https://doi.org/10.5194/egusphere-2025-5730
Preprint. Discussion started: 16 December 2025

Secondary processes driven by multi-factor interactions dominate the aerosol nitroaromatic compound pollution during winter in China

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https://doi.org/10.5194/egusphere-2025-5730
Preprint. Discussion started: 16 December 2025

Abstract: Previous observational and chamber studies have highlighted the significant promoting effects of relative humidity (RH) or aerosol liquid water (ALW) on the formation of aerosol NACs. However, the applicability of this pattern needs further validation in large-scale field observations. This study presents the simultaneous investigation of the composition, abundance, origins of nitroaromatic compounds (NACs) in $PM_{2.5}$ across 11 Chinese cities during winter, with a focus on the key factors controlling NAC formation. Nitrophenols (NPs) and nitrocatechols (NCs) were identified as the main NAC groups, with their relative dominance varying by city. Higher total NAC concentrations were observed in northern cities, likely due to intensified coal and biomass burning. While secondary processes dominated wintertime NAC formation across all investigated cities, the average proportion of secondarily formed NACs was lower in the north (87%) than in the south (93%). This north-south disparity was more pronounced during polluted periods (82% vs. 96%). Furthermore, insignificant promoting effect of RH or ALW was found for most NACs except nitrosalicylic acids. The constraining effects from O_3, ·OH, and solar radiation on NAC formation were stronger in northern China due to higher levels of light-absorbing air pollution, potentially offsetting the promoting effects of RH and ALW. These findings suggest that the RH- and ALW-promoted NAC formation may not be universally applicable in real atmospheric environments, where multi-factor interactions play a critical role. This study highlights the necessity of considering complex field conditions in future research on NAC formation mechanisms.

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1. Introduction

Nitrated phenol compounds are a class of aromatic organics characterized by the presence of both nitro (–NO_2) and hydroxyl (–OH) functional groups, which are ubiquitous in the atmospheric gas phase and particle phase (Cai et al., 2022; Li et al., 2020a; Huo et al., 2024). Key members of this nitroaromatic compound (NAC) class include nitrophenols (NPs), nitrocatechols (NCs), nitrosalicylic acids (NSAs), nitroguaiacols (NGs), and their derivatives (Li et al., 2020c; Huang et al., 2024). NACs are abundant constituents of atmospheric fine particulate matter ($PM_{2.5}$) and are well recognized for their strong light-absorbing properties (Huang et al., 2025; Harrison et al., 2005; Wang et al., 2022). It has been reported that NAC species can contribute 4–50% or more to brown carbon light absorption (Mohr et al., 2013; Huang et al., 2024; Gu et al., 2022). Additionally, NACs are capable of strengthening the atmospheric oxidative capacity, as they promote the formation of HONO and OH radicals (·OH) (Selimovic et al., 2020; Yang et al., 2021). These distinctive physicochemical properties ultimately influence regional air quality, radiative forcing, and climate dynamics (Harrison et al., 2005; Xiong et al., 2025; Liu et al., 2023b). In particular, NACs can also pose health risks due to their potential mutagenic and cytotoxic properties(Harrison et al., 2005; Hao et al., 2020). Thus, elucidating the abundances and main sources of NACs in urban aerosol particles and the key factors driving their formation is essential for advancing effective air pollution prevention efforts.

The molecular composition of aerosol NACs and the relative abundance of individual NAC species are strongly influenced by a combination of primary emission

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sources and secondary formation processes (Li et al., 2020b; Xie et al., 2019; Ma et al., 2024; Macfarlane et al., 2025; Wang et al., 2022). Extensive observational studies have confirmed that NACs in aerosols can originate from primary emissions such as coal combustion, biomass burning, and vehicle exhaust (Zhang et al., 2023; Ma et al., 2024; Macfarlane et al., 2025; Chen et al., 2022; Lu et al., 2019). Furthermore, NACs can be secondarily formed through gas-phase and liquid-phase oxidation of various precursors, such as toluene, benzene, xylene, phenol, catechol, m-cresol, guaiacol, and methyl catechol, in the presence of nitrogen oxides (NO_x), with their eventual distribution between gas and particle phases being significantly affected by gas-particle partitioning (Harrison et al., 2005; Wang and Li, 2021; Mayorga et al., 2021; Salvador et al., 2021; Vidović et al., 2019). Specifically, the formation of some NAC species in the particle phase involves nitration reactions of phenol, *o*-cresol, *o*-hydroxybenzoic acid, and *p*-hydroxybenzoic acid mediated by ·OH, NO_3·, NO_2·, N_2O_5, and $ClNO_2$ (Shi et al., 2023; Harrison et al., 2005; Wang and Li, 2021; Xiong et al., 2025). The atmospheric oxidation of catechol yields 4-nitrocatechol, a process initiated by ·OH and NO_3· (Finewax et al., 2018). Similarly, methylnitrophenol and methylnitrocatechol can be produced via the photooxidation of *m*-cresol followed by subsequent nitration (Olariu et al., 2002). These well documented pathways in both laboratory experiments and field observations facilitate the conversion of volatile organic compounds (VOCs) into NACs with relatively low volatility, thereby substantially contributing to the formation of secondary organic aerosols (SOA) (Harrison et al., 2005; Liu et al., 2023b; Kroflič et al., 2021; Finewax et al., 2018; Macfarlane et al., 2025). In particular, the formation

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of NACs is influenced by variations in ambient conditions such as relative humidity (RH), aerosol liquid water (ALW) concentration, and temperature (Xiong et al., 2025; Liu et al., 2023b; Guo et al., 2024). Among these, RH and ALW represent the most widely reported atmospheric variables affecting NAC formation (Xiong et al., 2025; Liu et al., 2023b). Nevertheless, the underlying RH- and/or ALW-related mechanisms controlling NAC production remain highly complex and not yet fully elucidated.

It is generally accepted that an increase in RH can elevate the concentration of ALW (Xu et al., 2023; Xu et al., 2020b; Nguyen et al., 2016). ALW not only promotes the partitioning of water-soluble gaseous organics into the particle phase but also functions as a reaction medium for aqueous-phase processes, which significantly increase SOA production (Sareen et al., 2017; Yang et al., 2024; Ma et al., 2025; Xu et al., 2022; Liu et al., 2023a). Recently, smog chamber experiments have suggested a water cluster catalysis mechanism underlying NAC formation, in which gaseous water molecules form proton-transfer bridges, increasing the reaction rate constants for the H-shift by approximately 8 to 17 orders of magnitude at 298 K compared to the scenario with liquid water (Xiong et al., 2025). However, previous field observations in cities such as Shanghai, Xi'an, and Beijing suggested that aerosol NAC levels did not exhibit a positive correlation with ALW (Huang et al., 2024; Liu et al., 2023b). Indeed, the mechanisms underlying the influence of RH and ALW on NAC formation remain a current research focus. However, to date, no large-scale synchronized observational studies in China have systematically investigated the linkages between aerosol NAC formation and RH or ALW.

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Rapid urbanization and industrialization in China have intensified air pollution, especially during winter when biomass and coal combustion activities increase substantially (Ma et al., 2025; Xu et al., 2024b; Yang et al., 2025). Disparities in economic development levels among cities may consequently shape a unique spatial and temporal signature for NAC abundances, which are also modulated by factors like RH and ALW. In this study, we measured 9 typical NAC species in $PM_{2.5}$ samples simultaneously collected from 11 Chinese cities during winter. The objectives are: (1) to examine spatial variations in the concentration and composition of aerosol NACs; (2) to evaluate the relative contributions of primary emissions and secondary formation processes to aerosol NACs; and (3) to identify key factors governing the formation of NACs, with particular focus on the relationships between NAC abundances and RH or ALW in northern and southern China.

2. Materials and methods

2.1. Sampling sites and sample collection

The $PM_{2.5}$ sampling was conducted across 11 cities in China, geographically categorized into southern and northern groups based on the Qinling–Huaihe climatic boundary (**Figure S1**). The southern group consists of Guangzhou (GZ), Chengdu (CD), Guiyang (GY), Kunming (KM), Wuhan (WH), and Hangzhou (HZ). The northern sites encompass Lanzhou (LZ), Xi'an (XA), Beijing (BJ), Haerbin (i.e., Harbin; HEB), and Taiyuan (TY). The sampling campaign was carried out from December 10, 2017 to January 14, 2018. This period was characterized by a distinct south–north temperature

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divide, with average air temperatures sustained above 4 °C in the southern cities generally below 2°C in the northern cities (**Tables S1**–**S4**). It is noteworthy that biomass burning activities are relatively active during winter in both southern and northern Chinese cities (Yang et al., 2025; Huang et al., 2024).

$PM_{2.5}$ samples were acquired using a high-volume air sampler (KC-1000, Laoying, China) operated at a constant flow rate of 1.05 ± 0.03 m^3 min^{-1}, with prebaked quartz fiber filters (Pallflex, Pall Corporation, USA) serving as the collection medium. Sampling was conducted simultaneously across 11 observation sites on a 2- to 3-day frequency cycle, with each sampling event lasting approximately 24 hours. Field blank samples were prepared at each site by mounting filters in an identical but non-operating air sampler. This campaign yielded a total of 154 filter samples, which were subsequently preserved at –30 °C. Concurrent meteorological data (e.g., temperature and RH) and air pollutant concentrations (e.g., SO_2, NO_x, CO, and O_3) recorded during the sampling dates were obtained from nearby monitoring stations. The solar shortwave radiation (SR) data were obtained from National Meteorological Information Center, China Meteorological Administration (http://data.cma.cn/). In addition, a $PM_{2.5}$ concentration threshold of 75 μg m^{-1} was applied to differentiate between clean and polluted days throughout the sampling campaign (Xu et al., 2024b; Zhang and Cao, 2015).

2.2. Chemical analysis and parameter calculation

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The protocol for extracting NACs from filter samples followed an optimized sample preparation workflow (Frka et al., 2022; Huang et al., 2024; Ma et al., 2024; Ma et al., 2025). Briefly, methanol was used for extracting the filter samples, after which the extract was filtered through a 0.22 μm polytetrafluoroethylene syringe filter (CNW Technologies GmbH). Subsequently, the filtrate was concentrated to near-dryness using a gentle stream of nitrogen gas. The residue was reconstituted by adding 300 µL of ultrapure water (~18.2 MΩ cm), followed by mixing and centrifugation. The final supernatant was injected for analysis using ultra-high-performance liquid chromatography-tandem mass spectrometry (UPLC-MS/MS, Waters, USA). Chromatographic separation was achieved on an ACQUITY UPLC HSS T3 analytical column (2.1 mm × 100 mm, 1.8 µm; Waters, USA).

Nine NAC species were targeted for quantification, including 4-nitrophenol (4NP), 2,4-dinitrophenol (2,4DNP), 3-methyl-4-nitrophenol (3M4NP), 2-methyl-4-nitrophenol (2M4NP), 4nitrocatechol (4NC), 4-methyl-5-nitrocatechol (4M5NC), 5-nitrosalicylic acid (5NSA), 3-nitro-salicylic acid (3NSA), and 4-nitroguaiacol (4NG). For the standard reference materials, recoveries fell within the range of 94% to 105%. None of these NACs were detectable in blank samples when analyzed using the identical measurement protocol. Furthermore, two typical anthropogenic organosulfate markers (i.e., $C_8H_{17}O_4S^-$ and $C_5H_7O_6S^-$) were also measured via a comparable analytical approach (Yang et al., 2023; Yang et al., 2024; Xu et al., 2025). Detailed procedures for the identification and quantification of these organosulfate species have been described in our previous publications (Yang et al., 2023; Yang et al., 2024).

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Levoglucosan (LGA) was additionally identified based on a similar UPLC-MS method outlined above (Ma et al., 2025).

The analytical procedure for inorganic ions in $PM_{2.5}$ samples involved the ultrapure water-based extraction via a ~4 °C ultrasonic bath (Gui et al., 2025; Xu et al., 2024a). After extraction, the solutions were passed through a polytetrafluoroethylene syringe filter. Analysis was conducted via ion chromatography (Dionex Aquion, Thermo Scientific, USA) to measure the concentrations of Mg^{2+}, Ca^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}, NO_3^{-}, NH_4^{+}, and K^{+} (Xu et al., 2020a; Gui et al., 2024). The concentration of ALW and the pH value were estimated by running the ISORROPIA-II thermodynamic model in forward mode under the assumption of a metastable state, following methodologies well-documented in our previous work (Yang et al., 2024; Ma et al., 2025; Gui et al., 2025). In addition, the non-sea-salt fractions of K^{+} (nss-K^{+}) and Cl^{-} (nss-Cl^{-}) were derived by subtracting 0.038 and 1.727 times the Na^{+} concentration from the total concentration of each respective ion (Boreddy and Kawamura, 2015; Morales et al., 1998). In addition, the levels of ambient ·OH were estimated using the empirical formula proposed by Ehhalt and Rohrer (2000), which was detailed in our previous publications (Liu et al., 2023a; Xu et al., 2024a).

3. Results and discussion

3.1. Spatial characteristics of NAC concentration and composition in $PM_{2.5}$

Figure 1a–d shows the average concentration distributions of different NAC groups in $PM_{2.5}$ samples collected from 11 cities across China, along with a comparative

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analysis of their levels in southern and northern cities. NACs are categorized into four groups, including nitrophenols (NPs), nitrocatechols (NCs), nitrosalicylic acids (NSAs), and nitroguaiacols (NGs) (**Table S1–S4**). On average, nitrophenols and nitrocatechols are the two dominant categories, constituting approximately 43.75 ± 14.33% and 42.44 ± 13.46% of the total measured NACs in the investigated cities, respectively (**Figure S2** and **Table S1–S2**). Nitrosalicylic acids and nitroguaiacols represent relatively minor proportions, account for only 6.12 ± 2.99% and 7.69 ± 1.80% of the total NACs, respectively. The highest average concentration of total nitrophenols was observed in TY, while the peak average level of total nitrocatechols was recorded in HEB. The lowest average total nitrophenol concentration was found in GZ, whereas HZ exhibited the lowest average total nitrocatechol level. Similarly, the average total abundances of nitrosalicylic acids and nitroguaiacils also showed significant spatial variations, with the highest mean values recorded in XA and HEB, respectively, and the lowest mean values in KM and HZ, respectively. Although neither nitrophenols nor nitrocatechols reached their individual peak concentrations in XA, the average total NAC concentration was the highest in this city (**Figure 1e** and **Table S1–S2**). Across all the investigated cities, the average concentration of total NACs was 20.09 ng m^{-3}, ranging from 5.55 ng m^{-3} to 44.87 ng m^{-3}. This falls within the range reported in previous studies (Huang et al., 2024; Liu et al., 2023b; Gu et al., 2022; Cai et al., 2022; Li et al., 2016). The second-highest total average NACs concentration was observed in HEB, followed by TY, XA, LZ, CD, BJ, GY, HW, HZ, KM, and GZ. For all four categories of NACs as well as the total NAC concentration, their average levels were consistently

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higher in northern cities than in southern cities (**Figure 1a-d** and **Figure S3**). This spatial pattern is similar to that of $PM_{2.5}$ and SO_2 (typical pollutants emitted from coal combustion) (**Figure 1f,g**). Many previous studies have documented that the abundance of NACs in winter aerosols can be significantly influenced by primary emissions such as coal and biomass burning (Wang et al., 2017; Wang et al., 2020; Huang et al., 2023). Thus, the north-south gradient in NAC concentrations is likely closely associated with divergent air pollution levels (as indicated by $PM_{2.5}$ levels) between northern and southern China, partly driven by differences in coal combustion and biomass burning intensity.

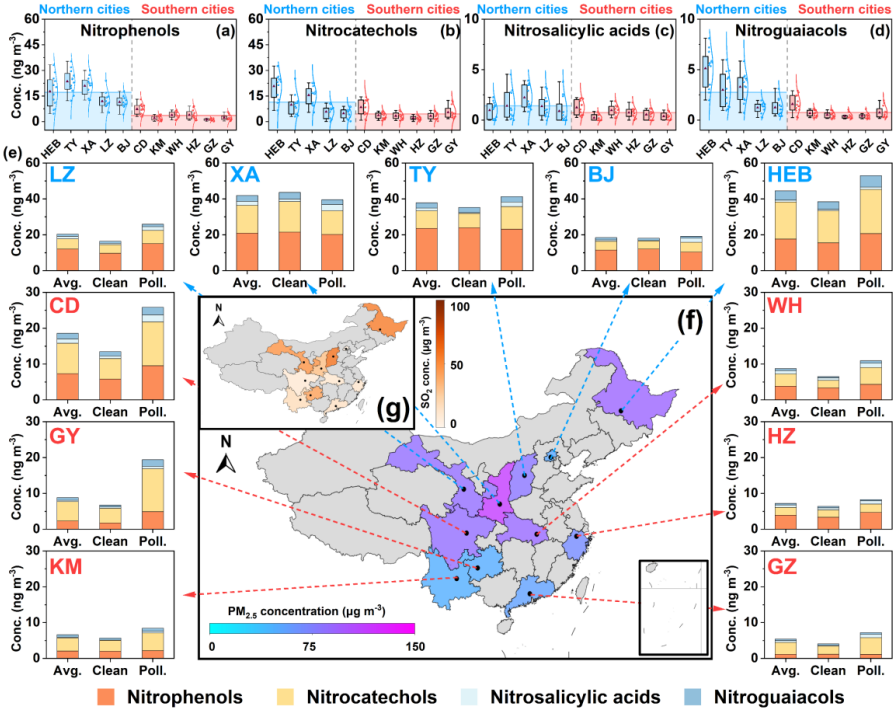

Figure 1. Box and whisker plots (a-d) showing the variations in the mean

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concentrations of different NAC groups in $PM_{2.5}$ collected in 11 Chinese cities. The boxes represent the interquartile range (25th to 75th percentiles). The whiskers extend from the 5th to the 95th percentiles. The solid triangles inside boxes indicate the mean. (e) Average concentration distributions of detected NACs in $PM_{2.5}$ during clean and polluted days in winter across 11 Chinese cities. The color blocks in the panels (f) and (g) represent the spatial variations in $PM_{2.5}$ and SO_2 pollution levels, respectively, across the sampled cities during the study period. The map was obtained from ©MeteoInfoMap (Chinese Academy of Meteorological Sciences, China).

Among nitrophenols, 4-nitrophenol (4NP) was the most abundant species, accounting for 63.21 ± 8.07% of the total measured nitrophenols in China during winter (**Figure S4** and **Table S1–S4**). Previous studies characterizing NACs in biomass burning emissions have reported 4NP as an important emitted species (Huang et al., 2024; Wang et al., 2020; Wang et al., 2017). 4-nitrocatechol (4NC) was the dominant species among nitrocatechols. The average concentration of 4NC across all cities was 7.55 ± 6.90 ng m^{-3}, representing 40.67 ± 12.89 % of total NACs. The emission factors for 4NC from coal combustion varied widely based on geological maturity, ranging from 8 to 3487 μg kg^{-1} (Huang et al., 2023). In contrast, the emission factors of 4NP from the same coal sources were significantly lower, generally below 14 μg kg^{-1} (Huang et al., 2023). Furthermore, the average emission factor for nitrocatechols from the combustion of biomass materials was also substantial, measured at 26.6 ± 5.40 μg kg^{-1} (Huang et al., 2023). These findings indicate that coal and biomass burning during

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winter may significantly contribute to the abundance of NACs in urban aerosols across China, particularly exacerbating NACs pollution in northern cities.

The mass concentration fractions of various NACs were further compared between clean and polluted days (**Figure 1e**). It was observed that the dominant NAC groups (i.e., nitrophenols and nitrocatechols) in $PM_{2.5}$ remained consistently predominant across all cities from clean to polluted periods, without being superseded by other NAC species. This pattern suggests that the main emission sources of aerosol NACs in these urban areas may not have undergone significant changes during pollution periods. In most cities, including LZ, HEB, CD, WH, GY, HZ, KM, and GZ, the average concentrations of total NACs and dominant NAC groups showed an increasing trend from clean to polluted periods (**Figure 1e** and **Table S1–S4**). In contrast, cities such as XA, TY, and BJ exhibited a decreasing trend in the concentrations of main NAC groups (i.e., nitrophenols). It should be noted that nitrophenols were not the primary species in GZ, and their average concentrations did not show an increasing trend from clean to polluted periods. As important contributors to haze formation, NACs would be expected to accumulate under polluted air conditions. Thus, the observed decrease in the abundance of some NAC groups on polluted days (typically associated with calm and stable weather conditions) in several cites suggests that the formation of NAC compounds may also be constrained by specific factors such as photolysis process (Liu et al., 2024; Yang et al., 2021), varied RH and ALW levels (Xiong et al., 2025; Liu et al., 2023b), and unfavorable atmospheric oxidation capacity (Wang and Li, 2021). These influencing factors will be further discussed in later sections. In general, the

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concentration and composition of NACs varied spatially (**Figure 1** and **Figure S2**), which may be attributed to spatial differences in precursor sources, emission intensities, and the key factors influencing aerosol NAC formation.

3.2. Temporal variations of NACs and their potential origins

Figure 2 shows the time series of concentrations of various NACs and key chemical components in winter $PM_{2.5}$ across northern and southern China. In northern China, the highest total NP concentration was observed in TY, whereas the highest total NC event occurred in HEB (**Figure 2a,c,e**). In HEB, XA, and BJ, total NPs and total NCs exhibited similar variation trends (linear regression, $P < 0.05$), implying potentially similar sources for aerosol NPs and NCs. In TY and LZ, total NPs and total NCs also showed consistent variation patterns during most observation periods. Furthermore, NGs were significantly ($P < 0.05$) correlated with total NCs in all regions except TY and LZ. In southern cities, the most severe NACs pollution events were recorded in CD (**Figure 2d,d,f**), which may be attributed to the city's basin topography that hinders pollutant dispersion (Liao et al., 2017). With the exception of GZ, major NAC species in southern cities exhibited similar temporal trends. In GZ, several anomalously high NC cases likely led to inconsistent variation patterns among different NAC groups. Overall, the temporal variation trends of major NAC groups were highly consistent across most Chinese cities, indicating that the sources of different NACs during winter may be similar in each city.

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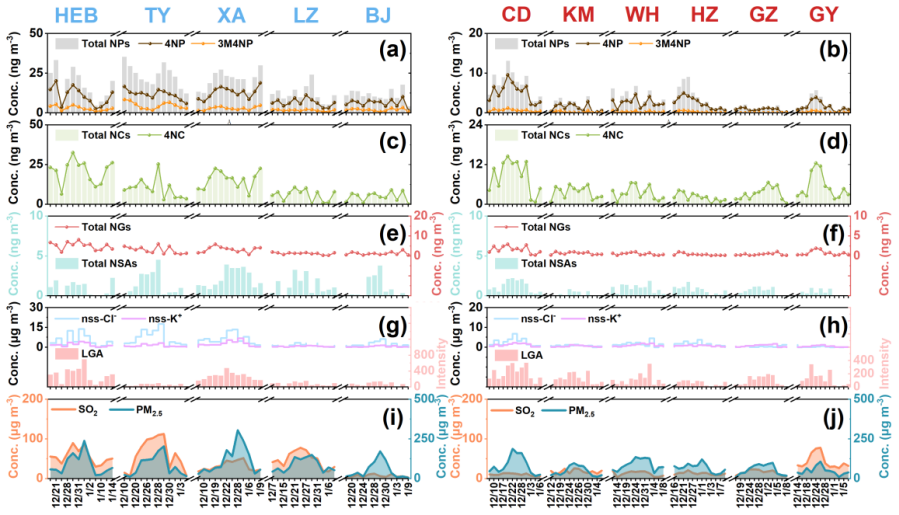

Figure 2. Temporal variations in (a–f) various NAC species and (g–l) key parameters in 11 Chinese cities.

Comparison of the temporal variation patterns (**Figure 2g–j**) and correlations of NACs against various combustion source tracers (**Figure 3a,b**) enabled the identification of their potential sources in the different cities (Huang et al., 2024; Cai et al., 2022; Wang et al., 2019; Kahnt et al., 2013). In northern cities, one or more NAC species showed consistent variation trends with indicators of biomass burning or coal combustion, including LGA, nss-K^+, SO_2, nss-Cl^-, and $C_8H_{17}O_4S^-$ (Kahnt et al., 2013; Ma et al., 2025; Yang et al., 2025; Yang et al., 2023) (**Figure 2g,i** and **Figure 3a**). The highest frequency of significant positive correlations between various NACs and biomass or coal combustion tracers (i.e., the number of orange-red rectangles marked with asterisks in the **Figure 3c**) was observed in HEB (n = 17), followed by LZ (n = 12), BJ (n = 10), TY (n = 7), and XA (n = 4). This suggests that the abundance of aerosol

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NACs in northern cities is indeed significantly contributed by biomass and coal combustion. In most northern cities, the vehicle emission tracer $C_5H_7O_6S^-$ (Blair et al., 2017; Wang et al., 2021) showed insignificant positive correlation with NACs (**Figure 3a**). $C_5H_7O_6S^-$ only exhibited a significant positive correlation with NGs (a minor NACs component) in BJ. This suggests that the contribution of vehicle emissions to aerosol NACs in northern cities may be significantly smaller than that of biomass and coal combustion. In southern cities, the highest frequency of significant positive correlations between NACs and biomass burning or coal combustion tracers was found in KM (n = 22), followed by CD (n = 19), HZ (n = 15), GY (n = 10), WH (n = 10), and GZ (n = 5) (**Figure 3b, c**). Clearly, the frequency of significant positive correlations between NACs and biomass burning or coal combustion tracers was generally higher in southern China than in northern China (**Figure 3**). Although this does not necessarily indicate that biomass burning released more NACs in southern China, the result is fully consistent with the spatial distribution pattern shown in open fire spot maps, where southern China exhibited a higher density of fire spots compared to northern China (**Figure S5**). The vehicle emission tracer $C_5H_7O_6S^-$ showed insignificant positive correlations with NACs in any southern cities (**Figure 3b**). Given that NACs in the actual atmospheric environment are affected not only by primary emissions but also by secondary formation and removal processes, insignificant or weak correlations between various NACs and source-specific tracers do not necessarily indicate a lack of substantial influence from corresponding sources. However, the above correlation analysis can at least suggest that biomass and coal combustion play important roles in

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controlling aerosol NAC abundances in both northern and southern Chinese cities.

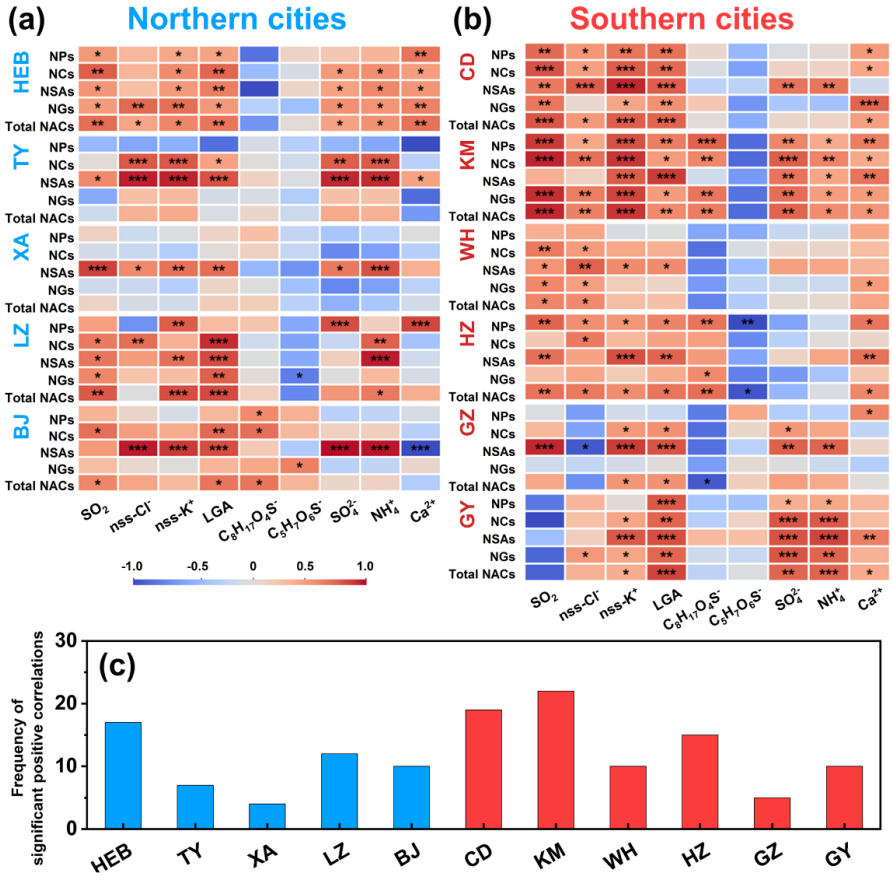

Figure 3. Correlations between various NAC species and indicative parameters in (a) northern and (b) southern China. The colors of different solid rectangles indicate different correlation coefficients *r*. Symbols * and ** indicate $P < 0.05$ and $P < 0.01$, respectively. NACs are categorized into four groups, including nitrophenols (NPs), nitrocatechols (NCs), nitrosalicylic acids (NSAs), and nitroguaiacols (NGs). (c) Frequency of significant positive correlations between NACs and biomass burning or coal combustion tracers (i.e., the number of orange-red rectangles marked with asterisks

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in the panels a and b).

Furthermore, it is important to note that a critical distinction should be made regarding the role of biomass and coal combustion in shaping aerosol NAC composition and abundances. These combustion sources emit both primary NACs and volatile precursors that facilitate secondary NAC formation through atmospheric reactions. Thus, even though the correlation analysis mentioned above strongly implies biomass and coal combustion (typically considered primary sources) as significant contributors to NACs in winter aerosols in China, this evidence alone cannot attribute the NAC burden predominantly to direct primary emissions. The significant contributions may be also derived from efficient secondary formation processes initiated by the precursors co-emitted from these combustion activities.

3.3. Aerosol NACs dominated by secondary formation

To further determine the relative contributions of secondary oxidation processes and primary emissions to the measured aerosol NACs, an approach based on a tracer species was employed (Salvador et al., 2021; Li et al., 2019). This method is similar to the elemental carbon-tracer technique utilized for estimating secondary organic carbon. Its specific application refers to the following equation 1 (Chen et al., 2022; Liu et al., 2023b).

$$[\mathrm{NACs}]_{\mathrm{sec.}} = [\mathrm{NACs}]_{\mathrm{total}} - \left(\frac{[\mathrm{NACs}]}{[\mathrm{Tracer}]}\right)_{\mathrm{pri.}} \times [\mathrm{Tracer}] \quad (1)$$

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where $[NACs]_{sec.}$, $[NACs]_{total}$, and [Tracer] correspond to the concentrations of secondarily formed NACs, the total measured NACs, and the tracer, respectively. Carbon monoxide (CO) served as the indicator for combustion sources. The term $(\frac{[NACs]}{[Tracer]})_{pri.}$ represents the concentration ratio of NACs to CO. This ratio was derived by fitting the lowest 15% of the observed $(\frac{[NACs]}{[Tracer]})$ values, with the underlying assumption that these data reflect periods dominated by primary emissions (Chen et al., 2022).

Figure 4 and **Figure S6** show the contribution of secondarily formed NACs to the total measured NAC mass in $PM_{2.5}$ across 11 Chinese cities. In northern cities, the proportion of secondary NACs in the particle phase was highest in XA (92 %), followed by HEB (91 %), BJ (87 %), LZ (83 %), and TY (80 %) (**Figure 4a** and **Table S5**). On average, the contribution of secondarily formed NACs to the total aerosol NAC mass in the investigated northern cities was 87%, which is slightly lower than that observed in the southern cities (93%) (**Figure 4b** and **Table S5**). Among the southern cities, the maximum and minimum average secondary NAC contributions to total aerosol NACs were observed in GZ (96 %) and GY (88 %), respectively. Overall, the secondary formation pathway dominated the total NAC masses in $PM_{2.5}$ during winter in Chinese cities. Similarly, an observational study on the secondary formation of brown carbon conducted in Chongming Island, Shanghai, also reported that the fraction of secondary NACs in $PM_{2.5}$ exceeded 80% during haze episodes, further corroborating the significance of secondary production in shaping aerosol NAC pollution (Liu et al., 2023b).

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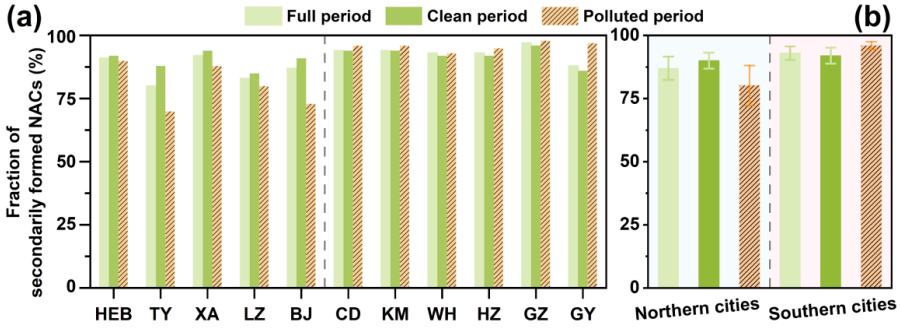

Figure 4. (a) Average contribution of secondarily formed NACs to the total measured NAC masses in $PM_{2.5}$ in different periods across 11 Chinese cities. (b) Average contribution of secondarily formed NACs to the total measured NAC masses in $PM_{2.5}$ in different periods in northern and southern China.

Furthermore, we observed a declining trend in the proportional contribution of secondarily formed NACs to total aerosol NACs from clean to polluted periods across all northern Chinese cities (**Figure 4**). This pattern suggests either an increased contribution from primary emission sources (e.g., biomass and coal combustion) to aerosol NACs, or the presence of limiting factors that suppress the yield of secondary NAC formation on polluted days. Biomass and coal combustion have been identified as significant primary sources of NACs during winter in China (**Figure 3**) (Salvador et al., 2021; Li et al., 2020a; Li et al., 2016); moreover, these anthropogenic activities occur regularly daily throughout the cold season. Thus, changing meteorological factors during polluted days (e.g., reduced planetary boundary layer height (PBLH) and weakened wind speed (**Tables S1–S4**)) may be important drivers of aerosol NAC accumulation. Nevertheless, the fact that the fraction of secondary NACs decreases

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during northern pollution episodes implies the existence of specific factors that constrained secondary NAC yields under polluted conditions. In contrast, southern cities exhibit an increasing trend in the relative abundance of secondary NACs from clean to polluted periods. This pattern may be more intuitively explained, as elevated ALW concentrations, lower PBLH, and increased NO_x levels during polluted episodes can promote the secondary formation of NACs or the direct partitioning of gaseous NACs into the particle phase. Overall, aerosol NACs in China during winter were dominated by secondary processes; however, the complex factors regulating NAC formation require further differentiation between northern and southern cities.

3.4. Potential promotion and constraint effects on the formation of aerosol NACs

The secondary formation of NACs proceeds via gas-phase photochemical reactions and aqueous-phase processes within aerosols (Harrison et al., 2005; Yang et al., 2020). For example, the gas-phase process often begins with the oxidation of volatile aromatic precursors like benzene and toluene by ·OH, leading to the formation of phenolic compounds (Chen et al., 2022). These phenols can further react with ·OH during the day or with NO_3· at night, generating phenoxy radicals (Wang and Li, 2021; Atkinson et al., 1992; Olariu et al., 2002; Olariu et al., 2013). The addition of NO_2 to these radicals results in the formation of nitrophenols and nitrocatechols (Rana and Guzman, 2022). Subsequently, these NACs can partition into the aqueous-phase in aerosols. Simultaneously, phenolic compounds in aqueous-phase can also undergo nitration (Vidović et al., 2018; Harrison et al., 2005). Thus, increased ALW levels are

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expected to promote the enrichment of NACs in aerosol particles. Conversely, photodegradation and enhanced atmospheric oxidation capacity can facilitate the removal of NACs. Recent field observations and chamber experiments have suggested a significant positive correlation between the concentration of particulate NACs and RH (Xiong et al., 2025). The authors (Xiong et al., 2025) proposed a previously overlooked but efficient NAC formation pathway driven by gaseous water clusters, in addition to the well-known ALW mediated processes. Additionally, recent simulations on nitrate-mediated aqueous-phase photooxidation of NACs have suggested that increasing aerosol nitrate concentrations can significantly enhance the photolysis rates of 4-nitrocatechol, 3-nitrosalicylic acid, and 3,4-dinitrophenol by 3 to 3.5 times compared to nitrate-free cases (Liu et al., 2025). Consequently, we further examined the correlations between the abundance of NACs and the key factors affecting their formation (e.g., ALW, RH, radiation intensity, atmospheric oxidation capacity, and nitrate levels) in field environments (**Figure 5**). This approach is commonly employed in observation studies to identify the critical factors affecting the concentrations of target compounds (Yang et al., 2020; Liu et al., 2023b; Huang et al., 2023; Liu et al., 2023a; Gui et al., 2025).

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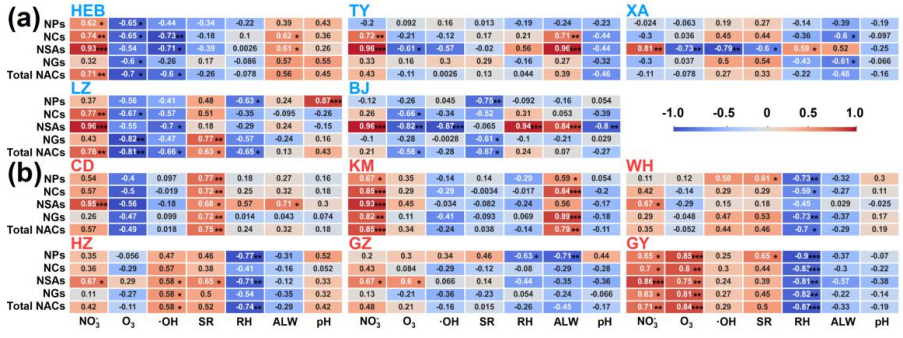

Figure 5. Correlations between various NAC species and factors potentially affecting their formation in (a) northern and (b) southern China. The colors of different solid rectangles indicate different correlation coefficients *r* (shown inside the rectangles). Symbols * and ** indicate $P < 0.05$ and $P < 0.01$, respectively.

In most northern Chinese cities (e.g., HEB, TY, XA, and LZ), insignificant positive correlations were observed between various NACs (except NSAs) and RH; instead, negative correlations were identified between them (**Figure 5a**). In XA and BJ, only NSAs show a significant positive correlation with RH. Similarly, a general negative correlation trend between NACs and RH was prevalent in southern cities (**Figure 5b**). These field observations clearly contrasted with recently reported laboratory findings where RH was shown to significantly promote NAC formation. This indicates that NAC formation in complex real-world environments may be co-controlled by multiple factors. The correlation patterns between ALW and NACs were largely similar to those of RH across most investigated Chinese cities. However, in TY and KM, ALW showed significant positive correlations with NACs. Furthermore, we found that ALW and RH levels were generally higher on polluted days compared to clean days across the studied

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cities (**Figure S7** and **Tables S1–S4**). However, as discussed above, the concentrations of major NAC species did not increase in some cities (**Figure 1**), further implying that ALW and RH are not deterministic factors for NAC accumulation during pollution episodes. Although a recent study conducted a laboratory located in XA has suggested that increased aerosol nitrate can enhance NAC photolysis (Liu et al., 2025), nitrate concentrations showed a positive correlation with NACs in most investigated cities (except XA) (**Figure 5**). This suggests that in ambient environments, the significant positive correlation between nitrate (a common transformation product of combustion-derived NO_x) and NACs likely indicates that NAC formation is closely linked to combustion emissions and NO_x-involved secondary chemistry. In addition, atmospheric oxidants (e.g., O_3 and ·OH) and SR exhibited negative correlations with NACs in most northern cities. In contrast, O_3, ·OH and SR exerted a promoting effect on NAC formation in some southern cities such as CD, WH, HZ, and GY. These distinctions underscore the necessity for region-specific assessment of NAC formation mechanisms and their drivers.

To visually compare the key factors influencing the formation of aerosol NACs in northern and southern China, we pooled data from all cities in these two regions to perform Mantel test analysis and principal component analysis (PCA) (**Figure 6**). In both southern and northern China, only NSAs exhibited a significant correlation with ALW (**Figure 6a,b**). This is likely because the carboxyl group present in NSAs promotes ionization in water, thereby enhancing their solubility. Although PCA results intuitively indicate the homology of various NACs (excluding NSAs) (**Figure 6c,d**),

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the significant promotional effects of RH and ALW on NCs, NPs, and NGs were not reflected in either the Mantel test or PCA analyses. Furthermore, in northern Chins, SR was distributed in a nearly opposite direction to NCs, NPs, and NGs in the PCA plot (**Figure 6c**), suggesting an inhibitory role of photodegradation on their accumulation in particles (Liu et al., 2024). During winter, the atmospheric fine particulate pollution is generally more severe in northern cities than in southern cities (**Figure 1f** and **Tables S1–S4**), and the abundance of NACs is also greater in the north (**Figure 1f** and **Figure S3**). These findings imply that the light absorption capacity of aerosols in northern cities are stronger that in southern cities (Huang et al., 2024). This may explain why NACs in northern cities showed a significant negative correlation with SR and why the proportion of secondarily formed NACs in the total measured NACs was lower in the north than in the south, especially during pollution episodes. Additionally, the constraining effect of O_3 or ·OH on NAC formation was greater in northern China (evidenced by larger angles between them in **Figure 6c**) than in southern China (**Figure 6d**). Similar conclusions can also be more intuitively obtained in the Mantel test analysis results (**Figure 6a,b**). Overall, our findings indicate that the promotional effects of RH and ALW on NAC formation were insignificant in field observation in China during winter. This could be attributed to the synergistic constraints of multiple factors, such as photolysis, O_3, and ·OH (**Figure 7**).

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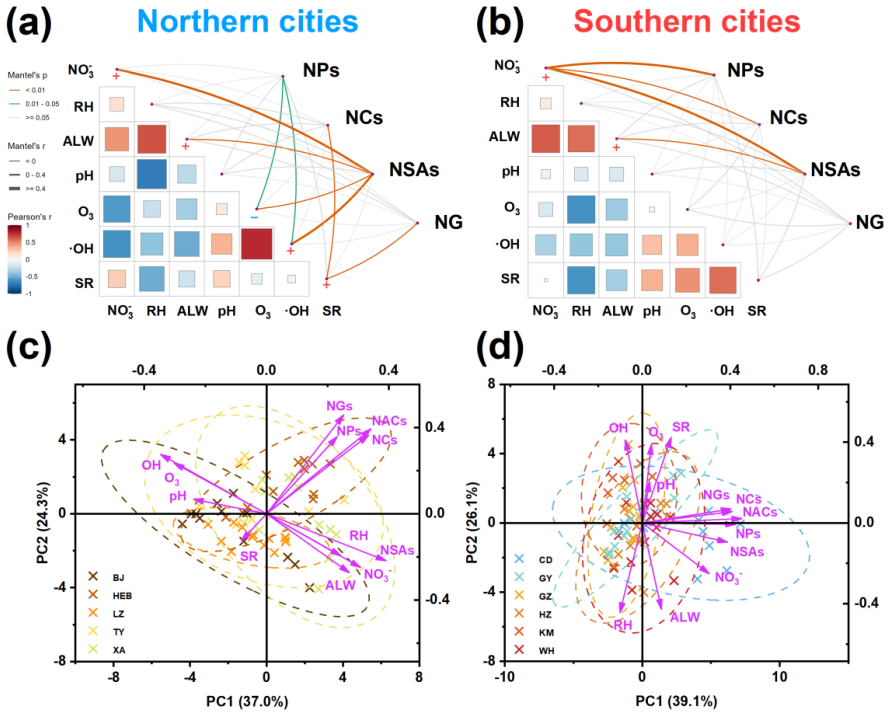

Figure 6. Mantel test correlation heatmap showing the interrelationships between different factors or parameters for the pooled data from (a) northern and (b) southern China. The size of the solid square indicates the significance of the correlation between the two corresponding parameters. The larger square indicates that the correlation is more significant. The colors of the different solid circles indicate different correlation coefficients (*r*). The symbols '+' and '–' refer to positive and negative correlations, respectively. Principal component analysis result deciphering the interrelationships among different factors or parameters for the pooled data from (c) northern and (d) southern China.

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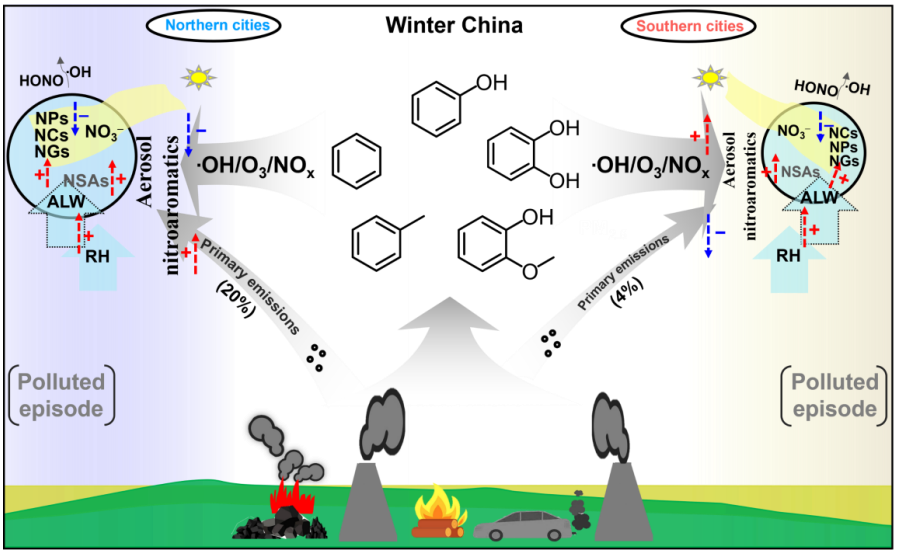

Figure 7. Conceptual illustration showing that the secondary processes driven by multi-factor interactions modulate the aerosol NAC pollution during winter in southern and northern China. The "+" and "–" symbols indicate promoting and constraining effects, respectively.

4. Conclusion and atmospheric implications

To the best of our knowledge, this study presents the first simultaneous investigation of the abundance, composition, and origins of NACs in $PM_{2.5}$ across 11 Chinese cities during winter, along with the key factors controlling their formation. On average, NPs and NCs were identified as the two predominant groups of NACs. Their relative contributions to the total NAC abundance varied by city, with either NPs or NCs being dominant depending on location. Overall, the abundance of aerosol NACs was higher in northern China compared to southern China, likely attributable to more intensive coal and biomass burning activities in the north. Furthermore, we found that

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aerosol NACs in China during winter were predominantly formed via secondary processes. However, the proportion of secondarily formed NACs in the total measured NACs was lower in the north than in the south. This north-south difference was further amplified during polluted periods.

The significant promotional effects of RH and ALW on NCs, NPs, and NGs were not observed in either northern or southern China. Only NSAs showed a significant positive correlation with ALW across both regions. Furthermore, the constraining effects of O_3, ·OH, or SR on NAC formation were more pronounced in northern China compared to southern China. This may have attenuated the promotional effects of RH and ALW on NAC formation (**Figure 7**). Previous observational and simulation studies have emphasized the significant promotional role of RH and ALW in the formation of aerosol nitrogen-containing organic compounds (including NACs) (Xiong et al., 2025; Xu et al., 2020b; Ma et al., 2025). However, this large-scale observational study suggests that the generalizability of such RH- and ALW-regulated promotional effects on NAC formation in real atmospheric environments requires further validation. We acknowledge that individual factors (e.g., RH or ALW) play a crucial role in governing aerosol NAC formation. Nevertheless, field environments are often more complex than laboratory-simulated scenarios. Thus, the overall results highlight that future investigations into NAC formation mechanisms should consider the impacts of multi-factor interactions.

Data availability. The data presented in this work are available upon request from the

https://doi.org/10.5194/egusphere-2025-5730
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corresponding authors.

Author contributions. YX, HYX, and HX designed the study; YX, YCY, TY, LG, JLT, TSC, HWX, and HX performed field measurements and sample collection; TY and YCY performed chemical analysis; YX and YCY performed data analysis; YX wrote the original manuscript; HYX and HX provided suggestions, and YX reviewed and edited the manuscript.

Financial support. This study was kindly supported by Key Program of the National Natural Science Foundation of China (grant number 42430501), National Natural Science Foundation of China (grant number 42303081 and 42403077), National Key Research and Development Program of China (grant number 2023YFF0806001).

Conflict of Interest. The authors declare no conflicts of interest relevant to this study.

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