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Invited review/perspective

$PM_{2.5}$ in China: Measurements, sources, visibility and health effects, and mitigation

David Y.H. Pui*, Sheng-Chieh Chen, Zhili Zuo

Department of Mechanical Engineering, College of Science and Engineering, University of Minnesota, Minneapolis, MN 55455, USA

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ABSTRACT

Concern over the health effects of fine particles in the ambient environment led the U.S. Environmental Protection Agency to develop the first standard for $PM_{2.5}$ (particulate matter less than 2.5 μm) in 1997. The Particle Technology Laboratory at the University of Minnesota has helped to establish the $PM_{2.5}$ standard by developing many instruments and samplers to perform atmospheric measurements. In this paper, we review various aspects of $PM_{2.5}$, including its measurement, source apportionment, visibility and health effects, and mitigation. We focus on $PM_{2.5}$ studies in China and where appropriate, compare them with those obtained in the U.S. Based on accurate $PM_{2.5}$ sampling, chemical analysis, and source apportionment models, the major $PM_{2.5}$ sources in China have been identified to be coal combustion, motor vehicle emissions, and industrial sources. Atmospheric visibility has been found to correlate well with $PM_{2.5}$ concentration. Sulfate, ammonium, and nitrate carried by $PM_{2.5}$, commonly found in coal burning and vehicle emissions, are the dominant contributors to regional haze in China. Short-term exposure to $PM_{2.5}$ is strongly associated with the increased risk of morbidity and mortality from cardiovascular and respiratory diseases in China. The strategy for $PM_{2.5}$ mitigation must be based on reducing the pollutants from the two primary sources of coal-fired power plants and vehicle emissions. Although conventional Particulate Emission Control Devices (PECD) such as electrostatic precipitators in Chinese coal-fired power plants are generally effective for large particles, most of them may not have high collection efficiency of $PM_{2.5}$. Baghouse filtration is gradually incorporated into the PECD to increase the $PM_{2.5}$ collection efficiency. By adopting stringent vehicle emissions standard such as Euro 5 and 6, the emissions from vehicles can be gradually reduced over the years. An integrative approach, from collaboration among academia, government, and industries, can effectively manage and mitigate the $PM_{2.5}$ pollution in China.

Abbreviations: AQG, Air Quality Guideline; BB, biomass burning; CAA, Clean Air Act; CASTNET, Clean Air Status and Trend Network; CC, coal combustion; CFB, circulating fluidized bed; CFR, Center for Filtration Research; CI, confidence interval; CMB, chemical mass balance; CMB-MM, molecular marker-based chemical mass balance; COPD, chronic obstructive pulmonary disease; CSN, Chemical Speciation Network; CVD, cardiovascular diseases; DFPSS, dual fine particle sequential sampler; DMPS, differential mobility particle sizer; DPF, diesel particulate filter; EAA, electrical aerosol analyzer; EC, elemental carbon; EF, enrichment factor; ESP, electrostatic precipitators; EU, European Union; GDI, gasoline direct injection; GPF, gasoline particulate filter; HA, hospital admission; HEDV, hospital emergency department visit; HEI, Health Effects Institute; HYSPLIT, hybrid single particle Lagrangian integrated trajectory; IC, ion-exchange chromatography or ion chromatography; ICP-AES, inductively coupled plasma atomic emission spectroscopy; ICP-MS, inductively coupled plasma mass spectrometry; IHD, ischemic heart disease; IMPROVE, Interagency Monitoring of Protected Visual Environments; IT, interim target; LAC, light absorbing carbon; MLR, multiple linear regression; MS, mass spectrometry; NA, not available; NAAQS, National Ambient Air Quality Standards; NCDC, National Clean Diesel Campaign; NDIR, nondispersive infrared; NOAA, National Oceanic and Atmospheric Administration; OC, organic carbon; PAHs, Polycyclic aromatic hydrocarbons; PC, pulverized coal; PCA, principal component analysis; PCM, Particulate Composition Monitor; PECD, particulate emission control device; PESA, proton elastic scattering analysis; PIXE, proton induced X-ray emission; PM, particulate matter; PMF, positive matrix factorization; PSCF, potential source contribution function; RA, risk assessment; RH, relative humidity; RHR, Regional Haze Rule; RIA, regulatory impact analysis; STN, Speciation Trend Network; TEOM, tapered element oscillating microbalance; TOR, thermal optical reflectance; TOT, thermal optical transmittance; TSP, total suspended particle; USEPA, U.S. Environmental Protection Agency; VE, vehicular emission; WAA, Whitby aerosol analyzer; WFGD, wet flue gas desulphurization; WHO, World Health Organization; XRF, X-ray fluorescence.

* Corresponding author at: 111 Church Street, S.E., Minneapolis, MN 55455, USA. Tel.: +1 6126252537.
E-mail address: dyhpui@umn.edu (D.Y.H. Pui).

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Contents

1. Introduction

1.1. Definition and background

$PM_{2.5}$ refers to particulate matter (PM) in air that is less than 2.5 μm in aerodynamic diameter. It was established in 1997 by the U.S. Environmental Protection Agency (USEPA) to protect public health. The standard has been progressively strengthened over the years and is currently set at 35 $\mu g/m^3$ over a 24-h period and 12 $\mu g/m^3$ for annual average in the U.S. $PM_{2.5}$ is fine particles of air pollutants primarily resulting from combustion and gas-to-particle conversion processes in the atmosphere. The principal sources include coal–oil–gasoline–diesel–wood combustion, high temperature industrial processes from smelters and steel mills, vehicle emissions, and biomass burning. Due to their small particle sizes, they have a life-time of days to weeks and can transport over thousands of kilometer distance. A significant fraction of the particles in $PM_{2.5}$ has particle diameter near the wavelength of light, so that they scatter light efficiently and cause visibility reduction. $PM_{2.5}$ is deposited throughout human respiratory tract, causing lung diseases, heart diseases and premature death.

1.2. Contribution by the Particle Technology Laboratory, University of Minnesota

Beginning in the 1960s, the Particle Technology Laboratory at the University of Minnesota has developed a range of real-time instruments and samplers for atmospheric particle size distribution measurements. Whitby and Clarke (1966) developed an electrical particle counter (Whitby aerosol analyzer, WAA) for measuring airborne particle size distribution in 0.01–1.0 μm range. Liu and Pui (1975) developed the widely used electrical aerosol analyzer (EAA), which was commercialized as TSI Model 3030 EAA. The technique, based on the same principle of Whitby's sizer, made use of aerosol charging, mobility analysis, and electrometer detection (Fig. 1(a)). TSI 3030 EAA was compact and robust, which was widely used for measuring submicron atmospheric aerosol size distributions during the 1970–1980s. Later, the EAA was replaced with a scanning mobility particle sizer (SMPS, e.g. TSI Model 3936), which made use of a high-resolution Differential Mobility Analyzer (Chen et al., 1998; Knutson & Whitby, 1975; Liu & Pui, 1974). Liu, Pui, Wang, and Lewis (1983) developed an omni-directional sampling inlet (Fig. 1(b)) for PM_{10} and $PM_{2.5}$ sampling. The inlet efficiently samples airborne particles up to 10 μm and at wind speed up to 24 km/h and is followed by an impactor with cut-size of 10 μm for PM_{10} sampling or cut-size of 2.5 μm for $PM_{2.5}$ sampling. Marple, Liu, and Burton (1990) and Marple and Olson (1995) at the Particle Technology Laboratory also developed a range of impactor samplers for atmospheric sampling. Other faculty members of the Particle Technology Laboratory have made major contributions to engine emission measurements and control (Kittelson, 1998; Kittelson, Watts, & Johnson, 2004), and to atmospheric aerosol measurements and visibility (McMurry, 2000; Saxena, Hildemann, McMurry, & Seinfeld, 1995).

During the 1960–1980s, Whitby, Liu, Pui, and colleagues assembled these instruments and several optical particle counters and performed many field studies throughout the U.S., starting with the 1969 Los Angeles smog study. Results of several major field projects showed that the atmospheric size distribution (Fig. 2) consists of two modes with a minimum around 1–2.5 μm that separates the

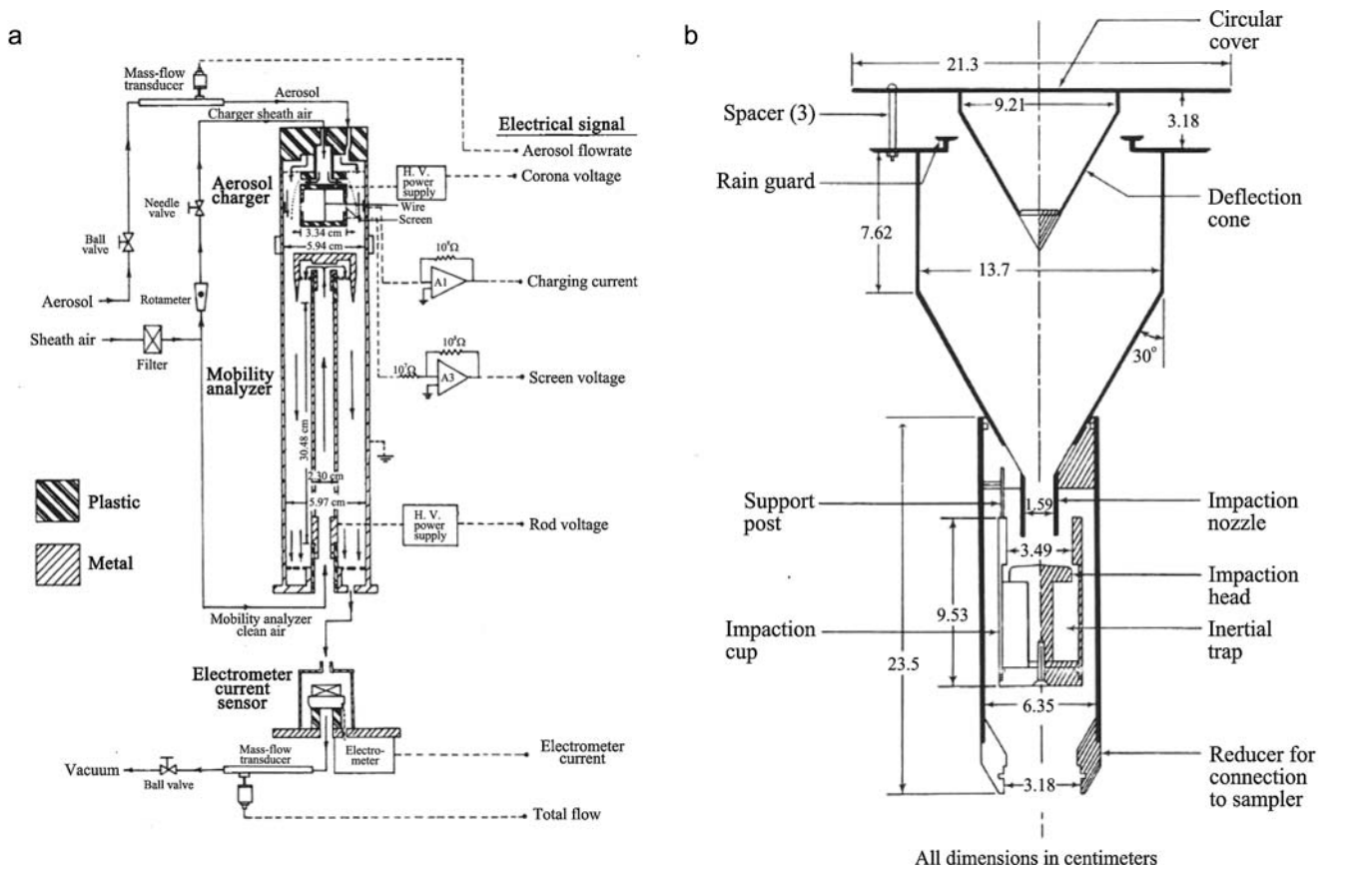

Fig. 1. Schematic diagrams of (a) the Electrical Aerosol Analyzer (TSI Model 3030) introduced in 1974 for submicron aerosol size distribution measurements (Liu & Pui, 1975) and (b) an omni-directional inlet for PM_{10} and $PM_{2.5}$ sampling (Liu et al., 1983).

fine mode (from air pollution) and coarse mode (from windblown dust and other natural sources) (Whitby, Husar, & Liu, 1972). These and other subsequent results form the basis of $PM_{2.5}$ established by the U.S. EPA to collect the $PM_{2.5}$ air pollutants and reject the larger particles mostly from natural origins (USEPA, 1996).

1.3. Process of setting $PM_{2.5}$ standards and improvement of PM pollution in the U.S.

$PM_{2.5}$ or fine particles, is regarded as one of the important air pollutants responsible for the adverse health effects because of its respirable and toxic chemical constituents. Americans suffered severe air pollution since the 1950s due to the increase of energy consumption and the number of motor vehicles (e.g. the Los Angeles and New York smog in the 1950–1960s). In order to improve air quality, the Air Pollution Control Act was established in 1955, which was the first federal legislation on air pollution. This Act provided funds for federal research on air pollution. Later, the Clean Air Act (CAA) was established in 1963, which was the first federal legislation on air pollution control, but only for smokestack emission. It organized a federal program within the U.S. public health service and authorized research on techniques for monitoring and controlling air pollution. In 1970, CAA authorized the development of comprehensive federal and state regulations to limit emissions from both stationary (industrial) sources and mobile sources. Besides, the National Ambient Air Quality Standards (NAAQS, 40 CFR Part 50) were set for air pollutants considered harmful to public health and the environment, such as ground-level ozone, lead, nitrogen dioxide (NO_2), carbon monoxide (CO), and sulfur dioxide (SO_2). In addition to the gaseous pollutants, under the CAA, USEPA also set and reviewed national air quality standards for PM. In 1971, NAAQS was first set for total suspended particles (TSP) (Federal Register, 1971). To be noted, the CAA established two types of national air quality standards, namely the primary and secondary standards. The primary standards set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards set limits to protect public welfare, including visibility impairment, damage to animals, crops, vegetation, and buildings. The PM standards presented in this article are only for the primary standards. Fig. 3 summarises the historical PM settings in the NAAQS, along with the programs by USEPA for reducing PM and the corresponding achievements

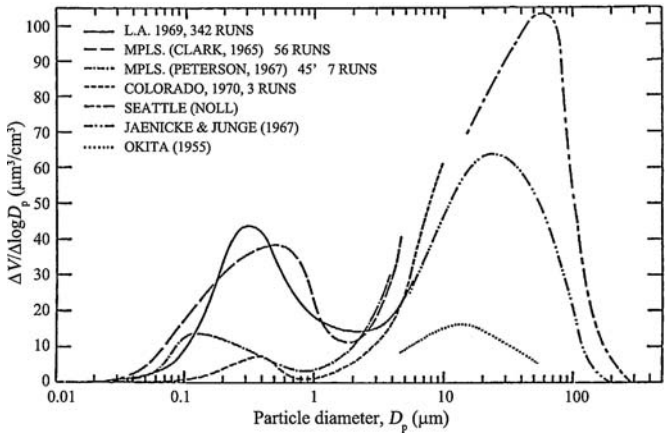

Fig. 2. Bimodal atmospheric size distribution showing a fine particle mode and a coarse particle mode with a minimum between 1 and 2.5 μm (Whitby et al., 1972).

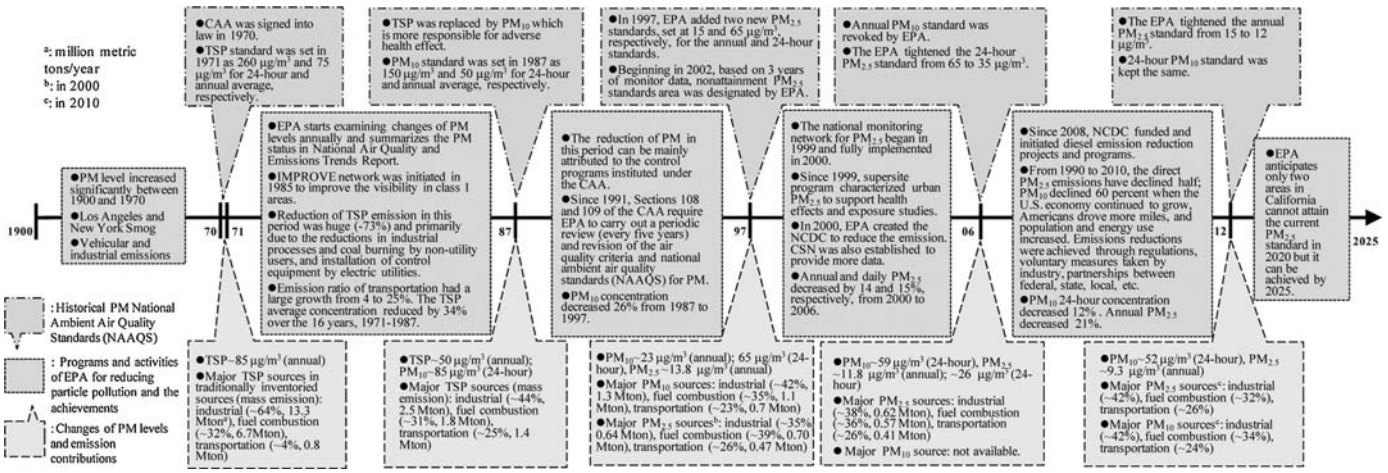

Fig. 3. The historical National Ambient Air Quality Standards (NAAQS) for PM in the U.S., programs and activities initiated by the U.S. Environmental Protection Agency (USEPA) for reducing PM pollution, their corresponding achievements, and source contribution of PM during specific time periods.

in specific time periods. It is clear that the PM standards have been strengthened over the years. Several national programs, such as the Interagency Monitoring of Protected Visual Environments (IMPROVE) Program, Chemical Speciation Network (CSN), Supersites Program, National Clean Diesel Campaign (NCDC), etc. were funded for reducing the PM pollution. In these programs, chemical composition of $PM_{2.5}$ at receptor sites was measured and source apportionment models (see Section 3.1) were often used to help develop emission reduction strategies for attaining the PM standards (Watson, Chen, Chow, Doraiswamy, & Lowenthal, 2008).

Based on the scientific findings that PM with an aerodynamic diameter of less than 10 μm (PM_{10}) is deposited in thoracic (trachea bronchial and alveolar) portions of the lower respiratory tract, the USEPA promulgated a standard for PM_{10} in 1987, where the 24-h (short-term) and annual (long-term) standard was 150 and 50 $\mu g/m^3$, respectively (Federal Register, 1987). The standard was later modified in 1997 to include $PM_{2.5}$, with 65 $\mu g/m^3$ (98th percentile, averaged over 3 years) and 15 $\mu g/m^3$ (annual arithmetic mean, averaged over 3 years) for the 24-h and annual standard, respectively (Federal Register, 1997). Then a more restrict standard was set for 24-h exposure to $PM_{2.5}$ in 2006, where it was reduced from 65 to 35 $\mu g/m^3$ (Federal Register, 2006). Most recently, in December 2012, the USEPA further tightened the annual standard of $PM_{2.5}$ from 15 to 12 $\mu g/m^3$ in order to better protect Americans from PM pollution (Federal Register, 2013).

In addition to the PM standards and various USEPA programs, the source contribution to PM is also shown in Fig. 3. The three major sources of PM are industrial, fuel combustion and transportation. TSP from these major sources has been found to reduce significantly by 73% from 20.8 Mton (i.e. million metric tons) in 1971 to 5.7 Mton in 1987, but with a large change of the contribution fractions, e.g. the fraction of transportation increased from 4% to 25%. The improvement of PM continued in the next period, 1987–1997. After 1987, the fractions remained relatively constant for both PM_{10} and $PM_{2.5}$, with around 42%, 33%, and 25% from industrials, fuel combustion, and transportation, respectively.

The process of setting U.S. $PM_{2.5}$ standard involves risk assessment (RA) and regulatory impact analysis (RIA), both conducted by the USEPA. RA provides quantitative assessment and supports the review of the $PM_{2.5}$ standards. By utilizing $PM_{2.5}$ data from specific urban areas, concentration–response functions derived from epidemiological studies (USEPA, 2004), baseline health incidence data for specific health endpoints, and population estimates, the assessment model derives estimates of the annual incidence of specified health effects attributable to ambient $PM_{2.5}$ concentrations under different air quality scenarios. Unlike RA, RIA provides the best estimates for the cost and benefit of an illustrative attainment strategy to meet the revised annual standard (USEPA, 2009a, 2010, 2012a). There are four major steps in the process of RIA: (1) establishing the analytical baseline, (2) selecting control strategies, (3) analyzing cost, and (4) obtaining the net benefit under full attainment. Some major national rules (control strategies) analyzed in the RIA include: Light-Duty Vehicle Tier Rule, Heavy Duty Diesel Rule, Clean Air Nonroad Diesel Rule, Control of Emissions for Nonroad Spark Ignition Engines and Equipment, Boiler MACT, Hospital/Medical/Infectious Waste Incinerators: New Source Performance Standards, and Emission Guidelines: Final Rule Amendments, Mercury and Air Toxics Standards, Cross-State Air Pollution Rule, etc.

Due to the continuous effects by the USEPA, the 24-h PM_{10} and annual $PM_{2.5}$ concentration have been reduced by 27% (from 87 to 64 $\mu g/m^3$) and 33% (from 13.8 to 9.3 $\mu g/m^3$) during 2000–2012, respectively (USEPA, 2013). Currently there are only 66 out of 3077 counties (<2%) in the U.S. which do not meet the $PM_{2.5}$ standard at 12 $\mu g/m^3$. The USEPA anticipates attainment with the standard by 2020 in all but two areas in California, which are not expected to attain the current standard until 2025. The USEPA predicts that the CCA amendments can prevent over 230,000 early deaths in 2020 (USEPA, 2011). The fact that the U.S. could achieve substantial reduction of $PM_{2.5}$ within only 15 years (1997–2012) may be attributed to the following efforts: (1) conducted nation-wide $PM_{2.5}$ measurements and sampling effectively, (2) measured $PM_{2.5}$ mass and chemical composition concentrations accurately, (3) derived the source apportionment of $PM_{2.5}$ accurately, (4) implemented both mandatory and voluntary emission control effectively, and (5) established partnerships between federal, state, local, and tribal governments, academia, industrial groups, and environmental organizations (USEPA, 2012b). It is worth mentioning that pollution in the U.S. has been continuously improved during 1990–2010, despite the fact that Americans drove 40% more miles, the U.S. economy, energy use, and population increased by 65%, 15%, and 24%, respectively (USEPA, 2012b).

Since the PM pollution was substantially improved in the U.S., it is interesting to know how the improvement programs were implemented. Here, two examples, the IMPROVE and Chemical Speciation Network (CSN or formally STN, Speciation Trend Network) programs, are briefly discussed. The objectives of the

IMPROVE program are: (1) to establish current visibility and aerosol conditions in mandatory class I areas (national parks); (2) to identify chemical species and emission sources responsible for existing anthropogenic visibility impairment; (3) to document long-term trends for assessing progress toward the national visibility goal; and (4) with the enactment of the Regional Haze Rule, to provide regional haze monitoring representing all visibility-protected federal class I areas where practical (IMPROVE, 2011). The program is still running and it periodically publishes reports entitled "Spatial and Seasonal Patterns and Temporal Variability of Haze and its Constituents in the United States". All the materials are accessible at http://vista.cira.colostate.edu/improve/Activities/activities.htm for public use. In addition to the remote or rural sites operated by IMPROVE, the CSN program has collected $PM_{2.5}$ chemical composition data at approximately 200 urban or suburban monitoring sites since 2000. Data from the IMPROVE and CSN networks are useful independently, but a more detailed geographical variation of key aerosol species can be analyzed by combining the two data sets. In any particular urban or Class I area, understanding the sources of ambient particulate matter has become increasingly important because the control strategies have to be developed based on the characteristics of the sources.

In this review, methods and results of $PM_{2.5}$ sampling, its chemical composition analysis, and source apportionment performed in the U.S. and in China will be compared and discussed, followed by the health and visibility effects of $PM_{2.5}$ as well as the control measures for $PM_{2.5}$ emission from coal-fired power plants. Knowledge gaps and future research need will also be identified. Finally, an integrative approach will be proposed to address the $PM_{2.5}$ issue in China.

2. Sampling and chemical analysis of $PM_{2.5}$

2.1. Principle of $PM_{2.5}$ sampling

An efficient $PM_{2.5}$ sampling system should include a 2.5 μm size-selective inlet, nitric acid removal denuder as a selective, filter holders or collection substrates, flow controllers and pumps (Chow & Watson, 2002; IMPROVE, 2011). Various samplers were used in different studies to obtain desired PM samples. In these samplers, cyclones (IMPROVE, 2011; John & Reischl, 1980; Leith & Mehta, 1973; Zhu & Lee, 1999), impactors (Chen, Tsai, Chen, Huang, & Roam, 2011; Hering, Flagan, & Friedlander, 1978; Marple, Rubow, & Behm, 1991; Peters, Vanderpool, & Wiener, 2001), and virtual impactors (Chen, Yeh, & Cheng, 1985; Loo & Cork, 1988; Marple & Chien, 1980; McFarland, Ortiz, & Bertch, 1978) are normally used as a 2.5 μm size-selective inlet to separate fine particles from larger ones.

In order to obtain a representative sample, homogeneous particle deposition on the collection substrates is required for multiple chemical analyses (Chen, Tsai, Chou, et al. 2010; Chen, Tsai, Huang, et al. 2010; Chen, Tsai, et al., 2011; Chow & Watson, 2007). Mass, elements, ions, and carbon fractions collected on the filter substrates are most commonly measured. The selection of a filter substrate is specific to the analysis planned. For example, glass–fiber filters can easily absorb and attract moisture, and therefore are not suitable for gravimetric analysis. Teflon media are chemically inactive and resistant, providing background level of elements an order of magnitude lower than quartz, and are thus recommended for elemental analysis. However, quartz is strongly refractory and can therefore facilitate the thermo analysis of organic carbon (OC) and elemental carbon (EC). In the IMPROVE program, Teflon filters are used for gravimetric and elemental analyses, Nylon filters for sulfate, nitrate and ions analyses, and quartz filters for OC and EC analyses. Note that excellent $PM_{2.5}$ sampling and the subsequent chemical analysis have been achieved in the current IMPROVE program after more than 25 years of modification and improvement. Therefore, the method shown in the IMPROVE program are often referred to for acquiring $PM_{2.5}$ mass and chemical species concentrations.

2.2. Chemical analysis of $PM_{2.5}$

The $PM_{2.5}$ sampler used in the IMPROVE project consists of four independent modules. Each module incorporates a separate inlet, filter pack, and pump assembly. Modules A, B, and C are equipped with a 2.5 μm cut cyclone inlet while module D is fitted with a PM_{10} impactor inlet. Each module contains a unique filter substrate, depending on the analysis planned. A more detailed method could be found elsewhere (IMPROVE, 2011). Briefly, module A is equipped with a Teflon filter for gravimetric, elemental, and light absorption analysis. Samples are pre- and post-weighed to determine $PM_{2.5}$ mass using electro-microbalance, after equilibrating at 30–40% relative humidity and 20–30 °C. Elemental analysis is achieved by X-ray fluorescence (XRF), proton elastic scattering analysis (PESA), and proton induced X-ray emission (PIXE). Module B is mainly for water-soluble ion analysis, in which a sodium carbonate denuder tube is placed downstream of the cyclone to remove gaseous nitric acid in the air, followed by a nylon filter to collect $PM_{2.5}$. The material collected on the nylon filter is extracted ultrasonically in an aqueous solution that is subsequently analyzed for anions sulfate, nitrate, nitrite, and chloride using ion chromatography. Nylon filters have been found to better preserve collected nitrate than Teflon filters (Yu et al., 2005). Module C utilizes quartz fiber filters that are analyzed by thermal optical reflectance (TOR) for OC and EC and module D utilizes a Teflon filter to determine PM_{10} mass concentrations.

3. Source apportionment of $PM_{2.5}$

3.1. Background of source apportionment models

Identification and quantification of the sources of $PM_{2.5}$ using source apportionment methods are critical, because the acquired information is used by policy makers to develop control strategies. In order to accurately determine the sources of a collected particle sample, a series of efforts are needed. First, a $PM_{2.5}$ sample has to be collected correctly, because the reported results in terms of the mass and chemical concentrations are based on the analysis of the sample. For example, an inaccurate sampling flow rate may shift the 2.5 μm cut size of a cyclone, impactor, or virtual impactor inlet, thus giving a non-representative $PM_{2.5}$ sample. Second, after a representative sample is collected, the sample must be analyzed correctly both gravimetrically and chemically. For example, positive artifact of OC may cause an increase of $PM_{2.5}$ mass by as high as 30–50% due to the adsorption of gaseous and semi-volatile OC (Chen, Tsai, Huang, et al., 2010). By using representative data combined with an appropriate source apportionment model, one can then better determine the sources of $PM_{2.5}$.

There are seven commonly used source apportionment models, including HYSPLIT (hybrid single particle Lagrangian integrated trajectory) backward trajectory analysis, enrichment factors (EF), principal component analysis (PCA), UNMIX Form of Factor Analysis, positive matrix factorization (PMF), and chemical mass balance (CMB). The last three models are relatively popular in recent years. A more detailed model description and comparison can be referred to Watson et al. (2008).

Tables 1 and 2 summarize the most widely used $PM_{2.5}$ sampling and chemical analysis methods in the U.S. and China, respectively. The following information is shown in tables: (1) sampling methods (e.g. samplers or data acquired from other sources), (2) sampling location, characteristics (e.g. urban, nonurban, industrial, residential), periods, frequency, and duration, (3) chemical analysis methods and source and receptor models, (4) source contribution and categories, (5) conclusion and recommendations, and (6) references. A more detailed review on the techniques for characterizing the ambient $PM_{2.5}$ can be found in Chow and Watson (2002) and Coutant, Engel-Cox, and Swinton (2003). Note that the studies surveyed are generally associated with source apportionment, because not only sampling conditions/methods but also comprehensive chemical analysis of $PM_{2.5}$ was reported. Also note that the studies listed in Table 1 were mainly conducted in 1980–2000, when the pollution level in the U.S. is expected to be close to that in China nowadays.

All the source apportionment models used chemical measurement of elements (usually as many as 20–40 elements), water-soluble ions (Cl^-, NO_3^- representing nitrate, SO_4^{2-} representing sulfate, NH_4^+ representing ammonium, Na^+, K^+, and Ca^{2+}), and carbon (organic carbon, OC, and elemental carbon, EC, or black carbon, BC). Other organic compounds (such as polycyclic aromatic hydrocarbons (PAHs), *n*-alkanes, *n*-alkenes, organic acids, hopanes, sterenes, lactones, sterols, guiacols, and syringols) were measured in several cases (Brook et al., 2000; Gao et al., 2013; Guo, Feng, Fang, Chen, & Lau, 2004; Huang, He, Hu, & Zhang, 2006; Lee, Brook, Dabek-Zlotorzynska, & Mabury, 2003; Li, Wang, Li, et al., 2010; Pinto et al., 1998; Schauer, Rogge, Hildemann, Mazurek, & Cass, 1996; Schauer & Cass, 2000; Zheng, Cass, Schauer, & Edgerton, 2002). The elements can be easily divided into two groups: crustal (Na, Mg, Al, K, Ca, Fe, and Si) and anthropogenic elements (S, Zn, Ni, Cu, Mn, Sr, Ag, Ba, Pb, V, Cr, and Ti). V and Ba are the additives of fuel while Pb, Zn, Ni, and Ba are produced from gasoline and diesel engines, and Si, Al, Ca, and Fe are the major bounded elements of diesel engine emissions (Chen, Tsai, Huang, et al., 2010; Monaci, Moni, Lanciotti, Grechi, & Bargagli, 2000). Contribution of cooking (OC3, carbon fraction evolved at 450 °C, palmitoleic acid, cholesterol, etc.) and wood burning (levoglucosan, propionylsyringol, butyrylsyringol, pimaric acid, isopimaric acid, etc.) has been shown to be distinguishable, implying that the vegetative burning category determined without those compounds should be redefined as a cooking/vegetative burning category (Chow & Watson, 2002). Similarly, diesel and gasoline engine emission can also be differentiated from motor vehicle exhaust using those organic markers. To better characterize contemporary source emissions, the following activities should be pursued: (1) evaluate and compile current source profiles, (2) undertake a systematic sampling effort to obtain source profiles for representative fuels, operating conditions, and combustion technologies, (3) evaluate data from multiple sites (e.g. the IMPROVE and CSN program) with the objective to identify unique "regional or urban source profiles", and (4) develop refined methods for comparing source profiles between model results and source measurement.

3.2. Comparison of different source apportionment models

Several studies compare the performance between two or more of the seven models mentioned earlier (Chen, Doddridge, Dickerson, Chow, & Henry, 2002; Coutant et al., 2002; Ke et al., 2008; Kim, Hopke, Larson, & Covert, 2004; Song, Xie, et al., 2006; Song, Zhang, et al., 2006; Watson et al., 2008, etc.). The following are two examples. Ke et al. (2008) conducted a comprehensive comparison of CMB-MM (molecular maker based) and PMF and found that the $PM_{2.5}$ mass contributions from road dust, gasoline exhaust, and wood combustion are in fair to good agreement between the two models. The CMB-MM diesel exhaust has poor correlation with the PMF diesel exhaust. The discrepancy in source apportionment results between CMB-MM and PMF may be due to the different source compositions or tracers in their source profiles. The authors expected that if there were more overlap in the compounds used in each type of analysis, better agreement may be expected. However, this may also mask errors in the results. There are still fundamental difference between PMF and CMB-MM, as shown by Jaeckels, Bae, and Schauer (2007). In general, CMB-MM results are in better agreement with the PMF analysis of traditional speciation data than with the eight-carbon-fraction PMF analysis. CMB-MM is a useful tool to apportion sources characterized by unique molecular markers such as wood combustion and meat cooking. It also performs fairly well for motor vehicle exhaust. The split between diesel and gasoline exhaust might be improved if thermal-resolved carbonaceous fractions can be incorporated into molecular marker-based source profile in the source tests. For PMF, the inclusion of gaseous species as well as carbonaceous fractions gives more constraints to model fits and thus helps to split diesel exhaust and gasoline exhaust estimates, though it may not be as powerful as CMB in apportioning primary motor vehicle exhaust from ambient $PM_{2.5}$ data.

Besides, the multivariate receptor models, PMF and UNMIX, were used along with the USEPA's Chemical Mass Balance model by Maykut, Lewtas, Kim, and Larson (2003) to deduce the sources of $PM_{2.5}$ at a centrally located urban site in Seattle, WA. A total of 289 filter samples were obtained with an IMPROVE sampler from 1996 through 1999 and were analyzed for 31 particulate elements including temperature-resolved fractions of the particulate organic and elemental carbon. All three receptor models predicted that the major sources of $PM_{2.5}$ were vegetative burning (including wood stoves), mobile sources, and secondary particle formation with less contribution from re-suspended soil and sea spray. The PMF and UNMIX models were able to resolve a fuel oil combustion source as well as distinguish between diesel emissions and other mobile sources. In addition, the average source contribution estimates via PMF and UNMIX agreed well with an existing emissions inventory. Using the temperature-resolved organic and elemental carbon fractions provided in the IMPROVE protocol, rather than the total organic and elemental carbon, allowed the UNMIX model to separate diesel from other mobile sources. The PMF model was able to do this without the additional carbon species, relying on selected trace elements to distinguish the various combustion sources.

Based on a detailed review of 27 source apportionment studies, Coutant et al. (2003) made the following summary and can be referred to in future research. Although the source apportionment models (e.g. PMF) have passed the proof-of-concept stage and are now being used to understand the ambient composition of the $PM_{2.5}$ for sites across the U.S. and the spatial relationship of sources to the receptor, this should not be taken as an indication that the tools and methods have been finalized. Instead, method development is important and must be continued. For example, there is still need for improvement in the main source apportionment tools, particularly error estimates and methods for identifying the number of sources. Very little research has been done to date on identifying the sources from the tool output.

3.3. Results from Chinese studies

Due to the rapid urbanization concurrent with a sharp increase of energy consumption and motor vehicles in several major cities in China after the 1980s, air pollution becomes a choking problem. Chinese researchers started conducting $PM_{2.5}$ measurement since the early 2000s, much earlier than the first Chinese $PM_{2.5}$ standard promulgated in January 2012 (Cao et al., 2003; Duan et al., 2006; Feng et al., 2005; Gu et al., 2010; Guo et al., 2004; He et al., 2001; Li,

Table 1
Summary of source apportionment studies of $PM_{2.5}$ conducted in the U.S. The sampling instruments are also included.

Sampling method	Sampling site and timing	Chemical analysis and source apportionment model	Findings, in terms of source types and contribution	Conclusion or recommendation	Reference
IMPROVE sampler, Partisol, VAPS and Dichotomous	An urban site in Evans and a semi-rural site in Egbert, Ontario, Canada March, April and July, 1998	23 elements by XRF, PESA and PIXE OC/EC by TOR 12 Organics, n-alkanes and PAHs by GC/MS Cl^-, NO_3^-, SO_4^{2-}, Na^+ and NH_4^+ by IC CMB model	Vehicle exhaust was the largest contributor (37%–63%) to $PM_{2.5}$ in the urban. Secondary ammonium sulfate was the largest contributor (32%–33%) at the semi-rural site. Source contributions from industry and fossil fuel use from Ontario and upwind areas may contribute to elevated sulfate concentrations which varied from 1% to 11%, with 2%–7% derived from coal-fired power plants.	Organic speciation (acids and alkanes) explains only 1%–10% of total organics. Biogenic sources (odd-number alkanes » even-number alkanes) may have contribution to primary and secondary organic at the semi-rural site.	Brook et al. (2000)
Dichotomous, MOUDI	Three coastal sites in central Taiwan, China 1992–1994	20 elements by XRF OC/EC by nondispersive infrared (NDIR) Sulfate by IC CMB model	The main sources for the coarse fraction of ambient aerosols in the region were found to be marine aerosol, coal and fuel oil combustion, burning of agricultural wastes, and paved road dust. The main sources for the fine fraction were burning of agricultural wastes, diesel exhaust, coal and oil combustion, and sulfates. Source apportionment for the fine fraction was relatively sensitive to the types of sources selected for calculations and the compositions of the sources.	The assessment of source contributions carried out in this study should be useful for evaluating the impending impact of a new petrochemical complex on the air quality of the Meliao region and for planning pollution control strategies.	Chen et al. (1997)
IMPROVE sampler, MOUDI, SFS, Partisol, VAPS, URG Cyclone and Dichotomous	Over 20 locations of all types in the U.S. (primarily western states) and internationally Mainly 1990–1998	40 elements by XRF, PESA and PIXE OC/EC by TOR and LIPM Cl^-, NO_3^-, SO_4^{2-}, Na^+ and NH_4^+ by IC CMB model	North American cities $PM_{2.5}$ from 8 to 66 $\mu g/m^3$. Most of the primary contributions to $PM_{2.5}$ and PM_{10} were from diesel and gasoline powered vehicle exhaust. Primary contributions from "ducted" sources (e.g., power stations) were significant only when they did not have modern pollution controls. The contribution from secondary sulfates and nitrates was identified but could not be attributed to specific precursor sources using CMB or other chemical transport models. Use of source and receptor models together improved estimates of source contribution. While CMB was developed for primary pollutants, several studies adapted it to model secondary pollutants.	CMB could be used to verify and improve emission inventories and to apportion PM sources, both valuable for air quality policy and enforcement. However, much more work needs to be done to increase the sampling to adequately represent the chemical compositions of the sources.	Chow and Watson (2002)
Data from 10 IMPROVE and 6 CASTNET (Clean Air Status and Trend Network) sites	16 sites in Class I and rural areas in the midwest, northeast, mid-Atlantic, and southeast plus one urban site 1988 to 2000	18 elements by XRF, PESA and PIXE OC/EC by TOR PMF and UNMIX models	When assessing the sources for the 20% best visibility days, no sources strongly dominated. For the 20% worst visibility dates, certain sources were dominant and in many cases over 50% of the light extinction could be attributed to secondary sulfate.	Some possible data artifacts in the two datasets should be further investigated. Emissions inventories and backward trajectory models could be used in conjunction with the source apportionment results to better understand sources. The source profiles need to be improved, including systematic sampling to obtain profiles for specific sources, evaluating data to better understand rural and urban profiles, and refining methods to compare measurement and model results.	Coutant et al. (2002)

Table 1 (*Continued*)

Sampling method	Sampling site and timing	Chemical analysis and source apportionment model	Findings, in terms of source types and contribution	Conclusion or recommendation	Reference
Particulate Composition Monitor (PCM) sampler, Home-made Hi-Vol dichotomous and Thermo Andersen Hi-Vol sampler	An urban site in Atlanta, GA January of 2000 to December 2002	14 elements by XRF OC/EC by TOR 32 organics by GC-MS NO_3^-, SO_4^{2-} and NH_4^+ by IC and AC PMF and CMB-MM (molecular marker based)	Seven primary sources and three secondary sources were resolved by CMB-MM, while a total of nine primary and secondary factors were resolved by PMF. On average, 107% and 85% of $PM_{2.5}$ mass were explained by CMB-MM and PMF, respectively, with secondary aerosols handled differently in the above two methods. Four similar sources were resolved by both methods, with good correlation for road dust, but fair for gasoline exhaust and wood combustion.	CMB-MM diesel exhaust has very poor correlation with the PMF resolved diesel exhaust. However, the CMB-MM combined mobile source has improved correlation with the PMF result as compared with the diesel exhaust source. If only the winter data were included, the CMB-MM combined mobile source shows enhanced correlation with the PMF combined source, as compared with the single source of diesel exhaust or gasoline exhaust.	Ke et al. (2008)
DMPS (differential mobility particle sizer)	Urban monitoring site of Seattle, WA	Size distribution data PMF and UNMIX models	Residential wood burning has the highest contribution to the particle volume concentrations (48%), secondary aerosol (21%), diesel emissions (20%), motor vehicle (11%).	Hourly size distribution data can be used with UNMIX and PMF. Speciation data would be needed to confirm the source identifications.	Kim et al. (2004a)
PCM (particulate composition monitor), PM_{10} cyclone and WINS $PM_{2.5}$ impactor	Urban monitoring site of Atlanta, GA	16 elements by XRF OC/EC by TOR NO_3^-, SO_4^{2-} and NH^+ by IC PMF model	Sulfate-rich secondary aerosol I (50%), onroad diesel emissions (11%), nitrate-rich secondary aerosol (9%), wood smoke (7%), gasoline vehicle (6%), sulfate-rich secondary aerosol II (6%), metal processing (3%), airborne soil (3%), railroad traffic (3%), cement kiln/carbon-rich (2%), and bus maintenance facility/highway traffic (2%)	Temperature resolved carbon fraction data can be used to separate gasoline and diesel sources, as well as improve source apportionment results.	Kim et al. (2004b)
Harvard $PM_{2.5}$ Impactor ($HI_{2.5}$), Harvard $PM_{2.5}$ Personal Environmental ($HPEM_{2.5}$) Monitor	One urban sampling site and outdoor and indoor of 10 subject's residential homes in Seattle, WA September 2000 to May 2001	33 elements by XRF OC/EC/LAC by TOT Levoglucosan by GC-MS PMF model	Five sources contributing to the indoor and outdoor samples were identified: vegetative burning, mobile emissions, secondary sulfate, a source rich in chlorine, and a source of crustal-derived material. Vegetative burning contributed more $PM_{2.5}$ mass on average than any other source in all microenvironments, with average values estimated by PMF2 and PMF3, respectively, of 7.6 and 8.7 $\mu g/m^3$ for the outdoor samples, 4 and 5.3 $\mu g/m^3$ for the indoor samples, and 3.8 and 3.4 $\mu g/m^3$ for the personal samples.	Personal exposure to the combustion-related particles was correlated with outdoor sources, whereas exposure to the crustal and chlorine-rich particles was not. Personal exposures to crustal sources were strongly associated with personal activities, especially time spent at school among the child subjects.	Larson et al. (2004)
Partisol-FRM 2000, VAPS	Urban of Toronto, ON	15 elements by ICP-AES/MS OC/EC by TOT Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, K^+, Na^+, NH_4^+ and oxalate by IC PMF model	Coal combustion related to regional transport and secondary sulfate (26%), secondary nitrate related to both local and upwind sources of NOx and NH_3 (36%), secondary organic aerosols (SOA) formed from a variety of precursor organic emissions (15%), and motor vehicle traffic (10%)	Water-soluble, low molecular weight organic acids should be included in PMF to improve apportionment of secondary sulfates. More research is needed to determine the processes creating the organic acid source and how it related to secondary coal sources.	Lee et al. (2003)
Dual fine particle sequential sampler (DFPSS)	Residential area (8 km WNW of the downtown) Urban of Phoenix, AZ,	8 elements by XRF OC/EC by TOT UNMIX model	Gasoline engines (33±4%), diesel engines (16±2%), secondary SO_4^{2-} (19±2%), crustal/soil (22±2%), and vegetative burning (10±2%)	UNMIX and PMF did not agree in preliminary independent evaluation. Thus, they recommend a concurrent iterative application of UNMIX and PMF. Due to the increasing power and complexity of these models, they should be used with caution, experience, and cooperation.	Lewis et al. (2003)

Table 1 (*Continued*)

Sampling method	Sampling site and timing	Chemical analysis and source apportionment model	Findings, in terms of source types and contribution	Conclusion or recommendation	Reference
IMPROVE sampler	More than 40 sites in or around Grand Canyon summer and winter in 1992	40 elements (Na to Pb) by PIXE OC/EC by TOR NO_3^-, SO_4^{2-}, NH_4^+ by IC CMB model	About 50% of the measured particle sulfur is attributable to coal-fired power plants during summer and winter months, while in the winter months, about 50% of the particle sulfur may be associated with primary sulfur emissions from burning activity and urban emissions during the summer. A variable is responsible for over 30% of the extinction, which is predominately associated with burning activity during the winter and to burning transportation, and suspended soil during the summer months.	Most visibility impairment is associated with sulfates, carbonaceous material, and soil-related material	Malm and Gebhart (1997)
IMPROVE sampler	Urban site in Seattle, WA 1996-1999	25 elements by XRF, PESA and PIXE EC/OC (8 fractions) by TOR Cl^-, NO_3^- and SO_4^{2-} by IC PMF: 8 sources and 32 species UNMIX: 6 sources and 15 species CMB: 7 sources and 23 species	Vegetative burning (CMB 16%, UNMIX 37%, PMF 28%, inventory 28%) mobile sources (CMB 44%, UNMIX 28% [diesel 19%, gasoline 9%], PMF 22% [diesel 18%, gas 4%], inventory 23% [diesel 18%, gas 5%]) secondary sulfate (CMB 17%, UNMIX NA, PMF 18%, inventory NA) fuel oil (CMB NA, UNMIX 15%, PMF 10%, inventory 2%) soil (CMB 4%, UNMIX 6%, PMF 14%, inventory 3%) marine/sea salt (CMB 7%, UNMIX 12%, PMF 3%, inventory NA)	The modeling results between the models were similar, the overall results varied considerably between them. The models responded differently to certain elements such as Mn, As, and carbon fractions.	Maykut et al. (2003)
IMPROVE sampler	Rural site in Underhill, VT 1988–1995	27 elements by XRF, PESA and PIXE UNMIX: 7 sources and 11 species PMF: 11 sources and 27 species	Both models (PMF and UNMIX) reproduced the daily mass results reasonably well. The average mass of the source contributions were Midwest summer coal (PMF 53%, UNMIX 55%), wood smoke (PMF 15%, UNMIX 16%), midwest winter coal (PMF 8%, UNMIX 14%), east Coast oil (PMF 7%, UNMIX 8%), Canadian Mn sources (PMF 2%, UNMIX 4%), soil (PMF 4%, UNMIX 2%), and Canadian smelter (PMF 1%, UNMIX 1%). PMF also identified sources of Zn-Pb (7%), Cu (2%), Na-S (<1%), and salt (<1%).	Both models and both trajectory analyses should be used for inter-comparison of results and should not be considered stand-alone techniques at this time. Both techniques are sensitive to systematic errors and biases in the input data, including decisions made in the treatment of missing data and data below detection limits.	Poirot et al. (2001)
Harvard-type impactors	11 urban sites in Greater Cincinnati, OH 2002 and 2006	39 elements by XRF OC/EC by TOT, 8 fractions by TOR PMF and UNMIX	Application of UNMIX to the two data sets generated four source factors: combustion related sulfate, traffic, metal processing and soil/crustal. The PMF application generated six source factors derived from analyzing two carbon fractions and seven factors from temperature-resolved eight carbon fractions. The source factors (with source contribution estimates by mass concentrations in parentheses) are: combustion sulfate (46.8%), vegetative burning (15.8%), secondary sulfate (12.9%), diesel vehicle emission (10.9%), metal processing (7.5%), gasoline vehicle emission (5.6%) and soil/crustal (0.7%).	Diesel and gasoline vehicle emission sources were separated using eight temperature-resolved organic and elemental carbon fractions. Application of PMF to both datasets also differentiated the sulfate rich source from the vegetative burning source, which are combined in a single factor by UNMIX modeling.	Sahu et al. (2011)

Table 2
Summary of source apportionment studies of $PM_{2.5}$ conducted in China. The sampling instruments are also included.

Sampling method	Sampling site and timing	Chemical analysis and source apportionment model	Findings, in terms of source types and contribution	Conclusion or recommendation	References
High-volume $PM_{2.5}$ samplers	Two urban, two suburban and two rural sites in Guangzhou (Pearl River Delta region), China November/December in 2009	OC/EC by TOT 18 PAHs by GC–MS PMF model NOAA-HYSPLIT backward trajectory	The three sources identified were vehicular emissions (VE), biomass burning (BB), and coal combustion (CC), accounting for $11 \pm 2\%$, $31 \pm 4\%$, and $58 \pm 4\%$ of the total PAHs, respectively. CC replaced VE to become the most important source of PAHs in Guangzhou, reflecting the effective control of VE in recent years. The three sources had different contributions to PAHs with different ring sizes, with higher BB contributions ($75 \pm 3\%$) to four-ring PAHs such as pyrene and higher CC contributions ($57 \pm 4\%$) to six-ring PAHs such as benzo[ghi]perylene	Temporal variations of VE and CC contributions were probably caused by the change of weather conditions, while temporal variations of BB contributions were additionally influenced by the fluctuation of BB emissions. Source contributions also showed some spatial variations, probably due to the source emission variations near the sampling sites	Gao et al. (2013)
Partiso-Plus Model 2025 Sequential Air Sampler, TEOM	Urban roadside site in Hong Kong, China January–May 2004	OC/EC by TOR HYSPLIT backward trajectory model	The average concentrations for $PM_{1.0}$ and $PM_{2.5}$ were 35.9 ± 12.4 and 52.3 ± 18.3 μg/cm^3. Carbonaceous aerosols were the dominant species in fine particles, accounting for ~45.7% of $PM_{1.0}$ and ~44.4% of $PM_{2.5}$. During the study period, seven fine-particle episodes occurred, due to the influence of long range transport of air masses from mainland China. $PM_{1.0}$ and $PM_{2.5}$ responded in similar ways; i.e. with elevated mass and OC concentrations in those episode days. During the sampling period, $PM_{1.0}$ OC and EC generally behaved similarly to the carbonaceous aerosols in $PM_{2.5}$, regardless of seasonal variations and influence by regional pollutions. The low and relatively constant OC/EC ratios in $PM_{1.0}$ and $PM_{2.5}$ indicated that vehicular emissions were major sources of carbonaceous aerosols	$PM_{1.0}$ and $PM_{2.5}$ had the same dominant sources of vehicular emissions in winter, while in spring $PM_{2.5}$ was more influenced by $PM_{1-2.5}$ that did not form from vehicle exhausts. The $PM_{1.0}$ was a better indicator for vehicular emissions at the roadside site	Lee, Cheng, et al. (2006)
	Four urban sites in Beijing, China January, April, July and October in 2000	Elements by XRF OC/EC by TOT Organics and PAHs by GC–MS Cl^-, NO_3^- and SO_4^{2-} by IC PMF and HYSPLIT model	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 Ca values of yellow dust enable it to be distinguished from road dust	The PMF method resolved 82% of $PM_{2.5}$ mass concentrations and showed excellent agreement with a previous calculation using organic tracers in a chemical mass balance (CMB) model. The present study is the first reported comparison between a PMF source apportionment model and a molecular marker-based CMB in Beijing (Zheng et al., 2005)	Song et al. (2006a)
Medium-volume sampler	Five sites in urban of Ordos, Inner Mongolia Autonomous Region, China September 2005	17 elements by ICP-AES OC/EC by TOR Cl^-, NO_3^- and SO_4^{2-} by IC PCA model HYSPLIT backward trajectory model	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%)	Potential Source Contribution Function (PSCF) analysis showed that for each source category, PM_{10} and $PM_{2.5}$ had similar potential source areas	Wang et al. (2012)

Mini-volume with $PM_{2.5}$ cut cyclone	Three urban and one semi-rural sites in Guangzhou, China August–September 2004	18 elements by ICP-MS OC/EC by TOR Cl^-, NO_3^-, SO_4^{2-} and NH_4^+ by IC EF model MLR model	The average concentration of $PM_{2.5}$ (98 μg/m^3) in Guangzhou Enrichment factors (EF) for elements are calculated to indicate that elements of anthropogenic origins (Zn, Pb, As, Se, V, Ni, Cu and Cd) are highly enriched with respect to crustal composition (Al, Fe, Ca, Ti and Mn). Ambient and source data are used in the multi-variable linearly regression analysis for source identification and apportionment, indicating that major sources and their apportionments of ambient particulate aerosols in Guangzhou are vehicle exhaust (38.4%) and coal combustion (26.0%)	The high loadings of carbonaceous aerosol (OC and EC) are observed in Guangzhou and the OC/EC ratios exceed 2, indicating the presence of secondary organic aerosol in Guangzhou. The major fractions of sulfate at four monitoring sites are NSS-sulfate (accounted for over 90% of total sulfate), also indicating a substantial anthropogenic origin	Wang et al. (2006)
IMPROVE sampler	Four urban sites in Beijing, China January, April, July and October in 2000	Elements by XRF OC/EC by TOT Orgaincs and PAHs by GC–MS Cl^-, NO_3^- and SO_4^{2-} by IC CMB model	Carbonaceous aerosols and major ions (sulfate, nitrate and ammonium) constituted 69% of $PM_{2.5}$ mass on average. The major sources of $PM_{2.5}$ mass in Beijing averaged over five sites on an annual basis were determined as dust (20%), secondary sulfate (17%), secondary nitrate (10%), coal combustion (7%), diesel and gasoline exhaust (7%), secondary ammonium (6%), biomass aerosol (6%), cigarette smoke (1%), and vegetative detritus (1%). The lowest PM2.5 mass concentration was found in January (60.9 μg/m^3), but the contribution of carbonaceous aerosol to $PM_{2.5}$ mass was maximal during this season, accounting for 57% of the mass. During cold heating season, the contributions from coal combustion and biomass aerosol to $PM_{2.5}$ mass increased, accounting for 20.9% of fine particle mass in October and 24.5% in January. The contribution of the biomass aerosols peaked in the fall	In April 2000, the dust storm was so significant that constituted 36% of $PM_{2.5}$ mass. Six sources of OC in $PM_{2.5}$, including diesel and gasoline exhaust, biomass aerosol, coal combustion, dust, vegetative detritus, and cigarette smoke, were identified with the chemical speciated results in combination with CMB analysis of fine particulate matter from five sites during four seasons in Beijing. These sources showed distinct seasonal trends. Levoglucosan, a unique tracer for biomass burning, was not measured in any July samples, indicating that biomass burning was not active at this time in Beijing	Zheng et al. (2005)

Bai, Liu, Chen, & Chen, 2009; Lee, Cheng, et al., 2006; Wang, Huang, Gao, Gao, & Wang, 2002; Wang, Niu, Liu, & Wang, 2002; Wang et al., 2005; Wang, Bi, Sheng, & Fu, 2006; Wei et al., 1999; Xu et al., 2002; Yang et al., 2005, 2011; Ye et al., 2003; Zhou et al., 2009). The $PM_{2.5}$ standards of China are 15 and 35 $\mu g/m^3$ for annual and 24-h average, respectively. Many studies further investigated the sources of $PM_{2.5}$ in China (Cao, Huang, et al., 2012; Cheng et al., 2011; Gao et al., 2013; He et al., 2001; Huang et al., 2006; Song, Xie, et al., 2006; Song, Zhang, et al., 2006; Wang, Zhuang, et al., 2008; Wang et al., 2012; Yu et al., 2013; Zhang et al., 2012, 2013; Zheng et al., 2002). The major sources of $PM_{2.5}$ in urban areas of China include motor vehicles, coal combustion, secondary aerosols, and industrial sources, which are very similar to what found in the U.S. during the 1980–1990s. However, northern China continuously suffers dust storms that prevail from early winter to spring. It was reported that the dust alone contributed 36% to $PM_{2.5}$ mass (Zheng et al., 2005), which is so far uncontrollable. Those reviewed Chinese studies, basically using the same sampling and analysis techniques as those in the U.S., provided valuable data for PM pollution control in China. However, how to combine the current data obtained from scattered locations to form a nation-wide network as has been achieved in the U.S. (e.g. the IMPROVE and CSN program) is the current challenge.

4. Visibility effects of $PM_{2.5}$

4.1. Effect of $PM_{2.5}$ on visibility

The elevated levels of $PM_{2.5}$, coming along with the fast economic growth and increased number of vehicles in China, have caused serious visibility problems in big cities such as Beijing. A visibility of <200 m on December 1st of 2004 has been reported, when the $PM_{2.5}$ was as high as 300 $\mu g/m^3$ (Sun, Zhuang, Tang, Wang, & An, 2006). More recently, in January 2013, $PM_{2.5}$ was measured to be as high as 500–800 $\mu g/m^3$ in Beijing, which resulted in a visibility of <100 m.

In the U.S., in order to improve the visibility in 156 national parks and wildness areas and to better understand the visibility effects of PM, the IMPROVE program was initiated in 1985 under CAA of USEPA, which mainly investigated the physio/chemical/optical properties of the aerosol, characterized spatial and temporal air quality patterns, and assessed the causes responsible for visibility impairment. Beginning in 2000, the urban monitoring data from the CSN program were included in the IMPROVE program. Regional Haze Rule (RHR), promulgated in 1999 by USEPA in response to the CAA mandate, has planned to reduce PM emission to reach natural haze conditions in these protected areas by 2064.

Visibility impairment is caused by light scattering and absorption by suspended particles and gases. There has been strong and consistent evidence that $PM_{2.5}$ is the overwhelming source of visibility impairment in both urban and remote areas (USEPA, 2009b). Ambient particles have such components as primary and secondary organics, inorganic salts (e.g. sulfate, nitrate, chloride and sodium), inorganic carbon, and elements. Elemental carbon and certain crustal minerals are the common components of particles that absorb light. All other components of particles scatter light, and generally light scattering is the largest light extinction components. Although a larger particle scatters more light than a similarly shaped smaller particle of the same composition, the light scattered per unit of mass is greatest for particles with diameters approximately within 0.3–1.0 μm (USEPA, 2009b). Particles in this size range are also most difficult to remove (see Section 6).

Pilinis, Seinfeld, and Grosjean (1989) pointed out that the ambient aerosols exhibit similar behavior to single component salts, including the deliquescence and hysteresis processes. The authors predicted that the deliquescence relative humidity (RH) of urban aerosols was about 60%, a common ambient condition for coastal cities. Particles composed of water soluble sulfate, nitrate, sodium chloride, etc. often show hygroscopic property, i.e. the water intake onto the particles will be a function of RH (Chen, Tsai, Chou, et al., 2010). With absorbing water by the chemical constituent of a particle, the particle becomes larger when RH increases, resulting in increased light scattering. If the size-resolved chemical composition of particles is available, accurate light extinction can be obtained. Light extinction can be reasonably estimated using routinely available PM speciation data and relatively simple algorithms, which multiply the concentration of each major $PM_{2.5}$ species by its dry extinction efficiency and a water growth term that accounts for hygroscopic species in particles. This estimation allows visibility impairment to be associated with each major $PM_{2.5}$ component. There are five major $PM_{2.5}$ components responsible for visibility impairment: SO_4^{2-} (usually assumed to be ammonium sulfate), NO_3^- (usually assumed to be ammonium nitrate), OC, EC, and crustal material (also known as fine soil).

4.2. Method for indentifying the visibility impairment sources of $PM_{2.5}$ by the USEPA

The following is a specific example showing how the visibility effect of $PM_{2.5}$ was studied in the U.S. (USEPA, 2009b). To better understand the causes of haze in remote areas, a total of 610 samples were collected from 70 monitoring sites in the western U.S. during the worst haze periods from 2001 to 2003. Elemental composition was used to assess the likelihood that the particles were associated with long-range transport from Asia. A regression analysis at each site between particle concentrations and coincident local wind speeds was used to generate site-specific estimates of local windblown particles for each sample period. Finally, backward trajectory analysis combined with maps constructed of wind erosion potential (i.e. developed by combining soil types and land cover classifications) were used in a manner similar to the weighted emissions potential analysis to identify the likelihood of regionally transported wind-blown particles as the source. To be noted, these assessments were conducted on each of the 610 so-called “worst particle haze days” at the 70 monitoring sites to classify each day by its likely contributions from Asian, local windblown, upwind transport and undetermined. The undetermined category includes those sample periods that failed to be classified into one of the other three source categories, suggesting that mechanically suspended dust activities such as unpaved road dust, agricultural, construction and mining activities may be responsible.

The visibility study in the U.S. has the following conclusions. Sulfate is the dominant source of regional haze in the eastern U.S. (>50% of the particulate light extinction) and an important contributor to haze elsewhere in the U.S. (>20% of particulate light extinction). EC and OC have the highest dry extinction efficiencies of the major $PM_{2.5}$ species and are most responsible for haze, especially in the Northwestern U.S., though absolute concentrations are as high as those in the eastern U.S. Both EC and OC are products of incomplete combustion of fuels, including gasoline and diesel emissions and open biomass burning. $PM_{2.5}$ crustal material and coarse mass are significant contributors to haze for remote areas sites in the arid Southwestern U.S., where they contribute a quarter to a third to the haze formation, with coarse mass often contributing twice that of fine soil (USEPA, 2009b). Again, due to the long range transport of fine particles, uniformly deployed sampling and monitoring sites are needed to track the sources of fine particles both temporally and spatially, so that causes of haze and visibility impairment can be better understood.

5. Health effects of $PM_{2.5}$

5.1. General understanding from studies in the U.S.

Numerous epidemiologic and toxicological studies have suggested that exposure to $PM_{2.5}$ leads to adverse health effects, particularly cardiovascular and respiratory diseases, as well as premature death (Pope & Dockery, 2006; USEPA, 2009b). According to a literature review coordinated by the U.S. Environmental Protection Agency (USEPA, 2009b), there exists a causal relationship with short- and long-term $PM_{2.5}$ exposure for cardiovascular effects and mortality; while a causal relationship is likely to exist between $PM_{2.5}$ exposure and respiratory effects. In addition, long-term $PM_{2.5}$ exposure may also be responsible for certain reproductive outcomes and cancers (USEPA, 2009b). However, the above conclusion is mainly established on studies performed in developed countries, where characteristics of $PM_{2.5}$ and socioeconomic status are quite different from those in developing countries. Therefore, results obtained in western countries cannot be simply extrapolated to developing countries such as China (HEI, 2010). Although abundant air pollution-related health studies have been conducted in China since the 1990s, as recently reviewed by Chen, Kan, Chen, Jiang, and Hong (2011), Kan, Chen, and Tong (2012), and Shang et al. (2013), most studies focused on PM_{10}, SO_2, and NO_2 while paid little attention to $PM_{2.5}$. This is partially due to the lack of routine monitoring data, since $PM_{2.5}$ has not been listed as a criteria pollutant in the Chinese Ambient Air Quality Standards until 2012.

5.2. Results from studies in China

There are only a few epidemiological studies on the health effects of short-term exposure to $PM_{2.5}$ in the Chinese population, with more studies on mortality than morbidity (Figs. 4 and 5). To examine the effects on different health outcomes of an increase of $PM_{2.5}$ mass concentration (i.e. effect estimates), these studies primarily used time-series Poisson regression with generalized additive models as the statistical method. In addition, some studies removed the confounding factors of $PM_{2.5}$ such as temporal or seasonal trends, meteorological conditions (e.g. temperature and relative humidity), and gaseous pollutants (e.g. SO_2 and NO_2) by using different smooth functions and multi-pollutant models.

In general, these Chinese studies demonstrated positive and statistically significant associations between short-term exposure to $PM_{2.5}$ and excessive risk for morbidity (e.g. hospital admissions and emergency department visits) and mortality from cardiovascular and respiratory diseases, as well as total non-accidental mortality (Figs. 4 and 5). Note that the reported spectrum of $PM_{2.5}$-related adverse health effects for Chinese is the same as what found in developed countries (USEPA, 2009b and references therein). Also note that all cities except Hong Kong and Taipei had $PM_{2.5}$ concentrations of >50 $\mu g/m^3$, often greatly exceeding the current Chinese Ambient Air Quality Standards, as well as the WHO, U.S., and European Union standards (Table 3). Among the morbidity studies (Fig. 4), the highest effect estimate was observed for hypertension, with an odds ratio of 1.084 per 10 $\mu g/m^3$ increase of $PM_{2.5}$. However, two studies observed no significant association between $PM_{2.5}$ and certain morbidity, which may be due to insufficient sample size (Chan et al., 2006). For the mortality studies (Fig. 5), the effect estimates for total, cardiovascular, and respiratory mortality ranged from 0.00 to 0.90%, 0.26 to 1.22%, and 0.07 to 0.97% per 10 $\mu g/m^3$ increase of $PM_{2.5}$, respectively. The associations between $PM_{2.5}$ and cardio-respiratory mortality were generally stronger than the associations with total mortality, with the mortality risk of respiratory diseases relatively higher than that of cardiovascular diseases. This observation is consistent with results from North America (USEPA, 2009b) and Europe (Samoli et al., 2013). Among the six cities studied, Guangzhou and Shenyang seemed to have higher effect estimates than other cities. Note that one study

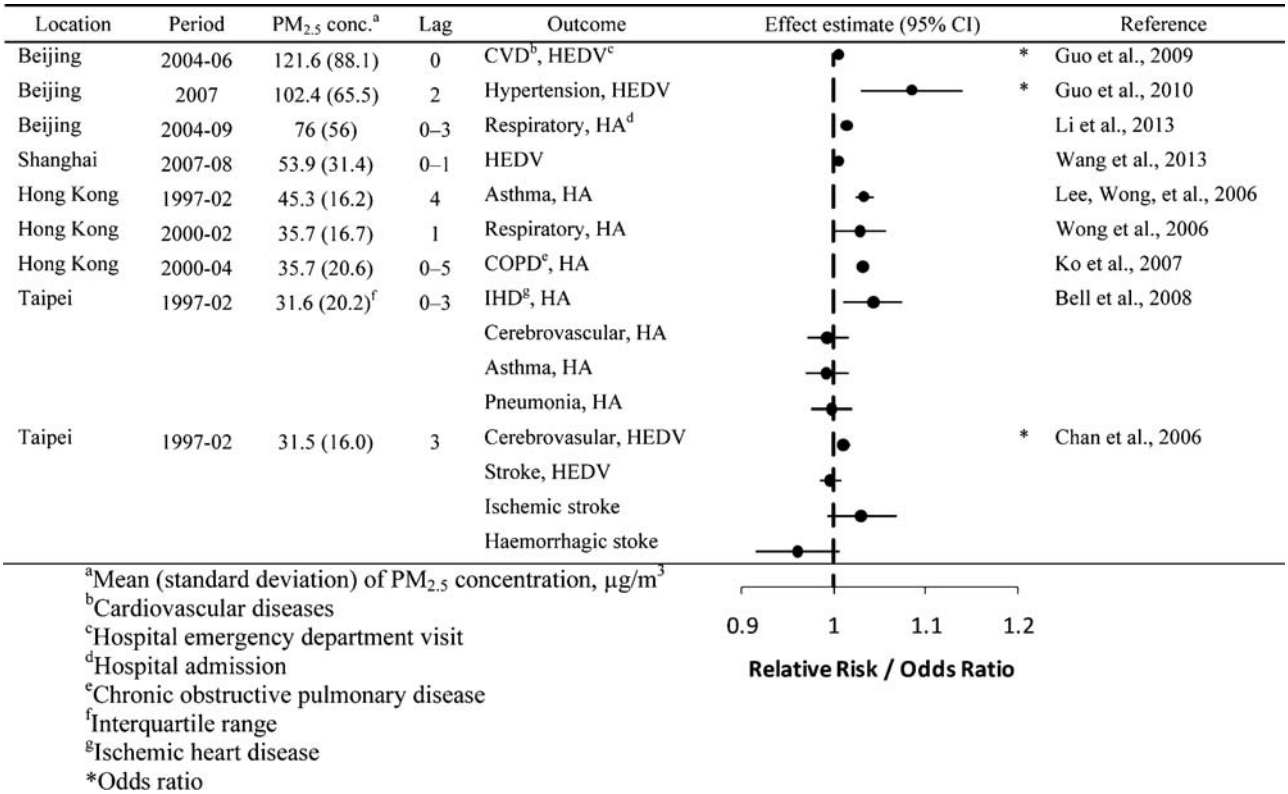

Fig. 4. Estimated relative risk/odds ratio and 95% confidence interval (CI) of cause-specific *morbidity* associated with each 10 $\mu g/m^3$ increase in $PM_{2.5}$ (Bell, Levy, & Lin, 2008; Guo, Jia, Pan, Liu, & Wichmann 2009; Guo et al., 2010; Ko et al., 2007; Lee, Wong, & Lau 2006; Wong et al., 2006).

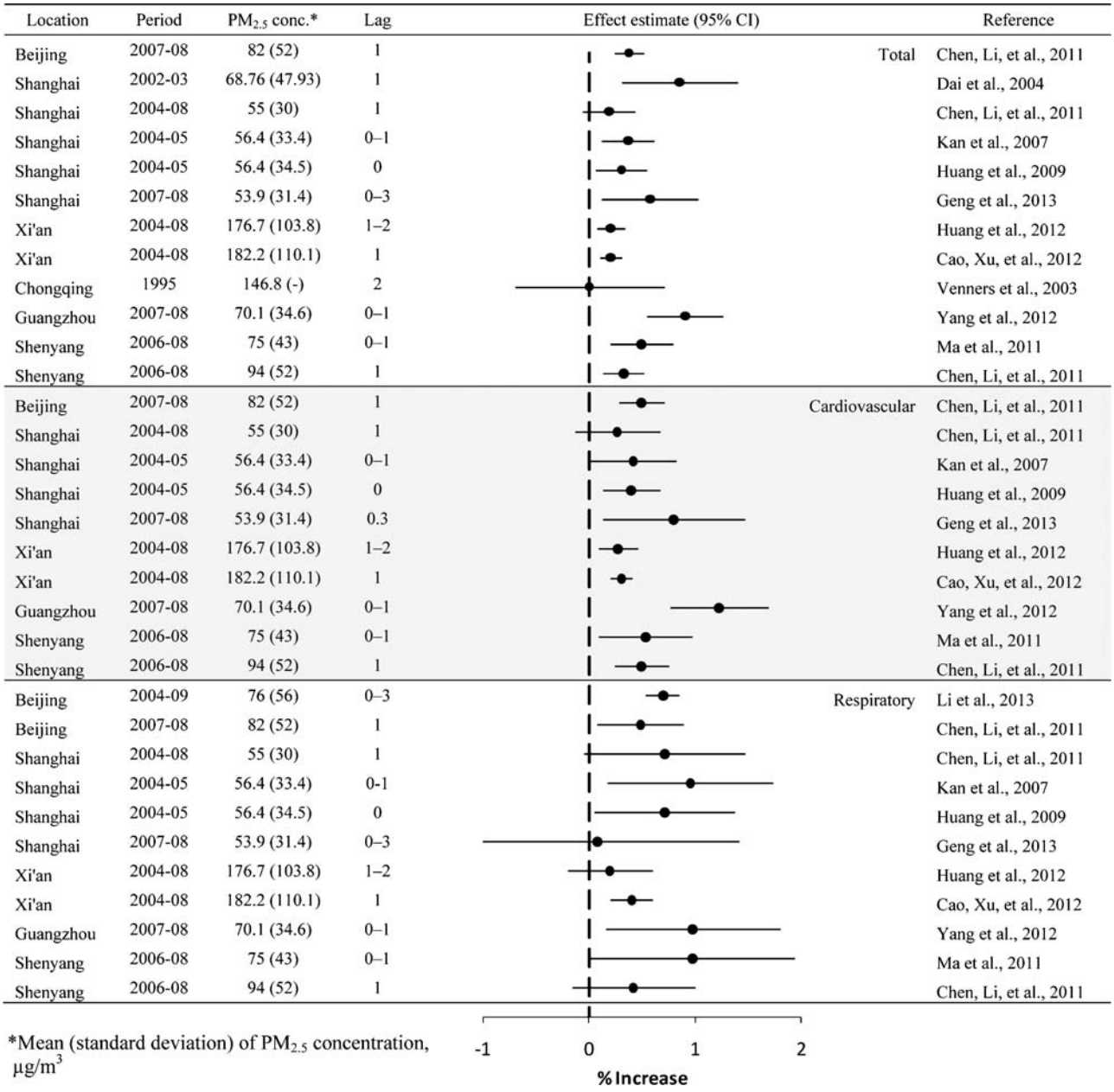

Fig. 5. Estimated percentage increase and 95% confidence interval (CI) in total (nonaccidental) and cause-specific *mortality* associated with each 10 μg/m^3 increase in $PM_{2.5}$ (Chen, Li, et al. 2011; Geng et al., 2013; Huang et al., 2009; Yang et al., 2012).

reported negative association between $PM_{2.5}$ exposure and daily mortality in Chongqing (Venners et al., 2003), which could result from the unadjusted confounders of $PM_{2.5}$ such as SO_2 and the relatively short study period.

By stratifying samples into different categories, several studies examined factors that could possibly modify the effect estimates for total mortality. As shown in Fig. 6, these potential effect modifiers include age, gender, education level, and season. Seniors (≥65 yr or

Table 3
World Health Organization (WHO) interim target (IT), WHO Air Quality Guideline (AQG), U.S. Environmental Protection Agency (USEPA), European Union (EU), and Chinese standard for $PM_{2.5}$.

$PM_{2.5}$ (μg/m^3)	WHO[a]				USEPA[b]	EU[c]	China[d]	
	IT-1	IT-2	IT-3	AQG			Grade 1	Grade 2
24-h average	75	50	37.5	25	35	–	35	75
Annual average	35	25	15	10	12	25	15	35

[a] *Source*: WHO (2006).
[b] *Source*: USEPA National Ambient Air Quality Standards (2012).
[c] *Source*: European Union Directive (2008).
[d] *Source*: Chinese Ambient Air Quality Standards (2012); Grade 1 applies to nature reserves, national parks, and other areas requiring special protection while Grade 2 applies to residential, cultural, industrial, and rural areas.

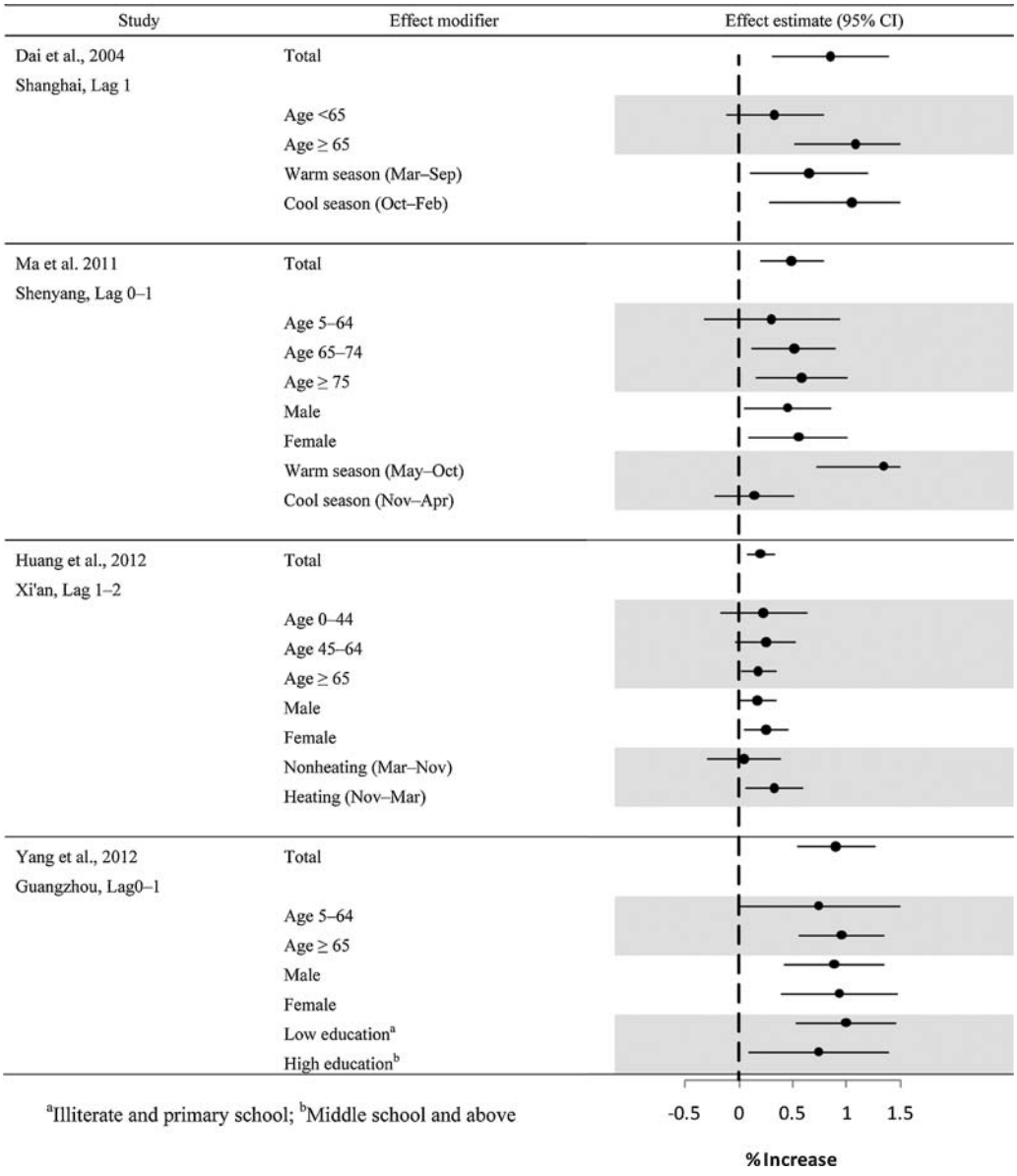

Fig. 6. Estimated percentage increase and 95% confidence interval (CI) in total (nonaccidental) mortality per 10 μg/m^3 increase in $PM_{2.5}$ by various effect modifiers.

≥75 yr), female, and those who with education attainment of primary school or below were found to have generally higher effect estimates of total mortality than their counterparts, though the difference was statistically insignificant. Women and seniors were further found to be at increased risk for cardiovascular and respiratory mortality when exposed to $PM_{2.5}$ (Ma et al., 2011). Similar to the studies in the U.S. (Franklin, Zeka, & Schwartz, 2007; Ostro, Broadwin, Green, Feng, & Lipsett, 2006; Schwartz, Dockery, & Neas, 1996), these results suggest that certain population subgroups are more susceptible to short-term exposure to $PM_{2.5}$ than others. Of additional interest is the seasonal variation of effect estimates. A stronger association between $PM_{2.5}$ and mortality was observed in warm season than cool season in Shanghai (Dai, Song, Gao, Chen, & Hu, 2004) while the opposite was reported for Shengyang (Ma et al., 2011) and Xi'an (Huang et al., 2012). This inconsistency is most likely due to the different seasonal variation of $PM_{2.5}$ emission/sources and exposure pattern in different cities. For example, the highest $PM_{2.5}$-induced respiratory morbidity and mortality in winter in Beijing (Li et al., 2013) coincides with the fact that Beijing has the highest emissions of toxic $PM_{2.5}$ constituents such as sulfur and metals in winter (Sun et al., 2004). Different season-dependent effect estimates were also found in different U.S. and European cities. For U.S., the highest effects were observed in spring on a national basis (Franklin, Koutrakis, & Schwartz, 2008; Zanobetti & Schwartz, 2009) while warm months gave higher effects than cold months in Europe (Samoli et al., 2013).

Another point of note is the comparison of mortality effect estimates between China and developed countries. A recent meta-analysis based on six Chinese cities reported that each 10 μg/m^3 increase in short-term exposure to $PM_{2.5}$ was associated with a 0.38% (95% confidence interval (CI): 0.31–0.45), 0.44% (95% CI: 0.33–0.54), and 0.51% (95% CI: 0.30–0.73) increase in total, cardiovascular, and respiratory mortality, respectively (Shang et al., 2013). Interestingly, these effect estimates are slightly lower than what reported in multi-city studies and meta-analyses in developed countries (see Fig. 7). This observation could suggest the nonlinear nature of the exposure–response relationships at high $PM_{2.5}$ concentrations (see the discussion in the following paragraph). It could also be explained by the different chemical composition of $PM_{2.5}$ in China vs. developed countries. Compared

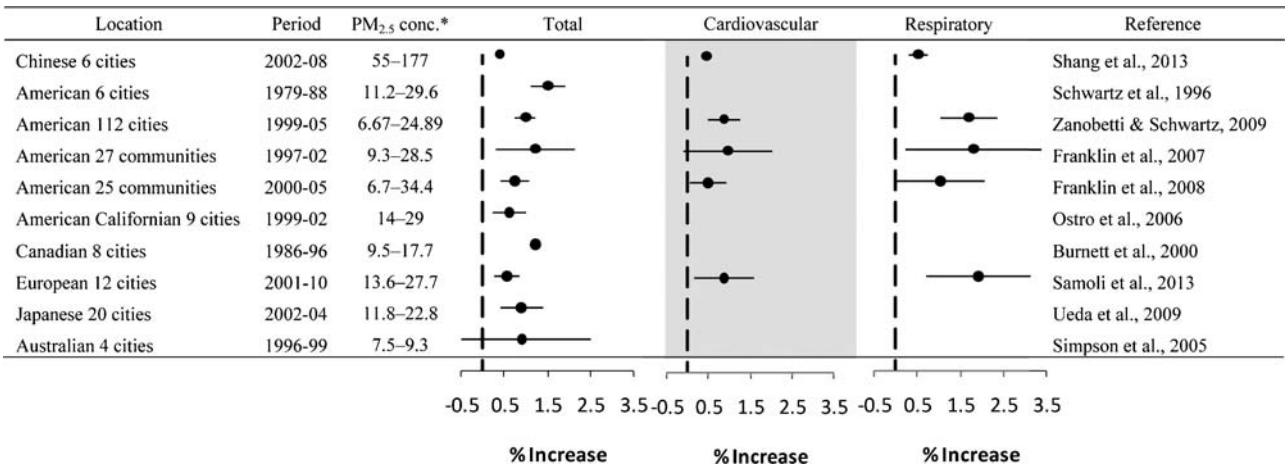

Fig. 7. Comparison of pooled estimates of percentage increase and 95% confidence interval in total (nonaccidental) and cause-specific mortality per 10 μg/m^3 increase in $PM_{2.5}$ between China and developed countries (Simpson et al., 2005).

with developed countries, currently a larger fraction of $PM_{2.5}$ pollution in China is due to coal combustion and fugitive dust with a less amount from vehicle emission (Cao, Shen, et al., 2012; Kan et al., 2007; Yang et al., 2011). On the other hand, research has shown that $PM_{2.5}$ from vehicle exhaust caused higher risk for mortality than that from coal combustion and crustal materials (Laden, Neas, Dockery, & Schwartz, 2000). Therefore, $PM_{2.5}$ in China might be less toxic than that in developed countries, thus giving lower effect estimates. Other common explanations including different population susceptibility to $PM_{2.5}$, age structures, population density, exposure patterns, dietary habits, and cultural background are also possible. Moreover, the use of different statistical methods (e.g. statistical models, smooth functions, and the amount of smoothing) and different lag periods and structures (e.g. single, multiple, or cumulative, see Figs. 5 and 6) could also affect effect estimates (Burnett & Goldberg, 2003; Dominici, McDermott, Zeger, & Samet, 2002; Peng, Dominici, & Louis, 2006; Ueda, Nitta, Ono, & Takeuchi, 2009).

A few Chinese studies also explored the shape of exposure–response relationships of $PM_{2.5}$ against mortality and morbidity, which is critical for setting environmental policy and air quality guidelines. The observed exposure–response relationships were generally linear and positive, with no evidence of threshold below which $PM_{2.5}$ had no adverse health effects (Cao, Xu, Xu, Chen, & Kan, 2012; Dai et al., 2004; Wang et al., 2013), which is consistent with western studies (Pope & Dockery, 2006; Samoli et al., 2013). However, higher concentration of $PM_{2.5}$ does not necessarily mean higher health risks. In some cases, health risks did not increase monotonically with $PM_{2.5}$, particularly at high $PM_{2.5}$ concentrations, suggesting somewhat nonlinear relationships (Kan et al., 2007; Li et al., 2013). One possible reason is that vulnerable individuals may already die at low levels of $PM_{2.5}$ concentrations, making the rest population more resistant to $PM_{2.5}$ at high concentrations (Wong, Vichit-Vadakan, Kan, & Qian, 2008). Similar observation was also reported in western studies. For example, a higher exposure–response coefficient was consistently observed for communities with annual concentrations $\leq$15 μg/m^3 than >15 μg/m^3 in an U.S. 27 communities study (Franklin et al., 2007). Pope et al. (2009) also found that the exposure–response relationship between cardiovascular mortality and $PM_{2.5}$ is relatively steep at low levels of exposure and tend to become flat at higher exposures. Nevertheless, the general observation of no threshold even at very low $PM_{2.5}$ concentrations indicates that continuous improvement of $PM_{2.5}$ pollution would warrant more public health benefits.

6. Control of $PM_{2.5}$ emission from coal-fired power plants

As mentioned earlier, coal combustion is one of the major sources of $PM_{2.5}$ in China. Electric power industry, the largest coal-consuming sector nowadays in China, accounts for the highest emission of particulate matter among all industries (Yi, Hao, Duan, Li, & Guo, 2006; Zhao, Wang, Nielsen, Li, & Hao, 2010). Technologies for controlling particulate matter emission from stationary sources such as coal-fired power plants are well established, as nicely reviewed by Henry, Podolski, and Saxena (1985), Darcovich, Jonasson, and Capes (1997), and Mizuno (2000). Major conventional particle emission control devices (PECD) include cyclones, wet scrubbers, electrostatic precipitators (ESP), and baghouses. Their brief description, advantages, disadvantages, and remarks for controlling $PM_{2.5}$ emission are listed in Table 4. Although generally effective against large particles, these conventional PECD have unsatisfying performance against fine particles such as $PM_{2.5}$. Therefore, a situation exists where the particles of greatest health concern are collected with the lowest efficiency (Mukhopadhyay, 2009).

6.1. Conventional particle emission control devices

Cyclones separate particles from the gas spinning in a vortex by centrifugal forces. Due to their simple structure and low cost, cyclones are the most common type of PECD. However, since particle inertia decreases with particle size, industrial-scale cyclones usually have low collection efficiency for fine particles such as $PM_{2.5}$. In fact, USEPA recommended that all industrial and commercial sources currently controlling PM using cyclones or multi-cyclones should be upgraded to high-efficiency PECD to collect the fine fraction of PM (USEPA, 2006). Nevertheless, cyclones are typically useful as pre-cleaners placed upstream of other PECD to reduce particulate loadings and larger abrasive particles (Darcovich et al., 1997).

In another conventional technology, wet scrubbers, utilize sprays of liquid to assist the removal of particles from the carrier gas stream. Their most important feature is that both PM and gaseous pollutants such as SO_2 and NOx can be removed simultaneously. For this reason, wet scrubber is one component in wet flue gas desulfurization (WFGD), the most important SO_2 control measure in Chinese thermal power plants (Wang, Song, Yao, & Chen, 2008). Although effective against gaseous pollutants, wet scrubbers have several disadvantages including high power requirements, metal corrosion, and effluent treatment. More importantly, they are not

Table 4
Removal efficiency of $PM_{2.5}$, PM_{10}, and TSP from coal-fired power plants in China.

Boiler type	Capacity (MW)	Load (%)	PECD	Collection efficiency (%)			References
				$PM_{2.5}$	PM_{10}	TSP	
Grate	29	–	Wet scrubber	71.73	82.37	94.08	Zhao et al. (2010)
PC	–	100	ESP	90.6	98.5	99.36	Liu et al. (2003)
CFB	–	–	ESP	91.4	94.3	96.63	Xu et al. (2004)
PC	50	80	ESP	95.58	98.2	99	Yi et al. (2006)
PC	600	90	ESP	99.16	99.62	99.89	Yi et al. (2006)
PC	600	100	ESP	96.75	98.58	99.76	Yi et al. (2006)
PC	200	–	ESP	78.05	95.34	98.47	Xu et al. (2004)
CFB	15	70	ESP	87.31	92.97	98.47	Yi et al. (2006)
PC	–	75–100	ESP	99.26–99.60	99.78–99.83	–	Liu et al. (2009)
PC	50	–	ESP	90.88	94.39[a]	99.53[b]	Zhao et al. (2010)
PC	50	–	ESP	97.86	99.16[a]	99.61[b]	Zhao et al. (2010)
PC	125	–	ESP	94.62	98.7[a]	99.37[b]	Zhao et al. (2010)
PC	165	–	ESP	94.44	98.22[a]	99.54[b]	Zhao et al. (2010)
PC	200	–	ESP	96.24	98.81[a]	99.79[b]	Zhao et al. (2010)
PC	200	–	ESP	92.65	95.71[a]	99.11[b]	Zhao et al. (2010)
PC	200	–	ESP	96.84	98.39[a]	99.74[b]	Zhao et al. (2010)
PC	300	100	WFGD	53.89	89.11[a]	74.5	Wang, Song, et al. (2008)
PC	165	–	WFGD	52.7	73.03[a]	92.82[b]	Zhao et al. (2010)
PC	200	–	WFGD	46.34	78.22[a]	90.46[b]	Zhao et al. (2010)
PC	125	80	ESP + WFGD	95.68	98.88	99.75	Wang et al. (2011)
PC	215	92	ESP + WFGD	97.11	98.93	99.75	Wang et al. (2011)
PC	300	83	ESP + WFGD	97.41	99.26	99.81	Wang et al. (2011)
PC	600	82	ESP + WFGD	98.47	99.61	99.86	Wang et al. (2011)
PC	600	100	ESP + WFGD	97.73	99.41	99.85	Wang et al. (2011)
PC	1000	85	ESP + WFGD	98.03	99.62	99.88	Wang et al. (2011)
PC	220	95	Baghouse	99.72	99.76	99.94	Yi et al. (2006)
PC	220	95	Baghouse	99.7	99.57	99.94	Yi et al. (2008)

PECD, particle emission control devices; PC, pulverized coal; CFB, circulating fluidized bed; WFGD, wet flue gas desulphurization.
[a] $PM_{2.5–10}$.
[b] $PM_{>10}$.

effective in controlling PM emissions, to say nothing of $PM_{2.5}$. For example, the $PM_{2.5}$ collection efficiency of wet scrubbers and WFGD in China was found to be only ~70% and ~50%, respectively (see Table 5). Another study even reported significant leak of fine particles and volatile metals during WFGD operation (Lu, Wu, & Pan, 2010).

Electrostatic precipitators (ESP) are the dominant PECD, currently installed in more than 90% coal-fired power plants in China (Yao, Li, Xu, Zhuo, & Song, 2009) and undergoing fast development (Lin & Liu, 2009). ESP utilizes electrostatic forces to facilitate the collection of particles. In general, both large (>1 μm) and ultrafine particles (<0.1 μm) can be removed effectively by ESP. However, intermediate-sized particles (e.g. $PM_{2.5}$) are most difficult to charge and consequently have the lowest removal efficiency by ESP (Hinds, 1999; Mizuno, 2000). This theory has been repeatedly verified by field measurements at Chinese thermal power plants, as many researchers observed significant increase in the mass fraction of $PM_{2.5}$ at the outlet of ESP compared with aerosol samples at the inlet (Liu, Fan, Zhou, Cao, & Cen, 2003; Liu et al., 2009; Xu et al., 2004; Yi et al., 2006; Zhao et al., 2010). In addition, the emission factor (i.e. the mass of emitted pollutant per unit fuel consumption) of $PM_{2.5}$ for power plants with ESP was larger than AP-42 data from the U.S. EPA (USEPA, 1999; Zhao et al., 2010), indicating that the $PM_{2.5}$ removal efficiency of ESP in China is lower than that in U.S. even 20 years ago. Although the use of ESP combined with WFGD generally gives higher collection efficiency for $PM_{2.5}$ of ~98% (Table 5), it is still much lower than the desired efficiency for fly ashes of 99.9% or above.

Baghouses, also known as fabric filters, collect particles from a gas by passing the stream through a porous textile fabric. The majority of the collected particles remain on the surface of baghouses, forming a layer of dust cake, which does the bulk of the filtration (Darcovich et al., 1997). When the dust cake is built up to a certain level, the fabric can be cleaned and regenerated, often by pulse jets (Mukhopadhyay, 2009). Particle capture mechanisms mainly include diffusion, interception, and impaction, with the first dominant for particles smaller than 0.05 μm and the later two dominant for particles larger than 0.5 μm. Particles with sizes in-between (0.05–0.5 μm) are too large for diffusion to be effective while too small for impaction or interception to be effective and therefore, have the minimum filtration efficiency (Hinds, 1999). Nevertheless, baghouses show the highest collection efficiency for $PM_{2.5}$ of ~99.7% among the three types of conventional PECD (see Table 5). Although there are currently only <10% thermal power plants equipped with baghouses, as the new Chinese Ambient Air Quality Standard starts to regulate $PM_{2.5}$ (SEPAC, 2012), baghouses are considered to be a retrofit or even replacement option by more and more Chinese thermal power plants, with a total market of $2.35 billion in China in 2008.

6.2. *Innovated technology for particulate emission control devices (PECDs)*

In order to better control the PM emissions from coal-fired power plants, technologies are being continuously innovated (Jaworek, Krupa, & Czech, 2007; Peukert & Wadenpohl, 2001). Table 5 summarizes some of the most important ones. The first example is the pretreatment of flue gases before PECD, including flue gas conditioning and the use of particle agglomerators. Various flue gas conditioning techniques have been reviewed by Shanthakumar, Singh, and Phadke (2008). By mixing different conditioning reagents such as NH_3, SO_3, and water/steam with flue gases, moisture is adsorbed onto particles, increasing their electrical conductivity and facilitating agglomeration, which enhances collection efficiency of ESP with reduced back-corona discharge and particle re-entrainment. The second example is particle agglomerators, whose essential idea is to increase the mean size of PM, thus making their collection by PECD easier. Different particle agglomeration techniques have been proposed (Yao et al., 2009), among which acoustic (Gallego-Juarez et al., 1999)

Table 5
Conventional particle emission control devices (PECD), their improved technology, and hybrid systems for control of PM emission from coal-fired power plants.

Device	Description	Features	Remarks	References
Conventional PECD				
Cyclone	Particle collection by centrifugal forces in a confined vortex	High efficiency for large particles, low cost, simple structure, small space; low efficiency for small particles	Not recommended for $PM_{2.5}$ removal	Darcovich et al. (1997)
Electrostatic precipitator (ESP)	Particle collection by electrostatic forces in an electric field	High efficiency for large and very small particles, low pressure drop, and low cost; low efficiency for small particles	Low efficiency for $PM_{2.5}$ removal	Mizuno (2000) and Jaworek et al. (2007)
Baghouse	Particle collection by porous filter media and dust cake	High collection efficiency; high cost, high pressure drop, large space requirement, temperature limitation	High efficiency for $PM_{2.5}$ removal	Mukhopadhyay (2009)
Wet scrubber	Particle collection by contact with a spray of liquid	Simultaneous removal of dust and gas, small space; very high pressure drop, high cost, corrosion, effluent treatment	Low efficiency for $PM_{2.5}$ removal	Darcovich et al. (1997) and Mukhopadhyay (2009)
Improved technology				
Flue gas conditioning	Injection of reagents such as NH_3 and SO_3 to cause moisture adsorption onto particles	Decreased resistivity of fly ash, enhanced particle agglomeration and cohesion, cost effective	Increased collection efficiency of PECD	Jaworek et al. (2007) and Shanthakumar et al. (2008)
Acoustic agglomerator	Enhanced particle coagulation by high intensity sound waves	Enhanced efficiency of PECD due to increased mean particle size	Limited industrial application due to high energy consumption	Gallego-Juarez et al. (1999)
Electrostatic agglomerator	Enhanced particle coagulation by bipolar/unipolar particle charging and AC/DC electric field	Enhanced efficiency of PECD due to increased mean particle size, agglomeration limited by charge depletion effect	Efficiency generally too low for industrial application	Watanabe et al. (1995) and Jaworek et al. (2007)
Multi-stage ESP	Particle charging and collection separated into different stages	Increased efficiency, back-corona discharge eliminated	Particle re-entrainment still a problem	Masuda and Hosokawa (1984) and Jayaram et al. (1996)
Wide-plate ESP	ESP with widened plate spacing	Higher applied voltage and electric field; increased power consumption	Increased collection efficiency of ESP, less effective for submicron particles	Chang and Bai (2000)
Electrode-modified ESP	Various modification of collection and discharge electrodes	Improved overall efficiency of ESP, particle re-entrainment, and back-corona discharge	Some designs particularly effective for $PM_{2.5}$ removal, but more verification needed	Jaworek et al. (2007) and references therein
Electrostatic-assisted baghouse	Particles first charged followed by conventional baghouse filtration	Increased efficiency, reduced pressure drop, and easy cleaning	High efficiency for $PM_{2.5}$ removal	Kwetkus (1997) and Lee et al. (2001)
Hybrid systems				
ESP + cyclone	Conventional cyclone with a central electrode and/or particle charging	Enhanced efficiency for fine particles at low flow rate; little effect at high flow rate	Low practical value unless small scale	Shrimpton and Crane (2001) and Li, Cai, and Dong (2003)
ESP + wet scrubber	Electrically charged dust particles and scrubbing droplets	Enhanced efficiency for fine particles, no back-corona discharge, lower pressure drop and water consumption; corrosion	Complementary device following the last stage of conventional ESP to remove submicron particles	Jaworek et al. (2006a) and references therein
ESP + baghouse	Simultaneous use of ESP and baghouse	Increased efficiency and flow rate, reduced pressure	Particularly effective for $PM_{2.5}$ and submicron particle removal	Chang (1992) and Miller (2003)

and electrostatic agglomerators (Watanabe et al., 1995) are most popular. However, both have limited industrial-scale applications, due to extremely high energy consumption and low efficiency, respectively.

As the two most widely used PECD in China, ESP and baghouses themselves also have drawn considerable research interest. Some technology improvement includes wide-plate ESP, multi-stage ESP, electrode-modified ESP, and electrostatic-assisted baghouses, as shown in Table 5. Widening ESP plate spacing and separating particle charging and collection into two or more stages successfully increase overall PM collection efficiency, but unfortunately they have limited effect on $PM_{2.5}$, as confirmed by field measurements in several Chinese thermal power plants, where multi-stage ESP with multiple electric fields were installed (Yi et al., 2006). This is mainly caused by the inevitable particle re-entrainment during electrode rapping. Jaworek et al. (2007) has reviewed various configurations of ESP with modified discharge and collection electrodes, which improve the inhomogeneous current distribution of traditional wire-to-plate ESP and thus have better control for fine particles. However, most designs require more experimental investigation and/or field measurement to confirm their performance. One example of electrode-modified ESP particularly promising for $PM_{2.5}$ control is the lentoid ESP. This concept was put forward the first time by several Chinese scholars

(Chen & Chen, 1998a,b; Wang, 1998), where the conventional collection plates were replaced by hollow collection electrodes with holes facing the discharge electrode. Under the lentoid electric field, charged particles are focused into hollow chambers, undergoing agglomeration by Coulomb force and turbulent flow and being collected efficiently. Compared with the conventional design, the lentoid ESP has much higher migration velocity with no back-corona discharge or particle re-entrainment. Besides, the wet-ESP has a potential to minimize particle re-entrainment and increase the collection efficiency (Lin et al., 2013). Improvement of filtration due to electrostatic effects has been well documented (Frederick, 1980; Wang, 2001), which lays the theoretical foundation of electrostatic-assisted baghouses. By charging incoming particles using a corona discharge, the collection efficiency of haghouses can be greatly increased, particularly for particles in the submicron size range. In addition, the electric forces cause particles to deposit primarily on the surface of baghouses, forming dendrite-like structure, which leads to lower pressure drop and more efficient pulse-jet cleaning (Henry et al., 1985; Jaworek et al., 2007).

In addition to technology innovation of each conventional PECD individually, the development of hybrid systems, which combines two or more types of conventional PECDs, also have raised intensive research interest. The most popular of those include electrocyclone, electroscrubber, and ESP-baghouse complex (Table 5).

The idea of electrocyclones is to impose an electric field inside a conventional cyclone, e.g. by adding a discharge electrode along the axis of the cyclone and particles can be either pre-charged or non-charged. Particles are collected mainly through two mechanisms, with large particles by centrifugal forces and small particles by electrostatic forces. However, there is usually trade-off between the two mechanisms in real application. Increasing flow rate decreases residence time and electrostatic effects and thus leads to little enhancement of $PM_{2.5}$ collection (Shrimpton & Crane, 2001). On the other hand, if gas velocity is too low, collection efficiency of large particles decreases. This trade-off often makes electrocyclones of low practical value in large-scale applications (Jaworek et al., 2007).

Unlike conventional wet scrubbers, electroscrubbers use spray droplets that are charged by corona discharges (Bologa, Paur, & Wäscher, 2001; Xu et al., 2003), induction (Metzler, Weiß, Büttner, & Ebert, 1997), and electrosprays (Jaworek, Balachandran, Lackowski, Kulon, & Krupa, 2006). Due to the additional electrostatic attraction/repulsion forces between dust particles and charged scrubbing droplets, electroscrubbers have high collection efficiency, especially for submicron particles. Compared with conventional wet scrubbers, they are also cheaper to operate, due to the lower water consumption and pressure drop. Because of these advantages, they have been recommended as a complementary PCED following the last stage of conventional ESP to help remove submicron particles (Jaworek, Balachandran, Krupa, Kulon, & Lackowski, 2006).

Hybrid systems that combine the advantages of both ESP and baghouses seem to be the most promising PECD for $PM_{2.5}$ control. Two famous examples are the compact hybrid particulate collector proposed by Electric Power Research Institute (Chang, 1992) and the advanced hybrid particle collector from Energy and Environmental Research Center (Miller, 2003). In the first example, a pulse jet baghouse and an ESP were used in-series while in the second example, baghosues and ESP were integrated into the same unit, providing collection efficiency of >99.99% for all particle sizes ranging from 10 nm to 50 μm.

Although conventional PECDs such as ESP in Chinese coal-fired power plants are generally effective for large particles, most of them have very limited effect on smaller-sized particles of greater health concern such as $PM_{2.5}$. This may be partially explained by the fact that the current Chinese PM emission standard for thermal power plants is only based on TSP, not $PM_{2.5}$ or PM_{10} (SEPAC, 2011). However, as regulations in fine particle emission become more rigorous (SEPAC, 2012), retrofit and/or replacement of conventional PECD in many Chinese coal-fired power plants is expected. It is suggested that hybrid systems utilizing multiple particle collection mechanisms, especially electrostatic-assisted filtration, are the most promising technology for reducing direct emission of $PM_{2.5}$ from power plants. However, more field measurements are needed to test and verify the industrial applications of newly designed, efficient, and economical PECD.

7. Current perspective and future research need of $PM_{2.5}$ in China

"To raise new questions, new possibilities, to regard old problems from a new angle, requires creative imagination and marks real advance in science."

—Albert Einstein

Air pollution has been with mankind since wood burning in caves. The pollution has accelerated since the industrial revolution and the rapid economic development as exemplified by the famous London Smog during the 1950's and Los Angeles Smog during the 1970's. It is an old problem with localized conditions. The solution may come from tackling the problem from a new angle based on localized conditions. Based on the current review, we have identified several new angles to address the air pollution problem in China.

7.1. PM sampling and monitoring

7.1.1. $PM_{2.5}$ vs. $PM_{1.0}$ sampling

In the air quality criteria document for particulate matter (USEPA, 1996) Section 3.7, Physical and Chemical Considerations in Selecting a Size Cut-Point for Separating Fine and Coarse Particulate Matter, the justification for selecting the cut-point at 2.5 μm is explained in details. It was based on the existing size distribution measurement results available at that time. Fig. 2 shows several grand average size distributions obtained by Whitby et al. (1972) in several major field studies. Two of the distributions show a natural separation point at 2.5 μm and two others at 1.0 μm. The decision to set the cut-point at 2.5 μm was in part due to the available dichotomous sampler with a cut-point at 2.5 μm (personal communication).

Several recent studies obtained in China and the surrounding areas suggested that the natural separation point is closer to 1.0 μm (Bergin et al., 2001; Chen, Tsai, Chou, et al. 2010). In northern China, the dry weather causes more windblown dust to be entrained, which forms a high coarse particle mode. A large coarse particle distribution "tail" could extend to below 2.5 μm, potentially causing interference in the $PM_{2.5}$ samples. As described earlier, the coarse particles are of naturally origin and are less toxic than the fine particles of air pollutants.

It will be desirable to perform a major study to determine whether $PM_{1.0}$ or $PM_{2.5}$ is more appropriate for China. $PM_{1.0}$ may give a more realistic indication of air pollution, which can then be controlled by strict regulations of automobile and industrial emissions. Without the "interference" of coarse particle component, the $PM_{1.0}$ may give a better correlation with the health effects study. The large scale $PM_{1.0}$ and $PM_{2.5}$ monitoring, together with corresponding mortality rates from the health effect studies in several regions and major cities in China, will allow a PM standard to be set up that is most appropriate for China.

7.1.2. Particle surface area monitoring

Most of the existing PM standards and health effect studies are based on mass concentration measurements. Recent toxicology studies showed that the health effects of fine particles seem to correlate better with the particle surface area than with the particle number or mass (Brown, Collings, Harrison, Maynard, & Maynard, 2000; Brown, Wilson, MacNee, Stone, & Donaldson, 2001; Donaldson, Li, & MacNee, 1998; Nygaard, Samuelsen, Aase, & Lovik, 2004; Oberdorster, 2000; Stoeger et al., 2006; Tran et al., 2005). The findings have motivated the development of several particle surface area monitors (Fissan, Neumann, Trampe, Pui, & Shin, 2007; Shin, Pui, Fissan, Neumann, & Trampe, 2007; Wilson et al., 2007; Woo, Chen, Pui, & Wilson, 2001), many of which are used to study the exposure assessment of nanoparticles in the workplaces. It will be desirable to extend these studies for atmospheric monitoring and to correlate the particle surface area results with the health effects.

7.2. Source apportionment and visibility

A significant influence of $PM_{2.5}$ on human health and atmospheric visibility has been widely reported. China, a rapid developing country, has been suffering from high $PM_{2.5}$ pollution due to the high usage of fossil fuel since the 1980s. Therefore, the adverse health effects to the people and severe atmospheric visibility impairment are intensified, especially at the big cities of China. Researchers are studying the mass concentration, chemical composition, and source apportionment of $PM_{2.5}$ in order to develop efficient $PM_{2.5}$ control strategies. The major $PM_{2.5}$ sources in China have been identified as coal burning, vehicle emissions and biomass burning, industrials, dust (winter to spring), among others (Cao, Xu, et al., 2012; Cheng et al., 2011; Gao et al., 2013; He et al., 2001; Huang et al., 2006; Song, Xie, et al., 2006; Song, Zhang, et al., 2006; Wang, Zhuang, et al., 2008; Wang et al., 2012; Yu et al., 2013; Zhang et al., 2012, 2013; Zheng et al., 2002). Currently, the equipment and techniques used by Chinese researchers for $PM_{2.5}$ measurement are comparable to or even the same as those in the U.S. and EU. Research results have been published in many high-impact journals. For $PM_{2.5}$ mitigation, some efforts have been taken by the Ministry of Environmental Protection of China, academia, and industry to improve air quality. For example, public transport systems are being developed and heavy industrial factories are enforced to move away from cities. However, the reduction rate of $PM_{2.5}$ concentration seems to be too slow to meet the current $PM_{2.5}$ standard in one or two decades. The rate was only 4 $\mu g/m^3$ per year in Beijing (from 126 $\mu g/m^3$ in 2004 reducing to 110 $\mu g/m^3$ in 2008 in Beijing) and 11 $\mu g/m^3$ per year in Xi'an (Cao, 2012; Yang et al., 2011). With this slow pace, people will be living with unhealthy air for another decade or two in these big cities. Therefore, it is recommended to adopt some of the methods applied in the U.S., including (1) to establish widely distributed monitoring sites (such as the IMPROVE and CSN program) to conduct source apportionment studies to quantify and characterize sources of $PM_{2.5}$ for the entire nation (including long range transport), (2) to have advisory committee or working groups to review the data and methods and direct future research (such as that of CAA), and (3) to develop more efficient control strategies based on the results.

7.3. Health effects of $PM_{2.5}$

Overall, some understanding has been gained regarding the acute health effects, especially cardiovascular and respiratory morbidity and mortality, attributable to short-term exposure to $PM_{2.5}$, which forms the foundation for updating environmental policy and air quality standards. However, there is still much to learn to fully understand the health effects of $PM_{2.5}$ in China.

First, it is unclear how well the results of current Chinese studies represent health effects of $PM_{2.5}$ exposure for the entire nation. So far all studies have been conducted in several large Chinese cities such as Beijing, Shanghai and Guangzhou, etc.; while other major cities with large population (e.g. Tianjing and Shenzhen) or high levels of $PM_{2.5}$ pollution (e.g. Taiyuan) are still largely understudied. In addition, it would be of interest to compare results from urban areas with those from suburban and rural areas, where half of the nation's population lives. These locales probably have different $PM_{2.5}$-related health effects from metropolitan areas because of different characteristics of $PM_{2.5}$ pollution, socioeconomic status of residents, and meteorological/environmental conditions. A U.S. 27-community study found consistently greater effect estimates in eastern than western communities, suggesting a regional pattern in the effect of $PM_{2.5}$ exposure (Franklin et al., 2007) while no significant heterogeneity was observed in the ten Mediterranean cities (Samoli et al., 2013). Whether such national heterogeneity or homogeneity exists in China is not clear and this piece of information is valuable for improving the current environmental policy and standards. In order to better assess $PM_{2.5}$ health effects nationwide, it is highly recommended to establish systematic $PM_{2.5}$ monitoring network and mortality/morbidity reporting systems.

Second, the long-term health effects of $PM_{2.5}$ in China remain unclear. Although the short-term time-series approach has been widely applied in air pollution-related epidemiological studies, it does not capture the effects of chronic diseases as the long-term cohort approach does, thus underestimating the health risk of $PM_{2.5}$ exposure (Kunzli et al., 2001). In fact, the famous Harvard Six Cities study (Dockery et al., 1993) and the American Cancer Society study (Pope et al., 1995) on long-term $PM_{2.5}$ exposure, their reanalysis (HEI, 2000), and extended analysis (Laden, Schwartz, Speizer, & Dockery, 2006; Pope et al., 2004) all showed mortality risk more than ten times higher than that of short-term exposure. By contrast, there is only one Chinese study showing positive albeit statistically insignificant association between $PM_{2.5}$ and respiratory morbidity in children in four Chinese cities (Zhang et al., 2002). Future research should address how health effects change as a function of exposure time.

Third, it is still unknown what $PM_{2.5}$ sources have the most adverse health effects. As the first step to address this question, two recent studies examined the association between $PM_{2.5}$ chemical composition and mortality in Xi'an (Cao, Xu, et al., 2012; Huang et al., 2012). Considerable risk heterogeneity was observed among various $PM_{2.5}$ constituents in both studies and secondary components (e.g. sulfate, ammonium, and nitrate) and elemental/organic carbon showed the strongest association with mortality, a finding similar to those of previous reports in the U.S. (Franklin et al., 2008; Laden et al., 2000; Ostro, Feng, Broadwin, Green, & Lipsett, 2007; Ostro et al., 2008). These results indicate that mass concentration of $PM_{2.5}$ alone cannot sufficiently explain its adverse health effects. Instead, the relative toxicity of different chemical constituents carried by $PM_{2.5}$ must be considered (Burnett et al., 2000). Considering the early source apportionment study conducted in Xi'an (Cao et al., 2005), combustion of fossil fuels such as coal and heavy oil may be the most responsible source for the observed mortality in these two studies. For future research, chemical speciation of $PM_{2.5}$ and epidemiological data should be coupled with formal source apportionment so that the relative contribution of different $PM_{2.5}$ sources to human health effects can be determined. Such information is crucial for effective control of $PM_{2.5}$ emission in China.

Fourth, the quantitative associations between actual health benefits and reduction in $PM_{2.5}$ concentration are poorly understood,

which could serve as strong support and rationales for revising the Chinese national $PM_{2.5}$ standard. However, the extremely heavy $PM_{2.5}$ pollution in China may take up to 20 years to solve, making it difficult to evaluate the actual health benefits, especially those of chronic diseases, by reducing $PM_{2.5}$ emission within a short time frame. By taking advantage of the dramatic change in $PM_{2.5}$ concentration during the Beijing Olympic Games in 2008, two $PM_{2.5}$ intervention studies showed that decrease in $PM_{2.5}$ was associated with a significant reduction in hospital visits due to asthma attack (Li, Wang, Kan, Xu, & Chen, 2010) and improved heart rate variability, a marker of cardiac autonomic function (Wu et al., 2010), both providing evidence for the health benefits of controlling $PM_{2.5}$ in China. In addition to intervention studies, toxicity (in vitro) studies and human exposure chamber (in vivo) studies may also be useful to quantify the health benefits associated with $PM_{2.5}$ reduction and potentially provide additional biological plausibility that is unique to the Chinese population. Unfortunately, both types of studies seem to be missing in China, in contrast to the abundant research in developed countries (Pope & Dockery, 2006; USEPA, 2009b).

Finally, a better understanding is needed of the relationship between measured ambient $PM_{2.5}$, indoor $PM_{2.5}$, and actual personal exposure. In almost all the Chinese studies, measurement error was listed to be one of the study limitations. Namely, data from one or several monitoring stations with limited geographic coverage were assumed to represent the average exposure for a large area. This assumption is certainly incorrect and may lead to bias in reported effect estimates (Zeger et al., 2000). In China, people spend more time outdoors and the prevalence of air conditioning indoors is lower than that in developed countries, making ambient measurement more representative to personal exposure. However, in addition to ambient $PM_{2.5}$, smoking and burning of biomass for cooking/heating indoors may significantly contribute to personal exposure to $PM_{2.5}$ and also deserve further research.

7.4. Mitigation of $PM_{2.5}$ by filtration

Approximately 70% of the $PM_{2.5}$ sources in northern China are from coal-fired combustion sources and vehicle emissions. A quick way to improve $PM_{2.5}$ will be to replace coal-fired plants with natural gas. Natural gas can reduce $PM_{2.5}$ emissions while increase the thermal efficiency of the plants. In localities where replacing with natural gas is not an option, the $PM_{2.5}$ mitigation can be achieved by adopting advanced gas cleaning technology by using novel filters. The Center for Filtration Research (CFR) at the University of Minnesota has conducted basic and applied research on air and gas filtration for over twenty years. Many of the CFR research are available online: www.me.umn.edu/cfr.

7.4.1. Vehicle emissions control

With 55% of the passenger cars being diesel powered in Europe, the European Union is introducing increasingly stringent standards for light passenger and commercial vehicles (Euro 5 and Euro 6) and diesel powered trucks and buses (Euro V and Euro VI). In addition to the particulate mass requirements, the new European legislation for Euro 6b includes a proposed particulate number requirement for Gasoline Direct Injection (GDI) engines for implementation in 2014, which will be further reduced with the implementation of Euro 6c in 2017. This recent adoption of particulate number standard vs. the traditional particulate mass standard allows the standard to be set ten times more stringent than the traditional mass standard. A variety of Diesel Particulate Filters (DPF) has been developed to meet the Euro standards. Industry is devoting efforts to develop the Gasoline Particulate Filters (GPF) to meet future GDI emission standards. By requiring vehicles sold in China meeting these stringent standards, the emissions from vehicles can be gradually reduced over the years.

7.4.2. Novel filtration devices to mitigate industrial pollutants

To increase the collection efficiency of fine particles from coal-fired power plants, China has implemented new technologies in electrostatic precipitators and added baghouse filters to set up ESP-baghouse complexes. Some of the ESPs are replaced with baghouse filter system. New technologies are developed to increase the collection efficiency, reduce the pressure drop, and facilitate the regeneration of the baghouse filters. For example, by adding a layer of nanofibers over the coarse substrates, the fine particles are collected with increased efficiency on the surface of the nanofibers to form dust cake, which can then be pulsed off effectively by reverse pulsed jet. It should be mentioned that the particle filters for primary fly ash collection can be supplemented with scrubbers for removing gaseous contaminants as they will lead to secondary particulate formation in the atmosphere.

7.4.3. Air cleaner for the general public

China has experienced an unprecedented high level of $PM_{2.5}$ concentrations during the past several years, resulting in significant concerns over its adverse health effects by the general public. While the stricter regulations in the coming years should help to reduce the $PM_{2.5}$ concentration, the past experience in the U.S. cities and recent data obtained by Institute of Earth Environment (IEECAS) in Xi'an indicate that it may take more than a decade before it is reduced to an acceptable level. It is also known that due to their small particle sizes, $PM_{2.5}$ can penetrate indoor to home and workplaces. In the near term, air cleaners for home use and office use can provide relief indoor where people live and work. There are a variety of air cleaners available in the China market. However, they are expensive and the replacement costs for air filters are even more expensive because they need to be replaced frequently. It is desirable to develop low cost, efficient air cleaners for the general public that can be used for homes, classrooms and offices.

8. Conclusions: an integrative approach in addressing $PM_{2.5}$ issues

$PM_{2.5}$ values are widely reported in China for major cities (http://www.pm25.in). Good descriptions of sources and effects of $PM_{2.5}$ are provided for the general public. Meanwhile, there are scientific papers (e.g. Chen, Ebenstein, Greenstone, & Li, 2013) and newspaper articles reporting on the harmful effects of $PM_{2.5}$. They have added to the urgency of addressing the $PM_{2.5}$ issues.

An integrative approach, from collaborations among academia, government, and industry, can accelerate the solution to the $PM_{2.5}$ problem in China (see Fig. 8). These three sectors of academia, government and industry represent three gears driving the wheel of progress: Sources ⇒ Effects ⇒ Regulation ⇒ Control. The academia can most effectively address the sources (coal burning and vehicle emissions) and their effects (visibility and health). To protect the public and environment health, the government can progressively set stricter regulations for $PM_{2.5}$ and vehicle emissions standards. The industry can respond by developing novel control technologies for baghouse filters and diesel/gasoline particulate filters. Further, the academia can also help the government to set the regulations and industry develop novel technologies.

The three gears of academia–government–industry can work more efficiently and effectively by turning in the same directions and with the same speed. The three gears can turn the wheel of progress together, and with each turn, the $PM_{2.5}$ level will be

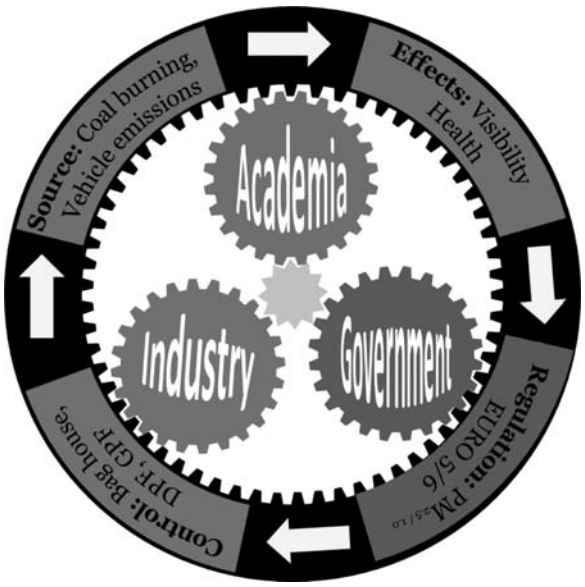

Fig. 8. An integrative approach to address $PM_{2.5}$ issues in China.

reduced. The general public can proactively help by conserving energy, adopting green technologies, driving cars that meet strict standards, and supporting the government regulations.

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