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 450ºC 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 ± 2ºC and a relative humidity below 40% for measurement. The filters were stored in a freezer at a temperature below -20ºC before chemical analysis.

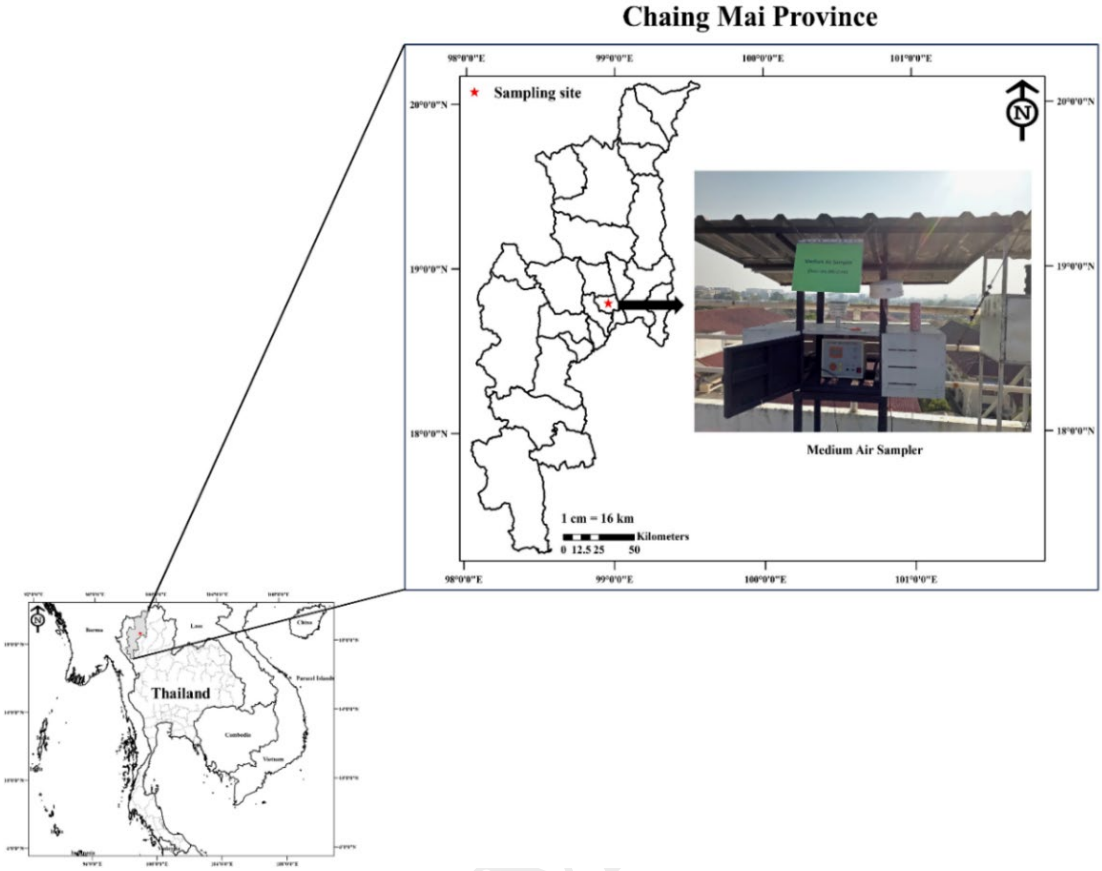

Fig. 1. The location of the sampling site is in Chiang Mai City. (18° 47' 42.67"N and 98° 57' 28.24"E).

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 (Chow et al., 2007).

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 μg 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 μg 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 MΩ cm (measured by a Sartorius Arium 611 UV instrument). Then, filtration using a 0.22 μm 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-Vcsh). 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).

155

156 **2.3 Data analysis**

157 The data obtained from the experiment was collected and evaluated using the SPSS statistical
158 software. The results are presented as the mean value and the standard deviation (S.D.). In addition,
159 the current study employed a Pearson correlation analysis to investigate the relationship between
160 $PM_{2.5}$ concentrations and various chemical compositions of $PM_{2.5}$.
161

162 # 3 RESULTS AND DISCUSSION

163 **3.1 Temporal Variation of OC and EC**

164 The collection of $PM_{2.5}$ samples was conducted by the Research Institute for Health Sciences at
165 Chiang Mai University (18° 47' 42.67"N and 98° 57' 28.24"E). The sampling continued every two
166 days, covering January 12 to May 30, 2017. The $PM_{2.5}$ concentrations were estimated using the
167 gravimetric method. The range of $PM_{2.5}$ concentrations ranges from 6.07 to 79.9 μg m^{-3}, with a
168 mean value of 35.8 ± 16.3 μg m^{-3}. The observed mean values were lower than the measurements
169 obtained at the Chiang Mai University campus in 2016 (64.3 ± 17.6 μg m^{-3}), which were monitored
170 during the same period (Thepnuan et al., 2019). Additionally, the mean values at the CMU site in
171 2016 were higher than in this study, with a mean of 44.5 ± 32.1 μg m^{-3} (Kawichai, 2021). The mean
172 concentrations of OC and EC were 9.75 ± 4.19 μg m^{-3} and 1.34 ± 0.60 μg m^{-3}, respectively, and
173 lower than those from the previous study were 14.6 ± 11.9 μg m^{-3} and 1.80 ± 1.60 μg m^{-3},

174 respectively (Kawichai, 2021), as shown in **Table 1**. The possible influence of various emission
175 sources across different seasons might contribute to the higher variability observed in
176 concentrations of OC and EC. The temporal variations of OC and EC concentrations are mainly
177 enriched in fine particulates, especially $PM_{2.5}$. The findings of this study show that the average
178 concentrations observed were greater compared to the explained levels in urban areas from the
179 previous studies (Viana et al., 2006; Monteiro dos Santos et al., 2016).

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

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

181 The sources of OC are not mainly identified with POC, which is directly emitted into $PM_{2.5}$ from
182 various sources of emissions such as vehicle exhaust, fuel combustion, and cooking. OC sources
183 also include SOC, which is formed through photochemical reactions with VOCs and nitrogen
184 oxides (NOx). The process of incomplete combustion of biomass burning, coal, or oil from EC. It
185 can only be detected in primary organic aerosol (Shi et al., 2016). Therefore, it was commonly
186 employed to monitor primary organic aerosols. These results can potentially provide information
187 regarding the source of carbonaceous particles. A strong positive correlation ($r = 0.8371$, $p < 0.001$)

was found between OC and EC, as shown in Fig. 2, suggesting the presence of comparable emission sources such as road traffic and biomass-burning (Pant et al., 2015). The correlation between OC 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).

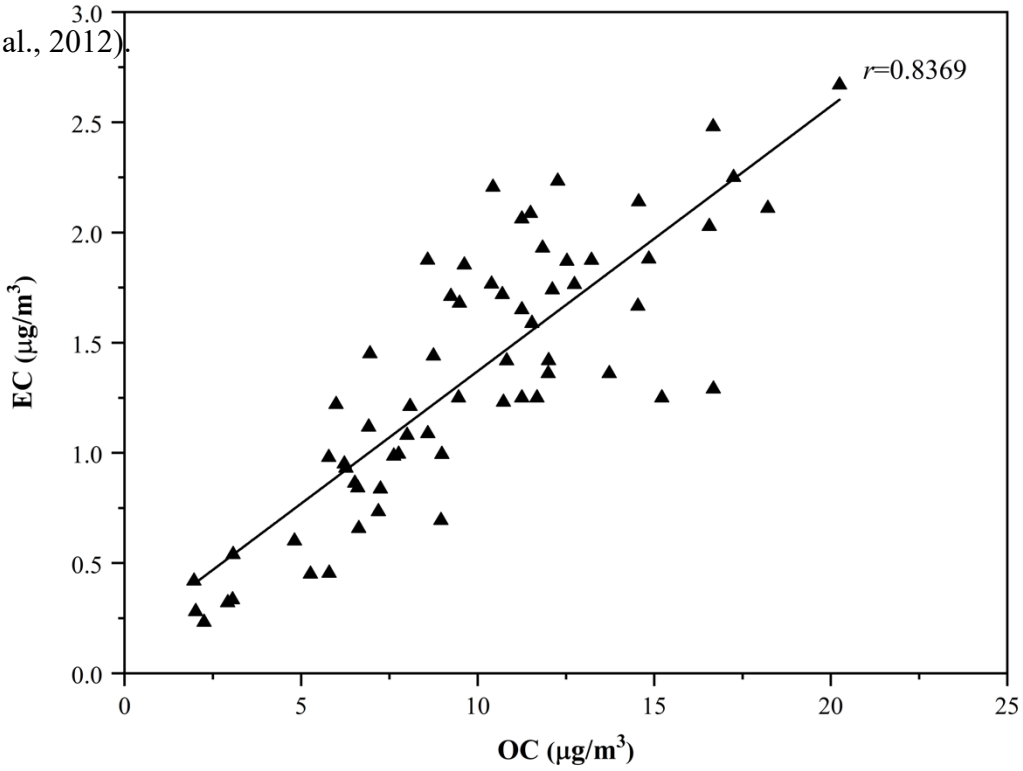

Fig. 2. Scatter plot of OC and EC in $PM_{2.5}$ in Chiang Mai City, 2017.

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 ($r = 0.8969$,

207 $p < 0.01$) (Fig. 3). Additionally, a moderate positive correlation is observed between $PM_{2.5}$ and EC
208 ($r = 0.7558$, $p < 0.01$). The $PM_{2.5}$ samples had a TC concentration of 32.6%. According to Qi et al.
209 (2018), the findings revealed that compared to Beijing and Tianjin, the $PM_{2.5}$ levels were 31% and
210 25% respectively. Nevertheless, there occurred asynchronous variation in the levels of $PM_{2.5}$
211 concentrations and carbonaceous species. The observed phenomenon can be attributed to the
212 proportion of carbonaceous aerosol, known as total carbonaceous aerosol (TCA), within the $PM_{2.5}$.
213 The present study considers the TCA concentration in the atmosphere, comprised of both EC and
214 organic matter (OM). TCA estimation involves multiplying the OC quantity by a factor of 1.6
215 (Turpin and Huntzicker, 1995). The study conducted in Chiang Mai City found that TCA accounted
216 for 49.8% of the $PM_{2.5}$ mass loading, consequently confirming it as the dominant component of
217 $PM_{2.5}$ (Cao et al., 2005). The results of the present study revealed that the levels of TCA in $PM_{2.5}$
218 were relatively high, with an average of 49.8 ± 13.7. This observation could perhaps be attributed
219 to the presence of biomass-burning emissions in the immediate area of the sampling site, as shown
220 in previous research (Shi et al., 2016). In previous studies, it was shown that the ambient $PM_{2.5}$ in
221 Hong Kong consists of 17.8% OC and 8.7% EC (Cao et al., 2003), resulting in a TCA of 36.5%.
222 The result indicates that roughly half of the total TCA concentration is present in the environment
223 near roads. The results from prior studies indicate that TCA contributed to approximately 32.0 ±
224 8.3% of $PM_{2.5}$ in several research (Niu et al., 2012).
225

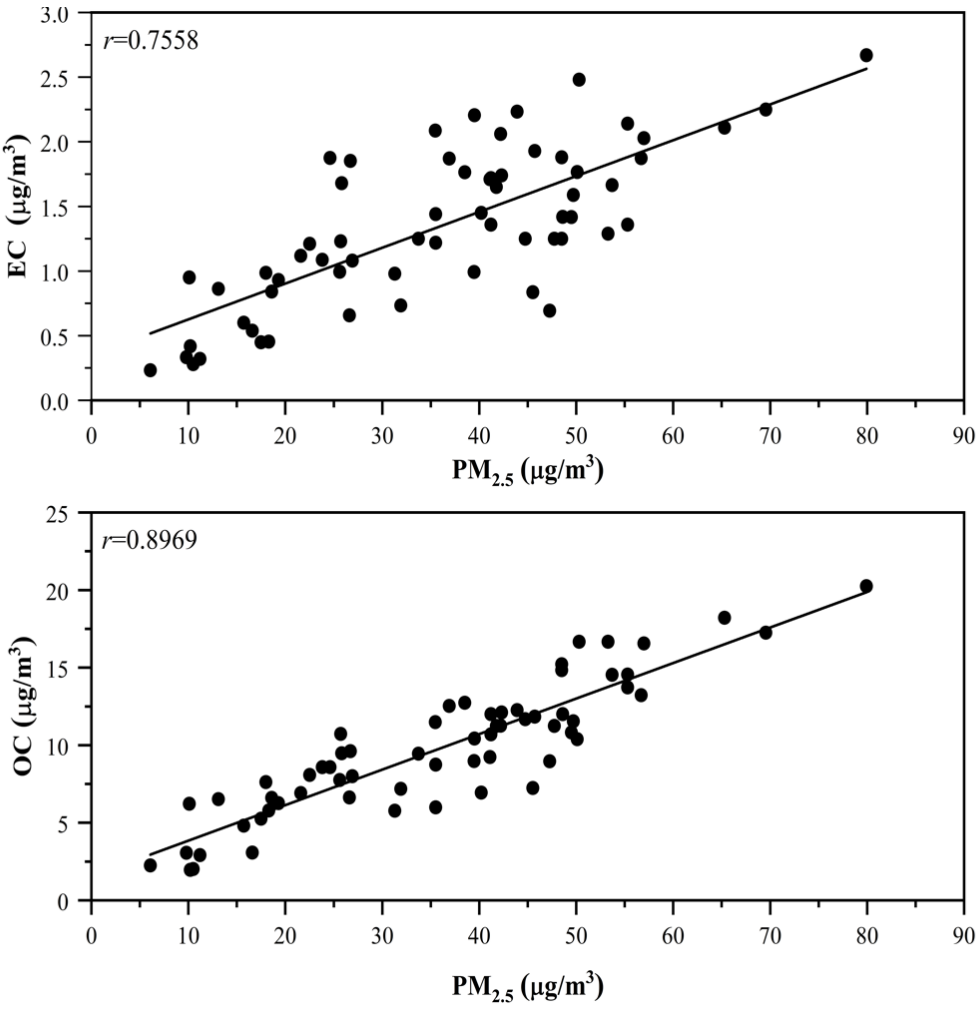

Fig. 3. Correlation between $PM_{2.5}$ and OC, EC in Chiang Mai City, 2017.

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

247 component of $PM_{2.5}$, according to previous research (Cao et al., 2005). Moreover, the higher
248 fraction of TCA in $PM_{2.5}$ in this region may be attributed to biomass-burning emissions (Shi et al.,
249 2016). Moreover, carbonaceous aerosols have been used to research emission and transformation
250 characteristics. The ratio of OC to EC in $PM_{2.5}$ can be employed to identify the sources of pollution
251 in atmospheric aerosols. The mean ratio of OC to EC in Chiang Mai City was 7.65 ± 2.03 and the
252 period during January and May had the highest OC/EC ratio values (which ranged from 4 to 8),
253 which can be attributed to the prevalence of significant open burning during forest fire incidents
254 within the region. The present study's finding indicate that aerosol carbonaceous particles can
255 potentially contribute to biomass burning (Cao et al., 2005). The observed high OC to EC ratio in
256 this study aligns with findings from other research that have associated it with emissions from wood
257 combustion (Schauer et al., 2002) and biomass burning (Zhang et al., 2007; Samara et al., 2014;
258 Wang et al., 2017). To enhance understanding, an OC/EC ratio over two has been employed as
259 evidence to support the presence of secondary organic aerosols. Schauer et al. (2002) suggest that
260 an OC/EC ratio within the range of 1.0-4.2 indicates emissions originating from diesel and gasoline
261 vehicle exhaust (Schauer et al., 2002). In contrast, a study conducted by Watsan et al. 2001 found
262 an OC/EC value of around 9.0, suggesting the significant of biomass-burning activities during the
263 study period (Watson et al., 2001). The OC/EC ratio of the samples that were collected from the
264 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 (Thepnuan et al., 2019). 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; Kraisitnitikul 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 (Cheung et al., 2009). Saarikoski et al. (2008) reported WSOC/OC ratios of 0.41 and 0.27 for biomass burning and vehicular emissions, respectively (Saarikoski et al., 2008). 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 (Daellenbach et al., 2016). 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 (Huang et al., 2012). 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.

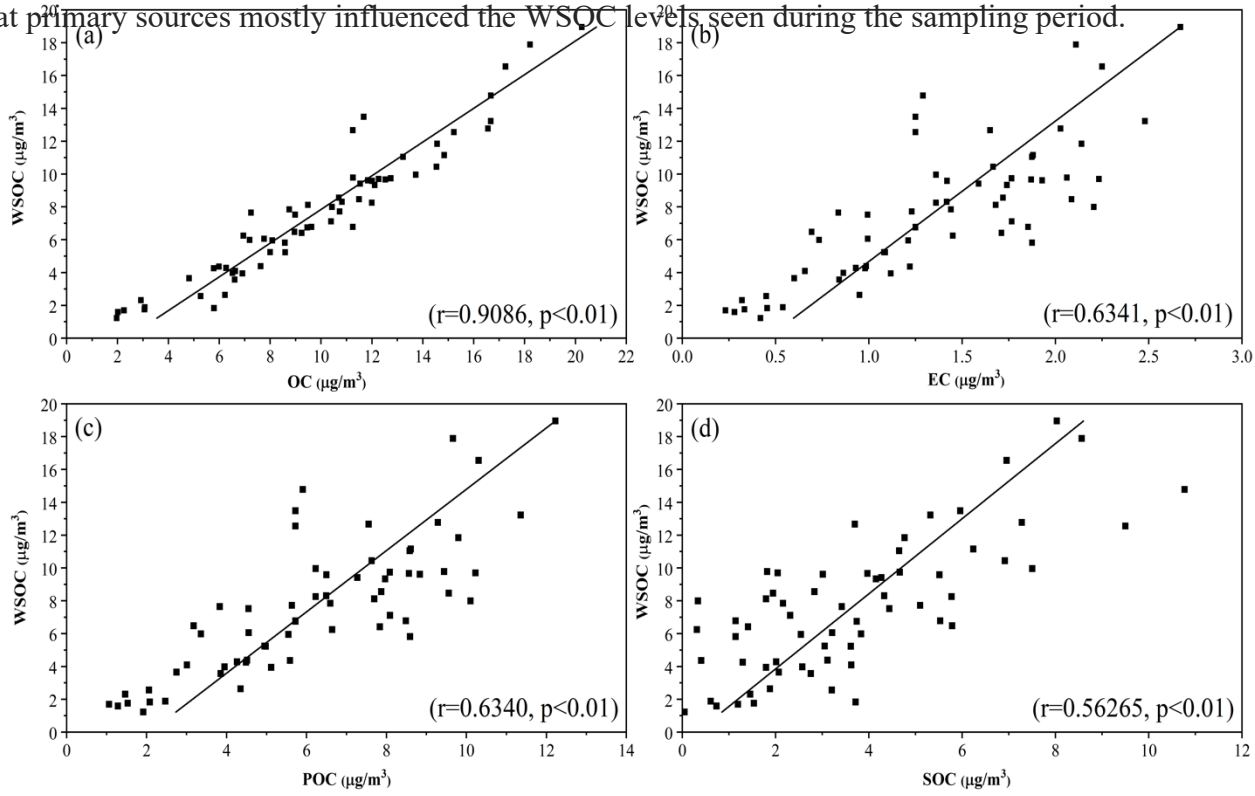

Fig. 4. Correlation of WSOC with (a) OC, (b) EC, (c) POC, and (d) SOC.

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).

$$POC = EC \times (OC/EC)_{primary} \quad (1)$$

$$SOC = TOC - POC \quad (2)$$

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 Feng et al., 2009, the mean concentration of estimated SOC in $PM_{2.5}$ was found to be 2.68 ± 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

340 the lowest OC/EC ratios, suggesting that incomplete combustion emissions from sources such as
341 motor vehicle exhaust, fuel burning, and biomass burning play a significant role in the overall OC
342 mass in Chiang Mai City (Wu et al., 2015; Kaskaoutis et al., 2020).

343 Based on the findings, it was observed that the SOC/OC ratio in Chiang Mai City was 36.7%
344 higher than compared to the values obtained from the CMB modeling results in urban areas, which
345 ranged between 18-19% (Feng et al., 2006). The results suggest that SOC was the primary
346 constituent of OC, and that SOC played a significant part in forming atmospheric particles within
347 Chiang Mai City. The observed pattern displayed a difference when compared to the findings of
348 Niu et al., 2012, and Qi et al. 2018, since their studies have shown higher values than the results
349 from our studies (Niu et al., 2012; Qi et al., 2018). On the other hand, urban areas defined by fossil
350 fuel combustion revealed the lowest SOC/OC ratio, suggesting that carbonaceous species primarily
351 originated from motor vehicles and other local pollutants, such as transportation (Gu, 2010). During
352 the study period, the mean concentration of TOC released by POC was 6.15 μg m^{-3}. The POC to
353 OC ratio for January to May has been reported as 63.0, 74.4, 62.4, 54.0, and 63.3%, respectively.
354 The study's results showed that biomass combustion was the predominant contributor to the source
355 of OC during this period (Ram et al., 2008; Kaskaoutis et al., 2020). Biomass burning usually
356 provides significant amounts of organic matter from plant spores, pollen, and non-combustion
357 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 Pear Review Delta is mainly influenced by gas-phase photochemical 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 ± 3.80 μg 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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