

# Assessment of atmospheric particulate matter and heavy metals: a critical review

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**Abstract** This paper gives detailed comprehensive review of atmospheric assessment of particulate matter and heavy metals. Previous research works executed on this subject matter in the past four decades were adequately scrutinized. Various equipments for assessing atmospheric particulate matter and heavy metals were presented. Mathematical modeling equations for source apportionment and characterization, deposition rate prediction and health risk characterization of PM<sub>10</sub> were also presented. However, the following conclusions were made: (1) there is need for improvement on the mathematical models by reducing the number of assumptions made in developing them. (2) Comparative analysis of concentrations of heavy metals in the atmosphere under the same environment for different methodologies should be executed for accuracy purposes. (3) Cost implication of assessing, monitoring and controlling these unfriendly substances should be examined, and hence, involvement of cost engineers may be of immense help. (4) Further research works should be done on Air-Q 2.2.3 model currently identified as a new methodology for provision of quantitative data on the impact of particulate matter exposure on the health of people. (5) Compliance monitoring networks should be

designed to ease data collection for the observables, locations and time periods that allowed receptor models to be applied. (6) There is need for much more research works that enable optimal control and regulation of emission of heavy metals into the atmosphere in order to reduce health effects of these inhalable substances.

**Keywords** Particulate matter · Heavy metal · Atmospheric assessment · Concentration · Air pollution · Atmospheric deposition

## Introduction

Atmosphere is a gaseous layer surrounding the earth. It is the transparent layer through which life-sustaining solar radiation passes and reaches the earth's surface or into the water (Critchfield 1987). However, the emergence of particulate matter and heavy metals due to industrial revolution has made present-day atmosphere to be quite different from the natural atmosphere (Ashton 1948). Rapid industrialization and urbanization during this time led to increase in anthropogenic emissions from both fossil fuel and biomass combustion (Chowdhury et al. 2001). Particulate matter refers to the solid and liquid particles that are dispersed into ambient air. Particulate matter is composed of a mixture of particles directly emitted into the air (primary particles) and particles formed in the air from the chemical transformation of gaseous pollutants (secondary particles). There are two major categories of particulate matter (PM): PM<sub>10</sub> and PM<sub>2.5</sub> (Martinez-Ramirez and Thompson 1998). The principal types of directly emitted particles are soil-related particles and organic and elemental carbon particles from the combustion of fossil fuels and biomass materials. The concentration of primary particles depends upon their

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emission rate, transport and dispersion and removal rate from the atmosphere. Situation with secondary particles is much more complex (US EPA 1996). As a result, it is considerably more difficult to relate ambient concentrations of secondary particles to sources of precursor emissions than it is to identify the sources of primary particles.

Heavy metals are metallic elements which are toxic and have high densities, specific gravities or atomic weights (Duffus 2002). They constitute important class of pollutants which have received the attention of researchers all over the world, mainly due to their harmful effects on living beings. Heavy metals enter into the environment mainly via three routes: deposition of atmospheric particulates; disposal of metal enriched sewage sludge and sewage effluents; and by-products from metal mining processes (Shrivastav 2001). Metals in the atmosphere result from processes both natural (dust re-suspension, foliage emissions, volcanic activity and bubble bursting from water bodies) and anthropogenic (primarily industrial and automotive emissions; Harris 1976; Pacyna 1986). Re-suspension of roadside dust and soil is another potential source of heavy metals. Iron is a metal present in significant concentration in most emission sources of air pollution particles while sources of lead were linked to vehicles, re-suspended soil and oil burning (Schroeder et al. 1987).

### Concentration range of particulate matter and atmospheric pollutant sizes

Schroeder et al. (1987) had reported 30–35  $\mu\text{g m}^{-3}$  heavy metals in atmospheric particulate matter. Manganese, copper, zinc, cadmium, chromium, iron, nickel, potassium, calcium, vanadium, barium, arsenic, selenium and strontium are the most commonly found metals in the pollution sources and have been studied widely. In Western Europe, North America and Western Pacific, except China, annual mean total suspended particulates (TSP) concentrations range between 20 and 80  $\mu\text{g m}^{-3}$  (Sivertsen 2002), and  $\text{PM}_{10}$  levels are between 10 and 55  $\mu\text{g m}^{-3}$ . High TSP and  $\text{PM}_{10}$  annual mean concentrations are found in Southeast Asia (Sivertsen 2002) ranging between 100 and 400  $\mu\text{g m}^{-3}$  for TSP and 100–300  $\mu\text{g m}^{-3}$  for  $\text{PM}_{10}$ . High annual TSP concentrations of 300–500  $\mu\text{g m}^{-3}$  are observed in the large cities of China. In Lahore (Pakistan), TSP mean annual values were 607–678  $\mu\text{g m}^{-3}$  (Smith et al. 1996). Similarly, the  $\text{PM}_{10}$  levels in Indian cities have been found to be in the range of 100–400  $\mu\text{g m}^{-3}$  (Sharma et al. 2003).

### Effects of particulate matter

Many epidemiological studies have found a positive correlation between  $\text{PM}_{10}$  mass and respiratory illnesses and cardiovascular diseases (Dockery et al. 1993; Abbey et al.

1999). Other studies suggest that it is the finer particles, which have the greatest impact on health (Schwartz et al. 1996; Cifuentes et al. 2000), which is supported by the fact that  $\text{PM}_{2.5}$  penetrates the human respiratory system more efficiently into the alveolar region. Nevertheless, studies have also found that higher concentrations of coarse particles ( $\text{PM}_{2.5-10}$ ) can also increase overall mortality rates (Castillejos et al. 2000). Miguel et al. (1999) suggested that re-suspended road dusts contain materials which can potentially initiate allergic reactions. Studies on both rodents and humans demonstrate that ultrafine particles have a greater effect per unit mass than larger particles (Oberdorster 2001; Donaldson et al. 2000), while another study on asthma patients performed in Germany and Finland (Wichmann and Peters 2000) suggested that both fine and ultrafine particles have health effects which might be independent of each other. Some studies have also shown that the chemical composition of the particles may mediate the health effects.

Atmospheric transport and deposition of pollutants over long distances had received much attention, particularly in connection with the acid rain problem, the formation of photochemical oxidants and ozone, and the global climatic effects (National Academy of Science 1978). Together with wet deposition, particle dry deposition is responsible for delivering to ecosystems atmospheric loads of compounds such as  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$  and  $\text{NH}_4^+$ , base cations (such as  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) and heavy metals (e.g., Pb, Cd and Zn). Deposition of particles containing  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$  and  $\text{NH}_4^+$  contributes to potential acidification and eutrophication of ecosystems. Base cation deposition can be important for nutrient cycling in solids, and it can also neutralize acid input. Heavy metals are known for their possible toxic effects (Schwartz and Slinn 1992). Measurement of heavy metals in particulate matter is, therefore, of immense importance for toxicological, environmental and occupational health studies (Pandey et al. 1998).

### Air quality management and pollution control of particulate matter

#### *Use of source apportionment method*

For the effective management of air quality, great importance is attached to the identification of the sources of suspended particulates (Baek et al. 1997). Source apportionment can be achieved by using a variety of air quality models. Among these, receptor-oriented modeling is one of the conventional techniques and has been in broad use for source apportionment studies in the past decades (Ke et al. 2008). The framework for using receptor models to solve air quality problems consists of: formulating a conceptual



model; identifying potential sources; characterizing source emissions; obtaining and analyzing ambient particulate matter samples for major components and source markers; confirming source types with multivariate receptor models; quantifying source contributions with the chemical mass balance; estimating profile changes and the limiting precursor gases for secondary aerosols; and reconciling receptor modeling results with source models, emissions inventories and receptor data analyses (Watson et al. 2002).

#### *Air quality surveillance method*

Air quality surveillance is the procedure for assessing the concentrations of atmospheric contaminants and other properties of the air so that air quality management requirements can be met. Environmental regulators have access to a large set of policy tools and instruments to create incentives for industrial facilities to abate pollution. Command and control is one approach where pollution standards for emissions or effluence are set, and fines and penalties are assessed against non-compliant facilities. Other options include pollution charges, tradable permits, voluntary participation programs, as well as environmental performance rating and public disclosure programs (World Bank 2000).

#### *Use of geographic information system (GIS) and global positioning system (GPS)*

Other identified means of managing air quality include geographic information systems (GIS) and global positioning system (GPS). GIS are systems of hardware, software, data, people, organizations and institutional arrangements for collecting, storing, analyzing and disseminating information about areas of the earth (Dueker and Kjerne 1989). GIS helps in the assessment of quality of life (QOL) which is emerging as a major indicator to monitor citizen's livelihood and well-being at the grass-roots level and thus inform local people and organizations of their living environment and optimize the allocations of resources to improve the community development (Hein et al. 2006; Loh et al. 2012). Global positioning system (GPS) receivers are another invaluable useful tool that can be used by state and local government agencies to address spatial coordinate deficiencies of inventory data of point sources (Alexis 2002). It consists of satellite, control and receiver segments in which the GPS receivers can be used to obtain emission release point locations if site access is available.

#### *Remote sensing technique*

Remote sensing is another technique of immense application in environmental pollution and involves collecting

information about the earth without taking a physical sample of the earth's surface or touching the surface using sensors placed on a platform at a distance from it (Liu et al. 1996). A sensor is used to measure the energy reflected from the earth and information gotten can be displayed as a digital image or as a photograph. It was based on the fact that the atmosphere affects satellite images of the earth's surface in the solar spectrum and signal observed by the satellite sensor was the sum of the effects from the ground and atmosphere (King et al. 1999).

#### *Meteorological and air pollution dispersion models*

There are many meteorological models available for weather prediction and the mainly used are Weather Research and Forecasting (WRF) modeling system, MM5 modeling system software and Regional Atmospheric Modeling System (RAMS). MM5 is a limited-area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation (Grell et al. 1995). RAMS is a highly versatile numerical code developed by scientists at Colorado State University for simulating and forecasting meteorological phenomena, and for depicting the results (<http://rams.atmos.colostate.edu/rams-description.html>). Other applicable air pollution dispersion models for atmospheric air pollution assessment include photochemical modeling, plume rise models, particle models, deposition modules, odor models and statistical models (Yerramilli et al. 2011).

#### **Previous studies on collection and assessment of particulate matter and heavy metals**

Generally, sources of metals and particulate matter in the atmosphere had been traced to originate either from anthropogenic activities or natural phenomena such as dust re-suspension, foliage emissions, volcanic eruption and bubble bursting from water bodies (Harris 1976). However, different methodologies had been proposed in collecting samples of heavy metals and particulate matter; and assessing their quantities in the atmosphere.

#### *Collection methods and measurement techniques*

Lindberg and Turne (1988) had been reported to have used automatic rain sensing collectors, made of chemically inert materials, to collect wet-only samples of precipitation. Abdul-Wahab (2004) used nuclepore polycarbonate filters to collect atmospheric aerosol particles coupled with high-volume sampling method. Replicate inert surfaces situated in automatic collectors designed to exclude rainfall had been used to collect dry deposited particles (Lindberg and Lovett 1985). Lovett and Lindberg (1984) estimated dry

deposition of metal containing particles from inert surface fluxes using an empirical model of coarse particle dry deposition to the full canopy developed from measurements of throughfall chemistry. Many researchers had measured concentrations of heavy metals in particulate matter using graphite furnace atomic absorption spectrophotometry using the method of standard additions (Momani et al. 2000; Greaney 2005; Vijayananda et al. 2008; Farahmandkia et al. 2010; Awan et al. 2011; Dubey et al. 2012; Kleckerová and Docekalová 2014). In a different approach, Rojas et al. (1991) used a mathematical approach based on the Monin–Obukhov similarity theory to predict wind speed, friction velocity and drag coefficient which were then introduced into a well-known deposition model of Slinn and Slinn (1980) to calculate dry deposition of heavy metals into North Sea.

Elemental composition of particulate matter had also been determined using particle-induced X-ray emission (PIXE) method (Makra et al. 1999; Abiye et al. 2014), atomic absorption spectrophotometer (Sharma et al. 2003), benzene-soluble organic fraction method (Sharma et al. 2003), wet sieving method (Greaney 2005) and inductively coupled plasma quadrupole mass spectrometer (Samontha et al. 2007). Determination of particle number concentration using condensation particle counter (Marple et al. 1987), particle size distribution using electrical aerosol spectrometer (Mirme et al. 2002) and absorption coefficient using filter reflectance (Mathys et al. 2001) in particulate matter had been investigated (Vallius 2005). In another development, results obtained from an organic speciation analysis had been used in a chemical mass balance (CMB) model, along with organic emissions profiles and key organic tracers typical of urban sources, to quantify the primary source contributions to  $PM_{2.5}$  mass concentrations in four major cities of India (Chowdhury et al. 2001). In a related work, Khodeir et al. (2012) modeled chemical composition data using factor analysis with Varimax orthogonal rotation to determine five and four particle source categories contributing significant amount of  $PM_{2.5}$  and  $PM_{10}$  mass, respectively.

Statistical multivariate method and deterministic method had been applied as source apportionate methods for determining particulate matter sources whose chemical composition is stable and well defined (Vallius 2005). Samontha et al. (2007) used continuous-flow sequential extraction procedure to study fractionation and elemental association of some heavy metals in air particulate matter from two different sources: a smelter and heavy-vehicle traffic. In a new development, comprehensive comparison of positive matrix factorization (PMF) and molecular marker-based chemical mass balance (CMB-MM) modeling on  $PM_{2.5}$  source contributions was conducted for particulate matter measurements taken at Jefferson Street,

Atlanta, Georgia (Ke et al. 2008). Gaussian predictive model had been applied for model prediction of particulate dispersion from a cement mill stack (Otaru et al. 2013). Holnicki and Nahorski (2013) used Gaussian puff dispersion and regional-scale transport models for air quality modeling of Warsaw Metropolitan Area, Poland. In recent time, Xu et al. (2014) utilized a remote sensing method to retrieve  $PM_{10}$  concentration during health risk assessment of inhalable particulate matter in Beijing based on thermal environment.

#### *Previous findings on particulate matter assessment*

In the result obtained by Momani et al. (2000), atmospheric concentrations and enrichment coefficients of Zn, Cu, Pb and Cd were 344, 170, 291 and 3.8  $ng/m^3$ ; and 12.1, 6.1, 11.7 and 1.1, respectively. Various results obtained by different researchers revealed that concentration of heavy metals in particulate matter depends on the nature of the environment being examined. In marine environment, chlorine had been reported to be of higher concentration (Makra et al. 1999). Higher concentrations of sulfur and lead were traced to be partly of anthropogenic and biogenic origins. In another work involving source characterization of atmospheric heavy metals in industrial/residential areas (Abdul-Wahab 2004), copper and manganese were sourced from copper industrial processes and reinforcement steel production while chromium, lead and zinc reflected contributions from black and galvanized iron pipes production, mechanical industries, vehicle construction and motor-vehicle tire wear with municipal incineration. On the other hand, industrial site was polluting air quality in the examined residential area with copper, chromium, lead, nickel and manganese.

Sharma et al. (2003) had shown that heavy metals in Kanpur, India, were almost 5–10 times higher than levels in European cities with reference to  $PM_{2.5}$  and  $PM_{10}$ . Diesel exhaust, gasoline exhaust, road dust, coal combustion and biomass combustion had also been identified as major sources of fine particle-phase inorganic and organic compounds in India (Chowdhury et al. 2001). In investigating fractionation and elemental association of metals in air particulate matter from smelter and heavy traffic sites sources, reducible phase (Fe/Mn oxides) was shown to be the largest fraction of Pb in air particulate matter from both the smelter and heavy traffic sites (Samontha et al. 2007). In the reducible fraction, Pb was found to dissolve earlier than Fe indicating that Pb was adsorbed onto Fe oxide surfaces in the air particulate matter. Ke et al. (2008) resolved four similar sources of  $PM_{2.5}$  using positive matrix factorization (PMF) and molecular marker-based chemical mass balance (CMB-MM) modeling methods, with good correlation for road dust, but fair for gasoline



exhaust and wood combustion. The CMB-MM diesel exhaust has very poor correlation with the PMF resolved diesel exhaust. Heavy oil combustion, mixed industrial activities and traffic had been identified as major sources of heavy metals in PM<sub>2.5</sub> and PM<sub>10</sub> (Khodeir et al. 2012).

The summary of previous studies executed on atmospheric assessment of particulate matter and heavy metals in the past four decades is presented in Table 1.

### Mathematical modeling

The modeling equations include source apportionment, deposition rate prediction modeling and health risk characterization of PM<sub>10</sub>. The source apportionment discusses enrichment factor analysis, chemical mass balance modeling, positive matrix factorization and factor analysis.

#### Source apportionment

##### Enrichment factor analysis

This is used for the comparison between the concentrations of atmospheric aerosol elements, when they are found to be higher than expected in their natural forms according to their proportions in the background aerosol. The enrichment factor is given as (Rahn 1976):

$$EF = \frac{[C]_{\text{sample}}/[C_{\text{ref}}]_{\text{sample}}}{[C]_{\text{crust}}/[C_{\text{ref}}]_{\text{crust}}}, \tag{1}$$

where  $[C]_{\text{sample}}$  = concentration of C (analyte element),  $[C_{\text{ref}}]_{\text{sample}}$  = concentration of the normalization reference element in the sample,  $[C]_{\text{crust}}$  = concentration in the continental crust,  $[C_{\text{ref}}]_{\text{crust}}$  = concentration in the continental crust for the reference element.

##### Chemical mass balance modeling

The CMB receptor method tends to extract information about a source’s contribution on the basis of the variability of elements measured in a large number of samples. The objective of this method is to detect common variability and imply source identity by comparing elements with common variability with elements associated with specific sources (Henry et al. 1984). At a given receptor site, a mass balance equation accounting for all conserved chemical species from  $p$  independent sources in a given sample can be expressed as follows (Ke et al. 2008; Jeong et al. 2011):

$$x_{ij} = \sum_{k=1}^p g_{ik}f_{kj} + e_{ij}, \tag{2}$$

where  $x_{ij}$  = concentration of the  $j$ th species measured in the  $i$ th sample,  $g_{ik}$  = mass contribution from the  $k$ th source to the  $i$ th sample,  $f_{kj}$  = fractional concentration of the  $j$ th species in the  $k$ th source,  $e_{ij}$  = residual associated with the ambient concentration of the  $j$ th species in the  $i$ th sample,  $p$  = total number of the contributed sources.

#### Positive matrix factorization (PMF)

Positive matrix factorization is one of the multivariate receptor models that utilize statistical techniques to reduce the data to meaningful terms for identifying sources of air pollutants and to estimate the source contributions (Qin and Oduyemi 2003). Its goal is to resolve the mixture of sources that contributes to particulate matter samples. Specifically, the mathematical model in matrix form is (Reff et al. 2007):

$$X = G \cdot F + E. \tag{3}$$

The index notation is as stated as Eq. 2. The goal is to find values of  $g_{ik}$ ,  $f_{kj}$  and  $p$  that best reproduce  $x_{ij}$ . The values of  $g_{ik}$  and  $f_{kj}$  are adjusted until a minimum value of  $Q$  for a given  $p$  is found.  $Q$  is defined as:

$$Q = \sum_{i=1}^n \sum_{j=1}^m \left( \frac{e_{ij}}{\sigma_{ij}} \right)^2, \tag{4}$$

where  $\sigma_{ij}$  = uncertainty of the  $j$ th species concentration in sample  $i$ ,  $n$  = number of samples and  $m$  = number of species.

Various formulas of calculating uncertainties ( $\sigma_{ij}$ ) for PMF analyses of PM data from previous literatures are presented in Table 2.

#### Factor analysis

Factor analysis is another multivariate receptor model in which data are transformed into a standardized form by normalizing the concentration of each element in each sample with respect to the mean value and standard deviation for the element. It begins with an eigenvector analysis of a cross product matrix of the data, frequently the matrix of correlation coefficients. Assuming each variable is linearly related to some number of underlying factors so that the values of variables may be expressed as a set of  $n$  linear equations, the factor model is given as (Gurjar et al. 2010):

$$X_{ij} = \sum_{k=1}^p C_{ik}S_{kj} + d_jU_{ij}, \quad k = 1, \dots, m, \tag{5}$$

where

**Table 1** Summary of previous studies on particulate matter assessment

References	Accomplished task	Research location	Methodology	Assessed PM and heavy metals	Conclusion
Lindberg and Turne (1988)	Factors influencing atmospheric deposition, stream export and landscape accumulation of trace metals in forested watersheds	Southeastern United States	1. Automatic rain sensing collectors 2. Replicate inert surfaces 3. Graphite furnace atomic absorption spectrophotometry	Cd, Mn, Pb, Zn and Al	1. Metal export was controlled by stream pH, organic carbon, bedrock geology and hydrologic characteristics of each site
Ruijgrok et al. (1995)	Assessment of current knowledge about dry deposition of particles with a focus on implications for Europe	Europe	–	–	1. Insufficient knowledge on particle dry deposition undermining reliable estimates of deposition fluxes over Europe
Shrivastav (2001)	Atmospheric heavy metal pollution: development of chronological records and geochemical monitoring	–	–	–	1. The problem of atmospheric heavy metal pollution would remain as a legacy of mass industrial activity for many generations and is likely to escalate further in future
Watson et al. (2002)	Receptor modeling application framework for particle source apportionment	USA	Enrichment factor, chemical mass balance, multiple linear regression, eigenvector, edge detection, neural network, aerosol evolution and aerosol equilibrium models	TSP, PM <sub>10</sub> and PM <sub>2.5</sub>	1. Compliance monitoring networks were not designed to obtain data for the observables, locations and time periods that allowed receptor models to be applied 2. Measurements from existing networks could be used to form conceptual models that allowed the needed monitoring network to be optimized
Abdul-Wahab (2004)	Source characterization of atmospheric heavy metals in industrial/residential areas	Oman	1. High-volume sampling method	Cr, Cu, Mn, Ni, Pb, Zn, Cd, V and Mo	1. Sources were linked to copper industrial processes and reinforcement steel production; black and galvanized iron pipes production; mechanical industries and vehicle construction; and motor-vehicle tire wear and municipal incineration



**Table 1** continued

References	Accomplished task	Research location	Methodology	Assessed PM and heavy metals	Conclusion
Samontha et al. (2007)	Determination of fractionation of metals in air particulate matter from two different sources, a smelter and heavy-vehicle traffic	Thailand	1. Continuous-flow sequential extraction system 2. Extractograms	Cd, Zn and Pb	1. Crustal enrichment factors suggested that Cd, Zn and Pb in the air particulate matter were predominantly of anthropogenic origin 2. Reducible phase (Fe/Mn oxides) was the largest fraction of Pb in air particulate matter from both the smelter and heavy traffic sites 3. Total Pb deposition in the dry season was found to be higher than that in the wet season and may be attributed to soil dust 4. Pb was found to dissolve earlier than Fe indicating that Pb could occur adsorbed onto Fe oxide surfaces in the air particulate matter
Razos and Christides (2010)	Presentation of a different analytical methodology for samples of airborne particulate matter	Industrial area of Eleusis, Greece	1. Anodic stripping voltammetry (ASV) 2. Inductively coupled plasma atomic emission spectrometry (ICP-AES)	Zn, Pb, Cd, Cu, Fe, Mn, Ni, PM <sub>10</sub> and PM <sub>2.5</sub>	1. Correlation analysis between airborne particulate matter (PM) and toxic elements gave the sources that affected the presence of these elements in coarse and fine particulates
Lee and Hieu (2011)	Seasonal variations in mass concentrations of particulate matter and compositions of heavy metals in PM <sub>2.5</sub> and PM <sub>10</sub> collected from a typical urban residential area	Ulsan, Korea	1. Inductively coupled plasma atomic emission spectrometry (ICP-AES)	PM <sub>2.5</sub> , PM <sub>10</sub> , Cd, Zn, Pb and Cu	1. Analysis of enrichment factors of heavy metals showed highly enriched Cd, Zn, Pb and Cu 2. Principal component analysis for heavy metals in PM <sub>2.5</sub> and PM <sub>10</sub> identified industrial emissions and road dust (soil and traffic) as major sources at the sampling site
Khodeir et al. (2012)	Source apportionment and elemental composition of PM <sub>2.5</sub> and PM <sub>10</sub>	Jeddah City, Saudi Arabia	1. Energy-dispersive X-ray fluorescence (ED-XRF) 2. Factor analysis with Varimax orthogonal rotation	PM <sub>2.5</sub> , PM <sub>10</sub> , Na, Mg, Al, Si, K, Ca, Ti, Cr, Mn, Fe, Rb, Sr P, V, Cr, Mn, Ni, Cu and Ba	1. PM <sub>2.5</sub> and PM <sub>10</sub> sources were attributed to heavy oil combustion, re-suspended soil, industrial and traffic characterized by high concentrations of different heavy metals



**Table 1** continued

References	Accomplished task	Research location	Methodology	Assessed PM and heavy metals	Conclusion
Otaru et al. (2013)	Model prediction of particulate dispersion from a Cement Mill Stack	Nigeria	<ol style="list-style-type: none"> <li>1. Gaussian predictive model</li> <li>2. SKC deployable particulate sampler</li> <li>3. In-stack iso-kinetic sampling method</li> <li>4. Vayubodhan stack sampler</li> </ol>	PM <sub>10</sub>	<ol style="list-style-type: none"> <li>1. Simulated results were in agreement with experimental results at an average value of 92% within a Gaussian distance of 200–2000 m</li> <li>2. Simulated safety distance beyond 7.0 km from the plant was recommended for human settlement and activities</li> </ol>
Schröder et al. (2013)	Correlation between atmospheric deposition of Cd, Hg and Pb and their concentrations in mosses specified for ecological land classes covering Europe	Europe	<ol style="list-style-type: none"> <li>1. Spatial autocorrelations</li> </ol>	Cd, Hg and Pb	<ol style="list-style-type: none"> <li>1. Spatial patterns of correlations between the atmospheric deposition and bioaccumulation were shown to vary by element and ecologically defined land classes</li> </ol>
Holnicki and Nahorski (2013)	Air quality modeling	Warsaw metropolitan area, Poland	<ol style="list-style-type: none"> <li>1. Gaussian puff dispersion model</li> <li>2. Regional-scale transport model</li> </ol>	–	<ol style="list-style-type: none"> <li>1. Relatively low uncertainty PM<sub>2.5</sub> applied to forecasts of SO<sub>2</sub>, while very substantial uncertainties related to PM<sub>10</sub> and NO<sub>x</sub> forecasts, which all strongly depended on very uncertain linear sources</li> <li>2. Kind of polluting compound and emission source category were two main factors indicating the relationship of air pollution forecast</li> </ol>
Habeebullah (2014)	Modeling particulate matter (PM <sub>10</sub> ) in Makkah, Saudi Arabia—a view point of health impact	Makkah, Saudi Arabia	<ol style="list-style-type: none"> <li>1. Continuous IP beta gage monitor device</li> <li>2. Air-Q 2.2.3 model</li> </ol>	PM <sub>10</sub>	<ol style="list-style-type: none"> <li>1. PM<sub>10</sub> levels in Makkah exceeded national and international air quality standards set for the protection of human health</li> <li>2. This study was the first to apply Air-Q 2.2.3 model to provide quantitative data on the impact of particulate matter exposure on the health of people living in Makkah City, KSA, during 2012 (1433H)</li> </ol>





**Table 1** continued

References	Accomplished task	Research location	Methodology	Assessed PM and heavy metals	Conclusion
Abiye et al. (2014)	Receptor modeling of atmospheric aerosols	Federal Capital Territory, Nigeria	1. Sequential double-stage sampler 2. Positive matrix factorization (PMF) receptor model 3. Ion beam analysis (IBA) technique 4. Particle-induced X-ray emission (PIXE) technique	PM <sub>2.5-10</sub> , Si, P, S, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Br, Cd, Sn, Ta and Pb	1. Three distinct sources, crustal 4.2%, biomass/fuel burning 8.8%, vehicular 87.0%, were identified and apportioned by PMF model 2. Traffic-related pollution posed a great hazard to the atmospheric environment of Abuja and likewise on human receptors in the studied areas 3. There was good correlation between on site measured concentrations and model predicted concentrations of PM

**Table 2** Formulas for calculating uncertainties ( $\sigma_{ij}$ ) for PMF analyses of PM data (Reff et al. 2007)

PMF uncertainty ( $\sigma_{ij}$ )	References
$k_j \cdot x_{ij} + \frac{DL_{ij}}{3}$	Kim et al. (2005)
$(0.05 \cdot x_{ij}) + DL_{ij}$	Ito et al. (2004)
$\sqrt{(rep)^2 + (0.05 \cdot x_{ij})^2}$	Prendes et al. (1999)
$\sqrt{a_j s_{ij}^2 + b_j DL_{ij}^2}$	Polissar et al. (1996)
$0.3 + DL_{ij}$	Xie et al. (1999)
$s_{ij} + C_3 \cdot  x_{ij} $	Chueinta et al. (2000)
$\bar{s}_j + \frac{DL_j}{3}$	Polissar et al. (1996)
$s_{ij} + \frac{DL_{ij}}{3}$	Kim et al. (2004)
$s_{ij} + 0.2 \cdot DL_{ij}$	Ramadan et al. (2000)
$\sqrt{3 \cdot (s_{ij})^2 + DL_{ij}^2}$	Song et al. (2001)

$s_{ij}$  analytical uncertainty,  $DL_{ij}$  method detection limit,  $C_3$  value between 0.1 and 0.2,  $rep$  reproducibility,  $k$  fraction developed for each species by analyzing uncertainty vs. concentration plots,  $a_j$ ,  $b_j$  scaling factors,  $overbar$  average

$$X_{ij} = \frac{X_{ij} - \bar{X}_i}{(\bar{X}_i^2 - \bar{X}_i^2)^{1/2}}, \tag{6}$$

$$S_{ik} = \frac{S_{kj} - \bar{S}_k}{(\bar{S}_k^2 - \bar{S}_k^2)^{1/2}}, \tag{7}$$

$$C_{ik} = C_{ik} \left( \frac{\bar{S}_k^2 - \bar{S}_k^2}{\bar{C}_i^2 - \bar{C}_i^2} \right), \tag{8}$$

where  $X_{ij}$  =  $i$ th elemental concentration measured in the  $j$ th sample,  $\bar{X}_i$  = average of  $i$ th elemental concentration,  $S_{ik}$  = airborne mass concentration of material from the  $i$ th source contributing to the  $k$ th sample,  $S_{kj}$  = airborne mass concentration of material from the  $k$ th source contributing to the  $j$ th sample,  $\bar{S}_k$  = average of airborne mass concentration of material from the  $k$ th source  $C_{ik}$  = gravimetric concentration of the  $i$ th element in material from the  $k$ th source,  $\bar{C}_i$  = average gravimetric concentration of the  $i$ th element in material.

**Deposition rate prediction modeling**

Three major transfer processes are involved in the transportation of pollutants in the atmosphere at the most fundamental physical and chemical level (Brankov et al. 1998). These include convection, diffusion and transformation of air pollutants. This is represented by a system of partial differential equations, known as the Fickian system, representing the mass balance of each pollutant species in any elementary volume  $dv = dx dy dz$  in which the pollutant species appears. The basic equation is thus (Holnicki 2006; Jacobson 2005; Sportisse 2007):

[Accumulation of pollutant  $p$  in  $dv$  during time  $dt$ ]  
 = [Rate of pollutants inflow into the element of volume]  
 - [Rate of pollutants outflow from the element of volume]  
 + [Emission rate from pollution sources located in  $dv$ ]  
 + [Production and destruction rates of the pollutant by chemical reaction]  
 - [Rate of pollutant removal through natural processes].

$$(9)$$

Mathematically,

$$\frac{\partial C_p}{\partial t} = -\nabla(uC_p) - \nabla q_p + E_p + R_p - S_p, \quad (10)$$

where  $C_p$  = concentration of pollutant  $p$  in volume  $dv$ ,  $t$  = time (sec),  $u$  = velocity,  $q_p$  = mass flux of pollutant  $p$  due to turbulent diffusion,  $E_p$  = emission rate from pollution sources located in  $dv$ ,  $R_p$  = production and destruction rates of the pollutant by chemical reaction,  $S_p$  = rate of pollutant removal through natural processes.

Equation (10) holds under the following assumptions:

- Rate of mass transfer due to diffusion is proportional to the concentration gradient.
- The chemical production rate involves the production of pollutant through the chemical interactions of other pollutants.

Under steady condition, Eq. (10) becomes

$$-\nabla(uC_p) - \nabla q_p + E_p + R_p - S_p = 0. \quad (11)$$

### Health risk assessment of PM<sub>10</sub>

A relative risk model based on Poisson regression, commonly used in epidemiological studies of air pollution to calculate the relative risk of inhalable particulates with certain health impacts, can be used to model PM<sub>10</sub> health risk characterization (Kan and Chen 2004; Yaduma et al. 2013). Average relative risk of all health impacts can then be used to represent health risk of inhalable particulate matter using the following equations (Xu et al. 2014):

$$TR_i = \frac{R_i}{R_{oi}} = e^{\beta_i \times (C - C_o)} \quad (12)$$

$$TR = \frac{1}{n} \sum_{i=1}^n TR_i, \quad (13)$$

where TR = health risk of inhalable particulate matter; TR<sub>*i*</sub> = relative risk caused by the *i*th health impact; *i* = 1,2,3,..., *n*; R<sub>*i*</sub> = actual risk of the *i*th health impact; R<sub>*oi*</sub> = reference risk value of the *i*th health impact; β<sub>*i*</sub> = exposure – response coefficient; C = actual concentration of inhalable particulate matter, μg/m<sup>3</sup>; C<sub>*o*</sub> = reference concentration in the risk assessment based on the

average year guiding value of inhalable particulate matter set by the WHO, μg/m<sup>3</sup>; *n* = number of health impact types caused by inhalable particulate matter.

### Conclusion

1. Numerous literatures had presented applicable mathematical models to quantify the amount of particulate matter and heavy metals in the atmosphere; and prediction of their concentrations over time in the atmosphere. However, there is need for improvement on the mathematical models by reducing the number of assumptions made in developing the models such as

- assuming linear relationship between variables of factor analysis model in order to have a set of *n* linear equations.
- each air pollutant source type having unique chemical properties. Thus, highly correlated chemical compounds originate from the same source for multivariate receptor models such as positive matrix factorization.
- using average relative risk of all health impacts to represent the health risk of inhalable particulate matter for health risk characterization of PM<sub>10</sub> models.
- using convection, diffusion and transformation of air pollutants only as transfer processes in the development of deposition rate prediction modeling.

Also, fewer researchers presented the simulation of these models using existing experimental data. This was as a result of difficulties normally experienced in the course of gathering data as observed in some literatures. Thus, compliance monitoring networks should be designed to obtain data for the observables, locations and time periods that allowed receptor models to be applied. Also, measurements from existing networks can be used to form conceptual models that allowed the needed monitoring network to be optimized as suggested by Watson et al. (2002). There is need for further work on development of applicable computer software that will allow easy simulation of these models. This will enhance prediction of concentrations of these heavy metals, control and monitoring in the atmosphere.

2. In the examined literatures, various methodologies for assessing concentrations of heavy metals in the atmosphere have been presented. This enabled the determination of increasing order of heavy metal concentrations in the atmosphere at various locations

under experimentation. This has been linked to the heaviness of source apportionment of each heavy metal. However, there is need for further research on comparative analysis of concentrations of these heavy metals in the atmosphere under different methodologies. This will enhance the determination of accuracies of each methodology, and thus, correlation models can be formed between examined methodologies. Though order of increasing concentrations of heavy metals may vary from one environment to another based on source apportionment, it was observed that there was no consistency in the increasing order of concentrations of heavy metals in consulted literatures.

3. Particle shape and size are critical factors controlling the extent to which particles can penetrate into the respiratory tract, how and where particles are deposited, and at what rate particles are cleared from respiratory tract (Hassan 2006). Air-Q 2.2.3 model had been currently identified as a new methodology which had found its application in provision of quantitative data on the impact of particulate matter exposure on the health of people (Shakour et al. 2011; Habeebullah 2014). Further research works are required on this new methodology to increase the number of cases of hospital admissions due to respiratory diseases that can be handled per year by this model for each concentration range of particulate matter and heavy metals.
4. It has been observed that heavy metals have severe effects on plants, animals, humans and ultimately on environment (Sardar et al. 2013). There is need to compare the concentrations of heavy metals in each of the aforementioned in a single environment for future research work. This will enable the determination of the most susceptible of plants, animals and humans to heavy metal exposure and at the same time the most that has affinity for inhaling or absorbing particulate matter and heavy metals.
5. In all the examined literatures, none gave consideration to economic effect and impact of assessing heavy metals and particulate matter in the atmosphere. The cost implication of assessing, monitoring and controlling these unfriendly substances should be examined, and hence, involvement of cost engineers will be of immense help. Comparisons can be made for cost implication of methodologies of assessing atmospheric heavy metals and particulate matter to determine the one with better result and low cost.
6. Lot has been done on source apportionment to determine origin of each heavy metal in particulate

matter present in the atmosphere. However, there is need for further research works that enable optimal control and regulation of emission of these heavy metals into the atmosphere in order to reduce health effects of these inhalable substances. Also, collection of comprehensive chemical composition information on airborne particles and measurement of composition of emissions from major source categories together with the application of organic source tracers would improve confidence in existing source apportionment models (Greaney 2005).

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## References

- Abbey DE, Nishino N, McDonnell WF, Burchette RJ, Knutsen SF, Beeson WL, Yang JX (1999) Long-term inhalable particles and other air pollutants related to mortality in non-smokers. *AM J Resp Crit Care Med* 159:373–382
- Abdul-Wahab SA (2004) Source characterization of atmospheric heavy metals in industrial/residential areas: a case study in Oman. *J Air Waste Manage Assoc* 54:425–431
- Abiye OE, Obioh IB, Ezech GC, Alfa A, Ojo EO, Ganiyu AK (2014) Receptor modeling of atmospheric aerosols in Federal Capital Territory (FCT), Nigeria. *Ife J Sci* 16(1):107–119
- Alexis A (2002) Use of GIS and GPS as a QA tool in emission inventory. In: International emission inventory conference, Atlanta, GA
- Ashton TS (1948) *The industrial revolution: 1760–1830*. Oxford University Press, London
- Awan MA, Ahmed SH, Aslam MR, Qazi IA (2011) Determination of total suspended particulate matter and heavy metals in ambient air of four cities of Pakistan. *Iran J Energy Environ* 2(2):128–132
- Baek SO, Choi JS, Hwang SM (1997) A quantitative estimation of source contributions to the concentrations of atmospheric suspended particulate matter in urban, suburban and industrial areas of Korea. *Environ Int* 23(2):205–213
- Brankov E, Rao ST, Porter PS (1998) A trajectory-clustering-correlation methodology for examining the long-range transport of air pollutants. *Atmos Environ* 32(9):1525–1534
- Castillejos M, Borja-Aburto VH, Dockery DW, Gold DR, Loomis D (2000) Airborne coarse particles and mortality. *Inhal Toxicol* 12:61–72
- Chowdhury Z, Hughes LS, Salmon LG, Cass GR (2001) Atmospheric particle size and composition measurements to support light extinction calculations over the Indian ocean. *J Geophys Res* 106(22):28597
- Chueinta W, Hopke PK, Paatero P (2000) Investigation of sources of atmospheric aerosol at urban and suburban residential areas of



- Thailand by positive matrix factorization. *Atmos Environ* 34:3319–3329
- Cifuentes LA, Vega J, Kopfer K, Lava LB (2000) Effect of the fine fraction of particulate matter versus the coarse mass and other pollutants on daily mortality in Santiago, Chile. *J Air Waste Manage Assoc* 50:1287–1298
- Critchfield HJ (1987) *General climatology*. Prentice Hall of India Pvt. Ltd., New Delhi
- Dockery DW, Pope CA, Xu XP, Spengler JD, Ware JH, Fay ME, Ferris BG, Speizer FE (1993) An association between air pollution and mortality in six U.S. cities. *N Engl J Med* 329:1753–1759
- Donaldson K, Stone V, Gilmour PS, Brown DM, MacNee W (2000) Ultrafine particles: mechanisms of lung injury. *Philos Trans R Soc Lond A* 358:2741–2749
- Dubey B, Pal AK, Singh G (2012) Trace metal composition of airborne particulate matter in the coal mining and non-mining areas of Dhanbad Region, Jharkhand, India. *Atmos Pollut Res* 3:238–246
- Dueker KJ, Kjerne D (1989) *Multipurpose cadastre: terms and definitions*. American Society for Photogrammetry and Remote Sensing, Falls Church, p 12
- Duffus JH (2002) Heavy metals: A meaningless term? *Pure Appl Chem* 74(5):793–807
- Farahmandkia Z, Mehrasbi MR, Sekhavatjou MS (2010) Relationship between concentrations of heavy metals in wet precipitation and atmospheric PM<sub>10</sub> particles in Zanjan, Iran. *Iran J Environ Health Sci Eng* 8(1):49–56
- Greaney KM (2005) An assessment of heavy metal contamination in the marine sediments of Las Perlas Archipelago, Gulf of Panama. M. Sc. Dissertation, Marine Resource Development and Protection, School of Life Sciences, Heriot-Watt University, Edinburgh
- Grell GA, Dudhia J, Stauffer DR (1995) A description of the fifth-generation Penn State/NCAR Mesoscale Model (MM5), NCAR Technical Note, 6-1995
- Gurjar BR, Molina LT, Ojha CSP (2010) *Air pollution: health and environmental impacts*. CRC Press, Boca Raton, p 33487–2742
- Habeebullah TM (2014) Modeling particulate matter (PM<sub>10</sub>) in Makkah, Saudi Arabia—a view point of health impact. *J Clean Energy Technol* 2(3):196–200
- Harris FS (1976) *Atmospheric aerosols: a literature survey of their physical characteristics and chemical composition*. Report NASA CR-2626, National Aeronautics and Space Administration, Washington
- Hassan SKM (2006) *Atmospheric polycyclic aromatic hydrocarbons and some heavy metals in suspended particulate matter in urban, industrial and residential areas in greater Cairo*. Ph.D. Thesis, Chemistry Department, Faculty of Science, Cairo University, Egypt
- Hein L, Van Koppen K, De Groot RS, Van Ierland EC (2006) Spatial scales, stakeholders and the valuation of ecosystem services. *J Ecol Econ* 57(2):209–228
- Henry RC, Lewis CW, Hopke PK, Williamson HJ (1984) Review of receptor model fundamentals. *Atmos Environ* 18(8):1507–1515
- Holnicki P (2006) *Air pollution transport models in air quality control*. EXIT Publishers, Warsaw (in Polish)
- Holnicki P, Nahorski Z (2013) Air quality modeling in Warsaw metropolitan area. *J Theor Appl Comput Sci* 7(1):56–69  
<http://rams.atmos.colostate.edu/rams-description.html>
- Ito K, Xue N, Thurston G (2004) Spatial variation of PM<sub>2.5</sub> chemical species and source apportioned mass concentrations in New York City. *Atmos Environ* 38:5269–5282
- Jacobson MZ (2005) *Fundamentals of atmospheric modeling*. Cambridge University Press, Cambridge
- Jeong CH, Maygan LM, Dennis H, Tom D, Ewa DZ, Daniel W, Luyi D, Valbona C, David M, Greg E (2011) Receptor model based identification of sources in Canadian cities. *Atmos Pollut Res* 2:158–171
- Kan H, Chen B (2004) Particulate air pollution in urban areas of Shanghai, China: health-based economic assessment. *Sci Total Environ* 322:71–79
- Ke L, Liu W, Wang Y, Russell AG, Edgerton ES, Zheng M (2008) Comparison of PM<sub>2.5</sub> source apportionment using positive matrix factorization and molecular marker-based chemical mass balance. *Sci Total Environ* 394:290–302
- Khodeir M, Shamy M, Alghamdi M, Zhong M, Sun H, Costa M, Chen LC, Maciejczyk P (2012) Source apportionment and elemental composition of PM<sub>2.5</sub> and PM<sub>10</sub> in Jeddah City, Saudi Arabia. *Atmos Pollut Res* 3:331–340
- Kim E, Hopke PK, Edgerton ES (2004) Improving source identification of Atlanta aerosol using temperature resolved carbon fractions in positive matrix factorization. *Atmos Environ* 38:3349–3362
- Kim E, Hopke PK, Qin Y (2005) Estimation of organic carbon blank values and error structures of the speciation trends network data for source apportionment. *J Air Waste Manage Assoc* 55:1190–1199
- King MD, Kaufman YJ, Tanre D, Nakajima T (1999) Remote sensing of tropospheric aerosol from space: past, present and future. *Bull Am Meteorol Soc* 80:2229–2259
- Kleckerová A, Dočekalová H (2014) Dandelion plants as a biomonitor of urban area contamination by heavy metals. *Int J Environ Res* 8(1):157–164
- Lee BK, Hieu NT (2011) Seasonal variation and sources of heavy metals in atmospheric aerosols in a residential area of Ulsan, Korea. *Aerosol Air Qual Res* 11:679–688
- Lindberg SE, Lovett GM (1985) Atmospheric chemistry, deposition, and canopy interactions. *Environ Sci Technol* 19:238
- Lindberg SE, Turne RR (1988) Factors influencing atmospheric deposition, stream export and landscape accumulation of trace metals in forested watersheds. *Water Air Soil Pollut* 39:123–156
- Liu CH, Chen AJ, Liu GR (1996) An image-based retrieval algorithm of aerosol characteristics and surface reflectance for satellite images. *Int J Remote Sens* 17(17):3477–3500
- Lovett GM, Lindberg SE (1984) Wet removal of heavy metals from the atmosphere. *J Appl Ecol* 21:1013
- Loh BJ, Cullen CF, Vogt N, Ohkura H (2012) The conserved kinase SRPK regulates karyosome formation and spindle microtubule assembly in *Drosophila* oocytes. *J Cell Sci* 125(19):4457–4462
- Makra L, Borbély-Kiss I, Koltay E, Sutikno Y (1999) Analysis of elemental composition of atmospheric aerosol in Indonesia. *Acta Clim Univ Szeged* 32(33):65–76
- Marple VA, Rubow KL, Turner W, Spengler JD (1987) Low flow-rate sharp cut impactors for indoor air sampling—design and calibration. *Int J Air Pollut Control Hazard Waste Manage* 37:1303–1307
- Martinez-Ramirez S, Thompson GE (1998) Dry and wet deposition studies of the degradation of cement mortars. *Mater Constr* 48:15–31
- Mathys P, Stern WB, Oglesby L, Braun-Fahrlander C, Ackermann-Liebrich U, Jantunen MJ, Künzli N (2001) Elemental analysis of airborne particulate matter by ED-XRF within the European EXPOLIS study. *ICP Inf Newslett* 27:29–34



- Miguel AG, Cass GR, Glovsky MM, Weiss J (1999) Allergens in paved road dust and airborne particles. *Environ Sci Technol* 33:4159–4168
- Mirme A, Kreyling WG, Khlystov A, ten Brink H, Ruuskanen J, Tuch T, Pekkanen J (2002) Intercomparison of aerosol spectrometers for ambient air monitoring. *Aerosol Sci Technol* 36:866–876
- Momani KA, Jiries AG, Jaradat QM (2000) Atmospheric deposition of Pb, Zn, Cu and Cd in Amman, Jordan. *Turk J Chem* 24:231–237
- National Academy of Science (1978) The tropospheric transport of pollutants and other substances to the oceans. National Academy of Science Press, Washington, p 194
- Oberdörster G (2001) Pulmonary effects of inhaled ultrafine particles. *Int Arch Occup Environ Health* 74:1–8
- Otaru AJ, Odigure JO, Okafor JO, Abdulkareem AS (2013) Model prediction of particulate dispersion from a cement mill stack: case study of a cement plant in Nigeria. *IOSR J Environ Sci Toxicol Food Technol* 3(2):97–110
- Pacyna JM (1986) Emission factors of atmospheric elements. In: Nriagu JO, Davidson CI (eds) *Toxic metals in the atmosphere*. Wiley, New York, pp 1–32
- Pandey PK, Patel KS, Subrt P (1998) Trace elemental composition of atmospheric particulate at Bhilai in Central-East India. *Sci Total Environ* 215:123–134
- Polissar AV, Hopke PK, Malm WC, Sisler JF (1996) The ratio of aerosol optical absorption coefficients to sulfur concentrations, as an indicator of smoke from forest fires when sampling in polar regions. *Atmos Environ* 30:1147–1157
- Prendes P, Andrade JM, Lopez-Mahia P, Prada D (1999) Source apportionment of inorganic ions in airborne urban particles from Coruna City (N.W. of Spain) using positive matrix factorization. *Talanta* 49:165–178
- Qin Y, Oduyemi K (2003) Atmospheric aerosol source identification and estimates of source contributions to air pollution in Dundee, UK. *Atmos Environ* 37:1799–1809
- Rahn KA (1976) The chemical composition of the atmospheric aerosol. Technical Report, Graduate School of Oceanography, University of Rhode Island, Kingston
- Ramadan Z, Song XH, Hopke PK (2000) Identification of sources of phoenix aerosol by positive matrix factorization. *J Air Waste Manage Assoc* 50:1308–1320
- Razos P, Christides A (2010) An investigation on heavy metals in an industrial area in Greece. *Int J Environ Res* 4(4):785–794
- Reff A, Eberly SI, Bhave PV (2007) Receptor modeling of ambient particulate matter data using positive matrix factorization: review of existing methods. *J Air Waste Manage Assoc* 57:146–154
- Rojas CM, Otten PM, van Grieken RE, Laane R (1991) Dry aerosol deposition over the North Sea estimated from aircraft measurements. *Air Pollut Model Appl* 8:417–425
- Ruijgrok W, Davidson CI, Nicholson KW (1995) Dry deposition of particles: implications for Europe. *Tellus* 47B:587–601
- Samantha A, Waiyawat W, Shiowatana J, McLaren RG (2007) Atmospheric deposition of metals associated with air particulate matter: fractionation of particulate-bound metals using continuous-flow sequential extraction. *Sci Asia* 33:421–428
- Sardar K, Ali S, Hameed S, Afzal S, Fatima S, Shakoob MB, Bharwana SA, Tauqeer HM (2013) Heavy metals contamination and what are the impacts on living organisms. *Greener J Environ Manage Public Saf* 2(4):172–179
- Schröder W, Pesch R, Hertel A, Schonrock S, Harmens H, Mills G, Ilyin I (2013) Correlation between atmospheric deposition of Cd, Hg and Pb and their concentrations in mosses specified for ecological land classes covering Europe. *Atmos Pollut Res* 4:267–274
- Schroeder WH, Dohson M, Kane DM, Johnson ND (1987) Toxic trace elements associated with air borne particulate matter: a review. *J Air Pollut Control Assoc* 33:1267–1285
- Schwartz SE, Slinn WGN (1992) Precipitation scavenging and atmosphere-surface exchange processes. Hemisphere Publication, Washington
- Schwartz J, Dockery DW, Neas LM (1996) Is daily mortality associated specifically with fine particles? *J Air Waste Manage Assoc* 46:927–939
- Shakour AA, El-Shahat MF, El-Taieb NM, Hassanein MA, Mohamed AMF (2011) Health impacts of particulate matter in greater Cairo, Egypt. *J Am Sci* 7(9):840–848
- Sharma M, Pandey R, Maheshwari M, Sengupta B, Misra A, Shukla BP (2003) Air quality index and its interpretation for city of Delhi. *Int J Energy Clean Environ* 3(4):67–75
- Shrivastav R (2001) Atmospheric heavy metal pollution: development of chronological records and geochemical monitoring. *Resonance* 2:62–68
- Sivertsen B (2002) Presenting air quality data. NILU-F 6/2002, National training course on air quality monitoring and management, Norwegian Institute for Air Research, Kjeller, Norway
- Slinn SA, Slinn WGN (1980) Predictions for particle deposition to vegetative surfaces. *Atmos Environ* 14:1013–1016
- Smith DJT, Harrison Roy M, Luhana L, Pio Casimiro A, Castro LM, Tariq MN, Hayat S, Quraishi T (1996) Concentrations of particulate airborne polycyclic aromatic hydrocarbons and metals collected in Lahore, Pakistan. *Atmos Environ* 30(23):4031–4040
- Song XH, Faber NM, Hopke PK, Seuss DT, Prather KA, Schauer JJ, Cass GR (2001) Source apportionment of gasoline and diesel by multivariate calibration based on single particle mass spectral data. *Anal Chim Acta* 446:327–343
- Sportisse B (2007) A review of current issues in air pollution modeling and simulation. *Comput Geosci* 11:159–181
- U.S. Environmental Protection Agency (1996) Air quality criteria for particulate matter. Office of Research and Development, Washington
- Vallius M (2005) Characteristics and sources of fine particulate matter in urban air. Academic Dissertation, National Public Health Institute, Department of Environmental Health, Finland
- Vijayananda C, Rajagurub P, Kalaiselvi K, Panneer Selvam C, Palanivel M (2008) Assessment of heavy metal contents in the ambient air of the Coimbatore City, Tamilnadu, India. *J Hazard Mater* 160:548–553
- Watson JG, Zhu T, Chow JC, Engelbrecht J, Fujita EM, Wilson WE (2002) Receptor modeling application framework for particle source apportionment. *Chemosphere* 49:1093–1136
- Wichmann HE, Peters A (2000) Epidemiological evidence of the effects of ultrafine particle exposure. *Philos Trans R Soc Lond A* 358:2751–2769
- World Bank (2000) Greening industry: new roles for communities, markets and governments. Oxford University Press Inc, New York
- Xie YL, Hopke PK, Paatero P, Barrie LA, Li SM (1999) Identification of source nature and seasonal variations of arctic aerosol by the multilinear engine. *Atmos Environ* 33:2549–2562
- Xu LY, Yin H, Xie XD (2014) Health risk assessment of inhalable particulate matter in Beijing based on the thermal environment. *Int J Environ Res Public Health* 11:12368–12388



- Yaduma N, Kortelainen M, Wossink A (2013) Estimating mortality and economic costs of particulate air pollution in developing countries: the case of Nigeria. *Environ Resour Econ* 54:361–387
- Yerramilli A, Rao Dodla VB, Yerramilli S (2011) Air pollution, modeling and GIS based decision support systems for air quality risk assessment. In: Farhad N (ed) *Advanced air pollution*, vol. 2. Cambridge: MIT Press, Massachusetts, pp 23–47. ISBN:978-953-307-511-2

