SPATIOTEMPORAL ANALYSIS OF NO_2, SO_2, AND CO DISTRIBUTION AFFECTING AIR QUALITY IN GREATER JAKARTA

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ABSTRACT

According to the WHO, nearly the entire global population, at approximately 97%, is exposed to air contaminated with pollutants exceeding the WHO guideline threshold. Air pollution results from the coalescence of pollutants with atmospheric air and has become a global challenge, primarily impacting the most significant urban areas worldwide. The Greater Jakarta, or Jabodetabek, is the world's second-largest metropolitan region, with a population of around 34.6 million distributed across 14 municipalities and cities. The high-intensity human activities in Greater Jakarta have severely deteriorated the air quality. This study employs a holistic approach, utilising spatiotemporal analysis and quantitative-descriptive methods to investigate the atmospheric concentrations of CO, NO_2, and SO_2 in Greater Jakarta and its surrounding areas. The spatial distribution patterns of pollutants and their driving factors, including stationary and climatic factors, are investigated during July-December 2023. Results indicated that CO, NO_2, and SO_2 concentrations are significantly above the thresholds defined by the WHO, particularly during the dry season. It is found that the combination of stationary sources, including coal-fired power plants and industrial areas, along with climatic factors, significantly affects pollutant dispersion. These findings underscore the urgent need for stricter emission controls in coal-fired power plants and industrial areas to mitigate the effects of air pollution on public health.

Keywords: *pollution; jabodetabek; climate aspect*

INTRODUCTION

According to the World Health Organisation (WHO), the majority of the world's population (97%) is exposed to air containing pollutants that exceed WHO guideline thresholds, with low- and middle-income countries experiencing the highest levels of exposure (WHO, 2021). Air pollution occurs when pollutants coalesce with atmospheric air, becoming a global challenge that predominantly affects major urban areas worldwide

(Gopikrishnan & Kuttippurath, 2025). Air pollutants are responsible for approximately 7 million fatalities worldwide, with Southeast Asia accounting for 2 million deaths, representing a substantial 28.5% of worldwide air pollution-related mortality. Air pollution is an inevitable challenge for developing urban areas, as their development among sectors correlates with increased air pollution (Ruhiat & Heryadi, 2019). Undeniably, Indonesia has been engaged in comprehensive development across all sectors to achieve future national progress (Sambodo et al., 2024). Based on. 60 Tahun 2020, among the regions designated by Indonesia as a national strategic economic area is the Greater Jakarta Metropolitan Area, commonly referred to as Jabodetabek.

Jabodetabek (Jakarta-Bogor-Depok-Tangerang-Bekasi) is a metropolitan agglomeration of 34.6 million people, distributed across 14 administrative districts and municipalities within a territory of 6,811 km² (Kementerian Dalam Negeri RI, 2023). The second-largest megapolitan area in the world, behind the Tokyo-Yokohama metropolitan area, exceeds the Indian Delhi metro region. This rapid economic growth over the years has led to considerable urban development, making Jabodetabek the leading megapolitan area in Southeast Asia (*Demographia World Urban Areas*, 2023). The significant development in Jabodetabek, characterised by increasing population growth and excellent infrastructure, has attracted numerous industries to establish industrial areas within this zone. The proliferation of industrial areas has created positive economic impacts, particularly in terms of local employment opportunities (Pravitasari et al., 2015). All operational systems and industrial product production require substantial electrical infrastructure (Sikorski et al., 2017); therefore, the National Electricity Company (PLN) has strategically prepared and ensured electrical supplies for the industrial zone area. According to the Electricity Supply Business Plan (RUPTL) for 2018-2027, 22,461 Mega Volt Ampere is allocated to industrial areas.

The electrical supply for the industrial zones in Jabodetabek is contributed to by 14 coal-fired power plants, or PLTUs, scattered throughout the metropolitan area, which, at the same time, significantly contributes to environments marked by industrial estates and PLTUs

(PT PLN (Persero), 2018). Industrial estates and coal-fired power plants, along with their derivative fuel sources, systematically degrade atmospheric quality due to pollutant emissions via smokestacks, which disperse into the environmental ecosystem (Filonchyk et al., 2024). The atmospheric environment around such industrial structures gradually gets heavily contaminated by various types of pollutants, leading to severe deterioration in air quality (D. Guo et al., 2020). In particular, the vital atmospheric pollutants released from industrial and power generation sources, including nitrogen dioxide (NO_2), carbon monoxide (CO), and sulfur dioxide (SO_2), contribute to the overall deterioration of the environment (Son et al., 2023). Besides industrial activities, air pollution sources in Jabodetabek are also greatly influenced by transportation emissions. The transportation sector significantly contributes to exhaust gas emissions due to the use of fossil fuels (Kansal et al., 2011), further worsening air quality in the Jabodetabek area.

There has been a significant exponential increase in the growth of private vehicles, both two-wheeled and four-wheeled, within the Jabodetabek area. Statistical data indicate that approximately 21.76 million vehicles passed through the Jabodetabek area, comprising cars, buses, trucks, and motorcycles, with an annual growth rate of 7% in 2021 (Kementerian Perhubungan RI, 2022). Overall, vehicle emissions from fossil fuel combustion in transportation are a significant contributor to atmospheric deterioration in the metropolitan region, as evidenced by the annual rate of increase in vehicle proliferation (John et al., 2025). The rising vehicular population is directly associated with increased concentrations of pollutants, resulting in far-reaching environmental and health impacts. The atmospheric pollution caused by industrial zones, coal-fired power plants, domestic activities, and fossil fuel-based transportation means has severe health impacts on the metropolitan population due to prolonged exposure to hazardous atmospheric particulates. Prolonged inhalation of contaminated atmospheric environments exponentially increases susceptibility to respiratory pathologies, including Acute Respiratory Infection (ARI), bronchitis, chronic obstructive pulmonary disease, and pulmonary neoplasms. Moreover, it has been observed that sustained atmospheric pollution may be associated with severe cardiovascular illness, including stroke and myocardial complications (Siloam Hospitals, 2024).

Air pollution is a complex problem in urban areas (Biagi et al., 2025)—research by T.-L. Liu et al. (2022) state that anthropogenic activities influence the increase in NO_2 concentration in urban areas across Switzerland. This finding aligns with a study by Aguilar-Dodier et al. (2020), which indicates that power plant activities in the area cause a rise in SO_2 concentration in Mexico City. Furthermore, Songsom et al. (2025) demonstrate that the increase in air pollution in the Bangkok Metropolitan Area is predominantly attributed to transportation. This statement is reinforced by Lestari et al. (2022), who found that the transportation sector and industrial activities are the main contributors to the increase in CO2 concentration in Jakarta. These various studies demonstrate that multiple sectors, including anthropogenic or domestic activities, transportation, industry, and power plants, significantly impact air pollution. Therefore, Jabodetabek, the second-largest urban region in the world, with diverse activities across various sectors, has significant potential for increased air pollution that will impact public health.

This study aims to conduct a comprehensive spatiotemporal analysis of NO_2, CO, and SO_2 concentrations in the Jabodetabek area using Sentinel-5P and Sentinel-2 satellite imagery, combined with climatological parameters such as rainfall, temperature, and wind direction. Although several previous studies have addressed air pollution in the Jabodetabek region, most have only focused on ground-based observational data and have not fully integrated spatial and temporal approaches. This has resulted in disparities and knowledge gaps in understanding the complex relationships between anthropogenic activities, meteorological conditions, and the spatial distribution of air pollution in large metropolitan areas. Therefore, this research aims to fill this gap through an integrative spatio-temporal approach based on Sentinel satellite data.

This study employs an integrative approach, combining remote sensing analysis and meteorological dynamics to assess pollutant distribution patterns over a specific period, specifically during the El Niño phenomenon (July–December 2023). The novelty of this study lies in the use of high-resolution satellite data, combined with cross-provincial mapping, which enables a more detailed understanding of pollutant behaviour across various administrative boundaries. The findings of this research offer valuable insights into the interactions between anthropogenic emission sources and climatological factors, thereby contributing to the strengthening of urban environmental governance and informed policy formulation in rapidly developing megapolitan areas. This study makes a significant contribution to the development of the scientific literature on urban air pollution in Southeast Asia, particularly in the context of climate variability and the pressures of metropolitan development.

MATERIALS AND METHODS

This study employs quantitative research with a descriptive approach, based on the analysis of time series. Besides, the CO, NO_2, and SO_2 levels will be considered, along with the factors that affect the distribution variability of these three atmospheric pollutants. Research for this study took place from July to December 2023 in the designated study area, involving the Jabodetabek area, the cities of Cilegon and Serang, and the districts of Serang and Karawang. Jabodetabek is a megacity area set within three provinces: Banten, Jakarta, and West Java. With a population of 34.6 million, it encompasses 14 districts and cities covering an area of 6,811 km², situated between latitudes 6°0'0" - 6°30'6" S and longitudes 106°20'0" – 107°27'29" (Kemendagri, 2023). **Figure 1** shows the location of the study.

Data on pollutant sources, such as SO_2, NO_2, and CO, delivered from Sentinel-2 and Sentinel-5P OFFL, were acquired with a spatial resolution of 113 meters. Data processing was accomplished using Google Earth Engine by adding the appropriate code. Column number density is a band used to illustrate vertical column density on the surface for each pollutant, calculated using the DOAS technique (Lange et al., 2023). The DOAS algorithm compares the observed spectral data with the characteristic absorption of gases (Honninger, 2004). To ensure the quality of the satellite image, cloud fraction bands are used. Cloud_fraction is used to mask out cloudy pixels (Latsch et al., 2022). Standardisation of the SO_2, NO_2, and CO concentration follows guidelines from the WHO. The period of analysis runs from July to December 2023.

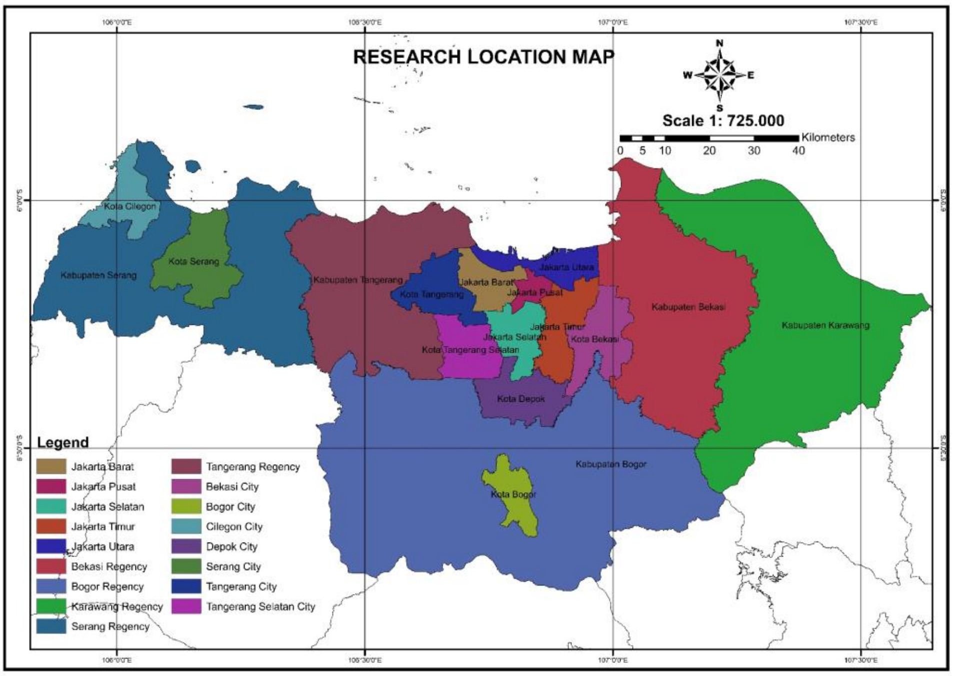

Figure 1. Study Area

Source: Research Analysis, 2024

Temperature data were derived from the processing of Landsat 8 imagery, in which Algorithm **equation 1** was applied (J. Guo et al., 2020).

$$Temperature = \left(\frac{1321.08}{\log\left(\frac{774.89}{(TIR \times 0.0003342) + 0.1} + 1 \right)} \right) - 272.1 \quad (1)$$

All precipitation data are recorded from the six meteorological stations within the research area, including the Tangerang Geophysical Station, Budiarto Meteorological Station, Soekarno Hatta Meteorological Station, Tanjung Priok Maritime Meteorological Station, Kemayoran Meteorological Station, and Citeko Meteorological Station.

Equation 2 was used to model the wind direction (Abdillah et al., 2022).

$$WindDirection = atan2(V, U) \times \frac{180}{\pi} \quad (2)$$

The data on wind direction were obtained from 12 stations, such as Banten Climatology Station, Tangerang Geophysical Station, Budiarto Meteorological Station, Serang Maritime

Station, Soekarno Hatta Meteorological Station, Tanjung Priok Maritime Meteorological Station, Kemayoran Meteorological Station, Citeko Meteorological Station, Penggung Geophysical Station, Bandung Geophysical Station, West Java Climatology Station, and Kertajati Climatology Station, which are scattered around Banten Province, Jakarta Province, and West Java Province.

RESULTS AND DISCUSSION

The analysis of Sentinel-2 imagery and 5P data reveals that CO and NO_2 concentrations in the study area, covering Jabodetabek and its surrounding region, exceed the thresholds set by WHO. In contrast, SO_2 concentration only exceeded the thresholds in the narrow portion of the area. The concentration levels of SO_2, NO_2, and CO in the atmosphere will be explained below.

1. Spatiotemporal Distribution of CO

The results show that CO concentrations in the Jabodetabek area had already exceeded the WHO standards for air quality. The concentration of carbon monoxide is divided into three categories: good, poor, and inferior. In this case, **Table 1** shows the CO Values in the Research Area. Therefore, 0 - 4,000 µg/m³ concentration is classified as good; >4,000 - 7,000 µg/m³ concentration is considered poor; >7,000 µg/m³ - very poor.

The CO concentration in the research area varied from July to December 2023. It had a complex temporal dynamic, with monthly concentrations ranging from 602 to 4,731 µg/m³. The analysis reveals an initial increase in CO concentration from July to August, followed by a continued rise in September, and a subsequent decline in concentrations from October to December. This correlates with **Figure 6**, which shows the rainfall in the same period. The rainfall trend shows a decrease in rainfall from July to August, continuing into September, and then increasing from October to December. The phenomenon indicates that as rainfall decreases, the CO concentration in the air also decreases, and vice versa. There is a significant relationship between precipitation and CO levels, with a substantial impact of rainfall on CO concentration. During precipitation, CO in the atmosphere can dissolve in raindrops, resulting in its deposition to the ground, a process commonly called acid rain. The atmospheric precipitation dynamics significantly affect various atmospheric activities (Triarjunet & Ahyuni, 2022). Additionally, **Figure 2** illustrates the spatial distribution of CO concentrations within the study area.

Table 1. CO Concentration in Jabodetabek from July to December

Concentration	Month	Value Range	Category
CO	July	602 μg/m^3 -	Good
		4,119 μg/m^3	Poor
	August	610 μg/m^3 -	Good
		4,585 μg/m^3	Poor
	September	703 μg/m^3 -	Good
		4,731 μg/m^3	Poor
	October	836 μg/m^3 -	Good
		4,695 μg/m^3	Poor
	November	850 μg/m^3 -	Good
		4,387 μg/m^3	Poor
	December	686 μg/m^3 -	Good
		4,190 μg/m^3	Poor

Source: Research Analysis, 2024

Based on **Figure 2**, CO concentrations were categorized as "good" or "poor". Poor category areas in July included Serang Regency, Tangerang Regency, Bogor Regency, Bekasi Regency, Karawang Regency, Tangerang City, South Tangerang City, and all administrative cities in Jakarta, as well as Depok City, Bogor City, and Bekasi City. Areas of poor quality in August were similar to those in the previous month, with Karawang Regency's rise to the good category and Serang City and Cilegon City's decline into the poor category. This trend continued into September and October, when Karawang again fell into the poor category. Poor areas in November remained the same as those in December; the poor classification was similar to that in July, except that Bogor City was no longer categorized as poor.

The spatial distribution of CO levels from July to December 2023 reflects the influence of climatic factors, including temperature and wind patterns. This study aligns with the research conducted by Zender-Świercz et al. (2024), which demonstrates that temperature affects particulate concentration. However, this influence is contextual and highly dependent on the local conditions of the area, such as the impact of anthropogenic activities. On the other

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hand, the study's findings (Hernández-Ceballos et al., 2025) indicate that wind circulation patterns in the urban area of Naples, Italy, particularly local winds, play an essential role in the distribution and accumulation of pollutants in the atmosphere.

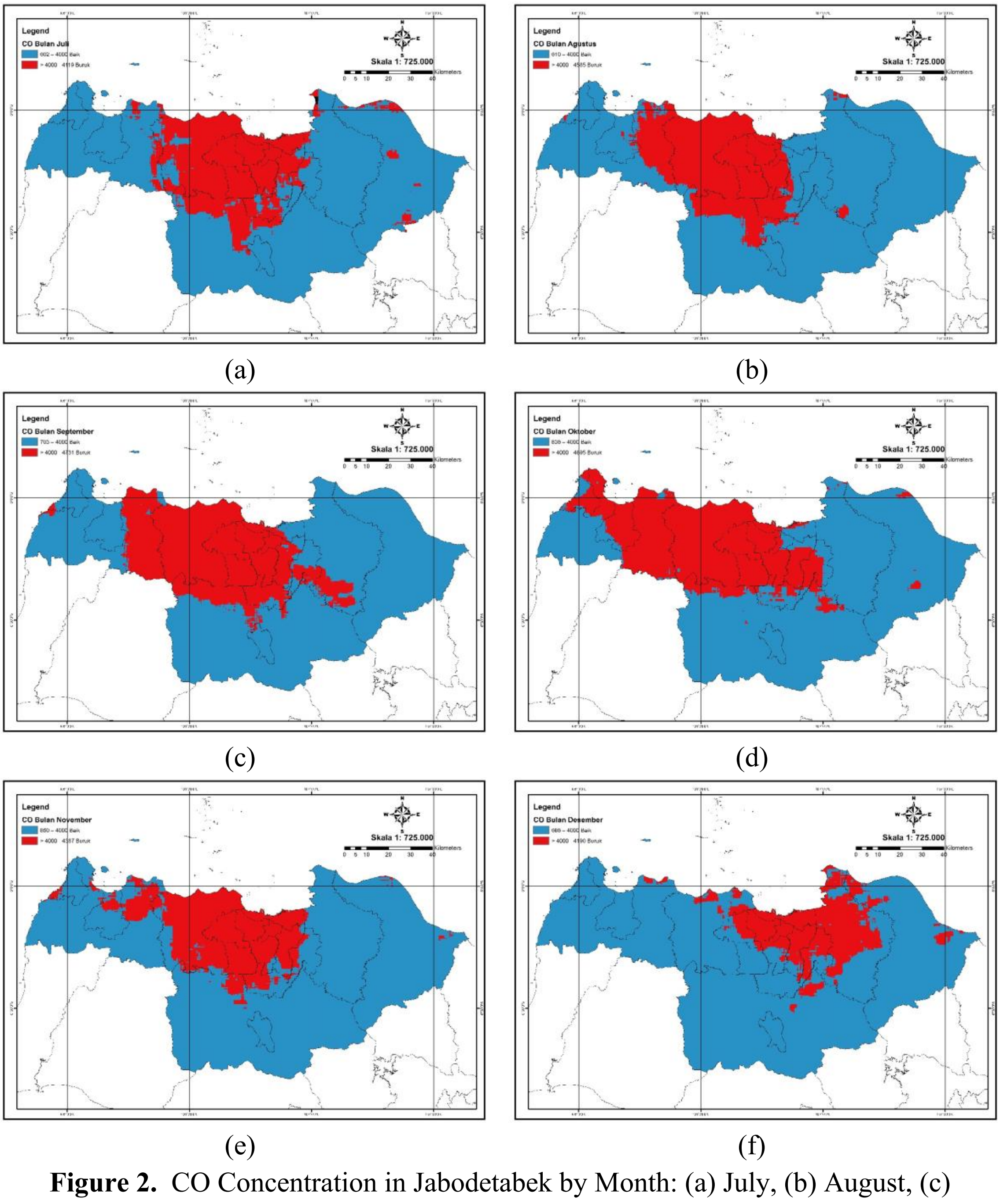


Figure 2. CO Concentration in Jabodetabek by Month: (a) July, (b) August, (c) September, (d) October, (e) November, and (f) December
Source: Research Analysis, 2024

The temperature in Jabodetabek from July to December is influenced by El Niño, which affects this region of Indonesia. The wind is related to temperature because the wind moves from areas with lower temperatures to regions with higher temperatures.

However, surrounding regions also influence the wind, and the wind direction also shifts toward Jabodetabek, centred on Jakarta. Other natural factors, such as high pressure, generate strong forces that affect wind movement (Ren & Luo, 2022). In **Figure 6**, the Jabodetabek area experiences higher temperatures than the surrounding regions, and the wind direction also tends to move toward Jabodetabek, with a centre located in Jakarta. This factor causes the accumulation process of CO content in Jabodetabek, with the accumulation center in Jakarta. As shown in **Figure 2**, the Jakarta area falls into the poor category almost every month from July to December across all its administrative regions. Also, areas with higher temperatures become gathering points for pollutants carried by winds moving from other surrounding areas in Jabodetabek.

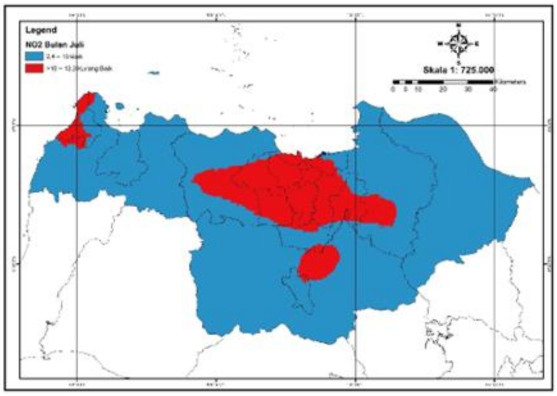
2. Spatiotemporal Distribution of NO_2

The NO_2 concentration in the research area exceeds the threshold set by the WHO. The four classes of NO_2 pollution levels in the air are given in **Table 2**: 0 - 10 µg/m^3 is classified as good, >10 - 20 µg/m^3 is classified as moderate, >20 - 30 µg/m^3 is classified as poor, and >30 µg/m^3 is classified as very poor (**Table 2**).

Table 2. NO_2 Concentration in Jabodetabek from July to December

Concentration	Month	Value Range	Category
NO_2	July	2.4 µg/m^3 - 13.3 µg/m^3	Good Moderate
	August	2.1 µg/m^3 - 14 µg/m^3	Good Moderate
	September	2 µg/m^3 - 13.5 µg/m^3	Good Moderate
	October	2.4 µg/m^3 - 12.7 µg/m^3	Good Moderate
	November	2.6 µg/m^3 - 11.4 µg/m^3	Good Moderate
	December	2.7 µg/m^3 - 10.3 µg/m^3	Good Moderate

Source: Research Analysis, 2024



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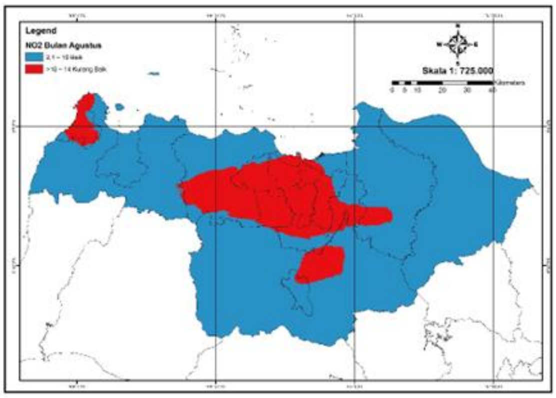

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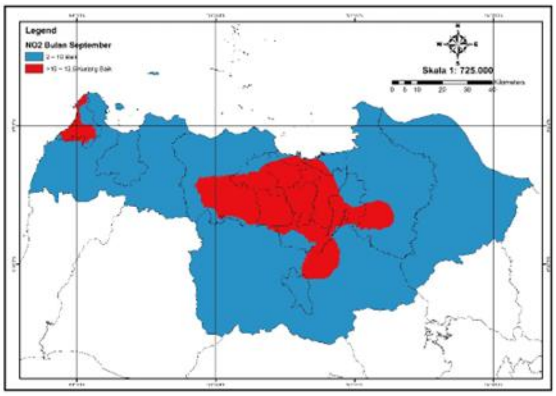

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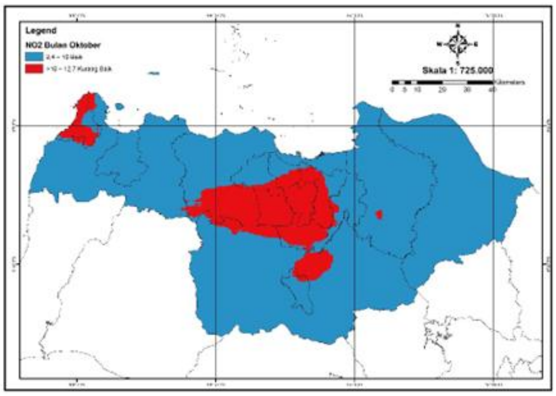

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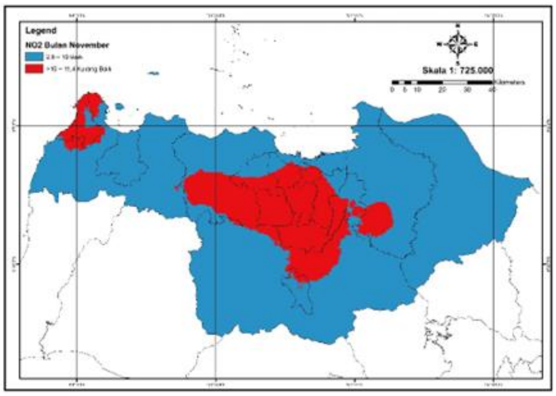

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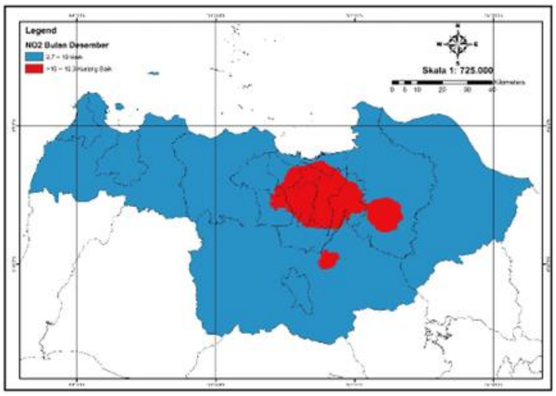

(f)

Figure 3. NO_2 Concentration in Jabodetabek by Month : (a) July, (b) August, (c) September, (d) October, (e) November, and (f) December
source: Research Analysis, 2024

NO_2 concentration in the research area from July to December 2023 is divided into two categories: good and moderate. The NO_2 concentration increases from

July to August, while a gradual decline is observed from September to December. The rainfall data from July to December show a decrease from July to October, followed by an increase in successive months until December, as shown in **Figure 6** below. This indicates that rainfalls may drive the variability of NO_2 concentrations within the study area. From July to November, areas with poor air quality include the districts and municipalities of Banten and Jakarta: Serang, Tangerang, Bogor, Bekasi, Cilegon, and all Jakarta administrative areas. In December, it declined to 11 municipalities. NO_2 movement exhibited complex geographical dynamics, characterised by westward, southward, and eastward trajectories. The dispersion of NO_2 has created three large polygons: one centred in Jakarta, the second in the regions of Greater Tangerang and Bekasi, and the third in Bogor and Cilegon. The spatial distribution and movement patterns of NO_2 concentrations from July to December 2023 are also influenced by weather elements. This finding aligns with the results of Rowland (2024), which demonstrated that weather factors, including temperature, wind speed, and rainfall, have a significant impact on NO_2 concentrations in Krakow, Paris, and Milan. The sources contributing to this concentration were identified as vehicular mobilisation, industrial zones, domestic activities, and the operations of seven coal-fired power plants (PLTU) located in Cilegon and Serang. While in the period of September-November, the first and second polygons combined into one big polygon, in December, these polygons started to separate: the third polygon passed to a good air quality category, which can be seen to illustrate the dynamics of NO_2 pollution within the research area (**Figure 3**). This study aligns with the findings of Hei et al. (2022), which state that industrial areas and coal-fired power plants contribute approximately 49% of the total NO_2 emissions, making them one of the primary sources of air pollution.

3. Spatiotemporal Distribution of SO_2

The concentration of SO_2 during the study period in the area under investigation exceeded the WHO air quality standard guidelines from July to December, except for the month of September. The four categories of SO_2 air pollution are tabulated in **Table 3**: the good category is from 0 to 40 $\mu g/m^3$, the moderate category is between 40 - 50 µg/m³, the poor category is between 50 - 120 µg/m³, and the very poor category is greater than 120 µg/m³.

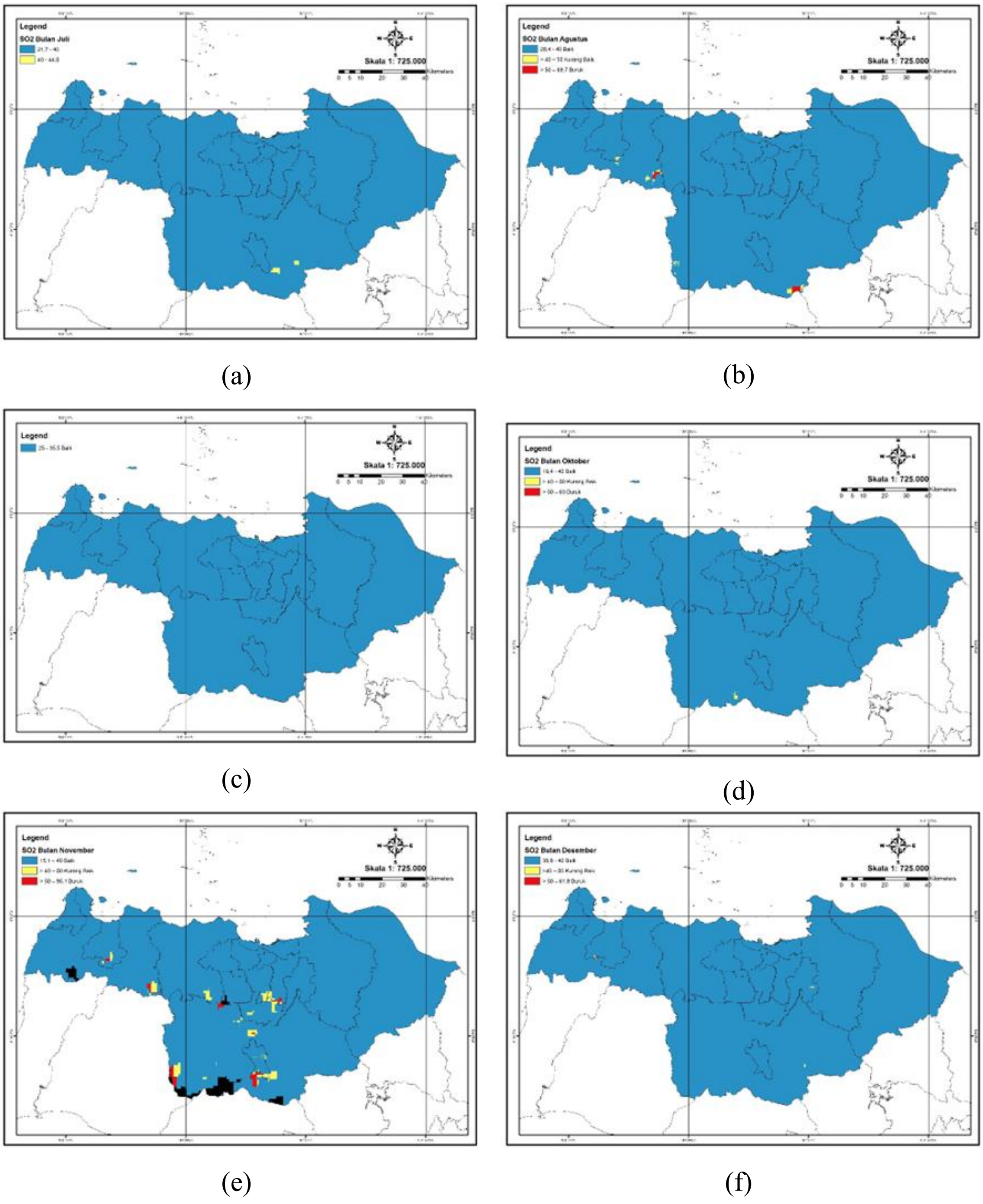

Figure 4. SO_2 Concentration in Jabodetabek by Month : (a) July, (b) August, (c) September, (d) October, (e) November, and (f) December
source: Research Analysis, 2024

Figure 4 describes the distribution of SO_2 concentrations in Jabodetabek and its surroundings. In July, all the measured SO_2 levels fell into the 'good' and 'moderate' categories. In August, an increase occurred, with measured concentrations of SO_2 falling into all three categories. That continued through September, at which point the entire region was classified as good, and further increased from October to December, with the three categories again present. However, **Figure 4** showcases that the area is relatively small and does not significantly impact anything, so it is assumed that the SO_2 concentrations do not greatly influence air pollution.

Table 3. SO_2 Concentration in Jabodetabek from July to December

Concentration	Month	Value Range	Category
SO_2	July	21.7 µg/m³ -	Good
		44.8 µg/m³	Moderate
	August	28.4 µg/m³ -	Good
		69.7 µg/m³	Poor
	September	25 µg/m³ -	Good
		35.5 µg/m³	Good
	October	19.4 µg/m³ -	Good
		63 µg/m³	Poor
	November	15.1 µg/m³ -	Good
		95.1 µg/m³	Poor
	December	38.8 µg/m³ -	Good
		61.8 µg/m³	Poor

Source: Research Analysis, 2024

The increase in SO_2 levels in certain months cannot be identified explicitly because this phenomenon occurs only in a small part of the area and does not exhibit a particular trend. For this reason, it is assumed that SO_2 levels do not significantly impact air pollution. Moreover, the trend analysis for monthly variations indicates that climatic factors have a minimal impact on SO_2 levels. This is manifested in the fluctuating movements of SO_2 concentrations from July to December, while precipitation decreased consecutively from July to October and increased consecutively from November to December. Therefore, it is reasonable to consider that the climatic factors do not affect SO_2 variation as much as in the cases of CO and NO_2 concentrations. These findings align with the research conducted by (Tritamtama et al. (2023), which analysed air quality in the Jabodetabek area and found that SO_2 concentration is not a dominant pollutant in Jakarta and its surroundings. The SO_2 levels are relatively low and do not significantly contribute to the air pollution levels in this region. This statement aligns with the study by Kusumaningtyas et al. (2018), which notes that although SO_2 is one of the parameters monitored in air quality assessments, its concentration in Jakarta is relatively low and not a primary factor.

4. Sources of Air Pollution

Pollution in the Jabodetabek has two primary sources: stationary sources and mobile sources (Badan Riset Inovasi Nasional, 2023). These stationary sources include pollution from coal-fired power plants, industries, and domestic activities. In contrast, mobile sources primarily consist of vehicles that still rely on fossil fuels and their derivatives.

a. Coal-fired Power Plant

Coal-fired power plants (PLTU) produce significant pollution levels due to their reliance on coal for electricity generation. Observations indicate that 14 coal-fired power plants are distributed throughout the Jabodetabek region and Banten, which are believed to contribute to the increase in air pollution in the Jabodetabek area.

Figures 2 and **3** reveal that carbon monoxide (CO) and nitrogen dioxide (NO_2) concentrations in the Cilegon area are poor to moderate. Cilegon has at least seven coal-fired power facilities, contributing to the region's high CO and NO_2 levels. Pollution from these power facilities may affect the neighbouring areas. CO and NO_2 emitted from the power plant's smokestacks can be released into the atmosphere. Once disseminated in the atmosphere, environmental conditions, such as wind, affect the movement.

This study is in line with the research conducted by (F. Liu et al., 2020), which shows that coal-fired power plants (PLTU) are the primary sources of nitrogen dioxide (NO_2) and carbon dioxide (CO_2) emissions, where satellite data is used to estimate the emissions of both pollutants simultaneously. The study confirms that NO_2 detected by satellites can be used as an indicator to estimate CO_2

emissions from PLTUs, especially from large power plants that use coal as their primary fuel. The research findings indicate that PLTUs do not significantly affect SO_2 levels because, in areas where PLTUs are located, SO_2 concentrations are not categorized as high and remain within established thresholds. Although PLTUs are known sources of SO_2 emissions, in the context of the Jabodetabek region, SO_2 concentrations are relatively low and do not constitute a major contributor to air pollution compared to NO_2 and CO. These findings align with the research by Tritamtama et al. (2023), which shows that SO_2 is not a dominant pollutant in the DKI Jakarta area.

b. Industrial Estate

Activities in industrial zones have also been linked to a rise in air pollution (Kementerian Perindustrian, 2022). The study area has the most extensive industrial estate in Indonesia, measuring 22,850 hectares (**Figure 5**). The activities within this large industrial estate are bound to produce high levels of pollutants. Among the three provinces studied, West Java has the most significant industrial area; correspondingly, it holds the highest levels of pollutants in the region. The tendency for high pollutant levels in these industrial zones is evident in **Figures 2** and **3**, where the map displays dense colours, indicating high concentrations of carbon monoxide (CO) and nitrogen dioxide (NO_2). Aside from West Java, the Jakarta area and Banten boast extensive industrial zones, including Tangerang, South Tangerang, Cilegon, and Serang, with at least 4,431 hectares in Banten and 1,019 hectares in Jakarta. Industrial activities contribute to the increased levels of CO and NO_2 in Jakarta, West Java, and Banten, as shown in **Figures 2** and **3**, which depict the distribution of CO and NO_2 concentrations. The high colouration on the map indicates that the range of CO and NO_2 in industrial areas in Jakarta and Banten falls into the high category due to industrial activities. On the contrary, the level of SO_2 in the industrial zones is not high and within safe limits according to the set standards of quality; thus, SO_2 is not considerably influenced by industrial activities. This study's findings align with those of Hei et al. (2022), which identified that industrial areas and coal-fired power plants contribute approximately 49% of the total CO and NO_2 emissions, making them one of the primary sources of air pollution. However, SO_2 levels are not significantly impacted. This study has not been able to identify the dominant types of industries that contribute significantly to air pollution due to limitations in the availability of specific data related to the industrial sector in the study area.

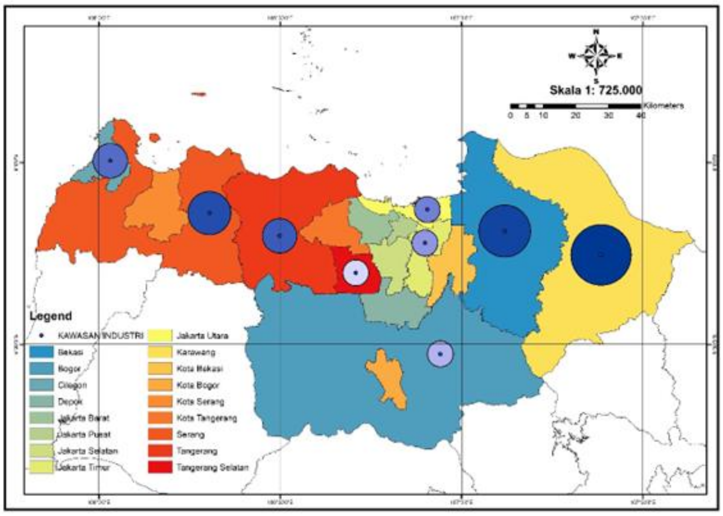

Figure 5. Industrial Estate in the Surrounding Jabodetabek Area
source: Research Analysis, 2024

c. Vehicle and Domestic Activities

Data from the Directorate General of Land Transportation show that in 2021, approximately 21.76 million vehicles, including cars, buses, trucks, and motorcycles, passed through the Jabodetabek area, representing a 7% annual growth. The number of cars is projected to increase to 23.28 million in 2022 and 24.9 million in 2023, reflecting the ongoing mobility within Jabodetabek. The region is known for its severe traffic congestion, exacerbated by an increasingly growing number of vehicles that struggle to match the existing road infrastructure. Year by year, congestion in Jabodetabek has continued to grow. Despite numerous efforts by the government, the congestion still needs to be solved.

The congestion contributes to increased acute emissions of vehicle exhaust gases, which are notably higher than those in areas without congestion. Vehicles, therefore, contribute to air quality deterioration in Jabodetabek. Research findings, as illustrated in **Figures 2** and **3**, show that the levels of carbon monoxide (CO) and nitrogen dioxide (NO_2) in surrounding areas, including Bogor, Depok, Tangerang, and Bekasi, are indicative of high vehicle movement or mobility. These areas exhibit elevated concentrations of CO and NO_2, as indicated by the dense colours on the map. This means that the darker the map's colour, the higher the concentration of pollutants in that area.

On the other hand, a lower population concentration and base vehicle mobility resulted in lower levels of CO and NO_2, as indicated by the blue colour on the map, which suggests that the concentrations of CO and NO_2 in this area are within permissible limits and do not exceed the standards. This study aligns with the previous research by Lestari et al. (2020), which showed that the transportation sector in Jakarta is the most significant contributor to the increase in CO and NO_2 emissions, with contributions reaching 93% for CO and 57% for NOx, primarily from motorcycles. These findings support the results of this study, which indicate the significant role of the transportation sector in contributing to air pollution in the Jabodetabek area.

5. Factors Influencing Air Pollution Distribution

a. Precipitation

Precipitation has a significant impact on the distribution of air pollutants. In highly polluted areas, heavy rains can bring atmospheric pollutants to the ground due to raindrops. After rain, air quality in that area improves as atmospheric pollutants are deposited. On the other hand, if the same pollutant concentration is present but rainfall is less, the same pollutants are kept suspended in the atmosphere. Acid rain is a phenomenon characterised by rainfall occurring in regions with high levels of pollutants (Tian et al., 2021). Acid rain occurs due to the interaction of various pollutants, such as CO, NO_2, and SO_2, combined with raindrops during precipitation.

Research from July to December 2023, as presented in **Table 4**, indicates that rainfall data were collected from measurements at six meteorological stations distributed throughout the Jabodetabek area. The data show a significant decrease in rainfall from July to August, which continued through October, with some stations recording no rainfall at all. Rainfall itself plays a vital role in the distribution of air pollution in Jabodetabek, particularly in areas with a shallow level of precipitation, such as those without rain. This is because abundant rainfall in a study area may prevent the dispersion of air pollutants by washing them down from the atmosphere to the ground during the entire rainfall process. From this, one can infer that the higher the rainfall in a particular region, the lower the concentration of air pollution in that area, resulting in lower levels of air pollution.

The low rainfall in Jabodetabek is attributed to a natural phenomenon known as El Niño, which has garnered worldwide attention in recent years and has become increasingly prominent in Indonesia. El Niño has altered the climate pattern in Indonesia, making it different from previous ones, and has changed the precipitation in Indonesia into a more extended and drier dry season, with extreme droughts and rainfall in Jabodetabek drastically decreasing.

Wet precipitation of atmospheric contaminants dissolved in clouds falls to the Earth's surface as rain. This resulting rainwater can contain sulfuric and nitric acids, yielding a rainwater pH of less than 5.60. During an acid rain event, sulfate and nitrate are deposited on the Earth's surface by precipitation and direct deposition, commonly referred to as wet and dry deposition. The phenomenon is exacerbated by high levels of air

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pollution in industrial areas or regions with extensive vehicle traffic, particularly in large urban centres, such as those comprising the Jabodetabek region.

Table 4. Precipitation (mm) from July to December

Month	Tangerang Geophysical Station	Budiarto Meteoro-logical Station	Soekarno-Hatta Meteorological Station	Tanjung Priok Maritime Meteorological Station	Kemayoran Meteorological Station	Citeko Meteo-rologi-cal Station
July	98.7	53.5	28.3	11.7	5.3	50.1
August	2	78.7	52.6	0	1.8	6.6
September	15.5	0	0	2.7	0	3.5
October	24.8	12.9	19.8	0	0	78.6
November	88.3	156.3	180	7	48.3	179.1
December	139.4	308.6	21.2	204.1	156.2	342.8

Source: Research Analysis, 2024

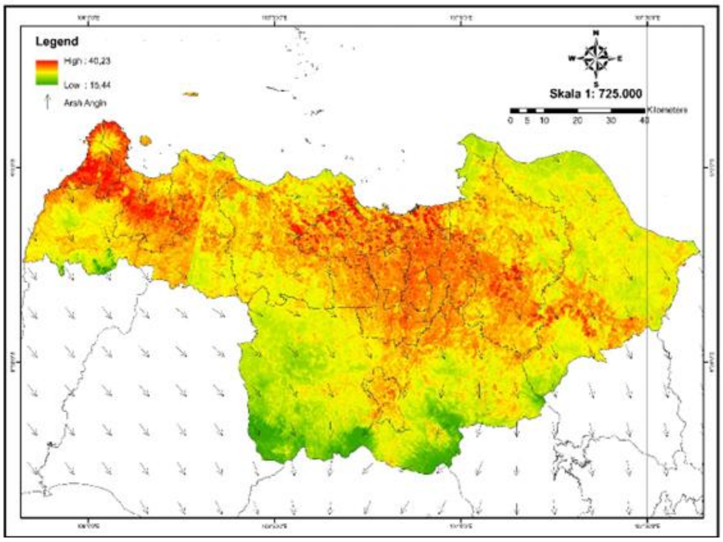

Figure 6. Temperature and Wind in the Surrounding Jabodetabek Area
source: Research Analysis, 2024

b. Temperature and Wind

Temperature and wind are interrelated climatic elements. Wind tends to move from areas of lower temperature to those of higher temperature. Surface temperature is influenced by building density, the intensity of human activities, and the density of vegetation. Surface temperatures tend to be higher in areas characterised by high building density, elevated activity levels, and sparse vegetation cover. Conversely, regions with low building density, reduced activity, and high vegetation density typically experience lower surface temperatures.

This phenomenon is illustrated in **Figure 6**, which shows that regions with high population density and significant mobilisation activities, such as Jakarta, Tangerang, Bekasi, Serang, Cilegon, and Depok, exhibit higher surface temperatures compared to areas with low population density, minimal activity, and dense vegetation, such as Bogor Regency and parts of Karawang.

The direction of wind movement has a significant influence on the distribution of air pollution in the Jabodetabek area. As depicted in **Figure 6**, wind flows from regions with lower temperatures to those with higher temperatures. Specifically, winds originate from the northern part of Java, moving from Cilegon, located in the western part of the island, towards Jabodetabek. Pollutants from windblown areas outside Jabodetabek are believed to contribute to the accumulation of air pollution in Jabodetabek. This is due to wind patterns that tend to converge on the Jabodetabek area, transporting emissions from surrounding industrial zones and causing an increase in pollutant concentrations in the metropolitan region. Upon reaching Jakarta, the wind shifts toward the south, passing through Depok, Bogor, and Bekasi. Wind plays a crucial role in the dispersion of pollutants; for instance, when pollutants are emitted from coal-fired power plants, industrial zones, and vehicular activities in Banten, these pollutants can be transported by prevailing winds toward Jabodetabek.

Meanwhile, the surface temperature of the Jabodetabek area is higher than that of its surroundings. Wind direction, which carries this wind from a cooler region, transports it to a warmer region. In this way, Jabodetabek is the potential area where the wind blows. This phenomenon will eventually lead to the accumulation of pollutants in the neighbouring regions of Jabodetabek. If this cycle continues for several months, the air quality will deteriorate, and the concentration of pollutants in Jabodetabek will increase accordingly. Moreover, El Niño has affected the area, drastically reducing rainfall to zero in a month. Rainfall decreases also reduce the dispersal of air pollutants because heavy rain can wash atmospheric pollutants down to the ground through raindrops, thereby decreasing the amount of airborne pollutants and further improving air quality indices in Jabodetabek. This study aligns with the findings of Zender-Świercz et al. (2024), which revealed that temperature affects particulate concentrations in the air. Still, its impact is highly dependent on the local conditions and anthropogenic activities of the area. Additionally, the study by Hernández-Ceballos et al. (2025) confirms that wind circulation patterns, primarily local winds in the urban area of Naples, Italy, play a crucial role in the dispersion and accumulation of pollutants in the atmosphere.

CONCLUSIONS

As a result, the air pollution levels in Jabodetabek from July to December 2023, including those of carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), have consistently exceeded the WHO-established ambient air quality standard. The results showed that the concentration of CO was at alarming levels, with high variation from month to month. At the same time, NO_2 exceeded the permissible limits for many months, indicating that air quality requires ongoing attention. In the case of SO_2, levels were within acceptable limits in September but exceeded standards in the previous and subsequent months, indicating variability in emissions.

The primary pollutants in Jabodetabek are from stationary and mobile sources. The interventions should, therefore, be specifically targeted. Stationary sources include coal-fired power plants, extensive industrial areas, and many fossil fuel-powered vehicles. All these factors combine to worsen the air quality. In addition to these emission sources, climatic factors influence dispersion and concentration in the atmosphere.

This study focuses solely on the spatial distribution and factors influencing air pollution in the Jabodetabek area without examining the subsequent impacts on the health, economic, environmental, and social sectors. Therefore, future research is recommended to explore these multidimensional impacts through an interdisciplinary approach.

Additionally, there is a need to strengthen real-time, spatially based air quality monitoring systems and to control emissions from primary sources, such as coal-fired power plants, industrial areas, and fossil fuel-powered transportation. The government is also expected to formulate stricter emission regulations, accelerate the transition to clean energy, and promote the development of environmentally friendly public transportation. Public education and awareness campaigns about the dangers of air pollution are also crucial for enhancing community awareness and promoting active participation in sustainable air pollution control efforts.

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