Measurement report: Crustal materials play an increasing role in elevating particle pH: Insights from 12-year records in a typical inland city of China.

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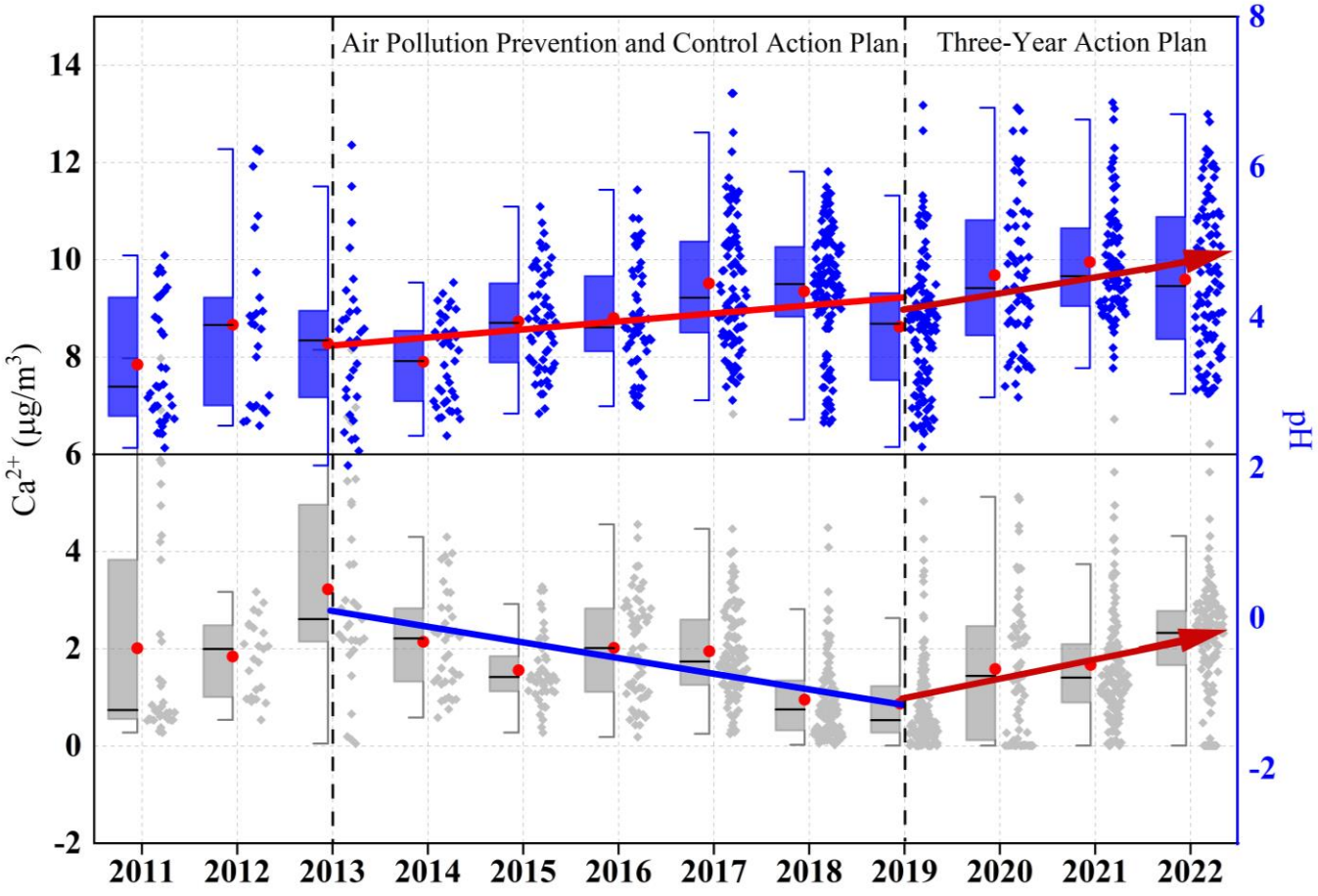
Abstract

Particle acidity serves as a key determinant in atmospheric chemical processes. Emerging concerns regarding aerosol acidity trends have been highlighted amid China's sustained initiatives to mitigate emissions of both acidic and alkaline precursors, especially in North China, which is significantly affected by dust aerosol. 12-year observational data in Zhengzhou reveal that the annual average $PM_{2.5}$ concentration decreased from 162 ± 81 μg/m^3 in 2011 to 60 ± 41 μg/m^3 in 2022, with the largest reduction in sulfate (73%). Correspondingly, the annual particle pH increased by 0.10 units from 2011 to 2019. In addition, the elevated particle pH in 2015 and 2018 was notably influenced by the increase in TNH_x (NH_3 + NH_4^+). Note that the crustal material concentrations and their proportions increased significantly during 2019–2022, which might be responsible for the resuspension of surrounding soil dust. Even though the TNH_x concentration was decreasing, the annual average growth rate of pH values increased to 0.21 units from 2019 to 2022. This phenomenon is not unique to Zhengzhou, as major cities in the North China Plain have also experienced a pronounced upward trend in coarse particles after 2019. Therefore, the long-term evolution of particle acidity in North China will require comprehensive consideration of synergistic effects involving acidic precursors, ammonia, and crustal materials.

Keywords: Dust, aerosol acidity, sources, North China Plain, control measurement

Synopsis: The future ammonia reduction policies in North China may not lead to a rapid increase in particle acidity in the presence of crustal materials., which further elevated the particle pH after 2019.

Graphical abstract:



Highlights:

- Crustal material concentrations and their proportions increased significantly during 2019–2022;
- The resuspension of surrounding soil dust may determine the rebound of crustal material concentrations;
- Rebound in crustal material further elevated the particle pH.

1 Introduction

Particle acidity is a critical parameter that affects atmospheric chemistry, such as the gas-particle partitioning of semi-volatile and volatile species (Surratt et al., 2010; Guo et al., 2016), the solubility of metals (Tao and Murphy, 2019), acid-catalyzed reactions (Rengarajan et al., 2011), and acid deposition (Mao et al., 2009), thereby determining aerosol concentration and chemical composition, as well as impacting human health, ecosystems, and climate (Li et al., 2017; Pye et al., 2020; Su et al., 2020; Nenes et al., 2021). Generally, the global fine particulate matter ($PM_{2.5}$, aerodynamic diameter ≤ 2.5 μm) exhibits a bimodal pH distribution ranging from 1–3 (e.g., in the United States and Europe) (Guo et al., 2015; Battaglia et al., 2017; Masiol et al., 2020; Zhang et al., 2021) and 4–5 (e.g., in East Asia) (Kim et al., 2022; Sharma et al., 2022). The atmosphere rich in gaseous ammonia (NH_3) and crustal material (CM) shows significant pH buffering effects (Wang et al., 2020; Zheng et al., 2020; Karydis et al., 2021), which is a dominant factor that drives the high particle pH in East Asia (Karydis et al., 2021; Zhang et al., 2021; Kim et al., 2022; Sharma et al., 2022).

In recent years, the changing trends in particle pH have become a research focus, especially in China, in response to air pollution control policies, i.e. Air Pollution Prevention and Control Action Plan (2013–2018) and Three-Year Action Plan (2018–2020). The annual average $PM_{2.5}$ concentration in Beijing dropped by 64% from 89.5 μg/m³ in 2013 to 32 μg/m³ in 2023 (MEP, 2023), with a clear downward trend of sulfate concentration, and nitrate surpassing sulfate as the primary component (Zhai et al., 2019; Zhou et al., 2019; Li et al., 2023). The atmospheric behavior of ammonium, governed by gas-particle partitioning processes involving ammonia (NH_3) as the predominant alkaline gas,

demonstrates notable stability in concentration levels, with observational records showing less than 5% interannual variation in NH_3 column densities over North China during 2015–2019 (Dong et al., 2023). Under such conditions, the dominant inorganic aerosol component transitions from ammonium sulfate to ammonium nitrate. This compositional shift enhances atmospheric particulate hygroscopicity due to ammonium nitrate's superior water uptake capability, ultimately elevating particle pH levels through aqueous-phase dilution mechanisms (Wexler and Seinfeld, 1991; Pinder et al., 2007, 2008; Heald et al., 2012; Weber et al., 2016). For instance, a significant increase in the nitrate-to-sulfate molar ratio from 2014–2017 in Beijing resulted in the particle pH increasing from 4.4 to 5.4 (Xie et al., 2020). Moreover, increased NH_3 concentrations raised particle pH by 0.3–0.4 units from 2014/2015 to 2018/2019 in Beijing (Song et al., 2019). Over Europe and North America, the pH has increased strongly from about 2.8 and 2.2 during the 1970s to 3.9 and 3.3 in 2020 respectively, especially during the 1990s, with significantly increasing NH_3 emission (Karydis et al., 2021). On the contrary, modeling results indicate a continuous decline in pH in East Asia from 1970 to 2020 due to sharp increases in SO_2 and NO_x emissions (Karydis et al., 2021). In addition, the $PM_{2.5}$ pH showed a slight decrease of 0.13 from 2018 to 2022 summer in Beijing due to the change in total nitrate (NO_3^- + HNO_3) (Li et al., 2023). Moreover, Zhou et al. (2022) found a decreasing pH trend from 2011 to 2019 in eastern China, primarily influenced by temperature, followed by sulfate and non-volatile cations. Similarly, Nah et al. (2023) observed a decreasing pH trend from 2011 to 2020 in Hong Kong, attributing it to temperature and sulfate levels. Thus, concerns have been raised about the potential increase in the acidity of aerosol and precipitation due to China's ongoing efforts to reduce ammonia emissions, which pose severe health risks and acid deposition (Liu et al., 2019; Shi al., 2019).

In addition to NH_3, CM is another key alkaline substance that buffers particle pH. Ca^{2+} can form insoluble $CaSO_4$ with sulfate, reducing sulfate concentration in the aqueous phase of aerosol, and thus lowering H^+ and aerosol liquid water content (ALWC) concentrations and enhancing particle pH (Ding et al., 2019; Karydis et al., 2021). Moreover, non-volatile cations can lower the molar ratio of ammonia to sulfate, leading to an increase in particle pH (Zheng et al., 2022). Karydis et al. (2021) framework demonstrated that CM played a critical buffering role in sustaining aerosol pH around 7 across the Middle East arid regions. The model sensitivity tests revealed that under hypothetical dust-free conditions (CM = 0), aerosol acidity would escalate to pH~4 due to NH_4^+/ SO_4^{2-}domination. Wang et al. (2022) reported that non-volatile cations accounted for approximately 8–17% of hourly aerosol pH variation. Li et al. (2023) indicated that the buffering effect of cations was the major reason for the relatively small pH changes from 2018 to 2022 in Beijing, emphasizing that reducing coarse particle emissions in the future could significantly decrease particle pH. In addition, there was a rising trend in the contribution of CM to particle pH in Tianjin, China (Shi et al., 2017). Therefore, it is evident that CM has a significant impact on the variation of particle pH, especially in North China, which is significantly affected by dust aerosol, but the trend of CM concentration and its long-term implications is still lacking unfortunately.

Zhengzhou presents unique atmospheric chemistry that distinguishes it from other mega-cities in North China. As the capital of China's foremost agricultural province (Henan Province, contributing 18% of national NH_3 emissions), Zhengzhou's $PM_{2.5}$ composition combined substantial crustal material (15 ± 3% in $PM_{2.5}$ vs. <10% in Beijing) with exceptional ammonia abundance (Huang et al., 2012; Liu et al., 2018; Wang et al., 2018). This created distinct particle acidity characteristics,

maintaining pH 4.5–6.0 compared to lower pH levels (3.3–5.4) in other cities like Beijing (Ding et al.,2019; Zhang et al., 2021). However, two critical research gaps persist: (1) the long-term evolution of CM under control policies remains unquantified; (2) the role of CM on pH buffer capacity in NH_3-enriched environments lacks systematic assessment.

To address these gaps, our study pioneers the first multi-decadal analysis (2011–2022) coupling $PM_{2.5}$ components with thermodynamic modeling through three key innovations: (1) revealing the long-term trends of CM, (2) analyzing the variations of CM sources, and (3) exploring pH trend and its relationship with CM. The resultant findings advance our understanding of urban aerosol acidity chemistry by underscoring the critical role of CM.

2 Experiment and method

2.1 Instruments and Measurements

Sampling was conducted on the fourth-floor platform at Zhengzhou University (34.75° N, 113.61° E) in Zhengzhou, China. The sampling site (Fig. S1), approximately 14 m above the ground, is primarily surrounded by residential areas with well-developed transportation networks and no significant industrial sources. There are two highways located 3 km to the south and 7 km to the east. Additionally, a coal-fired power plant located 6 km to the east was shut down in 2020, and a gas-fired power plant is situated 3 km to the south.

Samples were collected using a high-volume sampler (TE-6070D, Tisch, USA) and air particulate samplers (TH-16A, Tianhong, China) from April 2011 to December 2022. Two quartz filters and two

Teflon filters were used daily from 10:00 AM to 9:00 AM the next day, resulting in a total of 5848 samples. After excluding abnormal data due to instrument malfunctions, 4228 valid samples were obtained. Detailed information on the samples is provided in Table S1. Organic carbon (OC) and elemental carbon (EC) were analyzed using a carbon analyzer (Model 5L, Sunset Laboratory, USA). Water-soluble inorganic ions (Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+}) were measured using ion chromatography (ICS-90 and ICS-900 models, Dionex, USA) (Yu et al., 2017; Jiang et al., 2018). Elements were analyzed using a wavelength dispersive X-ray fluorescence spectrometer (S8 TIGER, Bruker, Germany) to determine concentrations of Fe, Na, Mg, Al, Si, Cl, K, Ca, V, Ni, Cu, Zn, Cr, Mn, Co, Cd, Ga, As, Se, Sr, Sn, Sb, Ba, and Pb (Tremper et al., 2018). Meteorological conditions, including temperature (T), relative humidity (RH), and wind speed (WS) were obtained using an automatic weather station (Wang et al., 2019). Blank filters were also routinely analyzed with each batch of samples to detect sample contamination and provide quality assurance on the elemental concentrations. Detailed analytical methods and quality control are described in the supplement (Text S1). The method detection limits and measurement uncertainties are summarized in Table S2. The quality assurance protocol excluded temporally discrete dust storm and precipitation periods to prevent contamination of the source analysis of CM and modeling particle pH, given that such events induce non-representative extremes in both crustal element concentrations and pH values, coupled with elevated PM measurement uncertainties. The annual mean $PM_{2.5}$ concentration data for cities in the North China Plain were obtained from the China National Environmental Monitoring Center (CNEMC), available at https://www.cnemc.cn/.

2.2 Data Analysis

2.2.1 Mass reconstruction

The calculation method for CM is as follows (Tian et al., 2016):

$$[CM]=1.89\times[Al] + 2.14\times[Si] + 1.4\times[Ca] + 1.43\times[Fe]+1.94[Ti] \quad (1)$$

where [Al], [Si], [Ca], [Fe] and [Ti] represent the concentrations of the respective elements ($\mu g/m^3$), but Ti was not measured.

2.2.2 Thermodynamic model

The particle pH was calculated using the ISORROPIA-II mode (version 2.1, http://isorropia.eas.gatech.edu). The input data (excluding RH ≤ 30%), including SO_4^{2-}, TNO_3 (HNO_3 + NO_3^-), TNH_x (NH_3+NH_4^+), Ca^{2+}, K^+, Na^+, Mg^{2+}, Cl^-, RH and T, with the temporal resolution aligned with the sampling periods (from 10:00 AM to 9:00 AM the following day). The concentrations of hydrogen ions in air (H^+_{air}) and ALWC were derived from the Na^+-K^+-Ca^{2+}-Mg^{2+}-NH_4^+-SO_4^{2-}-NO_3^--Cl^--H_2O equilibrium composition system. Activity coefficients for H^+ and OH^- were fixed at unity, while other ion pairs (e.g., H^+-Cl^-) employed the Kusik-Meissner parameterization for ionic activity calculations (Fountoukis and Nenes, 2007). pH values were calculated using the following formula:

$$pH = -\log_{10} H^+_{aq} \cong -\log_{10} \frac{1000H^+_{air}}{ALWC_i + ALWC_o} \cong -\log_{10} \frac{1000H^+_{air}}{ALWC_i} \quad (2)$$

$$ALWC_o = \frac{m_{org}\rho_w}{\rho_w} \frac{\kappa_{org}}{\left(\frac{1}{RH} - 1\right)} \quad (3)$$

where $ALWC_i$ and $ALWC_o$ refer to the ALWC for inorganic and organic components, respectively.

m_{org} denotes the mass of organic aerosol, ρ_w is the density of water (1.0 g/cm^3), ρ_{org} is the density of organic material (1.4 g/cm^3) (Guo et al., 2015), k_{org} is the hygroscopicity parameter for organic aerosol (0.087) (Chang et al., 2010; Li et al., 2016). The ISORROPIA-II model operated under metastable conditions in the forward mode. Due to the lack of measured data for gaseous HNO_3 and NH_3, TNO_3 was represented solely by NO_3^-. The concentration of NH_3 was simulated based on a linear regression equation proposed by Wei et al. (2023), who used the same data as this study from 2013 to 2020:

$$NH_3 = 19.909 \times RH + 0.559 \times T - 0.35 \times NH_4^+ + 0.123 \times NO_3^- + 2.159 \times Cl^- - 0.224 \times SO_4^{2-} - 154.923 \quad (4)$$

where NO_3^-, SO_4^{2-}, NH_4^+, and Cl^- correspond to their respective concentrations (μg/m^3). To validate the applicability of Equation 4 for annual NH_3 estimation and pH simulation in Zhengzhou, this study utilized both observed NH_3 data (from a Thermo Scientific URG-9000D ambient ion monitor, USA) and calculated NH_3 values derived from Equation 4 at the same monitoring site throughout 2022, inputting them into the thermodynamic model for pH simulation. As shown in Figure S2, pH values calculated from observed and simulated NH_3 exhibit good agreement ($r = 0.97$, $P < 0.01$). Furthermore, NH_3 concentrations modeled by ISORROPIA demonstrate a significant correlation ($r = 0.95$, $P < 0.01$) with that simulated NH_3 by Equation 4. These results collectively demonstrate the reliability of the NH_3 estimation method in this study.

2.2.3 HYSPLIT analysis

Backward trajectories were calculated using the mixed-particle Lagrangian integrated trajectory method (HYSPLIT, https:// www.ready.noaa.gov/HYSPLIT_traj.php). Meteorological input data were from the Global Data Assimilation System (GDAS) with 3D wind vectors, temperature, relative

183 humidity, geopotential height, surface pressure, and boundary layer diagnostics. 24-hour backward
184 trajectories were simulated for air masses arriving at 100 m above ground level in Zhengzhou, a
185 receptor height aligned with the city's average elevation (~100 m above sea level) to capture near-
186 surface pollutant transport dynamics within the boundary layer.

187 Trajectories from 2013–2018 and 2019–2022 were independently clustered via the Angle Distance
188 algorithm to compare policy-driven variations (Wang et al., 2009). The optimal cluster number (three,
189 Figure S3) was determined by tracking total spatial variance (TSV), with classification finalized at the
190 inflection point preceding the second TSV surge.

191 3 Results and discussion

192 3.1 Temporal variations in chemical components

193 Over the past twelve years, the Chinese government has implemented two major policies to
194 mitigate air pollution: the Air Pollution Prevention and Control Action Plans (2013–2018) and the
195 Three-Year Action Plan (2018–2020), with key targets and measures detailed in Tables S3 and S4. The
196 2013–2018 policy prioritized end-of-pipe controls in power generation and heavy industries,
197 mandating ≥10% PM_{10} reduction nationwide and region-specific $PM_{2.5}$ reduction targets (25% for
198 Beijing-Tianjin-Hebei, 20% for Yangtze River Delta, and 15% for Pearl River Delta). Subsequently,
199 the 2018–2020 campaign shifted toward structural reforms and multi-pollutant synergistic governance,
200 enforcing ≥15% nationwide SO_2/NO_x emission cuts and ≥18% $PM_{2.5}$ reduction in non-compliant cities
201 relative to 2015 levels.

The long-term trends in $PM_{2.5}$ concentrations and its chemical components in Zhengzhou from 2011 to 2022 are depicted in Fig. 1, with annual average concentrations listed in Table 1. Correspondingly, the annual average concentration of $PM_{2.5}$ in Zhengzhou decreased from 162 ± 81 μg/m^3 in 2011 to 60 ± 41 μg/m^3 in 2022, representing a reduction of approximately 63%. In particular, the reduction rate reached 72% after 2013. As for chemical components, the largest reductions were observed in SO_4^{2-} (79%), decreasing from 38.0 ± 19.9 μg/m^3 in 2013 to 7.9 ± 4.5 μg/m^3 in 2022, followed by EC (76%). Additionally, the concentrations of NH_4^+ and NO_3^- also significantly decreased by 68% and 56%, respectively. The proportion of each component in $PM_{2.5}$ (Fig. S4) reveals a decrease in SO_4^{2-}, K^+, and Cl^-, indicating effective control measures targeting coal and biomass combustion (Lei et al., 2021). However, the proportions of NO_3^- and OC in $PM_{2.5}$ rose from 11% and 12% in 2013 to 13% and 17% in 2022, respectively, similar to the trend observed in the North China Plain (Wen et al., 2018; Zhai et al., 2019; Li et al., 2023).

3.2 Temporal variations in CM

Notably, there is no clear declining trend in the CM concentration, with a rebound observed during 2020–2022 (Fig. 1i). Furthermore, the proportion of CM in $PM_{2.5}$ exhibits a significant upward trend (Fig. S4). To further analyze its trend, sampling data were divided into three periods corresponding to governmental stages: 2011–2013, when no special control measures were implemented; 2013–2019, coinciding with the implementation of the Air Pollution Prevention and Control Action Plan; and 2019–2022, coinciding with the Three-Year Action Plan. During these periods, Henan Province and Zhengzhou City implemented several dust control policies summarized in Table S5. As shown in Fig.

2a and 2b, the mass concentration of CM peaked at 14.6 ± 8.3 μg/m^3 in 2013, accounting for 8% of $PM_{2.5}$. To evaluate the inter - annual change trend of CM, the Mann - Kendall method, Sen's slope, and Least - Squares (LS) slope were comprehensively used with the results presented in Table S6. From 2013 to 2019, the CM concentration notably decreased from 14.6 ± 8.3 to 8.5 ± 7.8 μg/m^3, with an annual average decline rate of 0.81 μg/(m^3·year) from LS slope [0.015 μg/(m^3·year) from Sen's slope]. Apart from control measures, the interannual meteorological analysis shows (Fig. S5) WS exhibited a declining trend, with a decrease rate of 43%, while RH showed an increasing trend at a rate of 8% from 2013 to 2019, under which conditions that were unfavorable for dust resuspension (Wang et al., 2013, 2018). Seasonal trends (Fig. S6) reveal significant declines in CM during spring in 2013–2019 with WS decreasing from 2.2 m/s in 2013 to 1.4 m/s in 2019 (Fig. S7) and stable RH (Fig. S8). Similarly, summer CM reductions in 2013–2019 corresponded with WS declines. These patterns suggest spring-summer CM improvements resulted from the synergistic effects of meteorological changes and dust control policies. Conversely, autumn-winter seasons showed limited CM reductions despite comparable WS decreases in 2013–2019, highlighting the need for enhanced dust emission controls in Zhengzhou during these seasons. As for the individual crustal elements in Fig. S9, Ca exhibited the highest average annual decline rate of 33% during 2013–2019, followed by Al. Si showed a less pronounced decline, attributed to its association with soil dust, where control measures for exposed soil are lacking (Zhang et al., 2020). In addition, the Ca^{2+} concentration as depicted in Fig. 2c decreased from 3.2 ± 2.1 μg/m^3 in 2013 to 2.2 ± 1.1 μg/m^3 in 2019, with an approximate annual average decline rate of 0.32 μg/(m^3·year) from LS slope [4.14E–03 μg/(m^3·year) from Sen's slope] in Table S6, further demonstrating the decline in dust source. It was worth noting that the proportions of CM,

Ca, Al, Fe, Si, and Ca^{2+} in $PM_{2.5}$ have shown consecutive annual increases from 2013 to 2019, with CM proportion increasing from 8% in 2013 to 14% in 2019, indicating that CM reduction lagged behind $PM_{2.5}$ reduction efforts in Zhengzhou during this period. Additionally, both concentration and proportion of Ca^{2+} in 2022 (2.2 ± 1.1 μg/m^3 and 5%) were higher than in other cities of China, such as Beijing (1.0 μg/m^3 and 2.8%), Tianjin (0.5 μg/m^3 and 1.4%), and Xiamen (0.48 μg/m^3 and 1.5%) (Shi et al., 2017; Xu et al., 2025; Zhang et al., 2021). These results indicate that CM remained an important component of $PM_{2.5}$ in Zhengzhou City.

During 2019–2022, both CM and Ca^{2+} concentrations exhibited significant rebounds, with annual growth rates of 0.24 and 0.4 μg/(m^3·year) from LS slope [5.80E–03 and 5.42E–03 μg/(m^3·year) from Sen's slope], respectively, and their proportions increased from 14% and 2% in 2019 to 22% and 5% in 2022. CM concentrations rebounded in all seasons, particularly in winter (Fig. S6). Changes in meteorological conditions may be a significant factor contributing to these concentration rebounds, accompanied by the average WS increased by 0.14 m/s and RH decreased by 7% from 2020 to 2022 (Fig. S5, S7, and S8), facilitating dust resuspension. Furthermore, the lack of more effective dust control measures, as indicated by the absence of significant changes in the dust control policies from the Air Pollution Prevention and Control Action Plan and Three-Year Action Plan, may be another important factor contributing to the rebound of dust.

3.3 Sources of CM

Elemental ratios were employed to characterize the sources of CM, with the Ca/Al ratio widely recognized as a reliable indicator of sandy origin (Zhang et al., 2017). In addition, significant variations

in Ca/Si ratios (Table S7) were observed among different dust sources (Road, Construction, Piles, Soil). Fig. 3a illustrates the trend in Ca/Si ratios from 2011 to 2022. After 2013, Ca/Si ratios showed a declining trend annually, with the average ratio decreasing from a peak of 1.6 in 2016 to a lowest of 0.4 in 2022. Compared with Ca/Si ratios from different types of dust sources, the effect of road and construction dust on CM has gradually decreased. This may be attributed to the implementation of dust control measures such as enclosure, shielding, and dust suppression at construction and demolition sites, as well as dust control on ground surfaces and roads (Table S5). During 2019–2022, the average Ca/Si ratio remained below 1, with a mean of 0.4 in 2022, indicating that soil dust predominantly contributed to CM. Currently, measures for controlling soil-suspended dust are limited, primarily relying on long-term strategies such as afforestation and increasing urban green coverage, thus requiring a longer process and sustained investment.

Sand dust transport serves as a significant source of CM in the North China Plain (Zhang et al., 2024). The Ca/Al ratio from 2016 to 2022 (Fig. 3b) shows minimal variation, with annual averages ranging between 1.5 and 2.5, indicating no significant changes in the source regions of sand. The transport trajectories (Fig. 3c and 3d) reveal that a marked decline in the contribution of long-distance sand dust transport originating from Inner Mongolia (via Shaanxi and Shanxi provinces) from 13.9% during 2013–2018 to 7.2% in 2019–2022. In contrast, local transport within Henan province and short-distance transport from Shandong province exhibited contrasting increases. These findings suggest that the rebound in CM concentrations during 2019–2022 in Zhengzhou might be responsible for the

resuspension of surrounding soil dust.

3.4 Long-term trend of particle pH

Are shown in Fig. 4 and Table S6, pH values showed a clearly increasing trend after 2014. From 2013 to 2019, the annual pH increased by 0.11 units from the LS slope [9.15E–04 units from Sen's slope], reaching a maximum median value of 4.45 (Mean: 4.35) in 2018. Note that the annual average growth rate of pH values increased to 0.21 units from LS slope [2.93E–03 units from Sen's slope] from 2019 to 2022, with a maximum median value of 4.42 (Mean: 4.51) in 2022. Seasonally, pH values showed increasing trends in spring, summer, and autumn, and notably increased in winter from 2020 to 2022 (Fig. S10). The increasing trend in pH values observed in this study is similar to the findings in Beijing (Song et al., 2019; Xie et al., 2020), presumably attributable to the comparable chemical composition trends and meteorological conditions (Liu et al., 2017; Wang et al., 2020; Xu et al., 2015). In contrast, Shanghai and Hong Kong display divergent trends (Nah et al., 2023; Zhou et al., 2022). This disparity might be ascribed to the stronger buffering effect exerted by NH_3 and dust in Zhengzhou than marine aerosols (Na^+/Cl^-) in these coastal cities (Shi et al., 2017; Liu et al., 2019). Moreover, these coastal cities' warm climates amplify pH declines. Elevated temperatures reduce ALWC through moisture evaporation, concentrating H^+ and directly lowering pH. Concurrently, heat-enhanced NH_3 volatilization from particulate NH_4^+ weakened acid neutralization (Zhou et al., 2022; Nah et al., 2023).

Sensitivity analyses were conducted to explore the dominant factors driving the elevated particle pH in Zhengzhou by giving a range for one parameter (i.e., TNH_x) and average values for other parameters (i.e., SO_4^{2-}, NO_3^-, Na^+, Cl^-, Ca^{2+}, K^+, Mg^{2+}, RH, and T) input into the ISORROPIA-II

model. Are shown in Fig. S11, particle pH increases with the cation concentrations (e.g., TNH_x, K^+, Ca^{2+}, Mg^{2+}, and Na^+) and decreases with anion concentrations (e.g., SO_4^{2-} and NO_3^-). Additionally, RH does not significantly affect pH, whereas an increase in T leads to a noticeable decrease in particle pH.

Based on the sensitivity analysis curves, the pH values corresponding to a variable in different years were calculated according to the average values of this variable in different years (Table S8). The difference in pH values of this variable between two adjacent years was defined as ΔpH which is illustrated in Fig. 5. According to Equation (2), in addition to H^+ concentration, particle pH is primarily influenced by the dilution effect of ALWC. Moreover, ALWC affects the gas-particle partitioning of semi-volatile compounds, thereby influencing particle acidity (Zuend et al., 2010; Zuend and Seinfeld, 2012). As shown in Fig.5 and Table S8, only in 2015, 2019, and 2020 did the increases in ALWC concentration (17.6 μg/m³, 4.1 μg/m³, and 11.6 μg/m³, respectively) lead to pH increases of 0.22, 0.06, and 0.14 units. This clearly cannot fully explain the significant pH increase in Zhengzhou since 2013. Notably, since 2013, H^+ concentration has shown a decreasing trend. Particularly, H^+ concentrations decreased by 7.6×10^{-6}, 11.2×10^{-6}, and 7.2×10^{-6} mol/L in 2013, 2015, and 2017, respectively, leading to pH increases of 0.21, 0.36, and 0.42 units. After 2019, a continuous decline in H^+ concentration was observed for three consecutive years, resulting in pH increases of 0.21, 0.13, and 0.2 units in 2020, 2021, and 2022, respectively. These findings indicate that the increase in pH from 2019 to 2022 in Zhengzhou was primarily driven by the reduction in H^+ concentration.

The concentration of H^+ in the aerosol liquid phase is influenced by both chemical composition and meteorological conditions. To further understand the factors affecting ΔpH, we analyzed the

variations in $PM_{2.5}$ chemical components and meteorological parameters. Results indicate that the decline in SO_4^{2-} from 2013 to 2018 was the primary cause of the increase in particle pH, as it decreased H^+ and ALWC concentrations (Fig. S12) in aerosol (Ding et al., 2019; Zhang et al., 2021). The average SO_4^{2-} concentration decreased by 14.6 and 5.3 μg/m^3, resulting in a pH increase of 0.43 and 0.35 units from 2013 to 2014 and 2016 to 2017, respectively, which was comparable to an increased rate of 0.3 units in East Asia due to SO_2 emission controls since 2016 (Karydis et al., 2021). As another acidic ion, the decrease in nitrate concentration did not significantly contribute to the pH increases, consistent with findings from Ding et al. (2019) and Zhang et al. (2021). This is primarily because NO_3^- declined more slowly compared to sulfate ions and exceeded sulfate concentrations after 2016, under which conditions that nitrate-rich particles can absorb twice the amount of water that sulfate-rich particles, leading to an increase in ALWC concentration and inhibiting pH decline (Lin et al., 2020; Xie et al., 2020). On the other hand, increases in particle pH in 2015 and 2018 were notably influenced by changes in TNH_x with concentrations increased by 5.5 and 1.3 μg/m^3, respectively. Increased TNH_x concentrations could react with SO_4^{2-} or NO_3^- and consume a substantial amount of H^+, thereby raising particulate matter pH values (Seinfeld et al., 1998; Zhang et al., 2021). Substantial decreases in T in 2015 (4.2℃), 2017 (4.9℃), and 2018 (2.8℃), favoring NH_3 partitioning into the particle phase and reducing H^+ concentrations, drove increases in particle pH (Tao and Murphy, 2019).

During the period from 2020 to 2022, the influence of SO_4^{2-} on particle pH gradually decreased, with a decrease in concentration from 0.3 to 2.3 μg/m^3 (Table S8) only bringing about a pH decrease of 0.03 to 0.14 (Fig. 5). Moreover, a rebound in SO_4^{2-} concentration to 7.9 ± 4.5 μg/m^3 in 2022 even resulted in a decrease of 0.11 units in pH instead. On the other hand, TNHx began to show a slight

annual decline (0.9 to 2.2 μg/m^3), resulting in a significant decrease in pH (0.21–0.35). Consequently, the increase in pH values was closely related to the rise in Ca^{2+} concentration. Ca^{2+} is less volatile and competes preferentially with NH_3 to neutralize anions such as SO_4^{2-} to form insoluble $CaSO_4$, which precipitates from the aerosol aqueous phase (Ding et al., 2019; Karydis et al., 2021), thereby reducing H^+ concentrations (Fig. S12) and subsequently lowering particle acidity. Specifically, increases of 0.7 and 0.5 μg/m^3 in Ca^{2+} concentrations led to pH increases of 0.13 and 0.09 units in 2020 and 2022, respectively, making Ca^{2+} a primary controlling factor for pH elevation.

4 Conclusions

The annual average $PM_{2.5}$ concentration in Zhengzhou decreased from 212.4 ± 101.5 μg/m^3 in 2013 to 59.5 ± 41.2 μg/m^3 in 2022, with the largest reduction in SO_4^{2-}. As for CM, their concentrations notably decreased from 2013 to 2019, because of effective dust control measures, as well as decreased wind speed and increased relative humidity. However, the proportions of CM in $PM_{2.5}$ have shown consecutive annual increases. In addition, CM concentrations and their proportions increased significantly during 2019–2022, which might be responsible for the resuspension of surrounding soil dust. Correspondingly, the annual pH increased by 0.11 units from 2013 to 2019 mainly due to the decline in SO_4^{2-}, increased TNH_x, or decreased temperature. During the period from 2020 to 2022, the annual average growth rate of pH values increased to 0.21 units from 2019 to 2022, which was determined by the rise in Ca^{2+} concentration.

5 Implication

Control measures implemented by the Chinese government have proven effective in reducing dust, but this study reveals that the crustal materials in $PM_{2.5}$ rebounded after 2019. This phenomenon is not unique to Zhengzhou, as major cities in the North China Plain have also experienced a pronounced upward trend in coarse particles after 2019 (Fig. S13). Thus, crustal materials persist as a substantial constituent of atmospheric aerosols in North China, sustaining elevated particle pH levels. Extensive research has established that heightened particle pH inhibits nitrate reduction in aerosols (Ding et al., 2019; Lin et al., 2020; Wen et al., 2018), particularly significant given nitrate's predominant role in haze formation within this region. Notably, while moderately acidic aerosols demonstrate reduced health impacts, particles with pH < 3 exhibit substantially greater health risks (Shi et al., 2019). Consequently, future environmental management strategies must prioritize real-time assessment of regulatory impacts on particle acidity. This necessitates an integrated approach that simultaneously addresses acidic precursors, alkaline precursors, and crustal material contributions to atmospheric acid chemistry.

Data availability

All the data presented in this article can be accessed through https://doi.org/10.5281/zenodo.14032007 (Zhang, 2024).

Supporting Information

Additional data, figures, and tables, some of which are referenced directly within the manuscript, and detailed descriptions of field measurements and samples.

Author contributions

S.W. designed this study. H.Z. and Z.D. analyzed the data and prepared the manuscript with the contributions of all coauthors. X.L. conducted measurements. R.Z. provided funding acquisition. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Figures

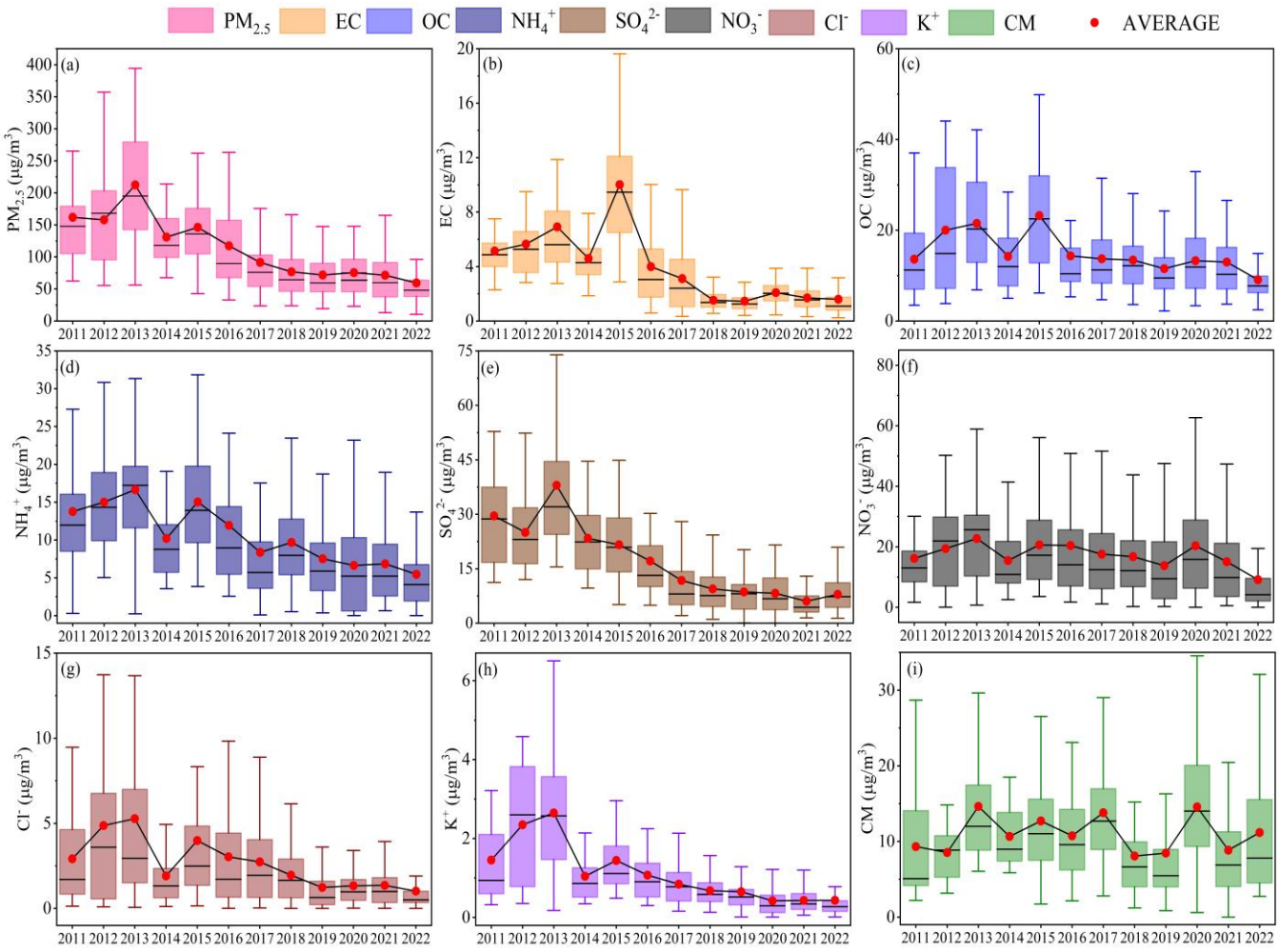
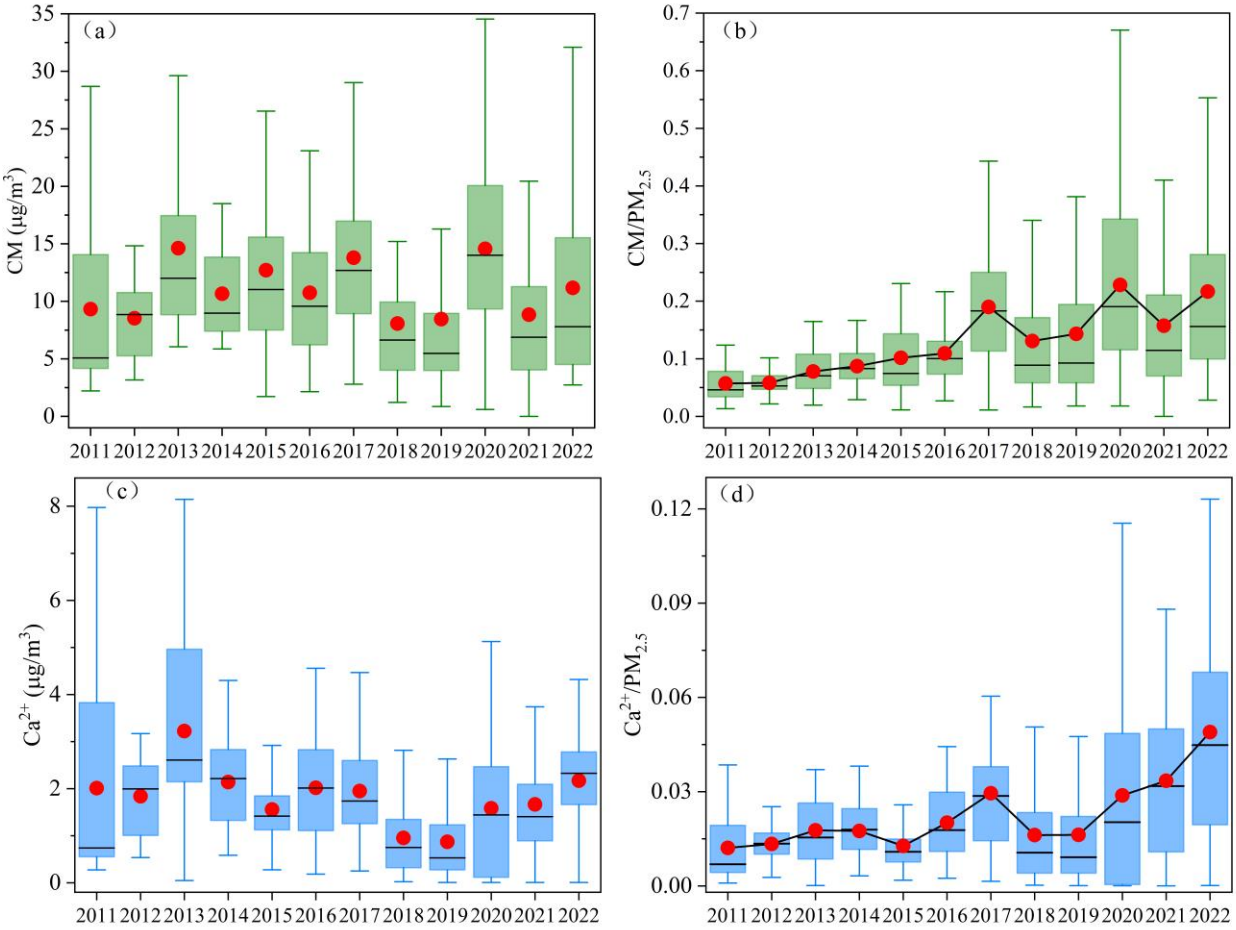


Figure 1. Long-term trends in the concentrations of $PM_{2.5}$ and its chemical components in from 2011 to 2022 in Zhengzhou. Box plots depict annual averages (red dots) and medians (black lines), the top, middle, and bottom lines represent the 75, 50, and 25 percentiles of statistical data, respectively, and the upper and lower whiskers represent the 90 and 10 percentiles of statistical data, respectively.



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629 Figure 2. (a) and (c) Long-term trends in CM and Ca^{2+} concentrations in Zhengzhou from 2011 to
630 2022, respectively. Box plots depict annual averages (red dots) and medians (black lines). (b) and (d)
631 Long-term trends in the proportions of CM and Ca^{2+} in $PM_{2.5}$, respectively.

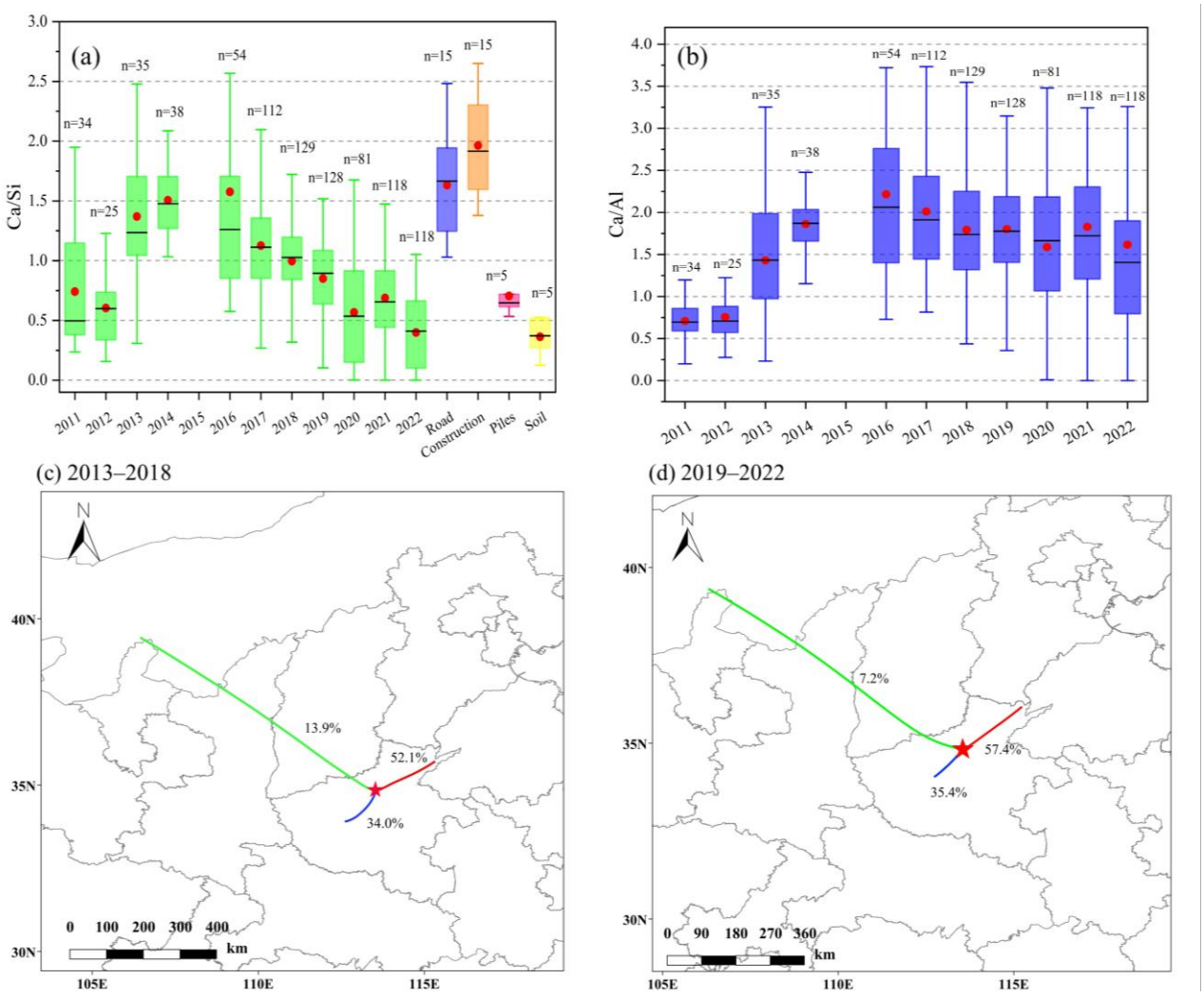
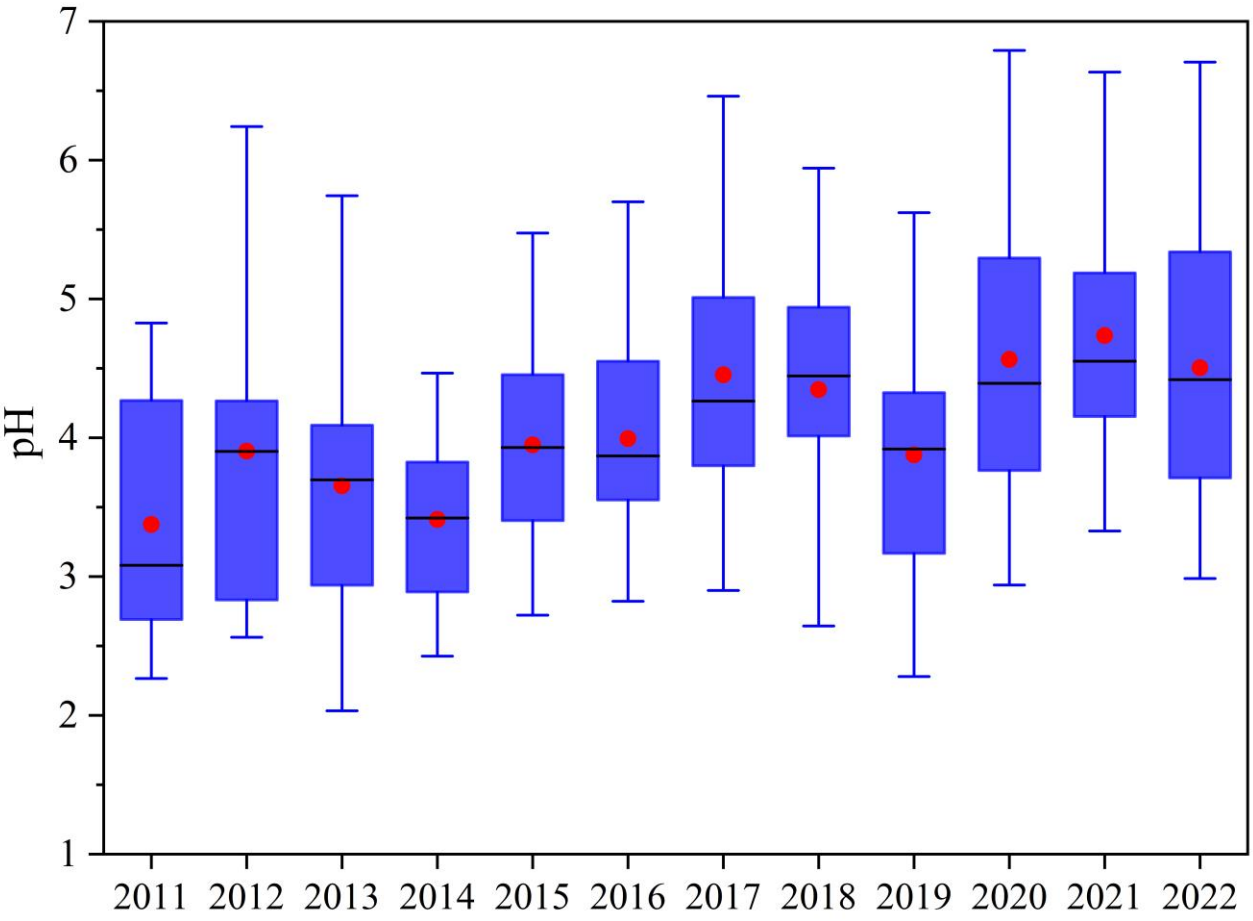


Figure 3. (a) The annual Ca/Si ratios in Zhengzhou from 2011 to 2022 compared with those in various dust sources (specific values and references in Table S7). The red dots and black lines in the box plots represent the annual averages and medians, respectively, with n indicating the sample size. (b) The Ca/Al ratios in Zhengzhou from 2011 to 2022. The red dots and black lines in the box plots represent the annual averages and medians, respectively, with n indicating the sample size. (c) and (d) The transport pathways of CM during 2013–2018 and 2019–2022, respectively.



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640 Figure 4. The time series of particle pH in Zhengzhou from 2011 to 2022. In the boxplots, red dots
641 and black lines represent the annual mean and median values, respectively.

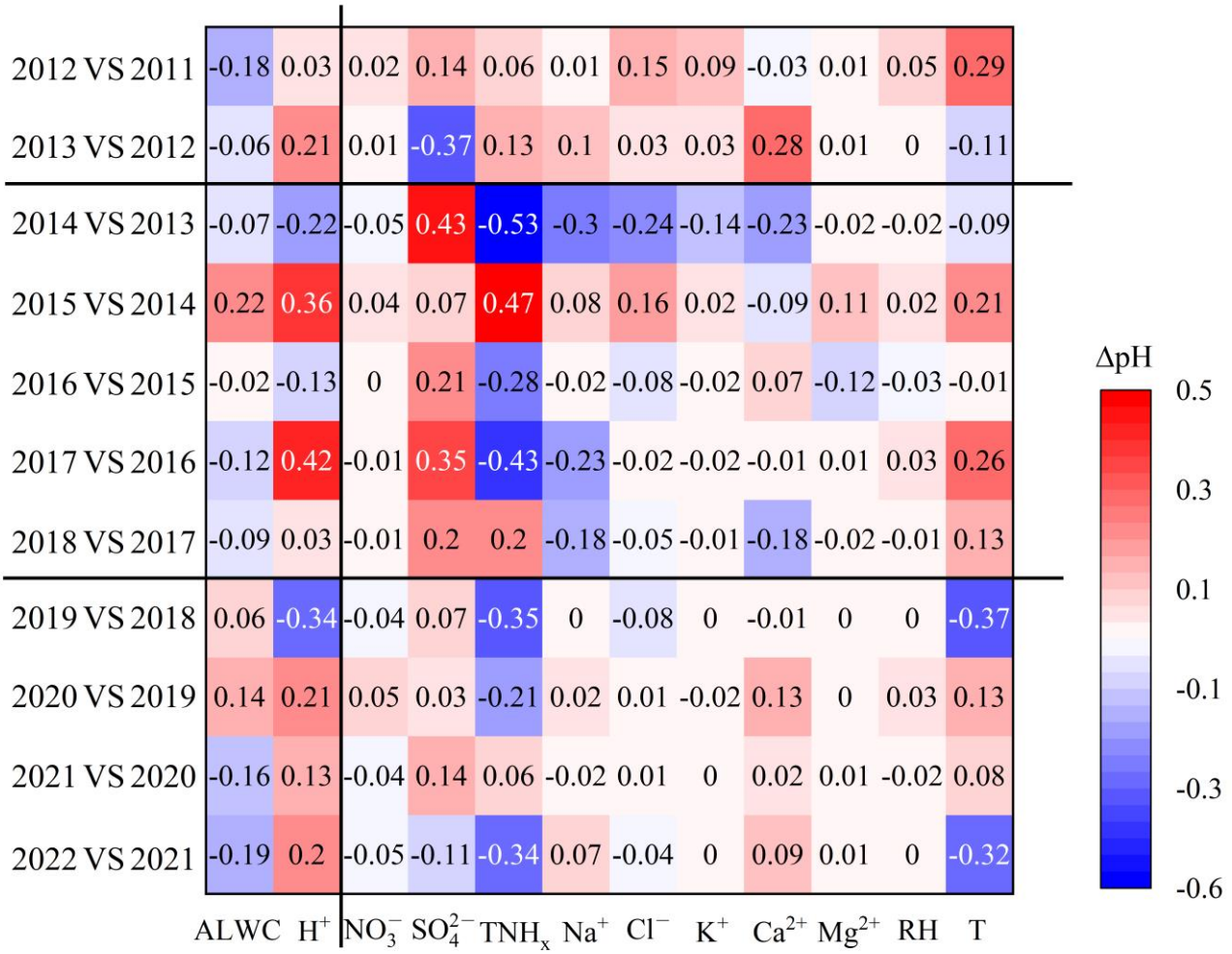

Figure 5. Contribution of each component to the changes in pH (ΔpH) between adjacent years. The difference between component concentrations and meteorological parameters between adjacent years is listed in Table S8.

646 **Table**

647 Table 1. Annual average concentrations of $PM_{2.5}$ and its components from 2011 to 2022 in Zhengzhou,
648 China ($\mu g/m^3$).

Years	$PM_{2.5}$	EC	OC	NO_3^-	SO_4^{2-}	NH_4^+	CM	Ca^{2+}
2011	161.9±81.4	5.1±2.1	13.6±8.6	16.2±11.2	29.6±14.3	13.8±8.3	9.3±7.3	2.0±2.2
2012	157.9±71.2	5.6±2.5	20.0±13.4	20.2±13.7	25.0±11.2	15.0±7.1	8.5±3.4	1.8±0.8
2013	212.4±101.5	6.9±3.8	21.5±10.4	22.7±13.2	38.0±19.9	17.1±6.9	14.6±8.3	3.2±2.1
2014	130.8±48.7	4.6±2.0	14.2±8.2	15.5±10.8	23.4±9.3	10.2±6.2	10.7±4.4	2.1±1.0
2015	146.1±61.0	10.0±4.7	23.2±11.6	20.6±14.5	21.6±9.8	15.7±7.5	12.7±6.8	1.6±0.7
2016	117.4±73.5	4.0±2.8	14.4±10.0	20.4±18.7	17.1±11.3	11.9±10.6	10.8±5.3	2.0±1.1
2017	91.5±61.1	3.1±2.5	13.7±7.5	17.6±15.9	11.8±11.6	8.4±7.9	13.8±6.5	2.0±1.0
2018	76.8±41.6	1.5±0.7	13.4±7.3	16.7±13.5	9.4±6.0	9.7±6.1	8.1±5.7	1.0±0.8
2019	68.4±34.8	1.5±0.8	11.5±6.8	13.8±13.9	8.6±6.4	7.5±6.1	8.5±7.8	0.9±0.9
2020	75.5±31.8	2.1±0.9	13.3±7.9	18.6±14.2	8.3±5.6	6.7±6.6	14.6±7.6	1.6±1.4
2021	71.5±45.9	1.7±0.9	13.0±8.0	15.1±15.1	6.1±4.5	6.8±6.0	8.9±7.0	1.7±1.2
2022	59.5±41.1	1.6±1.5	9.1±8.1	10.0±14.4	7.9±4.5	5.5±5.4	11.2±8.3	2.2±1.1

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