

Article

Increased PM_{2.5} Caused by Enhanced Fireworks Burning and Secondary Aerosols in a Forested City of North China During the 2023–2025 Spring Festivals

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Abstract

Fireworks burning (FB) constitutes a major but short-lived source of PM_{2.5} during the Chinese Spring Festival, significantly deteriorating air quality in certain regions. This study was conducted to evaluate its impact through real-time monitoring of PM_{2.5} chemical compositions in a forestry city (Xinyang) during the pre-fireworks and fireworks periods at the Spring Festival of 2023–2025. During the fireworks period, PM_{2.5} concentrations increased by 10.5–226.4% compared to pre-fireworks levels, of which the concentrations of secondary inorganic aerosols (SIA), K and Cl[−] rose by 1.6–4.8, 1.9–14.7 and 1.5–8.1 times, and they accounted for 33.2–47.7%, 6.7–12.5% and 3.8–6.4% of PM_{2.5}, respectively. Correspondingly, PM_{2.5}/CO and SIA/CO ratios in 2023–2025 elevated by factors of 1.4–2.3 and 1.1–3.4, indicating distinct enhancements in secondary inorganic aerosols formation. Additionally, acidity of PM_{2.5}, RH and O_x also increased during fireworks. Collectively, higher sulfur and nitrogen oxidation ratios (SOR and NOR) during the fireworks period under the combined effects of high RH, O_x and acidity conditions indicated a greater conversion of secondary inorganic aerosols. Positive Matrix Factorization (PMF) analysis confirmed that FB and secondary aerosols (SA) source levels during fireworks increased by 2.5–19.3 and 1.9–4.4 times compared to pre-fireworks values. This study underscores the need for implementing stringent management of fireworks and secondary formation mitigation to reduce PM_{2.5} concentrations during the Spring Festival.

Keywords: PM_{2.5}; source apportionment; secondary aerosol formation; fireworks emission



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1. Introduction

Fireworks used in global celebrations adversely affect air quality, consequently imposing a substantial burden on governments [1]. This is especially evident in China during the Spring Festival, where nationwide displays significantly elevate PM_{2.5} levels and substantially deteriorate air quality [2]. For instance, PM_{2.5} concentrations on firework days (248.9 µg m⁻³) was greatly higher than before firework days (90.8 µg m⁻³) in Beijing during the Spring Festival, with firework emissions identified as the primary contributor [3]. A similar pattern was observed in the United States, where fireworks combustion raised daily PM_{2.5} levels by 42% during the Independence Day [4]. Although fireworks burning activities are relatively short-lived in duration, the frequent use of fireworks during festivals poses irreversible risks to humans, by inhalation of high concentration particulates containing harmful chemicals (including heavy metals and polycyclic aromatic hydrocarbons) [5].

Numerous studies have demonstrated confirmed that firework combustion releases substantial gaseous pollutants (including SO₂ and NO₂) and particulate matter (including water-soluble ions, metallic elements, and organic compounds) [6–8]. Cao et al. (2018) found that the concentrations of SO₂ and CO during the Spring Festival were 9.2 times and 5 times higher than the background levels, respectively [9]. Concurrently, Hu et al. (2019) found the highest values of K⁺, Cl⁻ and SIA during the fireworks period in Beijing [10]. In addition, the combustion of fireworks and firecrackers also affects the aerosols' acidity and alters the gas-particle partitioning of semi-volatile substances, thereby influencing the formation of secondary inorganic aerosols [11,12]. Wu et al. (2018) found that fine nitrate was mainly formed by heterogeneous reaction of HNO₃ and NH₃, while sulfate was mainly formed by adsorption on wet particles (such as KCl) produced by SO₂ during firework activities [13]. Tian et al. (2014) quantified 29.7% contribution of fireworks to PM_{2.5} during the heavy-fireworks period by PMF model [14].

Since 2015, numerous cities in China have implemented regulations to restrict the discharge of fireworks during the Spring Festival, aiming to alleviate severe PM_{2.5} pollution [15]. Despite the marked improvements in air quality resulting from stringent clean-air measures, certain regions have recently loosened these restrictions, which posed critical challenges for air quality improvement strategy [16]. Xinyang, situated in the southern part of the North China Plain (NCP), is a representative forested city with a forest coverage rate of 36.2% [17]. Nevertheless, the prevalent phenomena of setting off fireworks in Xinyang, combined with its basin topography and stagnant winter meteorological conditions, still exacerbated the accumulation of PM_{2.5} [18]. In response, Xinyang launched an air pollution prevention and control initiative on fireworks and firecrackers in 2018 (<https://www.xinyang.gov.cn/2018/04-02/554574.html>, accessed on 3 October 2025). However, few studies have assessed the specific impact of firework emissions on air quality during the Spring Festival in Xinyang.

The study aims to address four major objectives: (1) quantify the temporal variations in air pollutants across the pre-fireworks, fireworks and post-fireworks phases; (2) investigate the impacts of fireworks on PM_{2.5} chemical composition and aerosol acidity; (3) analyze the formation of NO₃⁻ and SO₄²⁻ with intense firework discharge; and (4) estimate the source contribution and profile of the selected chemical compounds by the Positive Matrix Factorization (PMF) model. This approach enables a clear identification of the drivers of PM_{2.5} increases and compositional changes during firework events, thereby providing essential scientific support for strengthening pollution control in other regions severely affected by fireworks.

2. Materials and Methods

2.1. Observational Site

Integrated measurements were carried out in a forestry city, Xinyang (called XY; 114°09' E, 32°15' N) of Henan Province, situated in southern NCP (Figure 1). The study period spanned from 20 to 28 January 2023, 16 to 20 February 2024 and 27 January to 4 February 2025, respectively. The location is surrounded by residential areas and lacks industrial emissions. Given the extensive firework displays that occurred in the Spring Festival to celebrate the Lunar New Year, the monitoring period for each year was strategically categorized into three phases: pre-fireworks phase (from the day before New Year's Eve to 10:00 on New Year's Eve), fireworks phase (from 11:00 on New Year's Eve to the third day of the lunar new year) and post-fireworks phase (from the fourth to the seventh day), respectively.

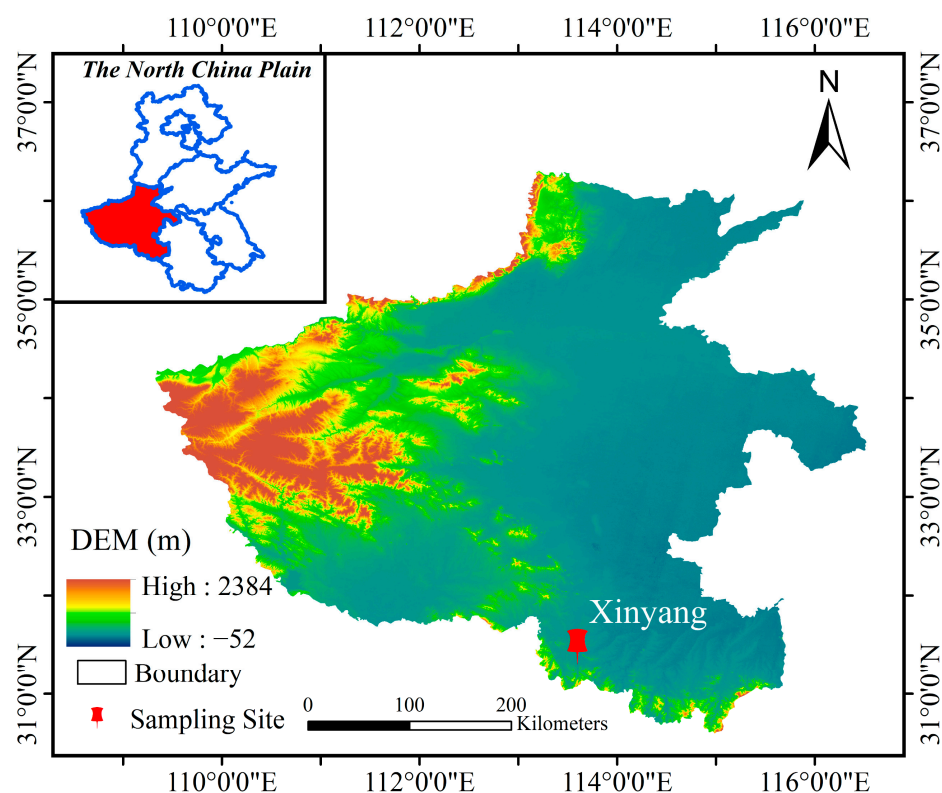


Figure 1. Map of the sampling site, was created using ArcGIS (ArcMap) v10.7. The geospatial data used were sourced from the National Platform for Common Geospatial Information Services (<https://www.tianditu.gov.cn/>, accessed on 3 October 2025).

2.2. Sample Collection and Laboratory Analysis

The monitoring station was established on the roof of the Xinyang Museum, approximately 18 m above ground level. Between 2023 and 2025, hourly PM_{2.5} concentrations were monitored with an ambient particulate matter analyzer (LGH-01E, Anhui Landun Photoelectron Co., Ltd., Lu'an, Anhui, China), with an airflow rate of 16.7 L/min. The product used the β -ray method, combined with a dynamic moderate control system and dynamic digital filtering technology, to achieve continuous monitoring of PM_{2.5}. Calibration followed the HJ 817-2018 standard [19]. Concurrently, gaseous pollutants including SO₂, NO₂ and O₃ were measured simultaneously with online analyzers (LGH-210, LGH-220 and LGH-240, Anhui Landun Photoelectron Co., Ltd., Lu'an, Anhui, China), with a time resolution of 1 h. These instruments enabled continuous monitoring based on ultraviolet fluorescence, chemiluminescence and ultraviolet absorption methods, respectively, and

were calibrated according to the GB/T 36090-2018 standard [20]. The inorganic water-soluble ions (NH_4^+ , NO_3^- , SO_4^{2-} , K^+ , Ca^{2+} , Mg^{2+} , Na^+ and Cl^-) were analyzed by ion chromatography (URG-9000, Thermo Fisher Scientific, Waltham, MA, USA), with a flow rate of 3 L/min and a time resolution of 1 h. Additionally, the sum of the mass concentrations of SO_4^{2-} , NO_3^- and NH_4^+ was defined as secondary inorganic aerosols (SIA) in this study. Detailed instrument principles and quality control procedures were adopted from prior research [21]. Elemental components in $\text{PM}_{2.5}$ (including K, Ca, Fe, Pb, Zn, Mn, Se, Hg, Cr, Cr, Cd, Cu, Ni, Ti, Sb, Sn, V, Ba, As, Co, Mo, Ag, Sc, Tl, Pd, Br, Te, Ga, Cs, Si and Al) were quantified with an online metal monitor (AMMS-100, Focused Photonics Inc., Hangzhou, Zhejiang, China), with a flow rate of 16.7 L/min and a time resolution of 1 h. Particles were collected on a 2 μm Teflon filter tape and the calibration of the elements was conducted using the NIST SRM 2783 reference material. Meteorological parameters (wind speed, wind direction, relative humidity, temperature) were recorded every minute by a compact weather station (LGH-01C, Anhui Landun Photoelectron Co., Ltd., Lu'an, Anhui, China, and hourly averages of meteorological conditions were applied, with the calibration based on the QX/T 291-2015 standard [22].

To ensure data quality and accuracy, all instruments underwent weekly calibration using relevant reference standards. Furthermore, a comprehensive quality assurance/quality control (QA/QC) protocol was implemented throughout the monitoring period from 2023 to 2025, which included the concurrent collection of field blanks and parallel samples.

2.3. Analysis Methods

2.3.1. Acidity of $\text{PM}_{2.5}$ Acidity

The ion balance is an effective approach to assess the acidity and alkalinity of atmospheric aerosols [23]. The anion equivalence (AE) and cation equivalence (CE) are estimated using Equations (1) and (2):

$$\text{AE} = \frac{[\text{F}^-]}{19} + \frac{[\text{Cl}^-]}{35.5} + \frac{[\text{SO}_4^{2-}]}{48} + \frac{[\text{NO}_3^-]}{62} \quad (1)$$

$$\text{CE} = \frac{[\text{Na}^+]}{23} + \frac{[\text{NH}_4^+]}{18} + \frac{[\text{K}^+]}{39} + \frac{[\text{Mg}^{2+}]}{12} + \frac{[\text{Ca}^{2+}]}{20} \quad (2)$$

where [X] represents the observed concentration of each element. The AE/CE ratio is commonly used to evaluate aerosol acidity: the ratio less than 1 indicates alkaline conditions, equal to 1 indicates neutrality, and greater than 1 indicates acidic conditions [24].

2.3.2. Nitrogen and Sulfur Oxidation Ratios

The sulfur and nitrogen oxidation ratios (SOR and NOR) are key indicators to evaluate the formation of secondary inorganic aerosols [25]. The NOR and SOR are calculated using Equations (3) and (4).

$$\text{NOR} = \frac{[\text{NO}_3^-]}{[\text{NO}_2] + [\text{NO}_3^-]} \quad (3)$$

$$\text{SOR} = \frac{[\text{SO}_4^{2-}]}{[\text{SO}_2] + [\text{SO}_4^{2-}]} \quad (4)$$

where the concentrations of SO_2 , NO_2 , NO_3^- and SO_4^{2-} are expressed as molar concentrations.

2.3.3. Source Apportionment of PM_{2.5} Positive Matrix Factorization (PMF) Model

The Positive Matrix Factorization (PMF) model (US EPA PMF 5.0) is an analytical tool, which is widely used to identify PM_{2.5} pollution sources and quantify their contributions based on the compositional profiles [26,27]. In this study, PMF method was applied to analyze the source apportionment of PM_{2.5}, while multiple PMF runs were performed based on Q-values, error estimation, and source chemical fingerprints to determine the optimal factor number [28]. Moreover, the reliability of PMF model was also confirmed by the strong correlation (Figure S2) between observed and reconstructed PM_{2.5} (the sums of NH₄⁺, NO₃[−], SO₄^{2−}, Ca²⁺, K⁺, Mg²⁺, Cl[−], OC, EC, Fe, Pb, Zn, Mn, Se, Cr, Cu, Ti, Ba, As, Br, Cs and Si) over three years. More details are depicted in the Supplementary Materials.

3. Results and Discussion

3.1. The Variations in Meteorological Conditions and Air Pollutants During the Spring Festival

Figure 2a–c and Tables S1–S3 illustrate the variations of PM_{2.5}, precursor concentrations and meteorological conditions in XY during the pre-fireworks, fireworks and post-fireworks periods. The PM_{2.5} concentrations were 113.6, 66.2 and 81.2 µg m^{−3} during the fireworks period from 2023 to 2025, which were 1.3, 1.1 and 3.3, and 2.3, 1.8 and 1.1 times higher than those at the pre-fireworks and post-fireworks periods, respectively. Previous research conducted in Tianjin, Beijing and Zhengzhou also revealed increased PM_{2.5} mass concentrations caused by fireworks events [29–31].

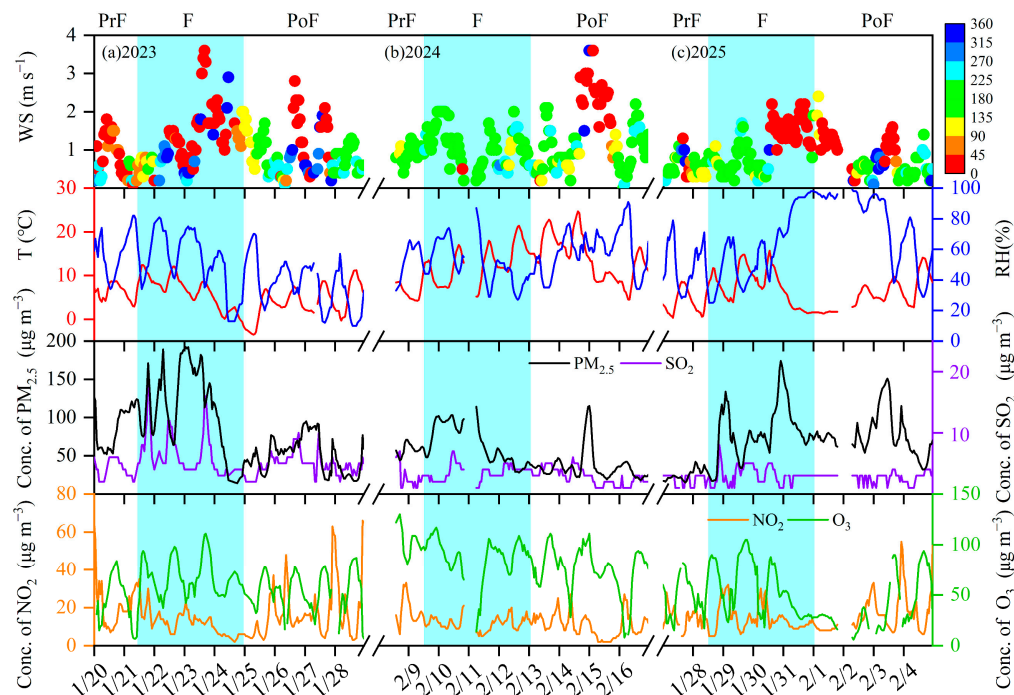


Figure 2. Time series of PM_{2.5}, air pollutants and meteorological conditions during pre-fireworks, fireworks and post-fireworks periods in XY of 2023–2025: (a) 2023; (b) 2024; (c) 2025. The PrF, F and PoF are the abbreviations of pre-fireworks, fireworks and post-fireworks periods, respectively. The Ws represents the wind speeds (Ws), and the color scale stands for the wind direction.

The concentration of SO₂ initially increased from 4.0 (2023), 2.7 (2024) and 2.3 (2025) µg m^{−3} pre-fireworks to 6.2, 3.5 and 3.0 µg m^{−3} during fireworks, and subsequently dropped by 22.9%, 18.5% and 11.6% post-fireworks. This was consistent with prior research, which found that the extensive fireworks burning resulted in sharply elevated concentrations of SO₂ during the Spring Festival at Shanghai [32]. The NO₂ levels decreased by 75.0% during

fireworks in 2023, compared with the pre-fireworks period concentration of $21.7 \mu\text{g m}^{-3}$, then greatly increasing by 41.6% post-fireworks. In 2024, its concentration declined from $19.1 \mu\text{g m}^{-3}$ pre-fireworks to $12.1 \mu\text{g m}^{-3}$ during fireworks and further to $10.9 \mu\text{g m}^{-3}$ post-fireworks. The generally lower NO_2 concentrations during fireworks were closely associated with reduced vehicle usage for celebrating the Spring Festival [33]. This result was consistent with prior research, which evaluated the air quality among 366 sites in China and found the reductions of NO_2 were positively linked with the decreased emissions from vehicles [34]. In 2025, the variations in NO_2 values were stable at pre-fireworks ($12.4 \mu\text{g m}^{-3}$) and fireworks periods ($12.1 \mu\text{g m}^{-3}$), while they increased to $16.5 \mu\text{g m}^{-3}$ post-fireworks. In terms of O_3 , its concentration reached $68.0 \mu\text{g m}^{-3}$ in 2023 and $58.0 \mu\text{g m}^{-3}$ in 2025 during fireworks, 1.3–1.7 and 1.4–1.6 times higher than those during fireworks and post-fireworks periods, respectively, suggesting the enhanced oxidizing capacity in ambient air was affected by fireworks [35]. However, the O_3 value in 2024 decreased from $103.2 \mu\text{g m}^{-3}$ pre-fireworks to $88.4 \mu\text{g m}^{-3}$ during fireworks, and subsequently to $74.8 \mu\text{g m}^{-3}$ post-fireworks.

Meteorological conditions exhibited notable variations across three periods. Although the average wind speeds (Ws) consistently increased during the fireworks period in three years, it remained below 2 m s^{-1} , reflecting calm wind conditions. Simultaneously, the average relative humidity (RH) maintained at high levels, ranging from 51.6% to 60.9% during the fireworks in three years. A consistent rise in average temperature (T) was also observed during the fireworks events in three years. Specifically, from 2023 to 2025, the average T enhanced from 3.8 to 6.1 °C pre-fireworks to 6.5–12.4 °C during fireworks from 2023 to 2025, indicating relatively warm weather conditions.

3.2. Impacts of Fireworks on Chemical Components and Aerosol Acid During the Spring Festival

3.2.1. Changes in Elemental Compositions and SIA

Figure 3 showed the time series of $\text{PM}_{2.5}$ and its chemical components, including sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), potassium (K), calcium (Ca), iron (Fe), lead (Pb), zinc (Zn), manganese (Mn), selenium (Se), chromium (Cr), copper (Cu), titanium (Ti), barium (Ba), arsenic (As), cesium (Cs), bromine (Br), silicon (Si), and aluminum (Al). Intensive fireworks burning activities substantially elevated $\text{PM}_{2.5}$ concentrations and altered its chemical compositions, such as secondary inorganic aerosols (SIA), K and Cl^- [36–38]. Common oxidizers used in fireworks included K compounds (such as KNO_3 , KClO_3 , KClO_4 , K_2CrO_4 and $\text{K}_2\text{Cr}_2\text{O}_7$) [39]. Cl^- serves as a key tracer for firework emissions, primarily employed in generating diverse color effects during combustion [40]. As shown in Figure 3 and Tables S1–S3, the concentrations of Cl^- and K were 0.6–4.2 and 0.7–4.0 $\mu\text{g m}^{-3}$ pre-fireworks, accounting for 2.4–4.8% and 2.3–4.5% to $\text{PM}_{2.5}$, respectively. Their contributions increased to 3.8–6.4% and 6.7–12.5% during fireworks, while they dropped to 2.6–5.3% and 4.2–5.8% post-fireworks, underscoring the predominant influence of fireworks on their atmospheric abundance. A previous study conducted in Linyi similarly found increases in Cl^- and K by factors of 3.6 and 11.0 during the fireworks burning period compared to non-fireworks burning period [41]. Moreover, compared with experiments from Changzhou and Zhengzhou, Cl^- and K values in this study were considerably higher, while K concentrations were markedly lower than those in Zaozhuang, Shandong Province [42–44]. This discrepancy might be attributed to Zaozhuang's abundant mineral resources of coal, which released significant quantities of K into the ambient environment through mining and smelting processes [45].

The concentration of SIA ($44.3 \mu\text{g m}^{-3}$) at fireworks period in 2023 was 1.6 and 2.3 times higher than the pre-fireworks and post-fireworks values. In 2024, the value of SIA was $39.3 \mu\text{g m}^{-3}$ pre-fireworks, decreasing by 19.7% during fireworks, and further by 42.6% post-fireworks. The decreased SIA level during the fireworks phases was extremely affected by the reduced RH, increased T and stronger Ws (Table S5, $p < 0.01$). In 2025, the contribution of SIA ($5.6 \mu\text{g m}^{-3}$) to $\text{PM}_{2.5}$ reached 22.6% pre-fireworks, increasing to 33.2% during fireworks, subsequently surged to 52.1% post-fireworks, suggesting markedly enhanced secondary formation under intensive fireworks emissions. Generally, the sum of contribution from SIA, Cl^- and K to $\text{PM}_{2.5}$ during the fireworks period accounted for 51.7% to 60.0% over three years, demonstrating the important role of secondary inorganic aerosols and firework-related species in increased $\text{PM}_{2.5}$.

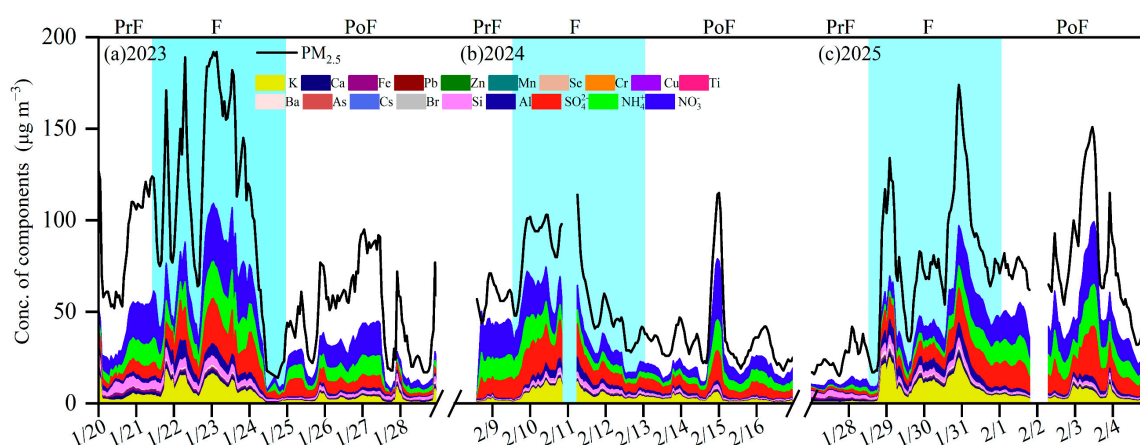


Figure 3. Time series of $\text{PM}_{2.5}$ and chemical compositions during pre-fireworks, fireworks and post-fireworks periods in XY over three years: (a) 2023; (b) 2024; (c) 2025. The PrF, F and PoF are the abbreviations of pre-fireworks, fireworks and post-fireworks periods, respectively.

Notably, the massive fireworks discharge led to significant increases in both the concentrations of $\text{PM}_{2.5}$ and SIA, while the contribution of SIA to $\text{PM}_{2.5}$ increased gradually (Figure S4). Similarly, Feng et al. (2016) analyzed the variations in SIA during the Spring Festival in Xinxiang and found a 36.5% increase in NO_3^- after intensive combustion of fireworks [46]. CO was used as a tracer for primary particulate matter [47]. The $\text{PM}_{2.5}/\text{CO}$ ratio was frequently used to exclude the influence of meteorological conditions, reflecting the contributions from emissions and chemical transformations [48,49]. The rising $\text{PM}_{2.5}/\text{CO}$ ratios represented a better contribution of secondary formation to $\text{PM}_{2.5}$ [50,51]. The robust correlation was found between $\text{PM}_{2.5}$ and CO (Table S6, $R^2 = 0.67\text{--}0.84$ in 2023–2025, $p < 0.01$). During the fireworks periods of 2023–2025, the highest $\text{PM}_{2.5}/\text{CO}$ ratios were 1.1×10^{-1} , 7.0×10^{-2} and 1.0×10^{-1} (Figure 4), exceeding the levels both in pre-fireworks and post-fireworks phases by factors of 1.4–2.3 and 1.4–2.0, respectively. The results suggested a greater contribution of secondary formation to $\text{PM}_{2.5}$. Moreover, the SIA/CO ratio was employed to quantify the contribution of SIA transformation. From 2023 to 2025, SIA/CO ratios were about 3.3×10^{-2} – 4.4×10^{-2} at the fireworks periods (Figure 4), and were 1.1–3.4 and 1.0–2.0 times higher than those in the pre-fireworks and post-fireworks phases, which suggested a better formation of secondary inorganic aerosols, supported by their strong correlations (Table S7, $R^2 = 0.31\text{--}0.72$ in 2023–2025, $p < 0.01$). In addition, large quantities of precursor pollutants (including SO_2 and NO_2) generated by fireworks [52] underwent homogeneous and heterogeneous processes, further affecting SIA/CO ratios [53,54]. These reactions markedly amplified the contribution of fireworks to secondary aerosol formation. Moreover, stagnant meteorological conditions during the

Spring Festival in XY also exerted pronounced influences on homogeneous and heterogeneous reactions.

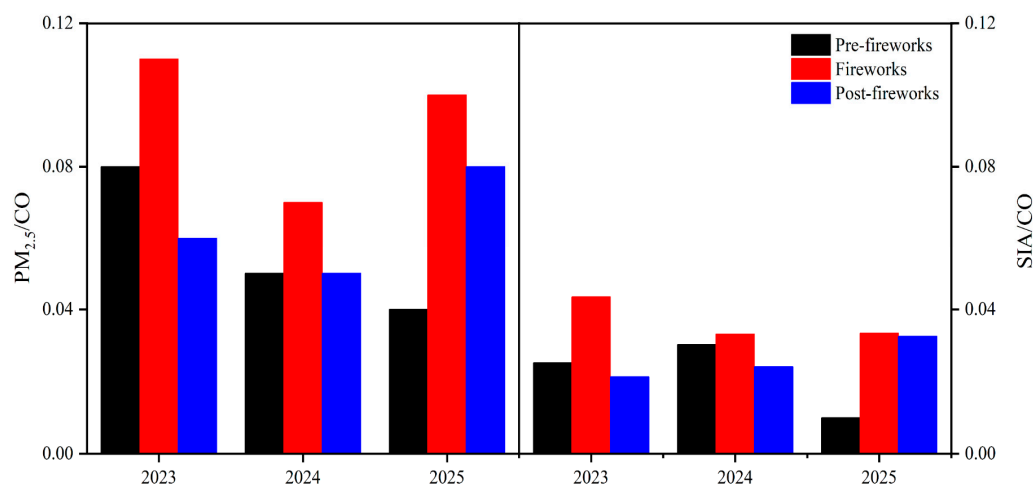


Figure 4. The PM_{2.5}/CO and SIA/CO ratios during pre-fireworks, fireworks and post-fireworks periods in XY of 2023–2025.

However, the increasing pattern between PM_{2.5}/CO and SIA/CO ratios was observed during the fireworks period across three years. While the difference between these ratios pre-fireworks and during fireworks was the lowest in 2024, these ratios in 2024 were also lower than those in 2023 and 2025. The Xinyang government adopted control measures on 24 December 2023 (<https://www.xyxxw.com.cn/jhtml/xinyang/353215.html>, accessed on 7 November 2025) and 31 January 2024 (<https://sthjj.xinyang.gov.cn/2024/01-31/130288.html>, accessed on 7 November 2025) to address heavy pollution during the Spring Festival. Concurrently, a notable temperature rise (from 5.9 °C to 12.4 °C) occurred during the fireworks period in 2024, which might enhance vertical convection, thereby facilitating the dispersion of PM_{2.5} and its components [55]. Under the synergistic effects of these factors, the differences of PM_{2.5}/CO and SIA/CO between the pre-fireworks and fireworks periods in 2024 were reduced, and led to correspondingly lower PM_{2.5}/CO and SIA/CO ratios compared to 2023 and 2025. In summary, the increased PM_{2.5}/CO and SIA/CO ratios from 2023 to 2025 underscored the necessity of implementing targeted controls on secondary emissions for effectively curbing the growth of PM_{2.5}.

3.2.2. Acidity of PM_{2.5}

The cation–anion balance was an effective approach for assessing the acidity and alkalinity of atmospheric aerosols [56]. Anions such as SO₄^{2−}, NO₃[−], F[−] and Cl[−] contributed to aerosol acidity, while cations NH₄⁺, K⁺, Na⁺ and Ca²⁺ could enhance particulate alkalinity [57]. Figure 5 illustrated the variations in acid and Figure S3 presented the correlation analysis between anion equivalents (AE) and cation equivalents (CE) in XY during pre-fireworks, fireworks and post-fireworks phases over three years. In 2023 and 2025, the acid showed the same dynamic patterns, enhanced from 0.70 and 0.73 pre-fireworks to 0.75 and 0.76 during fireworks, then to 0.84 and 0.79 post-fireworks, respectively. In 2024, the acid slightly increased from 0.78 pre-fireworks to 0.79 during fireworks, while it decreased to 0.74 post-fireworks. Similarly, Huang et al. (2019) confirmed a marked increase in acid influenced by massive firework activities in Xiamen [58]. Although the acid exhibited increasing trends during the fireworks period from 2023 to 2025, it remained below 1, indicating complete neutralization of anions and redundancies of cations, leading to an alkaline aerosol state. This result demonstrated that CE might play a significant role in the atmospheric environment, aligned with reports of Xu et al. (2012) which also noted

alkaline aerosol characteristics in Fuzhou [59]. Therefore, the persistent increases in aerosol acid in firework periods necessitated more stricter strategies on firework emissions during the Spring Festival in XY.

3.3. Nitrate and Sulfate Formation Mechanism

The nitrogen and sulfur oxidation ratios (NOR and SOR) served as key indicators for evaluating the formation of secondary inorganic aerosols [60]. The average values of NOR and SOR during the three stages were listed in Table 1, which were calculated as the mean of all valid hourly data points within each defined period. The NOR value ranged from 0.5 to 0.6 during the fireworks period in 2023–2024, which were 1.0–1.5 and 1.3–1.5 times higher than the pre-fireworks and post-fireworks periods. In 2025, NOR initially increased from 0.2 pre-fireworks to 0.4 during the fireworks stage, and subsequently to 0.5 post-fireworks. The SOR value varied from 0.6 to 0.8 during the fireworks period in 2023–2024, which were 1.0–1.2 and 1.1–1.2 times higher than the pre-fireworks and post-fireworks levels. In 2025, SOR increased significantly from 0.4 pre-fireworks to 0.7 during fireworks, then to 0.8 post-fireworks. The elevated NOR and SOR during fireworks clearly indicated enhanced NO_3^- and SO_4^{2-} formation.

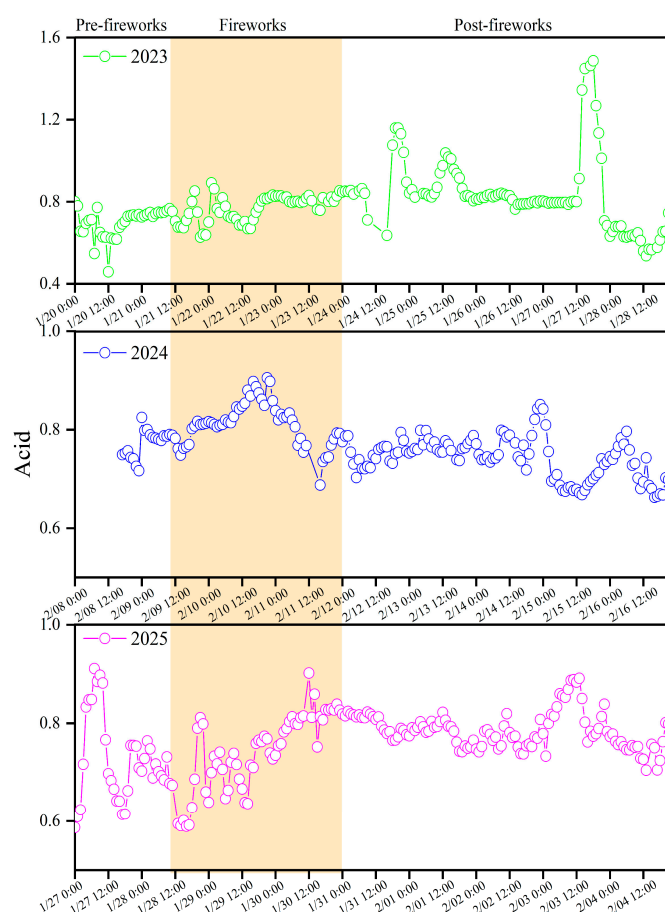


Figure 5. Variations in acid during pre-fireworks, fireworks and post-fireworks periods in XY from 2023 to 2025.

Table 1. The variations in SOR, NOR, meteorological conditions and air pollutants during the pre-fireworks, fireworks and post-fireworks phases in XY over three years.

Parameters	2023			2024			2025		
	Pre	During	Post	Pre	During	Post	Pre	During	Post
SOR	0.5	0.6	0.5	0.8	0.8	0.7	0.4	0.7	0.8
NOR	0.4	0.6	0.4	0.5	0.5	0.4	0.2	0.4	0.5
RH	59.3	53.2	35.8	55.2	51.6	58.3	50.2	60.9	77.3
T	6.1	6.5	3.9	5.9	12.4	14.1	3.8	7.5	5.6
Ws	0.7	1.3	0.9	0.9	1.1	1.4	0.6	1.0	0.8
SO ₂	4.0	6.2	4.8	2.7	3.5	2.8	2.3	3.0	2.7
NO ₂	21.7	12.4	17.6	19.1	12.1	10.9	14.1	14.3	16.5
O _x	62.4	86.4	67.1	121.4	100.5	74.8	60.3	72.2	52.2

NOR showed positive correlations with O_x ($R^2 = 0.44\text{--}0.53$, $p < 0.01$), acidity ($R^2 = 0.43\text{--}0.58$, $p < 0.01$) and K ($R^2 = 0.31\text{--}0.45$, $p < 0.01$) during fireworks period of 2023–2025 (Table S4). The strong association between NOR and O_x suggested that elevated O_x levels promoted the oxidation of NO₂ to NO₃[−]. Nitrate could be formed by reacting NO₂ with OH radicals under high oxidative conditions via the gas-phase [61,62]. Figure S5 revealed a consistent increase trend in both NOR and O_x during fireworks of 2023–2025. The high NOR implied a significant enhancement in NO₃[−], primarily driven by the gas-phase with the elevated O_x concentrations. The persistent positive relationship between NOR and acidity indicated that the enhanced acidic conditions also favored NO₃[−] formation. Consequently, the combined effects of high O_x levels and enhanced acidity collectively drove the increase in NOR (Figure 6a,b). Nevertheless, high NOR was observed in Figure 6c, accompanied by low O_x ($\leq 45 \mu\text{g m}^{-3}$) level but high RH (near 90.0%), indicating that nitrate was probably formed by the N₂O₅ hydrolysis through the heterogeneous processes under high-humidity conditions (Table S5, $R^2 = 0.80$, $p < 0.01$) [63]. This observation aligned with prior study, which reported enhanced nitrate conversion under high RH despite low O_x, likely due to heterogeneous processes [64]. Overall, these findings highlighted that the increase in NOR during firework events was driven by a combination of high O_x, RH and acidity conditions via gas-phase and heterogeneous processes, respectively.

Significant positive correlations were observed between SOR and RH ($R^2 = 0.73\text{--}0.88$, $p < 0.01$) acidity ($R^2 = 0.41\text{--}0.73$, $p < 0.01$), and K ($R^2 = 0.54\text{--}0.85$, $p < 0.01$) during fireworks in three years (Table S4). The good correlation between RH and SOR suggested that moist conditions were favorable for the conversion of SO₂ to SO₄^{2−}. This finding was in agreement with Wang et al. (2021), who identified a sharp increase in SOR in Beijing when RH exceeded 40% [65]. The consistent growth trend between SOR and RH (Figure 1 and Figure S5) further revealed that SO₄^{2−} formation was mainly facilitated by the aqueous-phase reaction [66]. Moreover, the positive relationship between SOR and acidity demonstrated that enhanced acidic conditions also promoted SO₄^{2−} formation, which was supported by Fu et al. (2024) who found the increased production of SO₄^{2−} under higher acidity [67]. Cheng et al. (2016) pointed out that elevated RH facilitated the rapid conversion of SO₂ into particulate sulfate by neutralizing with NH₃, which improved the particles' acid and further promoted the sulfate formation [66]. Collectively, these results underscored a synergistic effect between high RH and elevated aerosol acidity in promoting SO₄^{2−} production.

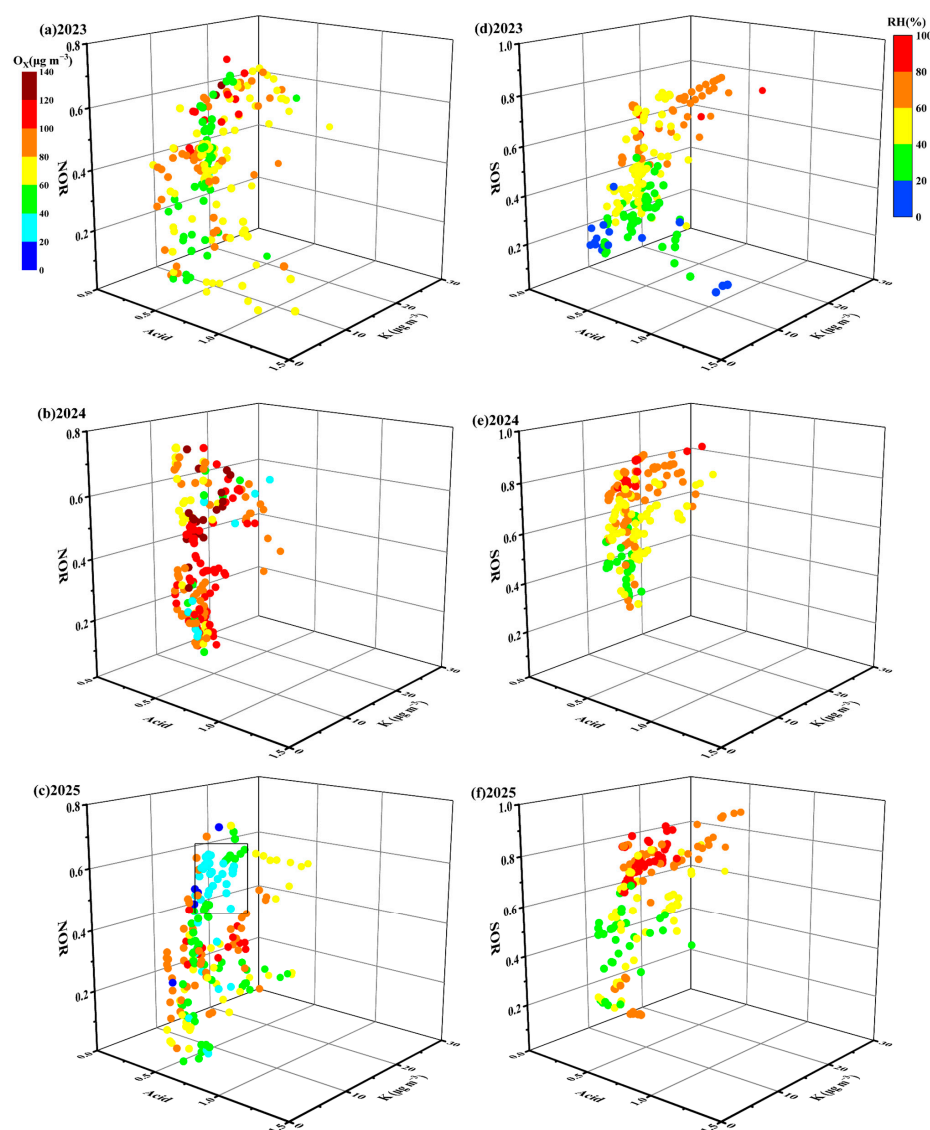


Figure 6. Relationship between NOR (SOR), O_x (RH), acid and K during the fireworks period in XY from 2023 to 2025: (a) NOR in 2023; (b) SOR in 2023; (c) NOR in 2024; (d) SOR in 2024; (e) NOR in 2025; (f) SOR in 2025. The rectangle in (c) represents several data points of high NOR, coupled with low O_x ($\leq 45 \mu\text{g m}^{-3}$) but high RH (near 90.0%).

3.4. Source Apportionment of $PM_{2.5}$

By using the Positive Matrix Factorization (PMF) monitoring model, six sources were identified in 2023 and 2025, including fireworks burning (FB), coal combustion (CC), vehicle emissions (VE), industrial emissions (IE), secondary aerosols (SA), and dust; five sources were analyzed in 2024, covering FB, CC, SA, dust and industrial emissions + vehicle emissions (IE + VE).

Figure S1 showed the source apportionment of $PM_{2.5}$ -bound elements resolved by the PMF model. Factor 1 was predominantly associated with OE, EC, Zn and Pb, which were typical tracers of vehicular emissions. Zn primarily originated from tire wear and brake abrasion [68]. Yan et al. (2022) found that the increasing numbers of motor vehicles in Shenzhen could significantly elevate Zn emission levels [69]. Although Pb has been phased out from gasoline in many regions, it might still derive from wear and tear of automotive components, such as brake pads and tires [70,71]. OC and EC were indicative of incomplete combustion processes, commonly associated with diesel and gasoline vehicles [72]. Factor 2 was characterized by high loadings of Cl^- , OC and EC, attributed to

coal combustion. Cl^- was mostly evolved from coal combustion, especially in domestic heating and power generation, while OC and EC were well-established markers of solid fuel combustion [73,74]. Factor 3 was defined by crustal elements, including Ca^{2+} , Fe, Ti and Si. These four elements are commonly derived from construction activities and road dust, indicative of dust sources [75,76]. Factor 4 exhibited elevated levels of K^+ , Mg, Cu and Ba, highly associated with fireworks burning. K^+ compounds served as key oxidizers, Mg enhanced brightness, Cu compounds produced blue light, and Ba was used for green flame coloration [77,78]. Factor 5 in 2023 and 2025 was dominated by SO_4^{2-} , NH_4^+ and NO_3^- , representing secondary aerosols' source. The formation mechanism mainly involved the oxidation of SO_2 and NO_x , and the neutralization with NH_3 [79]. However, factor 5 in 2024 was characterized by high loadings of Pb, Zn, Mn, Se, Cr, OC and EC. As mentioned earlier, Pb, Zn, OC and EC were characteristic elements of vehicle emissions. The high Mn, Se and Cr were typically emitted from ferrous metal smelting [80,81]. Therefore, this factor was identified as a mixed source, which was called the industrial emissions + vehicle emissions (IE + VE). Factor 6, heavily loaded by Se and Br, was indicative of industrial emissions. Se and Br were commonly released from coal-fired power plants, metal smelting, glass manufacturing and flame retardant processes [82].

The concentrations of each source were demonstrated in Figure 7. In 2023, the values of FB, SA and IE were 9.1, 10.5 and 7.4 $\mu\text{g m}^{-3}$ pre-fireworks, greatly increasing by 147.4%, 85.4% and 138.4% during fireworks, while dropping by 82.1%, 59.3% and 54.5% post-fireworks, respectively. The sharp rise in FB was driven by widespread fireworks displays. The increase in IE reflected industrial recovery following the lifting of the COVID-19 control measures in 2023 [83]. SA growth was also influenced by firework emissions [84]. Similar variation in FB source was observed in Shandong, where FB contribution significantly increased from 16.0% during the benchmark period to 59.0% during the concentrated fireworks discharge periods [85]. VE, CC and dust exhibited similar patterns, decreasing their concentrations to $\text{PM}_{2.5}$ from 21.2, 22.2 and 16.9 $\mu\text{g m}^{-3}$ pre-fireworks to 15.8, 22.0 and 6.6 $\mu\text{g m}^{-3}$ during fireworks, achieving 12.5, 11.9 and 4.5 $\mu\text{g m}^{-3}$ post-fireworks. The reason for decreased VE was that large numbers of workers have returned home for the Spring Festival, while reduced dust levels resulted from diminished traffic and construction activities in the same period [86].

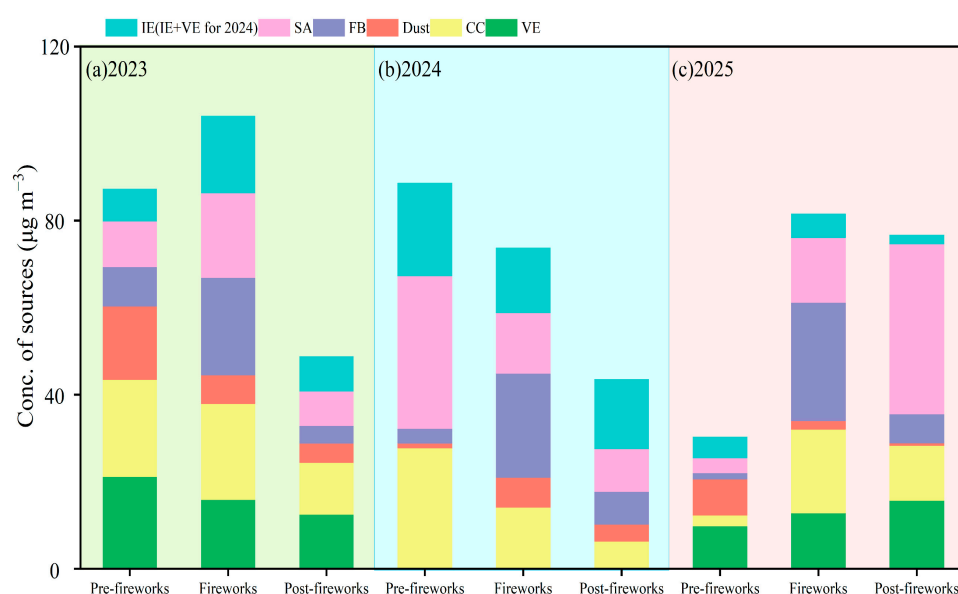


Figure 7. Concentration of emission sources to $\text{PM}_{2.5}$ during pre-fireworks, fireworks and post-fireworks periods in XY from 2023 to 2025: (a) 2023; (b) 2024; (c) 2025.

In 2024, the levels of FB and dust measured 19.9 and 5.7 $\mu\text{g m}^{-3}$ during fireworks, 6.3–7.1 and 1.7–3.2 times higher than the values of the pre-fireworks and post-fireworks periods, respectively. In contrast, the concentrations of SA and CC dramatically declined from 29.2 and 23.2 $\mu\text{g m}^{-3}$ to 11.6 to 11.8 $\mu\text{g m}^{-3}$, and kept dropping to 8.2 and 5.3 $\mu\text{g m}^{-3}$. The lower SA concentration during fireworks might be attributed to regional transport of secondary inorganic aerosols and favorable meteorological conditions [87], while the decreased CC was possibly due to elevated temperature (from 5.9 °C to 12.4 °C) during fireworks phase reducing residential coal consumption for heating. Meanwhile, the concentrations of IE + VE first declined from 17.7 $\mu\text{g m}^{-3}$ to 12.4 $\mu\text{g m}^{-3}$, and recovered to 13.3 $\mu\text{g m}^{-3}$, reflecting population mobility for celebrating the Spring Festival.

In 2025, the levels of FB, CC and IE reached 27.2, 19.2 and 5.4 $\mu\text{g m}^{-3}$ during fireworks, exceeding the pre-fireworks and post-fireworks values by factors of 1.1–19.3 and 1.5–4.1, respectively. The SA values showed a direct increasing trend, which were 3.4 $\mu\text{g m}^{-3}$ pre-fireworks, 14.9 $\mu\text{g m}^{-3}$ during fireworks and 39.1 $\mu\text{g m}^{-3}$ post-fireworks, suggesting enhanced secondary formation. The level of VE initially increased from 9.8 to 12.9, and subsequently to 15.7 $\mu\text{g m}^{-3}$. By contrast, dust values declined consistently, falling from 8.3 $\mu\text{g m}^{-3}$ to 1.9 $\mu\text{g m}^{-3}$, and further to 0.6 $\mu\text{g m}^{-3}$. Overall, FB and SA collectively accounted for 40.2% to 51.6% of $\text{PM}_{2.5}$ during the fireworks period from 2023 to 2025, which were the critical sources to the observed increase in $\text{PM}_{2.5}$.

4. Conclusions

This study investigated the impacts of fireworks displays on $\text{PM}_{2.5}$, chemical compositions, acidity and source contributions in a forestry city during the Spring Festival from 2023 to 2025. The results indicated that the fireworks period was characterized by significantly elevated levels of $\text{PM}_{2.5}$, fireworks-related species (K, Cl^-) and acidity. $\text{PM}_{2.5}/\text{CO}$ and SIA/CO ratios exhibited increasing trends during the fireworks period over three years, with factors of 1.4–2.3 and 1.1–3.4 related to levels of the pre-fireworks period, indicating obvious increases in secondary inorganic aerosols. Consequently, the increase in SOR ($R^2 = 0.73$ – 0.88 for RH, $R^2 = 0.41$ – 0.73 for acidity and $R^2 = 0.54$ – 0.85 for K in three years, $p < 0.01$) and NOR ($R^2 = 0.44$ – 0.53 for O_x , $R^2 = 0.43$ – 0.58 for acidity and $R^2 = 0.31$ – 0.45 for K in three years, $p < 0.01$) during the fireworks period were amplified by the synergistic effects of high RH, elevated O_x , and enhanced acidity, leading to more efficient SO_4^{2-} and NO_3^- formation. PMF method confirmed that the levels of fireworks burning (FB) and secondary aerosols (SA) source during fireworks rose by factors of 2.5–19.3 and 1.9–4.4, respectively, compared to the pre-fireworks phase. Therefore, this study emphasized the urgent need for adopting targeted policy interventions to inhibit fireworks combustion and secondary inorganic aerosols formation during the Spring Festival in future, given their promoting effects on increased $\text{PM}_{2.5}$.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/toxics13121009/s1>, Figure S1: Five and six factor profiles resolved by PMF in XY: (a) 2023; (b) 2024; (c) 2025; Figure S2: Correlation of observed $\text{PM}_{2.5}$ concentration and reconstructed $\text{PM}_{2.5}$ concentration resolved by PMF in XY; Figure S3: The relationships of AE with CE in XY; Figure S4: The concentrations of NO_2 and SO_2 changes with increasing acidity in three years: (a) 2023; (b) 2024; (c) 2025; Figure S5: The SOR and NOR ratios and O_x concentrations from 2023 to 2025 in XY: (a) 2023; (b) 2024; (c) 2025; Table S1: The concentrations of $\text{PM}_{2.5}$ and chemical compositions during the pre-fireworks, fireworks and post-fireworks periods in 2023. (unit: $\mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$ and inorganic water-soluble ions while ng m^{-3} for trace elements); Table S2: The concentrations of $\text{PM}_{2.5}$ and chemical compositions during the pre-fireworks, fireworks and post-fireworks periods in 2024. (unit: $\mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$ and inorganic water-soluble ions while ng m^{-3} for trace elements); Table S3: The concentrations of $\text{PM}_{2.5}$ and chemical compositions during the

pre-fireworks, fireworks and post-fireworks periods in 2025. (unit: $\mu\text{g m}^{-3}$ for PM_{2.5} and inorganic water-soluble ions while ng m^{-3} for trace elements); Table S4: Statistical analysis of NOR, SOR, RH, Ox, K and aerosol acid during three periods in 2023–2025; Table S5: Correlation analysis of SIA, Ws, RH and T during three periods in 2024; Table S6: Statistical analysis of PM_{2.5}, SIA and CO in three years; Table S7: Correlation analysis of PM_{2.5}, SIA and CO during three periods in 2023–2025. References [82,88–93] are cited in the Supplementary Materials.

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Abbreviations

The following abbreviations are used in this manuscript:

XY	Xinyang
FB	Fireworks burning
VE	Vehicle emissions
IE	Industrial emissions
IE + VE	Industrial emissions + Vehicle emissions
SA	Secondary aerosols
CC	Coal combustion

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