Annual Variation of PM$_{2.5}$ Chemical Composition in Ho Chi Minh City, Vietnam Including the COVID-19 Outbreak Period

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ABSTRACT

PM$_{2.5}$ was continuously collected in Ho Chi Minh City (HCMC), Vietnam, during the period from September 2019 to August 2020, which included the period of socioeconomic suppression caused by restrictions imposed in the face of the coronavirus disease of 2019. The concentrations of PM$_{2.5}$ mass, water-soluble ions (WSIs), organic carbon (OC), elemental carbon (EC), and water-soluble organic carbon (WSOC) were determined to evaluate the seasonal variations in PM$_{2.5}$, the effect of socioeconomic suppression on PM$_{2.5}$, and potential PM$_{2.5}$ sources in HCMC. The PM$_{2.5}$ mass concentration during the sampling period was $28.44 \pm 11.55 \mu g \cdot m^{-3}$ (average ± standard deviation). OC, EC, and total WSIs accounted for $30.7 \pm 6.6\%$, $9.7 \pm 2.9\%$, and $24.9 \pm 6.6\%$ of the PM$_{2.5}$ mass, respectively. WSOC contributed $46.4 \pm 10.1\%$ to OC mass. NO$_{3}^-$, SO$_{4}^{2-}$, and NH$_{4}^+$ were the dominant species in WSIs ($72.7 \pm 17.7\%$ of the total WSIs’ mass). The concentrations of PM$_{2.5}$ mass and total WSIs during the rainy season were lower than those during the dry season, whereas the concentrations of carbonaceous species during the rainy season were higher. The concentrations of PM$_{2.5}$ mass and chemical species during the socioeconomic suppression period significantly decreased by 45%–61% compared to the values before this period. The OC/EC ratio ($3.28 \pm 0.61$) and char-EC/soot-EC ($4.88 \pm 2.72$) suggested that biomass burning, coal combustion, vehicle emissions, cooking activities are major PM$_{2.5}$ sources in HCMC. Furthermore, the results of a concentration-weighted trajectory analysis suggested that the geological sources of PM$_{2.5}$ were in the local areas of HCMC and the northeast provinces of Vietnam (where coal-fired power plants are located).

Keywords: PM$_{2.5}$, Ho Chi Minh City, COVID-19, Vietnam, CWT

1 INTRODUCTION

Fine particulate matter (PM$_{2.5}$) is a major cause of air pollution in Southeast Asia, and high PM$_{2.5}$ concentrations are present here because of several complexed sources such as industry, automobiles, motorcycles, and biomass burning (Fujii et al., 2019; Koplitz et al., 2017; Nguyen et al., 2020; Yin et al., 2019). From 1998 to 2015, Southeast Asia (especially the Indo-China Peninsula) recorded the fastest urbanization rate and an increasing PM$_{2.5}$ trend compared to other areas such as Europe, Africa, and America (Yang et al., 2018). Furthermore, in Southeast Asia, the largest increases in SO$_{2}$ and NO$_{x}$ emission from coal combustion by 2030 are expected to occur in Indonesia and Vietnam (Koplitz et al., 2017).
Several studies on PM$_{2.5}$ were conducted in northern Vietnam (especially Hanoi) to evaluate their impacts on air quality and human health (Co et al., 2014; Hien et al., 2002; Luong et al., 2021; Lee et al., 2016; Popovicheva et al., 2016; Thuy et al., 2018; Tran et al., 2018). Most studies revealed the significant contribution of biomass burning (crop residue burning) to ambient PM$_{2.5}$ in Hanoi. Ho Chi Minh City (HCMC), located in southern Vietnam, is the most developed and populous city in Vietnam. In addition, the climate of HCMC is different from that of Hanoi, that is, HCMC is tropical monsoon and Hanoi is humid subtropical climate, resulting in different results of atmospheric pollution by PM$_{2.5}$. Few studies on PM$_{2.5}$ were conducted in HCMC, and only reports based on intensive field observations (Hien et al., 2019; Huong Giang and Kim Oanh, 2014; Huy et al., 2020) and emission inventories (Nguyen et al., 2021; Nguyen et al., 2022) are available. The results of these studies suggested that transportation and biomass burning were the main PM$_{2.5}$ sources in HCMC. However, no data based on long-term field observations of PM$_{2.5}$ are currently available. Data analysis based on long-term field observations is crucial to fully evaluate the PM$_{2.5}$ characteristics in HCMC.

Short-term and long-term exposure to PM$_{2.5}$ cause adverse effects on human health, such as respiratory and cardiovascular disorders, and lung cancer mortality (WHO, 2005). PM$_{2.5}$-bound chemical species, especially polycyclic aromatic hydrocarbons, have been considered as the major carcinogen to human (Ali-Taleshi et al., 2021). Luong et al. (2020) confirmed that the daily hospital admissions for acute lower respiratory infections among children in HCMC were associated with the ambient PM$_{2.5}$ concentration. HCMC has a high-density population of 4,097 individuals per square kilometer, whereas Hanoi has 2,300 individuals per square kilometer. Hence, it is crucial for policymakers to identify the major PM$_{2.5}$ sources to mitigate PM$_{2.5}$ air pollution in HCMC.

The coronavirus disease of 2019 (COVID-19) suddenly emerged in late 2019 and drastically changed our lifestyle. There are some reports regarding the effects of COVID-19 lockdown on ambient PM$_{2.5}$. For instance, ambient PM$_{2.5}$ mass concentrations in Wuhan (China) and Milan (Italy) decreased remarkably by 40% and 45%, respectively, during the COVID-19 outbreak periods (Rodríguez-Urrego and Rodríguez-Urrego, 2020; Zoran et al., 2020). In Southeast Asia, reductions in ambient PM$_{2.5}$ mass concentrations by 11% in Hanoi (Vietnam) (Rodríguez-Urrego and Rodríguez-Urrego, 2020), 17%–36% in Malaysia (Suhaimi et al., 2020), and 30% in Singapore (Li and Tartarini, 2020) were reported. These results indicate that the ambient PM$_{2.5}$ mass concentrations were substantially reduced during the COVID-19 lockdown.

In this study, we chemically characterized PM$_{2.5}$ based on ground-based samplings in HCMC throughout one year. To the best of our knowledge, this is the first of such study focusing on HCMC. Furthermore, the effects of the COVID-19 lockdown and the suppression of socioeconomic activities in HCMC on the ambient PM$_{2.5}$ mass concentrations and their chemical constituents were discussed.

2 MATERIAL AND METHODS

2.1 Sample Collection

A field study was conducted on the rooftop (49 m above the ground level) at Vietnam National University HCMC—University of Science in Vietnam from September 2019 to August 2020. The sampling site faces one of the main streets in HCMC and is surrounded by more than 10 industrial zones dominated by machinery and equipment, textile and apparel, fabricated metal products, rubber and plastic products, chemicals and chemical products, and food processing units within a 50 km radius from the site. Heavy traffic congestion occurred during peak hours (6:30–8:30 am and 4:00–6:00 pm) within a radius of 10 km from the site.

The sampling system had two sets of PM$_{2.5}$ samplers (PM$_{2.5}$ IMPACT Sampler, SKC). PM$_{2.5}$ Samples were collected on polytetrafluoroethylene (PTFE; pore size, 2.0 µm) and quartz fiber filters (diameter, 47 mm) for 24 h at a flow rate of 10 L min$^{-1}$. After sampling, the PTFE and quartz fiber filters were stored in a refrigerator at 4°C and a freezer at −20°C, respectively, until the analyses were conducted. Field blank samples were also collected and underwent the same analysis process with samples and were subtracted from loaded samples for blank correction.
2.2 Sample Analyses

Before and after sampling, PTFE filters were weighed on a microbalance (XSE 205DU, Mettler Toledo) with 0.01 mg of readability to determine the PM$_{2.5}$ mass concentration in a temperature- and humidity-controlled chamber (TBR-2EAOPT, ESPEC) to equilibrate at 21°C ± 0.5°C (average ± standard deviation) and 35% ± 4% relative humidity for 24 h. After weighting, each PTFE filter was cut in half and extracted with 10 mL of ultrapure water by ultrasonication for 20 min. The extracted solutions were filtered through a PTFE syringe filter (pore size, 0.45 μm) and analyzed by ion chromatography (Met-831, Metrohm) to determine five cations (Na$^+$, NH$_4^+$, K$^+$, Mg$^{2+}$, and Ca$^{2+}$) and four anions (Cl$^-$, NO$_3^-$, SO$_4^{2-}$, and C$_2$O$_4^{2-}$). The limits of WSIs detection, which is defined as three times as the standard deviation (7 sample) of the lowest concentrations of the standards, were: Na$^+$: 0.01 μg m$^{-3}$; NH$_4^+$: 0.01 μg m$^{-3}$; K$^+$: 0.05 μg m$^{-3}$; Mg$^{2+}$: 0.05 μg m$^{-3}$; Ca$^{2+}$: 0.02 μg m$^{-3}$; Cl$^-$: 0.01 μg m$^{-3}$; NO$_3^-$: 0.05 μg m$^{-3}$; SO$_4^{2-}$: 0.01 μg m$^{-3}$; C$_2$O$_4^{2-}$: 0.04 μg m$^{-3}$.

Quartz fiber filters were used to identify carbonaceous contents: organic carbon (OC), elemental carbon (EC), and water-soluble organic carbons (WSOC). A filter aliquot (~2 cm$^2$) was extracted with 15 mL of ultrapure water by ultrasonication for 20 min. The extracted solutions were filtered through a PTFE syringe filter (pore size, 0.45 μm) and analyzed by total organic carbon analyzer (TOC-L, Shimazu) to analyze WSOC, and the limit of WSOC detection were 0.01 μg m$^{-3}$. Meanwhile, OC and EC were quantified using the OC-EC Carbon Analyzer (Lab OC-EC Aerosol Analyzer, Sunset Laboratory), which employs the thermal optical reflectance method following the IMPROVE_A protocol (Chow et al., 2007). Carbon fractions were quantified at 140°C, 280°C, 480°C, and 580°C for OC1, OC2, OC3, and OC4, respectively, in helium and at 580°C, 740°C, and 840°C for EC1, EC2, and EC3, respectively, in helium:oxygen (98:2) gas. OC and EC were calculated as shown in the following equations (Chow et al., 2007):

\[
OC = OC1 + OC2 + OC3 + OC4 + OP
\]

\[
EC = EC1 + EC2 + EC3 - OP
\]

here, OP (i.e., pyrolyzed OC) is defined as the amount of carbon content measured after the introduction of oxygen until the reflectance returns to its initial value corresponding to the beginning of the analysis. Noted that the limits of detection were 0.66 μg m$^{-3}$ and 0.05 μg m$^{-3}$ for OC and EC, respectively.

To distinguish the primary organic carbon (POC) and the secondary organic carbon (SOC) in OC, we applied the EC tracer method (Turpin and Huntzicker, 1995). We used the OC-to-EC mass ratio (OC/EC) to estimate the SOC content. POC and SOC were calculated as shown in the following equations:

\[
POC = EC \times (OC/EC)_{pri}
\]

\[
SOC = OC_{tot} - POC
\]

here, OC$_{tot}$ is the total OC concentration, and (OC/EC)$_{pri}$ is calculated by averaging three lowest OC/EC values in the data set (ChooChuay et al., 2020; Bhowmik et al., 2021).

2.3 CWT Model

To interpret the geological origins of PM$_{2.5}$, we applied the weighted concentration-weighted trajectory (WCWT) model by using TrajStat software developed by Wang et al. (2009). The sampling site was set as the starting point (10°45′43.6″N; 106°40′52.8″E), and backward trajectories over 72 h were considered every 6 h (00:00, 06:00, 12:00, and 18:00 UTC) based on 1° × 1° Global Data Assimilation System data for a height of 500 m above ground level. A detailed description of the WCWT model and the criteria that we applied are available in the work of Hsu et al. (2003).

2.4 Data Categorization

HCMC is strongly affected by a monsoon-influenced tropical climate, resulting in two distinct
seasons: the dry season (December–April) and the rainy season (May–November). Since late 2019, the COVID-19 pandemic spread worldwide, and Vietnam recorded early cases since January 2020. Subsequently, the Vietnam government declared various directives that restricted the immigration, movement, assembly, and national lockdown of the citizens from February to April 2020 (during the dry season in 2020). Therefore, we divided the data into four stages: Stage 1 represents the rainy season before the assembly restriction and lockdown period (ARL), Stage 2 represents the dry season before ARL, Stage 3 represents the dry season during ARL, and Stage 4 represents the rainy season following ARL.

3 RESULTS

3.1 PM$_{2.5}$ Mass Concentration
The PM$_{2.5}$ mass concentrations during sampling period ranged from 9.57–61.94 µg m$^{-3}$ (avg ± sd: 28.44 ± 11.55 µg m$^{-3}$) (Table 1). The PM$_{2.5}$ mass concentration in each stage was: 35.01 ± 9.06 µg m$^{-3}$ (Stage 1), 41.09 ± 12.14 µg m$^{-3}$ (Stage 2), 24.03 ± 8.53 µg m$^{-3}$ (Stage 3), and 21.95 ± 7.72 µg m$^{-3}$ (Stage 4). Mostly, the 24 h average mass concentrations of PM$_{2.5}$ in Fig. 1(a) did not exceed the Vietnam National Technical Regulation on Ambient Air Quality (QCVN 05:2013; VEA, 2013) of 50 µg m$^{-3}$ for 24 h PM$_{2.5}$. In contrast, those for many samples exceeded the World Health Organization (WHO) guideline of 15 µg m$^{-3}$ for 24 h PM$_{2.5}$ (WHO, 2021).

3.2 Carbonaceous Species
During the whole sampling period, OC (8.77 ± 4.02 µg m$^{-3}$) and EC (2.82 ± 1.53 µg m$^{-3}$) accounted for 30.68 ± 6.56% and 9.72 ± 2.87% of PM$_{2.5}$ mass, respectively (Table 1). In this study, the weight percentage of total carbon (= OC + EC) in PM$_{2.5}$ was ~40%, which agrees well with the value obtained for Hanoi (~42%) (Thuy et al., 2018) and Chiang Mai (~41%) in Thailand (Thepnuan et al., 2019). In particular, the average OC concentration slightly decreased from Stage 1 (12.30 µg m$^{-3}$) to Stage 2 (11.81 µg m$^{-3}$) and slightly increased from Stage 3 (6.24 µg m$^{-3}$) to Stage 4 (6.90 µg m$^{-3}$) (Fig. 2(a) and Fig. 3). The EC concentration also decreased from Stage 1 (4.34 µg m$^{-3}$) to Stage 2 (3.54 µg m$^{-3}$) and increased from Stage 3 (1.71 µg m$^{-3}$) to Stage 4 (2.28 µg m$^{-3}$) (Fig. 2(a) and Fig. 3).

Table 1. Statistical results of PM$_{2.5}$ mass concentrations and chemical speciation during the whole sampling period (September 19, 2019–August 18, 2020).

<table>
<thead>
<tr>
<th>Species</th>
<th>Concentration (µg m$^{-3}$)</th>
<th>Contribution in PM$_{2.5}$ (%)</th>
<th>Avg ± Sd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg ± Sd</td>
<td>Min–max</td>
<td>Avg ± Sd</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>28.44 ± 11.55</td>
<td>9.57–61.94</td>
<td>-</td>
</tr>
<tr>
<td>OC</td>
<td>8.77 ± 4.02</td>
<td>2.09–22.46</td>
<td>30.68 ± 6.56</td>
</tr>
<tr>
<td>POC</td>
<td>5.95 ± 3.21</td>
<td>0.86–18.55</td>
<td>20.48 ± 6.05</td>
</tr>
<tr>
<td>SOC</td>
<td>2.85 ± 1.64</td>
<td>0.25–10.95</td>
<td>10.22 ± 4.11</td>
</tr>
<tr>
<td>EC</td>
<td>2.82 ± 1.53</td>
<td>0.41–8.80</td>
<td>9.72 ± 2.87</td>
</tr>
<tr>
<td>Char-EC</td>
<td>2.35 ± 1.46</td>
<td>0.25–8.03</td>
<td>7.84 ± 2.82</td>
</tr>
<tr>
<td>Soot-EC</td>
<td>0.47 ± 0.11</td>
<td>0.16–0.88</td>
<td>1.88 ± 0.74</td>
</tr>
<tr>
<td>WSOC</td>
<td>3.26 ± 1.95</td>
<td>0.65–9.03</td>
<td>13.98 ± 3.30</td>
</tr>
<tr>
<td>Total WSIs</td>
<td>7.16 ± 3.76</td>
<td>2.00–21.09</td>
<td>24.90 ± 6.57</td>
</tr>
<tr>
<td>$\text{SO}_\text{4}^{2-}$</td>
<td>3.95 ± 1.76</td>
<td>0.77–11.80</td>
<td>11.37 ± 4.27</td>
</tr>
<tr>
<td>$\text{NO}_\text{3}^{-}$</td>
<td>1.12 ± 0.75</td>
<td>0.07–5.06</td>
<td>3.82 ± 1.37</td>
</tr>
<tr>
<td>$\text{NH}_\text{4}$+</td>
<td>0.91 ± 0.71</td>
<td>0.09–4.13</td>
<td>3.13 ± 1.62</td>
</tr>
<tr>
<td>$\text{K}$+</td>
<td>0.80 ± 0.54</td>
<td>BDL–2.79</td>
<td>2.68 ± 1.29</td>
</tr>
<tr>
<td>$\text{Na}$+</td>
<td>0.44 ± 0.27</td>
<td>0.06–1.33</td>
<td>1.61 ± 0.86</td>
</tr>
<tr>
<td>$\text{Cl}$−</td>
<td>0.38 ± 0.27</td>
<td>0.02–1.40</td>
<td>1.42 ± 0.90</td>
</tr>
<tr>
<td>$\text{C}<em>\text{2}\text{O}</em>\text{4}^{2-}$</td>
<td>0.24 ± 0.12</td>
<td>0.01–0.73</td>
<td>0.89 ± 0.42</td>
</tr>
</tbody>
</table>

“Avg” indicates the average. “Sd” indicates standard deviation. BDL indicates below the detection limit.
Fig. 1. (a) Daily variations in PM$_{2.5}$ mass concentration during the sampling period and the average value for each stage, (b) the monthly average PM$_{2.5}$ mass concentrations and precipitation, and (c) temperature (T), relative humidity (RH), sunshine hours, and wind speed from September 19, 2019, to August 18, 2020. Stage 1 is the rainy season from September 19 to November 30, 2019; Stage 2 is the dry season from December 1, 2019, to January 18, 2020; Stage 3 is the dry season from February 4 to April 22, 2020; and Stage 4 is the rainy season from April 23 to August 18, 2020. Meteorological data were obtained from the Tan Son Hoa Monitoring Station (Southern Regional Hydrometeorological Center) located approximately 5 km to the southeast of the sampling location.

The mass ratio of OC-to-EC (OC/EC) has been widely used to investigate the possible sources of the carbonaceous species and the existence of SOC (Zhang et al., 2013). OC/EC over the whole sampling period was 3.28 ± 0.61, which was greater than 2 in most cases (Fig. 2(a)), indicating the presence of SOC (Turpin and Huntzicker, 1995). The estimated POC (5.95 ± 3.21 μg m$^{-3}$) and SOC (2.85 ± 1.64 μg m$^{-3}$) (Table 1) accounted for 68% and 32% of the OC mass on average, respectively, indicating the stronger impact of primary emission on OC.
WSOC is produced by two main processes: (1) directly emitted via combustion and industrial activities and from natural sources and (2) formation during homogeneous gas-phase and heterogeneous aerosol-phase oxidation of POC and SOC in the atmosphere (Pathak et al., 2011). The WSOC concentration was $3.26 \pm 1.95 \, \mu g \, m^{-3}$, accounted for $-14\%$ of PM$_{2.5}$ mass (Table 1). The concentration of WSOC in each stage was: $4.49 \pm 1.52 \, \mu g \, m^{-3}$ (Stage 1), $6.04 \pm 1.59 \, \mu g \, m^{-3}$ (Stage 2), $3.27 \pm 1.66 \, \mu g \, m^{-3}$ (Stage 3), $3.21 \pm 1.18 \, \mu g \, m^{-3}$ (Stage 4). The WSOC/OC mass ratio value in Stage 1 and Stage 2 showed little fluctuation at $0.36 \pm 0.04$ and $0.51 \pm 0.04$, respectively, compared to that in Stage 3 ($0.51 \pm 0.12$) and Stage 4 ($0.48 \pm 0.09$) (Fig. 2(c) and Fig. 3).

Fig. 2. Temporal variation of (a) OC, EC, and OC/EC; (b) POC, SOC, and SOC/OC; (c) WSOC, WSOC/OC; (d) char-EC, soot-EC, and char-EC/soot-EC.
Char-EC (= EC1 – OP) is the product formed from solid residues during coal combustion and biomass burning at low temperatures (smoldering combustion), and soot-EC (= EC2 + EC3) is formed by the agglomeration of volatiles from the high-temperature gas phase under oxygen-starved conditions (Cao et al., 2013; Han et al., 2009; Tham et al., 2019). Over the whole sampling period, the widely fluctuated char-EC concentration was 2.35 ± 1.46 µg m⁻³, while soot-EC remained stable at 0.47 ± 0.11 µg m⁻³ (~20% of the EC mass) (Table 1, Fig. 2(d)). Then, the significant correlation between char-EC and EC (r = 0.99, p < 0.01) was observed. This suggests the variation of EC during the sampling period was due to char-EC emission than soot-EC emission in HCMC.

### 3.3 Water-soluble Ions

On average, the total water-soluble ions (WSIs) accounted for ~25% of PM₂.₅ mass, and they form the predominant PM₂.₅ fractions in addition to OC and EC (Table 1). The concentration of WSIs in
Fig. 4. Average concentration of each WSIs in HCMC during four stages. Error bars indicate standard deviation.

Each stage was: 9.64 ± 2.51 μg m⁻³ (Stage 1), 10.98 ± 5.49 μg m⁻³ (Stage 2), 6.04 ± 1.75 μg m⁻³ (Stage 3), and 6.77 ± 2.34 μg m⁻³ (Stage 4) (Fig. 4). SO₄²⁻ (3.95 ± 1.76 μg m⁻³) was the most dominant species in WSIs, contributing 11.37 ± 4.27% to PM₂.⁵ mass (Table 1). NO₃⁻ (1.12 ± 0.75 μg m⁻³), NH₄⁺ (0.91 ± 0.71 μg m⁻³), and K⁺ (0.54 ± 0.04 μg m⁻³) concentrations were relatively low compared to SO₄²⁻. Na⁺, Cl⁻, and C₂O₄²⁻ were minor species, which contributed less than 2% to PM₂.⁵ mass (Table 1). The concentration of Mg²⁺ and Ca²⁺ in all samples were under detection limit. The total weight percentage of SO₄²⁻, NO₃⁻, and NH₄⁺ in the total WSI mass concentration was 73 ± 8%, indicating the presence of secondary inorganic aerosols in HCMC, probably because of the high oxidation rates of SO₂ and NOₓ (Zhou et al., 2016).

Anion equivalent (AE) and cation equivalent (CE) were used to determine the acidity of PM₂.⁵ based on the following equations (Han et al., 2010):

\[
AE = \frac{[\text{Cl}^⁻]}{35.5} + \frac{[\text{NO}_₃^-]}{62} + \frac{[\text{SO}_₄^{2-}]}{48} + \frac{[\text{C}_₂\text{O}_₄^{2-}]}{44}
\]

\[
CE = \frac{[\text{Na}^+]}{23} + \frac{[\text{NH}_₄^+]}{18} + \frac{[\text{K}^+]}{39}
\]

A good correlation \((r = 0.96, p < 0.01)\) between AE and CE during the sampling period is shown in Fig. 5(a). The ratio of AE to CE (AE/CE) in HCMC during the sampling periods was slightly higher than the unity line, indicating an acidic condition attributed to cation deficiency.

The relationships between SO₄²⁻, NO₃⁻, and NH₄⁺ during the sampling period are shown in Fig. 5(b) and Table 2. Strong correlations were found between [SO₄²⁻] \((r = 0.92, p < 0.01)\) and [NH₄⁺] and between [SO₄²⁻ + NO₃⁻] \((r = 0.92, p < 0.01)\) and [NH₄⁺]. However, the ratio of [SO₄²⁻] to [NH₄⁺] was closer to unity than the ratio of [SO₄²⁻ + NO₃⁻] to [NH₄⁺], suggesting the formation of (NH₄)₂SO₄. The scarcity of [NH₄⁺] during the sampling period (2019–2020) is similar to that in 2015 (Huy et al., 2020), indicating the incomplete neutralization of [SO₄²⁻].

4 DISCUSSION

4.1 Source Identification

4.1.1 Diagnostic ratios of chemical species

Biomass burning has been evaluated as a main source of PM₂.⁵ in Southeast Asia (ChooChuay et al., 2020; Fujii et al., 2014; Kim Oanh et al., 2018; Tham et al., 2019; Thuy et al., 2018). In this
study, the high correlation of $K^+$, which is generally known as biomass burning tracer (Andreae et al., 1998), to PM$_{2.5}$, OC, and EC during 4 stages (Table 2) indicated the presence of biomass burning source in HCMC. In this section, the potential emission sources in HCMC, including biomass burning, are discussed.

OC and EC mass concentrations varied significantly over the whole sampling periods, however, OC/EC showed little fluctuation (Fig. 2(a) and Fig. 3), suggesting the OC and EC sources did not change. Literature reviews have shown that OC/EC was in the range of 0.3–7.6 for coal combustion and 4.1–14.5 for biomass burning (Watson et al., 2001), 1.0–4.2 for vehicular exhaust (Schauer et al., 2002), 1.87–9.96 (with an average of 3.52 ± 1.41) for gasoline exhaust (ChooChuay et al., 2020), and 0.22–0.93 for diesel engine exhaust (Cui et al., 2020), and 1.4–4.6 for barbecue cooking (Wang et al., 2015). In this study, OC/EC ranged from 1.98 to 5.85 (3.28 ± 0.61), suggesting that OC and EC sources were derived from transportation, biomass burning, barbecue cooking, and coal combustion.

The mass ratio of char-EC to soot-EC (char-EC/soot-EC) has been used in previous works to identify the potential source more precisely than OC/EC, because char-EC/soot-EC can exclude the effects of SOC (Han et al., 2010, 2009). Char-EC/soot-EC < 1 indicates vehicular emission, 1.5–66.7 indicates coal combustion, and 2.2–6.7 indicates biomass burning (Han et al., 2010); 10.7–19.5 indicates peatland fire source (Fujii et al., 2016); 2–6 indicates meat cooking (Chow et al., 2004). Mishra and Kulshrestha (2021) suggested that char-EC/soot-EC from biomass burning was 4.8 ± 2.2, coal combustion was 1.3 ± 0.8, and vehicular emission was 0.6 ± 0.4. In this study, char-EC/soot-EC was in the range of 1.22–14.38, with an average value of 4.88 ± 2.72, suggesting that EC emission were from the mixed contribution of biomass burning, coal combustion, cooking. The WSOC-to-OC ratio (WSOC/OC) was used to identify the secondary formation of aerosols (Sullivan et al., 2004; Pathak et al., 2011) and source identification (Bhowmik et al., 2021). The presence of photochemical aged WSOC and the reduction of WSOC light absorption capacity were linked to the improvement of WSOC/OC (Choudhary et al., 2021). In particular, WSOC/OC > 0.4 suggested the presence of secondary organic aerosols and/or oxygenated OC (Pathak et al., 2011; Li et al., 2015). WSOC/OC ratio from different sources was summarized by Bhowmik et al. (2021), including traffic (0.1), oxidized organic aerosol (0.9), liquid fuel particles emitted from light-duty vehicles (0.06–0.19), vehicular emission (0.27); meanwhile WSOC/OC were 0.4 indicates biomass burning and urban aerosol (Choudhary et al., 2021), 0.1–0.4 indicates cooking activities (Li et al., 2015). In this study, WSOC/OC ranged from 0.26 to 0.87 (0.46 ± 0.10), suggesting the presence of aged aerosols and/or potential sources from biomass burning and cooking in HCMC.

The mass ratio NO$_3$/$SO_4^{2-}$ has been used as an indicator of stationary (such as coal combustion which highly emitted SO$_2$) and mobile sources (such as vehicle emission which mainly discharge NO$_x$ for the particle pollution (Luong et al., 2021; Qiao et al., 2019). The NO$_3$/$SO_4^{2-}$ for stationary

**Fig. 5.** Linear regression for (a) anion equivalent (AE) vs. cation equivalent (CE) and (b) for $SO_4^{2-}$ and $SO_4^{2-} + NO_3^-$ vs. $NH_4^+$. 

- $y = 0.9856x + 0.013$, $r = 0.96$, $p < 0.01$
- $y = 1.1256x + 0.0289$, $r = 0.91$, $p < 0.01$
Table 2. Correlation of PM$_{2.5}$ and its chemical compositions during the sampling period.

<table>
<thead>
<tr>
<th>Stage 1</th>
<th>PM$_{2.5}$</th>
<th>Cl$^-$</th>
<th>NO$_3^-$</th>
<th>SO$_4^{2-}$</th>
<th>C$_2$O$_4^{2-}$</th>
<th>Na$^+$</th>
<th>NH$_4^+$</th>
<th>K$^+$</th>
<th>OC</th>
<th>EC</th>
<th>WSOC</th>
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<td>PM$_{2.5}$</td>
<td>--</td>
<td>0.17</td>
<td>--</td>
<td>0.73**</td>
<td>0.50**</td>
<td>--</td>
<td>0.45*</td>
<td>-0.26</td>
<td>0.05</td>
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<td>0.79**</td>
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<th>PM$_{2.5}$</th>
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<th>NO$_3^-$</th>
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<th>Na$^+$</th>
<th>NH$_4^+$</th>
<th>K$^+$</th>
<th>OC</th>
<th>EC</th>
<th>WSOC</th>
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<tr>
<td>PM$_{2.5}$</td>
<td>--</td>
<td>0.57*</td>
<td>--</td>
<td>0.66**</td>
<td>0.73**</td>
<td>--</td>
<td>0.86**</td>
<td>0.50*</td>
<td>0.56</td>
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<td>0.88**</td>
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<th>NO$_3^-$</th>
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<th>Na$^+$</th>
<th>NH$_4^+$</th>
<th>K$^+$</th>
<th>OC</th>
<th>EC</th>
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<tr>
<td>PM$_{2.5}$</td>
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<td>0.47**</td>
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<td>0.86**</td>
<td>0.62**</td>
<td>--</td>
<td>0.34</td>
<td>-0.2</td>
<td>0.24</td>
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<td>0.69**</td>
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<th>Stage 4</th>
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<th>NO$_3^-$</th>
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<th>C$_2$O$_4^{2-}$</th>
<th>Na$^+$</th>
<th>NH$_4^+$</th>
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<tr>
<td>PM$_{2.5}$</td>
<td>--</td>
<td>0.60**</td>
<td>--</td>
<td>0.75**</td>
<td>0.76**</td>
<td>--</td>
<td>0.75**</td>
<td>0.64**</td>
<td>0.61**</td>
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**Correlation is significant at the 0.01 level (2-tailed).**

*Correlation is significant at the 0.05 level (2-tailed).
sources (coal combustion and/or coal-fired thermal plants) were 0.49 in Fuling, China (Qiao et al., 2019), 0.36 in Hanoi, Vietnam (Luong et al., 2021), while mobile sources have higher value. During the sampling period, the values of NO$_3^-$/SO$_4^{2-}$ were 0.38 ± 0.19, indicating the main emission of stationary emission in HCMC.

4.1.2 WCWT analysis

To reduce the ambient PM$_{2.5}$ mass concentrations in HCMC, it is crucial to identify the geological origins of PM$_{2.5}$. For this purpose, we conducted a backward trajectory cluster analysis and WCWT analysis. The potential emission source areas for PM$_{2.5}$ and the major chemical species (OC, SO$_4^{2-}$, and NH$_4^+$) based on WCWT analyses are shown in Fig. 6. The color bar shows the target concentration (µg m$^{-3}$), indicating the strong and weak source areas based on the pollutant concentrations (Ali-Taleshi et al., 2021; Jain et al., 2021).

As shown in Fig. 6, all pollutants were mainly emitted from local sources in and around HCMC and were scattered in the northeast direction. The patterns of the PM$_{2.5}$ and chemical species maps were similar, indicating that they had similar sources. The highest concentration grid of PM$_{2.5}$ (> 40 µg m$^{-3}$) was in the center of HCMC, indicating the impact of local sources. OC, SO$_4^{2-}$, and NH$_4^+$ maps suggest larger emission areas than PM$_{2.5}$ map, indicating long-range transport of aerosols into HCMC. The results of 72 h air-mass back trajectories at 500 m above the ground level are shown in Fig. 7. During the dry season, the main trajectories (~99%) came from the ocean to the northeast of HCMC. During the rainy season, the main trajectory passed through south Thailand (34.74%), and another came from the ocean to the northeast of HCMC (29.58%).

Fig. 6. Maps of Weighted Concentration Weighted Trajectory (WCWT) values for PM$_{2.5}$ and chemical species in HCMC during the sampling period. The unit of the WCWT value: µg m$^{-3}$. 
Fig. 7. Backward trajectories (72 h) by cluster calculation at 500 m for PM$_{2.5}$ and its chemical compositions during the dry season (from December 5, 2019, to April 22, 2020) and the rainy season (September 19–November 28, 2019, and April 23–August 18, 2020).

There is a coal-fired power plant region that is located roughly 300 km to the northeast of HCMC. This emission source was suggested as the long-range transport source of PM$_{2.5}$ dominant species during the sampling period.

4.2 Seasonal Variations of PM$_{2.5}$

The differences in the PM$_{2.5}$ mass concentrations and chemical species between the dry and rainy seasons are discussed in this section. The spread of COVID-19 in HCMC since Stage 3 toppled the lives of the residents here. Hence, we focus on the seasonal variations of PM$_{2.5}$ concentrations by distinguishing the data for Stages 1 and 2 (i.e., the period unaffected by the spread of COVID-19) from those for Stages 3 and 4 (i.e., the period affected by the spread of COVID-19).

The rainfall level during the rainy season was significantly higher than that during the dry season (Fig. 1(b)), meanwhile, meteorological conditions showed stable variations during the sampling period (Fig. 1(c)). Hence, the variation of PM$_{2.5}$ mass concentration and chemical compositions in HCMC attributed to the wet deposition during the rainy season, regardless of temperature, relative humidity, sunshine hours, and wind speeds. The average concentrations of PM$_{2.5}$ mass, WSIs (except SO$_4^{2-}$ and K$^+$), WSOC, and SOC were higher during the dry season than during the rainy season (Fig. 1(b), Fig. 3, and Fig. 4), indicating the effect of washout during rainy season. In contrast, the average concentrations of OC, EC, POC, char-EC, and soot-EC were higher during the rainy season than the dry season (Fig. 3). The reduction of EC, including char-EC and soot-EC, was explained by the dry deposition in the absence of precipitation during the dry seasons (Matsuda et al., 2012).

As mentioned above, SOC concentration was higher during the dry seasons, accompanied with the higher SOC/OC in Stage 2 (37%) and Stage 3 (42%) than in Stage 1 (26%) and Stage 4 (31%), suggested the intensive photochemical activities during the dry seasons in HCMC.

K$^+$ concentrations were strongly correlated with OC and EC ($r > 0.7, p < 0.01$) during the dry season (Table 2), indicating that biomass burning made a major contribution. The PM$_{2.5}$ mass and C$_2$O$_4^{2-}$ concentrations during the dry season were also strongly correlated ($r = 0.83, p < 0.01$). C$_2$O$_4^{2-}$ also showed higher correlations with OC, EC, SO$_4^{2-}$, NO$_3^-$, NH$_4^+$, and K$^+$ during the dry season (Table 2). C$_2$O$_4^{2-}$ originates from primary emissions (biomass burning and vehicular exhaust), and secondary sources via the photooxidation of volatile organic compounds (Wang et al., 2007; Thepnuan et al., 2019). Thus, the photochemical and burning activities were considered to have decreased during the rainy season.

3.3 Effects of COVID-19 Outbreak Period on PM$_{2.5}$

In this section, the variations in PM$_{2.5}$ mass and chemical species concentrations between Stage 2 (pre-ARL) and Stage 3 (during ARL) are discussed to identify the impact of ARL by COVID-19 pandemic on PM$_{2.5}$ chemical compositions.
The average PM$_{2.5}$ mass concentration decreased significantly by 41% from Stage 2 to Stage 3. In other countries, PM$_{2.5}$ mass concentrations reductions by 30%–70% were observed during the social distancing/lockdown periods (Table 3), and these reductions are comparable to our result (Cui et al., 2020; Liu et al., 2020; Rodriguez-Urrego and Rodriguez-Urrego, 2020; Zheng et al., 2020; Zoran et al., 2020). Thus, we consider that the effectively restricted human activities (especially, transportation) resulted in lower PM$_{2.5}$ mass concentration in HCMC in Stage 3. In Stage 4, human activities and domestic transportation recovered gradually.

Despite the notable decreases of OC (~45%) and EC (~50%), OC/EC did not change significantly from Stage 2 to Stage 3 (Fig. 2(a) and Fig. 3), indicating the similar emission sources during ARL. In addition, POC and SOC were also reduced by 52% and 39%, respectively, indicating the strong effect of ARL on the emissions of POC and precursor gases to form SOC (Fig. 2(b) and Fig. 3). The average WSOC concentration decreased by ~46% during ARL, along with the WSOC/OC in Stages 3 and 4 experienced larger fluctuations than that in Stages 1 and 2 (Fig. 2(c) and Fig. 3), indicating the unstable formation of WSOC based on the reduction in human activities. The average char-EC concentration also decreased by ~57% from Stage 2 (3.08 µg m$^{-3}$) to Stage 3 (1.39 µg m$^{-3}$), whereas soot-EC slightly decreased by ~15% from Stage 2 (0.45 µg m$^{-3}$) to Stage 3 (0.38 µg m$^{-3}$) (Fig. 2(d) and Fig. 3). Therefore, the mean char-EC/soot-EC in Stage 2 (6.92) reduced by ~50% compared to Stage 3 (3.52), indicating the significant reduction of smoldering combustion in Stage 3.

During the ARL, the local volume of transportation was reduced by Directive No. 16/CT-TTg (SRV, 2020), meanwhile industrial activities did not decrease. We inferred that soot-EC in HCMC was produced from industrial activities and was not affected by ARL or seasonal variation.

The average concentration of the total WSIs decreased by ~45% (Fig. 4). The significant decline in NO$_3^-$ (~57%) confirmed that the traffic volume and vehicular emission in HCMC decreased during the ARL. Wang et al. (2021) reported a similar trend of NO$_3^-$ related to the reduction of traffic emission, and they found that NO$_3^-$ decreased from 9.7 µg m$^{-3}$ (before COVID-19 outbreak) to 3.9 µg m$^{-3}$ (during COVID-19 outbreak). NH$_4^+$ mass concentration, which is regarded to originate from sewage and garbage (Huy et al., 2017), notably declined by 53% in Stage 3. In 2020, the municipal garbage in Vietnam and NH$_4^+$ concentrations in the Saigon River, HCMC decreased possibly because of the drop of tourists during the COVID-19 epidemic (The Vietnam National Environment Status Report 2016–2020; VEA, 2021). SO$_2^-$ concentration reduced by 42%, suggesting a decrease in coal combustion in Stage 3 (EVN, 2020a, 2020b, 2020c; Luong et al., 2021). The concentration of the total WSIs continued to decrease in Stage 4 probably because of wet deposition during the rainy season (Fig. 5(a)). However, the NO$_3^-$ concentration remained unchanged, suggesting the rebound of transportation in Stage 4.

5 CONCLUSION

In this study, PM$_{2.5}$ were collected from September 2019 to August 2020 at a site located at the center of HCMC, Vietnam. The PM$_{2.5}$ mass concentration and chemical composition, including WSIs and carbonaceous compounds (OC, EC, and WSOC), were quantified to understand the impact of seasonal variation and socioeconomic suppression and to identify possible emission sources. The main conclusions are as follows:

1. In most cases, the 24 h PM$_{2.5}$ mass concentrations did not exceed the Vietnam National
Technical Regulation of 50 µg m⁻³ for 24 h PM₂.₅. However, for many samples, the value exceeded the WHO guideline value of 15 µg m⁻³ for 24 h PM₂.₅. The PM₂.₅ mass concentrations in this study (except during ARL and post-ARL) were higher than those in previous studies, indicating that PM₂.₅ mass concentrations in HCMC have not improved.

2. Biomass burning, transportation, cooking, and coal combustion are the likely PM₂.₅ sources. This suggestion is based on the OC/EC (3.28 ± 0.61), char-EC/soot-EC range (1.22–14.38), and WSOC/OC (0.26–0.87) values. The strong correlations of K⁺ with PM₂.₅ mass, OC, EC, and WSOC indicate the effect of biomass burning. SO₄²⁻, NO₃⁻, and NH₄⁺ were the most abundant species, accounting for 78% of the total WSI mass. NO₃⁻/SO₄²⁻ ranging from 0.05 to 0.9 indicates the effects of both stationary and mobile sources. The formation of (NH₄)₂SO₄ and the acidity of PM₂.₅ are also recorded during the sampling period.

3. The WCWT results revealed the potential source areas located in the local HCMC and northeast of HCMC, reflecting the characteristics of large-scale and long-distance air transportation. Vehicular, industrial activities, and cooking are the likely local sources, and coal combustion and biomass burning are considered the transboundary source.

4. In terms of seasonal variation, the PM₂.₅ mass and total WSIs concentrations during the dry season were higher than those in the rainy season, whereas the mass concentrations of carbonaceous species were lower.

5. Regarding the effect of ARL during the COVID-19 pandemic, the mass concentrations of PM₂.₅ and chemical species decreased significantly during this period compared to the mass concentrations before the ARL. This result indicates the strong impact of direct emission from human activities, especially vehicle emission on ambient air.

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DISCLAIMER

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES


