

Article

Effectiveness of Control Strategies for Spring Atmospheric VOCs at a Typical Urban Site in Beijing: Evidence from Compositional and Source Variations

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Abstract

A retrospective analysis of atmospheric volatile organic compounds in urban Beijing during spring 2017–2019 and 2025 reveals a profound transition in pollution characteristics following long-term control policies. Integrating field observations with positive matrix factorization (PMF), results reveal a fundamental atmospheric transition toward mobile source predominance and reduced chemical reactivity. Total volatile organic compound concentrations declined by 31.0% (to 23.7 $\mu\text{g}/\text{m}^3$), driven by a massive 90.7% reduction in aromatics. Conversely, gasoline vehicle exhaust surged to constitute 66.9% of total volatile organic compound mass. This shift altered the chemical reactivity pattern: alkenes replaced aromatics as the primary drivers of ozone formation potential (46.4%), yet residual aromatics continued to dominate secondary organic aerosol formation potential (83.3%). Crucially, a coordinated total volatile organic compounds:NO_x reduction ratio of 0.48:1 compared to 2017 successfully lowered spring O₃ levels by 8.4%. These findings substantiate the efficacy of past synergistic controls but emphasize that future deep abatement must prioritize targeting high-reactivity alkenes from mobile sources and residual solvent-based aromatics.

Keywords: volatile organic compounds; ozone formation potential; positive matrix factorization; long-term control policies

1. Introduction

China's rapid industrialization and urbanization processes have substantially aggravated regional air pollution complexes. Notably, synergistic interactions between fine particulate matter (PM_{2.5}) and ozone (O₃) have emerged as a critical impediment constraining sustained air quality improvement [1]. Although the national annual average PM_{2.5} concentration has demonstrated a significant downward trajectory since 2013, O₃ pollution has persisted in worsening: in 2019, the 90th percentile MDA8-O₃ concentrations in Chinese prefecture-level cities increased by 6.5% year-on-year, with non-attainment days increasing by 2.3% [2]. The North China Plain exhibits distinctive spatiotemporal pollution characteristics; emission reduction measures driven by clean air initiatives have unexpectedly prolonged the O₃ pollution season, extending it toward winter and spring, resulting in frequent spring PM_{2.5}–O₃ complex pollution events in cities such as Beijing [3]. For instance, from 30 April to 1 May 2020, citywide monitoring stations recorded simultaneous concentrations of MDA8 O₃ exceeding 140 $\mu\text{g}/\text{m}^3$ and PM_{2.5} exceeding 100 $\mu\text{g}/\text{m}^3$.



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Volatile organic compounds (VOCs) are important precursors of O_3 and $PM_{2.5}$. Atmospheric chemistry indicates that springtime O_3 formation in Beijing generally falls within a VOC-sensitive regime [2,4]; furthermore, enhanced atmospheric oxidation capacity (e.g., elevated HO_x radical levels associated with higher O_3) promotes rapid secondary $PM_{2.5}$ formation. Therefore, controlling ambient VOCs is essential for synergistically reducing the frequency of spring O_3 – $PM_{2.5}$ complex pollution episodes.

To tackle this challenge, Beijing executed a comprehensive framework of VOC control strategies from 2017 to 2025, targeting both source structure and emission standards. For stationary sources, regulations were tightened to mandate low-VOC architectural coatings and enforce a water-based substitution rate of over 60% in the furniture-manufacturing sector [5]. Simultaneously, the transportation sector underwent rigorous upgrading with the implementation of the Phase 6b emission standards for both light-duty and heavy-duty vehicles [6,7]. Beyond specific sources, industrial precision management was enforced via the “one factory, one policy” approach across petrochemicals and ten other key sectors [8]. Ultimately, these measures were integrated into a broader framework for the synergistic reduction of pollution and carbon emissions, promoting deep treatment and coordinated control alongside energy conservation mandates [9].

Previous studies have extensively characterized VOC composition and source apportionment in Beijing and other Chinese cities, primarily focusing on summertime pollution episodes or single-year observational datasets [10–17]. These studies generally reported that vehicle exhaust, solvent utilization, and industrial emissions were dominant VOC sources and that highly reactive alkenes and aromatics played critical roles in ozone formation. However, systematic evaluations of the long-term evolution of VOC concentrations, chemical composition, and source contributions under multi-stage emission control policies remain limited. In particular, investigations targeting springtime VOC characteristics are relatively scarce, despite the observed extension of ozone pollution into this transitional season.

Accordingly, this study presents a long-term, spring-focused analysis linking species-resolved reactivity (OFP , LOH , and $SOAFP$) with policy implementation timelines, while quantifying structural shifts in VOC sources across successive control stages in Beijing. By integrating multi-year field observations with source apportionment, this study elucidates how coordinated precursor reduction strategies translate into observable changes in ozone responses, thereby providing scientific evidence for refining future VOC control frameworks.

2. Materials and Methods

2.1. Site Description and Observing Period

The observation site was located on the roof of the Atmospheric Photochemical Smog Simulation Laboratory at the Chinese Research Academy of Environmental Sciences (CRAES) (40.04° N, 116.42° E) in the Chaoyang District of Beijing. The sampling port was 8 m above ground. The sampling site was located in an urban area of Beijing, which is in a mixed functional area of commerce, transportation and residence. There were no large-scale pollution sources in the surroundings. Furthermore, an unobstructed view and good atmospheric diffusion were observed. Therefore, the sampling site can basically represent the level of VOC pollution in urban Beijing.

We selected the online observation data of atmospheric VOCs from 1 March to 31 May of each year from 2017 to 2019 and 2025 for this study.

2.2. Observing Instruments

VOCs were continuously observed and analyzed by an Airmo VOC online Analyzer (GC-866, Chromatotec Group, Saint-André-de-Cubzac, France). The instrument consists of two independent sampling and analysis systems. A total of 84 VOCs, including 26 alkanes, 15 alkenes, 25 halocarbons (not covered in this study), 17 aromatics and one alkyne (acetylene), were observed. Their detector is a flame ionization detector (FID). The detailed information about the observing instrument was described in our previous studies.

To ensure data accuracy and effectiveness, rigorous quality assurance and control (QA/QC) protocols were implemented: (1) external calibration showed strong linearity ($R^2 > 0.9$) with relative standard deviations (RSDs) $< 10\%$ across all seasons; (2) internal calibration using n-butane, n-hexane, and benzene was performed every 24 h, requiring deviations $\leq 10\%$; and (3) sample tubes were maintained at 22–27 °C via heated jackets with thermal insulation.

In this study, concentrations of O₃ and NO_x were observed by instruments from Thermo Environmental Instruments (Thermo Scientific, Waltham, MA, USA). The detailed information about the observing instrument was described in our previous studies.

2.3. Quality Assurance and Quality Control

In order to ensure the accuracy and effectiveness of Airmo VOC online observation data, strict quality assurance and control must be implemented. (1) Sample tubes were wrapped with a heating jacket and thermal insulation to ensure their temperature remained stable at 22–27 °C. (2) External calibration was conducted using the American Photochemical Assessment Monitoring Stations (PAMS) standard VOC mixtures. PAMS standard gases are standard VOC mixtures used for external instrument calibration. These gas mixtures are traceable and conform to EPA certification standards, ensuring the accuracy and consistency of measurement results. The specific formulations and concentrations of these standard gases are determined by EPA guidance documents, such as the EPA's PAMS Technical Assistance Document. They are not arbitrarily mixed but are rigorously certified to ensure data comparability among different monitoring stations. Five concentration gradients were prepared for each calibration, with three replicates per level, yielding correlation coefficients above 0.9. (3) Internal calibration was performed every 24 h using n-butane, n-hexane, and benzene, ensuring deviations within 10%. (4) The instrument was equipped with chromatogram analysis software. Thus, we could view the peak area, retention time and concentration of each component, allowing us to carry out timely debugging of the instrument.

The Model49i ozone analyzer and Model42i nitrogen oxide analyzer were referred to national standards of calibration. The automatic zero point correction instrument was used to correct the monitoring instrument every month, and full degree correction and accuracy correction of the multi-gas and multi-range infrared gas analysis system were carried out on the observation instrument every year to reduce the deviation error caused by the instrument.

2.4. Methods

2.4.1. Estimation of Secondary Organic Aerosol Formation Potential (SOAFP) and Ozone Formation Potential (OFP)

The OFP of the measured VOCs in CRAES is estimated using Equation (1):

$$\text{OFP}_{\text{voci}} = [\text{VOC}_i] \times \text{MIR}_{\text{value}_i} \quad (1)$$

where OFP_{voci} ($\mu\text{g}/\text{m}^3$) is the ozone formation potential of the i VOC, $[\text{VOC}_i]$ ($\mu\text{g}/\text{m}^3$) is the concentration of the i th VOC, and $\text{MIR}_{\text{value}_i}$ is the maximum incremental reactivity

(MIR) of the i th VOC, following the values reported by Carter (2010) [18]. Note that the uncertainty in OFP_{voci} stems primarily from measurement uncertainties in [VOC_{*i*}] and potential variations in representative MIR coefficients under different atmospheric conditions. In addition to OFP, the SOAFP of the VOCs was also estimated. Equation (2) was used to calculate the SOAFP of VOCs.

$$\text{SOAFP}_{\text{voci}} = [\text{VOC}_i] \times \text{FAC}_i \quad (2)$$

where SOAFP_{voci} ($\mu\text{g}/\text{m}^3$) is the secondary organic aerosol formation potential (SOAFP) of the i th VOC, [VOC_{*i*}] ($\mu\text{g}/\text{m}^3$) is the concentration of the i th VOC, and FAC_{*i*} is the fractional aerosol coefficient of the i th VOC [19]. Similar to OFP, the uncertainty in SOAFP_{voci} arises from concentration measurement errors and the inherent limitations or variability associated with FAC values. The FAC values for only 28 measured VOCs were available in the literature [19,20]; therefore, the SOAFP for only those VOCs was estimated.

2.4.2. PMF Model

Positive matrix factorization (PMF) is a conceptual model that can be used to explore potential source categories and contributions. In this study, the positive matrix factorization model (PMF 5.0) recommended by the US Environmental Protection Agency (EPA) was used to analyze the pollution sources of VOC species. As shown in Equations (3) and (4), the PMF model could be expressed as a chemical mass balance equation in terms of contributions from p -independent sources to the n chemical species measured.

$$X_{ij} = \sum_{k=1}^p G_{ik} \times F_{kj} + E_{ij}; i = 1, 2, 3, \dots, m, j = 1, 2, 3, \dots, n \quad (3)$$

where X_{ij} is the j th chemical species concentration determined in the i th sample; G_{ik} is the species contribution of the k th source to the i th sample; F_{kj} is the loading of the j th species on the k th factor; and E_{ij} is the residual representing the unexplained portion of the observation after factorization. The target of the PMF model is to find the global minimum of the following equation:

$$Q = \sum_{i=1}^n \sum_{j=1}^m \left(\frac{E_{ij}}{U_{ij}} \right)^2 \quad (4)$$

where U_{ij} is the uncertainty of the j th species in the i th sample calculated as the following equation:

$$U_{ij} = \frac{5}{6} \times \text{MDL} \quad (5)$$

$$U_{ij} = \sqrt{(\text{errorfraction} \times \text{concentration})^2 + (0.5 \times \text{MDL})^2} \quad (6)$$

If the concentration is less than the corresponding method detection limit (MDL), Equation (5) is used to calculate the uncertainty; if the concentration is higher than the MDL, Equation (6) is used.

Not all measured species were input into the PMF model in this study. There are some rules to choose the appropriate VOC species: (1) highly concentrated species are included; (2) species indicating VOC sources are retained; (3) species with a high percentage below the detection limit (>50%) are excluded [10,21,22].

Factor number determination was based on comprehensive diagnostics, including Q value trends, residual distribution, interpretability of source profiles, bootstrap stability tests, and displacement analysis. Among tested solutions (4–8 factors), the six-factor solution exhibited the most robust statistical performance, with $\Delta Q/Q = 95.1\%$, exceeding the 95% acceptance threshold, and demonstrated high factor mapping stability (>90% in bootstrap runs). Therefore, the six-factor solution was selected as the optimal configuration.

Importantly, identical PMF settings and selection criteria were applied consistently across different spring periods to ensure methodological comparability. This allows reliable evaluation of structural shifts in VOC source contributions before and after implementation of coordinated VOC control measures.

3. Results and Discussion

3.1. Ambient VOC Concentration Levels and Composition

Figure 1 and Table 1 present the variations in mass concentrations of ambient VOCs, NO_x, and O₃ in urban Beijing during spring from 2017 to 2019 and 2025. The average concentration of total VOCs (TVOCs) marginally decreased from $34.36 \pm 19.94 \mu\text{g}/\text{m}^3$ in 2017 to $33.48 \pm 20.46 \mu\text{g}/\text{m}^3$ in 2018, then increased to $39.14 \pm 32.07 \mu\text{g}/\text{m}^3$ in 2019. By 2025, the TVOC concentration substantially declined to $23.72 \pm 14.49 \mu\text{g}/\text{m}^3$, representing a 39.5% reduction compared to 2019, and the concentration fluctuation range was markedly narrower. The average NO_x concentration significantly decreased from $83.91 \mu\text{g}/\text{m}^3$ in 2017 to $66.04 \mu\text{g}/\text{m}^3$ in 2018, then rebounded to $70.00 \mu\text{g}/\text{m}^3$ in 2019 (a 16.09% reduction compared to 2017). By 2025, the average NO_x concentration had fallen to $24.40 \mu\text{g}/\text{m}^3$, representing a substantial 65.34% reduction compared to 2019. Compared to TVOCs, the reduction in NO_x concentration was more pronounced and commenced earlier. In contrast, the average O₃ concentration increased from $53.21 \mu\text{g}/\text{m}^3$ in 2017 to $63.87 \mu\text{g}/\text{m}^3$ in 2018, an increase of 20.03% occurring against a backdrop of significant NO_x reduction and a slight decrease in TVOCs. When both NO_x and VOC concentrations rebounded in 2019 relative to 2018, the O₃ concentration decreased by $4.40 \mu\text{g}/\text{m}^3$ to $61.06 \mu\text{g}/\text{m}^3$ compared to 2018. In the spring of 2025, both TVOCs and NO_x showed notable declines: with TVOC and NO_x reduced by 33.80% and 70.93%, respectively, since 2017, the overall mass reduction ratio reached 0.48:1 (TVOC:NO_x). The average O₃ concentration dropped to $48.72 \mu\text{g}/\text{m}^3$, an 8.44% decrease. The differing O₃ responses to precursor variations across years underscore the critical importance of synergistic VOCs and NO_x reduction.

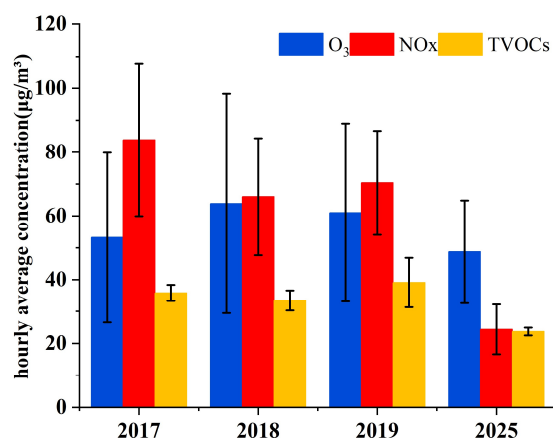


Figure 1. Hourly average concentrations of O₃, NO_x and VOCs in an urban area of Beijing during spring from 2017 to 2019 and 2025.

Table 2 reveals limited interannual thermal variability (12.2–13.5 °C), suggesting that temperature-driven changes in VOC volatilization and oxidation capacity were likely modest across years. Given the narrow temperature range, its contribution to interannual TVOC differences is expected to be small. In contrast, wind speed exhibited greater variability, particularly the elevated value in 2019, which may have enhanced atmospheric dispersion and reduced local accumulation. However, the VOC concentration in spring 2019 was highest, and NO_x concentrations were also higher than in 2018, which implies that emission intensity in 2019 may have been stronger than in 2018.

Table 1. Average hourly mass concentration of VOCs during the observation period of spring in an urban area of Beijing in 2017–2019 and 2025 (average concentration $\pm$ standard deviation) ($\mu\text{g}/\text{m}^3$).

Variety		In Spring of 2017		In Spring of 2018		In Spring of 2019		In Spring of 2025	
		Range	Average $\pm$ SD	Range	Average $\pm$ SD	Range	Average $\pm$ SD	Range	Average $\pm$ SD
Alkanes	concentration contribution	0.16–84.05	19.63 $\pm$ 12.88 57.13%	0.23–121.46	22.84 $\pm$ 14.15 68.26%	2.70–160.77	24.68 $\pm$ 20.25 63.07%	0–94.49	19.42 $\pm$ 12.73 81.87%
Alkenes	concentration contribution	0.15–60.19	2.59 $\pm$ 1.14 7.54%	0.12–18.34	1.57 $\pm$ 1.20 4.69%	0.10–65.85	5.07 $\pm$ 6.50 12.96%	0–14.55	2.15 $\pm$ 1.42 9.06%
Acetylene	concentration contribution	0.03–7.47	0.74 $\pm$ 0.75 2.15%	0.01–4.60	0.36 $\pm$ 0.66 1.08%	0.07–11.98	1.12 $\pm$ 1.60 2.86%	0–7.08	1.04 $\pm$ 0.81 4.49%
Aromatics	concentration contribution	0.21–90.40	11.40 $\pm$ 4.14 33.18%	0.12–41.22	8.68 $\pm$ 6.41 25.97%	0.26–127.59	8.26 $\pm$ 9.10 21.11%	0–16.24	1.06 $\pm$ 1.88 4.39%
TVOCs	concentration	4.18–120.31	34.36 $\pm$ 19.94	2.59–134.17	33.48 $\pm$ 20.46	5.13–229.37	39.14 $\pm$ 32.07	0–97.92	23.72 $\pm$ 14.49

Table 2. Meteorological conditions and atmospheric pollutant concentrations during spring 2017–2019 and 2025.

Year	2017	2018	2019	2025
Temperature ($^{\circ}\text{C}$)	13.5	12.9	13.2	12.2
Pressure (hPa)	1010.4	1014.2	1009.5	1012.2
Wind Direction ($^{\circ}$)	195.3	165.9	203.1	213.8
Wind Speed (m/s)	3.4	2.0	4.2	3.5
TVOCs ($\mu\text{g}/\text{m}^3$)	35.8	33.4	39.1	23.7

Figure 2 reveals the proportions of VOC components also underwent substantial changes. The dominance of alkanes was further enhanced. While their mass concentration remained relatively stable, their percentage contribution increased from 57.13% (mass concentration $19.63 \mu\text{g}/\text{m}^3$) in 2017 to 81.87% (mass concentration $19.42 \mu\text{g}/\text{m}^3$) in 2025, becoming the overwhelmingly predominant group. The ranking of high-concentration species changed markedly; the top four species in 2025 were short-chain alkanes: isobutane (25.4%), propane (18.0%), ethane (17.7%), and n-butane (15.3%). In 2017, however, the top four were propane (13.40%), benzene (10.53%), ethane (9.53%), and n-butane (7.84%). This indicates significant reductions in benzene and n-butane concentrations (though n-butane remains prominent in 2025 compared to 2017), a slight decrease in ethane concentration, no significant change in propane concentration, and a substantial increase in isobutane concentration. The distinct interannual variation patterns of different species suggest substantial changes in the sources of VOCs in Beijing's ambient air. The mass concentration of aromatics declined annually, and their percentage contribution also exhibited a pronounced downward trend, falling from 33.18% ($11.40 \mu\text{g}/\text{m}^3$) in 2017 to 4.39% (only $1.06 \mu\text{g}/\text{m}^3$) in 2025. The percentages of alkenes and alkynes (acetylene) displayed fluctuating changes. The alkene percentage reached a peak of 12.96% ($5.07 \mu\text{g}/\text{m}^3$) in 2019 but fell back to 9.06% in 2025, while the acetylene percentage marginally increased to 4.49%.

Based on Tables 1 and 3, total VOC control in Beijing in spring has been highly effective. Compared to 2014, the TVOC concentration decreased from $54.00 \mu\text{g}/\text{m}^3$ to $23.72 \mu\text{g}/\text{m}^3$ in 2025, representing a cumulative reduction of 56% over 11 years (an average annual decrease of 5.1%), with concentrations lowest in 2025 following a brief rebound in 2019 ($39.14 \mu\text{g}/\text{m}^3$). Aromatics, as key O_3 and SOA precursors, significantly decreased from $16.70 \mu\text{g}/\text{m}^3$ to $1.06 \mu\text{g}/\text{m}^3$ (a 94% reduction), and their contribution plummeted from 31% to 4%. Alkenes and alkynes were synchronously reduced by 71% (from $11.00 \mu\text{g}/\text{m}^3$ to $3.19 \mu\text{g}/\text{m}^3$), while the proportion of alkanes surged from 49% to 82% ($19.42 \mu\text{g}/\text{m}^3$).

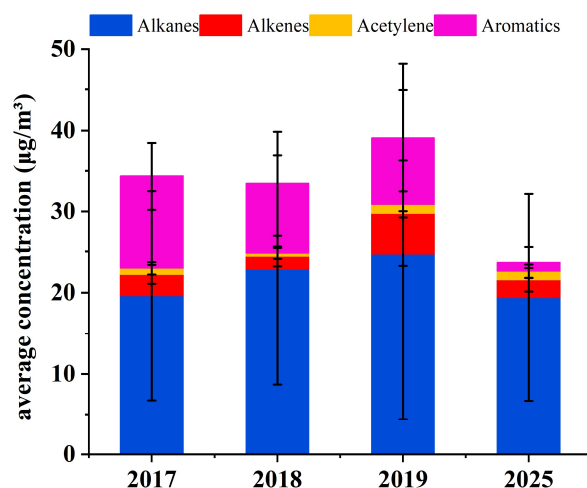


Figure 2. Average hourly mass concentrations of VOCs in an urban area of Beijing during spring from 2017 to 2019 and 2025.

Table 3. Comparison of ambient levels of alkanes, alkenes (alkynes) and aromatics in various cities during the spring observation period ($\mu\text{g}/\text{m}^3$).

Location	Beijing				Beijing [23]	Guangzhou [24]	Chengdu [25]	Wuhan [26]	Canada [27]	Turkey [28]	Korea [29]
Year	2017	2018	2019	2025	2014	2022	2019	2017	2016	2017	2021
Alkanes	19.63	22.84	24.68	19.42	26.30	42.11	45.71	65.11	33.68	41.2	15.50
Alkenes + Alkynes	3.33	1.93	6.19	3.19	11.00	8.63	20.86	13.87	4.37	9.30	-
Aromatics	11.40	8.68	8.26	1.06	16.70	17.47	52.41	12.24	7.48	26.2	12.92
Total VOCs	34.36	33.48	39.14	23.72	54.00	68.21	118.98	91.22	45.53	76.70	28.42

With spring 2025 in Beijing as a benchmark, the atmospheric TVOC mass concentration ($23.72 \mu\text{g}/\text{m}^3$) was found to be only 83% of that in South Korea ($28.42 \mu\text{g}/\text{m}^3$ in 2021), a country with a comparable level of development; only 33% of that in Guangzhou ($68.21 \mu\text{g}/\text{m}^3$ in 2022) and 20% of that in Chengdu ($118.98 \mu\text{g}/\text{m}^3$ in 2019), both major domestic cities; and only 52% of historical levels in developed countries such as Canada ($45.53 \mu\text{g}/\text{m}^3$ in 2016). The aromatic concentration ($1.06 \mu\text{g}/\text{m}^3$) was merely 8.2% of that in Seoul, South Korea ($12.92 \mu\text{g}/\text{m}^3$ in 2021), 6.1% ($17.47 \mu\text{g}/\text{m}^3$ in 2022) of Guangzhou's, and 2.0% ($52.41 \mu\text{g}/\text{m}^3$ in 2019) of Chengdu's. These data empirically demonstrate that Beijing has achieved international leadership in VOC deep pollution control by precisely targeting high-reactivity components (aromatics/alkenes/alkynes).

The interannual patterns observed here indicate that the response of O_3 to precursor emission reductions is not linear but strongly dependent on the relative magnitude and structural changes of NO_x and VOCs. Despite the substantial decline in NO_x concentrations, the staged variation in O_3 suggests that asynchronous reductions in precursors may have modulated photochemical efficiency. This finding highlights the importance of coordinated control strategies, as disproportionate reductions in individual precursors may alter photochemical responses and reduce the effectiveness of single-pollutant mitigation approaches.

3.2. Diurnal Variations in O_3 and Its Precursors

Diurnal variation characteristics provide a crucial window into air pollution mechanisms [30]. Figure 3 illustrates the diurnal evolution trends of TVOCs, O_3 , and NO_x from 2017–2019 to 2025. During nighttime (00:00–06:00), TVOC concentration stabilized within a range of 22.8 – $25.9 \mu\text{g}/\text{m}^3$ in 2025, showing a 51.6% decrease from the mid-night peak observed in 2019. In 2025, the peak TVOC concentration occurred at 10:00

($36.4 \mu\text{g}/\text{m}^3$), a 34.32% decrease compared to the average peak value ($36.13 \mu\text{g}/\text{m}^3$) during 2017–2019. During the afternoon (12:00–16:00), the minimum TVOC value dropped to $13.45 \mu\text{g}/\text{m}^3$, a 49.2% decrease from the 2017 to 2019 average value. The VOC consumption rate increased from $0.98 \mu\text{g}/(\text{h}\cdot\text{m}^3)$ to $1.68 \mu\text{g}/(\text{h}\cdot\text{m}^3)$, suggesting a possible enhancement of the atmospheric oxidation capacity in Beijing.

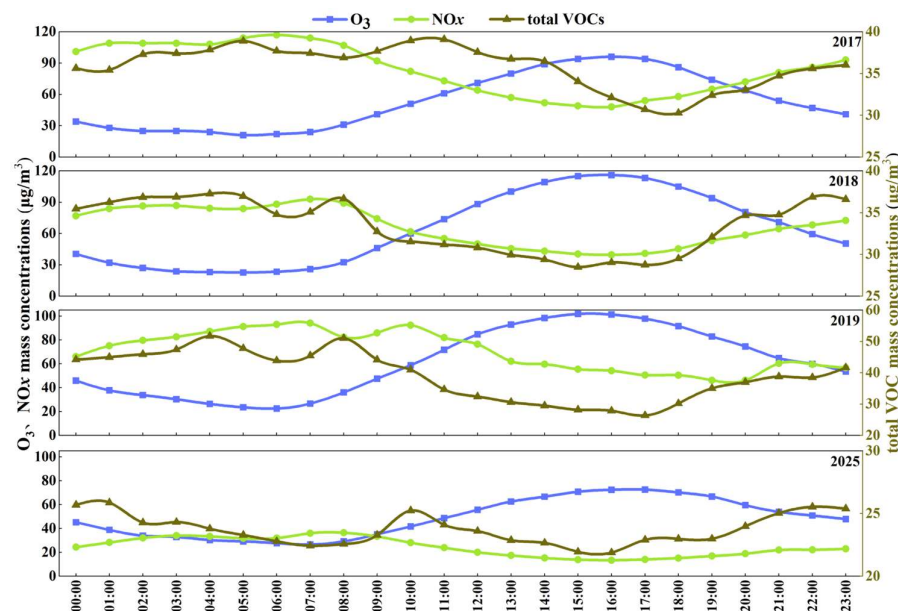


Figure 3. Daily variation trends of O_3 , NO_x , and total VOCs in urban Beijing during spring from 2017 to 2019 and 2025.

Analysis of the 2025 NO_x diurnal pattern shows that while the peak consistently occurred during the morning rush hour (07:00–08:00), the peak concentration decreased to $36 \mu\text{g}/\text{m}^3$, a 69.2% reduction compared to that of 2017. The evening rush hour peak (around 19:00) nearly disappeared, with concentrations maintained around $15 \mu\text{g}/\text{m}^3$. Furthermore, the NO_x valley at 16:00 was the lowest (as low as $13.45 \mu\text{g}/\text{m}^3$).

The diurnal pattern of O_3 in 2025 was characterized by a reduced peak and an elevated trough. The early morning valley increased to $29.19 \mu\text{g}/\text{m}^3$, a 39.8% rise compared to 2017. The afternoon peak plateaued between 70 and $72 \mu\text{g}/\text{m}^3$ from 15:00 to 17:00, a 24.04% decrease from the 2017 peak ($94.67 \mu\text{g}/\text{m}^3$). These changes are primarily attributed to NO_x reductions weakening the nocturnal titration of O_3 by NO_x , raising the morning valley. Simultaneously, the lower NO_x concentrations in the afternoon weakened the photochemical O_3 formation.

3.3. Identification of Key Compounds' Contributions Based on OFP, L_{OH} , and SOAFP

Tables 4 and 5 reveal that the profile of the top 10 compounds by mass concentration in spring 2025 changed substantially compared to the 2017–2019 period. As shown in Figure 4, the alkane contribution to total VOCs surged from 63.38% to 82.39%. Isobutane became the predominant compound in 2025, contributing 25.41%. Conversely, the total aromatic contribution decreased from 26.04% to 4.18%. Notably, toluene fell from 5.56% to 1.67%, and previously the second-largest contributor (10.53%), benzene, was excluded from the top 10 compounds by concentration.

Table 4. The top 10 key compounds based on their mass concentration (Conc.), OFP, L_{OH} and SOAFP and their contributions during the 2017–2019 observation period.

Compounds	Conc. (%)	Compounds	OFP (%)	Compounds	L ^{OH} (%)	Compounds	SOAFP (%)
Propane	13.40	Ethylene	13.42	Propene	12.05	Toluene	21.16
Benzene	10.53	Propene	9.62	<i>cis</i> -2-Butene	11.98	Benzene	14.52
Ethane	9.53	Toluene	9.33	Ethylene	10.59	<i>n</i> -Dodecane	9.60
<i>n</i> -Butane	7.84	<i>m</i> -Xylene + <i>p</i> -Xylene	9.19	<i>m</i> -Xylene + <i>p</i> -Xylene	5.11	<i>m</i> -Xylene + <i>p</i> -Xylene	8.76
Toluene	5.56	<i>cis</i> -2-Butene	7.26	Benzene	3.84	<i>n</i> -Decane	7.10
<i>n</i> -Decane	4.47	<i>n</i> -Butane	3.78	Cyclohexane	3.42	Ethylbenzene	6.88
Cyclohexane	4.21	<i>o</i> -Xylene	3.30	<i>n</i> -Decane	3.39	α -Pinene	4.48
<i>n</i> -Hexane	3.98	1,2,4-Trimethylbenzene	3.20	Toluene	3.33	<i>o</i> -Xylene	4.32
<i>n</i> -Dodecane	3.82	Benzene	3.18	Propane	3.25	<i>n</i> -Undecane	3.45
Ethylene	3.55	Propane	2.75	<i>n</i> -Butane	3.12	β -Pinene	3.02
Sum of the top 10	66.89	Sum of the top 10	65.03	Sum of the top 10	60.08	Sum of the top 10	83.29

Table 5. The top 10 key compounds based on their mass concentration, OFP, L_{OH} and SOAFP and their contributions in the spring of 2025.

Compounds	Conc. (%)	Compounds	OFP (%)	Compounds	L ^{OH} (%)	Compounds	SOAFP (%)
Isobutane	25.41	Ethylene	23.94	Isobutane	14.29	Toluene	34.85
Propane	18.02	Isobutane	14.29	Propylene	13.61	<i>m/p</i> -Xylene	13.38
Ethane	17.69	Propylene	12.73	Ethylene	12.26	<i>o</i> -Xylene	13.04
<i>n</i> -Butane	15.29	<i>n</i> -Butane	8.04	<i>n</i> -Butane	9.56	Ethylbenzene	9.66
Ethylene	5.72	<i>m/p</i> -Xylene	4.71	Isoprene	8.28	Benzene	8.64
Acetylene	4.51	Toluene	4.66	<i>trans</i> -2-Butene	6.23	Styrene	5.67
Isopentane	3.19	<i>trans</i> -2-Butene	4.26	Propane	5.26	<i>n</i> -Dodecane	5.20
Propylene	1.99	Propane	4.07	<i>m/p</i> -Xylene	4.16	Ethylene	1.55
Toluene	1.67	Isopentane	3.82	1-Pentene	3.22	<i>m</i> -Ethyltoluene	1.53
<i>m/p</i> -Xylene	0.85	<i>o</i> -Xylene	3.50	Isopentane	3.01	<i>n</i> -Undecane	1.23
Sum of the top 10	94.33	Sum of the top 10	84.01	Sum of the top 10	79.89	Sum of the top 10	94.73

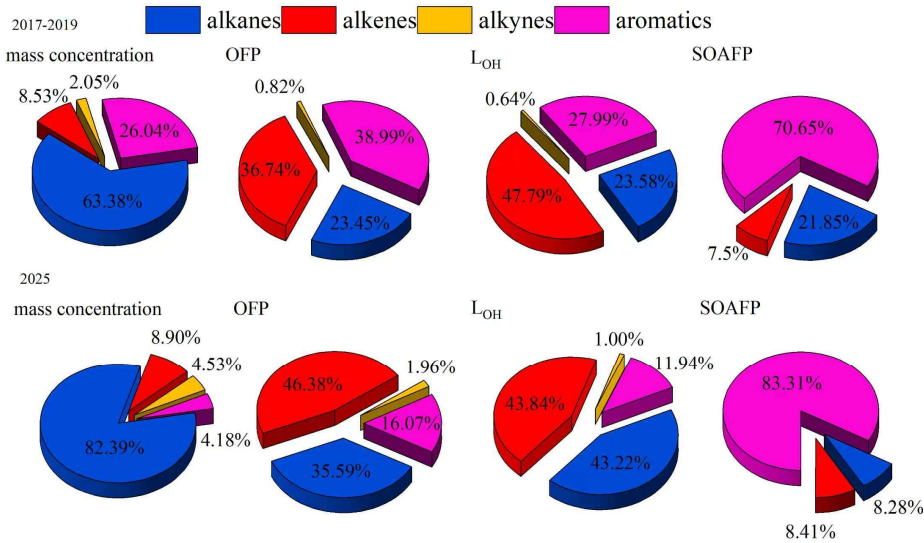


Figure 4. Contribution of different types of VOCs to mass concentration, OFP, L_{OH} and SOAFP from 2017 to 2019 and 2025.

Regarding the ozone formation potential (OFP), the alkene contribution to OFP rose from 36.74% to 46.38%, becoming the largest contributing group. Among key compounds, ethylene’s contribution surged from 13.42% to 23.94%, ranking first, followed by propylene, which increased from 9.62% to 12.73%. In contrast, the aromatic OFP contribution dropped from 38.99% to 16.07%. Specifically, toluene decreased from 9.33% to 4.66%, and xylene compounds declined from 12.49% to 8.21%. Meanwhile, the alkane OFP contribution increased from 23.45% to 35.59%, with isobutane alone contributing 14.29%.

The relative contribution of different VOC compounds to Hydroxyl Radical Loss Rate (L_{OH}) also underwent significant variations. The contribution of alkanes nearly doubled,

increasing from 23.58% to 43.22%, driven primarily by isobutane, which emerged as the largest contributor at 14.29%. In addition, alkene contribution slightly decreased from 47.79% to 43.84%, although the contributions of key compounds propylene (from 12.05% to 13.61%) and ethylene (from 10.59% to 12.26%) increased slightly. In contrast, the aromatic contribution fell from 27.99% to 11.94%.

For secondary organic aerosol formation potential (SOAFP): The aromatic contribution to SOAFP strengthened significantly, increasing by 12.65% to 83.31%. This increase was largely propelled by toluene, whose individual contribution surged from 21.16% to 34.85%, making it the single most important precursor. Xylene isomers also remained major contributors, collectively accounting for 26.42% of the total SOAFP (*m/p*-xylene: 13.38%; *o*-xylene: 13.04%). Conversely, the contribution from long-chain alkanes was substantially reduced, indicating the effectiveness of targeted control measures. For instance, *n*-dodecane's contribution decreased from 9.60% to 5.20%, while *n*-decane was no longer ranked among the top ten contributors.

These results suggest that while control strategies for long-chain alkanes and certain aromatics (e.g., benzene and xylenes) have been effective, compounds such as toluene, ethylene, and propylene emerge as crucial targets for future mitigation efforts in 2025. The substantial decline in aromatic contribution yet persistent dominance in SOAFP indicates that structural emission control reshapes mass composition more rapidly than secondary formation potential.

3.4. Source Apportionment Based on PMF

The source apportionment of VOCs by PMF revealed a dramatic restructuring of emission sources between the 2017 and 2019 periods and 2025 (Figure 5). The most profound change was the contribution of gasoline vehicle exhaust, which surged from an average of 26.24% to 66.92%, establishing it as the preeminent source of atmospheric VOCs in Beijing. In stark contrast, several key sources saw substantial reductions. The contribution from gasoline evaporation sharply decreased from a range of 15.03–17.85% to only 2.37% in 2025, representing an 84–87% decline. Similarly, fossil fuel combustion's share fell from 17.85–21.61% to 12.07% (a 29–44% reduction). Diesel exhaust contribution first increased, then decreased, peaking at 19.7% in 2019 but falling back to 5.28% in 2025 (lower than in 2017), demonstrating strengthened controls on diesel vehicles. Meanwhile, other sources exhibited more moderate changes. The contribution of solvent use remained relatively stable within the range of 4.52–7.74%, while the petrochemical industry's contribution showed a modest increase from 2.28% to 6.87%.

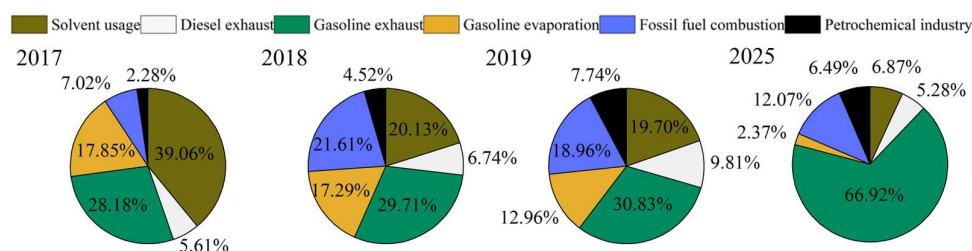


Figure 5. Source apportionment proportions via PMF in an urban area of Beijing during spring from 2017 to 2019 and 2025.

The analysis of OFP contributions further elucidated the chemical characteristics of each source and the origins of key reactive compound classes (Figure 6). Gasoline and diesel vehicle exhausts were identified as the primary drivers of OFP, with both being overwhelmingly dominated by alkenes (84.6% and 94.7% of their respective OFP

contributions). Together, these two mobile sources accounted for 91.2% of the total alkene-related OFP, underscoring their critical role in regional ozone formation.

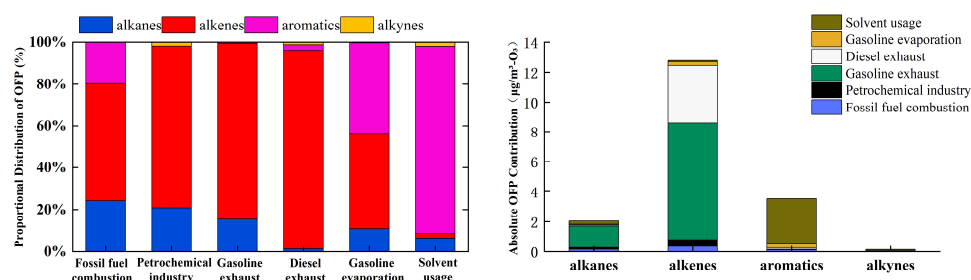


Figure 6. The atmospheric PMF-based OFP composition during 2025 spring.

In contrast, the OFP from solvent use was almost exclusively driven by aromatic compounds (89.5%), such as toluene, ethylbenzene, and xylenes. This source alone contributed to 85.4% of the total aromatic OFP, highlighting its importance as a target for controlling aromatic-driven ozone production. Other sources, such as fossil fuel combustion and the petrochemical industry, were also characterized mainly by alkenes (56.1% and 77.3%, respectively), while gasoline evaporation showed a more balanced profile between alkenes (45.3%) and aromatics (43.5%). The sources of alkanes were more dispersed, though gasoline vehicles remained the largest single contributor (70.0%).

These findings collectively indicate that effective ozone mitigation strategies must prioritize the control of alkenes from mobile sources while simultaneously addressing aromatic emissions from solvent use.

3.5. Study Limitations

Despite the robustness of the dataset, several limitations should be noted. This study is based on a single urban site, which may not fully represent spatial heterogeneity across different functional areas of Beijing. In addition, the measurement system does not comprehensively cover all oxygenated VOCs (OVOCs), higher-carbon species, or short-lived intermediates, potentially introducing uncertainty in OFP, L_{OH} , and SOAFP estimates. Furthermore, although meteorological conditions were compared descriptively, full meteorological normalization (deweathering) was not implemented, leaving some uncertainty in separating emission-driven changes from meteorological variability. Future multi-site observations, extended species coverage, and advanced deweathering methods would further strengthen the investigation of the effectiveness of control strategies for atmospheric VOCs.

4. Conclusions

Gasoline and diesel vehicle exhausts were identified as the primary contributors to alkene-related OFP, jointly accounting for 91.2% of total alkene-derived OFP. In contrast, solvent use contributed 85.4% of total aromatic OFP, representing the dominant source of aromatic-driven reactivity. Despite the substantial decline in aromatic mass concentrations, aromatics remained the major contributor to SOAFP. Therefore, effective mitigation strategies should prioritize reducing alkene emissions from mobile sources while sustaining stringent control of aromatic emissions from solvent-related activities.

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References

1. Liu, Z.; Gao, W.; Yu, Y.; Hu, B.; Xin, J.; Sun, Y.; Wang, L.; Wang, G.; Bi, X.; Zhang, G.; et al. Characteristics of PM_{2.5} mass concentrations and chemical species in urban and background areas of China: Emerging results from the CARE-China network. *Atmos. Chem. Phys.* **2018**, *18*, 8849–8887. [\[CrossRef\]](#)
2. Wang, T.; Xue, L.; Brimblecombe, P.; Lam, Y.F.; Li, L.; Zhang, L. Ozone pollution in China: A review of concentrations, meteorological influences, chemical precursors, and effects. *Sci. Total Environ.* **2017**, *575*, 1582–1596. [\[CrossRef\]](#)
3. Liu, Y.; Wang, H.; Jing, S.; Gao, Y.; Peng, Y.; Lou, S.; Cheng, T.; Tao, S.; Li, L.; Li, Y.; et al. Characteristics and sources of volatile organic compounds (VOCs) in Shanghai during summer: Implications of regional transport. *Atmos. Environ.* **2019**, *215*, 116902. [\[CrossRef\]](#)
4. Feng, T.; Zhao, S.; Zhang, X.; Wang, Q.; Liu, L.; Li, G.; Tie, X. Increasing wintertime ozone levels and secondary aerosol formation in the Guanzhong basin, central China. *Sci. Total Environ.* **2020**, *745*, 140961. [\[CrossRef\]](#) [\[PubMed\]](#)
5. GB/T 38597—2020; Technical Requirements for Low Volatile Organic Compounds Content Coating Products. China Standards Press: Beijing, China, 2020.
6. GB/T 18352.6-2016; Limits and Measurement Methods for Emissions from Light-Duty Vehicles (China 6). China Standards Press: Beijing, China, 2016.
7. GB/T 17691-2018; Limits and Measurement Methods for Emissions from Heavy-Duty Diesel Vehicles (China 6). China Standards Press: Beijing, China, 2018.
8. Ministry of Ecology and Environment of the People's Republic of China (MEE). MEE Notice No. 33; 2020 Volatile Organic Compounds Control Campaign Plan; Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2020.
9. Ministry of Ecology and Environment of the People's Republic of China (MEE). MEE Notice No. 42; Action Plan for Synergistic Reduction of Pollution and Carbon Emissions; Ministry of Ecology and Environment of the People's Republic of China: Beijing, China, 2022.
10. Li, H.; He, Q.; Song, Q.; Chen, L.; Song, Y.; Wang, Y.; Lin, K.; Xu, Z.; Shao, M. Diagnosing Tibetan pollutant sources via volatile organic compound observations. *Atmos. Environ.* **2017**, *166*, 244–254. [\[CrossRef\]](#)
11. Liu, B.; Liang, D.; Yang, J.; Dai, Q.; Bi, X.; Feng, Y.; Yuan, J.; Xiao, Z.; Zhang, Y.; Xu, H. Characterization and source apportionment of volatile organic compounds based on 1-year of observational data in Tianjin, China. *Environ. Pollut.* **2016**, *218*, 757–769. [\[CrossRef\]](#)
12. Liu, Y.; Song, M.; Liu, X.; Zhang, Y.; Hui, L.; Kong, L.; Zhang, Y.; Zhang, C.; Qu, Y.; An, J.; et al. Characterization and sources of volatile organic compounds (VOCs) and their related changes during ozone pollution days in 2016 in Beijing, China. *Environ. Pollut.* **2020**, *257*, 113599. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Mozaffar, A.; Zhang, Y.-L.; Fan, M.; Cao, F.; Lin, Y.-C. Characteristics of summertime ambient VOCs and their contributions to O₃ and SOA formation in a suburban area of Nanjing, China. *Atmos. Res.* **2020**, *240*, 104923. [\[CrossRef\]](#)
14. Wang, T.; Tao, J.; Li, Z.; Lu, X.; Liu, Y.; Zhang, X.; Wang, B.; Zhang, D.; Yin, S. Characteristic, source apportionment and effect of photochemical loss of ambient VOCs in an emerging megacity of Central China. *Atmos. Res.* **2024**, *305*, 107429. [\[CrossRef\]](#)
15. Wang, Z.; Tian, X.; Li, J.; Wang, F.; Liang, W.; Zhao, H.; Huang, B.; Wang, Z.; Feng, Y.; Shi, G. Quantitative evidence from VOCs source apportionment reveals O₃ control strategies in northern and southern China. *Environ. Int.* **2023**, *172*, 107429. [\[CrossRef\]](#)
16. Zhao, Q.; Bi, J.; Liu, Q.; Ling, Z.; Shen, G.; Chen, F.; Qiao, Y.; Li, C.; Ma, Z. Sources of volatile organic compounds and policy implications for regional ozone pollution control in an urban location of Nanjing, East China. *Atmos. Chem. Phys.* **2020**, *20*, 3905–3919. [\[CrossRef\]](#)

17. Zhu, Y.; Huang, L.; Li, J.; Ying, Q.; Zhang, H.; Liu, X.; Liao, H.; Li, N.; Liu, Z.; Mao, Y.; et al. Sources of particulate matter in China: Insights from source apportionment studies published in 1987–2017. *Environ. Int.* **2018**, *115*, 343–357. [[CrossRef](#)]
18. Carter, W.P.L. Development of the SAPRC-07 chemical mechanism. *Atmos. Environ.* **2010**, *44*, 5324–5335. [[CrossRef](#)]
19. Grosjean, D.; Seinfeld, J.H.J.A.E. Parameterization of the formation potential of secondary organic aerosols. *Atmos. Environ.* **1989**, *23*, 1733–1747. [[CrossRef](#)]
20. Grosjean, D. In situ organic aerosol formation during a smog episode: Estimated production and chemical functionality. *Atmos. Environ. Part A Gen. Top.* **1992**, *26*, 953–963. [[CrossRef](#)]
21. Sarkar, C.; Sinha, V.; Sinha, B.; Panday, A.K.; Rupakheti, M.; Lawrence, M.G. Source apportionment of NMVOCs in the Kathmandu Valley during the SusKat-ABC international field campaign using positive matrix factorization. *Atmos. Chem. Phys.* **2017**, *17*, 8129–8156. [[CrossRef](#)]
22. Zhou, X.; Li, Z.; Zhang, T.; Wang, F.; Wang, F.; Tao, Y.; Zhang, X.; Wang, F.; Huang, J. Volatile organic compounds in a typical petrochemical industrialized valley city of northwest China based on high-resolution PTR-MS measurements: Characterization, sources and chemical effects. *Sci. Total Environ.* **2019**, *671*, 883–896. [[CrossRef](#)]
23. Zhang, H.; Li, H.; Zhang, Q.; Zhang, Y.; Zhang, W.; Wang, X.; Bi, F.; Chai, F.; Gao, J.; Meng, L.; et al. Atmospheric Volatile Organic Compounds in a Typical Urban Area of Beijing: Pollution Characterization, Health Risk Assessment and Source Apportionment. *Atmosphere* **2017**, *8*, 61. [[CrossRef](#)]
24. He, C.Q.; Zou, Y.; Lv, S.J.; Flores, R.M.; Yan, X.L.; Deng, T.; Deng, X.J. The importance of photochemical loss to source analysis and ozone formation potential: Implications from in-situ observations of volatile organic compounds (VOCs) in Guangzhou, China. *Atmos. Environ.* **2024**, *320*, 120320. [[CrossRef](#)]
25. Wang, D.; Zhou, J.; Han, L.; Tian, W.; Wang, C.; Li, Y.; Chen, J. Source apportionment of VOCs and ozone formation potential and transport in Chengdu, China. *Atmos. Pollut. Res.* **2023**, *14*, 101730. [[CrossRef](#)]
26. Yang, Y.R.; Liu, X.G.; Qu, Y.; An, J.L.; Jiang, R.; Zhang, Y.H.; Sun, Y.L.; Wu, Z.J.; Zhang, F.; Xu, W.Q.; et al. Characteristics and formation mechanism of continuous hazes in China: A case study during the autumn of 2014 in the North China Plain. *Atmos. Chem. Phys.* **2015**, *15*, 8165–8178. [[CrossRef](#)]
27. Xiong, Y.; Bari, M.A.; Xing, Z.; Du, K. Ambient volatile organic compounds (VOCs) in two coastal cities in western Canada: Spatiotemporal variation, source apportionment, and health risk assessment. *Sci. Total Environ.* **2020**, *706*, 135970. [[CrossRef](#)]
28. Dörter, M.; Odabasi, M.; Yenisoğlu-Karakas, S. Source apportionment of biogenic and anthropogenic VOCs in Bolu plateau. *Sci. Total Environ.* **2020**, *731*, 139201. [[CrossRef](#)]
29. Lee, Y.; Won, S.R.; Shin, H.J.; Kim, D.G.; Lee, J.Y. Seasonal Characteristics of Volatile Organic Compounds in Seoul, Korea: Major Sources and Contribution to Secondary Organic Aerosol Formation. *Aerosol Air Qual. Res.* **2023**, *23*, 220429. [[CrossRef](#)]
30. Deng, Y.; Li, J.; Li, Y.; Wu, R.; Xie, S. Characteristics of volatile organic compounds, NO₂, and effects on ozone formation at a site with high ozone level in Chengdu. *J. Environ. Sci.* **2019**, *75*, 334–345. [[CrossRef](#)]

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