Responses to Referee #1:

This manuscript discussed chemical composition and source apportionment of \( \text{PM}_{2.5} \) in three northern Chinese cities based on high-time-resolution monitoring equipment. Furthermore, the authors qualitatively explored the mechanisms of secondary aerosols formation. And the authors also compared the changes in the chemical composition and sources of \( \text{PM}_{2.5} \) in the three pilot cities over past decades. At the end of the article, the authors provided policy recommendations for sustained air quality improvement in the future. In general, this article provides valuable data for local governments to develop scientific pollution control strategies. I recommend this article for publication on Atmospheric Chemistry and Physics. However, some issues should be addressed before the publication.

Response: We kindly appreciate the reviewer to providing those valuable comments and suggestions to our paper. We have carefully revised the relevant contents. We do believe that the revised manuscript has been significantly improved after the revision. The point-to-point responses to each comment are provided in blue, and the revised content is underlined in italics. Attached please also find the marked-up manuscript with tracked changes in the revised manuscript.

Major comments:

Comments (1): In Text S1 from supplement, the error fraction of all chemical species was used to 10% for calculation of uncertainty dataset inputted receptor model. Is it reasonable to choose the same error fraction for different instruments?

Response: Thank you for pointing out this problem. The error fraction value was normally calculated by parallel sample analysis, which can be achieved from off-line experiments. However, our campaigns were conducted by online instruments, the parallel test cannot be conducted due to limitation of instruments. For high time-resolution source apportionment, the value of error fraction was set from 0.05-0.5 (Yang et al., 2022). And the 10% for all species was been widely used to calculate the uncertainty dataset for source apportionment by receptor model in previous serval studies (Liu et al., 2016; Ji et al., 2018; Rai et al., 2020; Wu et al., 2020; Liu et al., 2021; Tian et al., 2022), and those all did not impact the interpretability of the source identification. Therefore, the 10% for error fraction was chosen to calculate the uncertainty data set in this study.

References:


Comments (2): In Sect3.2, the secondary sources from three cities were resolved by HERM model. And one factor named secondary nitrate plus sulfate was identified in Xi’an and Shijiazhuang (Fig. S6 and S7), but two factors named secondary nitrate and secondary sulfate were identified in Beijing (Fig. S8). What causes such differences in sources identification among cities? Moreover, the secondary sources were characterized by high EV values for SO42-, NO3-, NH4+, and those three species are inorganic aerosols. Secondary organic aerosols (SOA) were not identified in this study, dose SOA was ignored in this study?

Response: (a) Thank you for pointing out this out. The factor number for optimal solution of receptor model was depended on characteristics of data set inputted model (Chen et al., 2010). So, it is not unusual for the number of factors to vary in different cities. Although two factors about secondary source were identified in Beijing, the source characteristics reflected by these two factors together are equivalent those reflected by one factor in Xi’an and Shijiazhuang. And we also point out this in manuscript (see section 3.2).

(b) Due to lack of critical tracers of SOA in this study, the sources of SOA cannot be individually resolved by receptor model. In this study, the secondary sources were mainly characterized by high EV values for inorganic aerosols such as SO42-, NO3-, NH4+, but the medium EV values for OA (16~29%) were also presented on secondary sources in three pilot cities. This means that the SOA maybe mixed in with the factors of secondary sources. To
verify this, we estimated the SOA concentrations using a BC-tracer method (Wang et al., 2019) and then compared the results with those based on source apportionment. The formula of SOA calculation based on BC-tracer method was shown as follow:

\[
[\text{SOA}]_{\text{BC-tracer}} = [\text{OA}] - (\text{OA/BC})_{\text{pri}} \times [\text{BC}]
\]

(R-1)

where \([\ ]\) means mass concentration, (OA/BC)\text{pri} is the ratio of [OA] to [BC] in primary emission. The (OA/BC)\text{pri} ratios vary among sources, therefore, a minimum R squared (MRS) method was used to derive appropriate (OA/BC)\text{pri} values for three pilot cities. In previous studies (Srivastava et al., 2018; Wang et al., 2019), MRS method has been used to calculated the concentration of secondary organic carbon and brown carbon. Detailed information on the method and a validation of this approach can be found in Wang et al. (2019).

In addition, according source apportionment results, SOA concentration can also be estimated as follow based on EV values of OA from secondary source factors

\[
[\text{SOA}]_{\text{source apportionment}} = [\text{OA}] \times \text{EV}_{\text{OA}}
\]

(R-2)

where EV_{OA} represents the EV values of OA in secondary sources factors resolved by HERM model.

As shown in Fig. R1, the (OA/BC)\text{pri} ratios were determined as 4.73 for Xi’an, 3.12 for Shijiazhuang and 7.6 for Beijing, respectively. Furthermore, the concentrations of SOA from three pilot cities were shown in Table R1 based two different methods. As we can see, the SOA concentrations estimated by EV values of OA are close to that by BC-tracer method for three pilot cities. This indicated SOA was mixed in secondary sources factors.

To avoid unnecessary misunderstanding to the readers, we re-named the source of secondary nitrate plus sulfate as secondary formation source, secondary nitrate as secondary nitrate plus OA, and secondary sulfate as secondary sulfate plus OA, respectively in revised manuscript.

The main changes about identification of secondary source were revised as follows:

“The secondary sources resolved by HERM are different among the three cities. In Xi’an and Shijiazhuang, this factor are characterized by high EV values for SO_4^{2-} (62–75%), NO_3^- (55–53%), NH_4^+ (60–56%) and a medium EV value for OA (23–29%), which showed good correlations with SO_4^{2-} (R^2 = 0.85–0.90) and NO_3^- (R^2 = 0.85–0.92) (Dai et al., 2020; Tian et al., 2022). In addition, The OA concentration in this factor was calculated by EV value of OA, which was close to the secondary OA (SOA) concentration estimated by BC-trace method (see Text S3 and Table S6). This means that SOA was mixed in this factor, therefore, this factor was identified as secondary formation source. In Beijing, two secondary sources were resolved. The first one was characterized by high EV value for NO_3^- (58%), NH_4^+ (42%) and medium
values for OA (21%), another one was characterized by high EV value for SO₄²⁻ (58%), and medium values for OA (16%), NH₄⁺ (30%). The OA concentration in those two factors was also comparable to that estimated by BC-trace method (see Text S3). So, those two sources were identified as secondary nitrate plus OA and secondary sulfate plus OA, respectively. The combination of secondary nitrate plus OA and secondary sulfate plus OA is equivalent to the secondary formation source for next discussion.” (Page 10 Line 270–283)

Figure R1. Coefficients of determination (R²) for SOA versus BC mass concentration plotted against assumed ratios for OA to BC in primary emissions ((OA/BC)pri).

Table R1 Average concentrations of SOA in Xi’an, Shijiazhuang, and Beijing during sampling periods estimated by BC-tracer method and source apportionment results (μg m⁻³)

<table>
<thead>
<tr>
<th></th>
<th>Xi’an</th>
<th>Shijiazhuang</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOA₁ ᵃ</td>
<td>5.1 ± 5.8</td>
<td>4.2 ± 4.4</td>
<td>8.0 ± 9.0</td>
</tr>
<tr>
<td>SOAⅡ</td>
<td>6.0 ± 4.1</td>
<td>4.6 ± 2.8</td>
<td>8.2 ± 6.7</td>
</tr>
</tbody>
</table>

References:

Comments (3): In Sect3.3, the authors explored the potential function of aqueous-phase reaction to secondary aerosol formation based on data during nighttime. It should be noted that aqueous-phase reaction may also promote secondary aerosol formation during daytime. I suggest that the authors take the data from daytime hours into account when discussing the role
of the aqueous-phase reaction.

**Response:** Thanks for reviewer’s wonderful suggestion. We investigated the correlations of secondary formation source/ΔCO ration and ALWC based on data during daytime (08:00–17:00 LST). As shown in Fig. R2a-c, the secondary formation source/ΔCO also showed a significant linear correlation to ALWC (R² = 0.84–0.98) when RH < 80%, this indicated that the aqueous-phase reaction on the secondary aerosol formation also occurred during the daytime. Therefore, the functions of aqueous-phase reaction to the secondary aerosol formation in three pilot cities were re-evaluated by all data during sampling periods in revised manuscript.

**Figure R2.** Correlation of secondary formation source/ΔCO and ALWC during daytime (08:00–17:00 LST, a–c) and nighttime (18:00–7:00 the next day LST, d–f) in Xi’an, Shijiazhuang, and Beijing, respectively. The points and error bar represent the mean values and standard deviation values of secondary formation source/ΔCO and ALWC in each bin. In Xi’an, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³). In Shijiazhuang, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³) when ALWC ranged from 0 to 75 μg m⁻³, but 25 μg m⁻³ (ΔALWC = 25 μg m⁻³) for ALWC ranged from 75 to 200 μg m⁻³ due to limitations in data. In Beijing, during daytime, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³) when ALWC ranged from 0 to 40 μg m⁻³, but 100 μg m⁻³ (ΔALWC = 100 μg m⁻³) for ALWC ranged from 40 to 450 μg m⁻³ due to limitations in data. During nighttime, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³) when ALWC ranged from 0 to 50 μg m⁻³, but 100 μg m⁻³ (ΔALWC = 100 μg m⁻³) for ALWC ranged from 50 to 900 μg m⁻³ due to limitations in data.

In the revised manuscript, Figure 4 was replaced by Figure R3.
**Figure R3.** Correlation of secondary formation source/ΔCO and ALWC during sampling periods in (a) Xi’an, (b) Shijiazhuang, and (c) Beijing, respectively. The points and error bar represent the mean values and standard deviation values of secondary formation source/ΔCO and ALWC in each bin. In Xi’an, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³). In Shijiazhuang, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³) when ALWC ranged from 0 to 75 μg m⁻³, but 25 μg m⁻³ (ΔALWC = 25 μg m⁻³) for ALWC ranged from 75 to 200 μg m⁻³ due to limitations in data. In Beijing, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³) when ALWC ranged from 0 to 50 μg m⁻³, but 100 μg m⁻³ (ΔALWC = 100 μg m⁻³) for ALWC ranged from 50 to 900 μg m⁻³ due to limitations in data.

The relevant contents in section 3.3 were revised as follows:

“The aqueous-phase reaction is another important pathway for secondary aerosol formation in the atmosphere (Wang et al., 2018; Xue et al., 2014). ALWC is considered an indicator of an aqueous-phase reaction (Ervens et al., 2011). Considering that the aqueous-phase reaction occurs both during the daytime and nighttime characterized by good correlations between secondary formation source/ΔCO and ALWC (R² = 0.81–0.98, Fig. S14). The correlations of secondary formation source/ΔCO ratio and ALWC during all sampling periods were re-established in three pilot cities to assess the implications of aqueous-phase chemistry for secondary aerosol production. As shown in Fig. 4, the secondary formation source/ΔCO showed a significant linear correlation to ALWC (R² = 0.92–0.99) when RH < 80%, indicating an obvious effect of aqueous-phase reaction on the secondary aerosol formation during the sampling periods. However, when RH >80%, the secondary formation source/ΔCO showed no notable increase with ALWC in Shijiazhuang (Fig. 4b), whereas a tiny increase with ALWC in Beijing (Fig. 4c). The higher ALWC at RH > 80% probably inhibits secondary aerosol formation due to the decrease in aerosol acidity (Huang et al., 2019; Meng et al., 2014). Khan et al. (2008) found that NO₃ radicals can rapidly generate from the reaction between NO₂ and O₃ with unsaturated organic species during nighttime. The value of O₃×NO₂ can thus represent its production reaction rate or be used as a proxy for the NO₃ radical. The highest NO₃ radical production rate was found in Beijing, followed by Xi’an and Shijiazhuang, when RH~80%.

This could be used to explain the highest contribution of secondary formation source to PM₂.₅.
in Beijing during the daytime and nighttime (Fig. S13). Moreover, the results showed that both photochemical oxidation and aqueous-phase reaction play more important roles in Beijing, where the primary sources have been better controlled. This reflects that pollution control policies need to be focused on the suppression of secondary formations” (Page 11, Line 334–353)

**Specific Comments:**

**Comments (4):** line 18 & 352: change “progress of” to “process of”

**Response:** We have corrected the relevant sentences as follows:

“In this study, intensive real-time measurement campaigns were conducted in Xi’an, Shijiazhuang, and Beijing to investigate the chemical characteristics and source contributions of PM$_{2.5}$ and explored the formation of heavy pollution for policy implications.” (Page 1 Line 16–18)

“To gain insights into the process of pollution episodes, three typical pollution events were chosen for detailed discussion (i.e., EP2 in Xi’an, EP4 in Shijiazhuang, and EP7 in Beijing) based on the validity and integrity of the data and the representativeness of the selected pollution events.” (Page 14 Line 369–371)

**Comments (5):** line 22-23: change "but is no longer important contributor...." to "but is no longer an important contributor...."

**Response:** We have added an indefinite article of to this sentence as follows:

“The contribution of coal combustion to PM$_{2.5}$ is non-negligible in Xi’an and Shijiazhuang but is no longer an important contributor in the capital city of Beijing due to the execution of a strict coal-banning policy.” (Page 1 Line 22–24)

**Comments (6):** line 27: change “According to source variations, to “According to sources variations,”

**Response:** We have corrected the relevant sentence as follows:

“According to sources variations, air pollution events that occurred in campaigns were classified into three types: biomass combustion dominated, secondary formation source dominated, and a combination of primary and secondary sources.” (Page 1 Line 27–30)

**Comments (7):** line 49: change “In perspective of PM2.5 sources” to “In terms of PM2.5 sources”
Response: We have changed “In perspective of PM$_{2.5}$ sources” to “In terms of PM$_{2.5}$ sources” as follows:

“In terms of PM$_{2.5}$ sources, contribution of secondary source increased obviously while contribution of industrial emission and coal combustion decreased due to elimination of industries and enterprises with high pollutant emissions, promotion of desulfurization in industrial facilities, replacement of clean energy, and optimization of industrial and energy structures (Lu et al., 2021; Ma et al., 2022; Tao et al., 2017; Wang et al., 2019).” (Page 2 Line 50–54)

Response: Corrected. (Page 2 Line 68)

Comments (9): line 73: change “should be pointed out previous researches” to “should be pointed out that previous studies”
Response: We have corrected the relevant sentence as follows:

“It should be pointed out that previous researches were mainly focused on individual cities, and those results have some limitations in guiding the improvement of air quality in the entire northern region of China.” (Page 3 Line 73–75)

Comments (10): line 78 & 85-86: change “are located to” to “are located in”
Response: We have corrected the relevant sentence as follows:

“The cities of Beijing and Shijiazhuang are located in the North China Plain, which is one of the most polluted regions in China (Chan and Yao, 2008).” (Page 3 Line 79–80)

“Xi’an is located in the Fenwei Plain, which is a region that suffered from heavy pollution and was designated as a key region for TAPFAP in 2018 (Cao and Cui, 2021).” (Page 3 Line 87–88)

Comments (11): line 237: change “With increasing of the PM$_{2.5}$ mass concentration” to “With increases of the PM$_{2.5}$ mass concentration”
Response: We have corrected the relevant sentence as follows:

“With increases of the PM$_{2.5}$ mass concentration, the fractions of chemical components in Xi’an and Shijiazhuang changed notably.” (Page 9 Line 238–239)

Comments (12): line 431&454: change “atmosphere oxidation capacity” to “atmospheric oxidation capacity”
Response: We have corrected the relevant sentences as follows:

“Therefore, more control measures should focus on weakening the atmospheric oxidation capacity, such as reduction of O₃ formation, to reduce the formation of secondary pollutants which are now identified as the most critical drivers of pollution.” (Page 16, Line 453–456)

“Furthermore, to weaken the atmospheric oxidation capacity for reducing the contribution of secondary formation source, it is necessary to promote the collaborative control on ozone and particulate matter.” (Page 17 Line 477–479)
High-time-resolution chemical composition and source apportionment of PM$_{2.5}$ in northern Chinese cities: implications for policy

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Abstract: Fine particulate matter (PM$_{2.5}$) pollution is still one of China's most important environmental issues, especially in northern cities during wintertime. In this study, intensive real-time measurement campaigns were conducted in Xi’an, Shijiazhuang, and Beijing to investigate the chemical characteristics and source contributions of PM$_{2.5}$ and explored the formation progress of heavy pollution for policy implications. The chemical compositions of PM$_{2.5}$ in three cities were all dominated by organic aerosol (OA) and nitrate (NO$_3^-$). Results of source apportionment analyzed by hybrid environmental receptor model (HERM) showed that the secondary nitrate plus sulfate formation source contributed higher to PM$_{2.5}$ compared to other primary sources. Biomass burning was the dominant primary source in three pilot cities. The contribution of coal combustion to PM$_{2.5}$ is non-negligible in Xi’an and Shijiazhuang but is no longer an important contributor in the capital city of Beijing due to the execution of a strict coal-banning policy. The potential formation mechanisms of secondary aerosol in three cities were further explored by establishing the correlations between the secondary nitrate plus sulfate formation source and aerosol liquid water content (ALWC), and O$_x$ ($O_3 + NO_x$), respectively. The results showed that photochemical oxidation and aqueous-phase reaction were two important pathways of secondary aerosol formation. According to sources variations, air pollution events that occurred in campaigns were classified into three types: biomass combustion dominated, secondary nitrate plus sulfate formation source dominated, and a combination of primary and secondary sources. Additionally, this study compared the changes in chemical composition and source contributions of PM$_{2.5}$ in past decades. The results suggested that the clean energy replacements for rural household should be...
urgently encouraged to reduce the primary source emissions in northern China, and collaborative control on ozone and particulate matter need to be continuously promoted to weaken the atmosphere oxidation capacity for the sake of reducing secondary aerosol formation.

1. Introduction

Fine particulate matter (PM$_{2.5}$, aerodynamic diameter $\leq 2.5$ $\mu$m) is of large concern because of its adverse effects on both natural environment (Kuniyal and Guleria, 2019; Kuo et al., 2013) and human health (Pöschl, 2005; Shen et al., 2021; Zeng and He, 2019). With the soaring economic growth and urbanization in China, PM$_{2.5}$ pollution has been a most serious environmental issue in recent decades (Chan and Yao, 2008; He et al., 2002; Pui et al., 2014; Zhang et al., 2013). The most impressive case is that an extremely severe haze pollution episode occurred in eastern and central China in January 2013 with peak value of PM$_{2.5}$ concentration over 500 $\mu$g m$^{-3}$. This month had been reported as the haziest month in the past 60 years in Beijing, China (Wang et al., 2014; Huang et al., 2014). Thereafter, aiming to improve air quality, the China central government issued the Air Pollution Prevention and Control Action Plan (APCAP) in September 2013 (http://www.gov.cn/zwgk/2013-09/12/content_2486773.htm, in Chinese), and the Three-year Action Plan to Fight Air Pollution (TAPFAP) in June 2018 (http://www.gov.cn/zhengce/content/2018-07/03/content_5303158.htm, in Chinese). With the implementation of strict pollution controls, air quality in northern China has improved significantly over the past decade (Wang et al., 2020a, 2017; Li et al., 2020). Previous studies show that PM$_{2.5}$ concentration decreased notably in past two decades, and the composition of organic aerosol (OA), black carbon (BC) and sulfate (SO$_{4}^{2-}$) decreased as well, while the ammonium (NH$_{4}^{+}$) slightly increased and nitrate (NO$_{3}^{-}$) increased obviously. In perspective terms of PM$_{2.5}$ sources, contribution of secondary source increased obviously while contribution of industrial emission and coal combustion decreased due to elimination of industries and enterprises with high pollutant emissions, promotion of desulfurization in industrial facilities, replacement of clean energy, and optimization of industrial and energy structures (Lu et al., 2021; Ma et al., 2022; Tao et al., 2017; Wang et al., 2019). However, there is still a significant gap between the PM$_{2.5}$ concentration in northern China and its latest recommendations on air quality guideline (5 $\mu$g m$^{-3}$) by the World Health Organization (https://apps.who.int/iris/bitstream/handle/10665/345329/9789240034228-eng.pdf, page 78). In addition, severe PM$_{2.5}$ pollutions still frequently occurred in northern China during wintertime (Guo et al., 2021; Li et al., 2017a, 2021b). To figure out the causes behind the pollutions and further improve air quality in northern China, it is essential to use online high-time-resolution source apportionment technology to understand the chemical composition and source contribution of PM$_{2.5}$ in those pollution events.
Recently, more research on measurements of PM$_{2.5}$ and its source apportionments were conducted using online high-time-resolution technologies (Li et al., 2017c; Wang et al., 2021a; Elser et al., 2015). Compared to traditional offline filter-based approach, online methods characterize the short-time variation of PM$_{2.5}$. It allows for distinguishing the rapid changes and evolutions of chemical components, and is particularly profitable to gain knowledge on the formations of heavy air pollution or episode events (Liu et al., 2016; Ouyang et al., 2019; Zheng et al., 2016; Elser et al., 2015). For instance, Lv et al. (2021) employed a Positive matrix factorization (PMF) model with high-time-resolution online PM$_{2.5}$ data to accurately quantify and distinguish the source distributions in Beijing during two haze episodes in January 2019. Liu et al. (2019) recognized the main drivers of haze event occurred in winter Beijing in 2016 according to high-time-resolution source apportionment of PM$_{2.5}$ with multiple models. Furthermore, Wang et al. (2021b) found that vehicle emission contributed most to PM$_{2.5}$ during pollution episodes in downtown Lanzhou based on high-resolution online data source apportionment. Currently, to fully understand and solve heavy pollution events in winter that troubles local governments in northern cities of China (Wang et al., 2022b; Xu et al., 2022; Zhou et al., 2022), more advanced online measurement, and source apportionment is a better choice (Tao et al., 2015). It should be pointed out that previous researches were mainly focused on individual cities, and those results have some limitations in guiding the improvement of air quality in the entire northern region of China. Therefore, it is necessary to conduct comparative research among multiple cities.

Considering the differences in geographical location, population, economy, industrial/energy structure, air quality, and depth of air pollution control measures among different cities, three cities in northern China including Beijing, Shijiazhuang and Xi’an were chosen as pilot research subjects. The cities of Beijing and Shijiazhuang are located in the North China Plain, which is one of the most polluted regions in China (Chan and Yao, 2008). Beijing is the capital of China and its air quality has significantly improved under the implementation of the strictest clean air policy since 2013 (Li et al., 2021a; Pang et al., 2021; Vu et al., 2019; Zhang et al., 2020). However, the city was still plagued by pollution events in wintertime (Wang et al., 2020b; Yang et al., 2022c; Zhou et al., 2022). Shijiazhuang was recognized as one of the most serious air pollution cities worldwide (Liu et al., 2018b; Huang et al., 2019). Its air quality had also improved under the implementation of the Clean Air Plan, whereas its annual PM$_{2.5}$ concentration was still unable to meet the China’s National Ambient Air Quality Standards (NAAQS-II) of 35 µg m$^{-3}$ until 2021 (Fig. S1). Xi’an is located in the Fenwei Plain, which is a region that suffered from heavy pollution and was designated as a key region for TAPFAP in 2018 (Cao and Cui, 2021). Compared with Beijing and Shijiazhuang, high-intensity air pollution controls in Xi’an started late due to a lack of financial support. And the annual PM$_{2.5}$
concentration in Xi’an could not meet the NAAQS-II until 2021 as well (Fig. S1). Meanwhile, it is still unclear about the actual causes of the pollution, either topography, meteorological conditions, or local emissions (Chen et al., 2021; Tian et al., 2022; Wang et al., 2015, 2022b). In this study, we conducted intensive real-time observation of PM$_{2.5}$ chemical components in Xi’an, Shijiazhuang, and Beijing during wintertime. The objectives are 1) to determine the characteristics of PM$_{2.5}$ and its chemical components in the three typical northern China cities during wintertime; 2) to quantify the source contribution and explore the potential formation mechanism of secondary aerosols; 3) to explore the unique causes of heavy pollution events in different cities; and 4) to provide suggestions on establishment of efficient policies for air quality continuous improvement. This study provides scientific guidance for developing policy on air quality improvement for northern China cities.

2. Methods

2.1 Sampling sites and periods

In this study, intensive online measurements of PM$_{2.5}$ were conducted at three pilot cities of Xi’an, Shijiazhuang, and Beijing during wintertime (Fig. 1). The sampling sites in Xi’an and Beijing are located at two Chinese Academy of Sciences (CAS) stations. The one in Xi’an is the Guanzhong Plain Ecological Environment Change and Comprehensive Treatment National Observation and Research Station, Institute of Earth Environment (IEE) (34.24°N, 108.87°E), and another one in Beijing is Tower Branch of the Institute of Atmospheric Physics (IAP) (39.98°N, 116.39°E). Both two sites are surrounded by commercial and residential buildings without intense industrial emissions nearby. Previous studies indicated that these two sites were influenced by biomass and coal burning for heating and cooking during wintertime as well as usual local traffic emissions (Tian et al., 2021; Xu et al., 2021). The sampling site in Shijiazhuang is situated in the courtyard of Hebei Sailhero Environmental Protection High-tech Co., Ltd. (38.04°N, 114.65°E), which is surrounded by pharmaceutical and machine-building industries and close to the streets. The intensive campaigns were continuously conducted for ~1 month in each city (i.e., 12 December 2020 to January 7th 2021 in Xi’an, December 20th 2021 to January 24th 2022 in Shijiazhuang, and January 17th 2021 to February 20th 2021 in Beijing).

2.2 Online measurements of PM$_{2.5}$ chemical components

2.2.1 Organic aerosol and inorganic ions

Concentrations of OA, NO$_3^-$, SO$_4^{2-}$, ammonium (NH$_4^+$), and chloride (Cl$^-$) in PM$_{2.5}$ at a 15-minute time resolution
were monitored by a quadrupole aerosol chemical speciation monitor (Q-ACSM, Aerodyne Research Inc., Billerica, Massachusetts, USA) equipped with a PM\textsubscript{2.5} lens. The detailed operational principles and calibration method of the Q-ACSM are described elsewhere (Ng et al., 2011; Hu et al., 2017). First, the sampled ambient air stream passed through a PM\textsubscript{10} impactor inlet and a Nafion\textsuperscript{®} dryer (MD-700-24F-3; Perma Pure, Inc., Lakewood, NJ, USA) with a flowrate of 5 L min\textsuperscript{-1} before entering the Q-ACSM chamber. Then, the pre-treatment particles passed through a 100 μm critical orifice at 0.1 L min\textsuperscript{-1} and were focused into a narrow beam by an aerodynamic intermediate pressure lens. The focused particle beam was flash vaporized by a capture vaporizer (CV) at ~600 °C. The vaporized compounds were then ionized by an electron impactor (EI) ionization source at 70 eV and subsequently analyzed by the quadrupole mass spectrometer.

Based on calibration system consists of an atomizer (Model 9302, TSI Inc., Shoreview, MN, USA), a differential mobility analyzer (DMA, TSI model 3080, TSI Inc.), and a condensation particle counter (CPC, TSI model 3772, TSI Inc.), ammonium nitrate (NH\textsubscript{4}NO\textsubscript{3}) and ammonium sulfate ((NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4}) aerosol were used for calibration. The raw data of Q-ACSM were analyzed by the ACSM local tool (V1.5.3.5, Aerodyne Research Inc., Billerica, Massachusetts, USA) compiled with Igor Pro 6.37 (Wavemetrics, Lake Oswego, OR, USA). The response factors (RFs) for NO\textsubscript{3}\textsuperscript{-} in Xi’an, Shijiazhuang, and Beijing were set as 2.03×10\textsuperscript{-11}, and 5.9×10\textsuperscript{-11}, 2.20×10\textsuperscript{-11}, respectively, and the relative ionization efficiencies (RIEs) for NH\textsubscript{4}\textsuperscript{+} and SO\textsubscript{4}\textsuperscript{2-} were set as 8.06 and 0.83 in Xi’an, 5.82 and 0.30 in Shijiazhuang, 6.31 and 0.38 in Beijing, respectively. Other RIEs for NO\textsubscript{3}\textsuperscript{-}, OA, and Cl\textsuperscript{-} were set as default values of 1.4, 1.1, and 1.3, respectively (Ng et al., 2011). In addition, the collection efficiency (CE) value of Q-ACSM equipped with a PM\textsubscript{2.5} lens was recommended as 1 based on laboratory simulation experiments by Xu et al. (2017). Finally, the chemical components monitored by Q-ACSM was corrected by the results of offline filter sampling experiments during the same periods (Fig. S2).

### 2.2.2 Black carbon

BC concentration in PM\textsubscript{2.5} was obtained by an Aethalometer (Model AE33, Magee Scientific Inc., Berkeley, CA, USA) with a 1-minute time resolution. The AE33 monitors the light attenuation of seven wavelengths (\(\lambda = 370, 470, 525, 590, 660, 880, \text{ and } 940 \text{ nm}\)), and the light attenuation at \(\lambda = 880 \text{ nm}\) was used to calculate BC concentration (Wang et al., 2019; Drinovec et al., 2015). Briefly, the ambient air was first sampled on a filter tape inside the instrument through a PM\textsubscript{2.5} cyclone (SCC-1.829, BGI Inc., USA) at a flowrate of 5 L min\textsuperscript{-1}. The entering particles were divided into two sample spots on the filter through two channels with different follows. Then the light
attenuation transmitted through two parallel spots was detected. For quality accuracies of monitoring, the sampled particles were desiccated with a Nafion® dryer (MD-700-24F-3; Perma Pure, Inc., Lakewood, NJ, USA) before entering the AE33. Furthermore, a real-time loading effect compensation algorithm based on two spots measurement was used to eliminate the nonlinear loading effects of the Aethalometer. A detailed description of the Model AE33 principle can be found in Drinovec et al. (2015).

### 2.2.3 Elements

Twenty-four elements, including Si, K, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Ag, Cd, Sn, Ba, Au, Hg, Th, Pb, and Pd in PM$_{2.5}$, were analyzed by a Xact625 Ambient Metals Monitor (Cooper Environmental Services, Tigard, Oregon, USA) with a 1-hour time resolution. Si, K, Ca, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Ba, and Pb were selected for further analysis in Xi’an and Beijing, while other elements were excluded due to most of their concentration below the method detection limit. In Shijiazhuang, S, Cl, and Ti were analyzed by replacement of Ga, Ag and Au, respectively. Finally, Si, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Ba, and Pb were selected for further analysis. The description and detection principles of Xact625 were introduced by Furger et al. (2020) and Rai et al. (2020). In brief, the ambient air stream was firstly sampled on a Teflon filter tape inside the instrument through a PM$_{2.5}$ cyclone inlet at a constant flow rate of 16.7 L min$^{-1}$, and then the sample was automatically analyzed by nondestructive energy-dispersive X-ray fluorescence (XRF) to determine the mass of the species. For quality control and assurance, the Xact625 performed automatic internal quality control by testing the Pd rod every hour to ensure the stability of the instrument. Energy calibration was performed daily from 00:00 to 00:15 and a range calibration from 00:15 to 00:30 local standard time (LST) to monitor any possible shift and instability of the XRF (Liu et al., 2019). During our sampling periods, the concentration of Pd varies within 3 standard deviations (Fig. S3), illustrating the reliable and stable performance of the Xact625.

### 2.2.4 Complementary data

Online hourly concentrations of PM$_{2.5}$ and gas pollutants (i.e., NO$_x$, NO$_{2}$, CO, SO$_2$, and O$_3$) were acquired from the National Air Quality Monitoring Station (https://air.cnemc.cn:18007/). Meteorological parameters, including wind speed (WS), wind direction (WD), relative humidity (RH), and temperature (T) were obtained from National Meteorological Station (http://data.cma.cn/). The detailed information for complementary data was listed in Table S1.

### 2.3 Data analysis
2.3.1 PM$_{2.5}$ mass reconstruction

Chemical closure was utilized to assess whether chemical compositions can be representative of PM$_{2.5}$. The sum of OA, NO$_3^-$, SO$_4^{2-}$, NH$_4^+$, Cl$^-$, BC, mineral dust (MD), and trace elements (TE) was considered as the reconstructed PM$_{2.5}$, where MD and TE were calculated as follows (Chow et al., 2015).

\[
\text{[MD]} = 2.20 \times [\text{Al}] + 2.49 \times [\text{Si}] + 1.63 \times [\text{Ca}] + 2.42 \times [\text{Fe}] + 1.94 \times [\text{Ti}]
\]

\[
\text{[TE]} = [\text{K}] + [\text{Cr}] + [\text{Mn}] + [\text{Ni}] + [\text{Cu}] + [\text{Zn}] + [\text{As}] + [\text{Se}] + [\text{Ba}] + [\text{Pb}]
\]

where [ ] represents the chemical species concentration; [Al] and [Ti] were calculated by the concentration of Ca ([Al] = 4.3 × [Ca] and [Ti] = 0.25 × [Ca]) (Wei et al., 1991). Good correlations between online and reconstructed PM$_{2.5}$ mass (slope = 0.87–1.10, $R^2 = 0.82$–0.93) in three pilot cities (Fig. S4) indicated that our measurements could detect major components of PM$_{2.5}$. The PM$_{2.5}$ concentration used in the following discussion referred to the reconstructed PM$_{2.5}$ concentration.

2.3.2 Hybrid environment receptor model

Source apportionment of PM$_{2.5}$ was analyzed with a bilinear model named the hybrid environment receptor model (HERM). HERM is developed by the IEECAS and the University of Nevada, Las Vegas (Chen and Cao, 2018). Like other receptor models, the speciation of pollutants at a receptor site can be separated into emission sources and the chemical compositions of the sources. To solve the mass balance of PM$_{2.5}$, the bilinear HERM in matrix notation is defined as follows

\[
C_{mn} = \sum_{i=1}^{I} F_{mi} G_{in} + Q_{mn}
\]

where $C_{mn}$ is the measured concentration of chemical species $m$ during time $n$; $F_{mi}$ is the source profile, that is the fractional quantity of species $m$ in source $i$ emission; $G_{in}$ represents the contribution of source $i$ during time $n$; and $Q_{mn}$ is the model residual for species $m$ concentration measured during time $n$. Based on an iterative conjugate gradient algorithm, the HERM solves $G_{in}$ and unknown $F_{mi}$ by minimizing the $Q_{mn}$, which is defined as follows.

\[
Q_{mn} = \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{(C_{mn} - \sum_{i=1}^{I} F_{mi} G_{in})^2}{\sigma_{mn}^2 + \sum_{i=1}^{I} (\sigma_{mi}^2 G_{in}^2 + \delta_{mi}^2 C_{mn}^2)}
\]

where $M$, $N$, and $I$ are the number of samples, chemical species, and sources, respectively; $\sigma_{mi}$ represents the error in the variability in the constrained factor profile. $\delta_{mi}$ was set to 0 or 1 depending on whether the $i$th factor profile is constrained or unconstrained, respectively.

The HERM input data included the concentration and uncertainty data of chemical species. 19 chemical species in
Xi’an and Shijiazhuang and 20 chemical species in Beijing were selected for source apportionment, respectively. Details of selected chemical species and its uncertainty calculation was described in Text S1 in the Supplement. A range from two to ten factors solutions was investigated by HERM with completely unconstrained factor profiles to search for optimal solutions. The detailed diagnostics can be seen in Text S2 in the Supplement. A six-factor solution for Xi’an and Shijiazhuang and an eight-factor solution for Beijing were found to be the optimal solution based on multiple criteria including 1) variations in Q/Q_{exp} which can be used to choose the optimal number of resolved factors, 2) physical meaningfulness of distinct factor profiles and explained variation (EV) values of variables, 3) good correlations between sources contribution and external and internal tracers, and 4) agreement between the measured and modeled PM$_{2.5}$ mass. More detailed information on the final selected factor profiles and contributions is presented in Sect. 3.2.

### 2.3.3 Aerosol liquid water content

Aerosol liquid water content (ALWC) was calculated by ISORROPIA-II thermodynamic equilibrium model (http://isorropia.eas.gatech.edu/) based on data of PM$_{2.5}$ chemical species (including NO$_3^-$, SO$_4^{2-}$, NH$_4^+$, and Cl$^-$) and meteorological parameters including relative humidity (RH) and temperature (T), more model information can be found in Fountoukis and Nenes (2007). It should be noted that the ISORROPIA-II model does not consider the contribution of the organic, as inorganic aerosols are the most hygroscopic species and dominant contributor to ALWC (Huang et al., 2020).

### 3. Results and discussion

#### 3.1 Characteristics of PM$_{2.5}$ and its chemical components

Figure 1 illustrates the mass composition of PM$_{2.5}$ in three pilot cities during the sampling periods, and their concentrations levels are summarized in Table S4. The average PM$_{2.5}$ concentrations in Xi’an, Beijing, and Shijiazhuang were 77±47 μg m$^{-3}$, 64±57 μg m$^{-3}$, and 60±39 μg m$^{-3}$, respectively. It is noted that the average PM$_{2.5}$ concentrations in Xi’an, Beijing, and Shijiazhuang did not meet the second level of the NAAQS, indicating that it is necessary to establish more particular and efficient pollution reduction measures. As shown in Fig. 1, the chemical compositions of PM$_{2.5}$ were similar in Beijing and Shijiazhuang (Fig. 1b and c) which was mainly composed of OA (26.9–34.2%), followed by NO$_3^-$ (23.6–26.5%), SO$_4^{2-}$ (11.8–15.0%), NH$_4^+$ (11.8–14.8%), MD (7.4–10.1%), BC (2.9–6.5%), and Cl$^-$ (1.1–4.8%). However, in Xi’an, MD contributed in comparison more to PM$_{2.5}$ (17.3%), while SO$_4^{2-}$
had a smaller contribution (6.8%). This could be explained by more construction activities and MD transport from the Loess Plateau to Xi’an (Long et al., 2016; Yan et al., 2015). Meanwhile, the lowest sulfur oxidation ratio (SOR) was observed in Xi’an (0.18 ± 0.08, see Table S5), indicating weak efficiency of the second generation of SO₄²⁻. The sum of SO₄²⁻, NO₃⁻ and NH₄⁺ accounted for 39.0–53.0% of PM₂.₅ in three pilot cities, highlighting the importance of the secondary inorganic components in northern China. In addition, the fractions of BC, Cl⁻, and TE in PM₂.₅ were lower in Beijing than those in the other two cities, which can be explained by the stricter local control policies on solid fuels combustion and tightening the industrial emission standards in and near the capital city of China (Li et al., 2021a; Pang et al., 2021).

To have a better understanding of the impact of the chemical components, the mass fraction of each component was plotted as a function of the PM₂.₅ mass concentration (Fig. 2a–c). The two dominant components of PM₂.₅ were OA (25.7–38.0%) and MD (19.9–37.1%) while the PM₂.₅ concentrations were below 40 μg m⁻³. The faction of OA in PM₂.₅ was the highest in Shijiazhuang and Beijing, while MD contributed most to PM₂.₅ in Xi’an. This is potentially related to more emissions and higher backgrounds of local dust. With increasing increases of the PM₂.₅ mass concentration, the fractions of chemical components in Xi’an and Shijiazhuang changed notably. The factions of OA and NO₃⁻ increased the most and reached the peaks of 40.1% and 28.7%, respectively, when the PM₂.₅ concentration reached ~196 μg m⁻³ in Xi’an. On the contrary, NO₃⁻ and SO₄²⁻ were two dominant drivers of increasing PM₂.₅ concentrations in Shijiazhuang, showing peak contributions of 32.5% and 18.7%, respectively, when the PM₂.₅ concentration was over 100 μg m⁻³. Compared to Xi’an and Shijiazhuang, Beijing had relatively stable fractions of each chemical component with increasing PM₂.₅ concentrations. Particularly, the fractions of OA and NO₃⁻ contributed dominantly with averages of 33.3±3.0% and 25.3±2.5%, respectively, when the PM₂.₅ > 40 μg m⁻³.

### 3.2 Source apportionment of PM₂.₅

Six potential sources, including biomass burning, fugitive dust, industrial emission, coal combustion, vehicle emission, and secondary nitrate plus sulfate, secondary formation source, were resolved by the HERM analysis. In Beijing, secondary nitrate plus sulfate, secondary formation source was furtherly divided into secondary nitrate plus OA and secondary sulfate plus OA. A special pollution source of firework was separated due to the Chinese Spring Festival (from New Year’s Eve to January 3rd in the lunar calendar). Figures S6–S8 present the sources profiles and contributions in Xi’an, Shijiazhuang, and Beijing, respectively. Biomass burning features high Explained Variation (EV) for the two tracers Cl⁻ (33–58%) and K (30–44%) in the three cities (Ni et al., 2017; Zhao et al., 2021). The
fugitive dust is characterized by high EV values for Si (60–90%) and Ca (34–54%), which are the dominant chemical species in the fugitive dust profiles in northern China (Shen et al., 2016; Zhao et al., 2006). The fractions of industrial emission vary among the cities, showing high EV for Ni (55% and 87%) and Cr (25% and 70%) in Xi’an and Shijiazhuang, and high EV for Cr (26%), Mn (40%), and Pb (27%) in Beijing. Ni is possibly emitted from the semiconductor industry (Simka et al., 2005). Cr, Mn, and Pb could originate from the steel manufacturing and incinerator fly ash (Duan and Tan, 2013; Ledoux et al., 2017). Coal combustion is characterized by high EV values for As (38–75%), Se (40–50%), and Pb (31–57%). These elements are enriched in coals, which are reliable indicators of coal combustion (Tian et al., 2013; Xu et al., 2012). The vehicle non-exhaust emissions could be identified by the elements Ba, Cu, Ca, Fe, and Mn. Cu and Ba can be released from brake and tire wear of vehicles (Adachi and Tainosho, 2004; Thorpe and Harrison, 2008). Moreover, Fe and Mn could be emitted from the combustion of lubricating oil and fuel additives (Ålander et al., 2005; Lewis et al., 2003). Relatively high EV values for Ba (68%), Cu (36%), and Ca (35%) are seen in Xi’an, significantly high EV values of Mn (68%), Fe (65%), Cu (53%), and Ba (80%) are characterized in Shijiazhang and relatively high EV values of Fe (34%) and Cu (39%) are featured in Beijing, respectively. Moreover, moderate EV values for BC (18–27%) and OA (13–22%) are commonly regarded as contributions of vehicles engine exhaust, while the temporal variations of VE are well correlated with gaseous NO$_x$ or NO$_2$ in three cities ($R^2 = 0.45–0.78$), which is the good tracer of traffic-related emissions (Huang et al., 2017; Li et al., 2017b). The secondary sources resolved by HERM are different among the three cities. In Xi’an and Shijiazhuang, the source of secondary nitrate plus sulfate this factor are characterized by high EV values for SO$_4^{2-}$ (62–75%), NO$_3^-$ (55–53%), NH$_4^+$ (60–56%) and a medium EV value for OA (23–29%), which showed good correlations with SO$_4^{2-}$ ($R^2 = 0.85–0.90$) and NO$_3^-$ ($R^2 = 0.85–0.92$) (Dai et al., 2020; Tian et al., 2022). In addition, the OA concentration in this factor was calculated by EV value of OA, which was close to the secondary OA (SOA) concentration estimated by BC-trace method (see Text S3 and Table S6). This means that SOA was mixed in this factor, therefore, this factor was identified as secondary formation source. In Beijing, two secondary sources were resolved. The first one was characterized by high EV value for NO$_3^-$ (58%), NH$_4^+$ (42%) and medium values for OA (21%), another one was characterized by high EV value for SO$_4^{2-}$ (58%), and medium values for OA (16%), NH$_4^+$ (30%). The OA concentration in those two factors was also comparable to that estimated by BC-trace method (see Text S3). So, those two sources were identified as secondary nitrate plus OA and secondary sulfate plus OA, the secondary sources of nitrate and sulfate show high EV values of 58% and 65%, respectively. The combination of secondary nitrate plus OA and secondary sulfate plus OA secondary nitrate and secondary sulfate is equivalent to the secondary nitrate plus sulfate secondary formation source for next discussion. Additionally, the source of firework
emission is characterized by high EV values of Ba (83%), Cu (45%), and K (38%), which are recognized as common indication in fireworks (Rai et al., 2020; Tian et al., 2014).

The modeled PM$_{2.5}$ mass was well correlated with the reconstructed PM$_{2.5}$ mass ($R^2 = 0.99$, slope = 0.90–1.01, Fig. S9S10) in three pilot cities, indicating the established models are reasonable. As shown in Fig. 1d and e, the contributions of primary sources (i.e., the sum of biomass burning, fugitive dust, industrial emission, coal combustion, and vehicle emission) in PM$_{2.5}$ were significantly higher than those of the source of secondary nitrate plus sulfate secondary formation source in Xi’an and Shijiazhuang, indicating the PM$_{2.5}$ in these two cities are mainly influenced by the primary source emissions during wintertime. Particularly, biomass burning and coal combustion were two dominant contributors to PM$_{2.5}$ with contributions of 24.6% and 15.1%, respectively, in Xi’an; and 24.4% and 16.0%, respectively, in Shijiazhuang. These suggest that controls of solid fuel combustion are critical to reducing PM$_{2.5}$ pollution in these cities. In contrast, the contribution of secondary nitrate plus sulfate secondary formation source to PM$_{2.5}$ in Beijing was highly dominant (> 50%), potentially attributed to strict control of primary emissions under the execution of a series of pollution control policies (Lv et al., 2016; Pang et al., 2021), and more regional transportation of secondary pollutants (Liu et al., 2019; Wang and Zhao, 2018). Among the primary sources, the contributions of biomass burning and vehicle emission were only 18.4% and 11.3%, respectively, further reflecting the benefits of reductions of all primary emissions. Due to the Chinese Spring Festival, the contribution of firework (7.9%) to PM$_{2.5}$ ranked second in primary sources (Fig. S10S11). Which indicates more refined control schemes need to be encouraged to deal with such special event in the future. It should be noted that contribution of fugitive dust was all lower than fraction of mineral dust in the three pilot cities (Fig. 1). This is because fugitive dust defined here mainly refers road and construction dust emission. While mineral dust represents material assumed oxides of mineral elements such as Al, Si, Ca, Ti and Fe (Chow et al., 2015). These mineral elements in PM$_{2.5}$ comes from more emission sectors including industry, crust, and transportation, construction, combustion (Liu et al., 2018a; Lu et al., 2014; Pant and Harrison, 2013; Shen et al., 2016).

Figures 2d–f shows variations of source contribution with increases in PM$_{2.5}$ mass concentrations in three pilot cities. The most two dominant sources were secondary nitrate plus sulfate secondary formation source (32.1%) and fugitive dust (31.4%) in Xi’an, coal combustion (24.9%) and vehicle emission (21.3%) in Shijiazhuang, and secondary nitrate plus sulfate secondary formation source (24.3%) and fugitive dust (23.8%) in Beijing, when the PM$_{2.5}$ mass concentration <40 µg m$^{-3}$. In Xi’an, when the PM$_{2.5}$ mass concentrations exceeded 180 µg m$^{-3}$, the contribution of
biomass burning raised mostly and reached the peak of 38.4%, demonstrating that biomass burning plays an important role in worsening of air quality in Xi’an. On the contrary, the contributions of secondary nitrate plus sulfate secondary formation source increased mostly in comparison to other sources in Shijiazhuang and Beijing, indicating the PM$_{2.5}$ pollution was mainly dominated by the secondary aerosol formations during the wintertime. And the peak contributions of secondary nitrate and sulfate were 66.5% and 74.7% while the PM$_{2.5}$ mass concentration increased to 113 µg m$^{-3}$ and 223 µg m$^{-3}$ in Shijiazhuang and Beijing, respectively.

3.3 Formation of secondary aerosols

Using the high-time-resolution data, we further explored the possible formation mechanisms of secondary nitrate plus sulfate secondary formation source. The concentration of secondary nitrate plus sulfate secondary formation source is standardized by dividing background corrected CO ($\Delta$CO) to weaken impact of planetary boundary layer height (PBLH) (DeCarlo et al., 2010). In this study, $\Delta$CO is defined as the 1.25$^{th}$ percentile of CO concentration during the campaign, which are 0.17, 0.15, and 0.16 ppm in Xi’an, Shijiazhuang, and Beijing, respectively. O$_3$ (NO$_2$ + O$_3$) is an indicator of the photochemical oxidation degree (Wood et al., 2010). The function between secondary nitrate plus sulfate secondary formation source/$\Delta$CO ratio and O$_3$ during the daytime (i.e., 08:00-17:00 LST) (Fig. S1a) was plotted to explain the effect of photochemical oxidations in three pilot cities. As shown in Fig. 3, good linear correlations of secondary nitrate plus sulfate secondary formation source/$\Delta$CO and O$_3$ ($R^2 = 0.83$-$0.99$) suggest that photochemical oxidations play an important role in the formation of secondary aerosol during the daytime.

Compared to the low-level O$_3$, formation of secondary aerosol significantly enhanced at high-level O$_3$ (>50 ppb) in Xi’an and Beijing, characterized by larger slopes of 17.2 and 38.9, respectively (Fig. 3a and c). Furthermore, the highest atmospheric oxidation capacity was found in Beijing, inferring by the highest fraction of O$_3$ to O$_3$. This is consistent with the highest contribution of secondary nitrate plus sulfate secondary formation source to PM$_{2.5}$ in Beijing during the daytime (Fig. S1a–c).

The aqueous-phase reaction is another important pathway for secondary aerosol formation in the atmosphere (Wang et al., 2018; Xue et al., 2014). ALWC is considered an indicator of an aqueous-phase reaction (Ervens et al., 2011). Considering that the aqueous-phase reaction occurs both during the daytime and nighttime characterized by good correlations between secondary formation source/$\Delta$CO and ALWC ($R^2 = 0.81$-$0.98$, Fig. S14). The correlations of secondary nitrate plus sulfate secondary formation source/$\Delta$CO ratio and ALWC during nighttime—all sampling periods (18:00-07:00 the next day LST, Fig. S11) were established in three pilot cities to assess the implications
of aqueous-phase chemistry for secondary aerosol production. As shown in Fig. 4, the secondary formation source nitrate plus sulfate/ΔCO showed a significant linear correlation to ALWC (R² = 0.8192, 0.9599) when RH < 80% (Fig. 4), indicating an obvious effect of aqueous-phase reaction on the secondary aerosol formation during the nighttime sampling periods. However, when RH > 80%, the secondary formation source nitrate plus sulfate/ΔCO showed no notable increase with ALWC in Shijiazhuang (Fig. 4b), whereas a tiny increase with ALWC in Beijing (Fig. 4c). The higher ALWC at RH > 80% probably inhibits secondary aerosol formation due to the decrease in aerosol acidity (Huang et al., 2019; Meng et al., 2014). Khan et al. (2008) found that NO₃ radicals can rapidly generate from the reaction between NO₂ and O₃ with unsaturated organic species during nighttime. The value of O₃ × NO₂ can thus represent its production reaction rate or be used as a proxy for the NO₃ radical. The highest NO₃ radical production rate was found in Beijing, followed by Xi’an and Shijiazhuang, when RH < 80%. This could be used to explain the highest contribution of secondary formation source nitrate plus sulfate to PM$_{2.5}$ in Beijing during the daytime and nighttime (Fig. S123d-i). Moreover, the results showed that both photochemical oxidation and aqueous-phase reaction play more important roles in Beijing, where the primary sources have been better controlled. This reflects that pollution control policies need to be focused on the suppression of secondary formations.

### 3.4 Elaborations of different episode cases

During the sampling periods, the concentration of PM$_{2.5}$ and its chemical components simply accumulated within a short period in a few cases (Fig. S14aS15a-c). We define such a rapid rise in PM$_{2.5}$ mass concentration as a pollution episode. As shown in Table 1, meteorological conditions, the concentration levels of gaseous pollutants, chemical compositions, and source contributions of PM$_{2.5}$ during pollution episodes in three pilot cities are summarized. The episodes were accompanied by low wind speed (<2 m s⁻¹), leading to weak dispersions of the fresh emissions and accumulated pollutants (Chen et al., 2020b). OA and NO₃ were the two dominant chemical components in PM$_{2.5}$ during all pollution episode cases with fractions of 26–40% and 23–32%, respectively. Their high abundances could be explained by the significant reduction of SO₂ emissions by because of the prohibiting of burning bulk coals and executing the “Coal-to-Natural Gas” policy in recent years (Meng et al., 2022). In this study, eight pollution episodes (donated as EP1-EP8) were classified into three types: The first type was dominated by biomass burning (30–40%) (EP1, EP4, and EP8). The second type was dominated by secondary nitrate plus sulfate secondary formation source (61–70%) (EP5, EP6, and EP7). The two remaining pollution episodes were mutually contributed by both primary and secondary sources (EP2 and EP3), in which secondary nitrate plus sulfate secondary formation source (34–39%) and biomass burning (23–24%) were the two dominant contributors to PM$_{2.5}$.
To profoundly understand gain insights into the progress-process of pollution episodes, three typical pollution events were chosen for detailed discussion (i.e., EP2 in Xi’an, EP4 in Shijiazhuang, and EP7 in Beijing) based on the validity and integrity of the data and the representativeness of the selected pollution events. The two-stage evolution was distinguished for EP4 as an example of the first type of episode (Fig. S16). For the first type of episode represented by EP4 (Fig. S14), a two-stages evolution was distinguished. At Stage 1, the PM$_{2.5}$ mass concentrations rapidly increased from 7 to 82 μg m$^{-3}$ under stable weather conditions inferring by low wind speed (1.8±0.8 m s$^{-1}$, Fig. S14b-S16b), in which the concentrations (fractions) of biomass burning increased from 0.6 μg m$^{-3}$ (7%) to 36.7 μg m$^{-3}$ (55%) due to heating demand-activities during nighttime. Meanwhile, the chemical composition was relatively stable and dominated by OA (31±5%) and NO$_3$ (21±5%). At Stage 2, the PM$_{2.5}$ mass concentration continuously increased to 105 μg m$^{-3}$ in a few hours along with the most notable abundance of the source of secondary-nitrate plus sulfate-secondary formation source, which concentration (contribution) rapidly increased from 2.3 μg m$^{-3}$ (4%) to 54.4 μg m$^{-3}$ (52%) (Fig. S14g-S16g and h). This is due to the aqueous-phase reactions effect inferring by the rapid increase in ALWC (from 16 μg m$^{-3}$ to 78 μg m$^{-3}$, Fig. S14e-S16c) and RH (from 51% to 79%, Fig. S14a-S16a).

In contrast, a three-stage evolution was discriminated for the second type of episode, using EP7 as an example (Fig. S15-S17). At Stage 1, the PM$_{2.5}$ concentration gradually increased from 11 to 30 μg m$^{-3}$, as well as NO$_2$ (from 15 to 59 μg m$^{-3}$, Fig. S15a-S17d) due to the boosts of the predominant contributions of vehicle emission and biomass burning (Fig. S15g-S17g and h). In the meantime, the contribution of coal combustion also slowly increased along with SO$_2$ (Fig. S15d-S17d and h). At Stage 2, under the lowest average wind speed in the study period (0.7±0.4 m s$^{-1}$, Fig. S15b-S17b), the PM$_{2.5}$ mass concentrations moderately increased from 30 to 91 μg m$^{-3}$ with relatively stable chemical composition and source contribution (Fig. S15f-S17f and h). Compared to Stage 1, the fractions of NO$_3$ increased mostly from 9±3% to 23±3%, this is probably influenced by photochemical oxidations inferring by relative high O$_3$ and NO$_2$ concentration (Fig. S15e-S17c and d). At Stage 3, the PM$_{2.5}$ mass concentration rapidly rose to 142 μg m$^{-3}$ and then remained stable. Furthermore, the in which greatest increase of sources the concentrations (fractions contribution) of was secondary nitrate plus sulfate-secondary formation source increased mostly from 18.9 μg m$^{-3}$ (48%) to 120.6 μg m$^{-3}$ (80%). This might be due to the occurrence of an aqueous-phase reaction, which was indicated by the elevation of RH and ALWC (Fig. S15a-S17a and c).

Figure S16 illustrates the third type of episode using EP2 as an example, while in which a four-stages evolution was resolved. At Stage 1, the PM$_{2.5}$ mass concentration (14±3 μg m$^{-3}$) was relatively low and dominated by the
contribution of secondary nitrate plus sulfate (43±17%) and fugitive dust (24±8%), as well as MD (28±7%) and OA (26±7%). At Stage 2, the PM$_{2.5}$ mass concentrations promptly increased from 21 to 82 μg m$^{-3}$, with the two dominant chemical components of OA (21.7 μg m$^{-3}$) and NO$_3$ (17.1 μg m$^{-3}$). The PM$_{2.5}$ increases can be also attributed to the raise of secondary nitrate plus sulfate (25.3 μg m$^{-3}$) and biomass burning (14.4 μg m$^{-3}$). The PM$_{2.5}$ increases can also be contributed to the raise of secondary nitrate plus sulfate (25.3 μg m$^{-3}$) and biomass burning (14.4 μg m$^{-3}$). The enhancement of secondary aerosol was probably generated through the aqueous-phase reaction evidenced by the increase of ALWC and NO$_2$ (Fig. S16-S18). At Stage 3, the PM$_{2.5}$ mass continuously increased to 139 μg m$^{-3}$ with a dominant increase of primary sources emission including biomass burning (29.0 μg m$^{-3}$), vehicle emission (21.5 μg m$^{-3}$) and coal combustion (16.5 μg m$^{-3}$) along with the increases of SO$_2$ and NO$_2$ as well (Fig. S16-S18). The three primary sources contributed >60% of the total resolved sources. Meanwhile, the secondary nitrate plus sulfate (25.3 μg m$^{-3}$) also increased slowly through aqueous-phase reaction inferring by increase of ALWC (Fig. S16-S18c). At the final Stage 4, the PM$_{2.5}$ mass concentration maintained relatively stable with an average of 142±11 μg m$^{-3}$, dominated by sources of secondary nitrate plus sulfate (34±6%) and biomass burning (28±6%); and chemical components of OA (36±4%) and NO$_3$ (25±1%).

In summary, the pollution events occurred in Xi’an mainly derived by stronger emissions of primary sources under adverse meteorological conditions, even though the aqueous-phase reaction also contribute to secondary aerosol formation. In contrast, pollution events occurred in Shijiazhuang and Beijing were mainly influenced by formation of secondary aerosols through both of aqueous-phase reaction and photochemical oxidation. What’s more, in which aqueous-phase reaction plays a more important role than photochemical oxidation. Hence, to further improve the air quality in the north of China, primary source emissions should be prioritized for control in the northwest region, with a focus on biomass burning and coal combustion. In the North China Plain, the priority should be given to reducing emissions of the precursors from secondary sources, with a focus on NO$_x$ and volatile organic compounds (VOCs).

### 3.5 Policy implications

In past decades, the air quality in China improved notably under the implementation of air pollution control policies including APCAP and TAPFAP. The PM$_{2.5}$ mass in Xi’an, Shijiazhuang and Beijing were the lowest during campaigns compared with those in last decades (Table S6). The variations of the chemical composition and the source contribution of PM$_{2.5}$ in the three pilot cities are displayed in Fig. 5. As shown, the dominant chemical components
of PM$_{2.5}$ changed from OA and SO$_4^{2-}$ to OA and NO$_3^-$ (Fig. 5a–c). This could be attributed to the reduction in coal consumption due to clean energy replacement and the increase of vehicle ownership, which lead a decrease of the SO$_2$ and an increase of NO$_2$ (Wang et al., 2013). Since the atmospheric oxidation reaction (i.e., aqueous-phase reaction and photochemical oxidation) of the precursors (i.e., NO$_2$, VOCs) is the primary source for the OA and NO$_3^-$ in the atmosphere (Feng et al., 2018; Li et al., 2022; Tao et al., 2016; Yang et al., 2022b; Ziemann and Atkinson, 2012), and it is impossible to avoid, thus, the precursors of OA and NO$_3^-$ should be reduced from the combustion and transportation sectors (Fermo et al., 2021; Liu et al., 2022; Wang et al., 2021c; Zhang et al., 2019). In addition, the fraction of NH$_4^+$ in PM$_{2.5}$ increased with an alarming rate. This is coincidentally in a similar trend of NH$_3$. Studies have reported that controls of NH$_4^+$ is more effective than that of NO$_x$ in the reduction of PM$_{2.5}$ mass concentrations (Gu et al., 2021; Zheng et al., 2022). Therefore, collaborative control measures for the emissions of precursors including NO$_x$, VOCs, and NH$_3$ are necessary.

As shown Table S7–S8 and Fig. 5d-f, coal combustion decreased remarkably due to the coal-related policies implementation including the strength of emissions standards for coal-fired power plants, the change of energy sources from coal to natural gas in some industries, and the coal burning was forbidden in the main urban areas (Shen, 2016; Yang and Teng, 2018). The similar trend was also found in the results of PM$_{2.5}$ source apportionment in Beijing released by Beijing Municipal Ecology and Environment Bureau (Fig. S19). Meanwhile, the contribution of industrial emission and vehicle emission decreased slightly because of the improvement of industrial emission standards (He et al., 2020; Wang et al., 2020a) and the traffic-related policy implementation such as the strength of vehicle emission standards, improvement of fuel quality, and elimination of high-emission-vehicles. This resulted in the reduction of the precursor gases and PM$_{2.5}$ from vehicles (Feng et al., 2021; Fontaras et al., 2012; Jin et al., 2012). However, the emission of biomass burning did not show a significant reduction in recent years, and its contribution increased from 9% in 2014 to 25% in 2020 (Xi’an), from 3% in 2015 to 24% in 2022 (Shijiazhuang), and from 6% in 2013 to 18% in 2021 (Beijing) (Fig. 5d-f). This is likely because biomass burning is an open source, which makes it more difficult to control compare with other primary sources. Biomass used for residential heating in rural areas is still frequently occurred (Ren, 2021; Tian et al., 2022; Yang et al., 2022a; Zhang et al., 2017). Hence, the clean energy revolution should be promoted urgently especially in the entire regions in northwest China. Moreover, the contributions of secondary formation sources increased, it is potentially explained by the high reduction rate of primary emissions and the improvement of atmospheric oxidation capacity (Chen et al., 2020a; Feng et al., 2020). Therefore, more control measures should focus on weakening the atmospheric oxidation capacity, such as...
as reduction of O$_3$ formation, to reduce the formation of secondary pollutants which are now identified as the most critical drivers of pollution. Considering those factors, it is also important to promote the mitigation of both PM$_{2.5}$ and O$_3$.

4. Conclusion

The intensive real-time measurement campaigns about PM$_{2.5}$ chemical components were conducted in Xi’an, Shijiazhuang, and Beijing during the wintertime respectively. Chemical compositions of PM$_{2.5}$ in the three cities were all dominated by OA (26.9–34.2%) and NO$_3^-$ (23.6–26.5%). Six sources of PM$_{2.5}$ in Xi’an and Shijiazhuang were resolved by HERM and their contributions were similar, with a descending order of secondary nitrate plus sulfate secondary formation source (32.2–37.6%), biomass burning (24.4–24.6 %), coal combustion (15.1–16.0%), vehicle emission (12.2–12.5 %), industrial emission (5.5–7.7%) and fugitive dust (4.4–7.8%). However, the secondary nitrate (29.0%) and the secondary sulfate (23.0%) were separately resolved and relatively more important in Beijing. In addition, the contribution of firework (7.9%) to PM$_{2.5}$ was found during the Chinese Spring Festival.

The possible formation mechanism of secondary nitrate plus sulfate secondary formation source in three pilot cities was explored. The results showed that secondary aerosols were generated by both photochemical oxidation and aqueous-phase reaction. Meanwhile, the formation rate of secondary aerosols in Beijing was higher than that in Xi’an and Shijiazhuang. Furthermore, the eight pollution episodes within the sampling periods were categorized three types and characterized respectively. The dominant chemical compositions of PM$_{2.5}$ were OA (26–40%) and NO$_3^-$ (23–32%) during all pollution episodes. Furthermore, secondary nitrate plus sulfate secondary formation source and biomass burning were two major derivers of the pollution.

The dominant chemical components of PM$_{2.5}$ in pilot cities have changed from OA and SO$_4^{2-}$ to OA and NO$_3^-$ under the implementation of a clean air plan in past decades. This indicates that reduction of precursors including NO$_2$ and VOCs should be a key task in the future. In addition, the contribution of biomass burning increased, especially in Xi’an. This indicates that clean energy for heating activities in rural areas in northwest China is still insufficient. Furthermore, to weaken the atmospheric oxidation capacity for reducing the contribution of secondary nitrate plus sulfate secondary formation source, it is necessary to promote the collaborative control on ozone and particulate matter.

Data availability. Data used to support the findings in this study are archived at the Institute of Earth Environment,
Competing interest. The authors declare that they have no conflict of interest.

Author contributions. QW, YH, JC designed the campaigns. WR and YZ conducted the field measurements. YZ, JT, HL, LQ and TC performed data analysis and interpretation. MM, KRD, JGS and ASHP were involved supervision and review. YZ wrote the paper with contributions from all co-authors.

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Wang, Y., Yuan, Y., Wang, Q., Liu, C., Zhi, Q., and Cao, J.: Changes in air quality related to the control of coronavirus...


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Table 1. Meteorological conditions, gas pollutants, chemical composition, and source contribution of PM$_{2.5}$ during pollution episodes in Xi’an, Shijiazhuang, and Beijing

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Xi’an</th>
<th>Shijiazhuang</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (°C)</td>
<td>4.9 ± 2.6</td>
<td>1.5 ± 3.5</td>
<td>0.4 ± 3.4</td>
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<tr>
<td>RH (%)</td>
<td>52 ± 10</td>
<td>45 ± 10</td>
<td>61 ± 15</td>
</tr>
<tr>
<td>WS (m s$^{-1}$)</td>
<td>0.5 ± 0.2</td>
<td>0.7 ± 0.3</td>
<td>1.4 ± 0.6</td>
</tr>
<tr>
<td>Dominant WD$^a$</td>
<td>WSW</td>
<td>WSW</td>
<td>NNW</td>
</tr>
<tr>
<td>CO (mg m$^{-3}$)</td>
<td>1.39 ± 0.40</td>
<td>1.15 ± 0.56</td>
<td>1.47 ± 0.62</td>
</tr>
<tr>
<td>SO$_2$ (μg m$^{-3}$)</td>
<td>15 ± 3</td>
<td>15 ± 5</td>
<td>9 ± 4</td>
</tr>
<tr>
<td>NO$_2$ (μg m$^{-3}$)</td>
<td>74 ± 22</td>
<td>63 ± 32</td>
<td>63 ± 14</td>
</tr>
<tr>
<td>O$_3$ (ppm)</td>
<td>47 ± 8</td>
<td>42 ± 10</td>
<td>36 ± 7</td>
</tr>
<tr>
<td>ALWC (μg m$^{-3}$)</td>
<td>15 ± 11</td>
<td>8 ± 8</td>
<td>42 ± 37</td>
</tr>
<tr>
<td>Dominant Chemical source contribution$^b$</td>
<td>BB (30%)</td>
<td>SF (34%)</td>
<td>NO$_x$ (27%)</td>
</tr>
<tr>
<td></td>
<td>SF (25%)</td>
<td>BB (24%)</td>
<td>OA (26%)</td>
</tr>
<tr>
<td></td>
<td>BB (23%)</td>
<td>CC (16%)</td>
<td>BB (16%)</td>
</tr>
<tr>
<td></td>
<td>CC (17%)</td>
<td>VE (16%)</td>
<td>CC (16%)</td>
</tr>
</tbody>
</table>

$^a$ WSW: west-southwest; WNW: west-northwest; NNW: north-northwest; NNE: north-northeast; ENE: East-northeast

$^b$ BB: biomass burning; SF: secondary nitrate; SF: secondary sulfate; CC: coal combustion; VE: vehicle emission
Figure captions:

**Figure 1.** Chemical composition and source apportionment results of PM$_{2.5}$ in three pilot cities of northern China during the sampling period.

**Figure 2.** Mass fractions of chemical components (a-c) and sources contribution (d-f) with reconstructed PM$_{2.5}$ concentration in Xi’an, Shijiazhuang, and Beijing.

**Figure 3.** Correlations of secondary nitrate plus sulfate/ΔCO and O$_x$ mixing ratio in (a) Xi’an, (b) Shijiazhuang, and (c) Beijing. Each point and its error bar represent the mean and standard deviation in each bin (ΔO$_x$ = 5 ppb).

**Figure 4.** Correlation of secondary nitrate plus sulfate/ΔCO and ALWC during winter sampling periods in (a) Xi’an, (b) Shijiazhuang, and (c) Beijing, respectively. The points and error bar represent the mean values and standard deviation values of secondary nitrate plus sulfate/ΔCO and ALWC in each bin. In Xi’an, each bin is 5 μg m$^{-3}$ (ΔALWC = 5 μg m$^{-3}$). In Shijiazhuang, each bin is 5 μg m$^{-3}$ (ΔALWC = 5 μg m$^{-3}$) when ALWC ranged from 0 to 75 μg m$^{-3}$, but 25 μg m$^{-3}$ (ΔALWC = 25 μg m$^{-3}$) for ALWC ranged from 75 to 200 μg m$^{-3}$ due to limitations in data. In Beijing, each bin is 5 μg m$^{-3}$ (ΔALWC = 5 μg m$^{-3}$) when ALWC ranged from 0 to 50 μg m$^{-3}$, but 100 μg m$^{-3}$ (ΔALWC = 100 μg m$^{-3}$) for ALWC ranged from 50 to 900 μg m$^{-3}$ due to limitations in data.

**Figure 5.** Summary of PM$_{2.5}$ and its composition (a, b, c) and source contribution (d, e, f) in Xi’an, Shijiazhuang, and Beijing in winter in past decades. Where * represents the result of this study. The data and references used for this figure are listed in Table S5 and S7.
Figure 1. Chemical composition and source apportionment results of PM$_{2.5}$ in three pilot cities of northern China during the sampling period.
Figure 2. Mass fractions of chemical components (a-c) and sources contribution (d-f) with reconstructed PM$_{2.5}$ concentration in Xi'an, Shijiazhuang, and Beijing.
Figure 3. Correlations of secondary nitrate plus sulfate/ΔCO and O3 mixing ratio in (a) Xi'an, (b) Shijiazhuang, and (c) Beijing. Each point and its error bar represent the mean and standard deviation in each bin (ΔO3 = 5 ppb).
Figure 4. Correlation of secondary nitrate plus sulfate/ΔCO and ALWC during winter sampling periods in (a) Xi’an, (b) Shijiazhuang, and (c) Beijing, respectively. The points and error bar represent the mean values and standard deviation values of secondary nitrate plus sulfate/ΔCO and ALWC in each bin. In Xi’an, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³). In Shijiazhuang, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³) when ALWC ranged from 0 to 75 μg m⁻³, but 25 μg m⁻³ (ΔALWC = 25 μg m⁻³) for ALWC ranged from 75 to 200 μg m⁻³ due to limitations in data. In Beijing, each bin is 5 μg m⁻³ (ΔALWC = 5 μg m⁻³) when ALWC ranged from 0 to 50 μg m⁻³, but 100 μg m⁻³ (ΔALWC = 100 μg m⁻³) for ALWC ranged from 50 to 900 μg m⁻³ due to limitations in data.

(a) Xi’an

(b) Shijiazhuang

(c) Beijing
Figure 5. Summary of PM$_{2.5}$ and its composition (a, b, c) and source contribution (d, e, f) in Xi’an, Shijiazhuang, and Beijing in winter in past decades. Where * represents the result of this study, and the empty white area means no data. The data and references used for this figure are listed in Table S6-S7 and S7-S8.
Supplement of

High-time-resolution chemical composition and source apportionment of PM$_{2.5}$ in northern Chinese cities:

implications for policy

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Text S1. Selection of inputted HERM chemical species and its uncertainty calculation

Considering the validity and credibility of monitoring data, chemical species including OA, NO$_3^-$, SO$_4^{2-}$, NH$_4^+$, Cl$^-$, and BC were all selected to input HERM model for three pilot cities. For inorganic elements, Si, K, Ca, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Ba, and Pb in Xi’an and Beijing, and Si, K, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Ba, and Pb in Shijiazhuang were selected for source apportionment, respectively.

The uncertainty data of chemical species inputting HERM was calculated according to the recommendation in the PMF5.0 user guideline. If the measured chemical species concentration is greater than the minimum detection limit (MDL) provided, the uncertainty (Unc) calculation is based following equation:

$$Unc_i = \sqrt{(C_i \times E_i)^2 + (0.5 \times MDL_i)^2}$$  \hspace{1cm} (1)

where $C_i$ represents measured concentration for species $i$, $E_i$ represents error fraction of species $i$. For online measured data, the error fraction was recommended to use 10% (Rai et al., 2020). If the measured concentration is less than or equal to the MDL provided, the Unc is calculated as the following equation:

$$Unc = \frac{5}{6} \times MDL$$  \hspace{1cm} (2)

Text S2 Diagnostics of HERM solutions

In this study, factors numbering from two to ten were selected and run in the HERM software. Each factor solution was run thirty times with completely unconstrained profiles to explore the possible sources. The optimal factor number solution was determined by examining the ratio of $Q$ and expected $Q$ ($Q_{exp}$). The $Q_{exp}$ in HERM was equal to $(\text{samples} \times \text{species} - \text{factors} \times (\text{samples} + \text{species}) + \text{the number of constrained source profiles})$. As shown in Fig. S5, the value of $Q/Q_{exp}$ decreased with the increase of the factor number, which suggests increasing the factor number could lead to a better explanation of the variance by HERM. However, the utility of increasing factors declined with the number of factors. Too many factors could cause splitting profiles, although the $Q/Q_{exp}$ may be desirable (Liu et al., 2021; Salameh et al., 2018, 2016). Thus, the drops of $Q/Q_{exp}$ ($\Delta Q/Q_{exp}$) were subsequently evaluated to choose the optimal solution factor number. As shown in Table S2, when the number of factors increases to more than six in Xi’an, the value of $\Delta Q/Q_{exp}$ shows a relatively stable change trend. A six-factor solution is preferable because $\Delta Q/Q_{exp}$ between the five-solution and six-solution is smaller than that between the six-solution and seven-solution (Liu et al., 2021). In addition, secondary nitrate plus sulfate formation source and biomass burning were mixed when the factor number was five, and vehicle emission was split into two profiles when the factor number
was seven (Table S3). Therefore, the six-factor solution was determined as the optimal HERM solution for Xi’an. Similar criteria were used for Shijiazhuang and Beijing, six-factor and eight-factor solutions were determined as optimal HERM solutions, respectively.

**Text S3 Estimation of secondary organic aerosol (SOA).**

Due to lack of critical tracers of SOA, the sources of SOA cannot be individually resolved by receptor model. In this study, the secondary sources were mainly characterized by high EV values for inorganic aerosols such as $\text{SO}_4^{2-}$, $\text{NO}_3^-$, $\text{NH}_4^+$, but the medium EV values for OA (16~29%) were also presented on secondary sources in three pilot cities. This means that the SOA maybe mixed in with the factors of secondary sources. To verify this, the SOA concentrations we estimated by using a BC-tracer method (Wang et al., 2019) and then compared the results with those based on source apportionment. The SOA calculation by BC-tracer method was calculated as follow:

$$[\text{SOA}]_{\text{BC-tracer}} = [\text{OA}] - (\text{OA}/\text{BC})_{\text{pri}} \times [\text{BC}]$$ (S-1)

where [ ] means mass concentration, $(\text{OA}/\text{BC})_{\text{pri}}$ is the ratio of [OA] to [BC] in primary emission. The $(\text{OA}/\text{BC})_{\text{pri}}$ ratios vary among sources, therefore, a minimum $R^2$ method was used to derive appropriate $(\text{OA}/\text{BC})_{\text{pri}}$ values for three pilot cities. In previous studies (Srivastava et al., 2018; Wang et al., 2019), MRS method has been used to calculated the concetration of secondary organic carbon and brown carbon. More detailed information on the method and a validation of this approach can be found in Wang et al. (2019). In addition, according to results of receptor model, SOA concentration can also be estimated as follow based on EV values of OA from secondary source factors.

$$[\text{SOA}]_{\text{source apportionment}} = [\text{OA}] \times \text{EV}_{\text{OA}}$$ (S-2)

where EV$_{\text{OA}}$ represents the EV values of OA in secondary sources factors resolved by HERM model.

As shown in Fig. S9, the $(\text{OA}/\text{BC})_{\text{pri}}$ ratios were determined as 4.73 for Xi’an, 3.12 for Shijiazhuang and 7.6 for Beijing, respectively. Furthermore, the concentrations of SOA from three pilot cities were shown in Table R1 based two different methods. As we can see, the SOA concentrations estimated by EV values of OA are close to that by BC-tracer method for three pilot cities. This indicated SOA was mixed in secondary sources factors.
Figure S1. Annual average concentration of PM$_{2.5}$ from 2013 to 2021 in Xi’an, Shijiazhuang, and Beijing. (The data are from the website of the local Ecological Environment Bureau, Xi’an: [http://xaepb.xa.gov.cn/](http://xaepb.xa.gov.cn/), Shijiazhuang: [https://sthjj.sjz.gov.cn/](https://sthjj.sjz.gov.cn/), Beijing: [http://sthj.beijing.gov.cn/](http://sthj.beijing.gov.cn/)). The red dotted line represents the second level of the National Ambient Air Quality Standard (GB3095-2012, 35 $\mu$g m$^{-3}$).

Figure S2. Correction of chemical components measured by Q-ACSM in different cities. During the campaigns, offline filter samples were simultaneously sampled for the correction. In summary, 29 offline samples in Xi’an, 83 offline samples in Shijiazhuang, and 10 offline samples in Beijing were sampled respectively.
Figure S3. Concentration of the internal standard element (Pd) of Xact625 during sampling periods in (a) Xi’an, (b) Shijiazhuang, and (c) Beijing.

Figure S4. Correlation of online and reconstructed PM$_{2.5}$ concentration in (a) Xi’an, (b) Shijiazhuang, and (c) Beijing during the campaigns. The online PM$_{2.5}$ mass data in the X axis from national monitor stations near sampling sites.
Figure S5. Values of $Q/Q_{\text{exp}}$ for the unconstrained profile solutions with two to ten factors based on thirty runs in (a) Xi’an, (b) Shijiazhuang, and (c) Beijing, respectively.
Figure S6. (a) Sources profiles obtained from HERM with a six-factor solution in Xi’an, the columns in each factor are the profile that displays the relative relation of the absolute values of variables. The red dot represents the explained variation (EV) in species for different factors. (b) Time series plots of sources concentration, including biomass burning, fugitive dust, industrial emission, coal combustion, vehicle emission, and secondary nitrate-sulfate formation source. The corresponding time trends of chemical tracers are also shown.
Figure S7. (a) Sources profiles obtained from HERM with a six-factor solution in Shijiazhuang, the columns in each factor are the profile that displays the relative relation of the absolute values of variables. The red dot represents the explained variation (EV) in species for different factors. (b) Time series plots of sources concentration, including biomass burning, fugitive dust, industrial emission, coal combustion, vehicle emission, and secondary nitrate plus sulfate formation source. The corresponding time trends of chemical tracers are also shown.
<table>
<thead>
<tr>
<th>Chemical components</th>
<th>Date (dd/mm/yyyy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass burning</td>
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</tr>
<tr>
<td>Fugitive dust</td>
<td></td>
</tr>
<tr>
<td>Vehicle emission</td>
<td></td>
</tr>
<tr>
<td>Secondary nitrate</td>
<td></td>
</tr>
<tr>
<td>Industrial emission</td>
<td></td>
</tr>
<tr>
<td>Coal combustion</td>
<td></td>
</tr>
<tr>
<td>Secondary sulfate</td>
<td></td>
</tr>
<tr>
<td>Firework</td>
<td></td>
</tr>
</tbody>
</table>

- **Profile**
  - K $R^2 = 0.44$
  - Si $R^2 = 0.97$ Ca $R^2 = 0.83$
  - Mn $R^2 = 0.81$ Fe $R^2 = 0.34$
  - As $R^2 = 0.55$ Se $R^2 = 0.58$
  - NO$_2$ $R^2 = 0.45$
  - NO$_x$ $R^2 = 0.95$
  - SO$_2$ $R^2 = 0.87$
  - Cu $R^2 = 0.92$ Ba $R^2 = 0.99$
**Figure S8.** (a) Sources profiles obtained from HERM with an eight-factor solution in Beijing, the columns in each factor are the profile that displays the relative relation of the absolute values of variables. The red dot represents the explained variation (EV) in species for different factors. (b) Time series plots of sources concentration, including biomass burning, fugitive dust, industrial emission, coal combustion, vehicle emission, secondary nitrate plus OA, secondary sulfate plus OA, and firework. The corresponding time trends of chemical tracers are also shown.
Figure S9. Coefficients of determination ($R^2$) for SOA versus BC mass concentration plotted against assumed ratios for OA to BC in primary emissions ((OA/BC)$_\text{pri}$) in Xi’an, Shijiazhuang and Beijing.

Figure S9S10. Correlation between reconstructed PM$_{2.5}$ and modeled PM$_{2.5}$ mass concentrations derived by HERM in Xi’an, Shijiazhuang, and Beijing with optimal solutions.
**Figure S10S11.** Source contribution of PM$_{2.5}$ during Chinese Spring Festival (from New Year’s Eve to January 3$^{rd}$ of the Lunar Calendar) in Beijing
Secondary nitrate plus sulfate/∆CO (μg m⁻³ ppm⁻¹)

(a) Xi'an
(b) Shijiazhuang
(c) Beijing
**Figure S12.** Time series plots of secondary nitrate plus sulfate formation source/ΔCO in (a) Xi’an, (b) Shijiazhuang, and (c) Beijing. The red and black lines represent daytime (08:00-17:00 LST) and nighttime (18:00 - 07:00 the next day LST), respectively.

**Figure S12S13.** Source contribution of PM$_{2.5}$ in three pilot cities during daytime and nighttime, respectively.
Figure S14. Correlation of secondary formation source/ΔCO and ALWC during daytime (08:00–17:00 LST, a–c) and nighttime (18:00–7:00 the next day LST, d–f) in Xi’an, Shijiazhuang, and Beijing, respectively. The points and error bar represent the mean values and standard deviation values of secondary formation source/ΔCO and ALWC in each bin. In Xi’an, each bin is 5 μg m^{-3} (ΔALWC = 5 μg m^{-3}). In Shijiazhuang, each bin is 5 μg m^{-3} (ΔALWC = 5 μg m^{-3}) when ALWC ranged from 0 to 75 μg m^{-3}, but 25 μg m^{-3} (ΔALWC = 25 μg m^{-3}) for ALWC ranged from 75 to 200 μg m^{-3} due to limitations in data. In Beijing, during daytime, each bin is 5 μg m^{-3} (ΔALWC = 5 μg m^{-3}) when ALWC ranged from 0 to 40 μg m^{-3}, but 100 μg m^{-3} (ΔALWC = 100 μg m^{-3}) for ALWC ranged from 40 to 450 μg m^{-3} due to limitations in data. During nighttime, each bin is 5 μg m^{-3} (ΔALWC = 5 μg m^{-3}) when ALWC ranged from 0 to 50 μg m^{-3}, but 100 μg m^{-3} (ΔALWC = 100 μg m^{-3}) for ALWC ranged from 50 to 900 μg m^{-3} due to limitations in data.
Figure S43S15. The pollution episodes selection according to temporal variation of PM$_{2.5}$ chemical components (a-c) and source contribution (d-f) during the campaigns in Xi’an, Shijiazhuang, and Beijing, respectively. The gray shape parts were lack of MD values due to the out-of-order Xact625, and missing values in the time series owing to the out-of-order ACSM, AE33, and Xact625 at the same time.
Figure S14-6 Time series of T and RH (a), WS and WD (b), O₃ and ALWC (c), NO₂ and SO₂ (d), chemical components (e,f), and source contribution (g, h) of PM₂.₅ during EP4 in Shijiazhuang.
Figure S4S17. Time series of T and RH (a), WS and WD (b), O₃ and ALWC (c), NO₂ and SO₂ (d), chemical components (e, f), and source contribution (g, h) of PM₂.₅ during EP7 in Beijing.
Figure S16S18. Time series of T and RH (a), WS and WD (b), O$_x$ and ALWC (c), NO$_2$ and SO$_2$ (d), chemical components (e, f), and source contribution (g, h) of PM$_{2.5}$ during EP2 in Xi’an.
Figure S19. PM$_{2.5}$ sources apportionment in Beijing released by Beijing Municipal Ecology and Environment Bureau in the last decade (http://sthjj.beijing.gov.cn/so/s?tab=all&sourceCode=1100000122, in Chinese).
**Table S1.** Detailed information on complementary data for sampling sites

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>National Air Quality Monitoring Station</th>
<th>National Meteorological Station</th>
<th>Complementary data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xi’an</td>
<td>Gaoxinxiu station, 1.1km from the sampling site</td>
<td>Haidian station, 7.6 km from the sampling site</td>
<td>Hourly PM$_{2.5}$, NO$_2$, NO$_x$, CO, SO$_2$, O$_3$, WS, WD, T, RH</td>
</tr>
<tr>
<td>Shijiazhuang</td>
<td>Gaoxinqu station, 4.2 km from the sampling site</td>
<td>Shijiazhuang station, 23.8 km from the sampling site</td>
<td>Hourly PM$_{2.5}$, NO$_2$, CO, SO$_2$, O$_3$, WS, WD, T, RH</td>
</tr>
<tr>
<td>Beijing</td>
<td>ChaoyangAotizhongxin station, 1.2 km from the sampling site</td>
<td>Jinghe station, 21.2 km from the sampling site</td>
<td>Hourly PM$_{2.5}$, NO$_2$, CO, SO$_2$, O$_3$, WS, WD, T, RH</td>
</tr>
</tbody>
</table>


**Table S2.** The $\Delta Q/Q_{\text{exp}}$ value with increasing factor number from two to ten of the runs in Xi’an, Shijiazhuang, and Beijing.

<table>
<thead>
<tr>
<th>Parameter$^b$</th>
<th>Xi’an</th>
<th>Shijiazhuang</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>F2-F3</td>
<td>1.3</td>
<td>1.8</td>
<td>5.7</td>
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<tr>
<td>F3-F4</td>
<td>0.9</td>
<td>2.2</td>
<td>2.3</td>
</tr>
<tr>
<td>F4-F5</td>
<td>1.1</td>
<td>1.2</td>
<td>1.9</td>
</tr>
<tr>
<td>F5-F6</td>
<td>0.4</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>F6-F7</td>
<td>0.3</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>F7-F8</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>F8-F9</td>
<td>0.4</td>
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<td>0.4</td>
</tr>
<tr>
<td>F9-F10</td>
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</tr>
</tbody>
</table>

$^a$ $\Delta Q/Q_{\text{exp}}$ means the difference of $Q/Q_{\text{exp}}$ of two sequent factor numbers.

$^b$ Parameters represent the factor numbers (F) – (F+1).
### Table S3. Sources diagnostics with increasing factor numbers from four to ten of the runs in Xi’an, Shijiazhuang, and Beijing.

<table>
<thead>
<tr>
<th>Factor number</th>
<th>Xi'an</th>
<th>Shijiazhuang</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Secondary nitrate plus sulfate formation source mixed with biomass burning and coal burning mixed with industrial emission</td>
<td>i) Secondary nitrate plus sulfate formation source mixed with primary sources including biomass burning, coal combustion, and vehicle emission ii) Biomass burning, coal combustion, and vehicle emission was also mixed</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Secondary nitrate plus sulfate formation source mixed with biomass burning</td>
<td>Biomass burning, coal combustion, and vehicle emissions were mixed</td>
<td>Secondary sulfate plus OA mixed with coal combustion and secondary nitrate plus OA mixed with biomass burning</td>
</tr>
<tr>
<td>6</td>
<td>Six individual sources were identified</td>
<td>Six individual sources were identified</td>
<td>Secondary sulfate plus OA mixed with coal combustion and secondary nitrate plus OA mixed with industrial emission</td>
</tr>
<tr>
<td>7</td>
<td>Vehicle emission was split into two profiles</td>
<td>Coal combustion was split into two profiles</td>
<td>Secondary sulfate plus OA mixed with coal combustion</td>
</tr>
<tr>
<td>8</td>
<td>Vehicle emission and industrial emission was split into two profiles, respectively.</td>
<td>Vehicle emission and coal combustion were split into two profiles, respectively.</td>
<td>Eight individual sources were identified</td>
</tr>
</tbody>
</table>

8 individual sources were identified.

10 Coal combustion was split into two profiles

Coal combustion and biomass burning were split into two profiles, respectively.
Table S4. Average concentrations of reconstructed PM$_{2.5}$ and its chemical species in Xi'an, Shijiazhuang, and Beijing during the campaign* (μg m$^{-3}$)

<table>
<thead>
<tr>
<th>Chemical Species</th>
<th>Xi'an</th>
<th>Shijiazhuang</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstructed PM$_{2.5}$</td>
<td>77 ± 47</td>
<td>60 ± 39</td>
<td>64 ± 57</td>
</tr>
<tr>
<td>OA</td>
<td>25.9 ± 18.0</td>
<td>16.0 ± 9.7</td>
<td>22.1 ± 18.1</td>
</tr>
<tr>
<td>SO$_4^{2-}$</td>
<td>5.2 ± 3.4</td>
<td>7.0 ± 7.6</td>
<td>9.6 ± 11.3</td>
</tr>
<tr>
<td>NO$_3^-$</td>
<td>18.5 ± 14.5</td>
<td>15.8 ± 12.5</td>
<td>15.2 ± 16.7</td>
</tr>
<tr>
<td>NH$_4^+$</td>
<td>6.2 ± 4.5</td>
<td>7.0 ± 5.5</td>
<td>9.2 ± 10.3</td>
</tr>
<tr>
<td>Cl$^{-}$</td>
<td>1.9 ± 1.5</td>
<td>2.8 ± 2.2</td>
<td>0.7 ± 0.8</td>
</tr>
<tr>
<td>BC</td>
<td>4.5 ± 3.2</td>
<td>3.9 ± 2.5</td>
<td>1.9 ± 1.8</td>
</tr>
<tr>
<td>MD$^a$</td>
<td>13.2 ± 7.0</td>
<td>6.0 ± 4.0</td>
<td>4.8 ± 3.8</td>
</tr>
<tr>
<td>TE$^b$</td>
<td>1.1 ± 0.7</td>
<td>1.0 ± 0.6</td>
<td>0.9 ± 1.5</td>
</tr>
</tbody>
</table>

* Data during Xact625 failure shown in Figure S2 was excluded to calculate average concentration of campaign.

$^a$ MD means mineral dust, which is equal to 2.20Al + 2.49Si + 1.63Ca + 2.42Fe + 1.94Ti.

$^b$ TE means trace elements which is equal to K + Cr + Mn + Ni + Cu + Zn + As + Se + Ba + Pb.

Table S5. The nitrogen oxidation ratio (NOR) and sulfur oxidation ratio (SOR) in Xi'an, Beijing, and Shijiazhuang during the campaigns$^a$.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Xi'an</th>
<th>Shijiazhuang</th>
<th>Beijing</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOR</td>
<td>0.15 ± 0.08</td>
<td>0.20 ± 0.11</td>
<td>0.16 ± 0.12</td>
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<tr>
<td>SOR</td>
<td>0.18 ± 0.08</td>
<td>0.36 ± 0.25</td>
<td>0.48 ± 0.23</td>
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</tbody>
</table>

$^a$ NOR = n(NO$_3^-$)/(n(NO$_3^-$) + n(NO$_2^-$)); SOR = n(SO$_4^{2-}$)/(n(SO$_4^{2-}$) + n(SO$_2^-$)). where n(NO$_3^-$), n(NO$_2^-$), n(SO$_4^{2-}$), and n(SO$_2^-$) are the molar concentrations of NO$_3^-$, NO$_2^-$, SO$_4^{2-}$, and SO$_2^-$, respectively.

Table S6. Average concentrations of SOA in Xi'an, Shijiazhuang, and Beijing during sampling periods estimated by BC-tracer method and source apportionment results (μg m$^{-3}$).

<table>
<thead>
<tr>
<th>SOA</th>
<th>Xi'an</th>
<th>Shijiazhuang</th>
<th>Beijing</th>
</tr>
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<tbody>
<tr>
<td>SOA$_{BC}$-tracer</td>
<td>5.1 ± 5.8</td>
<td>4.2 ± 4.4</td>
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<td>SOA$_{source}$ apportionment</td>
<td>6.0 ± 4.1</td>
<td>4.6 ± 2.8</td>
<td>8.2 ± 6.7</td>
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</table>

* Data during Xact625 failure shown in Figure S2 was excluded to calculate average concentration of campaign.
Table S6S7. The concentration of PM$_{2.5}$ and its main chemical components during wintertime in Xi’an, Shijiazhuang, and Beijing in the last decades.

<table>
<thead>
<tr>
<th>City</th>
<th>Year</th>
<th>PM$_{2.5}$</th>
<th>OA$^a$</th>
<th>EC</th>
<th>SO$_4^{2-}$</th>
<th>NO$_3^-$</th>
<th>NH$_4^+$</th>
<th>Others</th>
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<td>μg m$^{-3}$</td>
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</tr>
</tbody>
</table>

* study was conducted on online monitoring equipment, and the rest studies were researched on filter sampling experiments.

$^a$ Assumption of OA = 1.6 × OC for the filter-based sampling experiments
Table S7S8. The concentration of PM$_{2.5}$ and its source contribution during wintertime in Xi’an, Shijiazhuang, and Beijing in the last decades.

<table>
<thead>
<tr>
<th>City</th>
<th>Year</th>
<th>PM$_{2.5}$</th>
<th>Vehicle emission</th>
<th>Coal combustion</th>
<th>Secondary formation source</th>
<th>Fugitive dust</th>
<th>Industrial emission</th>
<th>Biomass burning</th>
<th>Others</th>
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<tbody>
<tr>
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* study was conducted on online monitoring equipment, and the rest studies were researched on filter sampling experiments.
References:


