Monitoring changes of $PM_{2.5}$ and carbonaceous compositions during dry season in South Jakarta, Indonesia

Fatimah Dinan Qonitan[1,3*], *Mitsuhiko* Hata[2], and *Ari* Rahman[3]

[1]Department of Geosciences and Civil Engineering, Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa 920-1192, Ishikawa, Japan
[2]Faculty of Geosciences and Civil Engineering, Institute of Science and Engineering, Kanazawa University, Kanazawa 920-1192, Ishikawa, Japan
[3]Department of Environmental Engineering, Faculty of Infrastructure Planning, Universitas Pertamina, Jakarta, Indonesia

Abstract. Air pollution in Jakarta, Indonesia, poses major environmental and health concerns due to persistently high fine particulate matter ($PM_{2.5}$) concentrations. This study investigated $PM_{2.5}$ from May to September of 2023, covering early to late dry season, with a focus on carbonaceous components, including organic carbon (OC) and elemental carbon (EC), to assess monthly variability and understand emission influences. Daily $PM_{2.5}$ concentrations averaged 43.6 ± 9.4 μg/m³ (N = 153), exceeding the Indonesia NAAQS daily standard of 55 μg/m³ on 8.5% of days. Carbonaceous component were analyzed intermittently on 29 sampling days using the Thermal Optical Reflectance (TOR) Method. Total carbon (TC) accounted for 12–64% of $PM_{2.5}$ mass, with OC consistently exceeding EC. Mean OC and EC concentrations were 10.1 and 3.9 μg/m³, respectively, and the OC/EC ratio remained relatively stable (mean = 2.6), indicating persistently OC-rich aerosols. $PM_{2.5}$ increased from the early to the late dry season, whereas the TC fraction decreased, suggesting a greater contribution from non-carbonaceous components under prolonged dry conditions. These results highlight the important role of carbonaceous aerosols in Jakarta's urban $PM_{2.5}$ pollution and the need for more detailed chemical speciation to improve source apportionment.

1 Background

Air pollution in Jakarta, the capital of Indonesia, represents a major environmental and public health challenge due to the high concentrations of particulate matter (PM) associated with intensive urban, transportation, and industrial activities [1], [2]. The degradation of air quality is strongly influenced by emissions from both industrial operations and heavy vehicular traffic, which together contribute substantially to sustained particulate pollution in the city [3]. These persistent emissions have significant health consequences for the population, with studies showing that air pollution in Jakarta may be responsible for more than 7,000 adverse

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[*] Corresponding author: fatimahdinanq@gmail.com

health outcomes among children, over 10,000 premature deaths, and more than 5,000 hospital admissions each year, resulting in an estimated annual economic burden of approximately USD 2.94 billion [4].

At the global scale, fine particulate matter ($PM_{2.5}$), defined as airborne particles with aerodynamic diameters ≤2.5 μm plays a central role in air quality management because of its established associations with increased mortality, atmospheric chemistry changes, and climate-relevant radiative effects. $PM_{2.5}$ is a regulated criteria pollutant in environmental protection frameworks, including the U.S. National Ambient Air Quality Standard (NAAQS) and the World Health Organization (WHO) guidelines, which emphasize mass concentration as a key metric, also regulated by the Indonesian National Ambient Air Quality Standard. Its health relevance derives not only from particle size but also from its chemical composition, which reflects emission sources and atmospheric transformation processes [2].

Continuous PM monitoring and chemical characterization efforts in Jakarta have produced valuable datasets for evaluating emission sources, assessing policy effectiveness, and quantifying health risks [1], [3], [5]. Long-term assessments indicate that annual $PM_{2.5}$ concentrations consistently exceeded the Indonesian National Ambient Air Quality Standard (55 $\mu g\ m^{-3}$) from 2010 to 2019, with elevated concentrations during the dry season [3], [6]. The Indonesian dry season typically spans from April to October, and is strongly influenced by Asian monsoon system. In Jakarta, the prevailing air masses shows dominance from easterly winds during the dry season, resulting in reduced precipitation [1], [5]. Lower precipitation during this period may limit pollutant dispersion and accumulation of airborne particles in the region [1].

In urban environments, $PM_{2.5}$ mass is typically dominated by six major components; sulfate, nitrate, ammonium, organic carbon (OC), elemental carbon (EC), and geological material [3], [7]. Carbonaceous matter, particularly OC and EC, constitutes a substantial portion of $PM_{2.5}$ and primarily originates from combustion processes from various anthropogenic processes [8], [9]. OC originates from both primary emissions (primary organic carbon, POC) and secondary formation (secondary organic carbon, SOC) through atmospheric reactions of gaseous organic precursors. On the other hand, EC is emitted exclusively from primary combustion sources as a result of incomplete combustion of organic materials, such as from fossil fuel combustion or biomass burning [10]. Therefore, characterizing the OC and EC provides useful insight into dominant emission sources and combustion processes influencing $PM_{2.5}$.

Despite substantial research on Jakarta's air quality, detailed and updated information on carbonaceous components within airborne $PM_{2.5}$ remains limited, particularly to capture mass concentration and carbon component variability within the dry season. To address this gap, this study conducted $PM_{2.5}$ sampling from early to end of dry season, from May to September 2023, capturing recurring monthly conditions during a period characterized by intensified pollutant accumulation.

2 Materials and Methods

2.1 Sampling Site and Period

$PM_{2.5}$ sampling was conducted on the rooftop of 2nd floor lecture building of Universitas Pertamina (6° 13' 39.324" S, 106° 47' 30.9078" E), ± 10 m above ground level (Fig. 1). The site is located in a mixed urban environment influenced by residential, commercial, and traffic-related activities, as it is located 1 – 3 km away from the Sudirman Central Business District (SCBD) area. The sampling location lies approximately 100 – 200 m from two high-traffic secondary arterial roads, Jalan Teuku Nyak Arief and Jalan Tentara Pelajar in

Kebayoran Lama District, South Jakarta. Sampling was performed from May to September, which corresponds to Jakarta's early to late dry season period [1], [5].

In order to assess hourly $PM_{2.5}$ mass concentration, additional data was obtained from the DKI-1 Air Quality Monitoring Site (AQMS) in Central Jakarta (6°11′40.78″ S, 106°49′24.92″ E), operated by the Jakarta Provincial Environmental Agency. The AQMS is located nearby from the Hotel Indonesia Roundabout (Bundaran HI), a high-density, mixed-use urban centre characterized by business, tourism, and governmental activities, and influenced by surrounding high-traffic road networks. Continuous $PM_{2.5}$ mass concentrations, one of the parameters regulated under the Indonesian National Ambient Air Quality Standards (INAAQS), were measured using a Federal Equivalent Method (FEM) Beta Attenuation Monitor (BAM) Horiba APDA-371 [1].

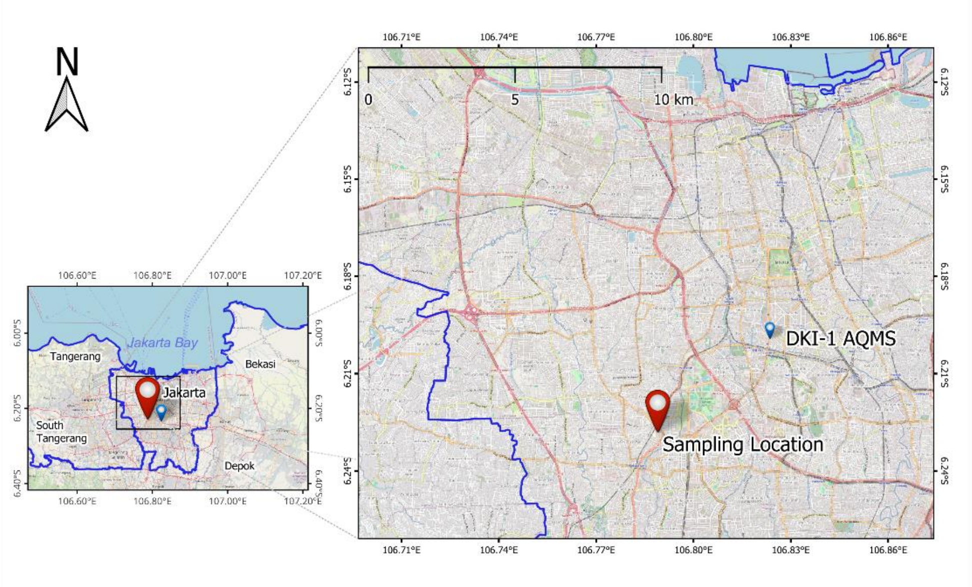

Fig. 1. Sampling and AQMS site in a mixed-activities urban locations in southern area of Jakarta, Indonesia

2.2 $PM_{2.5}$ Sampling

$PM_{2.5}$ samples were collected using a high-volume air sampling system consisting of a Tisch Environmental PM_{10} sampler (Model TE-6001) equipped with a retrofit $PM_{2.5}$ Size Selective (SSI) Inlet (TE-6001-2.5-I). The inlet operates based on the opposed-jet impactor design, providing aerodynamic separation of particles ≤ 2.5 µm in accordance with SNI 7119.14:2016. Sampling was performed over 24-hour periods, following the Indonesian National Standard requirements for determining $PM_{2.5}$ mass concentration in ambient air. The standard specifies operation of a High-Volume Air Sampler (HVAS) at an average flow rate of 1.1–1.7 $m^3\ min^{-1}$, using designated filter media and controlled environmental conditions during filter conditioning. In this study, the actual average sampling flowrate was 1.42 –1.70 $m^3\ min^{-1}$.

Sampling was performed at two-day intervals over a two-week period each month to represent all days of the week. $PM_{2.5}$ was collected on quartz fiber filters (Whatman Quartz Microfibre Filters QMA, 20.3 × 25.4 cm). Prior to sampling, filters were pre-baked to remove residual contaminants. After sampling, filters were folded in half and stored in clean containers during transportation prior to laboratory conditioning for carbon analysis.

2.3 Carbon Analysis

Carbonaceous components of $PM_{2.5}$ (organic carbon (OC) and elemental carbon (EC)), were quantified using a thermal-optical OC/EC Analyzer (Model 5L, Sunset Instruments Inc., USA) following the IMPROVE-TOR (Interagency Monitoring of Protected Visual Environments – Thermal/Optical Reflectance) protocol which widely applied in carbonaceous aerosol samples [11]. The sampled filters were punched into 1.0 cm^2 section for analysis. Full analytical procedure are described in previous studies [12], [13].

3 Results

3.1 $PM_{2.5}$ Mass Concentration

Based on AQMS data during 1st May 2023 to 30th September 2023 (N=153), daily average $PM_{2.5}$ concentrations ranged from 14.4 to 67.3 µg/m^3 (Fig 2), with average of 43.6 ± 9.4 µg/m^3 (N = 153 days). This value is within the range reported by previous long-term study of $PM_{2.5}$ concentrations in Jakarta 2010 – 2019 ranged from 15 to 31 µg/m^3 [2]; but lower compared to 2000 – 2016 study, which ranged from 38 to 112 µg/m^3 [1], [13]. Based on 153 observations, PM concentrations exceeded the WHO Air Quality Guidelines (WHO AQG) of 15 µg/m^3 on 99.3% days, demonstrating consistently unhealthy particulate levels throughout the dry season period. The Indonesia National Ambient Air Quality Standard (INAAQS) for 24 hour concentration (55 µg/m^3) was exceeded on 13 days (8.5%), with exceedances concentrated in late July to early August.

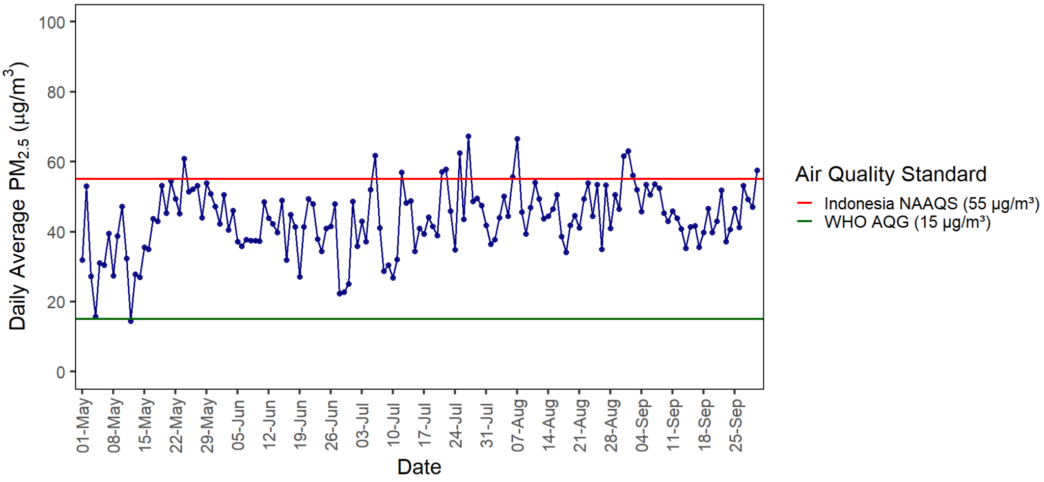

Fig. 2. $PM_{2.5}$ Concentration and Air Quality Guidelines from early to late dry season of 2023

3.2 Carbonaceous Component of $PM_{2.5}$

A total of 29 filter samples were collected intermittently, covering 19% of days in May to September 2023. During the sampling days, the average $PM_{2.5}$ concentration was 41.48 ± 9.21 µg m^{-3} (N = 29), which was only 5% lower than the mean over the full 153-day period. Temporal variability of $PM_{2.5}$ mass concentration and associated carbonaceous components (TC, OC, and EC) to cover early to late dry season (Fig 3).

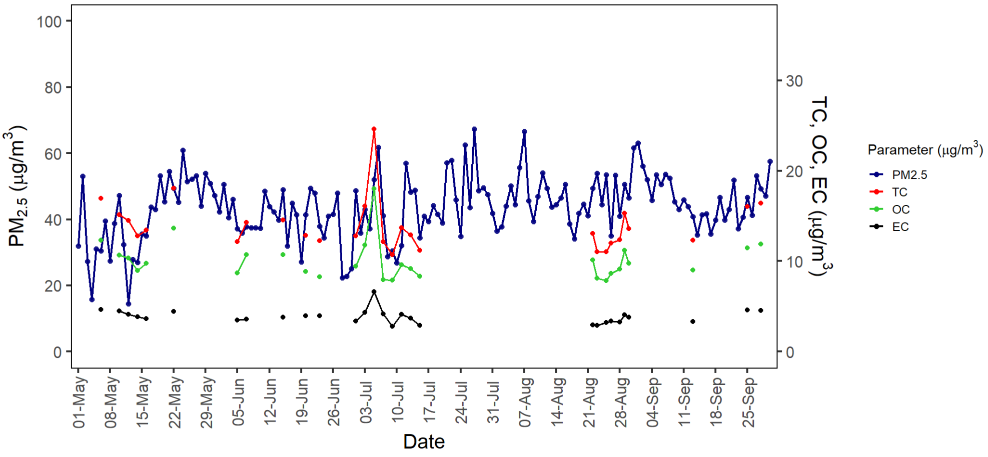

Fig. 3. $PM_{2.5}$ Concentration and Carbonaceous Component from early to late dry season of 2023

Several short-term $PM_{2.5}$ enhancement events were evident particularly during July to August, with some coincidence with elevated TC and OC concentrations (Fig 3). The highest $PM_{2.5}$ (51.99 µg/m³) and TC (24.62 µg/m³) were observed on 5 July, reflecting a concurrent increase in both OC and EC, suggesting that carbonaceous aerosols were a major contributor to the $PM_{2.5}$ burden (41%) during this period. This pattern likely indicates stronger influences from combustion-related sources, both organic carbon sources such as traffic emissions, biomass burning, and other anthropogenic activities, which simultaneously increase particulate mass and carbon fractions. However, not all high-$PM_{2.5}$ days corresponded to high carbon fractions; during late August, $PM_{2.5}$ remained elevated (mean = 47.1 µg/m³) while %TC declined to 28%, indicating that different sources or chemical components likely dominated $PM_{2.5}$ on these days.

Total carbon (TC) varied between 10.70 and 24.62 µg/m³ (mean: 13.9 ± 2.8 µg/m³), while organic carbon (OC) ranged from 7.84 to 18.01 µg/m³ (mean: 10.1 ± 2.1 µg/m³) and elemental carbon (EC) from 2.78 to 6.61 µg/m³ (mean: 3.9 ± 0.8 µg/m³) (Table 1). OC consistently accounted for the dominant fraction of TC across all sampling days, a pattern widely reported in urban aerosol studies where organic matter represents a major contributor to $PM_{2.5}$ mass [10]. Carbonaceous material contributed between 21% and 60% of $PM_{2.5}$, with an average contribution of 37% ± 12%. The highest %TC values occurred mainly in mid-May and mid-July, whereas lower contributions were observed during some $PM_{2.5}$ enhancement episodes in late August, further demonstrating that elevated $PM_{2.5}$ mass does not necessarily correspond to proportional increases in carbonaceous aerosol.

Table 1. Carbonaceous Component in $PM_{2.5}$ for South Jakarta site

Date	$PM_{2.5}$ (µg/m³)	TC (µg/m³)	OC (µg/m³)	EC (µg/m³)	OC/EC Ratio	%TC
6-May-23	30.41	16.96	12.29	4.67	2.63	64%
10-May-23	47.26	15.14	10.66	4.48	2.38	23%
12-May-23	14.39	14.48	10.36	4.13	2.51	52%
14-May-23	26.93	12.77	8.94	3.84	2.33	41%
16-May-23	34.94	13.40	9.78	3.62	2.70	39%
22-May-23	49.45	18.07	13.64	4.42	3.08	35%
5-Jun-23	37.24	12.15	8.68	3.47	2.50	32%
7-Jun-23	37.81	14.30	10.73	3.57	3.01	26%
15-Jun-23	48.89	14.53	10.71	3.82	2.81	34%
20-Jun-23	41.44	12.82	8.85	3.98	2.23	14%
23-Jun	37.89	12.24	8.29	3.95	2.10	37%
1-Jul-23	48.68	12.80	9.42	3.38	2.78	40%
3-Jul-23	42.98	16.10	11.79	4.31	2.74	42%
5-Jul-23	51.99	24.62	18.01	6.61	2.72	41%
7-Jul-23	41.10	12.13	7.95	4.18	1.90	40%
9-Jul-23	30.46	10.70	7.92	2.78	2.84	40%
11-Jul-23	32.08	13.69	9.58	4.11	2.33	60%
13-Jul-23	48.20	12.88	9.17	3.71	2.47	36%
15-Jul-23	34.45	11.22	8.30	2.92	2.85	38%
22-Aug-23	49.36	13.07	10.13	2.94	3.45	37%
23-Aug-23	53.95	11.02	8.11	2.90	2.80	33%
25-Aug	53.51	11.06	7.84	3.22	2.43	32%
26-Aug-23	34.96	12.02	8.62	3.39	2.54	27%
28-Aug-23	40.89	12.39	9.10	3.29	2.77	21%
29-Aug-23	50.60	15.27	11.21	4.06	2.76	24%
30-Aug-23	46.49	13.59	9.78	3.81	2.57	18%
13-Sep-23	40.86	12.33	9.03	3.30	2.74	39%
15-Sep-23	46.61	16.06	11.48	4.58	2.51	38%
28-Sep-23	49.23	16.42	11.90	4.52	2.63	61%
Average	41.48	13.94	10.08	3.86	2.62	37%
Standard Deviation	9.21	2.79	2.12	0.76	0.31	0.12
N	29	29	29	29	29	29

OC/EC ratios used widely used as diagnostic indicator of the origins of carbonaceous $PM_{2.5}$ [8], [9], [10]. Ratios below 2 are often associated with strong primary traffic emissions dominated by diesel exhaust, whereas higher ratios are indicative of increased organic contributions, potentially reflecting enhanced SOA formation or contributions from biomass-related combustion [10], [12]. Based on this study, OC/EC ratios in Jakarta, ranging from 1.90 to 3.45 with a mean of 2.6 ± 0.3 (Fig. 4), provide insight into the influence of those sources. Several days exhibited OC/EC ratios exceeding 3.0, with the highest value of 3.45 on August 22, 2023 during elevated $PM_{2.5}$ episode in late august, suggesting stronger influence from non-carbonaceous components to $PM_{2.5}$ concentration.

Temporal variability in the OC/EC ratio was moderate compared with $PM_{2.5}$ mass variability, indicating that although particulate concentrations fluctuated substantially, the relative balance between OC and EC remained relatively stable, except during enhancement episodes in late August. This stability implies persistent emission influences and atmospheric processing conditions over the sampling period. Similar patterns have been reported in other tropical urban settings, where continuous photochemical activity promotes organic aerosol formation while maintaining consistent EC contributions from traffic emissions [12].

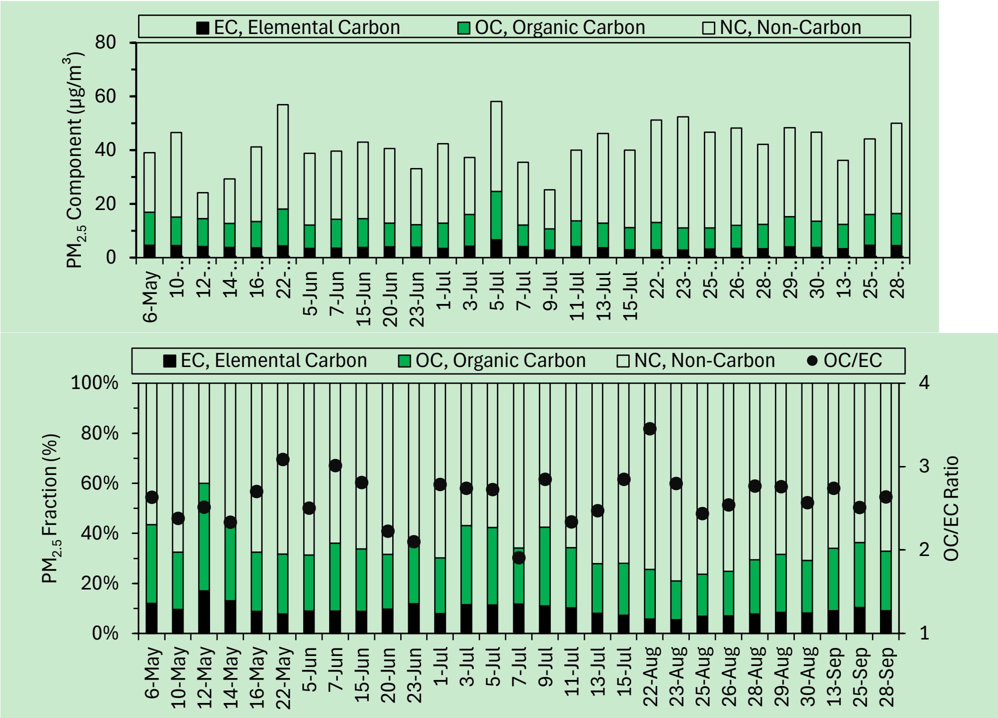

Fig 4. OC, EC Composition of $PM_{2.5}$ and OC/EC Ratio

Elemental carbon (EC) and black carbon (BC) are often used interchangeably in the literature, although they are defined operationally by different measurement approaches and both represent the light-absorbing, graphitic carbon fraction of aerosols relevant to climate and health studies [11]. Long-term observations in Jakarta suggest that BC concentrations have shown an increasing trend over 2010 to 2019 [3] (Fig. 4). However, to the best of our knowledge, no previous study has reported EC component of $PM_{2.5}$ measurements in Jakarta using the thermal–optical method prior to this work. The long-term increase in BC, together with the EC level observed in this study, suggests that combustion-related emissions remain an important contributor to urban particulate pollution in Jakarta. An increase in high-emission events like wildfires, regional biomass burning, or severe stagnant air/haze periods as shown in studies of high-haze periods, can significantly alter the OC/EC ratio and concentration [12].

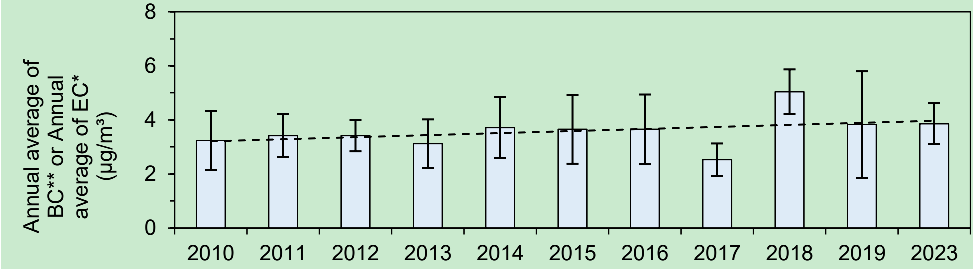

Fig 5. Long-term trend of elemental carbon or black carbon concentration in Jakarta,
*EC (Elemental Carbon) in 2023, this research data [Method: Thermal Optical Reflectance (TOR);]
**BC (Black Carbon) in 2008-2022, Santoso et al., 2020[3] [Method: EEL 121 Model 43D Smoke Stain Reflectometer]

Interpretation of OC/EC mass ratio values should be approached with caution, as differences in OC–EC split measurement protocols can introduce variability and lead to discrepancies among studies [8]. Therefore, comparisons in this study are limited to studies employing the Thermal Optical Reflectance (TOR) method as described by [11] (Fig 6).

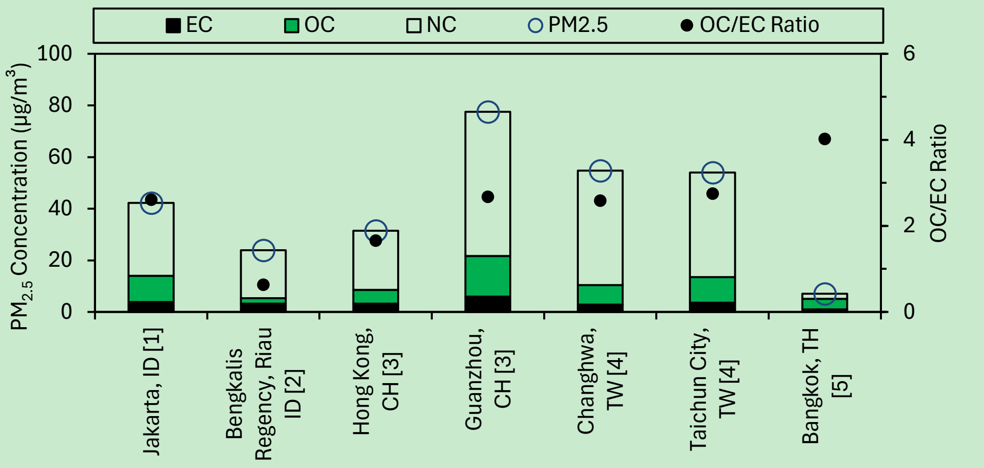

Fig 6. Comparison of $PM_{2.5}$ OC/EC Ratio among studies using the TOR Method
[1]This Research (2023); [2]Fujii et al. (2014)[8]; [3]Cao et al. (2004); [3]Cao et al. (2004)[10]; [4]Liu et al. (2005); [4]Liu et al. (2005) [14]; [5]Chomanee et al. (2024) [15]

Compared with the other sites, Jakarta shows a relatively high $PM_{2.5}$ concentration (42.18 µg/m³) and a moderately high OC/EC ratio (2.61). Its $PM_{2.5}$ level is lower than those reported for Guangzhou (77.50 µg/m³) and the two Taiwan sites, Changhwa (54.74 µg/m³) and Taichun City (54.00 µg/m³), but higher than those for Hong Kong (31.48 µg/m³), Bengkalis (23.90 µg/m³), and especially Bangkok (7.07 µg/m³). Compared with Bengkalis Regency, a rural site in Indonesia, Jakarta exhibits markedly higher OC and EC concentrations and a larger carbon fraction contribution (33.9% vs. 13.5%). This contrast likely reflects differences between urban and rural environments, including traffic density, fuel use, and energy consumption patterns, with Jakarta experiencing more intensive and sustained combustion-related emissions.

In terms of OC/EC ratio, Jakarta is similar to Guangzhou (2.68), Changhwa (2.59), and Taichun City (2.75), suggesting a broadly comparable balance between OC and EC at these sites. By contrast, Hong Kong (1.66) and Bengkalis (0.63) show much lower OC/EC ratios, indicating a relatively greater EC influence, whereas Bangkok (4.02) has the highest OC/EC ratio, reflecting a stronger dominance of OC relative to EC. The average OC/EC ratio in Jakarta (2.61) is above 2, a threshold often associated with secondary organic aerosol (SOA) formation in previous studies [11]. This suggests that secondary organic carbon likely contributed to $PM_{2.5}$ in Jakarta, although such interpretation should be made with caution because OC/EC ratios can also be influenced by primary emissions and atmospheric processing. Among the compared cities, Guangzhou reported the highest EC concentration, followed by Jakarta. Because EC is commonly associated with primary combustion emissions, especially motor vehicle exhaust, the relatively high EC level in Jakarta suggests that vehicular and other combustion-related sources remain important contributors to urban $PM_{2.5}$.

Overall, Jakarta appears to represent a moderately to highly urban $PM_{2.5}$ environment with a substantial contribution from carbonaceous aerosols. Although it does not show the highest $PM_{2.5}$ concentration among the compared locations, its $PM_{2.5}$ remains considerably elevated, and its OC/EC ratio places it closer to other heavily impacted Asian urban environments than to the lower-PM$_{2.5}$ sites such as Bengkalis, Hong Kong, or Bangkok. However, these inter-city comparisons should be interpreted cautiously, because the measurements were conducted in different years and seasons and thus provide indicative rather than strictly equivalent relationships.

3.3 Monthly Changes of PM$_{2.5}$ and Carbonaceous Component

Clear monthly variability was observed in PM$_{2.5}$ mass and carbonaceous aerosol characteristics from early to late dry season (Fig. 7). Monthly mean PM$_{2.5}$ concentrations increased from early dry season; May (46.46 μg/m^3) and June (39.44 m^{-3}); to the late dry season in July (44.76 μg/m^3), August (46.61 μg/m^3), and September (43.50 μg/m^3). This increase toward late dry season is consistent with reduced wet removal, enhanced atmospheric stability, and accumulation of fine particles under prolonged dry conditions, as reported in other tropical urban environments [6].

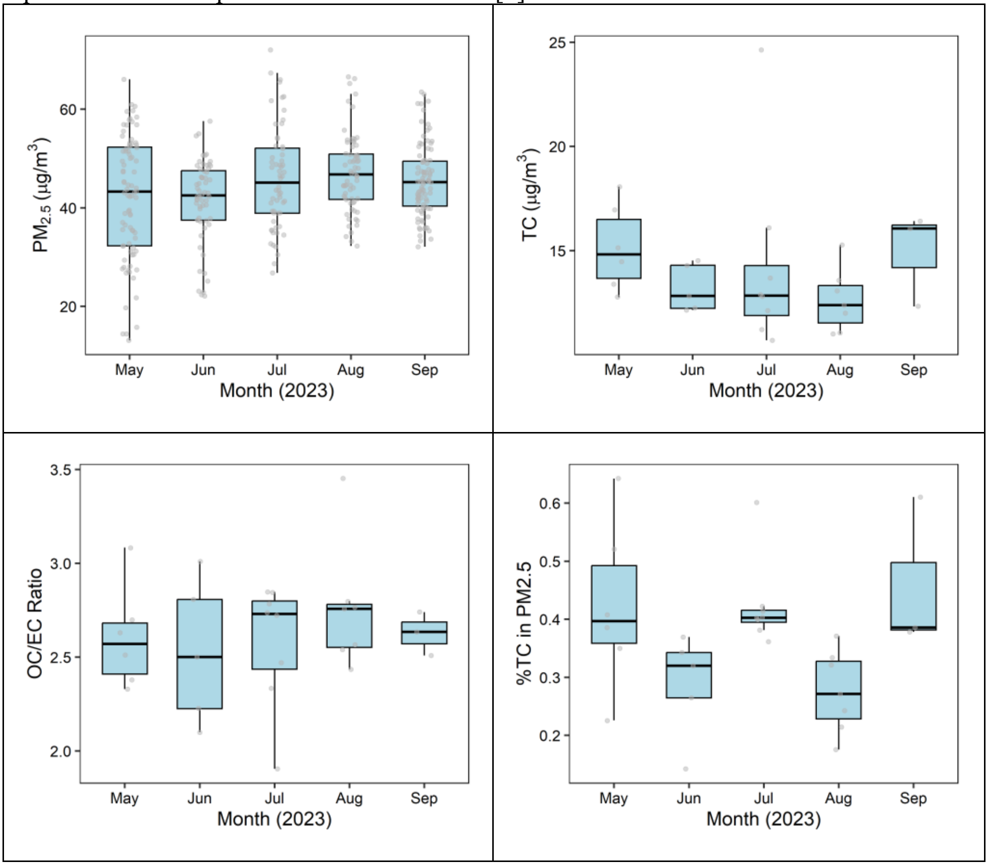

Fig 7. Seasonal Changes of PM$_{2.5}$ and Carbonaceous Components

In contrast to PM$_{2.5}$ mass, total carbon (TC) exhibited a different temporal pattern. TC decreased from May (15.14 μg/m^3) to a minimum in August (12.63 μg/m^3), followed by a marked increase in September (14.93 μg/m^3). This decoupling between PM$_{2.5}$ and TC suggests that non-carbonaceous components contributed more substantially to PM$_{2.5}$ mass during the peak dry month of August. This pattern may indicate enhanced contributions from non-carbonaceous PM$_{2.5}$ components, such as secondary inorganic aerosols or resuspended mineral dust, which are known to increase under prolonged dry conditions and reduced atmospheric cleansing [10]. This interpretation is further supported by the concurrent reduction in %TC, which declined from 42% in May and July to 28% in August, indicating a shift in aerosol composition rather than a uniform increase across all $PM_{2.5}$ constituents.

Organic carbon (OC) and elemental carbon (EC) followed broadly similar seasonal pattern, with relatively stable OC/EC ratios ranging narrowly between 2.53 and 2.76 across months. The limited variability in the OC/EC ratio suggests that the relative balance between organic and elemental carbon sources remained consistent throughout the dry season. Such stability may imply persistent emission influences, likely dominated by traffic and urban combustion sources, combined with ongoing secondary organic aerosol formation under strong photochemical conditions.

4 Conclusions

South Jakarta experienced persistently elevated $PM_{2.5}$ concentration during the 2023 dry season (mean: 43.6 ± 9.4 $\mu g/m^3$; N=153 days) with frequent exceedances of the WHO daily air quality guideline and episodic exceedances of the Indonesian NAAQS. Carbonaceous aerosols were a major component of $PM_{2.5}$, with TC contributing an average of 37 ± 12 % (N=29 days) and OC consistently exceeding EC with OC/EC ratio of 2.6 ± 0.3. Monthly differences were observed, with higher $PM_{2.5}$ but lower TC and %TC in August, indicating increased contributions from non-carbonaceous components during the late dry season. Based on the OC/EC ratio and $PM_{2.5}$ concentrations, a high-pollution episode was identified in late August; however, the lower %TC during this period suggests that non-carbonaceous components contributed substantially to $PM_{2.5}$ mass. These results emphasize the importance of carbonaceous aerosols in Jakarta's urban air pollution and the need for more detailed chemical characterization.

While this study provides a characterization of $PM_{2.5}$ mass and carbonaceous aerosol components in urban Jakarta, source identification remains limited by the scope of the chemical measurements. The analysis relies primarily on carbon fractions (OC/EC) which are insufficient for unequivocal source apportionment. As a result, contributions from specific sources such as traffic exhaust, biomass burning, industrial activities, and secondary organic aerosol formation cannot be quantitatively resolved. Future studies would benefit from expanded chemical speciation, including inorganic ions (e.g., sulfate, nitrate, ammonium), trace elements, and organic tracers (e.g., levoglucosan, hopanes, polycyclic aromatic hydrocarbons). The integration of such datasets with receptor modelling techniques (e.g., PMF or CMB) and meteorological analysis would enable more robust source attribution and improve understanding of the processes driving variability in $PM_{2.5}$ composition.

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