Environment and Natural Resources Journal

Volume 22
Issue 3
2024

Characteristics of Fine Particulate Matter ($PM_{2.5}$) Chemical Composition in the North Jakarta Industrial Area

Zeni Anggraini[1,2*], Muhayatun Santoso[2], and Asep Sofyan[1]

[1]*Department of Environmental Engineering, Bandung Institute of Technology, Bandung, Indonesia*
[2]*National Research and Innovation Agency (BRIN), South Tangerang, Indonesia*

ARTICLE INFO

Received: 27 Nov 2023
Received in revised: 31 Mar 2024
Accepted: 18 Apr 2024
Published online: 9 May 2024
DOI: 10.32526/ennrj/22/20230300

Keywords:
Air pollution/ $PM_{2.5}$/ Black carbon/ Chemical elements/ SuperSASS

*** Corresponding author:**
E-mail:
anggrainizeni@gmail.com

ABSTRACT

Air pollution around industrial area has become a serious concern for both the public and local government. Thus, research on $PM_{2.5}$ characterization is urgently needed. This study identifies the concentration and chemical characteristics of $PM_{2.5}$ to provide an in-depth understanding of the composition of these particles around the largest industrial complex in North Jakarta. Sixty samples of $PM_{2.5}$ were collected from residential sites around industrial areas in North Jakarta. Samples were collected on Teflon filters using a SuperSASS instrument during the period from February to July 2023, representing the wet and dry seasons. Mass concentrations of $PM_{2.5}$, black carbon, and 19 chemical elements were determined. The average mass concentration of $PM_{2.5}$ in the wet and dry seasons was 27.81±11.82 $\mu g/m^3$ and 46.63±14.37 $\mu g/m^3$, respectively. Although the concentration of $PM_{2.5}$ was lower during the wet season, the concentrations of black carbon and certain elements did not decrease significantly. This shows that pollutants play an important role in both seasons in the study location. Sulfur is the most abundant element with the average concentration in the dry season (2,727.89 ng/m^3) higher than in the wet season (1,983.18 ng/m^3). The $PM_{2.5}$ mass reconstruction results show that ammonium sulfate and black carbon have the largest portion of $PM_{2.5}$ mass. The results are expected to be used as a scientific reference in studying air pollution problems in this region and assist in formulating air protection policies to reduce $PM_{2.5}$ emissions.

1. INTRODUCTION

$PM_{2.5}$ is considered the most harmful pollutant because it can enter the lung alveoli and blood circulation (Xie et al., 2021). A comprehensive study on the increase in $PM_{2.5}$ concentrations during the dry season in Southeast Asia was reported by Nguyen et al. (2020). Previous research estimated that $PM_{2.5}$ exposure caused 4.2 million deaths, equivalent to 7.6% of total global mortality (Cohen et al., 2017). Several epidemiological studies revealed a more consistent correlation of $PM_{2.5}$ exposure with acute respiratory infection and decreased lung function (Wang et al., 2021; Yan et al., 2022). In 2016, the prevalence of Acute Respiratory Infection (ARI) in Indonesia reached 25%, with the proportion of infant deaths reaching 32.10% of all under-five deaths (Putra and Wulandari, 2019). Based on Riskesdas data, the prevalence of ARI in the Special Capital Region of Jakarta (DKI Jakarta) in 2018 was 8.49% and North Jakarta was ranked second with the highest number of ARI cases (Ministry of Health of the Republic of Indonesia, 2018).

North Jakarta is a region within the DKI Jakarta Province that has seen a significant increase in industrial activity and urbanization. Marunda is one of the most densely populated areas in North Jakarta which has a strategic location about 10 km from Tanjung Priok port. The port plays an important role in the sustainability of economic activities and the transportation sector in this region. High activity in the transportation and industrial sectors is expected to increase $PM_{2.5}$ concentrations. In recent years, people

Citation: Anggraini Z, Santoso M, Sofyan A. Characteristics of fine particulate matter ($PM_{2.5}$) chemical composition in the North Jakarta Industrial Area. Environ. Nat. Resour. J. 2024;22(3):222-231. (https://doi.org/10.32526/ennrj/22/20230300)

living around the Marunda Industrial Area have felt a decrease in air quality. In 2015, cases of ARI in infants recorded at the local health centers reached 60 cases per 1000 and continue to increase (Anggraeni and Iriani, 2017). Several studies have found that the incidence of ARI cases is related to the chemical composition of $PM_{2.5}$, which contains harmful substances, such as heavy metals, organic compounds, inorganic chemical elements, and black carbon that have a negative impact on the human respiratory system (Darrow et al., 2014; Nascimento et al., 2020; Peng et al., 2009). In order to establish efficient air pollution control strategies, it is important to assess air quality and characterize the chemical composition of $PM_{2.5}$ in the Marunda Industrial Area during seasonal changes.

2. METHODOLOGY

2.1 Sampling site

The Marunda Industrial Area, which covers most of North Jakarta, is a leading industrial center in DKI Jakarta due to its rapid industrial development. Marunda Industrial Area accommodates various production facilities and types of industries, such as coal loading and unloading, manufacturing, and processing. $PM_{2.5}$ samples were collected from 2 February 2023 to 29 July 2023. The Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) defines that the wet season in Indonesia usually occurs from December to March, while the dry season occurs from June to September, with transitional periods from April to May and October to November. During the transition period in April, the effect of the east monsoon starts to strengthen, indicating the onset of the dry season from April to September (Aldrian and Dwi Susanto, 2003). The wet season is influenced by the northwest monsoon which brings more water vapor, resulting in increased rainfall. Conversely, the southeast monsoon in the dry season brings warm and dry air, resulting in less rainfall (Kusumaningtyas et al., 2018). Therefore, this study defines February-March as the wet season and April-July 2023 as the dry season.

Sampling of $PM_{2.5}$ from ambient air in residential locations near the Marunda Industrial Area was conducted using a SuperSASS filter-based instrument (Super Speciation Air Sampling System; Met One Instrument, Inc., USA). Air was collected through an inlet with a flow rate of ±6.7 Lpm. The SuperSASS was operated for 24 h with a 3-days sampling interval following the EPA schedule. SuperSASS was installed on the rooftop of D2 Marunda Flat (coordinates -6º05'48.14" S and 106º 57'39.42" E) at the height of ±20 m above ground level as shown in Figure 1.

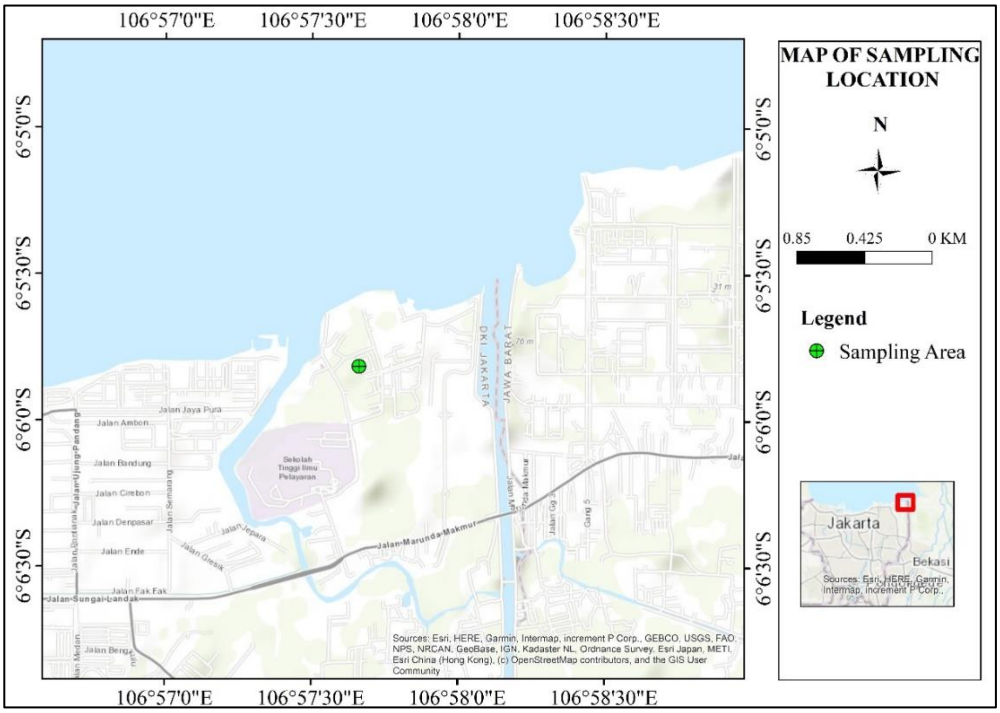

Figure 1. Map of $PM_{2.5}$ sampling location

2.2 Mass concentrations of $PM_{2.5}$ and black carbon analysis

Sixty samples were collected on Poly-tetrafluoroethylene (Teflon) filters with a diameter of 47mm. Before and after $PM_{2.5}$ collection, the filters were conditioned at a temperature of 20±5°C and a maximum relative humidity of 50±5% for at least 24 h for gravimetric mass determination using a Mettler Toledo XP6 electronic microbalance. $PM_{2.5}$ mass concentration was determined from the difference in mass before and after exposure divided by the volume of air passing through the filter. The black carbon (BC) concentrations in the $PM_{2.5}$ samples collected on the filter was analyzed using a Smoke Stain Reflectometer (type EEL 43M, Diffusion Systems, Ltd). The black carbon particles will absorb most of the light from the device directed to the filter sample. The amount of light that is not absorbed will be reflected into the detector and the reflectance value is proportional to the concentration of black carbon on the filter (Begum et al., 2012).

2.3 Elemental characterization

Energy Dispersive X-ray Fluorescence (ED-XRF) Spectrometry is suited for airborne particle elemental analysis due to its simple, fast sample preparation and multi-element analysis in a single measurement (Canepari et al., 2009; Owoade et al., 2015). ED-XRF PANalytical Epsilon 5 was used for the analysis of 19 chemical elements (Na, Mg, Al, Si, S, Cl, K, Cr, Fe, Ni, Cu, As, Pb, Ca, Ti, V, Mn, Zn, and Br). Before the XRF was used, a calibration curve was created using the MicroMatter Single Element Standard which establishes a linear relationship between X-ray intensity and element concentration. The XRF instrument's accuracy was assessed using the measurement of Standard Reference Material (SRM) NIST 2783.

2.4 Reconstructed mass (RCM)

The measured $PM_{2.5}$ mass was reconstructed from the sum of the analyzed chemical components to determine the relative contribution of various components to the $PM_{2.5}$ mass. In this study, the RCM calculation is based on the following equation (Santoso et al., 2020a):

$$\text{RCM} = \text{Ammonium sulfate} + \text{Elemental carbon} + \text{Crustal matter} + \text{Sea salt} + \text{Smoke} + \text{Trace elements} \quad (1)$$

2.4.1 Ammonium sulfate

Ammonium sulfate ($(NH_4)_2SO_4$) is a dissolved secondary sulfate. Chan et al. (1997) explained, the mass of dissolved sulfate measured is strongly correlated with sulfur (S). Therefore, the mass of ammonium sulfate can be calculated as follows (Malm et al., 1994):

$$\text{Ammonium sulfate} = 4.125\,[\text{S}] \quad (2)$$

2.4.2 Elemental carbon

The mass of elemental carbon is assumed to be the same as the mass of black carbon (BC), thus no multiplying factor is required (Watson et al., 2005).

$$\text{Elemental carbon} = [\text{Black Carbon}] \quad (3)$$

2.4.3 Crustal matter

Crustal matter is the sum of Al, Si, Ca, Fe, and Ti contained as oxides and a multiplying factor of 1.16 is required to exclude MgO, Na_2O, K_2O, and H_2O contained in the crustal mass (Chan et al., 1997; Rahman et al., 2019).

$$\text{Crustal matter} = 1.16\left(\begin{matrix}1.90\,[\text{Al}] + 2.15[\text{Si}] + 1.41[\text{Ca}] \\ + 1.67[\text{Ti}] + 2.09[\text{Fe}]\end{matrix}\right) \quad (4)$$

2.4.4 Sea salt

Na^+ and Cl^- are the main components of sea salt present in fine particles in the air (Watson et al., 2012). In this study, the contribution of sea salt was estimated using the following equation (Ho et al., 2003).

$$\text{Sea salt} = 2.54\,[\text{Na}] \quad (5)$$

2.4.5 Smoke

Potassium (K) can be associated as a trace element for smoke sources. However, K is also present in the crustal elements, which are assumed to have an average K/Fe ratio of 0.6. The equation used to estimate the mass of smoke in $PM_{2.5}$ mass is given below (Oanh et al., 2006):

$$\text{Smoke} = [\text{K}] - 0.6\,[\text{Fe}] \quad (6)$$

2.4.6 Trace elements

Trace elements not included in previous calculations can be added into the mass reconstruction analysis. Although their presence is only a small fraction (0.5-1.6%) of the total particulate mass, these elements are necessary to identify pollution sources and have a significant impact on the environment due to their toxicity (Chow et al., 2015).

2.5 Data analysis

Meteorological data in the form of wind direction and wind speed data from Air Quality Monitoring System (AQMS) near the research location were processed by creating a windrose to understand the wind distribution patterns around the Marunda Industrial Area. WRPlot View is the software used in the study to create windroses. Statistical analysis was performed using RStudio 2023.06.2+561 and Microsoft Excel 2019. All data were reported as mean ± standard deviation (SD). Data were analyzed using an independent t-test to determine whether or not there was an effect of season on the concentration and chemical composition of $PM_{2.5}$ in the Marunda area. Independent t-test results with a p-value <0.05 were considered significant.

3. RESULTS AND DISCUSSION

3.1 Mass characteristics of $PM_{2.5}$

Rainfall during the study in February, March, April, May, June, and July was 370, 262, 47.6, 12.9, 29.4, and 93 mm, respectively. February and March, the wet season, receive an abundance of precipitation exceeding 100 mm, whereas April through July receive less than 100 mm. Figure 2 shows the time series of 24-hour average $PM_{2.5}$ concentrations during the sampling period. The results show that from February to July 2023, some daily average $PM_{2.5}$ concentration data exceeded the national quality standard (55 μg/m^3), especially from May to July which is the dry season period (Republic of Indonesia Government Regulation, 2021). Compared to WHO global air quality guidelines and National Ambient Air Quality Standard (NAAQS), $PM_{2.5}$ levels in Marunda Industrial Area during the sampling period exceeded 74.57% and 94.92%, respectively, with the largest percentage occurring in the dry season (USEPA, 2006; WHO, 2021).

The seasonal variations in Indonesia have a significant influence on $PM_{2.5}$ level of concentration. The fluctuating daily average $PM_{2.5}$ concentrations shown in Figure 2 are most likely influenced by meteorological conditions. In the wet season, the average (±SD) $PM_{2.5}$ mass concentration at the study location was 27.81±11.82 μg/m^3, which was lower than the average concentration of 46.63±14.37 μg/m^3 reported during the dry season. The decrease in $PM_{2.5}$ concentration during the wet season can be due to the decrease in stagnant weather and the presence of strong winds from the southwest and northwest. These high-speed winds contribute, disperse, and carry away $PM_{2.5}$ dust particles (Chirasophon and Pochanart, 2020). The independent t-test results show a statistically significant difference in $PM_{2.5}$ mass concentration (p-value=6.14×10^{-6}, $\alpha<0.05$) between the two seasons.

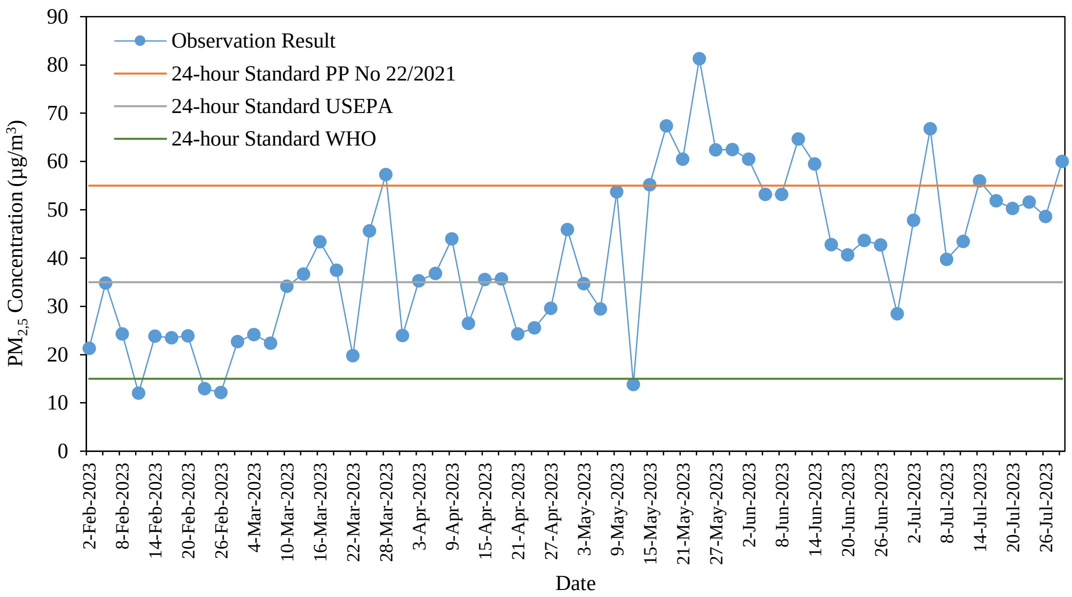

Figure 2. Daily mass concentrations of $PM_{2.5}$ during the sampling period

May has the highest mass average concentration of $PM_{2.5}$, as shown in Figure 3. This is likely due to the relatively low precipitation in May relative to other months. While the lowest concentration occurs in February when rainfall is abundant. These results are in line with research conducted by Istiana et al. (2023)

in Central Jakarta, a region situated at a considerable distance from the coast and serving as the epicenter of government and commerce. Despite the fact that air samples were collected in different areas, the findings from sampling in North Jakarta and Central Jakarta exhibit a comparable trend, with lower levels of $PM_{2.5}$ concentrations observed during the wet season compared to the dry season. This phenomenon arises due to the role of rainfall in effectively removing pollutants from the atmosphere. Rainfall accomplishes this by capturing pollutant particles and incorporating them into raindrops, which are then deposited onto various surfaces. Conversely, during the dry season, the eastern monsoon brings drier air and less rainfall, which restricts wet deposition. As a result, $PM_{2.5}$ particles accumulate and their concentration in the air increases (Narita et al., 2019).

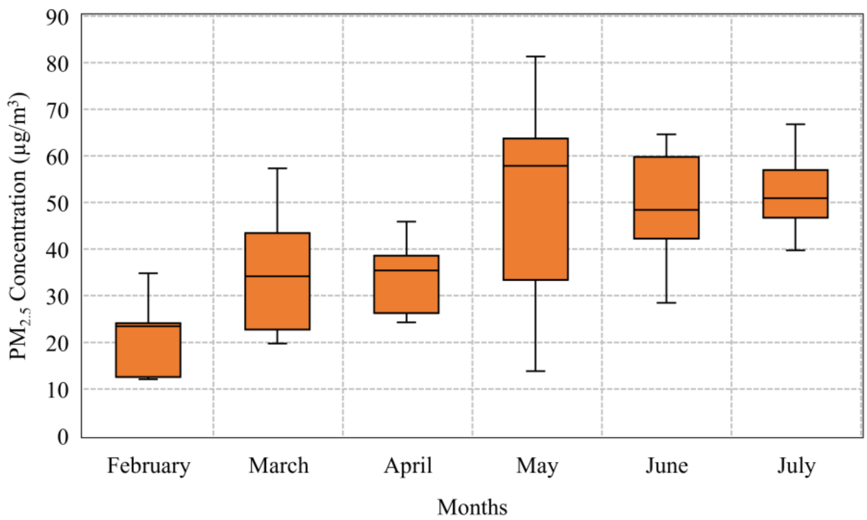

Figure 3. Monthly variations in $PM_{2.5}$ concentrations at the study location

The results of this study are still above the average $PM_{2.5}$ concentration value in industrial locations on Java Island, such as Waru Sidoarjo (18.26 µg/m^3) and Surabaya (16.00 µg/m^3) (Humairoh et al., 2020; Santoso et al., 2020b). This indicates that Marunda is more polluted than Waru and Surabaya. The $PM_{2.5}$ concentrations observed in the three industrial districts are influenced by variations in population, topography, type of industry, and amount of data. The exponential increase in population, industrialization, and vehicular activity in Marunda has had a significant impact on air quality, mostly due to the presence of $PM_{2.5}$ particles. Various kinds of public transportation, such as Bus Rapid Transit (BRT) and microtrans, have been constructed in the Marunda region. Nevertheless, these endeavors are inadequate to surmount the escalation in the quantity of automobiles and other activities that contribute to the emission of $PM_{2.5}$ pollutants in Marunda and its neighboring regions.

Windrose in Figure 4 shows that in the wet season, the prevailing wind originates from the northwest quadrant, accounting for approximately 25.75% of the total wind direction, while the southwest quadrant contributes around 12.02%. In contrast, during the dry season, the dominant wind blows from the northeast quadrant by 24.45% with weak winds from all directions. The average wind speed in the wet season is 1.43±0.98 m/s and 1.06±0.92 m/s in the dry season. The ambient temperature for each season was 27.55±1.78°C in the wet season and 28.60±2.50°C in the dry season. The relative humidity measured in the wet season and dry season were 69.18±15.92% and 65.03±32.19%, respectively. Variations in meteorological conditions between seasons have an impact on pollution levels and dispersion (Sasmita et al., 2019).

3.2 Characteristics of $PM_{2.5}$ chemical composition

3.2.1 Black carbon (BC)

Black carbon (BC) particles have a significant impact on climate change and are linked to adverse effects on human health (Ambade et al., 2022). The observed concentration of BC in $PM_{2.5}$ at the study location ranged from 1.90 to 11.39 µg/m^3 (N=60). The average values during the wet season (February-March) and dry season (April-July) were 5.42±2.23 µg/m^3 and 6.16±1.83 µg/m^3, respectively. Figure 5 shows that the average concentration in May was the highest compared to the other months. There was no statistically significant variation in the average concentration between the wet and dry seasons (p-value=0.18, α>0.05). The presence of BC concentrations in $PM_{2.5}$ in urban locations, serves as a tracer of anthropogenic emissions from diesel-engine vehicles in places with high traffic volume (Wang et al., 2009). The Marunda Industrial Area, located in an essential position between ports and industries, has high levels of transportation activities, primarily involving big vehicles predominantly powered by diesel engines. The average black carbon concentration at the location during the sampling period (5.91 $\mu g/m^3$) was above the average value reported by Santoso et al. (2020a) in Central Jakarta. The high concentration of BC is likely a result of the works on the Marunda Access Bridge, which contributed to increased traffic congestion.

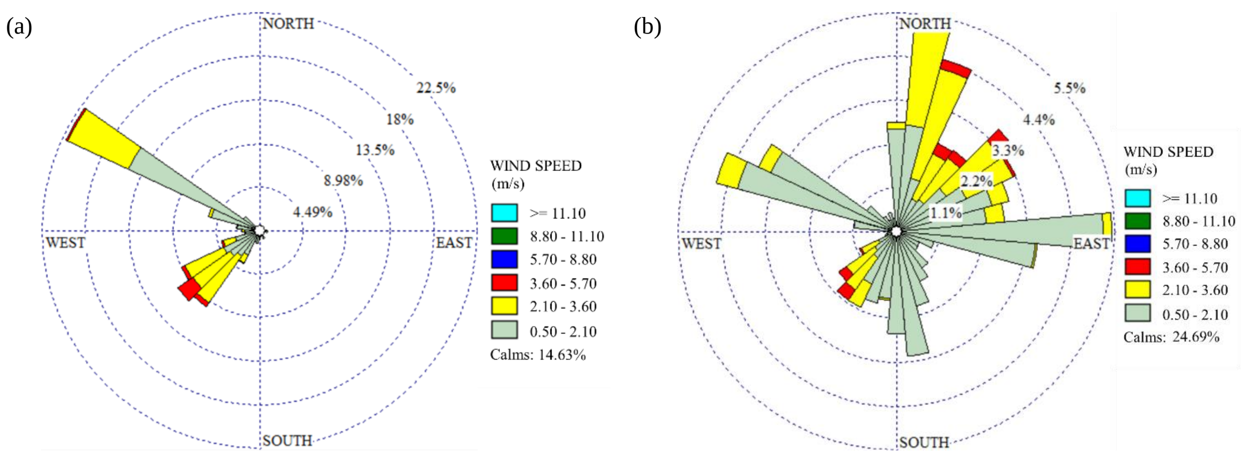

Figure 4. Wind directions and wind speeds in (a) wet season, (b) dry season

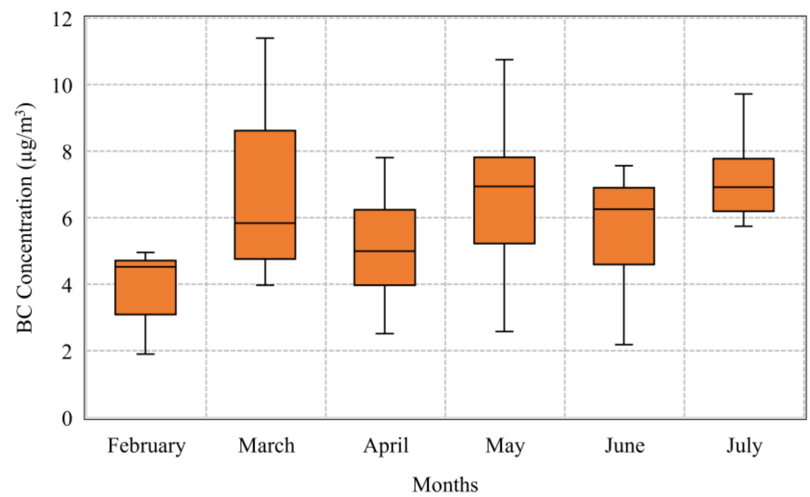

Figure 5. Monthly variations in black carbon concentration at the study location

3.2.2 Trace elements

Although the SRM NIST 2783 was not created by collecting $PM_{2.5}$ on a Polytetrafluoroethylene (Teflon) filter, it can still provide information about instrument performance. The results of elemental validation of the SRM NIST 2783 Air Particulate on Filter Media conducted by Kusmartini (2023) using the same PANalytical Epsilon 5 Energy Dispersive X-Ray Fluorescence (ED-XRF) spectrometer used in this study, as shown in Table 1, show that the ED-XRF accuracy described as % recovery is in the range of 92-101%, and the measurement precision expressed as relative standard deviation (%RSD) is less than 10%. These validation results indicate that the analysis meets the quality requirements. (Lei et al., 2020).

Table 1. Validation results

Elements	Analysis results (ng/cm^2)	Certified value (ng/cm^2)	% Recovery	% RSD
	Concentration	Concentration		
Mg	863.00	865.00	99.70	1.49
Al	2337.00	2330.00	100.30	0.49
Si	5723.00	5884.00	97.30	0.38
S	105.00	105.00	99.70	1.19
K	536.00	530.00	101.10	1.52
Ca	1313.00	1325.00	99.00	0.65
Ti	150.00	150.00	100.10	0.98
Mn	32.00	32.00	100.40	3.00
Fe	2608.00	2661.00	98.00	2.90
Cu	40.00	41.00	99.60	0.33
Zn	166.00	180.00	92.30	0.82
As	1.20	1.18	101.70	0.57
Pb	31.00	32.00	96.90	6.24

During the sampling period, the average concentration of the 19 trace elements measured was 5,752.71 ng/m^3, representing 14.25% of the total $PM_{2.5}$ mass concentration obtained. Table 2 shows that sulfur (S) was the dominant element in the $PM_{2.5}$ samples obtained from the Marunda Industrial Area. Its average concentration was higher during the dry season compared to the wet season. The presence of sulfur in $PM_{2.5}$ is a result from the combustion of fossil fuels, such as coal and high-sulfur vehicle fuels (Santoso et al., 2020a). In Indonesia, heavy diesel vehicles, particularly trucks and other large vehicles that frequently operate near industrial or main roads, commonly utilize fuels that contain sulfur levels of up to 2,500 ppm. The high sulfur concentration is probably due to the sampling location vicinity near industrial facilities that utilize coal as a fuel source, as well as its close proximity to Marunda's largest arterial road, which has frequent vehicle traffic.

Zinc (Zn) and Lead (Pb) were the heavy metals with the largest contribution to the total element concentration in $PM_{2.5}$. Zn and Pb have a significant impact on DNA and chromosome damage (Cavanagh et al., 2009; de Kok et al., 2005). Zinc originates primarily from the non-metallic smelting industry and vehicle tire wear (Farahani et al., 2021). Compared to the lead (Pb) levels observed in downtown Jakarta as reported by Santoso et al. (2020a), the average lead concentration at the study location was 1.5 times greater, but still below 24-hour ambient air quality guidelines. The chemical elements Na, Al, Si, S, K, Cr, Fe, As, Ti, and Br showed significant seasonal variations (p-value<0.05). The increase in concentrations of elements classified as anthropogenic sources, such as S, K, Cr, and Br, from the wet season to the dry season is thought to be related to the activities of local pollutant sources, such as industry, vehicles and biomass burning (Liu et al., 2023). Meanwhile, Na, Al, Si, Fe, As, and Ti are likely associated with soil dust originating from construction activities around the study location. These elements show a significant decrease in concentration from the wet to the dry season.

Table 2. $PM_{2.5}$ elements concentration (ng/m^3) in wet season (February-March) and dry season (April-July)

Elements	Wet season		Dry season	
	Average±SD	Range	Average±SD	Range
Na	1,215.38±317.91	574.88-1,763.77	855.59±565.19	135.94-3,399.61
Mg	70.85±73.93	3.43-287.39	47.96±36.33	1.46-214.92
Al	362.87±454.31	8.78-2,639.77	116.46±202.53	13.54-1,291.21
Si	479.67±420.05	83.43-1,600.05	224.32±263.25	23.34-1,727.28
S	1,983.18±815.90	842.27-4,097.98	2,727.89±657.45	970.96-4,233.99
Cl	273.48±457.93	25.08-2,160.28	127.24±95.35	16.15-417.34

Table 2. $PM_{2.5}$ elements concentration (ng/m^3) in wet season (February-March) and dry season (April-July) (cont.)

Elements	Wet season		Dry season	
	Average±SD	Range	Average±SD	Range
K	356.18±120.75	170.22-616.10	597.25±232.80	188.03-1,137.99
Cr	5.26±1.99	1.86-11.29	6.82±2.79	2.14-16.38
Fe	445.79±190.69	85.75-791.30	229.67±151.99	39.37-705.08
Ni	3.84±1.71	0.87-8.47	3.15±1.69	0.32-6.87
Cu	23.06±21.00	1.38-93.27	23.93±21.45	1.31-114.56
As	18.80±10.20	0.99-35.52	13.33±8.49	2.18-35.69
Pb	106.04±105.60	6.18-446.02	59.07±53.59	4.93-245.46
Ca	181.94±136.65	43.53-532.50	142.25±72.47	13.17-443.46
Ti	30.41±23.16	2.99-92.35	14.67±16.25	2.98-104.15
V	0.79±0.46	0.23-1.97	0.73±0.32	0.26-2.07
Mn	46.96±22.35	3.53-87.15	49.99±45.21	1.49-212.54
Zn	371.06±225.81	45.14-807.49	349.74±337.81	18.17-2,122.09
Br	17.98±10.60	3.86-40.65	42.16±36.39	7.08-170.53

3.3 Reconstructed mass (RCM)

Figure 6 shows the reconstructed $PM_{2.5}$ concentration based on average values during the wet and dry seasons. Based on the sum of six components, ammonium sulfate and black carbon account for the majority of $PM_{2.5}$ mass in both seasons. Organic compounds and secondary nitrates are examples of unaccounted-for masses in this investigation. In Marunda, ammonium sulfate mass contributed the most (31.19%) to $PM_{2.5}$ mass during the wet season compared with the dry season. The increase in relative humidity in the atmosphere increases the synthesis of $(NH_4)_2SO_4$ through chemical reactions, resulting in a larger concentration during the wet season. The ammonium sulfate found in this study was most likely caused by industrial and vehicular emissions. The research region is near an industrial sector that burns coal as its primary fuel, contributing to sulfur emissions into the atmosphere. In addition to industry, sulfur sources are expected to originate from the presence of ports on the northeast and northwest sides of the study area, which complicates matters with high volumes of heavy vehicle and ship emissions. In the wet season, black carbon accounts for 20.00% of $PM_{2.5}$ mass, while in the dry season, it accounts for 13.63%. Bangkok and Bandung, both cities with high traffic volumes, similarly have higher amounts of black carbon contribution in the wet season than in the dry (Oanh et al., 2006).

Sea salt is a chemical component that contributes to 13.22% of the reconstructed $PM_{2.5}$ mass during the wet season. The sampling location is less than one kilometer from the sea, where increased wind speeds assist in facilitating the transportation of sea salt particles to coastal areas. Consequently, the concentration of sea salt in $PM_{2.5}$ increases (Yin et al., 2005). The contribution of crustal matter is less than that of ammonium sulfate, sea salt, and unaccounted mass, indicating that crustal matter is more abundant in the coarse fraction than in the fine fraction, as reported by Oanh et al. (2006) in their investigation of six metropolitan cities in Asia. The mass of sea salt and crustal matter differed significantly in both seasons, with p-values of 2.2×10^{-6} and 0.2×10^{-2}, respectively. During the sampling period, the average smoke concentration was 342.69 ng/m^3, with the dry season contributing 0.97% more $PM_{2.5}$ mass. In Jakarta, source apportionment of pollutants identified biomass burning as one of the greatest contributors to $PM_{2.5}$ levels. Due to insufficient waste collection, open dumping and burning of waste in open areas remains a frequent practice in large urban areas such as Jakarta (Santoso et al., 2013). During the dry season, the practice of open burning is more prevalent, resulting in smoke plumes. Smoke plumes are lifted into the air and carried by the wind, increasing $PM_{2.5}$ concentrations in the atmosphere.

4. CONCLUSIONS

$PM_{2.5}$ mass concentration levels in the Marunda Industrial Area, North Jakarta, have significantly exceeded WHO and US EPA daily averages, especially in the dry season. Daily $PM_{2.5}$ trends indicate exposure to values ranging from 12.04 to 81.30 µg/m^3, potentially harmful to sensitive groups' health. Sulfur was the species with the highest

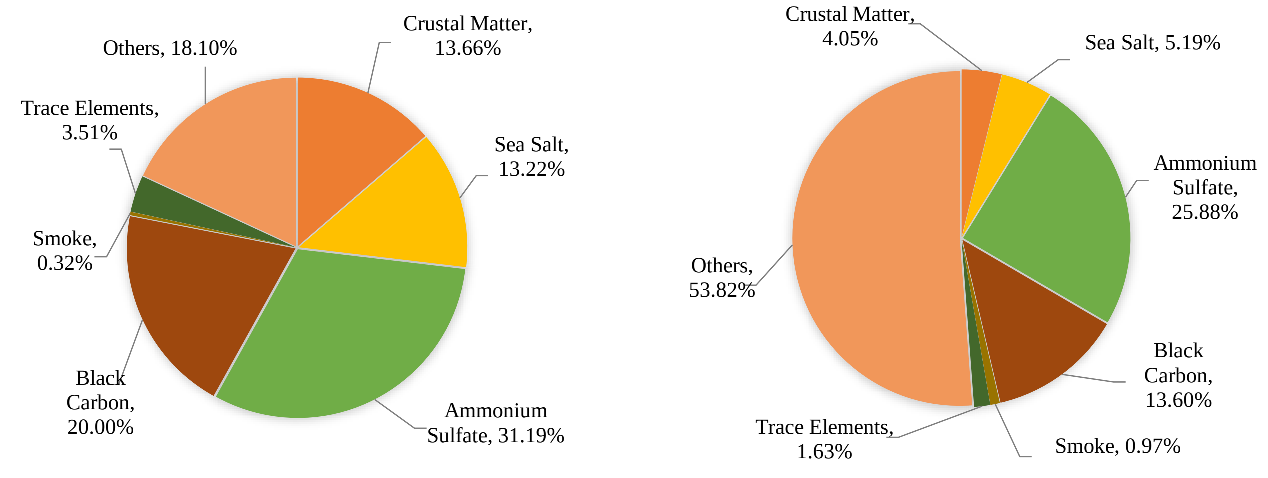

Figure 6. Reconstructed mass of $PM_{2.5}$ (a) wet season, (b) dry season

concentration, and ammonium sulfate contributed to the largest proportion of the $PM_{2.5}$ samples. Industrial activities involving coal are considered to be the source of excessive sulfur levels and a rise in ammonium sulfate in the atmosphere. Overall, this study demonstrates how climatic factors and pollutant sources contribute to $PM_{2.5}$. These findings can be used by local authorities to develop initiatives designed to lower the potential risk of $PM_{2.5}$.

ACKNOWLEDGEMENTS

This work was funded by National Research and Innovation Agency (BRIN) under the first batch of Riset Dan Inovasi Untuk Indonesia Maju (RIIM) program in 2022/2023, with contract number No: B-811/II.7.5/FR/6/2022 and No: B-2103/III.2/HK.04.03/7/2022.

REFERENCES

Aldrian E, Dwi Susanto R. Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. International Journal of Climatology: A Journal of the Royal Meteorological Society 2003;23(12):1435-52.

Ambade B, Sankar TK, Sahu LK, Dumka UC. Understanding sources and composition of black carbon and $PM_{2.5}$ in urban environments in East India. Urban Science 2022;6(3):Article No. 60.

Anggraeni SN, Iriani DU. Indoor air quality and symptoms of acute respiratory infection in children under five in Marunda Public Flats North Jakarta. Proceeding of the 1st International Integrative Conference on Health, Life and Social Sciences (ICHLaS 2017); 2017 Nov 11-12; Titan Conference Centre, South Tangerang: Indonesia; 2017.

Begum BA, Hossain A, Nahar N, Markwitz A, Hopke PK. Organic and black carbon in $PM_{2.5}$ at an urban site at Dhaka, Bangladesh. Aerosol and Air Quality Research 2012;12(6):1062-72.

Canepari S, Perrino C, Astolfi ML, Catrambone M, Perret D. Determination of soluble ions and elements in ambient air suspended particulate matter: Inter-technique comparison of XRF, IC and ICP for sample-by-sample quality control. Talanta 2009;77(5):1821-9.

Cavanagh J-AE, Trought K, Brown L, Duggan S. Exploratory investigation of the chemical characteristics and relative toxicity of ambient air particulates from two New Zealand cities. Science of the Total Environment 2009;407(18):5007-18.

Chan YC, Simpson RW, Mctainsh GH, Vowles PD, Cohen DD, Bailey GM. Characterisation of chemical species in $PM_{2.5}$ and PM_{10} aerosols in Brisbane, Australia. Atmospheric Environment 1997;31(22):3773-85.

Chirasophon S, Pochanart P. The long-term characteristics of PM_{10} and $PM_{2.5}$ in Bangkok, Thailand. Asian Journal of Atmospheric Environment 2020;14(1):73-83.

Chow JC, Lowenthal DH, Chen L-WA, Wang X, Watson JG. Mass reconstruction methods for $PM_{2.5}$: A review. Air Quality, Atmosphere and Health 2015;8:243-63.

Cohen AJ, Brauer M, Burnett R, Anderson HR, Frostad J, Estep K, et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. The Lancet 2017;389(10082):1907-18.

Darrow LA, Klein M, Flanders WD, Mulholland JA, Tolbert PE, Strickland MJ. Air pollution and acute respiratory infections among children 0-4 years of age: An 18-year time-series study. American Journal of Epidemiology 2014;180(10):968-77.

Farahani VJ, Soleimanian E, Pirhadi M, Sioutas C. Long-term trends in concentrations and sources of $PM_{2.5}$-bound metals and elements in central Los Angeles. Atmospheric Environment 2021;253(8):Article No. 118361.

Ho KF, Lee SC, Chan CK, Jimmy CY, Chow JC, Yao XH. Characterization of chemical species in $PM_{2.5}$ and PM_{10} aerosols in Hong Kong. Atmospheric Environment 2003; 37(1):31-9.

Humairoh GP, Syafei AD, Santoso M, Boedisantoso R, Assomadi AF, Hermana J. Identification of trace element in ambient air case study: Industrial Estate in Waru, Sidoarjo, East Java. Aerosol and Air Quality Research 2020;20(9):1910-21.

Istiana T, Kurniawan B, Soekirno S, Nahas A, Wihono A, Nuryanto DE, et al. Causality analysis of air quality and meteorological parameters for $PM_{2.5}$ characteristics determination: Evidence from Jakarta. Aerosol and Air Quality Research 2023;23(9):Article No. 230014.

de Kok TM, Hogervorst JG, Briedé JJ, van Herwijnen MH, Maas LM, Moonen EJ, et al. Genotoxicity and physicochemical characteristics of traffic-related ambient particulate matter. Environmental and Molecular Mutagenesis 2005;46(2):71-80.

Kusmartini I. Chemical Characterization of Fine Particulates ($PM_{2.5}$) using X-Ray Fluorescence and Ion Exchange Chromatography Methods [dissertation]. Bandung, Bandung Institute of Technology; 2023 (in Bahasa).

Kusumaningtyas SDA, Aldrian E, Wati T, Atmoko D, Sunaryo S. The recent state of ambient air quality in Jakarta. Aerosol and Air Quality Research 2018;18(9):2343-54.

Lei X, Chen R, Wang C, Shi J, Zhao Z, Li W, et al. Necessity of personal sampling for exposure assessment on specific constituents of $PM_{2.5}$: Results of a panel study in Shanghai, China. Environment International 2020;141:Article No. 105786.

Liu S, Wu T, Wang Q, Zhang Y, Tian J, Ran W, et al. High time-resolution source apportionment and health risk assessment for $PM_{2.5}$-bound elements at an industrial city in northwest China. Science of the Total Environment 2023;870:Article No. 161907.

Malm WC, Sisler JF, Huffman D, Eldred RA, Cahill TA. Spatial and seasonal trends in particle concentration and optical extinction in the United States. Journal of Geophysical Research: Atmospheres 1994;99(D1):1347-70.

Ministry of Health of the Republic of Indonesia. Indonesia Basic Health Research (RISKESDAS) 2018. Jakarta, Indonesia: The National Institute of Health Research and Development; 2018.

Narita D, Oanh NTK, Sato K, Huo M, Permadi DA, Chi NNH, et al. Pollution characteristics and policy actions on fine particulate matter in a growing Asian economy: The case of Bangkok Metropolitan Region. Atmosphere 2019;10(5): Article No. 227.

Nascimento AP, Santos JM, Mill JG, de Almeida Albuquerque TT, Júnior NCR, Reisen VA, et al. Association between the incidence of acute respiratory diseases in children and ambient concentrations of SO_2, PM_{10}, and chemical elements in fine particles. Environmental Research 2020;188:Article No. 109619.

Nguyen GTH, Shimadera H, Uranishi K, Matsuo T, Kondo A. Numerical assessment of $PM_{2.5}$ and O_3 air quality in Continental Southeast Asia: Impacts of future projected anthropogenic emission change and its impacts in combination with potential future climate change impacts. Atmospheric Environment 2020;226:Article No. 117398.

Oanh NTK, Upadhyay N, Zhuang Y-H, Hao Z-P, Murthy DVS, Lestari P, et al. Particulate air pollution in six Asian cities: Spatial and temporal distributions, and associated sources. Atmospheric Environment 2006;40(18):3367-80.

Owoade KO, Hopke PK, Olise FS, Ogundele LT, Fawole OG, Olaniyi BH, et al. Chemical compositions and source identification of particulate matter ($PM_{2.5}$ and $PM_{2.5-10}$) from a scrap iron and steel smelting industry along the Ife-Ibadan highway, Nigeria. Atmospheric Pollution Research 2015;6(1):107-19.

Peng RD, Bell ML, Geyh AS, McDermott A, Zeger SL, Samet JM, et al. Emergency admissions for cardiovascular and respiratory diseases and the chemical composition of fine particle air pollution. Environmental Health Perspectives 2009;117(6): 957-63.

Putra Y, Wulandari SS. Factors causing acute respiratory infection events. Health Journal 2019;10(1):Article No. 37 (in Bahasa).

Rahman MS, Akhter S, Rahman R, Choudhury TR, Jolly YN, Akter S, et al. Identification of sources of $PM_{2.5}$ at Farmgate Area, Dhaka using reconstructed mass calculation and statistical approaches. Nuclear Science and Applications 2019;28(1-2):13-23.

Republic of Indonesia Government Regulation. Republic of Indonesia Government Regulation No.22 of 2021 concerning Implementation of Environmental Protection and Management [Internet]. 2021 [cited 8 Feb 2023]. Available from: https://peraturan.bpk.go.id/Details/161852/pp-no-22-tahun-2021.

Santoso M, Lestiani DD, Damastuti E, Kurniawati S, Kusmartini I, Atmodjo DPD, et al. Long term characteristics of atmospheric particulate matter and compositions in Jakarta, Indonesia. Atmospheric Pollution Research 2020a;11(12): 2215-25.

Santoso M, Lestiani DD, Kurniawati S, Damastuti E, Kusmartini I, Atmodjo DPD, et al. Assessment of urban air quality in Indonesia. Aerosol and Air Quality Research 2020b;20(10): 2142-58.

Santoso M, Lestiani DD, Markwitz A. Characterization of airborne particulate matter collected at Jakarta roadside of an arterial road. Journal of Radioanalytical and Nuclear Chemistry 2013;297(2):165-9.

Sasmita A, Andrio D, Hasibuan P. Mapping the distribution of particulates from burning solid waste from the palm oil processing industry, in Kampar Regency, Riau. Journal of Science and Technology 2019;18(2):57-67 (in Bahasa).

United States Environmental Protection Agency (USEPA). NAAQS Table [Internet]. 2006 [cited 2023 Nov 14]. Available from: https://www.epa.gov/criteria-air-pollutants/naaqs-table.

Wang F, Chen T, Chang Q, Kao Y-W, Li J, Chen M, et al. Respiratory diseases are positively associated with $PM_{2.5}$ concentrations in different areas of Taiwan. PLoS One 2021;16(4):e0249694.

Wang X, Westerdahl D, Chen LC, Wu Y, Hao J, Pan X, et al. Evaluating the air quality impacts of the 2008 Beijing Olympic Games: On-road emission factors and black carbon profiles. Atmospheric Environment 2009;43(30):4535-43.

Watson JG, Chow JC, Chen L-WA. Summary of organic and elemental carbon/black carbon analysis methods and intercomparisons. Aerosol and Air Quality Research 2005; 5(1):65-102.

Watson JG, Chow JC, Lowenthal DH, Chen L-WA, Wang X, Biscay P. Reformulation of $PM_{2.5}$ Mass Reconstruction Assumptions for the San Joaquin Valley. Reno, Nevada: Desert Research Institute; 2012.

World Health Organization (WHO). WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide. Geneva, Switzerland: World Health Organization; 2021.

Xie W, You J, Zhi C, Li L. The toxicity of ambient fine particulate matter ($PM_{2.5}$) to vascular endothelial cells. Journal of Applied Toxicology 2021;41(5):713-23.

Yan M, Ge H, Zhang L, Chen X, Yang X, Liu F, et al. Long-term $PM_{2.5}$ exposure in association with chronic respiratory diseases morbidity: A cohort study in northern China. Ecotoxicology and Environmental Safety 2022;244:Article No. 114025.

Yin J, Allen AG, Harrison RM, Jennings SG, Wright E, Fitzpatrick M, et al. Major component composition of urban PM_{10} and $PM_{2.5}$ in Ireland. Atmospheric Research 2005;78(3-4):149-65.