Pollution Characterization, Meteorological Effects, and Sources of Carbon Aerosols in PM$_{2.5}$ in Urban Xiangtan during Winter

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Abstract

Urbanization and industrialization have contributed to increased air pollution in China, yet few studies have focused on carbon aerosols in Xiangtan. To investigate the temporal variations and origins of carbon aerosols in fine particulate matter (PM$_{2.5}$) in Xiangtan, hourly concentrations of elemental carbon (EC) and organic carbon (OC) were measured from December 2022 to February 2023. The average winter concentrations of OC and EC were 10.75 ± 5.75 µg·m$^{-3}$ and 1.92 ± 0.77 µg·m$^{-3}$, respectively, which accounted for 16.5 % and 3.5 % of the total PM$_{2.5}$, respectively. The winter average ratio of OC/EC was 5.82, and the correlation between EC and OC was weak, indicating that OC and EC originated from many different sources. The winter average level of secondary organic carbon (SOC) was 6.8 ± 5.1 µg·m$^{-3}$ using the lowest OC/EC value (OC/EC)$_{\text{min}}$, accounting for about 66 % of the OC, indicating that SOC is the main source of OC in winter PM$_{2.5}$ in Xiangtan. The OC level in Xiangtan exhibited clear diurnal variation, which did not coincide with the diurnal variation of OC observed in the metropolis. In contrast, the EC concentration showed relatively flat diurnal variation. Moreover, no uniform weekend patterns were observed for either OC or EC. High concentrations of OC mainly occurred at low and medium temperatures ranging from 7 to 17 °C and with relative humidity ranging from 60 to 85 %. Additionally, EC and OC concentrations were affected by local pollution sources at low wind speeds. According to potential source contribution function analysis, the EC and OC potential source regions were widely dispersed and the high value source areas of OC and EC were from major traffic cities that were prone to motor vehicle pollution, such as Chang–Zhu–Tan.

Keywords: Organic carbon, Elemental carbon, Chang–Zhu–Tan area.
1 INTRODUCTION

Rapid urbanization and industrialization in China have heightened air pollution caused by fine particulate matter (PM$_{2.5}$). Although air quality improved after the implementation of the Air Pollution Prevention and Control Action Plan in 2013, pollution incidents caused by PM$_{2.5}$ still occur occasionally. Carbonaceous aerosols, which mainly contain elemental carbon (EC) and organic carbon (OC), are the main constituents of PM$_{2.5}$ (Niu et al., 2013), making up approximately 20–70 % of PM$_{2.5}$ mass concentration (Turpin et al., 2000; Lim et al., 2002; Cao et al., 2003a; Pöschl et al., 2005). The composition of OC is complex, as it contains multiple organic substances (Rogge et al., 1993), including primary organic carbon (POC) directly emitted from pollution sources and secondary organic carbon (SOC) formed through photochemical or aqueous reactions (Cao et al., 2003b). Meanwhile, EC mainly results from the incomplete combustion of fossil fuels and biomass, and due to its good stability, it is often used as a pollution source tracer (Bond et al., 2013; Shen et al., 2013; Liu et al., 2017). Notably, OC contains large amounts of carcinogenic, teratogenic, and mutagenic organic compounds (Kelly et al., 2012; Shao et al., 2017), whereas EC can serve as a carrier for toxic substances, such as heavy metals, benzopyrene, and polychlorinated biphenyls; thus, both carbonaceous components are considered harmful to human health (Mauderly et al., 2008; Huang et al., 2012). Research has also shown that EC strongly absorbs solar radiation, making it one of the main driving factors of global warming (Jacobson et al., 2001). In addition, the combination of the OC light scattering and EC light absorption effects also has a considerable impact on atmospheric visibility.
(Offenberg et al., 2000; Lim et al., 2002). Owing to their substantial impacts on human health, the environment, and climate change, OC and EC have received widespread global attention. Research on carbonaceous aerosols in China has mainly focused on the Beijing–Tianjin–Hebei (Fan et al., 2018; Zhang et al., 2018; Ji et al., 2019), Pearl River Delta (Huang et al., 2012; Wu et al., 2019; Lu et al., 2021), Yangtze River Delta (Chang et al., 2017; Chen et al., 2017; Yao et al., 2020), and Taiwan Strait (Pöschl et al., 2005) regions, with Wuhan being the main focus in central China (Gao et al., 2019; Chen et al., 2022).

Xiangtan, located in the Chang–Zhu–Tan (CZT) region, is a relatively small city (5006 km²) with a population of 2.726 million (http://www.xiangtan.gov.cn/index.htm). It is a typical industrialized city with well-developed industries, such as manufacturing and transportation, which generate and emit a large number of pollutants (Tang et al., 2017; Ma et al., 2019, 2020). In addition, Xiangtan is located downstream of the air pollutant transmission pathway in Hunan Province, and pollutant transmission in the surrounding areas has exacerbated air pollution in Xiangtan. However, there are few reports on the pollution characteristics and spatiotemporal evolution of OC and EC in PM$_{2.5}$ in the CZT region. Due to the increased severity of PM$_{2.5}$ pollution in winter, we aimed to: (1) investigate the OC and EC concentration levels, pollution characteristics, temporal evolution, and pollution sources in Xiangtan during winter based on OC and EC hourly concentration monitoring data; (2) evaluate SOC concentration and its contributions to OC and PM$_{2.5}$ emissions in winter; and (3) examine the impacts of meteorological factors on carbonaceous aerosols in Xiangtan.
This study provides invaluable information for assessing the impacts of carbonaceous aerosol on human health and climate, as well as a valuable reference for the future effective management of carbonaceous aerosol pollution and a scientific basis for reducing carbon emissions in Xiangtan.

2 METHODS

2.1 Sampling Site

The monitoring station (27.85° N, 112.93° E) was situated on the sixth floor of the Hunan University of Engineering Library, which is located in the urban center of Xiangtan at a height of approximately 20 m above the ground, as shown in Fig. 1. The horizontal plane of the sampling inlet had a 360° capture space, and the airflow was not substantially affected by the surrounding buildings. Two of the important nationally controlled pollution sources in Xiangtan (Xiangtan Iron and Steel Group Co., Ltd. and Datang Power Generation Co., Ltd.) were located 4 km southwest and 7.6 km away from the monitoring station, respectively. Three main roads with high traffic flow were located 1.1 km east, 1.1 km south, and 1.8 km west of the station. Considering the lack of industrial pollution sources nearby and that the areas surrounding the monitoring site mainly consisted of residential and office region, this monitoring site comprehensively reflects the PM$_{2.5}$ pollution situation of a typical urban environment in Xiangtan.

![Fig. 1. Location of the sampling site.](image)
2.2 Field Measurements

An OC/EC analyzer equipped with a PM$_{2.5}$ very sharp cut cyclone (OCEC-100, Juguang Technology Co., Ltd., China) was used to monitor the hourly OC and EC concentrations from 1 December 2022 to 28 February 2023. A multi-channel parallel plate denuder was installed in front of the analyzer to remove the interference of volatile organic compounds (VOCs) with OC monitoring at a sample flow rate of 8 L·min$^{-1}$. Hourly OC and EC monitoring data were obtained by analyzing samples collected for 30 min on a quartz fiber filter (16 mm diameter). After collection, the oven was purged with helium. Based on one previous study (Lin et al., 2009), the temperature was increased in several programmed steps. OC was thermally volatilized and oxidized to CO$_2$, and was then quantified by a non-dispersive infrared detector (NDIR). Before the second part of the analysis, the oven was cooled while a mixture of 5 % oxygen in helium was flushed through the oven. The sample was then gradually reheated. Any remaining carbon in the sample was oxidized to CO$_2$. NDIR was used to measure the CO$_2$ concentration. A more detailed description of the instrumental method is provided in Chang et al. (2017). The determination of the separation point of EC and OC was based on the recovery of the laser transmittance efficiency to the initial state (Birch et al., 1996). The daily operation, maintenance, and calibration of the OC/EC analyzer strictly followed the technical specifications formulated by the China Environmental Monitoring Station. The method detection limits for OC and EC in this instrument were 0.2 and 0.1 µg·m$^{-3}$, respectively, and the relative standard deviation of the precision was less than 5 %, which was consistent with that in previous studies (Polidori et al., 2006).
During the traditional Chinese Spring Festival, air quality was substantially affected by fireworks; therefore, the OC and EC monitoring data from this time period were excluded. Hourly meteorological data, including ambient temperature (T), relative humidity (RH), wind direction (WD), and wind speed (WS), were recorded using an automatic weather workstation (Vantage Pro2, Davis Instruments, USA) throughout the sampling period.

2.3 Potential Source Contribution Function Method

The potential source contribution function (PSCF) analysis method (Ji et al., 2019) was used to identify and evaluate the potential source locations and transport channels of OC and EC in the Xiangtan urban area. A detailed description of this method is provided in Wang et al. (2009). In this study, the 48h backward trajectory of the air mass was calculated at a height of 500 m above ground by using the Hybrid Single Particle Lagrangian Integrated Trajectory model, or HYSPLIT, to represent a well-mixed convective boundary layer for regional transport studies. Trajectories were simulated every 4 h during the sampling period using the reanalyzed meteorological data (ftp://arlfip.arlhq.noaa.gov/pub/archives/gdas). The coverage area was set to 22–57° N, 89–121° E, with a horizontal resolution of 0.5° × 0.5°, and the winter average concentration of OC and EC was adopted as a specific threshold.

3 RESULTS AND DISCUSSION

3.1 Overview of PM$_{2.5}$, OC, EC, and OC/EC Ratio

During the study period, the daily average concentration of PM$_{2.5}$ ranged from 10 to
206 µg·m$^{-3}$, with an average concentration of 68.6 ± 32.1 µg·m$^{-3}$. The daily average concentration of PM$_{2.5}$ exceeded the maximum exposure limit of 75 µg·m$^{-3}$ set by China’s National Ambient Air Quality Standard (GB3095-2012) for Class 2 areas on 26 days during the study period, and the concentration exceeded the standard limit by up to 28.9%. Furthermore, the average concentration of PM$_{2.5}$ in winter was nearly twice the maximum annual exposure limit of 35 µg·m$^{-3}$ (National Ambient Air Quality Standard), indicating that PM$_{2.5}$ atmospheric pollution was relatively severe in urban Xiangtan in winter.

The hourly concentration of OC in the PM$_{2.5}$ ranged from 1.0 to 40.3 µg·m$^{-3}$, with an average level of 10.75 ± 5.75 µg·m$^{-3}$ in winter, accounting for 16.5% of the average concentration of PM$_{2.5}$. The hourly concentration range of EC in the PM$_{2.5}$ varied from 0.3 to 6.9 µg·m$^{-3}$, with a mean of 1.92 ± 0.77 µg·m$^{-3}$ in winter, accounting for 3.5% of the average concentration of PM$_{2.5}$. As shown in Fig. 2, the daily average concentrations of OC and PM$_{2.5}$ showed significant changes during the observation period, but their trends were basically consistent, with a correlation coefficient of 0.88 ($P < 0.05$). Possible factors such as increased coal consumption in winter and longer motor vehicle starting times may lead to increased emissions of volatile and semi-volatile organic compounds (SVOCs), resulting in an increase in the concentration of precursor compounds in secondary reactions. In addition, lower temperatures make it easier for SVOCs to exist in particulate matter and can also lead to an increase in SOC concentrations. The frequency of calm and stable weather in winter is relatively high, and the atmosphere is relatively stable, which is not conducive to the diffusion of
pollutants, resulting in a longer residence time of gaseous pollutants in the atmosphere, which is conducive to the formation of SOC. PM$_{2.5}$ concentration also increased as OC concentration increased, and the contribution of OC to PM$_{2.5}$ was relatively high. We selected 5% of the samples with the lowest OC/EC value (OC/EC)$_{\text{min}}$ (1.9) to evaluate the concentrations of SOC (Cao et al., 2003b). The winter average levels of POC and SOC were 3.5 ± 1.6 and 6.8 ± 5.1 µg·m$^{-3}$, respectively. SOC accounted for approximately 66% of the total OC, highlighting the relatively severe winter SOC pollution in Xiangtan. This result indicated that SOC was the main source of OC in winter PM$_{2.5}$ in Xiangtan. Although an increase in winter fuel consumption should lead to an increase in EC concentration, the daily average EC concentration did not change significantly and was poorly correlated with changes in PM$_{2.5}$ concentration ($R = 0.25$, $P > 0.05$). This result may be due to the stable nature of EC, which is not easily affected by temperature (T) or relative humidity (RH). Meanwhile, it also indicates that EC had a relatively low contribution to PM$_{2.5}$.

![Fig. 2 Daily average concentration variation of fine particulate matter (PM$_{2.5}$), organic carbon (OC), and elemental carbon (EC).](image)

Fig. 2 Daily average concentration variation of fine particulate matter (PM$_{2.5}$), organic
carbon (OC), and elemental carbon (EC) during the sampling period.

When comparing the average concentration of OC in Xiangtan during the study period, it was lower than that in Beijing and Chengdu; higher than that in Wuhan, Nanjing, and Zhaoqing; and comparable to that in Shanghai (Table 1). However, the winter average concentration of EC in Xiangtan was lower than that of Beijing, Chengdu, Wuhan, Nanjing, and Shanghai and relatively close to that of Zhaoqing. This may be because the Xiangtan urban area does not have a distinct heating season like northern China, and winter temperatures are significantly higher than in the northern regions. Residents rely mainly on electricity for heating, thus coal consumption in Xiangtan is lower than in northern cities. In addition, in the winter of 2022, many factories affected by the COVID-19 epidemic were in a state of production reduction or shutdown, and fossil fuel consumption was lower than before the epidemic, resulting in a significant reduction in primary pollutant emissions. The EC concentration was close to that of coastal cities such as Zhaoqing, which to some extent is an indication that the pollutants from Xiangtan’s combustion emissions are relatively low. However, due to the influence of the subtropical warm and humid climate in Xiangtan, the winter T and RH are relatively high, which is conducive to the secondary transformation of organic compounds (as described below in Section 3.4), resulting in a higher concentration of OC. The differences in OC and EC levels between cities suggest that the degree of carbonaceous aerosol pollution is related to emission loads from pollution sources, meteorological conditions.
Table 1. Comparison of OC, EC, and the OC/EC ratio in winter PM$_{2.5}$ between Xiangtan and other cities in China.

<table>
<thead>
<tr>
<th>City</th>
<th>Time</th>
<th>OC ($\mu$g·m$^{-3}$)</th>
<th>EC ($\mu$g·m$^{-3}$)</th>
<th>OC/EC</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xiangtan</td>
<td>Dec 2022–Feb 2023</td>
<td>10.75</td>
<td>1.92</td>
<td>5.82</td>
<td>Current study</td>
</tr>
<tr>
<td>Wuhan</td>
<td>Dec 2018–Jan 2019</td>
<td>7.9</td>
<td>4.2</td>
<td>2.04</td>
<td>Chen et al., 2022</td>
</tr>
<tr>
<td>Shanghai</td>
<td>Feb 2013–Feb 2014</td>
<td>10.13</td>
<td>3.06</td>
<td>3.38</td>
<td>Chang et al., 2017</td>
</tr>
<tr>
<td>Beijing</td>
<td>Dec 2015–Feb 2016</td>
<td>22.70</td>
<td>9.01</td>
<td>3.10</td>
<td>Zhang et al., 2018</td>
</tr>
<tr>
<td>Nanjing</td>
<td>Dec 2014–Feb 2015</td>
<td>7.98</td>
<td>4.37</td>
<td>1.83</td>
<td>Chen et al., 2017</td>
</tr>
<tr>
<td>Chengdu</td>
<td>Dec 2013–Feb 2014</td>
<td>20.7</td>
<td>7.5</td>
<td>3.1</td>
<td>Shi et al., 2020</td>
</tr>
<tr>
<td>Zhaoqing</td>
<td>Jan 2019–Dec 2019</td>
<td>7.20</td>
<td>2.12</td>
<td>3.81</td>
<td>Lu et al., 2021</td>
</tr>
</tbody>
</table>

The OC/EC ratio in PM$_{2.5}$ has been used to identify the type of emission source and the transformation characteristics of the carbonaceous aerosol. Vehicle exhaust, coal combustion, and biomass burning are typical sources of carbonaceous aerosols with OC/EC ratios ranging from 1.0–4.2 (Panicker et al., 2021), 2.5–10.5 (Chen et al., 2005), and 3.8–13.2 (Zhang et al., 2007), respectively. In this study, the OC/EC ratios were mainly concentrated in the range of 2.5–8.0, with a mean value of 5.82. According to these ratios, the source of carbon aerosols in Xiangtan is less affected by vehicle exhaust, and more affected by coal combustion and biomass combustion. Compared with the representative cities in Table 1, the OC/EC ratio of Xiangtan was significantly higher than that of other cities. This may be because carbon aerosols in certain regions of Beijing–Tianjin–Hebei, such as Beijing, were mainly from motor vehicles and coal (Zhang et al., 2018), whereas carbon aerosols in Wuhan (Chen et al., 2022), Nanjing (Chen et al., 2017), and Chengdu (Shi et al., 2020) mainly came from motor vehicles, resulting in lower OC/EC ratios. Chow et al. (1996) observed that the formation of SOC
can be identified when the OC/EC ratio is greater than 2. The winter average of the OC/EC in Xiangtan was significantly higher than 2, indicating that a large portion of carbonaceous compositions was derived from the secondary transformation. In addition, it has been reported that when OC and EC are emitted from primary sources, the correlation between OC and EC should be strong due to the fact that the emission rates of OC and EC are proportional to each other (Kim et al., 2020). On the contrary, a weak correlation between OC and EC would indicate that OC and EC originate from different sources. The correlation between OC and EC in winter in this study was weak ($R^2 = 0.38, P < 0.01$) (Fig. 3), reflecting the complexity of the pollution sources of OC and EC in Xiangtan. In particular, OC sources included not only vehicle exhaust, coal-fired power plant emissions, biomass combustion, and vegetation respiration but also the oxidation of VOCs in the atmosphere through photochemical reactions or gas–solid conversion and aqueous reactions of VOCs caused by condensation or absorption under high-RH and low-T conditions (Xu et al., 2017). The processes involving VOCs can produce SOC, and the relatively high concentrations of SOC in Xiangtan in winter confirm the generation of SOC in the study area. In turn, SOC formation may have resulted in the weak correlation between OC and EC. This result is consistent with that reported by Xue et al. (2020).
3.2 Distribution of OC and EC under Different Air Quality Levels

Based on the hourly concentrations of PM$_{2.5}$ in Xiangtan, five different air quality levels were set: excellent (PM$_{2.5}$ $\leq$ 35 $\mu$g·m$^{-3}$), good (35 < PM$_{2.5}$ $\leq$ 75 $\mu$g·m$^{-3}$), light pollution (75 < PM$_{2.5}$ $\leq$ 115 $\mu$g·m$^{-3}$), moderate pollution (115 < PM$_{2.5}$ $\leq$ 150 $\mu$g·m$^{-3}$), and high pollution (150 < PM$_{2.5}$ $\leq$ 250 $\mu$g·m$^{-3}$). As shown in Figs. 4(a–c), the corresponding OC and EC concentrations and OC/EC ratios for different levels of air quality were as follows: 4.4 $\mu$g m$^{-3}$, 1.5 $\mu$g m$^{-3}$, and 3.0 for “excellent”; 9.0 $\mu$g m$^{-3}$, 1.8 $\mu$g m$^{-3}$, and 5.4 for “good”; 14.6 $\mu$g m$^{-3}$, 2.2 $\mu$g m$^{-3}$, and 7.3 for “light pollution”; 21.6 $\mu$g m$^{-3}$, 2.7 $\mu$g m$^{-3}$, and 8.4 for “moderate pollution”; and 25.9 $\mu$g m$^{-3}$, 2.9 $\mu$g m$^{-3}$, and 9.4 for “high pollution”. As expected, the concentrations of OC and EC, as well as the values of OC/EC, increased with the increase in air pollution level. This is because PM$_{2.5}$ pollution is often accompanied by high humidity, temperature inversion, boundary layer height reduction, and other adverse meteorological conditions, resulting in continuous accumulation of atmospheric pollutants, including OC and EC. Therefore, the roles of OC and EC became increasingly important as the concentration of PM$_{2.5}$ increased in Xiangtan. These results are consistent with those of previous studies (Chen...
et al., 2017; Ji et al., 2019). However, as shown in Fig. 3(d), the proportions of OC and EC in the PM$_{2.5}$ decreased continuously as a function of PM$_{2.5}$ concentration. The proportions of OC and EC decreased from 18.4 % to 13.4 % and from 7.2 % to 1.5 %, respectively. Meanwhile, the concentrations of other inorganic chemical components such as sulfate, nitrate, and ammonium salts increased, in accordance with the results of previous studies (Chen et al., 2017; Ji et al., 2019). Notably, compared with that under light pollution, the percentage of OC in the PM$_{2.5}$ under moderate pollution increased slightly from 15.7 % to 16.5 %, which may have been related to the high RH under moderate pollution conditions (humidity statistics not displayed). When the RH is higher than 70 %, water uptake by particles result in increased SOC production (Xu et al., 2017). The effects of meteorological conditions on carbonaceous aerosols are discussed in detail later, in Section 3.4.

![Variation in OC (a) and EC (b) concentrations, OC/EC ratio (c), and percentage of OC and EC in PM$_{2.5}$ (d) for different air quality levels.](image_url)

**Fig. 4.** Variation in OC (a) and EC (b) concentrations, OC/EC ratio (c), and percentage of OC and EC in PM$_{2.5}$ (d) for different air quality levels.

### 3.3 Diurnal Variations in OC and EC and the Weekend Effect
The diurnal variations in OC and EC concentrations, as well as in the OC/EC ratios, during the study period, are depicted in Fig. 5. The OC levels exhibited clear diurnal variation, with a weak peak occurring at approximately 10:00 local time, which might have been caused by the combined effects of vehicle emissions and boundary layer height. As the boundary layer height evolves, the OC concentration variations showed a trough at 16:00, a downward trend from 10:00 to 16:00, and then an upward trend from 16:00 until early morning of the next day. Surprisingly, the nighttime traffic peak did not significantly cause the appearance of another peak in OC concentration. This result does not coincide with diurnal variations of OC previously observed in Wuhan (Chen et al., 2022), Nanjing (Chen et al., 2017), or Chengdu (Shi et al., 2020), as motor vehicles are the main source of OC in these cities. In contrast, OC concentrations in Xiangtan are dominated by the SOC concentration as mentioned previously in Section 3.1. Therefore, the influence of changes in the boundary layer height on the daily variation trend of OC is stronger than that generated by vehicles. Moreover, the more stable the boundary layer, the more favourable it is for the formation of SOC.

Compared with the diurnal variation in OC in Xiangtan, the values of EC concentration fluctuated within a small range from 1.89 to 2.0 \( \mu g \cdot m^{-3} \), resulting in a relatively flat diurnal variation, which indicated that no remarkable decrease or increase in EC occurred during the day. In addition, because CO and EC are mainly emitted from combustion sources, we conducted a diurnal variation analysis of CO concentration, and the results were very similar to the daily variation trend of EC. This might be because the number of cars in Xiangtan was only 447,000, according to the 2021 Xiangtan
statistical data (http://www.xiangtan.gov.cn/109/22876/content_1018069.htm), which is much lower than the average number of cars in megacities such as Tianjin (Cheng et al., 2018). Therefore, the dominant EC source in Xiangtan may have been coal combustion and biomass burning. The unique daily variation trend in EC concentration in Xiangtan differed from that in many cities where the diurnal variation in EC is substantially influenced by traffic flow and tends to show a bimodal pattern (Chang et al., 2017; Cheng et al., 2018; Yao et al., 2020). Based on our data in the present study, it was difficult to identify specific sources affecting the diurnal variation in EC in Xiangtan. Therefore, further studies are required to provide more information on the mechanisms of diurnal variation in EC.

As the EC concentration did not vary substantially throughout the day, the trend of daily variation in the OC/EC ratio depended on the daily variation in the OC concentration, resulting in a similar pattern of daily variation to that of OC.

![Graph showing diurnal variations in OC and EC levels and OC/EC ratios in Xiangtan during the study period.]

Researchers have observed that the concentration of air pollution is generally lower on weekends than on weekdays, which is known as the weekend effect. Accordingly, we
analyzed the daily variations in OC and EC on weekends and weekdays, as shown in Fig. 6. Overall, the diurnal variation trends of OC and EC on weekends and weekdays were similar. The mean values of EC and OC on weekdays were $1.90 \pm 0.05$ and $10.98 \pm 1.08 \mu g \cdot m^{-3}$, respectively, while their mean values on weekends were $2.05 \pm 0.08 \mu g \cdot m^{-3}$ ($P < 0.01$) and $11.04 \pm 0.81 \mu g \cdot m^{-3}$ ($P > 0.05$), respectively. The concentrations of EC and OC in urban Xiangtan were slightly higher on weekends than on weekdays, which was contrary to the traditional weekend effect. One possible reason for this discrepancy is that in December 2022, the control measures for COVID-19 were relaxed, leading to an increase in weekend traffic and production and consumption activities compared to the restricted activity levels during the earlier epidemic period. This increase in weekend activities likely increased the emission of air pollutants including EC and OC. These results are similar to those reported for Beijing in 2013 (Ji et al., 2016). Specifically, there was a significant difference between the hourly EC concentrations on weekends and weekdays ($P < 0.01$); the hourly EC concentrations were slightly lower on weekdays than on weekends. Meanwhile, the OC concentration results could be divided into two phases: before 12:00 local time, OC concentrations were lower on weekends than on weekdays, and after 12:00 local time, OC levels were higher on weekends than on weekdays. This may be due to the cold winter temperatures, which delay people’s transport and travel times, thus OC concentrations on weekends were obviously affected by additional traffic emissions, while EC concentration variations on weekends had little influence. The results indicate no uniform weekend patterns for either OC or EC.
3.4 Meteorological Effects

We found that high concentrations of OC mainly occurred at low to medium T ranging from 7 °C to 17 °C and an RH ranging from 60 % to 85 %, as shown in Fig. 7. As the gas-particle conversion of SVOCs shifts to the particle phase at lower ambient temperatures. On the other hand, higher ambient temperatures can accelerate the rate of SOC formation. Therefore, this could be explained by the fact that temperatures ranging from 7 °C to 17 °C are more suitable for the production of SOC. This aligns with the conclusion drawn by Lu et al. (2021) that OC levels in the Pearl River Delta were related to temperature. As mentioned earlier, this phenomenon might also be caused by higher RH being beneficial to SOC formation. Because RH has been shown to play a major role in forming SOC. Gas-particle partitioning studies of water-soluble organic compounds showed a significant increase in the particle phase fraction of these compounds at RH greater than or equal to 70 % (Xu et al., 2017). Therefore, the influence of RH on the formation of secondary organic particles during winter is further confirmed by the moderate positive correlation between OC concentrations and RH.
The RH- and T-related distributions of EC mass concentrations were generally similar to, but not as significant as, the OC distribution. This result may be due to the stable nature of EC, which is not easily affected by T or RH. Combining the wind speed (WS) with the RH- and T-dependent distributions revealed that that WS was usually below 1.5 m·s⁻¹ when OC and EC have high concentrations. These results strongly indicate that the variations in the mass concentrations of OC and EC in Xiangtan were WS-dependent, as a low WS is conducive to the accumulation of pollutants.

Fig. 7. Relationship between relative humidity and ambient temperature and OC concentration, EC concentration, and wind speed.

As shown in Fig. 8, we constructed polar plots of the OC and EC concentrations in urban Xiangtan during winter to further clarify the effects of different WSs and WDs at the sampling site on the mass concentrations of OC and EC. The highest OC concentrations occurred when WS was less than 1 m·s⁻¹, indicating that local pollution sources contributed to the increase in OC concentration. Additionally, when the northwest-by-north wind was dominated by WSs above 2 m·s⁻¹, the OC levels were substantially higher than those in other WDs under the same WS conditions, suggesting that OC concentrations were also affected by regional pollution transport. Furthermore, there was a large range of moderate OC concentration distributions in the southeastern direction, and WSs in this direction did not have a marked effect on the concentration.
distributions, which may have been linked to emissions from a coal-fired power plant located 7.4 km to the southeast. Similar to the OC concentration distributions, the highest EC concentrations (EC ≥ 2.0 µg·m⁻³) occurred mainly in regions with low WS (≤ 2 m·s⁻¹), and there was a wide range of higher EC concentration distributions in the southeast direction that lacked clear concentration gradients. These results also suggested that high EC concentrations were mainly influenced by local pollution sources such as the coal-fired power plant.

![Polar plots of mean concentrations of OC and EC in Xiangtan during winter.](image)

**Fig. 8.** Polar plots of mean concentrations of OC and EC in Xiangtan during winter.

### 3.5 PSCF Analysis

The results of the OC and EC PSCF analysis conducted throughout the winter in Xiangtan are shown in Fig. 9. The potential source regions for both OC and EC were widely distributed and differed to some extent. The potential source area of OC was mainly concentrated in the CZT area, forming a high-value zone of the PSCF, with the highest value (> 0.7) located in the Jingzhou area of Hubei Province in the north. This may be due to the fact that Jingzhou is an important motorway junction and port city on the middle reaches of the Yangtze River. Moreover, as the capital of Hunan Province, Changsha has a large number of motor vehicles. The traffic emissions of both generate a
large amount of pollutants and undergo secondary transformation during the transmission process to form additional OC. Compared to the distribution of potential OC source areas, the distribution range of potential EC source areas with high PSCF values was considerably wider. Except for the high-value zone in the CZT area (> 0.6), the highest PSCF values were mainly in the Jingzhou area of Hubei Province in the north and the Yichun and Nanchang areas of Jiangxi Province in the northeast. The high value source areas of EC were from major transport cities prone to motor vehicle pollution. Compared with other sources of pollution, the concentration of EC from motor vehicle exhaust is relatively low. This may also indirectly explain the reason for the low level of EC in Xiangtan.

**Fig. 9.** Potential source contribution function of OC and EC in winter in Xiangtan.

### 4 CONCLUSIONS

We conducted a comprehensive study based on real-time measurements of carbonaceous aerosols from December 2022 to February 2023 in urban Xiangtan. The mean winter concentrations of OC and EC were 10.75 ± 5.75 and 1.92 ± 0.77 µg·m⁻³, respectively, which accounted for 16.5 % and 3.5 % of the PM₂.₅, respectively. The winter average ratio of OC/EC was 5.82, and the correlation between OC and EC was weak (R² = 0.38, P < 0.01), indicating that OC and EC originate from many different
sources. Using the lowest OC/EC ratio value, \((\text{OC/EC})_{\text{min}}\), to evaluate the
concentrations of SOC, the winter average level of SOC was \(6.8 \pm 5.1 \, \mu g \cdot m^{-3}\),
accounting for about 66% of the OC. This result indicated that SOC is the main source
of OC in winter \(\text{PM}_{2.5}\) in Xiangtan. In addition, the concentrations of OC and EC, as
well as the OC/EC ratio, increased with increasing air pollution. However, the OC and
EC mass fraction in the \(\text{PM}_{2.5}\) tended to decline as a function of \(\text{PM}_{2.5}\) concentration,
implying that other chemical components may play a more dominant role. OC levels in
Xiangtan exhibited clear diurnal variation, which did not coincide with the diurnal
variation of OC observed in the metropolis, where motor vehicles are the main source of
OC. In contrast, EC concentrations exhibited relatively flat diurnal variation. The
average OC and EC concentrations on weekends in the Xiangtan urban were slightly
higher than those on weekdays, contrary to the traditional weekend effect. Moreover, no
uniform weekend patterns were observed for either OC or EC. The highest
concentrations of OC occurred mainly at low and medium T ranging from 7 °C to 17 °C
and an RH ranging from 60% to 85%. Such conditions are more suitable for the
production of SOC. The RH- and T-related distributions of EC mass concentrations
were generally similar to the OC distributions but were not as substantial as the OC
distribution. The highest OC and EC concentrations occurred mainly in regions with
low WSs, suggesting that the influence of local pollution sources was significant. The
OC and EC potential source regions were widely dispersed and differed to some extent
according to the PSCF analysis, and the highest value source areas of OC and EC were
from major transport cities prone to motor vehicle pollution, such as CZT. Overall, we
recommend further investigations into source apportionment and formation mechanisms that underlie carbon aerosols, especially for SOC.

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AUTHOR CONTRIBUTIONS

Lizhi He: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft; Zhenghui Xiao: Conceptualization, Formal analysis; Cheng Xie: Formal analysis, Project administration, Supervision, Writing – review & editing. YangFei Ou: Data curation, Formal analysis, Writing – review & editing; Sisi Wang: Data curation, Writing – review & editing.

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CONFLICT OF INTEREST

The authors declare no competing financial interests.
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