Characteristics of Carbonaceous Species of PM$_{2.5}$ in Chiang Mai City, Thailand

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ABSTRACT

Over the past decade, biomass burning has significantly elevated PM$_{2.5}$ levels in upper northern Thailand. However, studies of source contributions from carbonaceous aerosols are limited in upper northern Thailand. Therefore, this study aimed to investigate the concentrations and characteristics of carbonaceous in PM$_{2.5}$; and estimate their source contributions. The PM$_{2.5}$ samples were collected from January to May 2017 in Chiang Mai City, located in Chiang Mai Province, Thailand. The mean concentrations $\pm$ S.D. of PM$_{2.5}$, organic carbon (OC), elemental carbon (EC), and water-soluble organic carbon (WSOC) were 38.7 $\pm$ 18.2, 10.0 $\pm$ 4.89, 1.35 $\pm$ 0.68, and 7.61 $\pm$ 4.08 $\mu$g m$^{-3}$, respectively. The OC/EC ratio ranged from 2.03 to 12.9, with a mean of 7.71 $\pm$ 0.15. The study demonstrated a WSOC/OC ratio of 0.75 $\pm$ 0.15, indicating that the WSOC was significantly contributed by biomass burning. The high level of primary organic carbon (POC) found in this study confirms that biomass burning was the dominant source of OC in this season. The secondary organic carbon (SOC) contributions of 39.5% of TOC suggest a higher prevalence of air pollution and its role in encouraging the condensation or adsorption of volatile organic compounds (VOCs). Therefore, this finding indicates that the concentrations of carbonaceous aerosol pollution in Chiang Mai City are of significant concern.

Keywords: Biomass burning, PM$_{2.5}$, OC, EC, WSOC

1 INTRODUCTION

Air pollution is a global health issue that causes early deaths and respiratory diseases like asthma, chronic obstructive pulmonary disease (COPD), and lung cancer (Huang et al., 2014; Lelieveld et al., 2015). An estimated large portion of the global population lives in areas with air pollution over guideline limits (Cohen et al., 2017). The primary pollutants encompass particulate matter (PM), carbon monoxide (CO), ozone (O$_3$), nitrogen dioxide (NO$_2$), and sulfur dioxide (SO$_2$) (Majewski and Piotrowski, 2020). Air pollution, especially PM$_{2.5}$, has been related to higher morbidity and mortality, with the region of Asia having the most serious effects (Kantipudi et al., 2016). The emission of PM$_{2.5}$ generated by the combustion of biomass has been an important contributor to air pollution, an important contributor to air pollution, with wide-ranging effects on air quality, public health, and climate at both global and local scales (Chen et al., 2017). An air mass mechanics-based numerical simulation measures CO and PM$_{2.5}$ emissions from biomass burning in South America and Africa (Freitas et al., 2005). Long-range transported smoke emissions from biomass burning was significantly influences the concentrations of PM$_{2.5}$, leading to elevated levels of biomass-burning tracers and other constituents during periods of transportation (Saarikoski et al., 2007). Daily PM$_{2.5}$ samples collected in Chengdu, China, showed that biomass burning has contributed to the chemical aerosol properties, with increased concentrations of carbonaceous aerosols and elements during biomass-burning episodes (Tao et al., 2013). Joint observations in
Yangtze River Delta cities in China have shown that biomass burning increased PM_{2.5} concentrations and transported air pollutants inter-provincially (Cheng et al., 2014). Organic carbon (OC) and elemental carbon (EC) are major components of PM_{2.5} (Bond et al., 2013). The radiocarbon (^{14}C) content of PM_{2.5} samples has been used to determine the proportion of carbon derived from fossil and contemporary sources (Li et al., 2014). The non-fossil carbon in PM_{2.5} is mainly derived from biogenic sources, including secondary organic carbon (SOC) from biogenic volatile organic compounds (BVOCs) (Heal, 2014; Liu et al., 2021). Moreover, OC and EC significantly contribute to PM_{2.5}. The proportion of carbonaceous aerosols in PM_{2.5} varies depending on the emission source and can be used to characterize carbon aerosol emission and conversion (Schauer et al., 2002; Chen et al., 2006; Zhang et al., 2007; Ji et al., 2016; Tian et al., 2020). Additionally, PM_{2.5} contains water-soluble organic carbon (WSOC), which affects climate change and air quality. WSOC concentrations vary by season and location. Air pollution from WSOC contributed 8.1% of PM_{2.5} in Beijing. Autumn had the highest WSOC concentration (Xiang et al., 2017). The concentrations of WSOC were found to be significantly higher in Jinan as compared to Weihai in the study. The analysis revealed that biomass burning, and secondary formation processes played significant roles in the generation of WSOC in both cities (Zhang et al., 2022). WSOC is also strongly correlated with SOC. The dominant sources of carbonaceous aerosols, including WSOC and OC, are biomass burning from wood fuel and agricultural waste. These findings highlight the importance of understanding the spatiotemporal variation and sources of WSOC and OC in PM_{2.5} for effective air quality management (Ham et al., 2017; Ye et al., 2017; Rai et al., 2020; Bhowmik et al., 2021).

Several research studies have investigated the chemical composition of PM_{2.5} in Chiang Mai City. The major source of PM_{2.5} during episodes of haze has been identified as biomass burning (Yabueng et al., 2020; Chang et al., 2021; Chansuebsri et al., 2022; Kawichai et al., 2022; Song et al., 2022; Annuaylojaoren et al., 2023). Polycyclic aromatic hydrocarbons (PAHs) and water-soluble inorganic ions (WSIIs) were related to PM_{2.5} and significantly associated with its oxidative potential (OP), which may cause oxidative stress in humans (Tao et al., 2020). Stable carbon and nitrogen isotopes were used to identify the sources of ambient PM_{2.5}, confirming that biomass burning, particularly from C_{3} and C_{4} plants, was a major contributor (Kawichai et al., 2022). These studies provide insights into the sources and chemical compositions of PM_{2.5} in Chiang Mai City. This study aims to investigate the characterization concentrations of carbonaceous in PM_{2.5} and estimate the source contributions for carbonaceous aerosols.

2 METHODS

2.1 Sampling Site

The study was conducted at the Research Institute for Health Sciences (RIHES) at Chiang Mai University (CMU). Its coordinates are 18°47'42.67"N and 98°57'28.24"E. PM_{2.5} was collected between January and May 2017 on the rooftop of a four-story building, 30 meters above ground level (Fig. 1). PM_{2.5} samples were collected every two days using quartz filters from Pall Life Sciences (Port Washington, NY, USA). Ambient air data was collected using a 24-hour medium-volume sampler from Qingdao Laoying Ltd. (Qingdao, China), with a flow rate set at 100 L min^{-1}. Each quartz filter was heated in a 450°C oven for 6 hours before sampling. A thin aluminum foil covering protected the quartz filters from solar radiation. Before and after sampling, filters were stored in silica gel desiccators for 24 hours. Subsequently, the filters were weighed using a Mettler Toledo microbalance from Switzerland. Following sampling, the filters were placed in a controlled room with a temperature range of 25 ± 2°C and a relative humidity below 40% for measurement. The filters were stored in a freezer at a temperature below −20°C before chemical analysis.

2.2 OC, EC, and WSOC Analysis

The concentration of OC and EC in PM_{2.5} samples was analysed using a thermal optical transitions OC/EC analyser (Sunset Laboratory, Model-4, U.S.A.) using the thermal-optical transmittance (TOT) method and the NIOSH (National Institute for Occupational Safety and Health) 5040 protocol, that improved by Chow et al. (2007) at the School of Applied Meteorology, Nanjing University of Information Science and Technology (NUIST), Nanjing, China. In a concise summary, quartz filter
disks with a diameter of 17 mm were inserted into a quartz tube within the thermal desorption chamber for analysis. The pyrolysis products performed a redox reaction with manganese dioxide, which caused the conversion of CO$_2$. The quantification of CO$_2$ was performed with a self-contained nondispersive infrared (NDIR) device. Following the completion of each analysis, a consistent quantity of an internal standard consisting of 5% methane and 95% helium was used, therefore allowing the determination of a predetermined mass of carbon. A weekly calibration was performed using an external sucrose standard at a concentration of 4.21 $\mu$g L$^{-1}$ to ensure accurate quantification. A daily calibration was performed using an instrument blank. The detection limits for both OC and EC were 0.5 $\mu$g m$^{-3}$.

For WSOC analysis, following the method established by Haque et al. (2019), each sample was extracted using a filter with a surface area of 2.26 cm$^2$. This quartz filter samples were extracted for 30 min using an ultrasonicator in 10 mL of organic-free ultrapure water, which had a resistivity exceeding 18.2 M$\Omega$ cm (measured by a Sartorius Arium 611 UV instrument). Then, filtration using a 0.22 $\mu$m PTFE filter to eliminate the insoluble filter matrices. Then, the filtrates obtained went through an analysis for WSOC using a Shimadzu TOC analyzer (model: TOC-Vcs). The triplicate investigations conducted in the present study revealed that the analytical errors for all carbonaceous components were below 5%, and the reported quantities were within this acceptable range (Haque et al., 2019).
2.3 Data Analysis
The data obtained from the experiment was collected and evaluated using the SPSS statistical software. The results are presented as the mean value and the standard deviation (S.D.). In addition, the current study employed a Pearson correlation analysis to investigate the relationship between PM$_{2.5}$ concentrations and various chemical compositions of PM$_{2.5}$.

3 RESULTS AND DISCUSSION

3.1 Temporal Variation of OC and EC
The collection of PM$_{2.5}$ samples was conducted by the Research Institute for Health Sciences at Chiang Mai University (18°47′42.67″N and 98°57′28.24″E). The sampling continued every two days, covering January 12 to May 30, 2017. The PM$_{2.5}$ concentrations were estimated using the gravimetric method. The range of PM$_{2.5}$ concentrations ranges from 6.07 to 79.9 µg m$^{-3}$, with a mean value of 35.8 ± 16.3 µg m$^{-3}$. The mean values were lower than the measurements obtained at the Chiang Mai University campus in 2016 (64.3 ± 17.6 µg m$^{-3}$), which were monitored during the same period (Thepnuan et al., 2019). Additionally, the mean values at the CMU site in 2016 were higher than in this study, with a mean of 44.5 ± 32.1 µg m$^{-3}$ (Kawichai et al., 2021). The mean concentrations of OC and EC were 9.75 ± 4.19 µg m$^{-3}$ and 1.34 ± 0.60 µg m$^{-3}$, respectively, and lower than those from the previous study were 14.6 ± 11.9 µg m$^{-3}$ and 1.80 ± 1.60 µg m$^{-3}$, respectively (Kawichai et al., 2021), as shown in Table 1. The possible influence of various emission sources across different seasons might contribute to the higher variability observed in concentrations of OC and EC. The temporal variations of OC and EC concentrations are mainly enriched in fine particulates, especially PM$_{2.5}$. The findings of this study show that the average concentrations observed were greater compared to the explained levels in urban areas from the previous studies (Viana et al., 2006; Monteiro dos Santos et al., 2016).

The sources of OC are not mainly identified with POC, which is directly emitted into PM$_{2.5}$ from various sources of emissions such as vehicle exhaust, fuel combustion, and cooking. OC sources also include SOC, which is formed through photochemical reactions with VOCs and nitrogen oxides (NO$_x$). The process of incomplete combustion of biomass burning, coal, or oil from EC. It can only also include SOC, which is formed through photochemical reactions with VOCs and nitrogen oxides from various sources of emissions such as vehicle exhaust, fuel combustion, and cooking. The sources of OC are not mainly identified with POC, which is directly emitted into PM$_{2.5}$ from

Table 1. Comparison of OC, EC, OC/EC, WSOC, and WSOC/OC ratio with other studies.

<table>
<thead>
<tr>
<th>Study site</th>
<th>Sampling period</th>
<th>n</th>
<th>OC (µg m$^{-3}$)</th>
<th>EC (µg m$^{-3}$)</th>
<th>OC/EC (µg m$^{-3}$)</th>
<th>WSOC (µg m$^{-3}$)</th>
<th>WSOC/OC</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiang Mai, Thailand</td>
<td>Jan–May 2017</td>
<td>63</td>
<td>9.75 ± 4.19</td>
<td>1.34 ± 0.60</td>
<td>7.65 ± 2.03</td>
<td>7.61 ± 4.08</td>
<td>0.75 ± 0.15</td>
<td>This study</td>
</tr>
<tr>
<td>Guangzhou, China</td>
<td>Aug 2006–Aug 2007</td>
<td>52</td>
<td>7.10 ± 3.30</td>
<td>4.00 ± 2.50</td>
<td>no data</td>
<td>2.00 ± 1.20</td>
<td>0.28</td>
<td>(Huang et al., 2012)</td>
</tr>
<tr>
<td>Chiang Mai, Thailand</td>
<td>Aug 2016</td>
<td>30</td>
<td>14.6 ± 11.9</td>
<td>1.80 ± 1.60</td>
<td>15.8 ± 8.01</td>
<td>no data</td>
<td>no data</td>
<td>(Kawichai et al., 2021)</td>
</tr>
<tr>
<td>Chiang Mai, Thailand</td>
<td>Feb–March 2017</td>
<td>34</td>
<td>12.3 ± 4.68</td>
<td>3.01 ± 1.08</td>
<td>4.19 ± 1.10</td>
<td>no data</td>
<td>no data</td>
<td>(Kraisitnikul et al., 2024)</td>
</tr>
<tr>
<td>Chiang Mai, Thailand</td>
<td>Feb–March 2018</td>
<td>30</td>
<td>10.2 ± 4.10</td>
<td>1.20 ± 0.60</td>
<td>9.40 ± 1.50</td>
<td>8.00 ± 3.40</td>
<td>0.78 ± 0.17</td>
<td>(Song et al., 2022)</td>
</tr>
<tr>
<td>Chiang Mai, Thailand</td>
<td>Feb–March 2017</td>
<td>34</td>
<td>12.3 ± 4.68</td>
<td>3.01 ± 1.08</td>
<td>4.19 ± 1.10</td>
<td>no data</td>
<td>no data</td>
<td>(Kraisitnikul et al., 2024)</td>
</tr>
<tr>
<td>Beijing, China</td>
<td>Spring, 2017</td>
<td>276</td>
<td>9.54 ± 1.08</td>
<td>2.63 ± 1.71</td>
<td>4.38 ± 1.32</td>
<td>5.14 ± 3.25</td>
<td>0.49 ± 0.12</td>
<td>(Jin et al., 2020b)</td>
</tr>
<tr>
<td>Tsukuba, Japan</td>
<td>Aug 2017–July 2019</td>
<td>62</td>
<td>3.20 ± 1.00</td>
<td>1.20 ± 0.40</td>
<td>3.80 ± 1.40</td>
<td>1.20 ± 0.40</td>
<td>0.40 ± 0.10</td>
<td>(Suto and Kawashima, 2021)</td>
</tr>
</tbody>
</table>

This study employed a Pearson correlation analysis to investigate the relationship between PM$_{2.5}$ concentrations and various chemical compositions of PM$_{2.5}$. The possible influence of various emission sources across different seasons might contribute to the higher variability observed in concentrations of OC and EC. The temporal variations of OC and EC concentrations are mainly enriched in fine particulates, especially PM$_{2.5}$. The findings of this study show that the average concentrations observed were greater compared to the explained levels in urban areas from the previous studies (Viana et al., 2006; Monteiro dos Santos et al., 2016).
and EC implied that there are common sources of emissions for both OC and EC, which may provide helpful information regarding the source of carbonaceous materials in the described region (Zhou et al., 2012).

The findings from the linear regression analysis conducted on the mass concentration of OC and EC in Chiang Mai City demonstrate a strong association. This suggests that the sources throughout Chiang Mai City display a significant level of similarity (Qi et al., 2018). Furthermore, there is also a strong positive association between PM$_{2.5}$ and TC ($r = 0.8953$, $p < 0.01$) as well as OC ($r = 0.8969$, $p < 0.01$) (Fig. 3). Additionally, a moderate positive correlation is observed between PM$_{2.5}$ and EC ($r = 0.7558$, $p < 0.01$). The PM$_{2.5}$ samples had a TC concentration of 32.6%. According to Qi et al. (2018), the findings revealed that compared to Beijing and Tianjin, the PM$_{2.5}$ levels were 31% and 25% respectively. Nevertheless, there occurred asynchronous variation in the levels of PM$_{2.5}$ concentrations and carbonaceous species. The observed phenomenon can be attributed to the proportion of carbonaceous aerosol, known as total carbonaceous aerosol (TCA), within the PM$_{2.5}$. The present study considers the TCA concentration in the atmosphere, comprised of both EC and organic matter (OM). TCA estimation involves multiplying the OC quantity by a factor of 1.6 (Turpin and Huntzicker, 1995). The study conducted in Chiang Mai City found that TCA accounted for 49.8% of the PM$_{2.5}$ mass loading, consequently confirming it as the dominant component of PM$_{2.5}$ (Cao et al., 2005). The results of the present study revealed that the levels of TCA in PM$_{2.5}$ were relatively high, with an average of 49.8 ± 13.7. This observation could perhaps be attributed to the presence of biomass-burning emissions in the immediate area of the sampling site, as shown in previous research (Shi et al., 2016). In previous studies, it was shown that the ambient PM$_{2.5}$ in Hong Kong consists of 17.8% OC and 8.7% EC (Cao et al., 2003), resulting in a TCA of 36.5%. The result indicates that roughly half of the total TCA concentration is present in the environment near roads. The results from prior studies indicate that TCA contributed to approximately 32.0 ± 8.3% of PM$_{2.5}$ in several research (Niu et al., 2012).

However, a variation in temporality was observed in the levels of PM$_{2.5}$ concentrations and carbonaceous species, which can be attributed to the proportion of TCA present in the mass of PM$_{2.5}$. The determination of TCA in this study involved the summation of EC and OM. OM was estimated by multiplying the amount of OC by a factor of 1.6 (Turpin and Huntzicker, 1995). The present investigation has determined that the average contributions of TCA to the PM$_{2.5}$ mass amount to 49.8%. The findings of this study confirm the concept that TCA serves as the primary component of PM$_{2.5}$, according to previous research (Cao et al., 2005). Moreover, the higher
fraction of TCA in PM$_{2.5}$ in this region may be attributed to biomass-burning emissions (Shi et al., 2016). Moreover, carbonaceous aerosols have been used to research emission and transformation characteristics. The ratio of OC to EC in PM$_{2.5}$ can be employed to identify the sources of pollution in atmospheric aerosols. The mean ratio of OC to EC in Chiang Mai City was 7.65 ± 2.03 and the period during January and May had the highest OC/EC ratio values (which ranged from 4 to 8), which can be attributed to the prevalence of significant open burning during forest fire incidents within the region. The present study’s finding indicate that aerosol carbonaceous particles can potentially contribute to biomass burning (Cao et al., 2005). The observed high OC to EC ratio in this study aligns with findings from other research that have associated it with emissions from wood combustion (Schauer et al., 2002) and biomass burning (Zhang et al., 2007; Samara et al., 2014; Wang et al., 2017). To enhance understanding, an OC/EC ratio over two has been employed as evidence to support the presence of secondary organic aerosols. Schauer et al. (2002) suggest that an OC/EC ratio within the range of 1.0–4.2 indicates emissions originating from diesel and gasoline vehicle exhaust. In contrast, a study conducted by Watson et al. (2001) found an OC/EC value of around 9.0, suggesting the significant of biomass-burning activities during the study period. The OC/EC ratio of the samples that were collected from the CMU site between February 23 and April 28, 2016, was found to be 8.28. The finding given by Thepnuan et al. (2019) demonstrates an important prevalence of biomass-burning emissions within the study area. Furthermore, the study found that the average ratios of EC to TC in PM$_{2.5}$ were 0.12 ± 0.03. Consistent with prior research, EC/TC ratios ranging from 0.1 to 0.3 are considered an accurate indicator of a significant presence of carbonaceous substances originating from biomass burning (Engling et al., 2011; Ram and Sarin, 2011; Pani et al., 2019; Kraisnititkul et al., 2024).

### 3.2 WSOC Concentration

The study found that the average concentration of WSOC in PM$_{2.5}$ was 7.6 ± 4.1 µg m$^{-3}$, with
an observed range of WSOC concentrations over the period was 1.2–18.9 µg m\(^{-3}\). The values obtained in the present study were comparable to those found reported for the CMU site in Chiang Mai, Thailand, in 2019, at a similar sampling site. The average concentration recorded was 8.0 ± 3.4 µg m\(^{-3}\), while the range of concentrations varied from 1.3–12.5 µg m\(^{-3}\) (Song et al., 2022). Moreover, the concentration of WSOC revealed similarities to the levels reported in Urumqi, Northwest China (6.1 ± 0.7 µg m\(^{-3}\)). The observed concentration of WSOC was within the range typically associated with emission from biomass burning and the formation of secondary organic aerosol (SOA) (Zhang et al., 2023). The concentration of WSOC in this study was significantly higher when compared to previous studies in Beijing, China (5.1 ± 3.2 µg m\(^{-3}\)) (Jin et al., 2020a); Guangzhou, China (2.1 ± 1.7 µg m\(^{-3}\)) (Huang et al., 2012); and Atlanta, U.S.A. (1.9 ± 1.0 µg m\(^{-3}\)) (Sullivan et al., 2006). In this study, WSOC accounted for 75% of OC, indicated that the majority of OC in PM\(_{2.5}\) in Chiang Mai City is water soluble. Previous research suggests that vehicle emissions tend to have lower levels of WSOC and OC compared to biomass burning sources. This is primarily due to the reduced solubility of the organic components produced during the combustion of liquid fuels such as diesel and gasoline (Ram et al., 2012; Daellenbach et al., 2016). According to the study results of Cheung et al. (2009), the ratios of water-soluble organic carbon (WSOC) to organic carbon (OC) in liquid fuel particles emitted by light-duty vehicles range from 0.06 to 0.19. Saarikoski et al. (2008) reported WSOC/OC ratios of 0.41 and 0.27 for biomass burning and vehicular emissions, respectively. In an additional research investigation by Daellenbach et al. (2016), WSOC/OC ratios of 0.1, 0.7, and 0.9 were observed for traffic, biomass burning, and oxidized organic aerosol, respectively. This study determined the mean WSOC/OC ratio in PM\(_{2.5}\) in CMU was 0.75 ± 0.02. The ratio employed as an indicator of the aging process of aerosol (Cho and Park, 2013) and the highest WSOC/OC ratio observed in this study indicate that the OC was more oxidized in the atmosphere during the sampling period (Huang et al., 2012). The WSOC/OC ratios can become a reliable measure for the occurrence of SOA due to the significant solubility of the majority of SOA in water (Kondo et al., 2007; Weber et al., 2007; Huang et al., 2012). Additionally, an analysis was conducted to calculate the correlation coefficient between WSOC and other species in the samples collected at the CMU site. Fig. 4 illustrates a positive correlation between the WSOC and OC with a correlation coefficient of 0.9086 \(p < 0.01\). This finding suggests that the presence of OC and primary combustion emissions considerably influenced the abundance of WSOC during the study period. The study conducted by Huang et al. (2012) found a modest correlation between WSOC and EC, likely due to the fuel combustion and biomass burning being the main contributors to EC. Once again, the findings from the WSOC analysis conducted by WSOC demonstrated a statistically significant association with POC \(r = 0.6340, p < 0.01\) using the EC-tracer method. This correlation stronger than the correlation with SOC \(r = 0.5625, p < 0.01\). These results suggest that primary sources mostly influenced the WSOC levels seen during the sampling period.

### 3.3 Estimation of Secondary Organic Aerosol Concentrations

This study shows that the measurement of EC may be a useful measure for POC and SOC. EC comprises non-combustion primary organic carbon and primary organic carbon formed through combustion processes. The recommended method for EC tracing employed in this work relates to combustion sources, including primary organic components. In addition, there are many methods for measuring TOC; the concentration of SOC could be calculated by the experiential equation, following Castro’s equation (Turpin and Huntzicker, 1995).

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

\[
SOC = TOC - POC
\]

where "OC/EC primary" refers to an estimate of the minimum ratio between OC and EC. Nevertheless, the primary ratio of organic carbon to elemental carbon can be occasionally unavailable due to various factors, including the emission type, ambient temperature, and method applied to carbon determination. The minimum observed ratios of organic carbon to elemental carbon (OC/EC) in this study were found to be 4.58, with the highest ratio being observed in April. According to
The mean concentration of estimated SOC in PM$_{2.5}$ was found to be $2.68 \pm 2.38$ µg m$^{-3}$. This value was lower than the annual average concentrations of estimated SOC at ZB and JD sites in Shanghai, which were reported as 7.2 and 5.3 µg m$^{-3}$, respectively (Feng et al., 2009). Furthermore, the occurrence of photochemical reactions in the area might account for the lowest OC/EC ratios, suggesting that incomplete combustion emissions from sources such as motor vehicle exhaust, fuel burning, and biomass burning play a significant role in the overall OC mass in Chiang Mai City (Wu et al., 2015; Kaskaoutis et al., 2020).

Based on the findings, it was observed that the SOC/OC ratio in Chiang Mai City was 36.7% higher than compared to the values obtained from the CMB modeling results in urban areas, which ranged between 18–19% (Feng et al., 2006). The results suggest that SOC was the primary constituent of OC, and that SOC played a significant part in forming atmospheric particles within Chiang Mai City. The observed pattern displayed a difference when compared to the findings of Niu et al. (2012) and Qi et al. (2018), since their studies have shown higher values than the results from our studies. On the other hand, urban areas defined by fossil fuel combustion revealed the lowest SOC/OC ratio, suggesting that carbonaceous species primarily originated from motor vehicles and other local pollutants, such as transportation (Gu, 2010). During the study period, the mean concentration of TOC released by POC was 6.15 µg m$^{-3}$. The POC to OC ratio for January to May has been reported as 63.0, 74.4, 62.4, 54.0, and 63.3%, respectively. The study’s results showed that biomass combustion was the predominant contributor to the source of OC during this period (Ram et al., 2008; Kaskaoutis et al., 2020). Biomass burning usually provides significant amounts of organic matter from plant spores, pollen, and non-combustion emissions from industrial sources (Ding et al., 2008; Klejnowski et al., 2017; Hong et al., 2019). Nevertheless, it was observed that the concentration of SOC showed more of an increase compared to POC during the season. During this region’s dry season, it could be possible that increased levels of photochemical oxidants, such as volatile organic carbon emissions, can be attributed to the expected increased traffic in metropolitan regions and the release of biogenic compounds from plants. The results of this study demonstrated a slight correlation between SOC/OC and PM$_{2.5}$, suggesting that the formation of secondary species in the Pearl Review Delta is mainly influenced by gas-phase photochemical reactions.
processes occurring with particle phase (Poppe et al., 1993; Kang et al., 2004). In addition, it is essential to note that secondary organic aerosol (SOA) constitutes a significant amount of organic aerosol, resulting from the chemical transformations of VOCs through both homogeneous and heterogeneous processes (Claeys et al., 2004).

The determination of the concentration of SOA was achieved by multiplying the concentration of SOC by a factor of 1.6 (He et al., 2015). The study determined that the mean concentration of SOA in Chiang Mai City was $5.89 \pm 3.80 \ \mu g \ m^{-3}$, accounting for roughly 17.0% of PM$_{2.5}$. This value was lower than the reported concentrations in Taiyuan and at the JD site in Shanghai City (He et al., 2015; Feng et al., 2019). The research findings revealed that SOA emission at the study site were relatively low, contributing only a small portion to the overall concentration of PM$_{2.5}$. A temporal analysis of SOA concentration demonstrated elevated levels during March and April, particularly during periods marked by high levels of smoke haze in the area. Furthermore, it has been shown that the SOA does not contribute to a significant proportion of PM$_{2.5}$. This observation illustrates the significant impact of wildfire smoke, demonstrating its crucial role in influencing the atmospheric composition in this area (Keywood et al., 2011).

**4 CONCLUSIONS**

The present study investigated the characteristics of PM$_{2.5}$, OC, and EC in Chiang Mai City, Thailand, specifically during the smoke haze episode. The research revealed that biomass burning was identified as the primary contributor of OC in PM$_{2.5}$ during the period of smoke haze in Chiang Mai City, Thailand. This was supported by the significantly high percentage of POC relative to TOC. Additionally, the high ratio of OC/EC observed in PM$_{2.5}$ was attributed to an enhanced incidence of biomass burning. The combustion of biomass is widely recognized for being able to release significant amounts of primary organic matter. The highest value of the WSOC/OC ratio was seen during the sample period, providing significant evidence to support the assumption that WSOC is a significant constituent of OC. This observation implies that the primary sources that contribute to WSOC also have the possibility of being the primary sources of OC. Moreover, the research also revealed that contributions from SOC, accounting for 39.5% of TOC, indicate a higher presence of air pollution and its influence on driving the condensation or adsorption of volatile organic compounds. A higher level of photooxidation of precursors was seen during the dry season due to high ambient temperatures.

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