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CASE STUDY

Correlation between meteorological variables, air quality, and the Coronavirus-19 pandemic events

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ABSTRACT

BACKGROUND AND OBJECTIVES: The study explores the complex relationship between meteorological variables, air quality, and Coronavirus-19 pandemic events in Jakarta, emphasizing the global concern over air pollution's detrimental effects on both health and the economy. It emphasizes the correlation between climate change and exacerbating air pollution by changing weather patterns and meteorological conditions, leading to elevated levels of pollution. Additionally, the study underscores the impact of the Coronavirus-19 pandemic on air quality, with lockdowns temporarily reducing emissions but also revealing the complex interplay between climate change, agricultural practices, and air pollution spikes. The ongoing challenges in improving air quality persist despite the government's efforts, highlighting the need for a thorough understanding of the situation to inform effective policy interventions and strategies for reducing emissions.

METHODS: The study analyzed key pollutants from five monitoring stations in Jakarta including particulate matter 2.5 from a Swiss air quality technology company. Meteorological data (temperature, rainfall, wind speed, humidity, and sunshine hours) were sourced from the Indonesian Agency for Meteorology, Climatology, and Geophysics for the period 2018-2021. The restriction measures and case data pertaining to the Coronavirus disease-19 were acquired from Health Office in Jakarta. Data analysis utilized Microsoft excel and statistical package for the social sciences software, with spearman correlation tests due to non-normal distribution. This empirical approach investigated the associations among air pollutants, meteorological factors, and occurrences of Coronavirus disease-19 in Jakarta, Indonesia.

FINDINGS: Positive linear elationships were identified between the concentrations of particulate matter 10, particulate matter 2.5, carbon monoxide, and nitrogen dioxide. Conversely, a negative linear correlation was observed between carbon monoxide and ozone levels. Nonlinear correlations also existed between various pollutants. During the pandemic, carbon monoxide, nitrogen monoxide and sulphur dioxide concentrations increased, whereas particulate matter 2.5 and ozone levels decreased. Air quality parameters were generally higher in the dry season. Throughout the pandemic, the temperature and wind speed exhibited a consistent pattern, remaining stable. However, it is noteworthy that the levels of humidity and intensity of rainfall experienced a noticeable increase during this period. Particulate matter exhibited a negative correlation with both humidity and rainfall, whereas temperature displayed positive correlations. Despite improved air quality during the pandemic, the link between air pollutants, meteorological factors, and Coronavirus disease-19 transmission was unclear, with only weak correlations between air quality parameters and Coronavirus-19 related deaths. Moderate correlations were observed between specific levels of pollutants prior to and amidst the pandemic.

CONCLUSION: Based on the findings, there was a weak correlation between confirmed deaths because of Coronavirus-19 and all air quality parameters. Nevertheless, the study showcased a more distinct association between confirmed cases of Coronavirus-19 and particular pollutants. Coronavirus-19 This study identified several key meteorological variables, including wind speed, direction, temperature, humidity, and rainfall, as significant drivers of particulate matter and sulphur dioxide concentrations. It is essential to comprehend the intricate connections among meteorological factors, air quality indicators, and occurrences of Coronavirus disease-19 in order to formulate efficient public health measures and environmental regulations aimed at safeguarding communities from the impacts of air pollution and infectious diseases.

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58	5	4

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INTRODUCTION

The problem of air quality and air pollution has been a concern not only for individual cities or countries but also at a global level. Air pollution has negative effects on the economy and health of people residing in affected areas (Rodríguez-Urrego and Rodríguez-Urrego, 2020; Isaifan, 2020). Climate change has the potential to impact air quality through changes in weather patterns and meteorological conditions that create environments favorable for the accumulation of pollutants. This can result in an increased frequency, severity, and duration of heat waves, air stagnation events, and precipitation (Sun *et al.*, 2022). For instance, a study revealed that droughts in the southwestern region of the United States of America have the potential to escalate wildfires and dust, consequently exacerbating the levels of particulate matter (PM) pollution (Berman *et al.*, 2017). Additionally, warming climates can intensify ozone (O_3) pollution (Xu *et al.*, 2023). Scientists have discovered that air quality can be influenced by climate change and extreme weather events, and conversely, these events can also be impacted by air quality. Heatwaves, droughts, wildfires, cold waves, snowfall, and flooding have all been identified as factors that can have an effect on the quality of both air and water. For instance, stagnant air during heatwaves traps pollutants, leading to increased surface O_3 levels, whereas drought and heat can fuel wildfires and produce hazardous smoke. In contrast, cold waves can cause air pollution to accumulate (Peterson *et al.*, 2014). Pollutants released into the atmosphere have the potential to induce alterations in climate patterns, whereby O_3 plays a role in promoting warming, while PM can have either warming or cooling impacts. Furthermore, air temperature and precipitation can exert an influence on the overall quality of the air (Melamed *et al.*, 2016). The correlation between air pollution and climate change emphasizes the necessity for collaborative endeavors in tackling these concerns. The 2020 World Air Quality Report stated that in previous years, South and East Asia had the highest levels of pollution, with Bangladesh, China, India, and Pakistan accounting for almost all of the 50 most polluted cities worldwide (Mishra and Kulshrestha, 2021). The COVID-19 pandemic of 2019 had a significant impact on the air quality during the year 2020. The implementation of lockdown measures resulted in temporary reductions in the consumption of fossil fuels, which in turn led to a decrease in air pollution levels. As a result, 65 percent (%) of cities and 84% of countries saw improvements in air quality in 2020. Nevertheless, the enhancements achieved may prove to be temporary since the levels of pollutants are expected to bounce back (Tian *et al.*, 2021). Additionally, extreme air pollution events, such as wildfires and dust storms, in 2020 that were linked to climate change and agricultural practices resulted in significant air pollution spikes and greenhouse gas emissions. Despite the ongoing contribution of burning fossil fuels and industrialization to global air pollution, the pursuit of addressing climate change and air pollution is progressively proving advantageous (Raihan *et al.*, 2022). Many studies have reported a significant reduction in air pollutant concentrations owing to the lockdown implemented in the country. The cities that had better air quality in 2020 were Singapore (-38%), Wuhan (-18%), Seoul (-16%), and Delhi (-15%) (Adam *et al.*, 2021; Ali *et al.*, 2021; Karuppasamy *et al.*, 2020). Numerous studies, including those by Huang *et al.* (2020); Sahoo *et al.* (2020); Sulaymon *et al.* (2021), and Sarmadi *et al.* (2021), have investigated the correlation between air quality, meteorological parameters, and the COVID-19 pandemic. Sarmadi *et al.* (2021) concentrated on the timeframe spanning from 2020 to 2021, whereas the remaining three studies examined various months within the year 2020. A significant portion of the research articles that were published stemmed from brief observations conducted during the lockdown period. However, they did not consider long-term meteorological variables in the long run (He *et al.*, 2020; Linares *et al.*, 2021). Rapid population growth and economic development in Southeast Asia have led to significant challenges of air pollution. Fine particulate matter ($PM_{2.5}$) emissions originate from diverse sources across different countries, such as construction, industry, and transportation. Additionally, Southeast Asia is susceptible to wildfires, further contributing to the presence of $PM_{2.5}$ in the region (Phairuang *et al.*, 2020). However, in 2020, there were fewer fires than in 2019 because the dry season was wetter. This led to a 70% improvement in air quality in Southeast Asian cities by 2020 (Kanniah *et al.*, 2020). There is also a specific case in Indonesia where the air quality of every city worsened between 2018 and 2019 (Benchrif *et al.*, 2021). Due to the COVID-19 pandemic

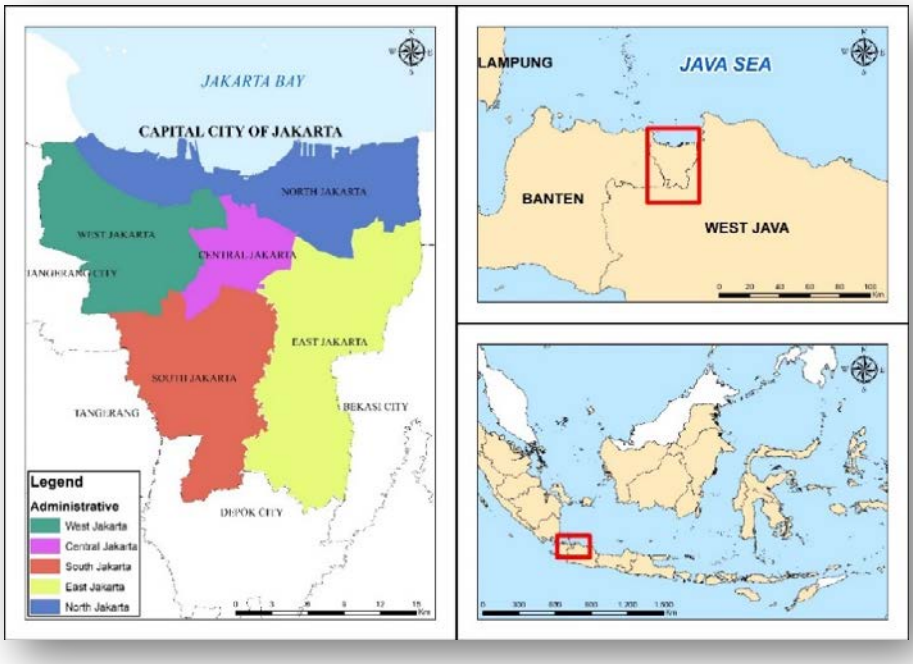


Fig. 1: Geographic location of the study area in Jakarta, the capital region of Indonesia

restrictions, the yearly levels of $PM_{2.5}$ in each urban area showed enhancement in 2020 when contrasted with those in 2018. For instance, the local government of Jakarta introduced many regulations related to air quality, such as odd and even number rules (starting September 9, 2019); limiting the mobility of older vehicles; more choices of public transportation; and new regulations such as mandatory emission tests, developing bigger pedestrian walkways, and more parks (Purwadi *et al.*, 2020). Despite the endeavors made by the local government to enhance the air quality, Jakarta still grapples with poor air quality. This predicament poses a significant challenge for the provincial government of Jakarta and other key stakeholders who are dedicated to enhancing the air quality in the region. It should also be noted that the slow implementation of Euro 4 is related to the several reasons described above. The lack of enforcement and socialization of residents has also slowed implementation (Greenstone and Fan, 2019). Identifying the cause or source of air pollution is also essential; the Government of Indonesia can then choose effective strategies to resolve air pollution and develop and implement effective policies to reduce emissions (Gunawan *et al.*, 2017). The current study was initiated due to the deteriorating air quality in Jakarta. Despite the many ongoing efforts of the government to resolve air quality issues, from improving public transportation to issuing air-quality-related regulations, the results are yet to be elucidated. A comprehensive comprehension of the circumstances can aid in assessing whether the existing strategies will successfully accomplish the government's objective of diminishing air pollutant emissions, or if alternative approaches should be explored. The objective of this study was to examine the potential associations between meteorological variables and air pollution or air quality in a city, as well as the impact of the COVID-19 pandemic-related regulations on vehicle mobility. The objective of the current study was to examine the impact of mobility limitations implemented during the pandemic period spanning from 2020 to 2021 on the quality of air, while also conducting a comparative analysis of air quality data from Jakarta over a four-year period, encompassing 2018 to 2019 (pre-pandemic) and 2020 to 2021 (pandemic period). Additionally, this study aimed to analyze other factors, such as weather

conditions, which may have influenced the air quality in Jakarta between 2018 and 2021.

MATERIALS AND METHODS

Study area and data collection

Jakarta, the capital region of Indonesia, is divided into five cities and one municipality (Fig. 1). The total area of Jakarta is 7,659.02 km^2, and the total population in 2019, 2020, and 2021 was 10,557,810, 10,562,088, and 10,609,681, respectively. Jakarta is renowned for its high population density, with a projected figure surpassing 16,000 individuals per square kilometer (km2). A commuter survey carried out by the National Statistics Agency of Jakarta revealed that around 2.43 million commuters journey within, to, and from the city on a daily basis.

Limited mass public transportation has increased vehicle ownership, in contrast to the growth in the length of roads. Traffic congestion in Jakarta typically arises during peak hours, such as in the morning as individuals commence their workday and in the evening as they make their way back home. Air quality in Jakarta has been one of the worst among Asian countries in recent years, owing to the significant number of vehicles and traffic jams. Air pollution stemming from automobiles is an inescapable reality in urban areas. The five types of mass public transportation in Jakarta are commuter lines, TransJakarta buses, mass rapid transit (MRT), and light rail transit (LRT) managed by the local government in Jakarta; taxis; and online transportation (operated by private companies such as Gojek and Grab) (Oktorini and Barus, 2022). The key pollutants considered in this study were carbon monoxide (CO), hydrocarbon (HC), nitric oxide (NO_x), particulate matter 10 (PM_{10}), carbon dioxide (CO_2), and sulphur dioxide (SO_2) as measured by the local government of Jakarta at five monitoring stations: Bundaran HI, Kelapa Gading, Kebun Jeruk, Jagakarsa, and Lubang Buaya (Fig. 2). Given that the monitoring stations failed to gather $PM_{2.5}$ data in both 2018 and 2019, the essential $PM_{2.5}$ data was acquired from the Swiss Air Quality Technology Company (IQAir), a Swiss company specializing in air quality technology. Daily temperature, rainfall, wind speed, humidity, and sunshine hours in Jakarta were obtained from the Indonesian Agency for Meteorology, Climatology, and Geophysics (*Badan Meteorologi, Klimatologi, dan Geofisika*) located in Jakarta. All the meteorological and air quality data spanning from 2018 to 2021 were acquired. The Health Office of Jakarta provided information regarding the implemented restriction measures and the count of COVID-19 victims.

Data analysis

Microsoft excel (Microsoft 365, version 2309) was utilized to summarize all the data collected in the survey. Scatter plots were employed to detect

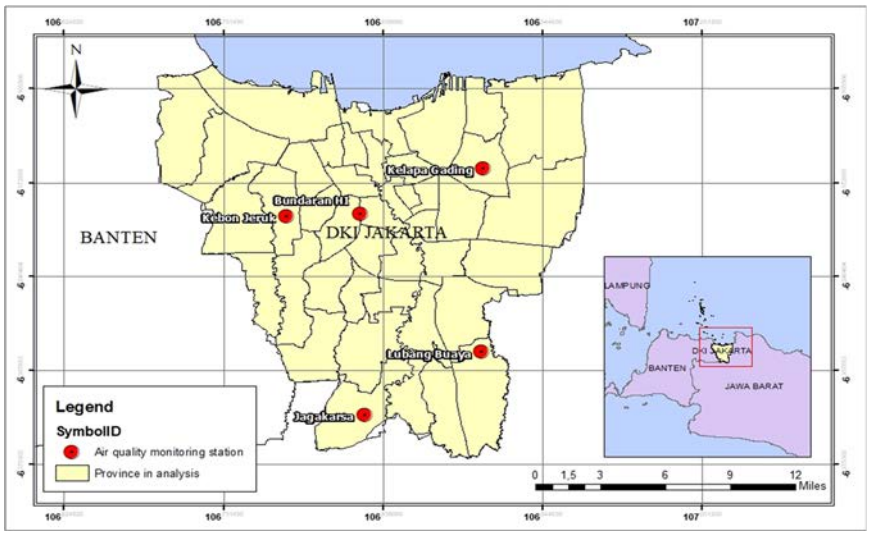


Fig. 2: Map of the sampling locations and air quality monitoring stations in Jakarta

the initial connections between variables (Khan and Khan, 2009). Statistical package for the social sciences (SPSS) software (version 16.0) was used to analyze meteorological characteristics, air quality data, and pandemic events. As the data used for this research project did not follow a normal distribution, the Spearman correlation test was employed as an empirical method to examine the relationship between air pollutants, meteorological variables, and COVID-19 in Jakarta. The Spearman correlation technique possesses ample strength to evaluate the direction and extent of the monotonic relationship between variables (Bashir *et al.*, 2020).

RESULTS AND DISCUSSION

According to the annual report by BMKG, (2000), the Indonesian Agency for Meteorology, Climatology, and Geophysics, the extreme temperature change in Jakarta in 2020 was much higher than the average temperature from 1981 to 2010. December and January are the months when Java experiences the highest amount of rainfall. When analyzing the average rainfall data between 1981 and 2010, it is evident that the precipitation levels were greater in the present year compared to previous years. News reports mentioned Jakarta multiple times as one of the cities with the poorest air quality in Asia and Southeast Asia. Air quality data from Jakarta, as reported in IQAir, showed that on Monday, June 20, 2022, Jakarta ranked second after Santiago, Chile, as the city with the worst air quality. The concentration of $PM_{2.5}$ in Jakarta was 27 times higher than that recommended by the World Health Organization. IQAir, (2018) identified Jakarta as one of the most polluted cities in Southeast Asia. In the report by IQAir, (2019), Jakarta was classified as the most polluted capital city in the region. Jakarta showed a higher ranking this year compared to the previous year and experienced enhanced air quality as a result of measures taken during the COVID-19 pandemic, as reported by IQAir (2020). A year later, IQAir, (2021) stated that Jakarta's ranking improved even further compared to 2020. The Government of Indonesia monitors the quality of critical air pollutants, including PM_{10}, SO_2, CO, O_3, and NO_2 (nitrogen dioxide), as mandated by the Environment Ministry Regulation No.12/2010. The transportation sector was the primary source of the following air pollutant parameters: NO_x (84%), PM_{10} (76%), and CO (90%). Despite the relatively modest growth in population (around 1%) and road length (less than 1%), the surge in the number of vehicles was substantial, surpassing 10%. In fact, the total number of vehicles in Jakarta in 2020 was twice the population count of the city. Heavy traffic congestion caused by the high volume of vehicles and inadequate infrastructure leads to elevated levels of air pollutants. The age limitation for vehicles in Indonesia is only applied to vehicles used for public transportation and not to privately owned cars or motorcycles (Local regulation No. 5 Year 2014). Private car owners are not required by any regulations to have garages. This is one reason that owning cars is easy for people in Jakarta. The demand for mobility and subsidies is expected to drive an annual increase of 5.9% in energy consumption in the transportation sector from 2012 to 2035. The insufficiency of trustworthy public transportation is projected to sustain the increase in private vehicle ownership. The number of passenger light-duty vehicles in Indonesia grew from 10.4 million in 2012 to 21.3 million in 2020 and is projected to reach 37.5 million in 2035. Emission tests conducted on approximately 12,024 vehicles in Jakarta in 2017 (92% with an age range of 1–10 years, 7% between 11–20 years, and 1% over 20 years old) found that almost 12% (or approximately 1,400) of vehicles did not pass the test. More than 50% of the cars over 10 years of age failed the test (Open Data Jakarta, 2018). Vehicles with operation periods exceeding 40 years are still in use. In spite of surpassing a 40-year operational span, there are still vehicles that remain in active service. With regards to the assessment of emissions, a total of 9,581 vehicles underwent testing in 2019. Among these, a notable 3.4% (322 vehicles) failed to meet the required standards and did not pass the test. Based on Regulation of Jakarta's Governor No. 66 Year 2020, vehicles over 3 years of age must carry out and pass emission tests. In the first semester of 2020, of the 3,869 vehicles tested, 2.5 percent of the vehicles (98 vehicles) did not pass the test.

COVID-19 counter measures policy in Jakarta

Indonesian patients with COVID-19 were first identified on February 14, 2020 in Jakarta. Subsequently, there has been a rise in the number of COVID-19 cases among patients in Jakarta, a city considered as one of the epicenters of the pandemic. According to the Government of Indonesia data, there

were more than six million cases and approximately 157,000 deaths as of June 19, 2022, attributed to COVID-19. Until June 21, 2022, the total cumulative number of positive COVID-19 cases in Jakarta was 1,258,665, with 1,238,059 declared cured, 15,309 dead, and 5,297 hospitalized. The Indonesian Government has implemented various measures to limit transportation and industrial operations in light of the pandemic. The following is a chronology of the regulations regarding the limitations on vehicle usage in Jakarta (Anugerah *et al.*, 2021):

a. On March 14, 2020, all tourist places were closed for two weeks.

b. On March 16, 2020, all schools were closed for two weeks.

c. On March 16, 2020, all TransJakarta buses, MRT, and LRT were limited to running only from 06.00 a.m. (before noon) to 06.00 p.m. (after noon) and with specific numbers of fleets (TransJakarta, 248 routes reduced to 13 routes; MRT, 16 fleets to only 4 fleets with arrival only every 20 minutes instead of 5 to 10 minutes; and LRT, from every 10 minutes to 30 minutes) for two weeks.

d. On March 17, 2020, all TransJakarta buses, MRT, and LRT resumed their regular working hours and fleet sizes; however, they limited the total number of passengers per fleet.

e. On March 16, 2020, the rules for odd and even numbered vehicles in a wider area were stopped, but applied again on August 3, 2020.

f. On March 16, 2020, letters from the Jakarta local government regarding suggestions for working from home were disseminated to all companies in Jakarta, and approximately 220 companies, including ministries and government agencies, immediately applied the work-from-home system.

g. On March 16, 2020, all religious events were suspended.

h. Indonesia's large-scale social restrictions (PSBB - *Pembatasan Sosial Berskala Besar*) were effectively implemented on April 10, 2020, based on the local government of Jakarta regulation No. 33, Year 2020 and the Ministry of Health Regulation No.9, Year 2020 Article 13 on the limitation of transportation mode.

i. The PSBB Transition was effectively applied from June 5 to June 18, 2020, and another PSBB Transition from June 19 to July 2, 2020. Two additional extensions of the PSBB Transition were applied until July 30, 2020. Other extensions were from July 31 to August 13, 2020. Odd and even numbered vehicles were used again starting August 3, 2020. The MRT began to normalize again on June 3, 2020. The critical period in which transportation limitations in Jakarta were applied was from March 16 to the end of May 2020.

j. Community activities restriction enforcement (PPKM; *Pemberlakuan Pembatasan Kegiatan Masyarakat*) Levelling represents the culmination of previous government policies and is implemented according to specific conditions in each region. This policy was introduced as previous policies were deemed unsuccessful in managing the increasing number of COVID-19 cases, which continued to rise in Indonesia. This policy was applied from January 11, 2021 to December 30, 2022.

Correlation between air quality parameters

This study identified various correlations between air quality parameters such as $PM_{2.5}$, PM_{10}, CO, O_3, SO_2, and NO_2. Positive linear correlations were observed between $PM_{2.5}$– PM_{10} (R^2 or R-squared = 0.53), PM_{10}–CO (R^2 = 0.03), PM_{10}– O_3 (R^2 = 0.11), and CO– NO_2 (R^2 = 0.50) concentrations. The levels of $PM_{2.5}$ and PM10, which are parameters used to measure ambient air quality, exhibit a strong positive correlation. This can be attributed to the fact that they originate from the same source and are influenced by similar meteorological conditions (Zoran *et al.*, 2020). $PM_{2.5}$ and PM_{10} are fine particulate matter; however, PM_{10} includes larger particles that can be inhaled into the upper respiratory tract, whereas $PM_{2.5}$ includes smaller particles that can reach the lower respiratory tract and enter the bloodstream, causing more severe health effects (Ramadan *et al.*, 2023). Strong correlations were also noted between CO and NO_2. These two indicators of air quality are typically linked to shared origins, including vehicle emissions, industrial discharges, and biomass combustion. Both CO and NO_2 are produced during the incomplete combustion of fuels and are emitted from the same sources, leading to their co-occurrence in the atmosphere (Shao *et al.*, 2022). Positive nonlinear correlations were observed between PM_{10}– SO_2 (R^2 = 0.03), $PM_{2.5}$ – SO_2 (R^2 = 0.39), $PM_{2.5}$ – CO (R^2 = 0.29) and – NO_2 (R^2 = 0.46), and SO_2 – NO_2 (R^2 = 0.38) and – CO (R^2 = 0.51). In contrast, a negative linear correlation was observed between CO and O_3 (R^2 = 0.27). Negative nonlinear correlations were observed

in $PM_{2.5}$– O_3 (R^2 = 0.42) and SO_2– O_3 (R^2 = 0.40) and – NO_2 (R^2 = 0.38). The levels of the atmospheric pollutants CO and O_3 exhibit an inverse relationship due to the fact that CO can serve as a reservoir for O_3 by undergoing a chemical reaction with it to produce CO_2, thereby impeding the generation of O_3. Additionally, CO has the ability to diminish the quantity of sunlight necessary for the formation of O_3, which is a photochemical process reliant on sunlight (Yao *et al.*, 2023). Therefore, high levels of CO can limit O_3 formation in the atmosphere, leading to a negative correlation between these two pollutants (Liu *et al.*, 2020). The formation mechanisms of ground-level O_3 and PM differ, resulting in an inverse relationship between the two. Particulate matter is generated mainly by the combustion of fossil fuels and industrial activities, whereas O_3 is formed by the photochemical reaction of volatile organic compounds and NO_x in the presence of sunlight. Ozone production escalates during sunny weather due to photochemical reactions, while particulate matter concentration decreases as a result of dispersion and dilution by atmospheric mixing. In contrast, during cloudy weather, the concentration of PM increases because it is trapped near the surface in the absence of atmospheric mixing, whereas the production of O_3 decreases because of the lack of sunlight. As a result, there tends to be a reverse association between O_3 and PM levels (Ravina *et al.*, 2022; Zhao, S., *et al.*, 2020). The scatterplots of all air pollutants from 2018 to 2021 are shown in Fig. 3.

The average concentrations of CO, NO, and SO_2 before the COVID-19 pandemic remained mostly constant. However, during COVID-19, the average

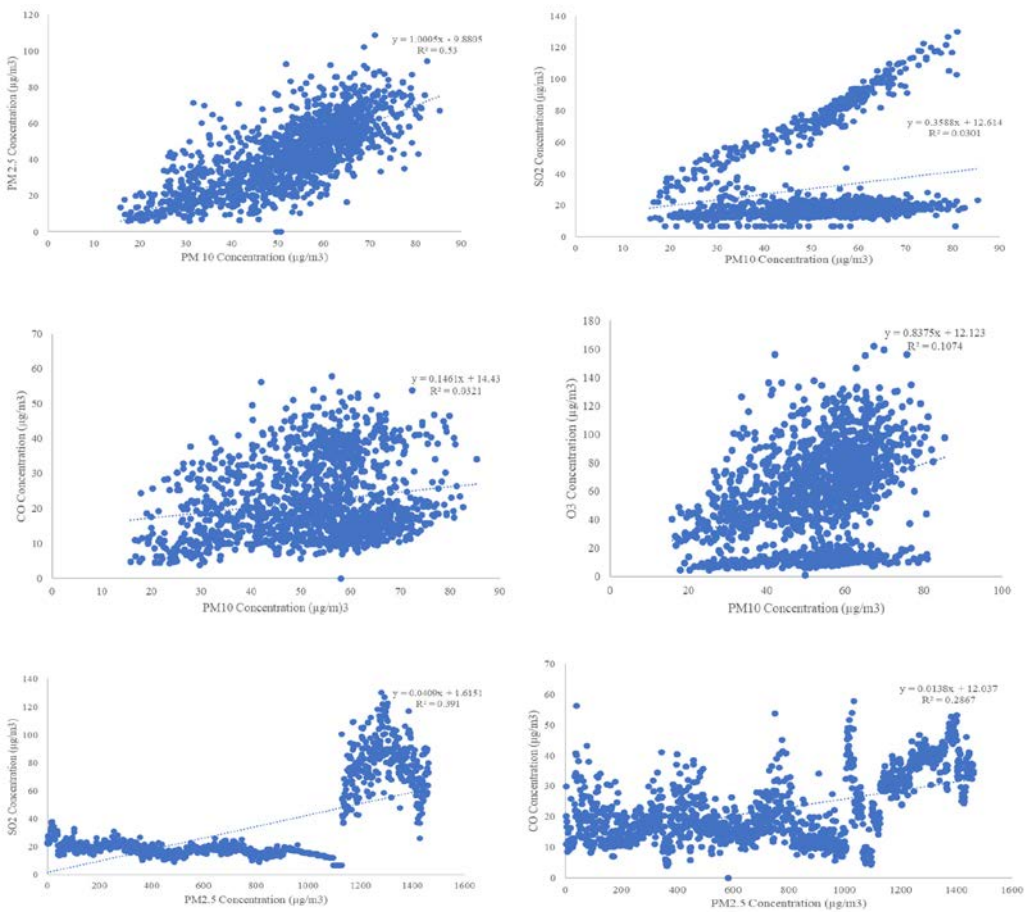
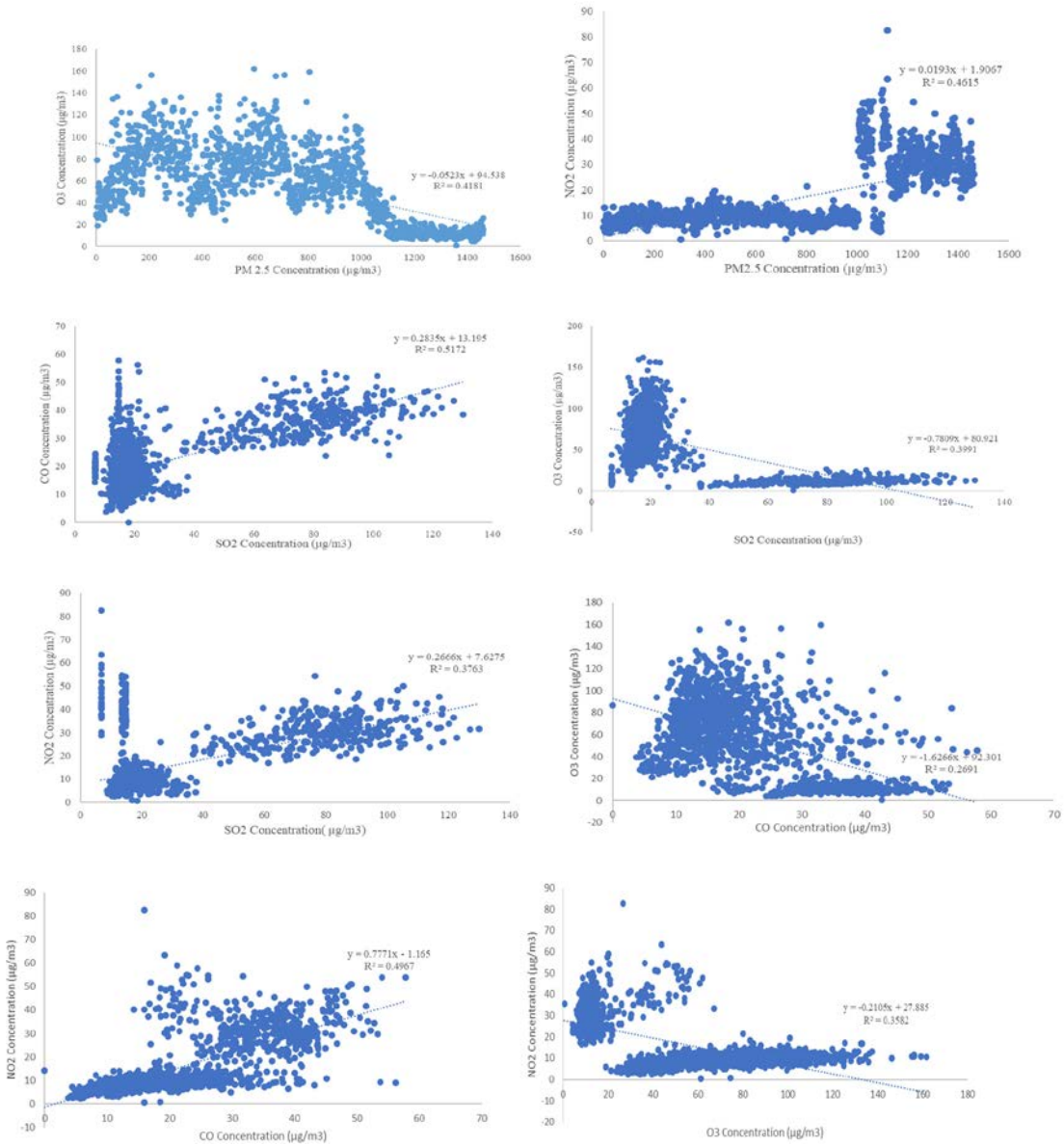


Fig. 3: Scatterplots of all air quality parameter during 2018–2021



Contiued Fig. 3: Scatterplots of all air quality parameter during 2018–2021

concentrations were higher than before COVID-19. As shown in Fig. 4, PM_{10} and $PM_{2.5}$ before and during the COVID-19 episode, had similar average concentrations. However, during the pandemic, there was a noticeable decline in the levels of $PM_{2.5}$ and O_3. This decline can be attributed to the decrease in traffic and industrial activities, which in turn resulted in a reduction in the concentration of $PM_{2.5}$. With the implementation of lockdowns and quarantine measures, traffic and industrial activities decreased, leading to low air pollutant emissions. In addition, lower energy usage and variations in weather conditions, such as increased precipitation, wind intensity, and humidity, can also contribute to the decrease in levels of $PM_{2.5}$ and O_3 in the air (Anugerah *et al.*, 2021).

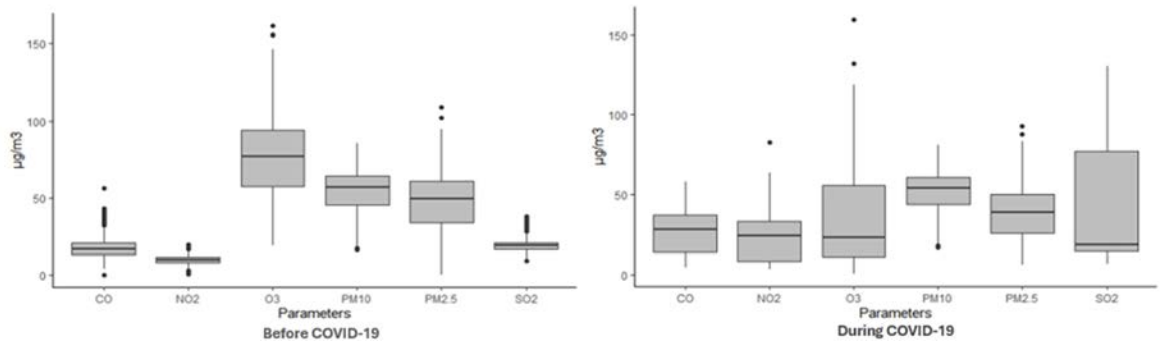


Fig. 4: Average concentration of ambient air quality parameter before and during COVID-19

Air quality parameters in different seasons

Before and during the pandemic, similar average levels of PM_{10} were observed in ambient air during the rainy and dry seasons. However, $PM_{2.5}$ and O_3 levels decreased during the pandemic in both the dry and rainy seasons. Moreover, SO_2, CO, and NO_2 concentrations increased during the pandemic in both seasons. Generally, all air quality parameters were higher during the dry season than during the rainy season (Fig. 5). As per the Air Quality Report that encompasses the timeframe of 2020 to 2021, there was an observed drop of roughly 5% in $PM_{2.5}$ concentrations in the area. An improvement in air quality was observed in six countries, with Indonesia contributing the most by demonstrating a 16% decrease in annual $PM_{2.5}$. The application of the PPKM level regulation amid the COVID-19 pandemic had consequences on the mobility of people. With reduced vehicle and human activity during COVID-19, but also less improvement in green open spaces, the level of O_3 decreased (Stratoulias and Nuthammachot, 2020).

The decrease in O_3 could also be explained by the effect of increased NO_2 during COVID-19. According to Li *et al.* (2014), NO_x and volatile organic compounds are critical precursors to ground-level O_3. A negative relationship between NO_2 and O_3 was also found by Hashim *et al.* (2021), who explained that the presence of large amounts of NO in the air exerts considerable influence on O_3 to form NO_2. A study conducted by Wyche *et al*. (2021) provides evidence to support the idea that a decrease in titration is associated with a significant reduction in NOx concentrations, especially in the early stages of the pandemic. They also explained that a decrease in total NO_x compared to total non-methane hydrocarbons was a significant factor in the increase in O_3 levels in urban areas in Asia and Europe. The rise in levels of SO_2, CO, and NO_2 observed during the COVID-19 pandemic can be attributed to various factors such as the combustion of household waste, the release of pollutants from coal burning, and the heightened reliance on private vehicles due to perceived hygiene concerns compared to public transportation. The result is also consistent with the findings of Wibowo *et al.* (2020), who indicated that the use of private vehicles, as well as the implementation of strict health protocols in outdoor areas, led to continued vehicle mobility during the pandemic in Jakarta, rather than a reliance on public transportation. The increase in CO and NO_2 is also consistent with the findings of Rendana *et al.* (2022); concentrations increased owing to the migration of pollution carried in the cardinal directions from east and southeast Jakarta.

Description of meteorological parameters

The temperature and wind speed before and during the COVID-19 pandemic were similar at 28–29 degrees Celsius (°C) and 1.3–1.6 speed per strength (m/s), respectively. The humidity before the pandemic in the dry season (71.323%) was lower than that during the pandemic (75.094%), whereas during the rainy season (77.638%), the humidity was only slightly lower than that before the pandemic (78.086%). The rainfall intensity exhibited a significant surge during the pandemic in comparison to the period preceding it. In the dry season, the precipitation escalated from 0.859 mm to 3.132 mm, while in the rainy season, it

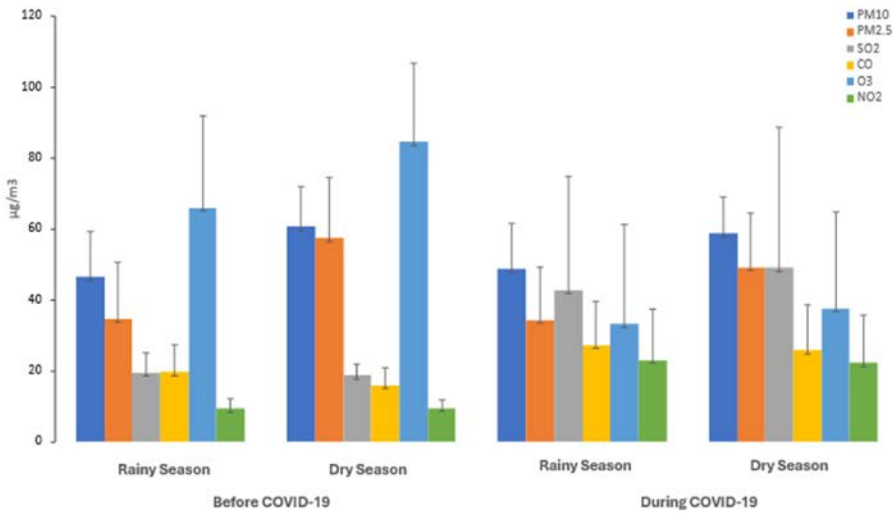


Fig. 5: Average level of ambient air quality parameters in different seasons before and during COVID-19

Table 1: Summary of meteorological parameters in Jakarta before and during COVID-19

Year	Season	Temperature (°C)	Humidity (%)	Rainfall Intensity (mm)	Duration of Radiation (h)	Wind Speed (m/s)
Before COVID-19 Pandemic (2018-2019)	Dry	28.916 ± 0.825	71.323 ± 5.088	0.859 ± 3.799	5.414 ± 1.982	1.300 ± 0.558
	Rainy	28.317 ± 1.034	78.086 ± 5.301	8.785 ± 16.098	4.264 ± 2.656	1.468 ± 0.568
During COVID-19 Pandemic (2020-2021)	Dry	28.871 ± 0.837	75.094 ± 4.829	3.132 ± 6.185	4.440 ± 2.217	1.360 ± 0.528
	Rainy	28.415 ± 1.033	77.638 ± 6.170	12.654 ± 22.720	4.216 ± 2.557	1.535 ± 0.658

rose from 8.785 mm to 12.654 mm. This heightened intensity of rainfall during the pandemic highlights the potential impact of global events on weather patterns. The duration of radiation showed a slight decrease during the dry season, from 5.414 h (hour) before the pandemic to 4.440 h during the pandemic. A summary of the meteorological parameters is presented in Table 1.

Correlation of Meteorological and Air Quality Parameters

As shown in Table 2, negative correlations were found between humidity or rainfall and PM_{10} or $PM_{2.5}$, indicating that when humidity or rainfall is high, PM_{10} or $PM_{2.5}$ will be low. The data revealed a direct relationship between temperature and PM10 as well as $PM_{2.5}$, showing that an increase in temperature leads to higher levels of these particulate matters. No correlation was observed between NO_2 and any of the meteorological characteristics. Weak correlations observed among various meteorological parameters and SO_2, CO, ground-level ozone O_3, radiation, and wind speed to PM. Moderate correlations were found between temperature, humidity, and rainfall and PM_{10} (0.29, 0.38, and 0.36, respectively) and $PM_{2.5}$ (0.30, 0.34, and 0.35, respectively).

Inhalation of particulate matter, which consists of tiny solid and liquid particles, can lead to negative health impacts due to its complex composition. The concentrations of both PM_{10} and $PM_{2.5}$ in ambient air were found to be affected by a variety of factors, including weather conditions such as temperature, humidity, and rainfall. Previous studies have shown that the concentration of PM is positively correlated with temperature, which means that as temperature increases, so does the concentration of PM in air. Elevated

Table 2: Correlation of meteorological and air quality parameters

Parameters	PM_{10}	$PM_{2.5}$	SO_2	CO	O_3	NO_2
Temperature	0.299**	0.303**	0.060*	-0.076**	0.153**	-0.032
Humidity	-0.375**	-0.335**	-0.204**	0.168**	-0.174**	0.012
Rainfall	-0.363**	-0.346**	-0.100**	0.149**	-0.166**	0.039
Radiation	0.198**	0.236**	0.127**	-0.086**	0.144**	0.015
Wind speed	-0.134**	-0.200**	-0.063*	-0.080**	-0.085**	-0.033

**Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)
Notes: White, grey, green, and blue boxes indicate no correlation and weak, moderate, and strong correlations, respectively.

Table 3: Correlation of air quality parameters and COVID-19 events

Events	PM_{10}	$PM_{2.5}$	SO_2	CO	O_3	NO_2
Confirmed death	0.247**	0.206**	0.202**	0.078*	0.078*	0.084*
Recovered	0.127**	0.216**	0.194**	0.022	0.022	0.139**
Positive cases	0.680**	-0.558**	0.385**	0.668**	0.669**	0.067

**Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)
Notes: White, grey, green, and blue boxes indicate no correlation and weak, moderate, and strong correlations, respectively.

temperatures have the potential to enhance the chemical processes responsible for generating particulate matter (PM). This can result in a rise in the occurrence and severity of wildfires and dust storms, both of which have the capacity to release substantial quantities of PM into the atmosphere (Srivastava, 2021; Zhu *et al.*, 2020). However, the concentration of PM was negatively correlated with humidity and rainfall, indicating that as humidity and rainfall increased, the concentration of PM in the air decreased. The presence of higher humidity and greater rainfall has a significant impact on the elimination of particulate matter (PM) from the air. This is primarily attributed to the role of these environmental factors in increasing the size of PM particles, thereby enhancing their susceptibility to removal through precipitation and deposition mechanisms (Zhao, X., *et al.*, 2020).

Correlation of meteorological parameters and COVID-19 events

Despite improved air quality during the COVID-19 pandemic and related lockdown measures, the contribution of air pollutants and meteorology to the transmission of the virus remains unclear. According to Kolluru *et al.* (2021), several air pollutants and meteorological variables, including $PM_{2.5}$, PM_{10}, CO, O_3, temperature, relative humidity, and wind speed, promoted COVID-19 transmission in five Indian megacities. During the lockdown period, a notable correlation was discovered between the levels of pollutants, meteorological factors, Air Quality Index (AQI), and the number of confirmed cases and fatalities, as indicated in a prior investigation (Kolluru *et al.*, 2021). The correlation between COVID-19 cases and deaths was most pronounced with temperature compared to other meteorological variables, whether during lockdown or when restrictions were not in plac (Chelani and Gautam, 2022). Ozone and temperature explained most of the variability in COVID-19 cases and deaths, whereas the AQI was not significant. Wind speed and relative humidity had less explanatory power. The data implies that meteorological factors, specifically temperature, might contribute to the transmission of COVID-19.

Correlation of air quality parameters and COVID-19 events

In contrast to the study conducted by Huang *et al.* (2020), which found a substantial association between COVID-19 mortality rates and average temperature as well as air quality index in 12 Chinese cities, the current research, as outlined in Table 3, indicates only a minor correlation between confirmed COVID-19 deaths and the various air quality parameters measured. Moderate correlations were found between positive COVID-19 cases and SO_2 ($R^2 = 0.39$), whereas a strong correlation was found between PM_{10} ($R^2 = 0.68$), $PM_{2.5}$ ($R^2 = 0.56$), CO ($R^2 = 0.67$), and O_3 ($R^2 = 0.67$). A possible explanation for this correlation is that exposure to air pollution can weaken the immune system and increase the susceptibility to respiratory infections,

Table 4: Correlation of air quality parameters before and during COVID-19

		During COVID-19 Pandemic (2018-2019)					
		PM_{10}	$PM_{2.5}$	SO_2	CO	O_3	NO_2
Before COVID-19 Pandemic (2020-2021)	PM_{10}	0.383**	0.430**	0.363**	0.226**	-0.112**	0.169**
	$PM_{2.5}$	0.441**	0.488**	0.364**	0.190**	-0.03972	0.167**
	SO_2	0.027	0.028	-0.223**	-0.188**	0.432**	-0.324**
	CO	-0.084*	-0.043	-0.078*	0.031	-0.000	0.114**
	O_3	0.294**	0.320**	0.167**	0.073	0.048	0.134**
	NO_2	0.080*	0.121**	0.250**	0.203**	**-0.266	0.244**

**Correlation is significant at the 0.01 level (2-tailed)
*Correlation is significant at the 0.05 level (2-tailed)
Notes: White, grey, green, and blue boxes indicate no correlation and weak, moderate, and strong correlations, respectively.

including COVID-19. Furthermore, air pollution has the potential to trigger inflammation in the lungs and other organs, worsening the symptoms of COVID-19 and resulting in more serious consequences (Wu *et al.*, 2020). An alternative explanation could be that air pollution serves as a vehicle for the virus, enabling it to spread over greater distances and linger in the air for extended durations. This, in turn, raises the chances of transmission (Botto *et al.*, 2023). Although the PPKM level was determined by the number of positive cases, death rate, and number of hospitalized COVID patients, it seems that the number of positive cases is strongly related to the level of almost all air quality parameters.

Correlation of air quality parameter before and during COVID-19

The concentrations of PM and SO_2 during the pandemic moderately correlated with their concentrations before the pandemic. A similar trend was also observed in the relationship between $PM_{2.5}$ levels prior to the pandemic and O_3 levels post-pandemic, as well as O_3 levels prior to the pandemic and SO_2 levels post-pandemic. SO_2 before the pandemic and NO_2 after the pandemic had a moderately negative correlation (Table 4). One possible reason for the correlation between PM and SO_2 is that their sources, such as industrial emissions and transportation, are generally persistent and remain relatively stable over time (Hilker *et al.*, 2021). Therefore, their levels can be impacted by various short- and long-term factors like weather patterns, air mass movements, and seasonal fluctuations. Moreover, the concentrations of PM and SO_2 are influenced by meteorological factors, such as wind speed and direction, temperature, humidity, and rainfall (Adha and Hadi, 2021). For instance, the velocity and orientation of wind can impact the movement and scattering of contaminants from their origins, while the temperature and humidity can influence the chemical reactions that result in the creation of PM and SO_2. The existence of regulatory policies aimed at decreasing the emissions of these pollutants could also be a contributing factor to the moderate correlation (Lu *et al.*, 2021). Although the effects of these policies may not be immediately visible, their long-term impacts can be observed through changes in air quality over time. The negative correlation between SO_2 and NO_2 may be attributed to the different sources of these pollutants. SO_2 primarily originates from industrial activities, whereas transportation is the main source of NO_2. As a result of the lockdowns implemented during the pandemic, transportation activities experienced a notable decline, potentially resulting in a reduction in NO_2 concentrations. However, industrial activities were not affected as much; therefore, the SO_2 concentrations may have remained relatively stable. This difference in source reduction may explain why the correlation between SO_2 and NO_2 changed from positive before the pandemic to negative during the pandemic (Filonchyk *et al.*, 2020; Kolluru *et al.*, 2021).

Limitation of the study

At the time of this study, data from the post-pandemic period were not yet available. To enhance the robustness and depth of the findings, future study should consider incorporating more comprehensive data. This can be achieved by comparing the findings with other cities that are experiencing similar conditions and restrictions. Additionally, exploring more potential factors such as socio-economic factors and utilizing more advanced statistical methods will contribute to a more comprehensive analysis. Given the limitations related to geography, limited air quality monitoring numbers, data availability, and statistical methodologies, it is anticipated that future studies will

provide a more nuanced and insightful conclusion.

CONCLUSION

Based on the findings of this study, there was a weak correlation between confirmed deaths because of COVID-19 and all air quality parameters. The findings of the study highlighted a distinct relationship between positive COVID-19 cases and particular pollutants. Positive cases of COVID-19 were strongly correlated with PM_{10}, $PM_{2.5}$, CO, and O_3, whereas $PM_{2.5}$ alone, showed a negative correlation. The positive correlation that existed between positive COVID-19 cases and PM_{10}, CO, and O_3 indicated that higher levels of these pollutants may indicate higher citizen mobility, which is a potential risk factor for COVID-19 transmission. The data indicates that air pollution might intensify the effects of the COVID-19 pandemic. Pollutants like PM_{10} and $PM_{2.5}$ can impair lung function and weaken immune system defenses, making individuals more susceptible to respiratory infections, including COVID-19. Furthermore, CO and O_3, known for their adverse effects on respiratory health, may also contribute to increased vulnerability. The study also analyzed air quality parameters before and during the pandemic, uncovering intriguing trends. PM and SO_2 concentrations during the pandemic showed moderate correlations with their pre-pandemic levels, indicating that existing pollution trends continued despite the pandemic. However, over the time, the interplay among pollutants has undergone changes. $PM_{2.5}$ concentrations before the pandemic correlated with O_3 and SO_2 levels after the pandemic, suggesting changes in atmospheric chemistry and pollution dynamics due to altered environmental factors and human activities. Furthermore, a modestly adverse association was identified between pre-pandemic SO_2 levels and post-pandemic NO_2 concentrations. This inverse relationship underscores the complex interplay between different pollutants and highlights the possible effect of modified emission sources and environmental regulations during the pandemic. This study pinpointed various important meteorological factors such as wind speed, wind direction, temperature, humidity, and rainfall, which play a crucial role in influencing the levelsof PM and SO_2 concentrations. Temperature was positively correlated with PM_{10} and $PM_{2.5}$, while humidity and rainfall showed negative correlations. It is important for individuals to be mindful of the heightened risk of PM exposure during hot weather, as it can result in long-term health issues. This suggests that temperature variations can affect virus transmission rates and severity. This highlights the necessity for additional research in order to unravel the intricacies of air quality, meteorology, and the dynamics of infectious diseases. Further study that includes more data and advanced statistical methods is needed since understanding the complex relationships between the meteorological variables, air quality parameters and COVID-19 events is crucial for developing effective public health strategies and environmental policies to protect communities from both air pollution and infectious diseases.

AUTHOR CONTRIBUTIONS

M. Gidarjati performed the literature review, gathered, processed, analyzed and interpreted the data, prepared the manuscript text and manuscript edition. T. Matsumoto provided assistance in research design, manuscript review and third-party proofreading.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
µg/m³	Micrograms per cubic meter
a.m.	Ante meridiem (before noon)
AQI	Air quality index
°C	Degree Celsius
CO	Carbon monoxide
CO_2	Carbon dioxide
COVID-19	Coronavirus disease 2019
h	Hour
HC	Hydrocarbons
IQAir	The Swiss Air Quality Technology Company
km²	Square kilometer
LRT	Light rail transit
mm	Millimeter
MRT	Mass rapid transit
m/s	Speed-strength
NO_x	Nitric oxide
NO_2	Nitrogen dioxide
O_3	Ozone
p.m.	Post meridiem (afternoon or after midday)
PM	Particulate matter
$PM_{2.5}$	Particulate matter 2.5
PM_{10}	Particulate matter 10
PPKM	*Pemberlakuan Pembatasan Kegiatan Masyarakat* (Community activities restriction enforcement)
SO_2	Sulphur dioxide
SPSS	Statistical package for the social sciences
PSBB	*Pembatasan Sosial Berskala Besar* (Large-scale social restrictions)
R^2	R-Squared (coefficient of determination)

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