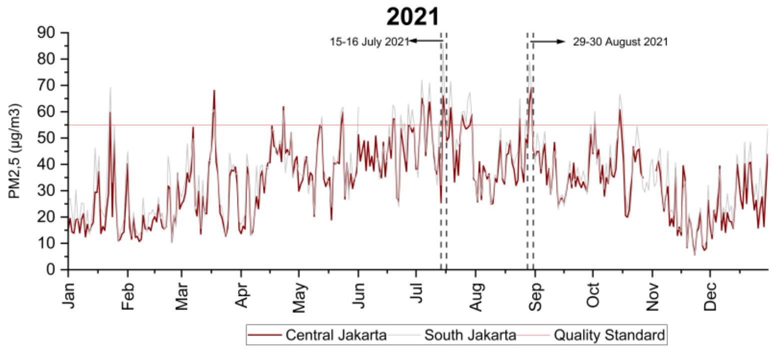
Month	Temperature		Relative Humidity		Precipitation		Wind Speed	
	JP	JS	JP	JS	JP	JS	JP	JS
January	7.297*	6.415*	-1.329	-1.153	-0.292*	-0.213*	-8.623	-9.873
February	4.615*	2.814*	-0.658*	-0.374*	-0.085*	-0.096*	-4.539	-6.186
March	8.846*	12.001*	-2.525	-3.190	-0.08*	-0.118*	-8.265	-9.894
April	6.026*	9.782*	-1.835	-2.103	-0.270*	-0.131*	-7.252	-9.351
May	9.442*	3.738*	-1.556	-0.932	-0.218*	-0.066*	0.913*	-1.884*
June	-0.041*	-6.003*	0.756*	0.321*	-0.117*	-0.237*	0.266*	-3.205*
July	0.493	2.937	-1.769	-1.346	-1.128	-0.835	0.421*	-1.542*
August	-3.629	-7.296	-1.122	-0.977	-1.462	-1.130	-0.606*	-3.830
September	3.002	1.746	-0.963	-0.166*	-0.971	-0.512	-0.761*	-2.511
October	11.754	10.073	-1.930	-1.583	-0.962	-0.879	-2.341*	-3.469*
November	3.367*	4.104*	-1.298	-1.647	0.026*	0.096*	-5.824	-7.450
December	6.241*	6.318*	-1.387	-1.417	-0.143*	-0.165*	-5.408	-5.887

* sig value > 0.05

3.6 Episode Analysis of Particulate Matter 2.5

The hourly PM2.5 concentrations analyzed for each day are derived from two air quality monitoring stations operated by the U.S. Department of State Indonesia, situated in Central Jakarta and South Jakarta, covering the period from January 2021 to October 2023. These concentrations are compared against the quality standards outlined in Government Regulation of the Republic of Indonesia Number 22 of 2021 concerning the Implementation of Environmental Protection and Management (Fig 5.). Observations indicate that, in both 2021 and 2022, the frequency of daily average PM2.5 concentrations exceeding quality standards was notably higher in the mid-year months, specifically from April to August. Conversely, in 2023, daily average PM2.5 concentrations began surpassing quality standards from May to October. Noteworthy high PM2.5 episodes selected for in-depth analysis include (i) July 15-16, 2021; (ii) August 29-30, 2021; (iii) March 30-31, 2022; (iv) June 24-25, 2022; (v) May 24-25, 2023; and (vi) October 1-2, 2023. The highest daily mean PM2.5 values observed in these six episodes ranged from 62 to 85.88

µg/m3, 63.42 to 79 µg/m3, 47.38 to 64.3 µg/m3, 45.67 to 74.71 µg/m3, 56.88 to 66.04 µg/m3, and 59.79 to 63.13 µg/m3, respectively.



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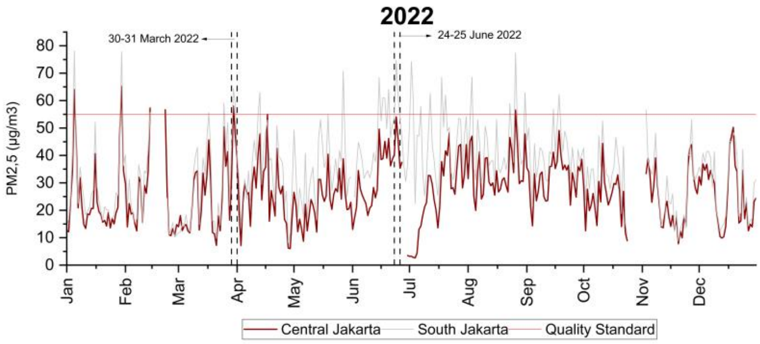

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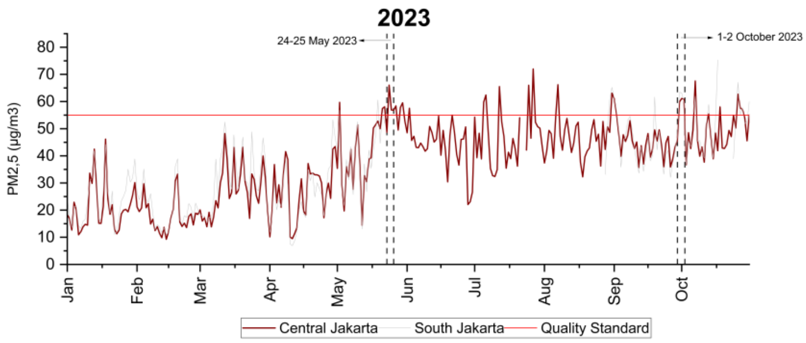
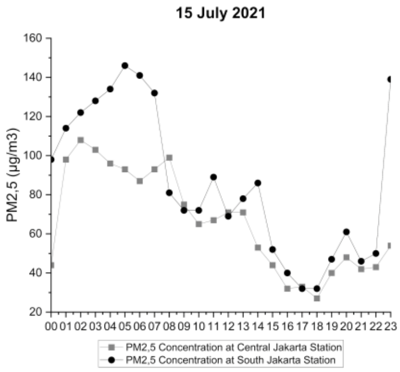


(c)

Figure 5. Time series of daily PM2.5 concentrations in Jakarta at two monitoring stations during (a) 2021, (b) 2022, and (c) 2023 period.

The elevated daily average PM2.5 concentrations observed in all six episodes are attributed to the prevailing weather conditions during those periods. In 2021-2022, the mid-year months experienced minimal rainfall in Jakarta, whereas in 2023, the lowest precipitation occurred from August to October (Fig 3.b). This underscores the significant influence of the rainy season in mitigating PM2.5 concentrations, as the air washing process during rainfall effectively carries away particulates from the atmosphere (Driejana et al., 2020; Mukhtar et al., 2013). Research by L.-C. Guo et al. (2014) further supports this, emphasizing the pivotal role of wet deposition in reducing atmospheric PM pollution. In addition to precipitation, meteorological factors such as humidity and wind speed also contribute to the heightened concentrations of PM2.5 in the air (Fig 3.a and Fig 3.c). Increased wind speed correlates with a decrease in PM2.5 concentration, while higher humidity levels are associated with a similar reduction in PM2.5 concentration (Yang et al., 2011).

Examining the diurnal pattern during the period of July 15-16, 2021 (Fig 6.), reveals a resemblance to the annual diurnal variation of PM2.5 concentrations discussed earlier (Fig 4.). Both days exhibit a similar pattern, wherein the hourly concentration of PM2.5 rises in the morning between 05:00-07:00 and reaches its lowest concentration at 16:00-18:00. This trend is attributed to anthropogenic activities, particularly morning traffic, contributing to heightened PM2.5 concentrations (Manning et al., 2018).



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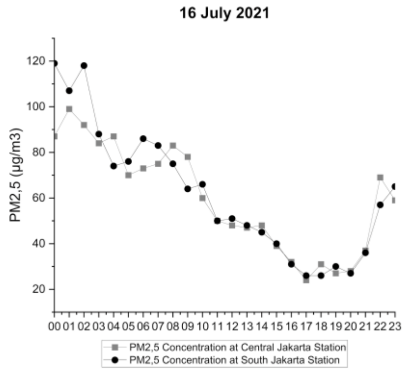

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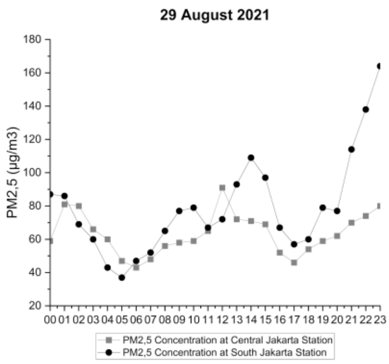

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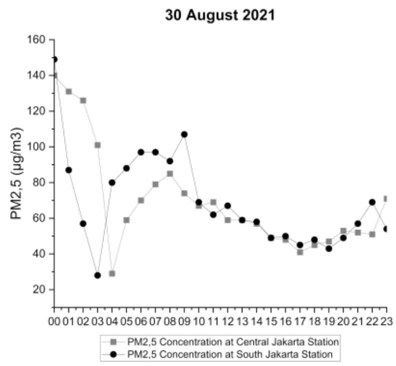

(d)

Figure 6. Diurnal variation of PM 2.5 during (a,b) the first and (c,d) second episodes

The pattern observed during the episode on August 29-30, 2021 (Fig 6.) deviates from the preceding episode. On August 29, 2021, the peak hourly PM2.5 concentration was recorded between 21:00-23:00, and the lowest concentration was observed at 04:00-06:00. Conversely, on August 30, 2021, the highest hourly PM2.5 concentration occurred in the early morning, specifically at 00:00-02:00. This discrepancy is attributed to a significant increase in PM2.5 concentration during the nighttime of the previous day. However, there was a noteworthy and rapid decrease in PM2.5 concentration during a brief period at 03:00-04:00, marking the time when the PM2.5 concentration reached its minimum value.

The episode on March 30-31, 2022 (Fig 7.) displays distinct patterns for each day. On March 31, 2022, the pattern closely resembles that observed in the July episode, featuring a morning peak extending from 04:00-08:00 and the lowest point occurring between 20:00-23:00. Meanwhile, on March 30, 2022, the highest hourly PM2.5 concentrations are observed at various times, namely between 05:00-08:00, 14:00-16:00, and 21:00-23:00, with the lowest concentration recorded at noon from 09:00-11:00. During the period of June 24-25, 2022 (Fig 6.), a similar pattern emerges as observed in the episode on July 15-16, 2021. On June 24, 2022, the hourly PM2.5 concentration peaks in the morning between 05:00-07:00, while the lowest concentration occurs in the afternoon from 16:00-18:00. In contrast, on June 25, 2022, the hourly PM2.5 concentration peaks in the early morning from 00:00-03:00, with the lowest concentration persisting into the afternoon.

The timeframe of May 24-25, 2023 (Fig 8.) exhibits a similar pattern to what transpired on June 25, 2022, wherein the PM2.5 concentration peaks in the early morning between 01:00-03:00 and reaches its lowest point at 16:00-18:00. However, there is a slight variation on May 25, 2023, where the lowest concentration occurs at different times, specifically at 17:00-18:00 and 20:00. It is noteworthy that during this period, the Jakarta Selatan Station did not provide PM2.5 concentration data for that particular month. In the period of October 1-2, 2023 (Fig 8.), both days present different patterns. On October 1, 2023, the morning peak is observed from 08:00-12:00, with the lowest concentration occurring at night. Conversely, on October 2, 2023, the highest PM2.5 concentration is recorded in the early morning between 00:00-02:00, with the lowest concentration occurring at night at 23:00.

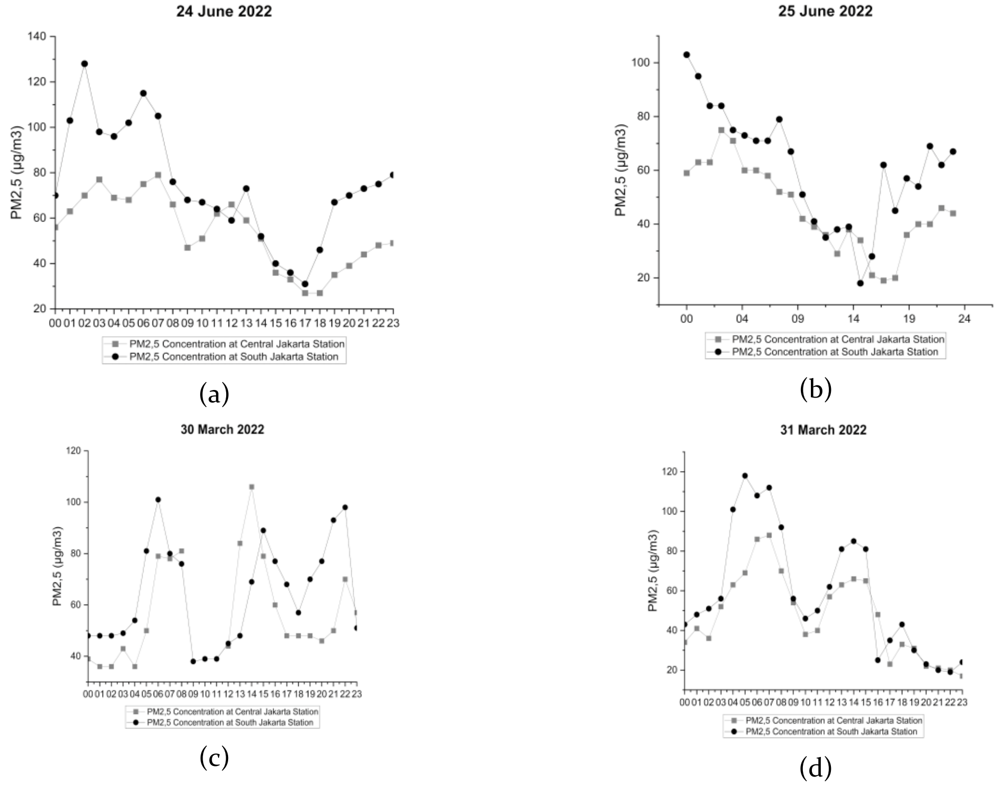

Figure 7. Diurnal variations of PM 2.5 during (a,b) the third and (c,d) fourth episodes

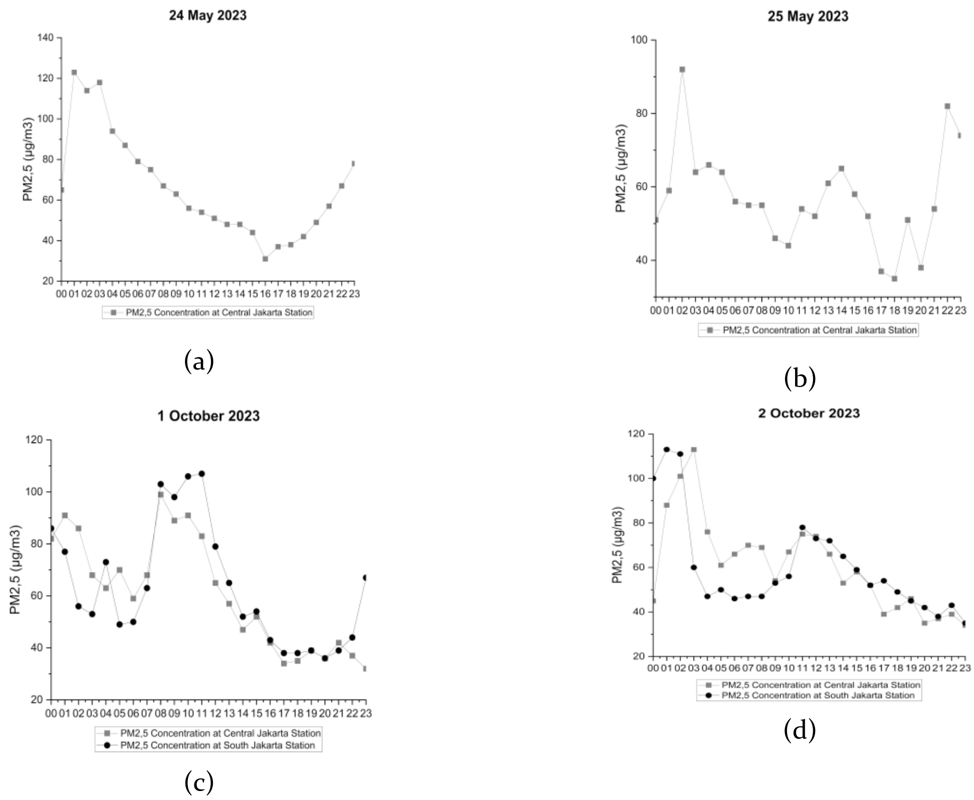

Figure 8. Diurnal variation of PM2.5 during (a,b) the fifth and (c,d) sixth episodes

4. Conclusions

The in-depth analysis of PM2.5 monitoring data in Jakarta reveals the impact of meteorological conditions on PM2.5 concentrations in the city. Consequently, the diurnal pattern of observed PM2.5 aligns with previous studies, exhibiting peaks in the early morning and early afternoon showing the significant impact of on-road transport induced emission. This pattern is attributed to lower surface temperatures causing denser air masses or aerosols in the lower layers, hindering their ascent into the atmosphere. The elevated PM2.5 concentrations in Jakarta are significantly influenced by seasonal variations, with monthly concentrations peaking during the dry season, which correlates with lower rainfall compared to the rainy season. Wind speed and humidity also play pivotal roles in determining the monthly PM2.5 concentrations in Jakarta. The lowest PM2.5 concentrations are observed during periods of high wind speed and humidity. To gain a more comprehensive understanding of PM2.5 formation over the city, further analysis of long-term monitoring records for PM2.5, coupled with an exploration of photochemistry, is deemed essential. Air quality modeling should be further conducted by focusing on the episodes to analyze emission source contribution. Once it is done, control measures can be formulated based on the major contributing emission sources.

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