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REVIEW

Status and chemical characteristics of ambient PM2.5 pollutions in China: a review

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Abstract The ambient fine particulate matter is a considerable hazard to human health and the surrounding environment of the majority of Chinese cities. This article reviews the status of air pollution, especially $PM_{2.5}$, in 21 cities of China, on the basis of their status, chemical characteristics, and regulations data collected from the published literature. The observed results show Zhengzhou, Yulin, Jinan, Qingdao, and Changchun as significantly polluted cities where the annual mean concentration of $PM_{2.5}$ was noted to be greater than 120 μg m^{-3}. However, some cities such as Xiamen, Hong Kong, Shenzhen, and Jinchang reported average annual $PM_{2.5}$ concentrations less than 40 μg m^{-3}. In general, the results of spatial distribution reported that the cities of the east, north, and northeast China are highly polluted. According to the average mass of $PM_{2.5}$ in maximum cities of China, the sum of sulfate, nitrate and ammonium (SNA) and organic matter (OM) contributed over 40 and 35%, respectively. The higher amount of SNA and OM in $PM_{2.5}$ results from heavy traffic or vehicle emission and burning solid fuel utilized in most part of China. A proposed systemic approach to address the $PM_{2.5}$ in China can improve the quality of ambient atmosphere.

Keywords $PM_{2.5}$ · Source apportionment · Exposure · Control strategies · Regulation

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1 Introduction

Fine particulate matter ($PM_{2.5}$; aerodynamic diameter ≤ 2.5 μm) is responsible for the global burden of diseases and adverse effects on human health and surrounding environment such as respiratory problems, visibility, climate change (Cheng et al. 2016; IPCC 2013; Brauer et al. 2012). Health-related impacts are very distinguished for Asian environments (Tsiouri et al. 2015). The higher concentrations of particulate matter (PM) in metropolitan cities result from the higher consumption of energy (Patra et al. 2016a; Butler et al. 2008). Gurjar et al. (2010) have suggested the exposure to $PM_{2.5}$ is a more severe problem in the urban area as compared to the rural area. $PM_{2.5}$ pollution is defined by both quantitative and qualitative measurements of a number of activities conducted by different groups at particular places for short time intervals (Gautam et al. 2016a, b; Patra et al. 2016b; Gautam and Patra 2015). Moreover, most of the research work on $PM_{2.5}$ has paid more attention to urban areas than to rural areas for the exploration of the sources and adverse effects (Gautam et al. 2016b; Lin et al. 2015a; Vela et al. 2015; Kumar et al. 2013). However, $PM_{2.5}$ control strategies need to be taken or developed to minimize the impact of $PM_{2.5}$ on the human and surrounding environment in the urban area. World Health Organization (WHO) (2014) has reported comprehensive data of $PM_{2.5}$ concentrations of all possible and assessable locations of the world but need to be required more additional analysis in the present database.

The past literature has reported that higher exposure to $PM_{2.5}$ is responsible for several types of health problems such as lung diseases (Chow et al. 2006), respiratory problems (Xia and Wang 2016; Chow et al. 2006), irregular heartbeat (Xie et al. 2016a; Kim et al. 2015), breathing problems (Yang et al. 2015; Labelle et al. 2015), eyes and itching problems (Salvi et al. 2016) and other associated problems in respiratory system (Xia and Wang 2016; Huang et al. 2016). Previous studies on topics such as source apportionment, chemical characterization, emission rate, emission inventory, chemical modeling, tempo-spatial variation, monitoring, dispersion analysis, health impact, exposure analysis, size distribution and statistical modeling of ambient $PM_{2.5}$ have been carried out. All these past studies point for a holistic assessment of $PM_{2.5}$ in China. Therefore, these works curtly synthesize the previously published research on $PM_{2.5}$ at a different place of China, including monitoring networks and source area.

In China, the current status of air pollution is not acceptable because of exceedences against the national and international standards. The air quality status of different cities of China is more notable in the world (Zheng et al. 2016; Song et al. 2016; Hao and Wang 2005). A number of studies (quantitative and qualitative) have been reported the chemical composition and mass concentration of $PM_{2.5}$ in China (Cheng et al. 2016; Yang et al. 2011). Because of the higher values of $PM_{2.5}$ reducing the air quality, China introduced new national standards for $PM_{2.5}$ in 2012. On the other hand, China has 1436 $PM_{2.5}$ monitoring stations as compared with the 1500 monitoring stations in the USA (USEPA 2014). Data from these monitoring stations give the essential information for this study. The published literature (21 cities of China) on the $PM_{2.5}$ level, distribution and composition in China was collected and reviewed. The main aim of the review is to introduce the status of the $PM_{2.5}$ level, chemical composition and distribution in various cities of China, which will provide a good platform to the scientific community working on health impact related to $PM_{2.5}$ and control strategies to minimize the exposure.

Approximately 190 published articles in the English language on source apportionment, health risk assessment, monitoring, and control of $PM_{2.5}$ have been reviewed. We also

included the literature from computer searches and bibliographic databases (e.g., Google scholar, Pub Med, Academia, Research Gate) in the analysis. We used the keywords such as $PM_{2.5}$, air pollution, source apportionment, chemical composition, and China to search the suitable literature for this review article.

2 Chemical composition of $PM_{2.5}$

The previous literature showed that heavy metal elements (i.e., Cd As, Pb, S, Si, K, Cl, Ca, Na, Fe, Al, Mg, Mn, Ba Br, Ba, Sb, and Ni) dominate the $PM_{2.5}$ concentrations in urban atmosphere of China (Xie et al. 2016b; Cao et al. 2005; Dan et al. 2004). The high variations in elements composition could be ascribed to different sources or activities. All these elements are of great importance to assess the sources or related activities. Several studies have suggested the need of sensitive analytical techniques such as inductively coupled plasma mass spectrometry (ICPMS), particle elastic scattering analysis (PESA), particle-induced X-ray emission (PIXE), X-ray fluorescence (XRF), energy-dispersive X-ray fluorescence (EDXRF), scanning electron microscopy (SEM)–energy-dispersive X-ray spectroscopy (EDS), time-of-flight mass spectrometry (TOFMS), atomic absorption spectrophometer (AAS), and high-resolution continuum source atomic absorption spectrophometer (HR–CSGF–AAS) to identify the comprehensive details (toxic nature) of elemental information about $PM_{2.5}$ in China's atmosphere (Zhang et al. 2014d). Moreover, the hazardous nature of $PM_{2.5}$ and its impact on human health, and measurement of water solubility of elements have been assessed in published articles (Jiang et al. 2014).

In case of analytical instrument, European countries are frequently using X-ray diffraction (XRD), scanning electron microscopy–energy-dispersive spectroscopy (SEM–EDS), inductively coupled plasma mass spectrometry (ICL–MS), and energy dispersive X-ray fluorescence (EDXRF), or aerosol mass spectrometer (AMS) and other related physicochemical characterization instruments to assess the accurate physical and chemical properties of fine PM. Similarly, Chinese environment (urban/rural) exhaustively needs to assess the chemical composition of fine PM and their effects on health and to comparatively improve the air quality of working environments (Cheng et al. 2016).

Different levels of $PM_{2.5}$ concentrations originate from activities around rural (Zhu et al. 2012), urban (Zhang and Cao 2015), industrial areas, including mining (Zhang and Cao 2015; Hu et al. 2014; Hu and Jiang 2013) and marine activities (Wang et al. 2006). The composition of $PM_{2.5}$ has been well reported to be the mixture of organic, inorganic, water-soluble ions, elemental carbon, crustal material, and hydrocarbons (Wang et al. 2006; Zheng et al. 2005; Yao et al. 2002; Wei et al. 1999). Some elements like barium (Ba), bromine (Br), nickel (Ni), sulfur (S), and magnesium (Mg) are observed higher in composition than other elements in $PM_{2.5}$ in China (Wu et al. 2014; Chao and Wong 2002). On the other hand, several studies (Pui et al. 2014; Huang et al. 2012; Kan et al. 2007) organized in China indicate potential hazards (cardiovascular diseases, low birth weight, urinary effects, eyes irritation, and other health problems) due to higher amount of different elements with varying chemical composition. The assessment of $PM_{2.5}$ related studies in different cities of China, based on average concentration and chemical composition, is presented in Fig. 1.

The presented database covers most part of China where the average concentration of $PM_{2.5}$ was reported to vary in a broad range of 31–175 μg m^{-3}. The higher amount of SNA, organic matter, and elemental carbon can be identified in fine PM, besides other

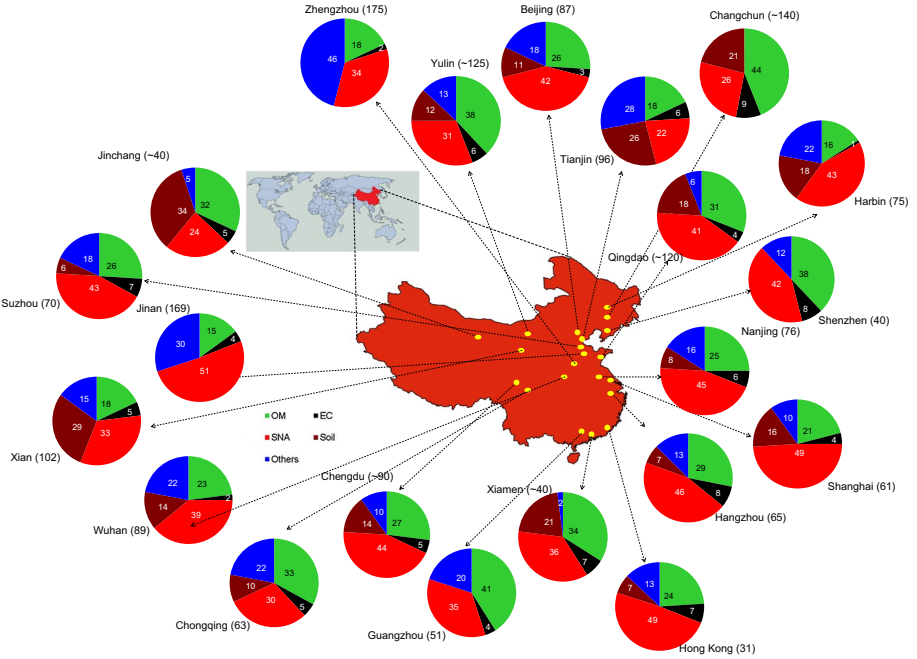

Fig. 1 $PM_{2.5}$ concentrations (μg m^{-3}) and chemical composition (%) in different Chinese cities. Reported data are taken from Guangzhou EPB (Guangzhou), Shenzhen EPB (Shenzhen), Hong Kong (Huang et al. 2014b), Hangzhou (Cheng 2014), Qingdao (Cao et al. 2012), Nanjing (Chen et al. 2015a), Wuhan (Zhang et al. 2015), Xiamen (Cao et al. 2012), Xi'an (Wang et al. 2015b), Chongqing (Yang et al. 2011), Jinchang (Cao et al. 2012), Chengdu (Chen et al. 2015b), Yulin (Cao et al. 2012), Suzhou (Cheng 2013), Tianjin (Xu et al. 2015), Shanghai (Shanghai EPB), Harbin (Jia 2014), Beijing (Liu et al. 2015a), Jinan (Gu et al. 2014), Zhengzhou (Geng et al. 2013), Changchun (Cao et al. 2012)

unidentified substances. Transportation, household activities, vehicular movement, and industrial sector are possible $PM_{2.5}$ sources in China (Liu et al. 2015a). However, most Chinese cities, especially Beijing, Yulin, Qingdao, and Zhengzhou, are mostly dependent on transportation and on solid fuels for household activities (Liu et al. 2015a). The variation of concentration occurs due to the number of residents or working area (urban/rural) (Smith et al. 2013). A number of studies have been done on chemical characterization and monitoring practice of particle in China, however, quantitative assessments for aerosol, its distribution formation and relationship between personal exposure, household exposure and ambient exposure are still needed.

3 Source apportionment

Source apportionment (SA) is used to investigate emission from different sources or the impact of fine PM at different monitoring sites (Balachandran et al. 2013). SA techniques are basically the statistical methods (i.e., monitoring data analyzed using basic statistics or numerical technique to identify the emission sources) including PCA (principal component analysis), nonparametric wind regression, back trajectory analysis, FA-MR (factor analysis

with multiple regression), PMF (positive matrix factorization), and CMB (chemical mass balance) (Balachandran et al. 2013). PMF is useful to assess factors without source information of receptor site, but some techniques such as CMB models require unique profiles of each source (Gao et al. 2013). Nowadays, PMF is popular because of its convenient and realistic performance. However, the SA was underestimated by highly time-resolved data of $PM_{2.5}$ compared to Vedantham et al. (2014). To solve this problem, the results should be validated by characterization of $PM_{2.5}$ at local spatial and temporal patterns, local emissions, and meteorological parameters.

3.1 Positive matrix factorization (PMF)

Since information about the chemical characterization of fine PM necessary for researchers to make control strategies requires to be very accurate, it is tough to assess the source of air pollutants using traditional SA methods. However, Paatero and Tapper (1994) developed the PMF technique that is now widely used in China and elsewhere to investigate the source distribution and identification of $PM_{2.5}$ (Liu et al. 2015b; Cheng et al. 2015; Gu et al. 2014). Numbers of studies have been reported with results on different proportions of composition (i.e., SNA, OC, EC, heavy metals) of $PM_{2.5}$ with PMF (Shi et al. 2016; Wang et al. 2016; Geng et al. 2013). Table 1 comprehensively summarizes related PMF studies in China.

Table 1 indicates the wide use of PMF methods to assess the source and chemical characterization of $PM_{2.5}$ in different cities of China. However, source marker data (tracer methods) is needed to avoid the pre-assumptions in field measurement and overcome limited analysis in particle-based PMF analysis (Xie et al. 2013, 2016a, b). Similarly, the combination of PMF and AMS with radiocarbon is very useful to understand the atmospheric oxidation. Chemical transport CAMx model with PMF is rare in source apportionment analysis (Bove et al. 2014). However, it should be combined or integrated into future research on emission inventories. The results of this approach will demonstrate the role of atmospheric dynamics with respect to $PM_{2.5}$ composition. Similarly, the outputs from the combination of PMF with cluster analysis would be useful to investigate the role of meteorological parameters on $PM_{2.5}$ sources (Masiol et al. 2014).

3.2 PCA

A huge dataset can be easily handled by using of PCA, which is considered as most successful methods to explore the different set of variables and potential results of the input data. The method includes mathematical relationships to investigate the association of the different source of air pollutant and health effects. The recent results of SA on $PM_{2.5}$ by PCA in different cities of China are summarized in Table 2.

The outcomes of PCA method are very useful to understand the relationship between the source of air pollutant and the exposure analysis. However, it provides an only qualitative assessment of source variation, with some limitation on utility in health studies. Some advanced receptor models such as PCA (absolute PCA), CMB (chemical mass balance), and PMF (positive matrix factorization) are now being used to understand the source contribution (i.e., specific concentration increments) and are of help to the researcher who is working on chemical exposure analysis of fine PM.

Table 1 Comprehensive details of recent SA results of $PM_{2.5}$ (μg m^{-3}) by using PMF in China

Study location	*$PM_{2.5}$ (μg m^{-3})	Key observations	Author (years)
Tanggu	110.63	WALSPMF and EPAPMF models were used to apportion $PM_{2.5}$ sources	Shi et al. (2016)
Tangshan	–	Hybrid approaches for primary and secondary species apportionment for $PM_{2.5}$	Wen et al. (2016)
Xi'an	233 ± 96.5	Fugitive dust was reported higher due to construction activities and mobile sources	Xu et al. (2016)
Shanghai city	53	Long-range transport contributed to 13 and 61% of annual LMW and HMW PAHs	Wang et al. (2016)
Huaniao Island Hangzhou	108	Emission sources (transportation and burning of coal) of $PM_{2.5}$ were identified	Liu et al. (2015b)
Hong Kong	55	Reported that $PM_{10–2.5}$ revealed a different chemical composition and potential sources from $PM_{2.5}$	Cheng et al. (2015)
Handan	160	Coal combustion source (25.9%), secondary source (21.8%), and industry source (16.2%) are reported as main sources of $PM_{2.5}$	Wei et al. (2014)
Jinan	169	PMF is used to investigate the source (i.e., secondary sulfate, soil dust, secondary nitrate, and vehicle emissions) of $PM_{2.5}$	Gu et al. (2014)
Chengdu	165	Biomass burning significantly changed $PM_{2.5}$ composition according to the season (late spring to early summer) has been reported	Tao et al. (2013)
Zhengzhou	175	Soil dust, secondary aerosol, and coal combustion have been identified the major source by PMF	Geng et al. (2013)

*Annual mean concentration

Table 2 Summary of the recent studies on PCA of $PM_{2.5}$ in China

Study location	Key observations	Author (years)
Huaniao Isle	Introduced the particulate mercury (PHg) over the ECS higher in concentration and demonstrated that the contribution of Asian continental outflow in the transfer of PHg from mainland China to ECS	Qin et al. (2016)
Beijing-Tianjin	It is reported that the carbonaceous components came from mixed emission sources (coal combustion, vehicle exhaust, and biomass burning). In Beijing, 63% contribution of the carbonaceous component is reported by vehicle emissions which is much higher than that in Tangshan	Wang et al. (2015a)
China	PCA was used to investigate the pattern of all supply chain paths ($PM_{2.5}$ emissions in electricity, cement, and the ferrous metal industries)	Meng et al. (2015)
Guangzhou	Source identification from industrial sources, vehicle movement, and soil dust	Xiao et al. (2014)
Shanghai	Industrial activities, coal burning and utilization, and transportation sources were identified as a major source of $PM_{2.5}$	Wang et al. (2013)
Nanjing	SBET were used to investigate the bioaccessibility of metal(loid)s in $PM_{2.5}$ and reported health risk from metal(loid)s in $PM_{2.5}$ is higher than that in others	Hu et al. (2012)
Jinan	SA of $PM_{2.5}$ by using principal component analysis/absolute PC sources and UNMIX	Song et al. (2006)
Xian	Reported $PM_{2.5}$ OC and EC concentrations were 61.9 ± 33.2 μg m^{-3} and 12.3 ± 5.3 μg m^{-3}, respectively	Cao et al. (2005)

3.3 Other SA methods and summary

Figure 2 summarizes prominent source apportionment studies and its key findings in China. In addition to the use of coal for electricity generation, goal is an important fuel for cooking in North China. Vehicular traffic is another considerable source of $PM_{2.5}$ in most part of China. Fine particles could not settle immediately after their formation. Due to rapid urbanization and industrialization with higher energy consumption in China after 1985s, air pollution has become a major problem for human health. Moreover, a comprehensive summary of relevant past SA studies is presented in Table 3.

Chinese scientists started their work on fine PM monitoring and measurement in the 2000s, while standards were promulgated in 2012s in China (Yang et al. 2011; Gu et al. 2010; Feng et al. 2005). In China, the national standard is 15 μg m^{-3} for annual and 35 μg m^{-3} for 24 h average (Gautam et al. 2016c). Several studies have been conducted to assess the source of $PM_{2.5}$ in different places of China (Liang et al. 2016; Huang et al. 2012; Yang et al. 2011; Cheng et al. 2011). Coal burning, vehicle movement, industrial pollution, and secondary aerosol formation are the major source of fine PM in megacities of China. However, dust storm affects the northern part of China every year (early winter to spring). Zheng et al. (2005) reported that 36% of the $PM_{2.5}$ mass is contributed by dust only, which has not yet well controlled. Most of the measurement and modeling technique of USA are being applied in China for air pollution control. However, a technique is very

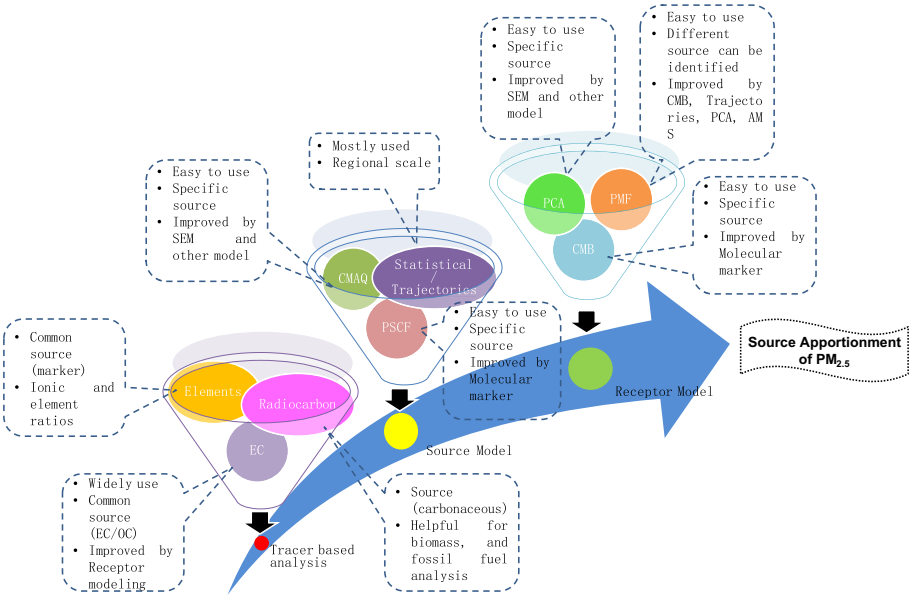

Fig. 2 A systemic diagram of recently used source appointment methods of $PM_{2.5}$. Reported data are taken from different previous studies such as PMF (Shi et al. 2016; Masiol et al. 2014; Gu et al. 2014; Gao et al. 2014; Tao et al. 2013), PCA (Qin et al. 2016; Meng et al. 2015; Zhao et al. 2014), CMB (Zhang et al. 2014a; Gao et al. 2013), statistical/trajectories (Li et al. 2015a), CMAQ; Community Multiscale Air Quality (Wang et al. 2014; Ying et al. 2014a, b), PSCF; Potential Source Contribution Function (Zhang et al. 2014b), Radiocarbon (Liu et al. 2013, 2014), elements (Yu et al. 2014; Yang et al. 2014) and EC (Huang et al. 2014a; Zhang et al. 2014c)

Table 3 Summary of SA studies on $PM_{2.5}$ at different places in China

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
Beijing, China	January 1, 2010–December 31, 2010	24-h continuous $PM_{2.5}$ sampling from 12:00 am to 12:00 am using automated cartridge collection unit (ACCU) Concentration: mean: 55.4 ± 40.2 μg m^{-3}. Range: 9.8–219 μg m^{-3}	21 elements were determined: Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Se, Br, Ba, and Pb using particle-induced X-ray emission (PIXE)	EPA's positive matrix factorization (PMF)	Seven sources and their contributions to the total $PM_{2.5}$ mass were identified, which include secondary sulfur—13.8 μg m^{-3}, 26.5%; vehicle exhaust—8.9 μg m^{-3}, 17.1%; fossil fuel combustion—8.3 μg m^{-3}, 16%; road dust—6.6 μg m^{-3}, 12.7%; biomass burning—5.8 μg m^{-3}, 11.2%; soil dust—5.4 μg m^{-3}, 10.4%; and metal processing—3.1 μg m^{-3}, 6.0%	Fugitive dust represented the highest contribution of 20.7 μg m^{-3} in the spring, doubling those in other seasons. On the contrary, contributions of the combustion source types were significantly higher in the fall (14.2 μg m^{-3}) and in the winter (24.5 μg m^{-3}) compared to those in the spring and summer (9.6 and 8.0 μg m^{-3}, respectively). Secondary sulfur contributed the most in the summer, while vehicle exhaust and metal processing sources did not show any clear seasonal pattern	Yu et al. (2013)
Beijing, China (Urban Site)	April, July, October 2009 and January 2010	Two collocated aerosol samplers (from OMNI™, BGI, USA) were used to collect 24-h $PM_{2.5}$ samples simultaneously Concentration: Mean: 135 ± 63 μg/m^3	Ionic species (Na+, NH4+, K+, Mg2+, Ca2+, F−, Cl−, SO2−4 and NO−3) in the leachate were analyzed through a Dionex model ICS-90 (for anions) and ICS-1500 (for cations) ion chromatograph equipped with a conductivity detector (ASRS-ULTRA). Trace elements in the digestion solutions, including Al, Fe, Na, Mg, K, Ca, Ba, Ti, Mn, Co, Ni, Cu, Zn, Mo, Cd, Sn, Sr, Sb, Pb, Tl, Ge, Cs, Ga, V, Cr, As, Se, and Rb, were analyzed by inductively coupled plasma mass spectrometry (ICP–MS)	Chemical mass balance (CMB), PMF, trajectory analysis, and potential source contribution function (PSCF)	The PMF model identified six main sources: soil dust, coal combustion, biomass burning, traffic and waste incineration emission, industrial pollution, and secondary inorganic aerosol. Each of these sources has an annual mean contribution of 16, 14, 13, 3, 28, and 26%, respectively, to $PM_{2.5}$. The results of trajectory clustering and the PSCF method demonstrated that regional sources could be crucial contributors to PM pollution in Beijing	Results have shown distinctive seasonality for various aerosol speciation associated with $PM_{2.5}$ in Beijing. Soil dust waxes in the spring and wanes in the summer. Regarding the secondary aerosol components, inorganic and organic species may behave in different manners. The former preferentially forms in the hot and humid summer via photochemical reactions, although their precursor gases, such as SO_2 and NO_x, are emitted much more in winter. Synoptic meteorological and climate conditions can overwhelm the emission pattern in the formation of secondary aerosols	Zhang et al. (2013)

Table 3 (continued)

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
Beijing, China (Metropolitan Area)	January, April, July, October 2000	24-h sampling of $PM_{2.5}$ using commercial sampler	Chemical composition was then analyzed for sulfate, nitrate, chloride, and ammonium ions by ion chromatography (IC) and for metals by X-ray fluorescence (XRF) spectroscopy. The OC and EC were determined by NIOSH thermal-optical procedures, with organic speciation by GC/MS	EPA's PMF	Eight sources were identified: biomass burning (11%), secondary sulfates (17%), secondary nitrates (14%), coal combustion (19%), industry (6%), motor vehicles (6%), road dust (9%), and yellow dust	The lower organic carbon (OC), elemental carbon (EC), SO_4^{2-}, and cavalues of yellow dust enable it to be distinguished from road dust. The PMF method resolved 82% of $PM_{2.5}$ mass concentrations	Song et al. (2006)
Three different functional areas (Yuzhong County, Xigu District and Chengguan District) of Lanzhou				PMF analysis		The highest seasonal mean concentrations of PM_{10} (369.48 μg m^{-3}) and $PM_{2.5}$ (295.42 μg m^{-3}) were detected in Xigu District in the winter, the lowest concentration of $PM_{2.5}$ (53.15 μg m^{-3}) was observed in Yuzhong District in the fall and PM_{10} (89.60 μg m^{-3}) in Xigu District in the fall. The content of SNA (the sum of sulfate, nitrate, ammonium, SNA) in $PM_{2.5}$ in Yuzhong County was generally lower than that at other sites in all seasons. The content of SNA in $PM_{2.5}$ and PM_{10} in Yuzhong County was generally lower than that at other sites in all seasons (0.24–0.38), indicating that the conversion ratios from precursors to secondary aerosols in the low concentration area was slower than in the area with high and intense pollutants	Qiu et al. (2016)

Table 3 (continued)

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
North China Plain	January 2011 to November 2011			Positive matrix factorization (PMF) analysis and a potential source contribution function (PSCF) model	PMF analysis indicated that secondary sulfate and nitrate (54.3%), biomass burning (15.8%), industry (10.7%), crustal matter (8.3%), vehicles (5.2%), and copper smelting (4.9%) were important sources of $PM_{2.5}$ at YRDNNR on an annual average. The source of secondary sulfate and nitrate was probably industrial coal combustion. PSCF analysis indicated a significant regional impact on $PM_{2.5}$ at YRDNNR all year	Concentrations of $PM_{2.5}$ at YRDNNR were 71.2, 92.7, 97.1, and 62.5 μg m^{-3} in spring, summer, autumn, and winter, respectively, with 66.0% of the daily samples exhibiting higher concentrations of $PM_{2.5}$ than the national air quality standard. Sulfate, nitrate, and ammonium were the dominant fractions of $PM_{2.5}$ in summer (58.0%), whereas $PM_{2.5}$ was characterized by a high load of organic aerosols (40.2%) in winter	Yao et al. (2016)

Table 3 (continued)

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
Eastern China	January 2013		Source contributions to $PM_{2.5}$ and its major components at six receptors (Urban Shanghai, Chongming, Dianshan Lake, Urban Suzhou, Hangzhou and Zhoushan) in the Yangtze River Delta (YRD) region. Contributions from 4 source areas (including Shanghai, South Jiangsu, North Zhejiang and Super-region) and 9 emission sectors (including power plants, industrial boilers and kilns, industrial processing, mobile source, residential, volatile emissions, dust, agriculture, and biogenic emissions) to $PM_{2.5}$ and its major components (sulfate, nitrate, ammonia, organic carbon and elemental carbon) at the six receptors in the YRD region are quantified	Particulate matter source apportionment technology (PSAT) method coupled with the comprehensive air quality model with extensions (CAMx)	Major source categories include industrial processing (with contributions ranging between 12.7 and 38.7% at different receptors), combustion source (21.7–37.3%), mobile source (7.5–17.7%) and fugitive dust (8.4–27.3%). Agricultural contribution is also very significant at Zhoushan site (24.5%)	Accumulation of local pollution was the largest contributor during this air pollution episode in urban Shanghai (55%) and Suzhou (46%), followed by long-range transport (37% contribution to Shanghai and 44% to Suzhou). Super-regional emissions play an important role in $PM_{2.5}$ formation at Hangzhou (48%) and Zhoushan site (68%)	Li et al. (2015b)

Table 3 (continued)

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
Northern city in China			12-h averaged concentrations of particulate matter and species were analyzed	PCA-MLR model potential source contribution function (PSCF)	Five factors were extracted for the PM_{10} samples, and their percentage contributions were estimated as follows: crustal dust—39.87%; vehicle exhaust—30.16%; secondary sulfate and nitrate—14.42%; metal emission source—6.77%; and residual oil combustion source—1.82%. Four factors were resolved for the $PM_{2.5}$ dataset, and their contributions were obtained: crustal dust—35.81%; vehicle exhaust—22.67% Secondary sulfate and nitrate—32.35%; and metal emission and residual oil combustion sources—4.57%	The PSCF results showed that for each source category, PM_{10} and $PM_{2.5}$ had similar potential source areas	Wang et al. (2012)
Xi'an, Shaanxi Province, China	September 2003 through February 2004	Continuous measurements of atmospheric organic and elemental carbon (OC and EC) were taken during the high-pollution fall and winter seasons Battery-powered mini-volume samplers	OC/EC by thermal/optical reflectance (TOR) following the interagency monitoring of protected visual environments (IMPROVE) protocol		The higher wintertime OC/EC corresponded to increased residential coal combustion for heating. Total carbon (TC) was associated with source contributions using absolute principal component analysis (APCA) with eight thermally derived carbon fractions. During fall, 73% of TC was attributed to gasoline engine exhaust, 23% to diesel exhaust, and 4% to biomass burning. During winter, 44% of TC was attributed to gasoline engine exhaust, 44% to coal burning, 9% to biomass burning, and 3% to diesel engine exhaust	OC and EC levels at Xi'an are higher than most urban cities in Asia. Average $PM_{2.5}$ OC concentrations in fall and winter were 34.1 ± 18.0 μg m^{-3} and 61.9 ± 33.2 μg m^{-3}, respectively; while EC concentrations were 11.3 ± 6.9 μg m^{-3} and 12.3 ± 5.3 μg m^{-3}, respectively. Most of the OC and EC were in the $PM_{2.5}$ fraction. OC was strongly correlated ($R > 0.95$) with EC in the autumn and moderately correlated ($R = 0.81$) with EC during winter. Carbonaceous aerosol ($OC \times 1.6 + EC$) accounted for $48.8\% \pm 10.1\%$ of the PM2.5 mass during fall and $45.9 \pm 7.5\%$ during winter. The average OC/EC ratio was 3.3 in fall and 5.1 in winter, with individual OC/EC ratios nearly always exceeding 2.0	Cao et al. (2005)

Table 3 (continued)

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
East Asia and North China at 36 and 12-km horizontal grid resolutions the source apportionment of $PM_{2.5}$ in the three top polluted cities in Hebei, i.e., Shijiazhuang, Xingtai, and Handan				Mesoscale Modeling System Generation 5 (MM5) and the Models-3/Community Multiscale Air Quality (CMAQ) modeling system brute force method		$PM_{2.5}$ are 27.9% in Shijiazhuang, 46.6% in Xingtai, and 40.4% in Handan. The major local contributors are industrial, domestic, and agricultural sources in all the three cities with the contributions of 39.8, 15.8, and 10.6% in Shijiazhuang, 30.5, 13.6, and 6.9% in Xingtai, 35.9, 13.5, and 6.2% in Handan, respectively. As to the secondary aerosols of sulfate (SO_4^{2-}), nitrate (NO_3^-), and ammonium (NH_4^+) in $PM_{2.5}$, which are important chemical species in $PM_{2.5}$ (about 30–40% in $PM_{2.5}$) and cannot be further apportioned by receptor models, the regional source contributions to the total concentrations of SO_4^{2-}, NO_3^-, and NH_4 are 40.9, 62.0, and 59.1% in Shijiazhuang, Xingtai, and Handan, respectively. The local industrial, domestic, and agricultural contributions to those are 23.7, 6.6, and 29.8% in total in Shijiazhuang, 17.5, 5.0, and 17.7% in Xingtai, and 20.6, 4.8, and 17.8% in Handan, respectively	Wang et al. (2015c)
China	2009 to 2011		Determined the transport of particulate matter (PM) and chemical species is an essential mechanism for the fate of PM pollutants and their effects	Source directional apportionment (SDA)		Crustal dust (7.9, 9.1, 6.4, and 6.2%, respectively), cement dust (1.0, 1.2, 1.3, and 1.1%, respectively), vehicular exhaust (6.4, 6.0, 5.6, and 7.0%, respectively), secondary sulfate (5.1, 5.2, 5.6, and 8.6%, respectively), and secondary nitrate (2.0, 2.4, 2.5, and 2.3%, respectively). Finally, the source directional contributions to important chemical species were quantified to determine their transport from sources to receptor	Tian et al. (2015)

Table 3 (continued)

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
Hangzhou, China	April 2004 to March 2005		Water-soluble ions, metal elements, and total carbon (TC) in $PM_{2.5}$			24-h mean concentrations of $PM_{2.5}$ ranged from 17.1 to 267.0 μg m^{-3}, with an annual average value of 108.2 μg m^{-3}. Moreover, the seasonal mean values for $PM_{2.5}$ in spring, summer, autumn, and winter were 116, 73.1, 114.2, and 136.0 μg m^{-3}, respectively. According to the Chinese ambient quality standard, at least 70% of the monitoring data exceeded the limit value. The total contribution of water-soluble ions, including F^-, Cl^-, NO_3^-, SO_4^{2-}, NH_4^+, K^+, and Na+, to PM2.5 mass varied from 32.3 to 36.7%. SO_4^{2-}, NO_3^-, and NH_4^+ were the main constituents of the ions, with contributions to $PM_{2.5}$ varying from 14.1 to 14.7%, 6.0% to 7.8%, and 6.4 to 7.7%, respectively. In addition, the annual mean mass fraction of TC in $PM_{2.5}$ was 27.8%. The annual average total contribution of the group of elements of Zn, Pb, Cu, Mn, Cr, Ni, Se, Mo, Cd, Sb, and Ag to the aerosol was in the range of 1.7–2.0%. Furthermore, PMF was applied to analyze the $PM_{2.5}$ data collected from the central area, and five factors were identified. The factor contributions to $PM_{2.5}$ mass were 12.8, 31.9, 10.1, 17.2, and 27.9%, respectively. Iron/steel manufacturing and secondary aerosol were the main sources for the fine particles	Liu et al. (2015a, b)

Table 3 (continued)

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
Eastern China	June 2013		The contribution of the open burning of wheat straw residues to local $PM_{2.5}$ during the season. Chemical compositions were analyzed, and source apportionment was undertaken using the positive matrix factorization model		The average $PM_{2.5}$ concentration was 110.7 mg/m3, containing 36.4 mg/m3 organics, 7.3 mg/m3 EC, 6.0 mg m^{-3} potassium (K), and 4.9 mg m^{-3} chloride ion (Cl^-). The sampling period was divided into three phases: the pre-local-burning phase (Phase 1), the local-burning phase (Phase 2), and the post-local-burning phase (Phase 3). In Phase 2, the concentrations of $PM_{2.5}$ and the organics, EC, K, and Cl_ in $PM_{2.5}$ were 163.6 mg m^{-3}, 59.0 mg m^{-3}, 12.2 mg m^{-3}, 11.0 mg m^{-3} and 10.8 mg m^{-3}, respectively, which were all remarkably higher than in both Phase 1 and Phase 3. Eight sources of $PM_{2.5}$ were determined, including two types of wheat residue burning sources, which showed a significant difference in Cl_ content. The atmospheric relative humidity (RH) and the aging process of $PM_{2.5}$ might be the causes: only fresh particulate emissions from wheat residue burning could feature high-concentration Cl^- under high RH conditions. In Phase 2, wheat residue burning contributed 51.3% of $PM_{2.5}$, 75.8% of OC, 74.5% of EC, 90.1% of K, and 104.1% of Cl^-. These percentages were lower in Phases 1 and 3 than in Phase 2. Wheat residue burning caused such severe air pollution that it is necessary to prohibit the open burning of crop residues in order to protect public health and the environment		Li et al. (2014)

Table 3 (continued)

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
Beijing, China	December 2010 to January 2012		The vehicular emission contributions (VECs) to primary organic aerosols (POA), element carbon (EC), SO2, NOX, NH3, elements, and VOC were estimated based on the MM5-CMAQ simulation, factor analysis and references investigation. The VECs to different components and to the total $PM_{2.5}$ were then calculated	MM5-CMAQ modeling system		No clear difference in the total VECs of different seasons. The annual average contribution ratio was approximately 22.5–3.5%. Among all the chemical species, nitrate and SOA accounted for the highest contribution percentages. In addition, the influence of road dust on the $PM_{2.5}$ pollution was also simulated using the MM5-CMAQ modeling system. It is indicated that the road dust contributed approximately 4.9–1.3% of the total $PM_{2.5}$ on an annual average. Considering both the contributions from motor vehicles and road dust emissions, the annual average direct contributions from road transport to the $PM_{2.5}$ in Beijing was approximately 27.4–4.8%	Cheng et al. (2013)
Urban downtown site, a traffic roadside site, a suburban site, and a rural site in Beijing	April 2011 to January 2012	$TSP/PM_{10}/PM_{2.5}$	Seasonal and spatial variation of 19 elements (Al, As, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, S, Sb, Se, Zn)	PMF methods		Eight toxic elements (As, Cd, Cr, Cu, Ni, Pb, Sb, and Zn) exhibited higher mobility in $PM_{2.5}$ than in PM_{10}. Notably, elements of As, Cd, Pb, and Zn were presented with higher mobility than the other elements, and these elements were light to release into the environment and easily available to the human body. Additionally, As, Cd, Pb, and Zn also accounted for higher percentages in the bound to mobile fractions at the central urban areas of Beijing	Gao et al. (2014)

Table 3 (continued)

Sampling site	Time period	$PM_{2.5}$ sampling technique and concentration	Chemical analysis	Source apportionment method	Source types and contribution	Key findings	References
Jinan, the capital of Shandong Province	December 2007 to October 2008		Secondary aerosol pollution and potential source regions, semi-continuous measurement of water-soluble ions	Redistributed concentration field (RCF) model and PCA	PCA indicated that the major sources contributing to $PM_{2.5}$ pollution were secondary aerosols, coal/biomass burnings, and traffic emissions.	SO_4^{2-}, NO_3^-, and NH_4 were the most abundant ionic species with annual mean concentrations (standard deviations) of 38.33 (26.20), 15.77 (12.06), and 21.26 (16.28) mg m_3, respectively, which are among the highest levels reported in the literature in the world. Well-defined seasonal and diurnal patterns of SO_2^{-4}, NO_3^-, and NHþ 4 were observed. The fine sulfate and nitrate oxidation ratios (SOR and NOR) were much higher in summer (SOR: 0.47 ± 0.13; NOR: 0.28 ± 0.03) than those in other seasons (SOR: 0.17 ± 0.30; NOR: 0.12 ± 0.14), indicating more extensive formations of SO_4^{2-} and NO_3 in summer	Gao et al. (2011)

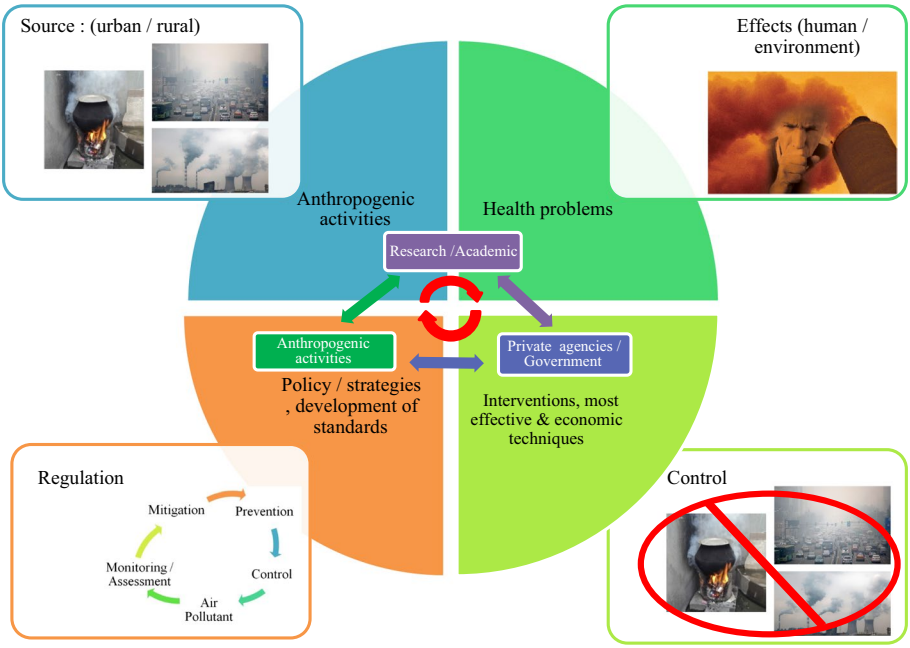

Fig. 3 A systemic approach to address the $PM_{2.5}$ emission and exposure

much required to explain data collected from the nation-wide network. This technique has been applied in the USA (i.e., IMPROVE 2011), but it is a challenging area for research in China.

4 Future perspectives and conclusions

A number of key research challenges and associated future direction on the assessment and mitigation of $PM_{2.5}$ can be foreseen. These may include:

4.1 Measurement and methodology

The assessment or monitoring process should be accurate and following the international guidelines, in order to minimize the error during data collection. Therefore, methods should be developed according to location and climate condition to get more accurate details such as chemical composition and quantitative data, for making successful strategies or policies.

4.2 Chemical analysis

Organic and related microorganisms which are present in very high concentrations in $PM_{2.5}$ are yet to be identified. To assess the tempo-spatial variation and source identification of $PM_{2.5}$, tracer methods using ions, elements, radiocarbon, and EC need to be improved.

4.3 Particle formation

Studies on the assessment of secondary aerosol formation in rural areas of China are lacking. More studies should be carried out on the secondary aerosol formation to identify their impact on primary users during cooking and heating especially in the rural area, China.

4.4 Monitoring network and standards

According to MEPPRC (2015), China has developed huge monitoring network with 1436 monitoring stations in 367 cities to understand the air quality status and concentration level of $PM_{2.5}$ to develop the air quality management. Similarly, China has minimized the concentration level of $PM_{2.5}$ in different cities by awareness through free mobile APPs, online facility to monitor concentration from static and mobile sources, ban on certain vehicles and machines run by diesel, promotion of environment-friendly transport for public, and launching of programs for adopting new cleaner fuel technology for cooking and heating. However, most of these initiatives are confined to urban or township area. Promotion and implementation of these policies and installation of $PM_{2.5}$ monitoring network in rural areas are therefore needed for effective implementation of strategies or policies for air quality management across the country.

$PM_{2.5}$ concentrations in China are reported well in the literature and scientific reports (MEPPRC 2015; Zhang and Cao 2015). There are several current and upcoming issues (i.e., source, effects, and control) very common with $PM_{2.5}$ exposure in China (Zhang and Cao 2015), and they are indicating attention on $PM_{2.5}$ related issues. A systematic approach to the act of research (academic), anthropogenic activities, private agency, and government authority can minimize the pollution level in China (Fig. 3).

The outcomes from academic and research could provide correct information about the sources and effects of $PM_{2.5}$ which will help in improving the regulations/standards and controlling the $PM_{2.5}$ concentration profile. The actions of government and the private agency are very important to develop new regulations/standards commensurate with the outcomes of research and academic that will protect human health and help with air quality management. The industry should be bounded by regulations and follow the national standards suggested by the Federal Government and local authorities. Figure 3 suggests that each stakeholder can support others to reduce the level of $PM_{2.5}$. The general public will move forward to minimize the pollution level by the use of less of diesel vehicles, adoption of the cleaner fuel, increased use of public transport, and support for green technologies.

The current study is a combination of recently published articles from 2012 to 2016 with the $PM_{2.5}$ title and source apportionment-related study. Several measurements such as concentration variation with respect to time and space and chemical composition are taken in the various parts of the world, especially in China, where the $PM_{2.5}$ concentration is reported higher as compared to other Asian countries.

The chemical composition of $PM_{2.5}$, secondary aerosol formation, tertiary aerosol formation, microbes, intervention, climate change, personal and ambient exposure relationship, and exposure apportionment are emerging subject and should be addressed by future research. To assess and control the $PM_{2.5}$ concentrations, cost-effective and updated instruments for quantitative measurement and new control or intervention studies are highly needed.

Source apportionment, exposure, and emission studies are very necessary to improve or develop the policy to minimize $PM_{2.5}$ in the surrounding atmosphere. China has conducted

to a large extent the source apportionment studies to understand the social consumption, energy structure profile, emission inventories in urban and township area. Identification of $PM_{2.5}$ source or exposure apportionment in rural area of China should now be rigorously carried out in order to identify the $PM_{2.5}$ emission source (traditional stove, open biomass burning), fuel types (cow dung, brushwood, forest wood, etc.), emission duration (food type and kitchen use), in order to better understand the $PM_{2.5}$ level in rural areas. The outcomes of the suggested studies will improve the policy strategies to control the emission and reduce the exposure to $PM_{2.5}$.

Qualitative and quantitative information on $PM_{2.5}$ has been found from the past literature. However, further understanding on the $PM_{2.5}$ issue should be supported by the utilization of multidisciplinary approaches involving: (1) dispersion, deposition and suspension dynamics, (2) the role of meteorology, chemistry, and terrain, and (iii) assessment through remote sensing and computational program.

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