



# Recent Developments in the Determination of PM<sub>2.5</sub> Chemical Composition

Susu Pan<sup>2</sup> · Yanting Qiu<sup>1</sup> · Ming Li<sup>3</sup> · Zhenqi Yang<sup>2</sup> · Dapeng Liang<sup>1</sup>

Received: 21 January 2021 / Accepted: 16 March 2022 / Published online: 6 April 2022  
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

## Abstract

Fine particulate matter (named PM<sub>2.5</sub>) has become a prominent and dangerous form of air pollution. The chemical composition of PM<sub>2.5</sub> mainly includes inorganic elements, water soluble ions, elemental carbon (EC), organic carbon (OC), and organic compounds. The detection method for inorganic elements mainly includes X ray fluorescence, inductively coupled plasma-atomic emission spectrometry, and inductively coupled plasma mass spectrometry. As for water soluble ions, ion chromatography is the most common detection method. EC and OC are usually detected by carbon analyzer. The organic compounds are determined by gas chromatography–mass spectrometry and liquid chromatography–mass spectrometry. In this paper, the merits and drawbacks of each analytical methods for the determination of PM<sub>2.5</sub> chemical composition are summarized. This review also includes our discussion on the improvement of the analytical accuracy for the determination of PM<sub>2.5</sub> chemical composition owing to the development of reference materials.

**Keywords** Air pollution · PM<sub>2.5</sub> · Chemical composition · Source appointment · Reference material · Analytical accuracy

Air pollution is a global problem and thus has been attracted more attention since 1930s. In 1952, the Big Smoke in London makes people concentrate on particulate matters (PM), which is divided into two kinds according to aerodynamics diameter ( $D_p$ ). The particles with  $D_p \geq 2.5 \mu\text{m}$  are called coarse particles, while others with  $D_p < 2.5 \mu\text{m}$  are defined as fine particle matters and also named as PM<sub>2.5</sub>.

The primary sources of PM<sub>2.5</sub> are traffic, industry, domestic fuel burning, and natural sources from volcanos, soil dust, and sea spray particles etc. Generally, particles which come from the burning of fossil fuel are considered as the major source of PM<sub>2.5</sub>. The particles exhausted by nature and human activities are defined as primary particles (Streets et al. 2003). Another source of PM<sub>2.5</sub> is the growth of condensable vapors in the atmosphere, which is called new particle formation (NPF)

(Kumala 2003). There are four different modes of NPF according to the particle diameter: nucleation mode, aitenken mode, accumulation mode, and coarse mode. Particles with nucleation mode come from the condensation and coagulation of low volatility compounds (Kumala 2003), and then grow to aitenken mode, accumulation mode, and coarse mode. The mechanism of particle growth is generally acknowledged in three ways: H<sub>2</sub>SO<sub>4</sub>–H<sub>2</sub>O nucleation, H<sub>2</sub>SO<sub>4</sub>–H<sub>2</sub>O–NH<sub>3</sub> nucleation and ion nucleation (Kirkby et al. 2011). The diameter of particles increases 40–100 nm in a few hours under high concentration of gaseous pollutant and strong oxidative (Wiedensohler et al. 2012). With the size growth of the particles, several chemical reactions such as photocatalytic reactions (Griffith et al. 2013) and free radical oxidation reactions (Schaefer et al. 2015) may occur, which makes the chemical composition of PM<sub>2.5</sub> more complex. To determine the chemical composition of PM<sub>2.5</sub> is significant to understand the mechanism of NPF. The atmosphere and regional climate may be influenced by PM<sub>2.5</sub>. Atmospheric visibility is reduced by PM<sub>2.5</sub> since it increases scattering and absorption coefficients of air. With the concentration of PM<sub>2.5</sub> increasing, the cyclone in the East U.S. is continually extended during the last 40 years (Tai et al. 2010). Besides the influence on the atmosphere and climate, PM<sub>2.5</sub> also seriously effects on the human health, especially respiratory system and cardiovascular system, even at PM<sub>2.5</sub>

✉ Dapeng Liang  
liangdp@jlu.edu.cn

<sup>1</sup> Key Laboratory of Groundwater Resources and Environment of the Ministry of Education, Jilin University, Changchun 130012, China

<sup>2</sup> Division of Ecology Environment and Energy Resources, Beijing Institute of Metrology, Beijing 100012, China

<sup>3</sup> Division of Chemical Metrology & Analytical Science, National Institute of Metrology, Beijing 100029, China

levels below the current standards (deSouza 2021). Statistical data showed that the number of SARS-CoV-2 infections cases and deaths increased significantly along with increasing levels of PM<sub>2.5</sub> in five regions of the USA, Los Angeles, New Mexico, New York, Ohio, and Florida (Meo et al. 2021). Heavy metals (e.g. Pb and Hg) in PM<sub>2.5</sub> may cause asthma and heart failure (Prendes et al. 1999). Polycyclic aromatic hydrocarbons (PAHs) (Shen et al. 2019) and heavy metals in PM<sub>2.5</sub> are considered as the main reason for the increase risk of cancer. Determination of PM<sub>2.5</sub> chemical composition is useful to evaluate the risk of PM<sub>2.5</sub> on human health. The PM<sub>2.5</sub>-related health impact and corresponding economic losses for both society and individual were estimated, which can provide insightful observations for policy makers to keep the social equality, welfare and environment conservation. In the European Union, Directive 2008/50/EC has been enforced to monitor and reduce the contamination levels of PM<sub>2.5</sub>. Based on the information of PM<sub>2.5</sub> chemical composition, source apportionment for pollution can be clearly identified, which is helpful to effectively control the air pollution (in't Veld et al. 2021).

In light of the reasons mentioned above, it is essential for the determination of PM<sub>2.5</sub> chemical composition. In this paper, the analytical methods for the determination of inorganic elements, water soluble ions, element carbon and organic carbon, organic compounds in PM<sub>2.5</sub> are carefully reviewed.

## Sample Collection

PM<sub>2.5</sub> needs to be collected in the atmosphere prior to analysis. Quartz fiber filter and teflon filter are commonly used in collecting PM<sub>2.5</sub>. Quartz fiber filter has outstanding performance of high temperature resistance and therefore is suitable for the analysis of element carbon, organic carbon, organic compounds, and water soluble ions. In order to reduce the background of organic compounds, quartz fiber filter needs to be baked for a few hours under temperature higher than 300°C before used. Considering some inorganic elements (e.g. Al, Si and Fe) are inherently reserved in quartz fiber filter, it is not suitable to use quartz fiber filter for the analysis of inorganic element. Teflon filter is usually used in determination of inorganic inorganic elements and water soluble ions. The treatment of teflon filter is similar to quartz fiber filter.

## Detection Methods for PM<sub>2.5</sub> Chemical Composition

### Determination of Inorganic Elements in PM<sub>2.5</sub>

Several inorganic elements are extremely harmful to human health. X ray fluorescence (XRF) is a technique

used to characterize inorganic elements by measuring the fluorescence emitting from a chemical compound subjected to continuous X-ray radiation. XRF has the advantages of relatively easy operation and low cost of sample preparation, and thus is widely used for the determination of major and trace inorganic elements in several kinds of material, e.g. rock, mineral, and sediment. For the analysis of PM<sub>2.5</sub>, XRF is usually used to detect heavy metals (e.g. Pb, Cu, and Cd) with detection limits between 1 and 100 ng cm<sup>-2</sup> (Gemenetzis et al. 2006). For example, 18 kinds of inorganic elements (e.g. Zn, As, and Sr) determined using energy dispersive X-ray fluorescence (ED-XRF), which results have an uncertainty between 5% and 15%, was adopted for source appointment of air pollution (Owoade et al. 2016). The ED-XRF system used had detection limits (mg/g) as shown in parenthesis: Na(2000), Mg(1000), Al(600), Si(300), P(120), S(30), Cl(10), K(150), Ca(80), Ti(25), Mn(0.5), Fe(15), Zn(0.8), As(0.6), Br(0.6), Rb(0.5), Sr(0.5) and Pb(1.7). Synchrotron radiation X-ray fluorescence (SR-XRF) is another XRF with synchrotron radiation used as excitation source. With main advantage of high sensitivity (detection limits in the range of ng m<sup>-3</sup>), SR-XRF has proved to be a powerful tool to quantify the major, minor, trace constituents, which results were correlated with possible sources (López et al. 2011). XRF has the advantages of high speed, high precision, and simple sample treatment.

Inductively coupled plasma-atomic emission spectrometry (ICP-AES) is another technique used for detecting inorganic elements. Using ICP-AES, it proved that heavy metals in PM<sub>2.5</sub> are closely related with industrial production. For example, the concentrations of Cr, Co, Ni, As, and Sb in Shandong province were the highest in China because of the large amount of industries in this province (Liu et al. 2018). Alternatively, inductively coupled plasma-mass spectrometry (ICP-MS) is an analytical method for determination of inorganic elements in PM<sub>2.5</sub>. For example, Cu, Pb, Se, and As were found to be the highest inorganic elements in PM<sub>2.5</sub> sample collected in Mountain Tai by using ICP-MS, and these inorganic elements mainly come from coal-fired power plants (Qie et al. 2018). With ICP-MS, 23 kinds of trace inorganic elements in PM<sub>2.5</sub> sample collected in south Taiwan were detected, and their concentrations in cold season were higher than those in hot season (Hwang et al. 2018). The method detection limits were in the range  $1.83 \times 10^{-2}$ –24.3 μg L<sup>-1</sup> for all selected trace elements. Briefly, both ICP-AES and ICP-MS are highly effective analytical techniques. ICP-AES allows for a wide range of elements with major concentrations down to part per billion. With MS as detector, ICP-MS provides a lower detection limit of part per trillion.

## Determination of Water Soluble Ions in PM<sub>2.5</sub>

Water soluble ions are major composition of PM<sub>2.5</sub>. Water soluble ions have strong hygroscopicity, which may influence the formation of cloud and thus the climate (Hassanvand et al. 2014). Atmospheric visibility is reduced by water soluble ions in PM<sub>2.5</sub> via scattering sunlight (Christine et al. 1991). In addition, water soluble ions may form secondary aerosol inorganic ions (SAII) (Sharma et al. 2007). Resultly study showed heavy metals play an important role in the genotoxicity of PM<sub>2.5</sub> (Kogianni et al. 2021). Ion chromatography has the advantages of high speed and good separation efficiency, it thus is widely used for the determination of water soluble ions in PM<sub>2.5</sub>. For example, a study on water soluble ions in PM<sub>2.5</sub> using ion chromatography, with detection limit of each ion lower than 0.015 µg m<sup>-3</sup>, showed that the secondary sulfate was ascribed to aqueous phase sulfur oxidation promoted by high concentration NO<sub>2</sub> and high relative humidity (Guo et al. 2019). Seasonal variability of NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> is governed by dissociation of NH<sub>4</sub>NO<sub>3</sub> under high temperature in summer (Qiao et al. 2019).

Besides ion chromatography, atomic absorption spectrophotometry (AAS) is another analytical method for determination of water soluble ions. The principle of AAS is absorption of specific frequencies of light by atoms, and thus AAS can only analyze metal ions. Nessler spectrophotometry, selectfluor spectrophotometry, ferrithiocyanate spectrophotometry, and barium sulfate precipitation are traditional analytical methods for NH<sub>4</sub><sup>+</sup>, F<sup>-</sup>, Cl<sup>-</sup>, and SO<sub>4</sub><sup>2-</sup>. These methods need complicated sample preparation and thus are not very popular in the detection of water soluble ions in PM<sub>2.5</sub>. Several metal ions in PM<sub>2.5</sub> can be used as a marker for source apportionment of air pollution. For example, Ca<sup>2+</sup> and Mg<sup>2+</sup> can be used as a marker of construction dust (Owoade et al. 2016), since the use of cement is the only source of Ca<sup>2+</sup> and Mg<sup>2+</sup> in an inland city. F<sup>-</sup> can be used as a marker of coal burning (Galvao et al. 2019) because the only source of F<sup>-</sup> is coal burning in a city. BaTiO<sub>3</sub> analyzed by synchrotron XRD was proved to be a vehicular marker formed during brake action. Maghemite (gamma-Fe<sub>2</sub>O<sub>3</sub>), pyracmonite [(NH<sub>4</sub>)<sub>3</sub>Fe(SO<sub>4</sub>)<sub>3</sub>], ammonium perchlorate (NH<sub>3</sub>OHCIO<sub>4</sub>) and potassium ferrate (K<sub>2</sub>Fe<sub>2</sub>O<sub>4</sub>) found in PM<sub>2.5</sub> were proved to be markers of industrial activities (Galvão et al. 2020).

## Determination of Elemental Carbon (EC) and Organic Carbon (OC) in PM<sub>2.5</sub>

20–70% weight of PM<sub>2.5</sub> is composed of EC and OC. EC absorbs sunlight and thus heats the air, which directly contributes to global warming. EC has been considered as secondary factor contributing to global warming, followed with CO<sub>2</sub> (Jacobson 2001). OC mainly comes from exhaust of

vehicles and industry. The direct exhaust is called primary organic carbon, which can react with sunlight and oxidants (e.g. ozone and free radical) forming secondary organic carbon (Kelly and Fussell 2012). Besides, OC frequently derives from biomass burning (Zhang et al. 2010).

Carbon analyzer (e.g. DRI carbon analyzer, Sunset carbon analyzer) coupling with IMPROVE, NIOSH or EUSAAR2 thermal-optical protocols is widely used for the detection of EC and OC. Using either IMPROVE, NIOSH or EUSAAR2 protocol, the results of the total carbon (TC) were always the same, however the ratio of OC/EC was sometimes different because of different laser correction methods used (Bautista et al. 2015). How to choose a protocol depends on the actual situation, IMPROVE is a popular protocol, while EUSAAR2 protocol is mainly used in Europe (Vodicka et al. 2015). A typical limit detection for carbon analyzer is 0.33 µg Carbon m<sup>-3</sup> (Zhang et al. 2010).

Single particle aerosol mass spectrometry (SPA-MS) is a new technique for detecting the EC and OC in PM<sub>2.5</sub>. Compared with traditional carbon analyzer, SPA-MS can determine the chemical composition of PM<sub>2.5</sub> in real-time without sample pretreatment.

## Determination of Organic Compounds in PM<sub>2.5</sub>

In recent years, more researches have been focused on the study of organic composition in PM<sub>2.5</sub> because of the high toxicity of organic compounds. It is difficult to accurately analyze all organic compounds in PM<sub>2.5</sub> because of the instability and low concentration of some complex organic compounds. PAHs are strong carcinogens and thus the risk of cancer arising from PAHs in PM<sub>2.5</sub> has been carefully studied (Shen et al. 2019). Dioxin is a typical PAH in PM<sub>2.5</sub>, its high risk of carcinogenicity and mutagenicity has been intensively studied (Tsai et al. 2018). Besides PAHs, other organic compounds such as polychlorinated biphenyls (PCBs), fatty acid, and phthalate may participate in photochemical reaction forming more toxic compounds (Canonica et al. 2005).

Gas chromatography–mass spectrometry (GC–MS) and liquid chromatography–mass spectrometry (LC–MS) are two common methods for detecting organic compounds in PM<sub>2.5</sub>. One significant advantage of GC–MS and LC–MS is good separation efficiency especially when a series of organic compounds with similar structures detected. GC–MS is used to detect small thermo-stable molecules with low boiling point. For the determination of PAH in PM<sub>2.5</sub>, the recoveries were from 75% to 120% and relative deviation of six times duplicate was less than 10% (Shen et al. 2019). A GC–MS method was developed for simultaneous detection of 16 kinds of United States Environmental Protection Agency (US-EPA)-PAHs in PM<sub>2.5</sub>, and the recovery obtained from urban dust SRM 649 A (NIST

reference material) was between 63% and 102%. The results showed the concentrations of PAHs were increased with the use of wet wood for residential combustion (Guerrero et al. 2019). Another GC–MS method was developed for detecting the concentrations of PM<sub>2.5</sub>-associated non-polar organic compounds (NPOCs), including PAHs, *n*-alkanes, *iso*-alkanes, hopanes, and steranes. With this method, the size-specific distributions of NPOCs from 0.01 to 18 µm were also determined (Han et al. 2018). LC-MS has been applied to detect larger molecules (e.g. organosulfates) and thermo-unstable small organic molecules (e.g. amino acids) (Samy et al. 2011) in PM<sub>2.5</sub>. For example, an LC–MS/MS method was developed for the detection of methylene blue active substances (MBAS) and linear alkylbenzene sulphonates (LAS) in PM<sub>2.5</sub> sampled in a coastal city, the limit of quantifications for LAS and MBAS were 2.2 ng m<sup>-3</sup> and 45 ng m<sup>-3</sup>, respectively. The results showed that the source of MBAS was anthropogenic origins and the source of LAS was sea surface (Becagli et al. 2011). Several methods based on GC–MS and LC–MS have been developed for detecting organic compounds in PM<sub>2.5</sub>, there are still some unknown organic compounds to be intensively studied. Also, complex sample preparation is needed before GC-MS and LC-MS analysis.

Alternatively, aerosol mass spectrometer (AMS) is a powerful technique for the direct study on atmospheric particles (Nash et al. 2006) and thus is widely used in the world. Using AMS, the organic component in the PM<sub>2.5</sub> can be efficiently ionized by electron impact, or chemical ionization. Subsequently, the ions are determined by a mass analyzer, such as time of flight, quadrupole mass filter, and quadrupole ion trap. Because complex sample preparation is not needed, AMS has potential application in the field of online determination of chemical composition in PM<sub>2.5</sub> and thus the source appointment of air pollution can be rapidly obtained.

## Conclusions

PM<sub>2.5</sub> is a common air pollutant seriously effecting on human health. The chemical composition of PM<sub>2.5</sub> is complex mainly including inorganic elements, water soluble ions, EC, OC, and organic compounds. Accurate determination of chemical composition of PM<sub>2.5</sub> is useful for source appointment of air pollution, which is conducive to pollution control and environmental protection. Many methods are available for the detection of inorganic elements, water soluble ions, EC and OC in PM<sub>2.5</sub>. However, comprehensive determination of organic compounds in PM<sub>2.5</sub> is still challenging although several methods based on GC–MS and LC–MS have been established. Therefore, several methods based on high resolution mass spectrometry should be developed for comprehensive characterization of organic compounds

in PM<sub>2.5</sub>. In the future, the accurate analytical method for determining PM<sub>2.5</sub> chemical composition needs to be further developed. A reference material of PM<sub>2.5</sub>-like atmospheric dust material for accurate monitoring of anions and cations has been prepared (Charoud-Got et al. 2017) approaching the EN12341 definition of PM<sub>2.5</sub> containing the ions mentioned in Directive 2008/50/EC. This reference material is very useful as a quality control sample for ensuring compatibility of results among PM<sub>2.5</sub> monitoring studies and can be used to assess the accuracy of analytical methods used. Continuous efforts and achievements in the development of reference materials for monitoring other chemicals in PM<sub>2.5</sub> would significantly improve the analytical accuracy for the determination of PM<sub>2.5</sub> chemical compositions. Development of portable monitor achieving tempo-spatial patterns of chemicals in PM<sub>2.5</sub> is also highly recommended to manage air pollution.

## References

- Bautista AT, Pabroa PCB, Santos FL, Quirit LL, Asis JLB, Dy MAK, Martinez JPG (2015) Intercomparison between NIOSH, IMPROVE\_A, and EUSAAR\_2 protocols: finding an optimal thermal-optical protocol for Philippines OC/EC samples. *Atmos Pollut Res* 6:334–342
- Becagli S, Ghedini C, Peeters S, Rottiers A, Traversi R, Udisti R, Chiari M, Jalba A, Despiou S, Dayan U, Temara A (2011) MBAS (methylene blue active substances) and LAS (linear alkylbenzene sulphonates) in Mediterranean coastal aerosols: sources and transport processes. *Atmos Environ* 45:6788–6801
- Canonica S, Kohn T, Mac M, Real FJ, Wirz J, Von Gunten U (2005) Photosensitizer method to determine rate constants for the reaction of carbonate radical with organic compounds. *Environ Sci Technol* 39:9182–9188
- Charoud-Got J, Emma G, Seghers J, Tumba-Tshilumba MF, Santoro A, Held A, Snell J, Emteborg H (2017) Preparation of a PM<sub>2.5</sub>-like reference material in sufficient quantities for accurate monitoring of anions and cations in fine atmospheric dust. *Anal Bioanal Chem* 409:7121–7131
- Christine SS, John W, Judith C, Lyle P, Richard LW (1991) Size-segregated fine particle measurements by chemical species and their impact on visibility impairment in Denver. *Atmos Environ* 25:1013–1024
- deSouza P, Braun D, Parks RM, Schwartz J, Dominici F, Kioumourtzoglou MA (2021) Nationwide study of short-term exposure to fine particulate matter and cardiovascular hospitalizations among medicaid enrollees. *Epidemiology* 32:6–13
- Galvão ES, Reis NC, Lima AT, Stuetz RM, Orlando MTD, Santos JM (2019) Use of inorganic and organic markers associated with their directionality for the apportionment of highly correlated sources of particulate matter. *Sci Total Environ* 651:1332–1343
- Galvão ES, Orlando MTD, Santos JM, Lima AT (2020) Uncommon chemical species in PM<sub>2.5</sub> and PM<sub>10</sub> and its potential use as industrial and vehicular markers for source apportionment studies. *Chemosphere* 240:12493
- Gemenetzi P, Moussas P, Arditoglou A, Samara C (2006) Mass concentration and elemental composition of indoor PM<sub>2.5</sub> and PM<sub>10</sub> in university rooms in Thessaloniki, Northern Greece. *Atmos Environ* 40:3195–3206

- Griffith EC, Carpenter BK, Shoemaker RK, Vaida V (2013) Photochemistry of aqueous pyruvic acid. *Proc Natl Acad Sci USA* 110:11714–11719
- Guerrero F, Yanez K, Vidal V, Cereceda-Balic F (2019) Effects of wood moisture on emission factors for PM<sub>2.5</sub>, particle numbers and particulate-phase PAHs from *Eucalyptus globulus* combustion using a controlled combustion chamber for emissions. *Sci Total Environ* 648:737–744
- Guo ZY, Guo QJ, Chen SL, Zhu B, Zhang YL, Yu JH, Guo ZB (2019) Study on pollution behavior and sulfate formation during the typical haze event in Nanjing with water soluble inorganic ions and sulfur isotopes. *Atmos Res* 217:198–207
- Han DM, Fu QY, Gao S, Li L, Ma YG, Qiao LP, Xu H, Liang S, Cheng PF, Chen XJ (2018) Non-polar organic compounds in autumn and winter aerosols in a typical city of eastern China: size distribution and impact of gas-particle partitioning on PM<sub>2.5</sub> source apportionment. *Atmos Chem Phys* 18:9375–9391
- Hassanvand MS, Naddafi K, Faridi S et al (2014) Indoor/outdoor relationships of PM<sub>10</sub>, PM<sub>2.5</sub>, and PM<sub>1</sub> mass concentrations and their water-soluble ions in a retirement home and a school dormitory. *Atmos Environ* 82:375–382
- Hwang SL, Chi MC, Guo SE, Lin YC, Chou CT, Lin CM (2018) Seasonal variation and source apportionment of PM<sub>2.5</sub>-bound trace elements at a coastal area in Southwestern Taiwan. *Environ Sci Pollut Res* 25:9101–9113
- in't Veld M, Alastuey A, Pandolfi M, Amato F, Perez N, Reche C, Via M, Minguillón MC, Escudero M, Querol X (2021) Compositional changes of PM<sub>2.5</sub> in NE Spain during 2009–2018: a trend analysis of the chemical composition and source apportionment. *Sci Total Environ* 795:148728
- Jacobson MZ (2001) Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols. *Nature* 409:695–697
- Kelly FJ, Fussell JC (2012) Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. *Atmos Environ* 60:504–526
- Kirkby J, Curtius J, Almeida J et al (2011) Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation. *Nature* 476:429–433
- Kogianni E, Samara C, Lialiaris T (2021) Genotoxicity induced in vitro by water-soluble indoor PM<sub>2.5</sub> fractions in relation to heavy metal concentrations. *Environ Monit Assess* 193:82
- Kumala M (2003) How particles nucleate and grow. *Science* 32:1000–1001
- Liu YY, Xing J, Wang SX, Fu X, Zheng HT (2018) Source-specific speciation profiles of PM<sub>2.5</sub> for heavy metals and their anthropogenic emissions in China. *Environ Pollut* 239:544–553
- López ML, Ceppi S, Palancar GG, Olcese LE, Tirao G, Toselli BM (2011) Elemental concentration and source identification of PM<sub>10</sub> and PM<sub>2.5</sub> by SR-XRF in Cordoba City, Argentina. *Atmos Environ* 45:5450–5457
- Meo SA, Abukhalaf AA, Alessa OM, Alarifi AS, Sami W, Klonoff DC (2021) Effect of environmental pollutants PM<sub>2.5</sub>, CO, NO<sub>2</sub>, and O<sub>3</sub> on the incidence and mortality of SARS-CoV-2 infection in five regions of the USA. *Int J Environ Res Public Health* 18:7810
- Nash DG, Baer T, Johnston MV (2006) Aerosol mass spectrometry: an introductory review. *Int J Mass Spectrom* 258:2–12
- Owoade KO, Hopke PK, Olise FS, Adewole OO, Ogundele LT, Fawole OG (2016) Source apportionment analyses for fine (PM<sub>2.5</sub>) and coarse (PM<sub>2.5–10</sub>) mode particulate matter (PM) measured in an urban area in Southwestern Nigeria. *Atmos Pollut Res* 7:843–857
- Prendes P, Andeade JM, Lopez-Mahia P, Prada D (1999) Source apportionment of inorganic ions in airborne urban particles from Coruna city (N W of Spain) using positive matrix factorization. *Talanta* 49:165–178
- Qiao BQ, Chen Y, Tian M, Wang HB, Yang FM, Shi GM, Zhang LM, Peng C, Luo Q, Ding SM (2019) Characterization of water soluble inorganic ions and their evolution processes during PM<sub>2.5</sub> pollution episodes in a small city in Southwest China. *Sci Total Environ* 650:2605–2613
- Qie GH, Wang Y, Wu C, Mao HT, Zhang P, Li T, Li YX, Talbot R, Hou CX, Yue TX (2018) Distribution and sources of particulate mercury and other trace elements in PM<sub>2.5</sub> and PM<sub>10</sub> atop Mount Tai, China. *J Environ Manage* 215:195–205
- Samy S, Robinson J, Hays MD (2011) An advanced LC-MS (Q-TOF) technique for the detection of amino acids in atmospheric aerosols. *Anal Bioanal Chem* 401:3103–3113
- Schaefer T, van Pinxteren D, Herrmann H (2015) Multiphase chemistry of glyoxal: revised kinetics of the alkyl radical reaction with molecular oxygen and the reaction of glyoxal with OH<sup>•</sup>, NO<sub>3</sub><sup>•</sup>, and SO<sub>4</sub><sup>2-</sup> in aqueous solution. *Environ Sci Technol* 49:343–350
- Sharma M, Kishore S, Tripathi SN, Behera SN (2007) Role of atmospheric ammonia in the formation of inorganic secondary particulate matter: a study at Kanpur, India. *J Atmos Chem* 58:1–17
- Shen RR, Liu ZR, Chen X, Wang YS, Wang LL, Liu YS, Li XR (2019) Atmospheric levels, variations, sources and health risk of PM<sub>2.5</sub>-bound polycyclic aromatic hydrocarbons during winter over the North China Plain. *Sci Total Environ* 655:581–590
- Streets DG, Bond TC, Carmichael GR, Fernandes SD, Fu Q, He D, Klimont Z, Nelson SM, Tsai NY, Wang MQ, Woo JH, Yarber KF (2003) An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *J Geophys Res* 108(D21):30–1–30–23
- Tai APK, Mickley LJ, Jacob DJ (2010) Correlations between fine particulate matter (PM<sub>2.5</sub>) and meteorological variables in the United States: implications for the sensitivity of PM<sub>2.5</sub> to climate change. *Atmos Environ* 44:3976–3984
- Tsai JH, Chen SJ, Li PM, Chang-Chien GP, Huang KL, Tsai CH, Hsieh CY, Lin CC (2018) Characteristics of PM<sub>2.5</sub>-bound PCDD/Fs, PCBs, PBDD/Fs and PBDEs from a diesel generator using waste cooking oil-based biodiesel blends. *Aerosol Air Qual Res* 18:2583–2590
- Vodicka P, Schwarz J, Cusack M, Zdimar V (2015) Detailed comparison of OC/EC aerosol at an urban and a rural Czech background site during summer and winter. *Sci Total Environ* 518:424–433
- Wiedensohler A, Birmili W, Nowak A et al (2012) Mobility particle size spectrometers: harmonization of technical standards and data structure to facilitate high quality long-term observations of atmospheric particle number size distributions. *Atmos Meas Tech* 5:657–685
- Zhang X, Hecobian A, Zheng M, Frank NH, Weber RJ (2010) Biomass burning impact on PM<sub>2.5</sub> over the southeastern US during 2007: integrating chemically speciated FRM filter measurements, MODIS fire counts and PMF analysis. *Atmos Chem Phys* 10:6839–6853

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.