Saurabh Sonwani
Anuradha Shukla *Editors*

Airborne Particulate Matter

Source, Chemistry and Health

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ISBN 978-981-16-5386-5 ISBN 978-981-16-5387-2 (eBook)
https://doi.org/10.1007/978-981-16-5387-2

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

In the early 1990s, it was thought that ozone was the principle air pollutant driving adverse health and environmental effects. However, a seminal publication by Dockery et al. (Dockery, D.W., Pope, C.A., Xu, X., et al., 1993. An association between air pollution and mortality in six US cities. N. Engl. J. Med. 329 (24), 1753–1759) demonstrated that fine particulate matter (particles with aerodynamic diameters $\leq$2.5 μm), generally referred to as $PM_{2.5}$, was the major driver of mortality in the six US cities that they had been studying. The other aspect of air pollution and health that was prevalent then was that the health effects were primarily respiratory. Again, as further studies of $PM_{2.5}$ took place, it became clear that the most prominent mortality cause was cardiovascular disease although substantial respiratory morbidity was also induced by exposure to $PM_{2.5}$ (U.S. Environmental Protection Agency, 1996. Air Quality Criteria for Particulate Matter, Report No. EPA/600/P-95/001aF, https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=2832). In the absence of biological mechanisms, the USA embarked on a major research program to better understand the role of $PM_{2.5}$ in inducing human health effects.

A major issue with understanding particulate matter effects is that it is not a single, clearly defined chemical species like the major gaseous pollutants (CO, O_3, SO_2, NO_2) that are the same compounds anywhere in the world. $PM_{2.5}$ varies in composition throughout a year even in a single location. The nature of emission sources varies widely between different societies ranging from simple three-stone fires burning biomass (wood, dung, bagasse, etc.) to tangentially fired gigawatt coal-fired power plants burning pulverized coal, but with coal having different mixtures of associated mineral matter. Thus, the primary particles from coal-fired power plants vary from location to location.

At the same time, combustion sources produce SO_2, NO_x, and often organic compounds that can then oxidize in the air. The addition of oxygen molecules leads to species that are less volatile and materials that can condense into pre-existing particles or nucleate to form new particles that can coagulate and grow to larger sizes. When inorganic gases oxidize, they form acids whereas when organic compounds are oxidized, they form peroxy radicals that can rearrange to alkoxy radicals that represent reactive oxygen species (ROS). Thus, there is a wide range of possible toxicants in airborne particles, but at this time, there is still limited understanding of the role of particle composition in inducing the adverse effects. Some

work has also been done on source-specific $PM_{2.5}$ and health outcomes that suggest that particles from certain source types that can induced effects while other source type particles did not. However, the relationships between compositions, concentrations, and health outcomes are still quite uncertain and regulations continue to use PM mass as the metric on which to base controls, likely leading to inefficiencies and additional costs in attaining the minimum of particulate initiated health outcomes.

In this volume, a range of topics related to PM issues are presented including PM sources, spatial and temporal variations, indoor–outdoor relationships, particulate chemistry, toxicology, environmental effects, control technologies and regulatory strategies are reviewed showing the progress that has been made over the past two decades.

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Preface

It is now a well-known fact that the airborne particulate matter is one of the rising global environmental problems. Coal power plants, industries and motor vehicles are the important anthropogenic emission sources of particulate matter. However, emission from the burning of biomass, crop residue and dung cake are also an increasing concern, especially in South Asia. Particulate matter releasing from a variety of sources affects air quality, atmospheric chemistry and health. These particles have both short- and long-term effects on atmospheric processes such as radiative forcing, cloud formation, monsoon and hydrological cycle. Such increasing particulate matter load is also responsible for respiratory, cardiovascular and gastrointestinal problems and found associated with the global burden of disease. Long-term exposure to ambient fine particulate matter is responsible for added extra cases of mortality. All the contributing authors have written their respective chapters in a simple language without any ambiguity. The objective of this book is to provide information and facts to the researchers working in the field of atmospheric science, environment and health. This book will not only be useful for teachers and research scholars, but also be of great value to policymakers in understanding the source and human health impact of ambient particulate matter.

Delhi, India

Saurabh Sonwani
Anuradha Shukla

Acknowledgement

First of all, we are indeed grateful to all the reviewers for their valuable comments and suggestions. The first editor (Dr. Saurabh Sonwani) wishes to convey his heartfelt gratitude to the Principal Zakir Husain Delhi College, University of Delhi. He acknowledges his wife, Dr. Pallavi Saxena for her constant motivation and support during compilation of the book. He also wishes to extend his acknowledgment to "The Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS)" for their encouragement for research and related activities. His sincere appreciation and gratitude to his parents Mr. Puttilal and Mrs. Shobha Devi for their love, care and encouragement. He also wishes to convey his regards to his sisters Mrs. Vandana Sonwani, Mrs. Neelam Sonwani and his brother, Mr. Gaurav Sonwani for their understanding in his tough time.

The second editor (Dr. Anuradha Shukla) acknowledges the help and assistance of staff during her tenure as Chief Scientist at Central Road Research Institute, CSIR, New Delhi. She also acknowledges her husband, Dr. Dilip Shukla, and daughters, Dr. Ankeeta Shukla and Ms. Akanksha Shukla, for their love and support.

We also wish to pay our sincere thanks to Ms. Aakansha Tyagi, Associate Editor, Springer, for her cooperation and help during this project.

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Saurabh Sonwani is currently working as Assistant Professor at the Department of Environmental Studies, Zakir Husain Delhi College, University of Delhi. Till now, he has 8 years of research and 3 years of teaching experience in the field of Atmospheric and Environmental Sciences. He has awarded Ph.D. from the School of Environmental Sciences, Jawaharlal Nehru University, New Delhi in the field of Environmental Sciences with specialization in Atmospheric Chemistry. He was awarded a Junior Research Fellowship (JRF) by the Council of Scientific and Industrial Research (CSIR) in the subject of Earth, Atmospheric, Planetary and Ocean Sciences in 2012. He also qualified from the University Grants Commission's National Eligibility Test (UGC-NET) in the subject of Environmental Sciences, conducted by the Government of India, in 2012, and was awarded the reputed Fall Meeting Student Travel Grant to attend the American Geophysical Union's (AGU) 2017 Fall Meeting in New Orleans, USA.

He completed his M.Phil. (Environmental Sciences) at Jawaharlal Nehru University and his M.Sc. (Environmental Sciences) from Banaras Hindu University, India. He has worked in the area of Carbonaceous Aerosol, Organic Pollutants, such as Polycyclic Aromatic Hydrocarbons (PAHs), Volatile Organic Compounds (VOCs) and Trace Metals. He has published more than 10 book chapters and more than 20 research publications in high impact factor journals in the areas of air pollution, global warming, air pollution exposure assessment and its impact on human and plant health. He has also published an authored book *Criteria Air Pollutants and their Impact on Environmental Health* and an edited book *Greenhouse Gases: Sources, Sinks and Mitigation* with Springer publisher.

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Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
AD	Aerodynamic diameter
AERMOD	Atmospheric dispersion module
AIHA	American Industrial Hygiene Association
AOD	Aerosol optical depth
API	Anticipated performance index
APM	Atmospheric particulate matter
APTI	Air pollution tolerance index
BAM	Beta attenuation monitoring
BC	Black carbon
BEV	Battery-related vehicle
BSOA	Biogenic secondary organic aerosols
CAAQMS	Continuous ambient air quality monitoring stations
CBPF	Conditional bivariate probability function
CC	Carbonate carbon
CCN	Cloud condensation nuclei
CFB	Circulating fluidised bed
CNG	Compressed natural gas
CO	Carbon monoxide
COPD	Chronic obstructive pulmonary disease
CPCB	Central Pollution Control Board
CPF	Conditional probability function
CRP	C-reactive protein
CTDMPLUS	Complex Terrain Dispersion Model
DALY	Daily-adjusted life year
DMS	Dimethylsulphide
DOCs	Diesel oxidation catalysts
DPFs	Diesel particle filters
DRH	Deliquescence relative humidity
DS	Dust storm
EC	Elemental carbon
EDX	Energy dispersive X-ray
EI	Emission inventory

EU	European Union
FCV	Fuel cell vehicle
FEM	Federal equivalent method
FRM	Federal reference method
FVC	Forced vital capacity
GBD	Global burden disease
GC-MS	Gas chromatography–mass spectrometry
GHGs	Greenhouse gases
GWR	Geographically weighted regression
H_2O_2	Hydrogen peroxide
HAP	Household air pollution
HF	Heart failure
HNO3	Nitric acid
HP	Hypersensitivity pneumonitis
HPLC	High performance liquid chromatography
HR	Heart rate
HRV	Heart rate variability
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
IAP	Indoor air pollution
IAQ	Indoor Air Quality Association
IGP	Indo-gangetic plain
IPCC	Intergovernmental panel for climate change
IPM	Inhalable particulate matter
LDV	Low duty vehicle
LRTAP	Long-range transport of air pollutants
NAAQS	National ambient air quality standards
NOAA	National Center for Marine Atmospheric Research
NOx	Nitrogen oxides
O_3	Ozone
OC	Organic carbon
ODTS	Organic dust toxic syndrome
OH	Hydroxyl radical
OP	Oxidative potential
OSHA	Occupational Safety and Health Administration
PAHs	Polycyclic aromatic hydrocarbons
PAR	Photosynthetically active radiation
PF	Penetration factor
PM	Particulate matter
POPs	Persistent organic pollutants
PSCF	Potential source contribution function
RH	Relative humidity
ROS	Reactive oxygen species
RPM	Respirable particulate matter
RWC	Relative water content
SARS	Severe acute respiratory syndrome

SEM	Scanning electron microscopy
SIA	Secondary inorganic aerosols
SO_2	Sulphur dioxide
SOA	Secondary organic aerosol
SSA	Single scattering albedo
TEOM	Tapered element oscillating microbalance
TMS	Traffic management strategies
TPM	Thoracic particulate matter
UFP	Ultrafine particles
UNECE	United Nations Economic Commission for Europe
USEPA	United States Environmental Protection Agency
VOCs	Volatile organic compounds
WHO	World Health Organization
WSII	Water-insoluble inorganic ionic species
ZEV	Zero emission vehicle

Introduction to Airborne Particulate Matter: Source, Chemistry and Health

1

Saurabh Sonwani and Anuradha Shukla

Abstract

The problem of airborne particulate matter is rising since past few decades, and now it has been a major cause of concern for air quality, climate and environmental health, especially for the developing nations. Characteristics of the particulate matter depend on their source of origin, morphology and composition. Variety of airborne particulate participates in the atmospheric chemistry and physics and impacts on human health after their exposure. The present chapter provides a brief outline of the airborne particulate matter with respect to their source, chemistry and health impacts on human health. It also mentioned the important source apportionment analysis used for possible source identification. Secondary aerosol formation through gas-to-particle conversion and atmospheric deposition process (dry and wet deposition) for the removal of particulate matter was also discussed in detail. The adverse effect of increasing level of ambient particulate matter through various exposure pathways (inhalation, ingestion and dermal) was also mentioned. Such expose can cause cardiopulmonary and lung cancer-related issues and is responsible for the increase in the rate of mortality. Thus, it was suggested that by following the ambient air quality standards, the average life expectancy can be improved across the world.

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_1

Keywords

Particulate matter · Emission source · Atmospheric process · Human health

1.1 Introduction

Airborne particulate matters, consisting of solid or liquid particles suspended into the atmosphere, may be a complex mixture of organic chemicals, metals, and soil or dust particles. Such particulates range in size from few tens of Ångstroms to several hundred micrometres. Particulate matters (PMs) are classified on the basis of their size range, source of origin, chemical composition and effects. PMs are originated from variety of natural (dust, sea salt, forest fire and volcanic eruption) and anthropogenic sources (traffic, coal combustion, industries and biomass burning). It can be categorized into primary (directly release from their sources) and secondary pollutants (form through atmospheric chemical transformation reaction) on the basis of their origin. Source apportionment studies are performed to identify the possible source of the particulate matters in the atmosphere. The finer particles comprise the secondary aerosol, combustion particles, and recondensed metallic and organic vapours. Finer particles also contain carbonaceous fraction of fine particles that consist of elemental carbon (produced by incomplete combustion) and organic carbon (produced by combustion exhaust and secondary organic compounds formed by photochemistry). These constituents are the most abundant in fine particles after sulphates. Additionally, sulphates and nitrate are designated as the most abundant chemical species along with coarser PM. However, the most common combination of the coarser particles consists of oxides of silicon, aluminium, calcium and iron. The size of airborne particulate matter differs over different orders of magnitude (Fig. 1.1). Coarser PM, less than 10 μm or less in diameter, is considered as PM_{10}, whereas finer particles (PM less or equal to 2.5 μm in diameter) are considered as $PM_{2.5}$.

The coarse mode particles are mechanically produced by the break-up of larger solid particles. These particles can be originated from resuspension of soil dust during agricultural processes, uncovered land or mining operations. Seal salt spray, pollen grain and resuspension of road dust are also considered as coarse mode particles. Fine mode particles are largely produced from gases. The particle less than 0.1 μm is formed by the condensation of low vapour pressure substances or by atmospheric chemical reactions. Gas or vapour molecule is attached on the particle surfaces resulting in increase in the particle size, known as condensation, and it is the most common process in the finer particles, whereas the coagulation is the most efficient for large numbers of particles.

Apart from size and shape of the particle, the chemistry of the PM is very much dependent on its chemical composition. Inorganic ions and organic compounds constitute a major fraction of the particulate matter, while elemental carbon (EC) also known as black carbon (BC) contributes to a lesser fraction (Krivacsy et al. 2001). The concentration of different inorganic ions has been reported by several studies across the world, whereas the data for carbonaceous components are

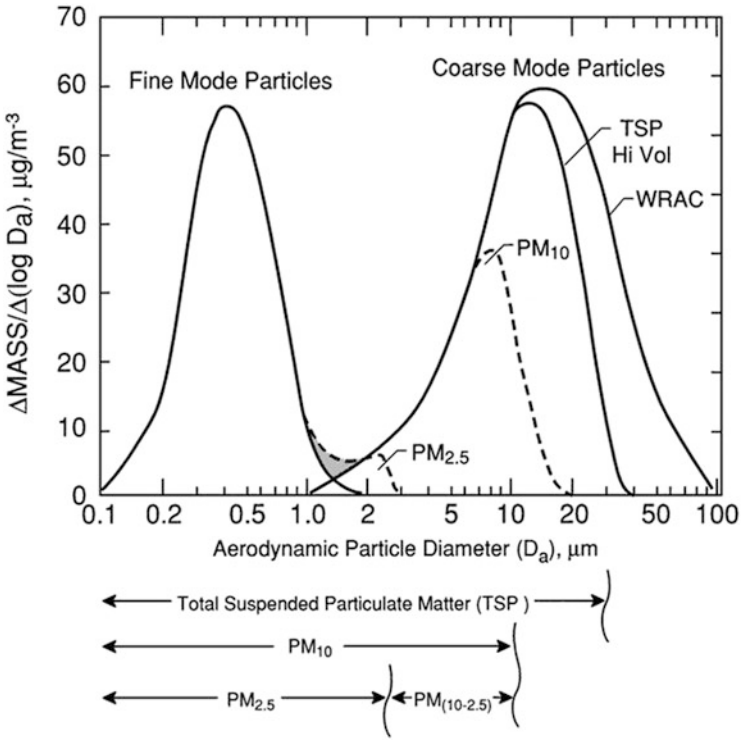

Fig. 1.1 Schematic illustration of the size distribution of airborne particulate matter in atmosphere (USEPA 1996)

still limited due to the unavailability of instrumentation facility for OC and EC quantification. In the recent decade, new instrumentation facility (aerosol mass spectrometry, thermal–optical carbonaceous analysers) has been introduced for the quantitative determination of the OC and EC fraction, which confirmed their dominant fraction of the fine particulate matter emitted from variety of sources (Zhang et al. 2007; Sonwani et al. 2021a, b). The sources of such carbonaceous aerosol can be different in urban area from rural area. In most of the cases, predominant source of carbonaceous aerosol in urban area is emission from coal thermal power plants, motor vehicles, biomass burning and industries.

The gas-to-particle conversion is another way for the formation of aerosol through nucleation process (Anisimov 2003). In this process, gases present in the atmosphere are transformed into condensable molecular species, e.g. formation of nitric acid from NO_2 and sulphuric acid from SO_2. A number of studies mentioned the formation of secondary aerosol (SA) through the chemical reactions are a significant fraction of PM in Asian region (Balachandran et al. 2000; Kulshrestha et al. 2009; Huang et al. 2014; Sudheer et al. 2015; Sonwani and Saxena 2021). The physical and chemical properties of secondary organic aerosol (SOA) and secondary inorganic aerosol (SIA) are different from the aerosol that is directly released into the

atmosphere from any source. Therefore, their impact on climate, visibility and health can be significantly different. The water-soluble fraction of SOA and SIA within PM can also affect their hygroscopic properties (Sonwani and Kulshrestha 2019). Source apportionment of carbonaceous aerosol and their fraction has been carried out by several studies across the world. Chemical mass balance (CMB), principal component analysis (PCA) and positive matrix factorization (PMF) are the most common source apportionment analysis used for the PM and their chemical components (Khillare et al. 2004; Gupta et al. 2007; Salim et al. 2019; Jain et al. 2020).

Atmospheric dry deposition and wet deposition are important atmospheric processes to reduce PM load in the atmosphere. Dry deposition of PM refers to its deposition through the direct delivery of mass to the surface (Dolske and Gatz 1985). On the other hand, wet deposition chemistry of PM is referred as the scavenging of PM through 'rainout particles/in-cloud scavenging' (undergoing capture by cloud water) and as 'washout/below-cloud scavenging' (removal of below-cloud particles by raindrops as they fall) (Sonwani and Kulshrestha 2019; Sonwani et al. 2021a). Fine PM can play a significant role in the formation of cloud condensation nuclei (CCN) during the process of cloud formation. Several studies also reported the role of atmospheric PM in radiative forcing, global carbon cycle, climate change and environmental health (Sonwani et al. 2021b; Jolliet et al. 2018; Jimoda 2012; Saxena and Sonwani 2019a, b). PM_{10} particles are also considered as respiratory suspended particulate matter (RSPM) as they are capable of penetrating deep inside the lungs and cause several adverse health-related issues (Sonwani et al. 2022). $PM_{2.5}$ particles are the most harmful among all air pollutants, as they can easily enter inside the alveoli and subsequently stuck to the lung parenchyma (Pope et al. 1992). The short-term exposure of $PM_{2.5}$ can worsen the condition of patient suffering from asthma and bronchitis, whereas long-term exposure can cause cardiovascular problems, respiratory disorders and lung cancer (Turner et al. 2011; Sonwani and Kulshreshtha 2016).

PM exposure causes various environmental health issues. The effect of PM exposure to human health is widely known and discussed across the world. There are several routes of PM exposure viz. inhalation, ingestion and dermal exposure, in which inhalation exposure is the most common route of exposure in human beings. The effects of the exposed particulate on health depend on its size, shape, concentration and chemical composition of the PM in surrounding environment (Pope III and Dockery 2006; Kelly and Fussell 2012; Saxena et al. 2017; Sonwani et al. 2021a, b; Sonwani and Kulshreshtha 2016). People's age, gender, immunity and occupancy of a person in a particulate environment are other important factors to decide the overall impact of air pollutants on human health (Kan et al. 2008; Kim et al. 2013; Goel et al. 2021). PM exposure causes 3% and 5% cases of cardiopulmonary and lung cancer-related mortality globally. In European countries, this fraction is ranged between 1–3% and 2–5%, respectively (Cohen et al. 2017). It was also estimated that the annual exposure of $PM_{2.5}$ causes 3.1 million deaths and around 3.1% of global disability-adjusted life years (Lim et al. 2012). Thus, the average life expectancy of any population is decreased due to $PM_{2.5}$ exposure. Studies also reported that the average life expectancy increased after following the air quality guidelines of WHO (Goel et al. 2021; Sonwani et al. 2021c; Nagpure et al. 2017).

1.2 Summary of Chapters

Second chapter provides an overview of particulate matter in atmosphere viz. sources, emissions and classification according to size, dynamics, properties and characteristics in atmosphere. The chapter also details the optical and radiative properties.

Third chapter summarizes the geographical distribution and dispersion of particulate matter under the influence of the role of meteorological parameters. It also discusses the air dispersion model and statistics that are employed to observe the path and travel of pollutants.

Fourth chapter discusses briefly the abundance, measurement and characteristics of airborne particles in indoor and outdoor environments. This chapter also includes the possible impact of indoor and outdoor particulate on environmental and human health.

Fifth chapter includes detailed insight about some of the important observations on temporal variability and processes from high-resolution atmospheric data set of aerosols and reactive gases. This chapter also highlights the utility of other Continuous Ambient Air Quality Monitoring Stations in India for the exploration of air quality research, public health and awareness, and policy decision-makers.

Sixth chapter presents a detailed review on the characterization of primary and secondary airborne particulates with a brief outline of emission sources of primary and secondary particles to identify the main sources of origin, chemical structure and size distribution of particles.

Seventh chapter provides the information regarding regulations and standards of fine particles and discusses the primary and secondary sources of fine particulate pollution. This chapter demonstrated the biological and chemical components of fine particles that play a critical role in the toxicological implications of fine particulates. This chapter also provides an overview of the molecular mechanisms connecting fine particulate exposure and health effects.

Eighth chapter discusses and provides an overview on the various types of bioaerosols, their probable sources, emission mechanism and classification. It also discusses bioaerosol toxicity and related disease due to exposure in indoor and outdoor environment.

Ninth chapter primarily focuses on the impact of respirable particulate exposure on cardiopulmonary, nervous system and related mortality. It also provides information about the epidemiological and experimental studies demonstrating the effects of airborne particles on human health and related mechanism of toxicity.

Tenth chapter reviews the significant impact of particulate pollution on plant species by considering their morphological characteristics, reproduction and biochemical parameters and physiological parameters. This chapter also mentioned tolerance and sensitivity of plants in relation to particulate pollution that can be helpful in greenbelt development and landscape planning.

Eleventh chapter provides a comprehensive review of the tools, technologies and approaches employed to manage and mitigate ambient particulate matter. The authors propose a framework for the management of PM considering the entire

impact pathway of PM, from source to the receiving environment, and mentioned that the management of PM needs to be approached holistically.

Twelfth chapter is an attempt to understand the policies and regulation related to PM across the world in transport sector across the world. This chapter also provides a detailed review of the particulate policy regulation in the transport sector and also describes the science–policy gaps in regulation of air pollution.

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Emission Sources of Particulate Matter

2

Swagata Payra, Preeti Gunwani, and Sunita Verma

Abstract

Particulate matter is recognised to have profound effect on environment and climate changes. It is essential that the sources of particulate matter in atmosphere are well understood and quantified to provide a sound basis for formulating policies for the reduction in anthropogenic influences on climate. For the formulation of preliminary estimate of particulate matter burden and impacts, it is necessary to know the relative importance of generation of these particles and the relevant pathways in atmosphere. This chapter provides an overview on emission sources of particulate matters in the atmosphere. The chapter also details the optical and radiative properties.

Keywords

Particulate matter · Emission source · Composition · Dynamics · Properties

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_2

2.1 Introduction

Air pollution occurs when gases, chemicals or particles in the air are present in the concentration that can harm the health of humans, animals and plants. Rapid industrialisation and urbanisation over the past few decades have led to high levels of outdoor pollution throughout the world, and air pollution has become a major environmental and public health challenge. WHO data show that 9 out of 10 people breathe air containing high levels of pollutants and estimated death toll of seven million people worldwide every year due to air pollution (WHO 2018). Greenstone et al. (2015) estimated that half of the Indian population (660 million) is living in the areas where air pollution levels exceed the National Ambient Air Quality Standard (NAAQS) for fine particulate pollution. Venkataraman et al. (2018) indicated that 99.9% of Indian population resides in areas where the World Health Organization (WHO) Air Quality Guideline of 10 μg/m^3 is exceeded. Thus, among all the air pollutants, particulate matter has been identified as the most critical pollutant. These fine particles are of great concern as they give rise to health-related air pollution risks on urban scales, reduce visibility on regional scales and suppress the rainfall leading to weaker hydrological cycle (Kampa and Castanas 2008; Gurjar et al. 2010; Mohan and Payra 2009; Jaswal et al. 2013; Ramanathan et al. 2001).

2.2 Classification of Particulate Matter

Particulate matter (PM) can be classified into four distinct groups based on number, surface area and volume distributions—nucleation, Aitken, accumulation and coarse mode (Fig. 2.1). Classification of particulate matter into different modes and size bins is very significant to understand their physical, chemical and optical properties, as well as their health impacts. Atmospheric particles undergo different processes in the atmosphere such as formation (gas-to-particle conversion and photochemical reactions), growth (coagulation and condensation) and removal (deposition and washout). These particles are distinct in their properties and compositions and have different atmospheric lifetimes.

- Nucleation mode—These particles have diameters smaller than 0.01 μm. They are emitted into the atmosphere directly due to combustion processes or formed in the atmosphere by gas-to-particle conversion processes. Nucleus particles have very short atmospheric lifetimes, and their concentrations reduce rapidly with increasing distance from the source. These particles move under Brownian motion, collide with adjacent particles and then coagulate and condense upon existing particles.
- Aitken mode—These particles have diameters extending from 0.01 to 0.1 μm. Aitken mode particles are formed by coagulation and condensational growth of nucleation mode particles. They also have a short lifetime and get lost by coagulation with larger particles.

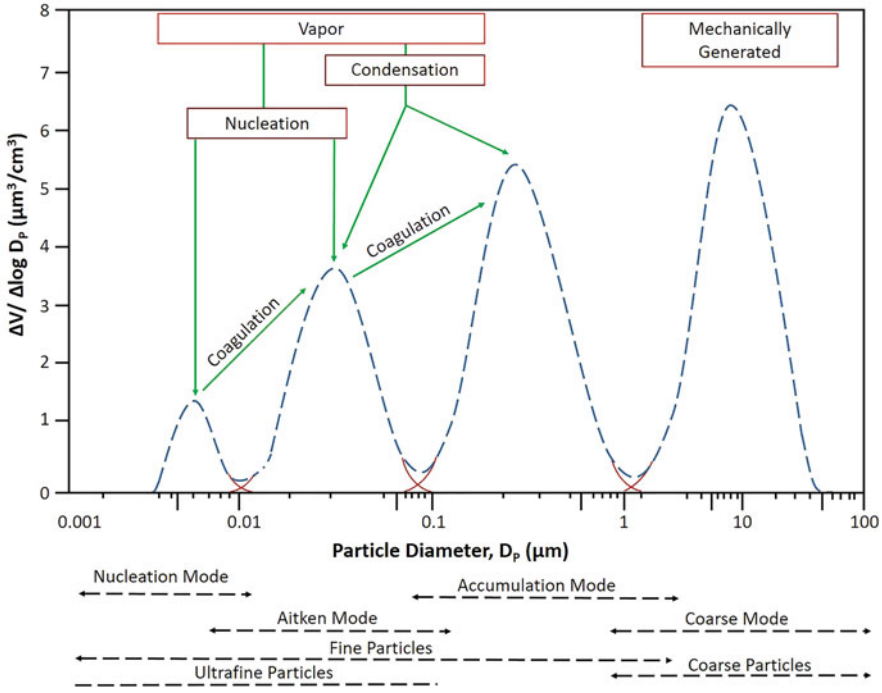

Fig. 2.1 Illustration of different modes in a typical atmospheric particle volume distribution (adapted from Araujo and Nel 2009)

- Accumulation mode—These particles have diameters extending from 0.1 to 1.0 μm. They are emitted into the atmosphere either due to incomplete combustion of fuels or due to coagulation of nucleation/Aitken mode particles. These particles are aerodynamically stable and have a relatively longer lifetime in the atmosphere, thus tend to accumulate in the atmosphere.
- Coarse mode—These particles have diameters larger than 1.0 μm and are emitted via mechanical abrasion processes. The coarse mode particles are introduced into the atmosphere via both natural (wind-blown dust, large salt particles from sea spray) and anthropogenic sources (agricultural and industrial processes). Since coarse particles have relatively larger size, they have a short lifetime in the atmosphere and readily settle down by sedimentation.

The number concentration of the particles is usually dominated by nucleation and Aitken mode fine particles, whereas the particle surface area and volume (and thus mass) are dominated by accumulation and course mode larger particles.

For health purposes, particulate matter is typically defined by size, within certain size classes (Fig. 2.2) as follows:

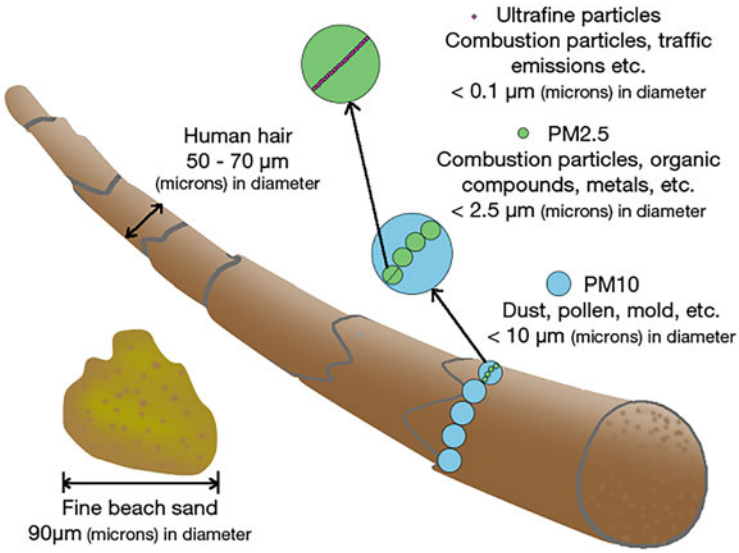

Fig. 2.2 Size comparison of particles (https://www.epa.gov/pm-pollution/particulate-matter-pm-basics)

Total suspended particulates (TSP)—with diameter $\leq$ 30 µm;
Coarse particulates (PM10)—with diameter $<$ 10 µm;
Fine particulates (PM2.5)—with diameter $<$ 2.5 µm; and.
Ultrafine particulates (PM0.1)—with diameter $<$ 0.1 µm.

There is a huge concern in public health community about the adverse effect of these particulates on human health. They have the ability to penetrate and deposit on the respiratory tract. Ultrafine particulates can reach the most distal alveolar lung region and cause respiratory and cardiovascular illnesses.

Thus, to safeguard the public health and protect the environment air quality regulations are made and standards are set up around the world to support a safe threshold level of exposure. Based on known health effects, both short-term (24-h) and long-term (annual mean) guidelines are provided. Air Quality Index (AQI) is a measure of air quality keeping the heath in consideration. The AQI is based on the five major air pollutants where particulate matter is major contributor. According to Clean Air Act, particle pollution ($PM_{2.5}$ and PM_{10}), ozone (O_3), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and carbon monoxide (CO) are main parameter. We can also use ammonia (NH_3), lead (Pb), etc., for calculation of AQI. For each of these pollutants, the concentration of the pollutant in the air is converted to a number on the AQI. The WHO guideline stipulates that $PM_{2.5}$ should not exceed 10 µg/m^3 annual mean or 25 µg/m^3 24-h mean; and PM_{10} should not exceed 20 µg/m^3 annual mean or 50 µg/m^3 24-h mean. Central Pollution Control Board (CPCB) in India also set up National Ambient Air Quality Standards (NAAQS) under the Air (Prevention

Table 2.1 AQI scale 0–500 (units: μg/m^3 unless mentioned otherwise)

AQI category (range)	PM_{10} (24 h)	$PM_{2.5}$ (24 h)
Good	0–50	0–30
Satisfactory	51–100	31–60
Moderately polluted	101–250	61–90
Poor	251–350	91–120
Very poor	351–430	121–250
Severe	>430	>250

and Control of Pollution) Act 1981. The CPCB guideline stipulates that $PM_{2.5}$ should not exceed 40 μg/m^3 annual mean and 60 μg/m^3 24-h mean; and PM_{10} should not exceed 60 μg/m^3 annual mean and 100 μg/m^3 24-h mean (Table 2.1). Indian Standards are slightly less stringent as compared to WHO guidelines.

2.3 Sources of Particulate Matter

Air pollutants consist of a complex combination of gases and particulate matter (PM). Particulate matter is made up of a collection of solid and/or liquid materials of various sizes that range from a few nanometres in diameter (about the size of a virus) to around 100 micrometres (100 μm, about the thickness of a human hair).

PM is either emitted directly from the source into the atmosphere (**primary**) or formed due to chemical transformation of the primary particulates in the atmosphere through gas-to-particle conversion (**secondary**). Primarily, all the emission sources contributing to atmospheric PM concentration are classified into two categories namely stationary and mobile sources. Further, these sources can be sub-categorised based on the nature of origin (natural and anthropogenic) and processes involved in emission (combustion and non-combustion). Sources of **primary** particulate matter can be both **natural** (Fig. 2.3) and **anthropogenic** (Fig. 2.4) in nature. The bulk of aerosols by mass have natural origins. Anthropogenic PMs are less abundant than natural PMs, but they dominate the air downwind of urban and industrial areas. Annual global emission flux of natural and anthropogenic particulates from various sources is estimated to be 5875 Tg/year and 440 Tg/year, respectively (IPCC 2001).

In this section, effective classification and sub-classification of PM emission sources have been presented.

2.3.1 Stationary Sources

In air quality terminology, stationary source is defined as a fixed emitter of pollutants in the atmosphere (in this case PM). The nature of origin of pollutant can be both natural (e.g. forest fire and volcanic eruption) and anthropogenic (e.g. industries, biomass burning, construction activity and cooking activity). A few examples of natural and anthropogenic stationary emission sources are described below.

Fig. 2.3 Sources of natural particulate matter (https://www.pexels.com/)

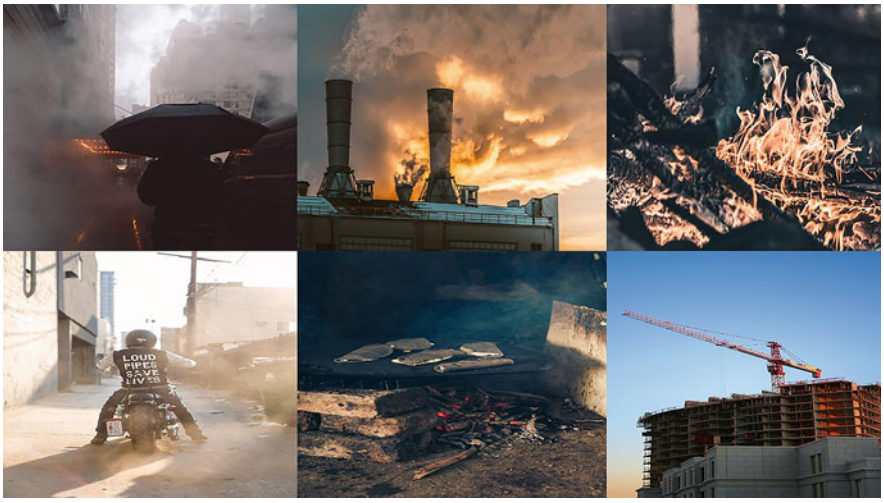

Fig. 2.4 Sources of anthropogenic particulate matter (https://www.pexels.com/)

2.3.1.1 Natural Stationary Sources

Particulate matter originates naturally from a variety of stationary sources. Out of these, two most prominent sources are volcanic eruptions and wildfires.

- *Volcanic eruptions* inject large quantities of ash and gases into the atmosphere. The particles ejected from volcanoes in the form of dust and ash consist of substances like minerals, silicates and metallic oxides; and gases like carbon dioxide, water vapour and sulphur dioxide. The scattering and absorbing

properties of volcanic particles affect the Earth's radiation budget. Volcanic eruption of Mount Pinatubo in 1991 injected about 15 million tons of sulphur dioxide, where it reacted to form sulphuric acid droplets and increased the aerosol optical depth of the atmosphere. This resulted in reduction in global mean air temperatures, by up to 0.5 °C at the surface and 0.6 °C in the troposphere, for some months (Parker et al. 1996).

- *Wildfires* are the uncontrolled fires in natural areas like forest, grassland, savannas and prairie. They can start during dry weather with natural occurrence like lightning or due to human-caused spark. Particulate fraction of wildfire consists of small smoke particles mainly having submicron sizes. These fires cause health and safety hazards, affect the air quality, change the cloud microphysical processes and reduce the visibility to a few metres. Wildfire smoke is highly variable in terms of physical properties and chemical composition (Patterson and McMahon 1984; Jain et al. 2021).

2.3.1.2 Anthropogenic Stationary Sources

Particulates formed from **anthropogenic activities** are due to fossil fuel combustion from power plants, industries and residential sector; agricultural activities; and stubble burning and construction activities.

- Emissions from *power plants* contain fine particulate matter precursors. In India, *power plants* majorly use coal (50–55%) for electricity production and account for 15% for $PM_{2.5}$ estimated annual anthropogenic emissions (GAINS 2012). 503 million tons of coal was consumed at the power plants in India with a total capacity to generate 120,727 MW of electricity in 2010–2011 (CEA 2011), and the demands for power are further increasing at a rapid rate.
- Major *industries* such as cement, iron and steel, brick, fertiliser, aluminium, glass, paper and chemical use fuels such as coal (51%), petroleum products (16%) and electricity (13%) to meet energy demands for manufacturing products (Sharma et al. 2016).
- Fossil fuel combustion from r*esidential sector* is used mainly for the purpose of cooking, lighting and heating. In the residential sector, fuel choices include fuel wood, dung cake, crop residue, coal (solid fuels); kerosene (liquid fuel); and LPG, natural gas and biogas (gaseous fuel). In rural households, fuel wood (60%), crop residues (12%) and cow dung cakes (11%) are mainly used (Census of India 2011).
- *Agricultural activities* contribute to particulates majorly from livestock, land preparation, crop harvesting, pesticides, erosion due to wind and crop residue burning. The stubble burning is a common practice in agriculture after harvesting as a low-cost action to reduce the time between harvesting and sowing for the second winter crop. Open burning of crop residue is a major source of fine particulate matter during the months of October and November each year in the area of Indo-Gangetic Plains (IGP), which significantly impacts the regional air quality.

- Processes of *construction activities* such as land clearing, demolition, transportation of materials and operation of machines contribute to particulate pollution.

2.3.2 Mobile Sources

A mobile source is defined as any source that is non-stationary or moving. Examples of mobile PM emission sources are sea spray, wind-blown dust, automobiles and various other vehicles. Mobile sources can also be further classified into natural mobile sources and anthropogenic mobile sources.

2.3.2.1 Natural Mobile Sources

Major natural mobile sources, i.e. biological particles, wind-blown dust and sea salt, are discussed below.

- *Biological particles* are solid airborne primary particles derived from fragments of biological materials such as plant debris (cuticular waxes, leaf fragments), humic matter, animal dander and microbial particles (bacteria, fungi, viruses, algae, pollen, spores, litchen, protozoa, archaea). These particles exhibit a large variety of shapes and cover a wide size range from 1 nm to 100 μm. Primary biogenic particles have the ability to act as both cloud droplet and ice nuclei (IPCC 2001; Després et al. 2012).
- *Dust particles* originate from arid and semi-arid regions or areas with little or no vegetation with the action of strong winds. Normally, size of wind-blown dust can range from 0.1 to 20 μm. Dust can interact with atmospheric radiation directly (scattering and absorbing radiation) or indirectly (by acting as cloud condensation nuclei or ice nuclei), and impact the atmospheric visibility. An accurate information of particle size distribution, morphology and chemical composition of dust is key to estimate the magnitude of its impacts on atmosphere (Formenti et al. 2011).
- *Sea spray particles* are formed through wave breaking at the ocean surface and represent one of the most abundant sources of natural aerosols. Size range of these particles is about 0.05–10 μm diameter and has a correspondingly wide range of atmospheric lifetimes. Sea spray particles have the ability to scatter light and serve as cloud condensation and ice nuclei, thus impact Earth's radiation budget (Bertram et al. 2018).

2.3.2.2 Anthropogenic Mobile Sources

Two of the most dominant anthropogenic mobile source contributing significantly to the atmospheric PM concentration, i.e. transportation and entrainment of road dust into the air, are discussed below.

- *Transport sector* emits different kinds of emissions (primary PM emissions from exhaust; organic and inorganic gaseous PM precursors from the fuel combustion) from various vehicle types. There has been rapid growth in transport sector in India that has led to increase in particulate pollution from vehicular sources.

- *Road dust* is dust lying on roads that gets resuspended in air due to vehicular movement. This dust can include wear and tear from the tyres, small gravels and asphalt.

There is a higher contribution of the transport sector at the urban scales compared to national scales (CPCB 2011). The BC emissions are dominated by diesel-driven vehicles, whereas OC emissions are dominated from gasoline-driven vehicles (Sonwani et al. 2021). According to Sharma et al. (2016), PM_{10} emissions are dominated by the industrial (36%) and residential combustion (39%) sectors. Power plant contributes 4%, whereas transport contributes 3% at the national scale. According to study conducted by IIT Kanpur (DPCC 2016), sources of PM10 and PM2.5 contributing to ambient air quality during summer include coal and fly ash (37–26%), soil and road dust (26–27%), secondary particles (10–15%), biomass burning (7–12%), vehicles (6–9%) and waste burning (8–7%), whereas that during winter include secondary particles (25–30%), vehicles (20–25%), biomass burning (17–26%) and waste burning (9–8%).

2.3.3 Secondary Particulate Matter

Secondary particles are formed in the atmosphere through oxidation of precursor gases—NH_3, SO_2, NO_X and organic compounds via gas-to-particle conversion. Sulphates, nitrates, ammonium and secondary organic compounds are the most common secondary particulates. These particles are subject to growth and transformations on the surface of existing particles.

2.4 PM Emission Inventory: Global Approach

Air pollutant emission inventory is an all-inclusive list of pollutants from all emission sources in a given geographic region for the given time period. In order to create a reliable emission inventory for a particular region, the subsequent procedure can be followed:

1. Make a record of all the types of emission sources,
2. Ascertain the kinds of pollutant emission from each of the listed sources,
3. Find out the emission factor (EF) for each of the pollutants,
4. Ascertain the number and size of specific sources in the region and.
5. Multiply the appropriate numbers from steps (3) and (4) to obtain the total emissions and then sum up the similar emissions to obtain the total for the region (Bang and Khue 2019).

The data sets in emission inventories are used to determine the amount of air pollutants being emitted to the atmosphere, produced from natural or anthropogenic sources, at a definite geographic region for a given time period. Emission inventories

Table 2.2 Inventories including particulate matter (PM) emissions (list is not exhaustive)

	Spatial resolution	Temporal resolution	Species considered (only PM and related species are listed)	Source
EDGARv4.2 (Global)	0.1° × 0.1°	Annual, 1970–2008	PM_{10}	Janssens-Maenhout et al. (2011)
EDGAR-HTAP_v2 (Global)	0.1° × 0.1°	Annual, 2008–2010	PM_{10}, $PM_{2.5}$, BC and OC	Janssens-Maenhout et al. (2015)
GEIA (Global)	1° × 1°		BC only	Penner et al. (1993)
GAINS (Europe)	50 × 50 km	Annual, 1990–2030	BC, OC, TSP, PM_{10}, $PM_{2.5}$	Kupiainen and Klimont (2004)
EMEP (Europe)	0.1° × 0.1°	Annual, 1980–2013	PM_{10}, $PM_{2.5}$	http://www.ceip.at/
TNO-MACC-II (Europe)	1/8° × 1/16°	Annual, 2003–2009	PM_{10}, $PM_{2.5}$, OC and EC	Kuenen et al. (2014)
REAS 2.1 (Asia)	0.25° × 0.25°	Monthly, 2000–2008	PM_{10}, $PM_{2.5}$, BC and OC	Kurokawa et al. (2013)
REASv3 (Asia)	0.25° × 0.25°	Monthly, 1950–2015	PM_{10}, $PM_{2.5}$, BC and OC	Kurokawa and Ohara (2020)
MIX (Asia)	0.25° × 0.25°	Monthly, 2008 and 2010	PM_{10}, $PM_{2.5}$, BC and OC	Li et al. (2017)

Note: Only global- and continental-level emission inventories are listed

are generally recognised as key inputs in modelling studies and where prediction of pollutant concentration is to be determined. Some of the most widely used emission inventories to ascertain particulate matter (PM) emissions and its damaging effects on ambient air quality are listed below (Table 2.2).

2.4.1 Development Methods

Emission inventories for air pollutants may be collected and developed using various methods, out of which two of the most common methods are as follows: bottom-up method and top-down method. The bottom-up method of estimating pollutant emission is based on the emission rates of that particular pollutant. On the contrary, top-down method utilises ambient observations for emission inventory development. Both of the aforementioned approaches are discussed in detail.

2.4.1.1 Bottom-Up Method

Emission estimates utilised in the bottom-up approach are based on three factors namely activity factor, emission factors and control factors, as expressed in Eq. (2.1) (Simon et al. 2008).

$$\text{Emission rate} = \text{Activity factor} * \text{Emission factor} * \text{Control factor} \tag{2.1}$$

where

Activity factor describes emission source use,
Emission factor is the amount of pollutant released per unit activity, and
Control factor is the fractional decrease in pollutant release by an air pollution control device (APCD).

Some examples representing activity factors can be the amount of diesel burned by a non-mobile source annually or the distance covered by any vehicle in a month. Representatives of emission factors can be pollutant emissions per unit mass of coal combusted or pollutant emissions per kilometre distance covered by the vehicle. In general, emission factors are supposed to be indicative of long-term arithmetic means for all emission sources listed in the category. The emission factors may need modifications to transform the activity into spatial and temporal units appropriate for the emission inventory, and it is preferable to have emission factors for particulate matter that describes its size and composition (Simon et al. 2008). Emission factors for PM are assembled in numerous scientific literatures and government reports. Control factors represent the fractional decrement of the unrestrained discharge by an air pollution control device used afore the emission point of pollutant. Control factors may differ from one source type to another and also, by area in consideration, since pollution regulation is often assigned by local or state agencies. The emissions for each source category are calculated using Eq. (2.1) and emission factors.

2.4.1.2 Top-Down Method

Numerous computational and analytical methods are used to compare PM concentration observational data sets to data present in PM emission inventories. These methods can also be utilised to deduce whether the relative emission rates in the inventory are correct or whether emission sources are missing from the inventory. Among these methods are chemical transport models, source receptor models and trajectory analyses.

2.4.2 Emission Factor

An emission factor is the amount of pollutant released per unit activity. It is a relative measure and can be used to estimate emissions from multiple sources of air pollution. Emission factors are often developed for specific sources but are then applied as

is or with minor modifications based on engineering assumptions to other related sources. It is possible that surrogate factors and/or size and speciation profiles will be used in early PM planning activities, simply because factors and profiles will not be available for all sources. Many of the emission factors and distribution profiles that are available today were developed several years ago and may not be representative of current operating and production conditions. Emission factors are generally assumed to be representative of long-term averages for all sources in the emission category represented by the emission factor. The emission factors may require adjustment to convert the activity into a temporal and spatial unit suitable for the inventory, and it is desirable to have emission factors for PM that specifies PM composition and size. Examples of emission factors are the emissions per kilometre travelled by an automobile or the emissions per mass of fuel combusted. Due to the lack of data monitoring from factories, emission factors are adopted.

2.5 Composition of Particulate Matter

Chemical compositions of atmospheric particles are highly diverse and vary by time, season, source and location. These particles are generally composed of elements, metals, sulphates, nitrates, ammonium and carbonaceous material (Fig. 2.5). Particulate matter within a given size mode or size bin can be either externally mixed (when distinct, homogeneous chemical species occur within the same particle) or internally mixed (when each particle is composed of a single chemical species). Mixing state of aerosol particles tends to change with transported distance, relative humidity and in polluted atmosphere.

- Elements and metals—Mineral particles coming from rock, soil, construction and road dust are generally rich in elements such as silicon, aluminium, calcium and iron. Sea salt is rich in sodium and chloride. Potassium particles come from open agricultural biomass burning. Iron, zinc, lead, copper, vanadium, nickel, chromium and manganese come from combustion processes and industrial activities (Saxena et al. 2020; Sonwani and Kulshrestha 2018). These insoluble metal particles are generally mixed with sulphate, nitrate and organics. Sea salt can mix with gaseous SO_2, NOx and organic acid to form $NaNO_3$, Na_2SO_4 and Na containing organic salts.
- Inorganic secondary components—This primarily includes sulphate, nitrate and ammonium. These are secondary components of particulates and are formed in the atmosphere from the gases sulphur dioxide (SO_2), nitrogen oxides (NOx) and ammonia (NH_3) (by gas-to-particle conversion). Initially in the atmosphere, sulphate and nitrate are formed as sulphuric (H_2SO_4) and nitric acid (HNO_3), which then reacts with atmospheric ammonia to form ammonium sulphate, $(NH_4)_2SO_4$ and ammonium nitrate (NH_4HSO_4). Sulphates and nitrates are the most dominant inorganic secondary particulates.

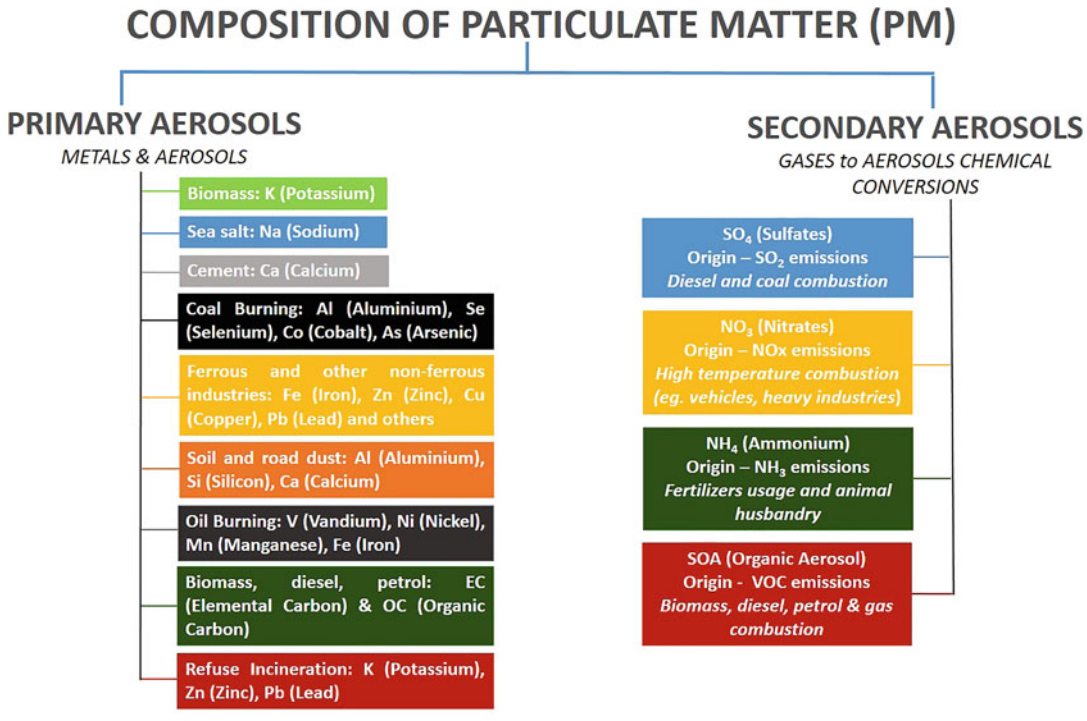

Fig. 2.5 Composition of particulate matter. (Adapted from http://urbanemissions.info/wp-content/uploads/docs/2017-01-PM-Composition.pdf)

Sulphates are internally mixed with organics and nitrates. Sulphates are highly hygroscopic in nature; act as CCN in the atmosphere; and scatter radiation causing cooling (IPCC, 2007). But sulphates mixed with absorbing organics can enhance absorption. Thus, it is important to know the mixing state and hygroscopicity of these particles to understand their optical properties.

- Primary carbonaceous fraction—It consists of elemental carbon (EC) and organic carbon (OC). Elemental carbon is also called black carbon (BC)/graphitic carbon or soot, and is formed due to forest fires, incomplete combustion of fossil fuels and biomass burning. BC in the troposphere is the second greatest contributor to global warming after CO2 (IPCC 2013). Organic carbon is also emitted from fossil fuels and biomass burning. They are composed of mixture of chain-like aggregate and organically bound carbon. They are generally mixed with sulphur- and potassium-rich particles.
- Secondary organics—It is transformed from volatile organic compounds (VOCs) emitted from various anthropogenic and natural sources. Primary organics undergo physical and chemical transformation in the atmosphere to form secondary organics. They are mixture of different chemical species like aliphatic and aromatic hydrocarbons, polycyclic aromatic hydrocarbons, carbonyls and acids. They are generally mixed with other organic particles.

Due to highly complex nature of the particulate matter, their chemical composition, atmospheric chemistry, formation pathways and transformation processes are not very well characterised. These particles have significant impact on climate, air quality and human health. Thus, it is very crucial to improve our knowledge about their sources, chemistry and composition. The recent advances in the state-of-the-art analytical–chemical techniques including aerosol mass spectrometry (AMS), and chromatographic and optical spectroscopy methods have allowed high-resolution characterisation of these particulates.

2.6 Dynamics of Particulate Matter in the Atmosphere

A complete description of the particles size distribution is a challenging problem due to varying ranges. In the real atmosphere, particle size distributions are continuous and are typically represented with number size distribution functions.

$$n(r) = \frac{\mathrm{d}N}{\mathrm{d}r}\mathrm{d}r \tag{2.2}$$

where $n(r)$ is the number (concentration) of particles in diameter size ranging from r to $r + \mathrm{d}r$. To plot such curve, size characteristics of a great number of particles are required. There are several mathematical approaches proposed to characterise and represent the diverse aerosol size distribution.

2.6.1 Junge Distributions

Junge (1955) showed that observed particle distribution in the atmosphere from a few tenths of a micron to few tens of microns gives a constant particulate volume per log radius interval. This tendency can be expressed mathematically as

$$\frac{\mathrm{d}N}{d\ln r} \approx r^{-\alpha}, 2 \leq \alpha \geq 3 \tag{2.3}$$

The dominance of large or smaller particles depends on the value of α. This distribution function assumes that the aerosol number concentration decreases monotonically with increasing particle size. This is not generally true for atmospheric aerosols so the distribution can be used for particles of radius, $r > 0.1$ m. The main advantage of distribution is its simplicity.

2.6.2 Gamma Distributions

A modified form of Gamma distribution is largely used to describe the aerosol ranges. The distribution can readily be derived as

$$n(r) = a\, r^{\alpha} \exp\left(-br^{\gamma}\right) \tag{2.4}$$

where r is the particle radius, $n(r)$ is the number density of particles per radius interval, and a, b, α, and γ are parameters to fit the observed distribution (Deirmendjian 1969; Lenoble and Brogniez 1984).

2.6.3 Log-Normal Distributions

A log-normal function is very often used to represent aerosol size distribution because of its properties. It reads as

$$n(\ln D) = \frac{N}{\sqrt{2\pi}\,\ln\sigma_g} \exp\left[-0.5\left(\frac{\ln\frac{D}{D_g}}{\ln\sigma_g}\right)^2\right] \tag{2.5}$$

where D is the particle diameter, and D_g and σ_g refer to geometric mean diameter and geometric standard deviation, respectively.

Particulate matter undergoes different processes in the atmosphere during their formation, growth or transformation and removal. Nucleation, condensation, coagulation and removal are important processes in the atmosphere, and ensemble of these processes is known as particulate dynamics.

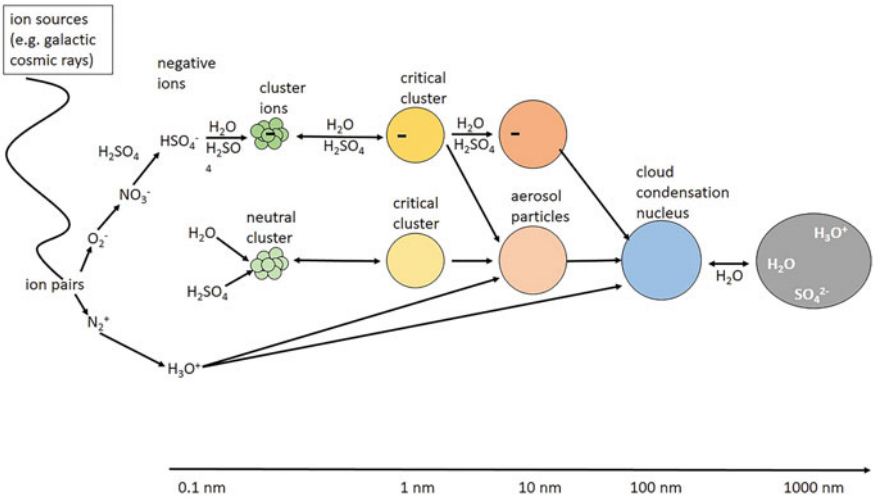

Fig. 2.6 Schematic representation of formation and growth of particulates by nucleation. (Adapted from Curtius et al. 2006)

- **Nucleation** is the process by which gas molecules aggregate together to form stable cluster of new particles. This process depends upon the vapour pressure of condensable gas species. Nucleation can be homogeneous and heterogeneous. Homogeneous nucleation occurs when the gaseous molecules nucleate without the aid of a surface to nucleate upon. For example, when gaseous H_2SO_4 molecules collide with other H_2SO_4 and H_2O molecules they may overcome the nucleation barrier to form thermodynamically stable particles. Homogeneous nucleation has a large activation energy arising from the Kelvin effect, i.e. enhancement of the evaporation rate of small clusters because of curvature (Warren and Seinfeld 1984). In heterogeneous nucleation, gaseous molecules form a cluster on an existing particle or charged ion. Nucleation can also be termed as homomolecular (one) or heteromolecular (two or more) depending on number of species that nucleate. In nucleation, there is increase in number concentration and mean size of the particle. The binary nucleation of sulphuric acid and water; ternary nucleation of sulphuric acid, water and ammonia; and ion-induced nucleation and nucleation involving sulphuric acid and organic acids are prominent nucleation mechanisms in the atmosphere (Fig. 2.6).
- **Condensation** is the process where particles grow in size by taking up vapours from the gas phase. It is the most important mechanism of particle growth in the atmosphere and is most effective in the size range <0.1 μm. In condensation, there is no change in particle number concentration, but there is increase in the mean size of the particle.
- **Coagulation** is the process when two aerosol particles collide with each other in the air and stick together. It is usually caused by the particle Brownian motion, shear, gravitation or turbulence. In coagulation, the number concentration decreases and the mean size of the particulate increases.

- **Deposition**—Particulates have a limited lifetime in the atmosphere ranging from few days to one week. Particles are removed from the atmosphere by dry or wet deposition. In dry deposition, particles hit and settle onto the surfaces. In wet deposition, particles are removed from the atmosphere by rain or fog. Dry deposition is the most important removal pathway for coarse particles, whereas wet deposition is important removal pathway for fine particles.

2.7 Properties of Particulate Matter

Particulates are highly complex systems with very diverse properties. Impact of PM on human health and climate depends upon their properties. Physical, chemical and optical properties of particulates include size, diameter, morphology, hygroscopic behaviour, mixing state, composition, scattering and absorption coefficients, single scattering albedo, asymmetry parameter and Angstrom exponent.

2.7.1 Morphology

It is characterised by the mean of fractal dimension. Aggregation can lead to creation of diverse morphology, while coagulation creates more simple and spherical particles. Particle morphology helps to determine its other properties as the drag force and settling velocity of the particle are influenced by its shape.

2.7.2 Hygroscopic Property

It is the ability of particle to absorb moisture from the atmosphere. Size of the particle can be changed after moisture is taken up by the particle. Hygroscopic nature primarily depends on the chemical nature of the particle (Sonwani and Kulshrestha 2019). Change in size of the particulate matter will also change its light scattering property. Soot particle directly emitted from vehicle exhaust has very poor hygroscopic property. Particles that can take up water are classed as hygroscopic, while those that cannot take up water are classed as hydrophobic. Ratio of the wet diameter to the dry diameter is known as growth factor, which is important to determine relative humidity during measurement of wet diameter (Jackson 2009).

2.7.3 Optical Property

It is the interaction of particles with radiation or light, which determines its optical property. Optical property of particulate matter has major effect on climate change. By comparing how much an aerosol scatters or absorbs the radiation will determine whether it has warming effect or cooling effect in the atmosphere. Soot particle absorbs the radiation causing warming effect. Scattering causes cooling effect and

limits the visibility in the troposphere. Scattering occurs when a beam of radiation alters its path into new direction without being absorbed after colliding with particles present in the atmosphere. Scattering is maximum when particle size matches with wavelength of radiation. Scattering may occur by reflection, refraction or diffraction. Aerosol particle in accumulation mode is efficient in scattering because the size range matches with wavelength of the radiation. The ratio of scattering to extinction, single scattering albedo, measures total extinction due to scattering. For example, while looking down at earth from the space cloud appears brighter and ocean appears darker and this is because cloud has good scattering ability and has high single scattering albedo and ocean has higher ability to absorb incoming solar radiation, hence low single scattering albedo (Jackson 2009).

2.8 Conclusion

The chapter provides an overview of particulate matter in atmosphere viz. sources, emissions and classification according to size, dynamics, properties and characteristics in atmosphere. Particulate matter increasing concentration level is of concern for doing more harm than good, from various health hazards to visibility reduction, and even lowering the amount of reaching sunlight at the surface, and hence reducing the evaporation as well. Therefore, understanding PM is very important in order to examine the emissions, source apportionment and climate implications and to help policymakers for control policies to mitigate their effects on human health, ecosystems and climate. Further research and technical advancements are needed to control particulates emitted from anthropogenic activities.

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Geographical Distribution and Transport of Atmospheric Particulate Matter

3

Atar Singh Pipal, Stuti Dubey, Shailendra Pratap Singh, and Ajay Taneja

Abstract

The problem of particulate pollution is a global concern because it not only leads to large number of acute and severe diseases but also leads to a major cause of mortality and morbidity worldwide. The travel of particulate matter (PM) in the atmosphere is also an emerging issue because it not only pollutes the surrounding regions but also crosses the country and continent leading to increase in the level of air pollution in those areas. This systematic chapter reported that meteorological parameters (viz. wind speed, wind direction and topography) play a vital role in travelling and dispersion of PM. There are a number of air dispersion models and statistical tools that are employed to examine the travel path of air pollutants from various locations toward the receptor site. This will help to implement and regulate the policies regarding controlling of air pollutants sources. The brief overview of atmospheric PM includes classification, sources and characteristics that are also mentioned in this scientific document. In addition, the current geographical distribution of $PM_{2.5}$ and PM_{10} studies conducted by various researches globally is incorporated in this chapter. Apart from the dispersion models, which are used for assessment of dispersion and long range, transportation of atmospheric particles mass concentration is also mentioned in the chapter. This scientific document is very useful and informative for the researchers and environmentalist in the field of particulate air pollution.

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_3

Keywords

Atmospheric particulate matter · Sources · Transportation · Geographical distribution

3.1 Introduction

Particulate matter (PM) is complex mixture of solid and liquid particles suspended in the atmosphere and is also a key indicator of air pollution (USEPA 2015). These particles are released from natural and anthropogenic sources and may vary in shape, size and chemical composition (Tiwari et al. 2020; Pipal et al. 2011). Atmospheric particulate matter (APM) is emitted from natural source that includes volcanic eruption, forest fire, sea spray and resuspension of organic matter (such as leaf litter, mineral dust and other natural phenomena) (Jain et al. 2021). While anthropogenic or human-made activities are fossil fuel combustion, construction and agricultural activities, industrial emission, transport, etc., lead to release of PM into the atmosphere. The classification of PM is based on their formation in the environment, sources, size and their region of deposition in the respiratory tract (Sonwani et al. 2021; Saxena and Sonwani 2019). On the basis of mechanism of formation, PMs are classified as primary and secondary in which primary PMs are directly emitted into the atmosphere by the source, while secondary PMs are formed from the precursors in the atmosphere via different chemical reactions. Moreover, World Health Organization (WHO) had differentiated PM as coarse (10–2.5 μm), fine (2.5–1 μm) and ultrafine (<0.1 μm) on the basis of its particle aerodynamic diameter (WHO 2006). The sources such as crushing or grinding operations, mining, farming and constructional activities add up to the coarse PM level. Sources such as combustion, pollen plants, residential wood burning, motor vehicles, agriculture burning, forest fires and some industrial processes are the sources of fine particles, while source of ultrafine particles includes printer toner, automobile exhaust, ocean spray and hot volcanic lava. Further, the European Committee for Standardization, the International Standards Organization (ISO 1995) and the American Conference of Governmental Industrial Hygienists (ACGIH), 1998 (Vincent and Vincent 1999), have divided PM into three categories according to the region of their deposition in the human respiratory tract. Inhalable particulate matter (IPM) (diameter <100 μm) can deposit anywhere in the respiratory tract and are cleared by cilia within minutes and are translocated to the gastro-intestinal tract. Thoracic particulate matter (TPM) (diameter <25 μm) may be deposited only in the tracheobronchial region. Respirable particulate matter (RPM) (diameter <10 μm) can reach the alveolar region, which does not expel RPM often. In this manner, the destiny of RPM is decided by the specific respiratory move and physicochemical characteristics of the PM. Respirable PM tends to increase oxidative stress and may lead to inflammatory adverse effects on the respiratory system (Yadav et al. 2019).

The modal classification of PM was first proposed by Whitby et al. (1975) in terms of size distribution and it can exist in three different modes viz. coarse, nuclei

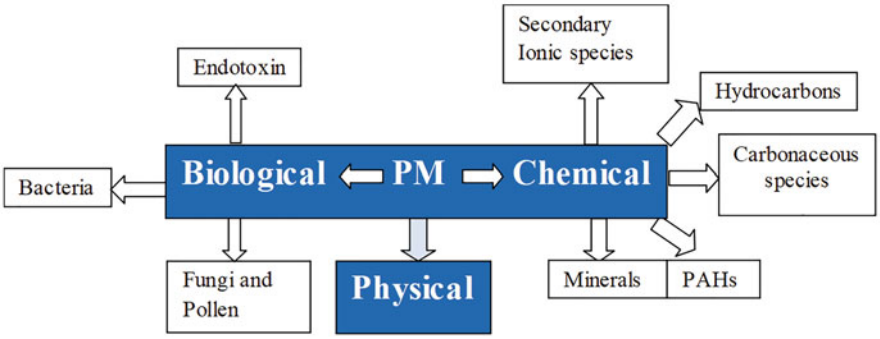

Fig. 3.1 Schematic diagram showing particulate matter and its physical, chemical and biological characteristics

and accumulation. Particles in the coarse particle range ($d > 2.0$ μm) are ordinarily created by mechanical forms such as grinding, wind or erosion. As a result, they are moderately huge and thus settle within the air by sediment action except on windy days, where fall out is balanced by entrainment. Particle in nuclei mode (size <0.1 μm) comprises basically combustion particles emitted directly into the atmosphere and particle formation in the atmosphere occurs by gas-to-particle conversion. They are ordinarily found close to highways and other sources of combustion, while particles in the accumulation range with diameter from < 2.0 and >0.1 μm typically emerge from condensation of low volatility vapours and from coagulation of small particles in or more likely, with the bigger particles in the accumulation range.

PM adversely affects human health, ecosystem, visibility and radiative forcing (Sonwani and Kulshrestha 2016; Goel et al. 2021). The effect of PM relies on particle size, their composition and the duration of exposure. Smaller particles are more harmful than bigger one as they penetrate deeper into respiratory system and cause severe diseases (Pražnikar and Pražnikar 2012). The smaller the size the more carcinogenic it will be. There is persuading and steady prove that short- and long-term exposures to PM can cause a wide range of adverse health effects (Pope III and Dockery 2006). PM is not only harmful for human health but it is also harmful for plants and environment. It inhibits plant growth due to inheritance in photosynthesis process and also penetrating into the stomata pores leading to disorder in transpiration process (Cohan et al. 2002). Figure 3.1 shows the distinguished characteristics of PM and their classifications.

3.2 Geographical distribution of PM ($PM_{2.5}$ and PM_{10})

The geographical distribution of PM_{10} and $PM_{2.5}$ reported by various researchers globally and their scientific outcomes are discussed below.

The estimation of high-resolution $PM_{2.5}$ over Indo-Gangetic Plain (IGP) by fusion of satellite data, meteorology and land use variables was done by Mhawish et al. (2020). The estimate from random forest (RF) showed high $PM_{2.5}$ levels over the middle and lower IGP, with the annual mean exceeding 110 μg/m^3. Spatiotemporal variation in concentration of ambient $PM_{2.5}$ over Delhi, India, during 2010–2016 was assessed by Mandal et al. (2020). Spatiotemporal predictors were modelled, which predicted annual average concentrations ranging from 87 to 138 μg/m^3. Chowdhury et al. (2019) tracked ambient $PM_{2.5}$ build-up in Delhi NCR during the dry season (October–June) by analysing 15 years (2001–2002 to 2015–2016) of high-resolution (1 km) satellite data that have been bias-corrected using coincident in situ data. The mean concentration of ambient $PM_{2.5}$ remained >300 μg/m^3 for several weeks around the two peak pollution episodes (viz. 1st from October to early November and 2nd from end of December through early January). The first peak is attributed to pollution transport from upwind areas affected by open biomass burning, coupled with stable atmospheric conditions, while the second is attributed to enhanced local emissions and perhaps secondary aerosol formation under favourable meteorological conditions.

Zhang et al. examined dynamics of $PM_{2.5}$ for 33 cities included on the UN list of megacities published in 2018. It was observed that higher $PM_{2.5}$ concentration was experienced by areas with higher population density than those with moderately and sparsely populated. It was also found that China, South Asia and India were the most polluted regions, while Europe and Japan were the least ones. Moreover, none of the 33 megacities fell in the WHO's $PM_{2.5}$ attainment class (<10 μg/m^3) and 9 megacities fall into the $PM_{2.5}$ non-attainment class (>35 μg/m^3). Delhi was the most polluted megacity with mean annual $PM_{2.5}$ concentration of 110 μg/m^3, while New York was least polluted in 2016.

In Italy, daily concentration of PM_{10} and $PM_{2.5}$ between 2013 and 2015 was estimated by Stafoggia et al. (2019). In this study, a five-stage random forest model was developed to impute missing satellite AOD data and predict daily PM_{10}, $PM_{2.5}$ and $PM_{2.5–10}$ concentrations at fine spatial resolution nationwide. The mean concentration of PM_{10} and $PM_{2.5}$ ranged from 25.5 to 26.7 μg/m^3 and 17.4 to 18.3 μg/m^3, respectively, in years 2013–2015. Wang et al. (2019) explored the strength and direction of nexus between various factors and $PM_{2.5}$ in Chinese cities using geographically weighted regression (GWR) model. The result of the study indicated that $PM_{2.5}$ concentration levels were spatially heterogeneous and markedly higher in cities in eastern China than in cities in the west of the country. GWR results showed significant spatial heterogeneity in both the direction and strength of the determinants at the local scale.

In Tehran, Yunesian et al. (2019) estimated daily, seasonal and annual variations of $PM_{2.5}$ and PM_{10} concentration in the ambient air for 2 years (January 2016–December 2017). From the data of ten selected air quality monitoring stations, annual mean concentrations of $PM_{2.5}$ and PM_{10} varied from 22.6 to 39.5 μg/m^3 and from 62.5 to 104.3 μg/m^3, respectively, which exceeded WHO Air Quality Guideline (AQG), US Environmental Protection Agency (USEPA) and Iranian standard levels during the study period. In a study of 10 years (from 2003 to

2013) across Switzerland by de Hoogh et al. (2018), it was observed that on average 73% of the total, 71% of the spatial and 75% of the temporal variation (all cross-validated) globally and on average 89% (total), 95% (spatial) and 88% (temporal) of the variation locally measured $PM_{2.5}$ concentrations.

Ground-level concentration of $PM_{2.5}$ was estimated by Jung et al. (2018) using satellite-based aerosol optical depth (AOD) over Taiwan. The results provided $PM_{2.5}$ estimations at locations while not surface stations. The estimation disclosed $PM_{2.5}$ concentration hotspots within the central and southern a part of the western plain areas, notably in winter and spring. The annual average of $PM_{2.5}$ concentrations over Taiwan systematically declined throughout 2005–2015. The study by Yang et al. (2018) investigated global distribution and evolvement of urbanization and $PM_{2.5}$ from 1998 to 2015. Under the impact of increased urbanization, $PM_{2.5}$ was increased in most Asian countries and some African countries, but decreased $PM_{2.5}$ concentrations in most European and American countries. As a result of rapid urbanization, rising trend in $PM_{2.5}$ concentrations was observed from 1998 to 2015, but the evolution relationship between $PM_{2.5}$ and urbanization rate was complex in different countries and regions. Most countries in East Asia, Southeast Asia, South Asia and some African countries urbanized rapidly, together with high risk of $PM_{2.5}$ pollution, which are often countries with high-speed industrialization. The study advocated implication of some reasonable or healthy urbanization policies to tackle $PM_{2.5}$ pollution. Beloconi et al. (2018) employed remotely sensed predictors to estimate yearly averages of both, fine ($PM_{2.5}$) and coarse (PM_{10}) surface PM concentrations, at 1 km^2 spatial resolution over 46 European countries. The resulting estimates of PM_{10} and $PM_{2.5}$ indicated that in 2016, 66.2% of the European population was breathing air above the WHO air quality guidelines thresholds. A study carried out by Zhang et al. also employed satellite-derived aerosol optical depth (AOD) and found that the average $PM_{2.5}$ concentrations in Wuhan, Beijing and Shanghai, respectively, reached up to 95.66 $\mu g/m^3$, 90.44 $\mu g/m^3$ and 73.84 $\mu g/m^3$. The results also showed that the emissions from industrial production accounted for 32% of $PM_{2.5}$ local emissions, proving that evaluating the $PM_{2.5}$ contribution proportion of different elemental zone from Total $PM_{2.5}$ Emission Index was acceptable. In the meantime, roughly 56.16% of local $PM_{2.5}$ emissions in Wuhan stemmed from comprehensive zones were due to intensive human activity and dense urban construction. Spatiotemporal characteristics of $PM_{2.5}$ and PM_{10} at urban and corresponding background sites in 23 cities in China were observed by Xu et al. (2017). The mean concentrations of $PM_{2.5}$ and PM_{10} at the contrast sites were 56 ± 26 and 91 ± 44 $\mu g/m^3$, respectively, and daily and annual average air quality standards of the country were frequently exceeded. The concentration of $PM_{2.5}$ and PM_{10} in most cities exceeded levels (average of only 14 ± 14 and 26 ± 27 $\mu g/m^3$, respectively) at the corresponding contrast sites. $PM_{2.5}$ and PM_{10} concentrations increased two- to threefold in winter at several sites.

The results of the study conducted by Cheng et al. (2016) showed that among 45 global megacities in 2013, Cairo, Delhi, Tianjin, Xi'an and Chengdu were the five most polluted megacities with an annual average concentration of $PM_{2.5}$ greater than 89 $\mu g/m^3$, while the five cleanest megacities were Miami, New York, Madrid,

Toronto and Philadelphia with the annual averages less than 10 μg/m^3. From the spatial distribution, it was found that the highly polluted megacities are concentrated in east-central China and the Indo-Gangetic Plain. Polluted megacities of China and India experienced the most notable seasonal variation of $PM_{2.5}$ resulted in frequent heavy pollution episodes in winter. Marked differences in $PM_{2.5}$ pollution between developing and developed megacities require more effort on local emissions reduction and global cooperation to address the $PM_{2.5}$ pollution of those megacities mainly in Asia.

Spatiotemporal characteristics and determinants of $PM_{2.5}$ in the Bohai Rim Urban Agglomeration (BRUA) were determined by Wang and Fang (2016). Among 241 newly located observation points, the mean PM concentration in the region was 74 μg/m^3. Beloconi et al. (2016) estimated daily mean concentrations of fine ($PM_{2.5}$) and coarse (PM_{10}) over the area of London (UK) for 2002–2012. The mass concentration of PM_{10} and $PM_{2.5}$ ranged from 27.89 μg/m^3 to 33.35 μg/m^3 and from 16.25 μg/m^3 to 19.72 μg/m^3, respectively.

Spatiotemporal distribution and short-term trends of particulate matter ($PM_{2.5}$ and PM_{10}) concentration over China from 2006 to 2010 were observed by Yao and Lu (2014). The concentration of PM_{10} was found to be high in Xinjiang, Qinghai, Gansu, Ningxia, Hubei and parts of Inner Mongolia, whereas the distribution of $PM_{2.5}$ concentration was found to be consistent with China's three gradient terrains. Southeast coastal cities and central regions in South China experienced high $PM_{2.5}$ and PM_{10} load, respectively. Results of Mann–Kendall test method showed the significant changes in reduction of PM2.5 (3–5 μg/m^3) and PM10 (10–20 μg/m^3) concentrations of China in the past 5 years in the most provinces.

In the study conducted using a high-resolution emission inventory (EI) by Sahu et al. (2011) during Commonwealth Games 2010 in Delhi, it was found that among transport, residential, industries, thermal power plants and commercial cooking along with windblown, road dust plays a major role for Delhi environment. Total emissions of PM_{10} and $PM_{2.5}$ including windblown dust over the study area were 236 Gg year^{-1} and 94 Gg year^{-1}, respectively. The contribution of windblown road dust was found to be as high as 131 Gg year^{-1} for PM_{10}. In the study over an eastern Mediterranean city (Beirut, Lebanon), origin and variability of PM_{10} and $PM_{2.5}$ mass concentrations were studied by Saliba et al. (2010) and were found that aged dust increased by 64% in total PM_{10} and secondary aerosols by 150% in fine PM in Haret Hreik over Bourj Hammoud. Mean concentration of PM_{10} (between 2003 and 2007) in Beirut varied from 55.1 to 103.8 μg/m^3, while for $PM_{2.5}$ variation was from 27.6 to 41.0 μg/m^3. Strong interaction between land and sea breezes, high circulation potential in region and local emission were factors that influenced distribution and

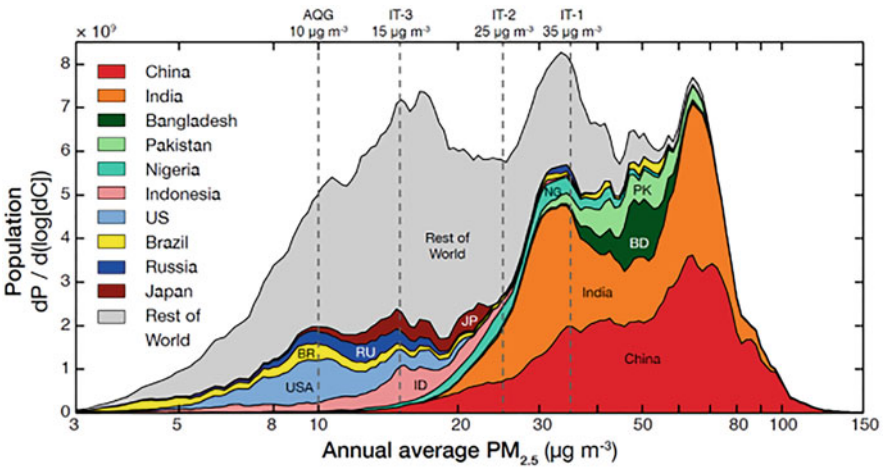

Fig. 3.2 Different interim targets for $PM_{2.5}$ given by WHO. (Source: Brauer et al. (2016))

nature of particles in Beirut. Figure 3.2 depicts the WHO interim targets for $PM_{2.5}$ concentration.

3.3 Composition of Atmospheric PM

The chemical composition of PM can be metals, inorganic salts, elemental carbon (EC), and organic carbon (OC) compounds and surface elements. The largest portion of PM consists of ammonium salts such as NH_4NO_3 and $(NH_4)_2SO_4$, and EC/OC (Yin et al. 2010). Some of these chemical species are released directly from the source, while others, particularly $\leq PM_{2.5}$, are produced from a gas-to-particle conversion through chemical reactions (Engel-Cox et al. 2013). EC is liberated in the form of soot, while OC consists of hundreds of different individual compounds (Yin et al. 2010). A third form of carbon is known as inorganic or carbonate carbon and is often overlooked as it is found in low quantities in $PM_{2.5}$. It is mostly associated with calcium and magnesium salts found in mineral dust, which is found in measurable quantities in PM_{10} (Jankowski et al. 2008; Sonwani and Kulshrestha 2019). Moreover, two chemical forms of organic carbon such as polycyclic aromatic hydrocarbons (PAHs) and anhydrosugars are commonly found in the atmosphere (Sonwani et al. 2022). Chow et al. (1993) reported that fine particles ($PM_{2.5}$) were found to comprise primarily of nitrate (NO_3^-), sulphate (SO_4^{2-}) and ammonium (NH_4^+) ions, which, together with elemental and organic carbon, was made up of 70–80% of the total $PM_{2.5}$ mass. In contrast, these components were made up as if they were almost 10–20% of the coarse fraction between 2.5 and 10 μm. The coarse fraction was dominated by aluminium (Al), silicon (Si), sulphur (S), potassium (K), calcium (Ca) and iron (Fe), which was made up of 40–50% of its mass.

3.4 Meaning of Distribution and Transport of PM in Environment

PM air pollution and meteorology studies showed that how the different size PMs are delivered, transported and dispersed into the ambient air (Pipal et al. 2011). Transport, dispersion and deposition are the atmospheric phenomenon that results in the movement of pollutants in the atmosphere. Transport is movement caused by a time-averaged wind flow, while long-range transport of air pollutants (LRTAPs) refers to travel of air pollutants greater than 100 km. Dispersion (distribution of pollutant into the atmosphere) results from local turbulence, i.e. motions that last less than the time used to average the transport and maximum in unstable atmosphere (when super-adiabatic condition prevails) (Watson et al. 1988). The PMs acts as vehicle for the atmospheric transport of various toxic substances like heavy metals (Murphy et al. 2007). Due to the critical effect of heavy metal on human health and representation of vital transport form of heavy metals in the atmosphere, transport of PM is a significant environmental issue (WHO 2013). Figure 3.3 shows different factors that influence transportation of PM.

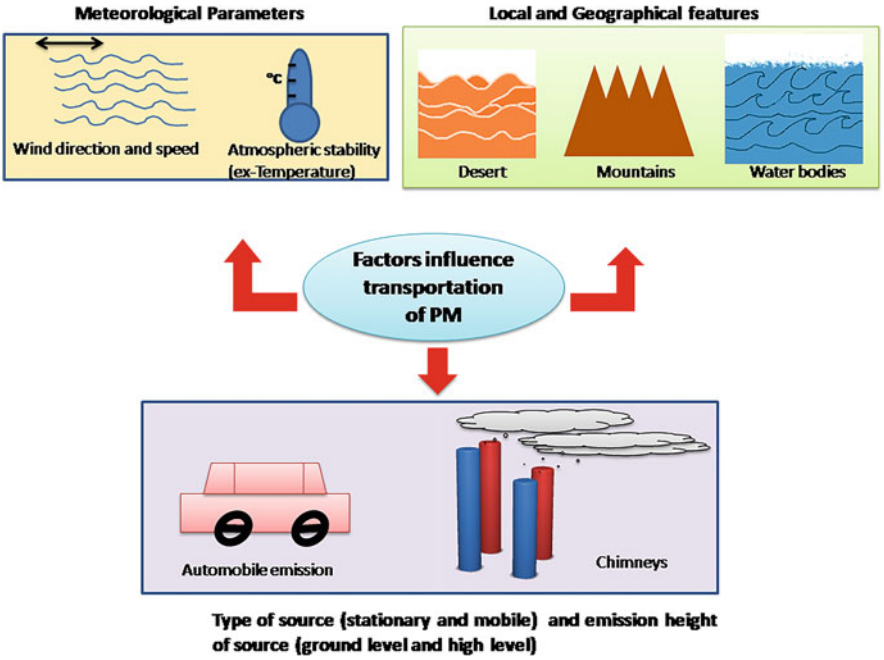

Fig. 3.3 Different factors influence transportation of PM

3.5 Cause of Distribution and Transport of PM and Factors That Affected Its Distribution and Transport

Dimension is a very critical characteristic of PM and has connection to form physical and chemical properties, transport, transformation and particle evacuation from the atmosphere (Garcia et al. 2016). As a common principle, the residence time of PM is inversely proportional to its size, which means smaller the particle size, the longer residence time in the atmosphere (Bargagli 1998) and smaller particles (such as $PM_{2.5}$) can be transported over longer distances than bigger particles. According to a report by WHO, the residence time of PM in the atmosphere is usually from 1–2 days to 4–6 days and typical travel distances for primary fine particles are about 2000–3000 km and 500–1000 km for primary coarse particles (WHO 2006). The transport primarily occurs through episodic events related to biomass burning plumes, dust storms and quick transport of industrial pollution. Concentrations of pollutants in ambient air rely on the release of pollutants, which are too impacted by atmospheric phenomena that play vital role in the processes of transport, transformation and dispersion of pollutants into the atmosphere (HEI 2018; Saxena et al. 2021). Moreover, these processes are affected by the following atmospheric conditions.

1. Meteorological conditions (especially wind direction, wind speed and atmospheric stability)
   The metrological factor and wind have direct and determinant effect on dispersion conditions of pollutant. The velocity of wind plays key role in the determination of mechanical turbulence production, which in turn leads to local dispersion of pollutants. Strong winds (low pressure) favour appearance of pollutants in its flowing direction, and moderate wind leads to its dispersion, while stability of wind (high pressure) leads to the concentration of pollutants near the ground (Garcia et al. 2018; Sonwani et al. 2021). Prevailing winds help PM to travel long distances in the atmosphere from the source, which can affect air quality at locally and long distance away. The long-range travel of PM_{10} and $PM_{2.5}$ exceeded natural border is evident (Abdalmogith and Harrison 2005). The atmospheric stability decides the local convective processes being characterized by the vertical temperature gradient that restricts the vertical mixture of pollutants in case of a thermal inversion. With altitude, the temperature of air tends to reduce in altitude, but under definite conditions, a thermal inversion (an increase in temperature) may occur, which results in creation of a layer of hot air that inhibits contaminated air near the ground from rising and disperse (Garcia et al. 2018).
2. The emission height (e.g. ground-level sources such as road traffic or high-level sources such as tall chimneys).
   The emission height (road traffic and tall chimneys) and vehicular emissions that are transported beyond about 100 m from a highway are also affected by air pollutant dispersion.
3. Local and regional geographical features also play an important role in dispersion of air pollutants, especially PM.

3.6 Air Dispersion Modelling

Dispersion modelling is one that employs mathematical equations to delineate the atmosphere, dispersion and chemical and physical forms inside the plume and to estimate pollutant's concentrations at different locations (Holmes and Morawska 2006) with the help of emissions, and meteorological and topographical data. Dispersion modelling types include Gaussian, computation fluid dynamics, Eulerian, dense gas, Lagrangian, aerosol dynamic, photochemical and box models (Modi and Hussain 2013). Atmospheric dispersion models are computer programmes that utilize mathematical algorithms to re-enact how pollutants in the ambient atmosphere disperse and, in a few cases, how they react in the atmosphere. These models are used to evaluate the downwind ambient concentration of air pollutants or toxins released from sources such as vehicular traffic, industrial plants or accidental chemical releases. These models help to forecast and predict future concentrations beneath particular scenarios (i.e. changes in emission sources). Hence, they are the supreme type of model used in making policy related to air quality. They are most valuable for pollutants that are dispersed over large distances and that may react in the atmosphere. Dispersion models are vital to governmental agencies entrusted with protecting and managing the ambient air quality (Table 3.1).

Apart from these, many methods have been developed to investigate the relationship between air quality data and transport over distances of few hundred kilometres. Three main methods that are commonly used to measure long-range transport of pollutants are (1) multiple linear regressions, (2) non-linear multiple regressions or artificial neural networks and (3) back trajectory modelling in combination with chemical species and/or synoptic weather maps.

Among ample of studies that have employed these methods, few are used multiple linear regression (Stadlober et al. 2008); (Demuzere et al. 2008), while non-linear multiple regressions or artificial neural networks were adopted by Pérez et al. (2000) and Papanastasiou et al. 2007) to observe transport of PM. Back trajectory modelling in combination with chemical species and/or synoptic weather maps to identify long-range transport sources of polluted air masses were used by Viana et al. (2003) and Vardoulakis and Kassomenos (2008). It is noteworthy that if there is transport of pollutant from one region to another region, then surface measurements cannot capture the synoptic nature of these events and it is difficult to identify the source of pollutants. Since satellite measurements are routinely available on a global basis, the transportation of pollutants can be examined. Along with these data sets, local wind patterns using wind data can be important to identify the sources of pollutants (Gupta et al. 2006).

The HYSPLIT (Hybrid Single Particle Lagrangian Integrated Trajectory) model developed by the National Center for Marine Atmospheric Research (NOAA) is a specialized model for calculating and analysing the transport and diffusion trajectories of atmospheric pollutants (Stein et al. 2015; Chai et al. 2017). The HYSPLIT model is widely used in the field of atmospheric science to analyse the transport and diffusion of air pollutants (Ashrafi et al. 2014; Rashki et al. 2015; Saxena et al. 2020). Pipal et al. (2014) identified the source origin using air mass

Table 3.1 List of atmospheric dispersion model developed/accepted by USEPA

Model	Pollutants	Specification	Usage
1. Preferred and recommended models			
1.1. Atmospheric dispersion module (AERMOD)	Gas and particles	Gaussian dispersion for stable atmosphere and vice versa	Flat or complex terrain and rural or urban boundary layer (Perry et al. 2005)
1.1.2. CALPUFF	Gas and particles	Non-steady-state puff dispersion model	Applied for long-range transport around complex terrain, industrial and urban areas (Yamada et al. 1992 and Wu et al. 2006)
1.1.3. CAL3QHC and CAL3QHCR	Gas and PM	Traffic model	Delays and queues occur at signalized interactions (Claggett 2014)
1.1.4. Complex terrain dispersion model (CTDMPLUS)	Gas and PM	Refined air quality model	Complex terrain (Perry 1992)
2. Alternative models			
2.1. Atmospheric dispersion modelling system (ADMS3)	Gas and particles	Gaussian plume model	Concentration of pollutants continuously emitted from point, line, volume and area sources (Hanna et al. 1999)
2.2AFTOX		Gaussian model	Continuous liquid or gas from elevated or surface
Dense gas dispersion (DEGADIS)			Dispersion at ground level
2.3. HOTMAC and RAPTAD		HOTMAC is weather forecaster, and RAPTAG is puff model	Pollutant transport and dispersion in complex terrain, coastal region, urban areas and around buildings
2.4. Hybrid road-way model (HYROAD)	Gas and PM	Puff model	Concentration of PM, CO and other gaseous pollutants as well as dispersion of emission from vehicular traffic (Oladnia et al. 2008)
2.5. ISC 3	Gas and particles	Straight-line trajectory and Gaussian model	Pollutant concentration from sources associated with industrial complex (Hanna et al. 1999)
2.6. OBODM		Dispersion and deposition algorithms	Transport and dispersion from open burning and detonation operations
2.7. PANACHE	PM	3D finite fluid mechanic models	Dispersion in simple or complex terrain
2.8. PLUVUEII	Gas and particles		Transport, dispersion, chemical reaction, optical effects and surface emission from single point or area source

(continued)

Table 3.1 (continued)

Model	Pollutants	Specification	Usage
2.9. SCIPUFF	–	Puff dispersion model	Statistical variance in concentration due to wind fluctuation.
2.10 Shoreline dispersion model (SDM)	–	Gaussian dispersion model	Ground-level concentration near shoreline
2.11. SLAB	–		Ground-level releases, elevated jet releases
3. Screening models			
3.1. AERSCREEN	–	(Screening version of AERMOD)	
3.2. TSCREEN	–	Gaussian model	Screen emission and dispersion of toxic air pollutants
3.3. VALLEY	–	Gaussian dispersion model	24 h or annual concentration up to 50 points and area emission sources
3.4. COMPLEX1	–	Multiple point source screening model	Terrain
3.5. Rough terrain diffusion model (RTDM3.2)	–	Gaussian model	Ground-level concentrations in rough (or flat) terrain
3.6. VISCREEN	–		Specified emissions for specific transport and dispersion conditions
4. Photochemical models			
4.1. Models-3/CMAQ	O_3 and PM	Chemical transport model	Transport, transformation and deposition of precursors and air pollutants (Bailey et al. 2007)
4.2. Comprehensive air quality model with extensions (CAMx)	Gas and PM	Chemical transport model	PM, inorganic and organic $PM_{2.5}/PM_{10}$ (Nopmongcol et al. 2012)
4.3. Regional modelling system for aerosols and deposition (REMSAD)	O_3 and $PM_{2.5}$	Regional-scale model	Chemistry, transport and deposition of airborne pollutants (Bailey et al. 2007)

backward trajectory cluster analysis at Agra and Delhi during study period in different months, which supports the transport of aerosols from the long-range transportation from Thar Desert and other parts of the world over northern Indian region (Fig. 3.4a and b).

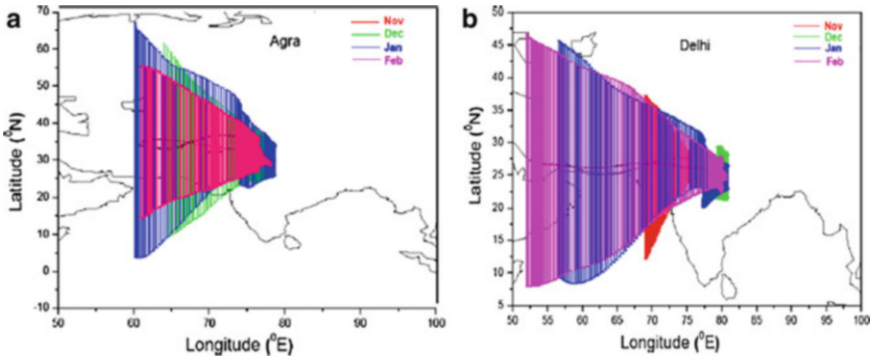

Fig. 3.4 (**a** and **b**) 7-day air mass backward trajectory clusters analysis at Agra and Delhi during different months (Pipal et al. 2014)

3.7 Effect of Transport and Dispersion of PM in Atmosphere

Long-range transport at global and intercontinental scales may affect national control strategies for PM of a nation and also lead to episodic spikes in concentrations. Studies reported an increase in PM concentration due to long-range transport. The air quality of western USA is primarily affected by Asian dust and pollution plume (containing PM), and the effect is easily observed at higher elevation sites of continental USA (VanCuren and Cahill 2002). Jaffe et al. (2003) mentioned that remarkable increase in PM_{10} was due to the Asian plume of 2001. Corbett et al. (2007) reported that in some heavily travelled coastal regions, due to international shipping operations the annual average contribution of $PM_{2.5}$ was as high as 2 μg/m^3. Analysis of combined data of surface PM and satellite by (Fischer et al. 2009) showed notable inter annual variations in the amount of transported Asian dust and pollution and indicates that variations in transport and dust emissions could explain ~50 per cent of the interannual variations in PM $_{2.5}$ concentrations in the USA. The result of the study from a coordinated comparison of 17 models by Shindell et al. (2008) suggested that European emissions dominate aerosol transport to the surface in the Arctic, whereas East Asian emissions dominate in the upper troposphere. A source apportionment study by Lenschow et al. (2001) in Berlin concluded that approximately 50% of the urban PM_{10} background is related to long-range transport and natural particle sources. By applying combined analysis of backward trajectories and aerosol chemistry for 7 years, Salvador et al. (2008) found that total suspended particles and PM_{10} concentrations in central Spain were probably affected remarkably by long-range transport of desert dust from different desert regions in North Africa, while western and central areas of the Mediterranean basin seem to significantly influence $PM_{2.5}$ and secondary inorganic aerosol concentrations in this region. South Asian region receives air masses from Europe, Middle East, Africa and Indian Ocean depending upon the season. These air masses are responsible for export and import of pollutants depositing in nearby states.

Trajectory analysis revealed that soil is contributed by the dust storms coming from Oman through Gulf and Iran, while most of the black carbon (BC) sources are located in India. A detailed review of trajectories associated with wet deposition events indicated that air masses coming from Europe and Middle East carry high concentration of acidic pollutants, which are deposited in Himalayan ranges. Similarly, trajectory analysis revealed that acidic pollutants from continental anthropogenic sources are transported to an ecosensitive site in Western Ghats in India and the outward fluxes of anthropogenic activities of Indo-Gangetic region are transported towards Bay of Bengal (Kulshrestha and Kumar 2014).

3.8 Conclusion

Atmospheric PM is an air criterion pollutant, which is a complex mixture of chemical agents in particles ranging from nanometre-sized molecular clusters to dust particles too large to be aspirated into the lung airways. PM pollution has become an issue of rising significance due to its conspicuous effects on human health and on climate change. Thus, it is very important to examine the entire aspects, especially transportation and geographical distribution of atmospheric PM. The current information on geographical distribution of $PM_{2.5}$ and PM_{10} is also discussed in the chapter that will help researchers. The chapter is important scientific document, which revealed the origin, formation and characteristics of atmospheric PM. In addition, the document also reported the various dispersion models given by USEPA to examine the long-range transportation and geographical distribution of atmospheric PM. Therefore, it will be a comprehensive set of knowledge for researchers, environmentalist and policymakers for proper development of mitigation policies and control of air pollution.

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Airborne Particles in Indoor and Outdoor Environments

4

Atinderpal Singh and Neeraj Rastogi

Abstract

The role of particulate pollutants is being increasingly recognized because of their capacity to impact the air quality, human health, Earth's radiation balance, hydrological cycle, atmospheric visibility, and aquatic biogeochemistry. Both natural and anthropogenic sources contribute to particulate pollution in outdoor environments. Air pollution is shown to be responsible for more than four million deaths prematurely per year on a global scale. Aerosol-induced production of reactive oxygen species (ROS) in situ in the human respiratory system on inhalation is one of the important mechanisms through which aerosol affects human health. The capacity of particulate matter (PM) to produce ROS is relatively more dependent on the chemical composition of PM rather than their mass concentrations. Here, the relative abundance of redox-active species plays a very important role. The air quality of indoors, where people spend most of their time, is also affected by outdoor pollution in addition to indoor sources. The exchange between outdoor air and indoor air depends on various factors such as mechanical ventilation, natural ventilation, and infiltration. The present chapter discusses briefly the abundance and characteristics of airborne particles in indoor and outdoor environments and their possible impacts.

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_4

Keywords

Particulate matter · Properties · Sources · Distribution · Impact · Indoor · Outdoor

4.1 Introduction

In the present-day state of rapid urbanization and industrialization, various types of resources (e.g., energy and water) are needed to sustain our daily life activities. These activities lead to the production of various types of pollutions. Among the various types of pollutions, the role of air pollution is being increasingly recognized recently because of its capacity to impact the air quality, Earth's radiation balance, and climate (IPCC 2013). Air pollutants mainly consist of nitrogen oxides, sulfur oxides, ozone, carbon monoxide, and particulate matter (PM). The PM is a complex blend of tiny solid particles and liquid droplets suspended in the air. These suspended particles (also called atmospheric aerosols) have a different composition and sizes depending upon their source of origin. The suspended particles can have an irregular shape and variable density so their size is expressed in aerodynamic diameter (AD) by assuming the shape of the particles as spherical. The AD of a particle is the diameter of a unit density sphere that settles with the same velocity as the irregular particle. The AD is a very important property of airborne particles as their transport and removal from the air are mainly decided by their size. The deposition of particles within the respiratory system is also governed by their AD size. The size of the particles also provides info about their emission sources and formation mechanism. The PM is generally classified into fine and coarse PMs. In general, the fine mode PM is denoted by $PM_{2.5}$ ($AD \leq 2.5$ μm) and coarse mode PM by $PM_{2.5–10}$ (2.5 μm $< AD \leq 10$ μm). To understand these size ranges, the relative sizes of $PM_{2.5}$ and PM_{10} compared to human hair and sand grain are displayed in Fig. 4.1.

Recently, the assessment of indoor air pollutants has drawn greater attention from scientists working on human health-related studies, as people spend a maximum of their time at home (Jenkins et al. 1992). However, time used up by people indoors is a function of various factors such as age, nature of work, seasons, and medical history of inhabitants. So, healthy indoor air is vital for human health. The quality of indoor air should be healthier than that of outdoor air due to safeguarding of the home, but it is an illusion as recent studies showed that the concentrations of the indoor pollutants are often more than the outdoor pollutants (Chen and Zhao 2011). The publications related to indoor air pollution problems increased significantly in the last two decades due to their immense potential to affect human health. Most of these studies reported that the quality of indoor air is also altered by pollution levels in outdoor environments. Thus, both indoor and outdoor environments need to be considered to discuss the problem of air pollution in detail.

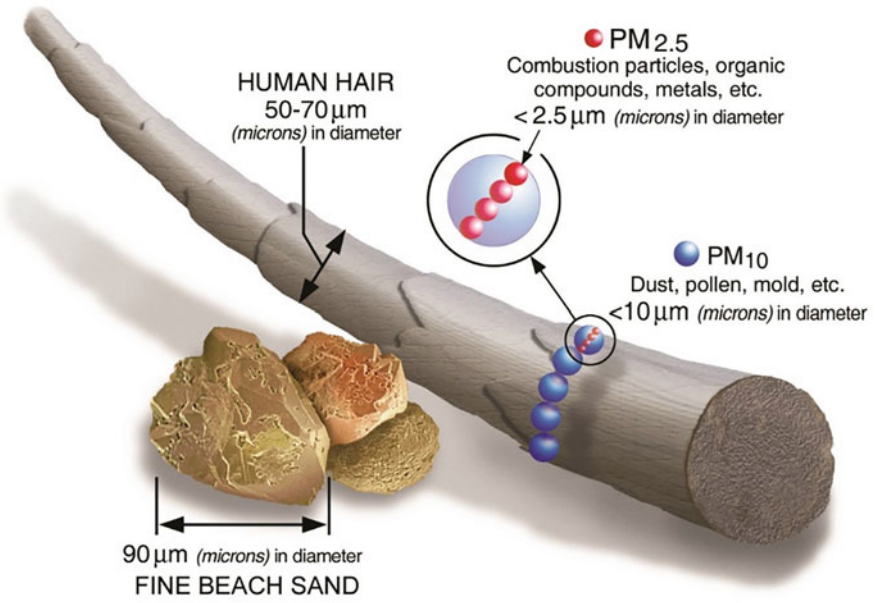

Fig. 4.1 Relative size of particulate matter. (Adapted from https://www.epa.gov/pm-pollution/particulate-matter-pm-basics)

4.2 Potential Sources: Outdoor and Indoor Airborne Particles

Both natural and anthropogenic sources are responsible for the production of ambient aerosols. Major natural sources of outdoor PM include wind-blown dust, sea salts, forest fires, and volcanic eruptions, whereas anthropogenic (man-made) sources include agriculture waste burning, trash burning, industrial, thermal power plant, and vehicular emissions. On a regional scale, the anthropogenic sources of outdoor PM can be significant, but the natural sources are dominant globally (Charlson et al. 1992). In general, coarse mode airborne particles come from natural sources as they are produced by physical mechanism, while fine mode particles come from anthropogenic sources (Singh et al. 2016a). Airborne particles are also classified as primary and secondary aerosols depending upon their production mechanisms. Primary aerosols are emitted directly from their sources in particulate phases such as uplifted dust, sea salt spray, and emission of soot from biomass/biofuel burning, whereas secondary aerosols including organic and inorganic species are formed from their precursor gases released into the atmosphere, and subsequently converted into particles, e.g., secondary organic aerosol (SOA), nitrates, and sulfates (Saxena and Sonwani 2019; Saxena et al. 2020, 2021). On the other hand, pollutants in indoor environments are a mixture of aerosol that have infiltrated indoors and emitted indoors. The aerosols emitted indoor include the emissions from

cigarettes, stoves, fireplaces, and wood stoves. The sources of indoor pollution also include household products, construction materials, and biological agents (e.g., microbes and pets). Secondary aerosol also exists in the indoor environments that are produced through the reaction of gas-to-particle conversion. Some studies reported that the chemical and morphological characteristics of indoor and outdoor PMs are different from each other (Sonwani and Kulshrestha 2018; Sonwani et al. 2021a). Chithra and Nagendra (2013) studied the chemical and morphological characteristics of indoor and outdoor PMs at a naturally ventilated school building (indoor) and an adjacent roadway (outdoor) in Chennai, India. They reported that concentrations of the crustal elements (Ca, Al, K, Fe, Na, and Mg) were significantly higher in the indoor environment as compared to toxic elements (Sr, Ba, Ti, Cr, Cu, Mo, Mn, Ni, Zn, and V) usually emitted from vehicles. Further, they found the presence of soot particles in both indoor and outdoor PMs, which were confirmed by SEM-EDX (scanning electron microscope in combination with energy-dispersive X-ray spectrometry). It indicates the infiltration of outdoor vehicular emissions into the indoor environment.

4.3 Measurement Methods of PM Mass

The mass of PM (total suspended PM, PM_{10}, $PM_{2.5}$, size-segregated PM) can be measured by both offline and online methods. The traditional offline measurement involves the collection of aerosols using high-volume air samplers by pulling ambient air at a certain flow rate through the filter paper. The size of the collected PM is governed by either geometry of the cyclone of inlet or impactor. The numerous types of filter paper are available, i.e., fibrous mats, porous sheets, and membranes. The collection efficiency of a filter depends upon the size of particles. The mass concentration (in $\mu g\ m^{-3}$) of aerosol in the air is estimated by the deposited aerosol mass on the filter determined by the sample weight ($W_{Loaded\ filter}$-$W_{blank\ filter}$; μg) divided by the volume of air filtered (m^3). The volume of air is estimated by multiplying the flow rate of high-volume (or low volume) sampler ($m^3\ min^{-1}$) with integrated sampling time (min). In the online measurements, beta-attenuation monitoring (BAM) and tapered element oscillating microbalance (TEOM) are extensively used to determine the PM mass. The BAM uses beta-ray attenuation from particles to measure the ambient mass concentration of PM. In TEOM, a hollow glass tube with a filter on its tip for collecting the particles is used as a microbalance, and its oscillating frequency is proportional to the mass of the deposited particles on the filter. So, the change in mass alters the oscillating frequency, which is used to calculate the particle concentration. In recent times, the low-cost PM sensors are also popular to monitor the PM concentration in real time. The low-cost PM sensors utilize the scattering from particles to calculate the number concentration, which is in turn used for PM estimation. Some dedicated sensors are also installed on the various satellites to monitor the airborne pollutants from the space. Detailed methodology, data uncertainties, and comparisons of these measuring techniques are out of the scope of this chapter.

4.4 Physical, Chemical, and Optical Characteristics of Airborne Particles

Quantification of characteristics of airborne particles (physical, optical, and chemical) is of great importance in assessing any of their effects including climate and human health. The major components of PM are carbonaceous aerosol, secondary inorganic constituents, mineral dust, trace metals, particle-bound water, and sea salts (Seinfeld and Pankow 2003). In addition, biological species such as allergens and microbial composites can also be a part of the PM. Further, carbonaceous aerosols are comprised of elemental (EC), organic (OC), and carbonate carbon (CC). On the other hand, the major water-soluble inorganic ions (WSIIs) are SO_4^{2-}, NO_3^-, Cl^-, NH_4^+, Na^+, Ca^{2+}, K^+, and Mg^{2+}. Some of these WSIIs have the sea salts and crustal dust origin. Mineral dust is mainly composed of clays, calcite, quartz, and iron oxides. The chemical configuration and size of atmospheric aerosols at any geographical site depend upon the relative contribution from different sources and meteorological parameters over that region. Aerosol size distribution is among the key features to understand their primary sources and secondary formation processes in the atmosphere. The aerosols of natural origin formed by the physical process are relatively coarser than those produced from anthropogenic activities. Generally, carbonaceous aerosols contribute a considerable portion (~30–50%) to the total aerosol mass, followed by water-soluble inorganic ionic species (WSIIs) over the urban and rural atmosphere (Andreae et al. 2008; Fuzzi et al. 2006; Guo et al. 2010; Kanakidou et al. 2005; Rengarajan et al. 2007; Tare et al. 2006; Rastogi et al. 2016, 2020). Recent studies on the oxidative potential of PM suggest that possible aerosol toxicity mainly depends on chemical composition of PM (Patel and Rastogi 2018). So, the information on the PM chemical composition is very vital in assessing their health impacts.

During atmospheric aging, the chemical reactions among aerosols and with atmospheric trace gases could further lead to changes in their characteristics, and thus, they lose their original identity and rarely exist as a single entity in the atmosphere (Sonwani and Kulshrestha 2019). Instead, they are found as a mixture of different species and their optical properties are governed by the mixing state. In general, two types of the mixing states are suggested: externally mixed (particles retain their original identity and can be treated as an individual species) and internally mixed (all the particles of the same size in given aerosol populations have uniform composition and do not behave as an individual species). The external mixing can be considered as a speculative case and may be true only for freshly emitted aerosols, which have not undergone any chemical and physical transformations yet. Internal mixing could lead to modification of the optical properties of original particles. Bond et al. (2006) reported that the absorption of radiation is enhanced for the given amount of black carbon (BC) as high as by 50% when it is internally mixed (Bond et al. 2006), and thus, the mixing state can alter the estimation of radiation budget significantly (Jacobson 2001; Satheesh and Ramanathan 2000). Atmospheric aerosols are primarily a mixture of both absorbing and scattering types of species. Warming or cooling of the atmospheric system by aerosols relies on numerous factors, among which the single scattering albedo (SSA)

is the most crucial (Satheesh et al. 2010). The SSA is the fraction of scattered radiation in the total extinction of radiation due to particles. It mainly depends upon the relative abundances of absorbing EC or BC along with other scattering types of aerosols (e.g., sulfates and organic carbon). However, some types of organics can also absorb in nature called brown carbon (Laskin et al. 2015; Satish et al. 2020; Sonwani et al. 2021b). The SSA ranges from 0 to 1 with unity value for totally scattering aerosols and less than unity for absorbing aerosols. The SSA is also a function of wavelength and decreases with an increase in wavelength for anthropogenic emissions (industrial and biomass burning emission), while for desert dust, SSA increases with an increase in wavelength (Dey et al. 2004).

4.5 Impact of Airborne Particles on the Earth's Radiation Balance

Climate drives by solar energy, but not all the solar energy that strikes the top of the atmosphere finds its way to the surface mainly due to the existence of airborne particles and clouds in the lower atmosphere. Ultimately, the climate system is driven by solar radiation.

The role of aerosols in the Earth's climate system is being increasingly recognized because of their potential to alter climate forcing by changing the radiative balance of Earth directly through the extinction of the received solar energy and indirectly by acting as cloud condensation nuclei (Fig. 4.2; Ramanathan et al.

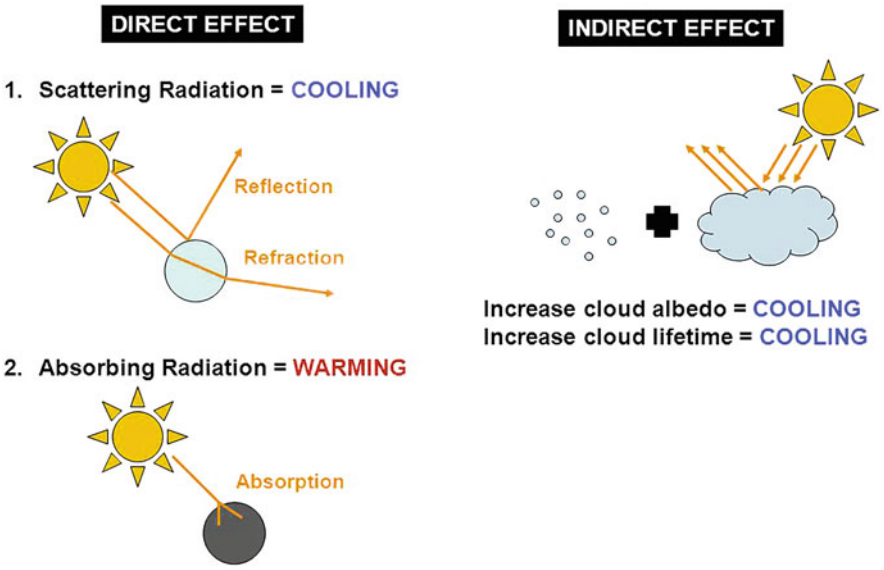

Fig. 4.2 Direct and indirect effects of airborne particles on Earth's radiation balance (https://slideplayer.com/slide/5003192/, accessed on September 16, 2020)

2001; IPCC 2013). These direct and indirect effects are quantified by aerosol radiative forcing. The aerosol radiative forcing represents the energy confinement by aerosols in the atmosphere. The attenuation of radiation by aerosols affects photochemistry, such as the production of tropospheric ozone, through alteration of the atmosphere energy balance. The aerosols also influence crop production by attenuating the incoming solar radiation. Recently, Ghude et al. (2014) reported that ozone lowers the yield of India's crop.

The assessment of aerosol characteristics across numerous sites over the globe has its significance in understanding climate change in Earth during the post-industrial period (post-1750) (IPCC 2001). The absorption or scattering of the solar radiation and magnitudes of atmospheric radiative forcing due to the long-lived greenhouse gases (GHGs) are well known (IPCC 2007). The total net radiative forcing of GHGs is positive (+2.83 W m^{-2}) and known with a high confidence level as shown in Fig. 4.3 (adapted from IPCC 2013). In contrast, some components of atmospheric aerosols have positive forcing and others have negative forcing with overall negative forcing. However, a large degree of uncertainty is involved in these estimations (Fig. 4.3; IPCC 2013). The uncertainty was aroused due to inadequate information on the abundance of aerosols and their linked properties worldwide (Pathak et al. 2010). Additionally, due to shorter residence time and numerous aerosol categories of erratic optical characteristics with non-uniform distribution around the globe, aerosols exhibit significant regional variations in their radiative forcing (Kiehl and Briegleb 1993; Chung et al. 2005). Radiative properties of aerosols strongly depend upon their chemical composition, e.g., BC is the absorbing type of aerosol while sulfate scattered the radiation. Thus, aerosols play a critical role in the climate. Further, atmospheric processing changes the physicochemical characteristics of ambient aerosols, which further complicate their proper assessment.

4.6 The Role of Airborne Particles in Affecting Air Quality, Visibility, and the Hydrological Cycle

Airborne particles have a noteworthy effect on air quality, visibility, and atmospheric chemistry (IPCC 2007). Primary and secondary aerosols have been recently known as a central component contributing to air pollution over urban areas (Dall'Osto et al. 2009; Guo et al. 2010; Zhang et al. 2010). Several studies reported that fine particulates have negative impacts on human health (Pöschl 2005; Pope et al. 2020). Ultrafine particles (<100 nm) are more dangerous for humans as being sufficiently small in size they are capable of pass through the membranes of the respiratory system (Oberdoster et al. 2005). The high concentration of $PM_{2.5}$ causes mortality in children's below 5 years in age globally at the rate of about 5% due to cancer of the lung and bronchus, 3% due to cardiopulmonary disease, and 1% from acute respiratory infections leading to premature deaths of ~0.8 million (Cohen et al. 2005). Furthermore, the reduction in visibility has been observed due to the hygroscopic properties of secondary aerosols (Malm et al. 1996). An enhanced concentration in particulate matter modifies visibility significantly as shown in Fig. 4.4.

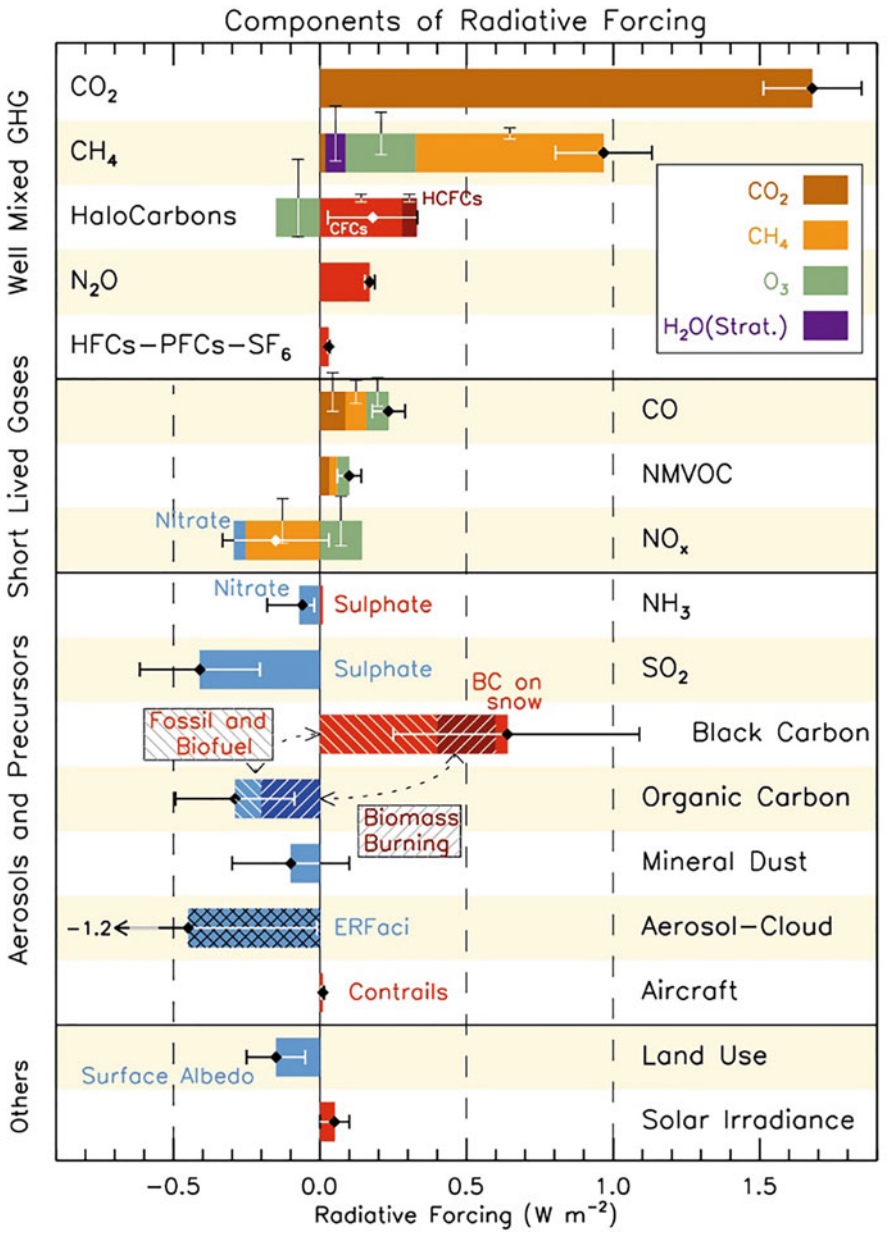

Fig. 4.3 Global radiative forcing of different atmospheric constituents relative to 1750. (Adapted from IPCC 2013)

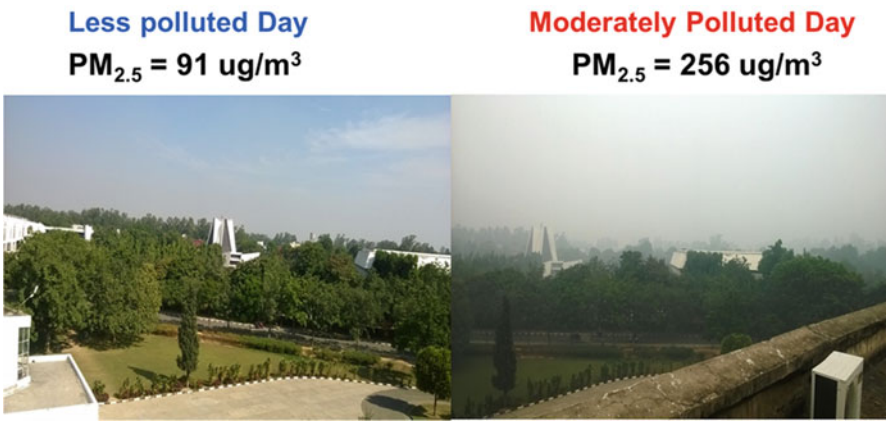

Fig. 4.4 Impact of PM on the atmospheric visibility

Fig. 4.5 Fog and haze blanket the IGP region. (Adapted from NASA)

However, visibility is also affected by the chemical composition of PM, in addition to PM mass. The same has been observed in many regions of the world, e.g., the vast Indo-Gangetic Plain (IGP) in South Asia experiences severe fog, haze, and smog most of the time during the winter and second half of autumn, resulting in the reduction in visibility due to the existence of a high level of pollutants (Tare et al. 2006; Badarinath et al. 2007; Nair et al. 2007).

Figure 4.5 shows fog and haze over the IGP region during autumn 2017. The hygroscopic nature and sub-micron size of secondary organic aerosols (SOAs) make

them an important component for the cloud activation processes, hydrological cycle, and indirect climatic effect of aerosols by acting as cloud condensation nuclei (Haywood and Boucher 2000; Sun and Ariya 2006). The optical properties of clouds are controlled by CCN (Ramanathan et al. 2001; Schwartz and Harshvardhan Benkovitz 2002). Anthropogenic aerosols can lead to an enhancement in the CCN number concentrations (Andreae and Crutzen 1997). A lessening in the cloud droplet size and precipitation has been observed due to an intensification in the CCN number concentrations (Rissman et al. 2004). These effects also increase the reflectivity of the solar radiation ensuing in a higher cloud albedo (known as the first indirect climatic impact of aerosols). Thus, it is very important to know the composition of the CCN population and hygroscopicity of aerosols to assess the cloud droplet formation and precipitation phenomenon (Haywood and Boucher 2000; Rosenfeld et al. 2007; Wang et al. 2009).

4.7 Global Distribution of Natural and Anthropogenic Aerosols

When we observe the world through the eyes of satellites from the space, several high aerosol loading regions are appeared called hot spots. These hot spots are dominated by both natural and anthropogenic aerosols. On a global scale, natural aerosols are dominating as mentioned earlier. Figure 4.6 displays these hot spots in yellow and red colors. Yellow color refers to the coarse mode particles (e.g., dust), and the red color represents the find mode particles (e.g., smoke). On the other hand,

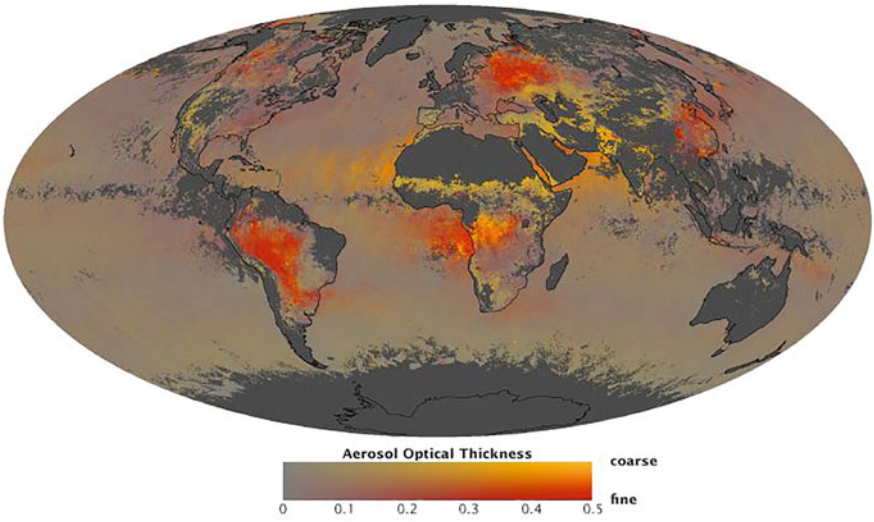

Fig. 4.6 Distribution of aerosols on the global scale. (Adopted from NASA, published in November 2010)

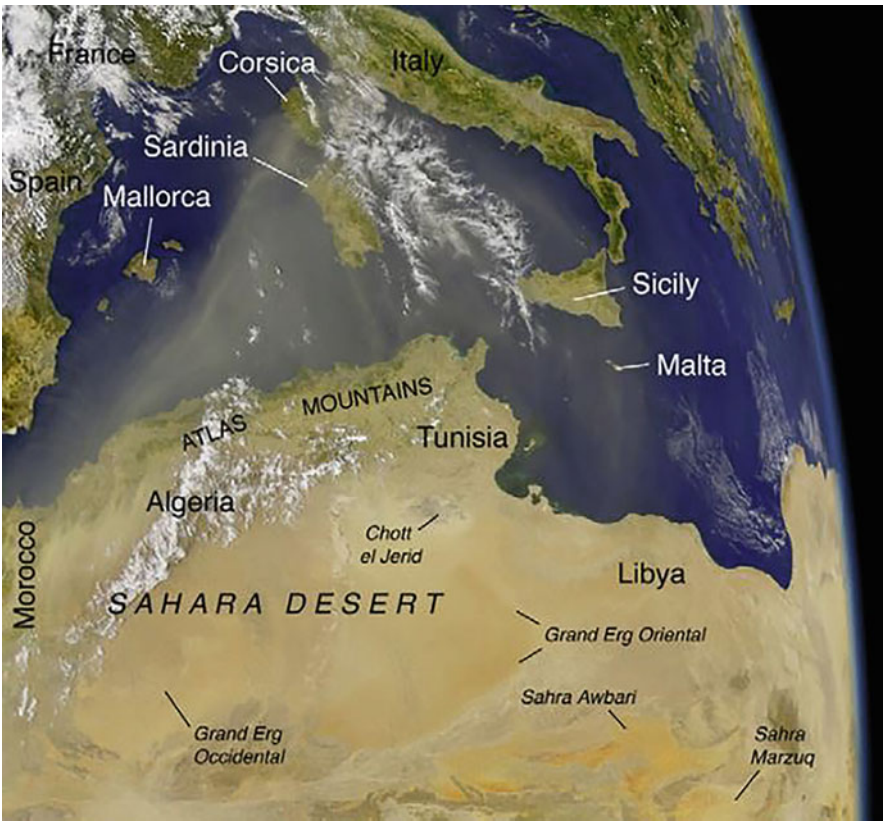

Fig. 4.7 Satellite picture showing the transport of dust to southern Europe. (Adapted from Muhs et al. 2010)

areas in gray color indicate there are no data available for these regions. Figure 4.6 shows that anthropogenic aerosol is dominated in the eastern portion of the USA and most of the parts of Europe. In the eastern USA, it is due to the plumes of industrial and vehicular emissions from cities like New York. The big urban centers such as London and Berlin are a big contributor to European pollution. The western part of the USA is cleaner than that of the eastern part (Fig. 4.6). However, the heavy loading of soil dust is also experienced in California due to agricultural activities. Sometimes, forest fire also contributed to the pollution level of the western USA.

The meteorological conditions also play a vital role along with emission sources. In general, the winter season displays higher primary particulate pollution as compared to the warmer season due to the shallower boundary layer and stagnant atmospheric conditions (Singh et al. 2016a). However, the enhancement in the formation of secondary pollutants is often observed in summer due to strong photochemical reactions (Wang et al. 2016). But pollutants disperse easily due to strong convection during the summer season. In the Africa continent, the yellow

color shows the dominance due to the existence of Saharan dust aerosol over the region and displays a mixture of coarse mode (dust) and fine particles (biomass burning-derived aerosol) over the central part of Africa (Sayer et al. 2019). Occasionally, the dust aerosols originated from the Sahara Desert also affected the air quality of Europe through long-range transport (Ansmann et al. 2003). The satellite captures such events of long-range transport (Fig. 4.7). Figure 4.6 depicts that most of the southern American regions are engulfed with fine aerosols that mainly come from biomass burning and urban emission sources (Magi et al. 2012; Zhu et al. 2013). Amazonian forest fire events during dry season also contributed to fine aerosol loading over the northern part of the southern American continent (Morton et al. 2013).

Nowadays, Asia emerged as an important hot spot for aerosol loading. The Indo-Gangetic Plain (IGP) covered northern Pakistan, northern India, and Bangladesh is a highly polluted region of the world with the highest population density. The northwestern part of IGP experienced large-scale crop residue burning emissions during the post-monsoon that transported to the Bay of Bengal and the Arabian Sea through the IGP and thus affects regional air quality and marine atmospheric chemistry (Sarin et al. 2010; Kaskaoutis et al. 2014; Rastogi et al. 2020). During the pre-monsoon, the aerosols over the IGP are the complex blends of dust blowing from the Thar Desert and pollutants from the densely populated plains. The mixing of dust with aerosols of an anthropogenic origin of IGP can change their optical properties and made dust more absorbing (Gautam et al. 2011).

With the onset of a dust storm (DS) in the region, the PM mass concentration was enhanced by many times as observed in the dust storm of March 20, 2012 (Fig. 4.8). High aerosol loading during the DS also reduced the surface reaching net radiation flux (short wave) by 20% as compared to clean days and the heating rate of lower atmosphere reached as high as +2.2 K per day (Singh et al. 2016b). Thus, dust storms affect air quality along with the climate. The other regions of Asia, eastern China, also produce heavy pollution. China got success in declining SO_2 emissions during recent years (Lu et al. 2011; Li et al. 2017). However, NO_x emissions still displayed an increasing trend during 2005–2015 over China (Liu et al. 2017).

4.8 Global Distribution of Outdoor Pollutants

The recent trends in $PM_{2.5}$ mass have been discussed in this section as it is the most important fraction for studying the impact of airborne particles on human health. There are more than four million deaths prematurely per year on a global scale due to air pollution in outdoor environments (Cohen et al. 2017).

Figure 4.9 displays the average concentration of $PM_{2.5}$ across the globe (Shaddick et al. 2020). It represents the average concentration of the year 2016 and is estimated by the data integration model for the air quality of WHO. Higher concentrations were observed generally in low- and middle-income countries located in the tropical/subtropical regions. Figure 4.9 shows the higher concentrations over the middle east region, south and east Asia, and sub-Saharan

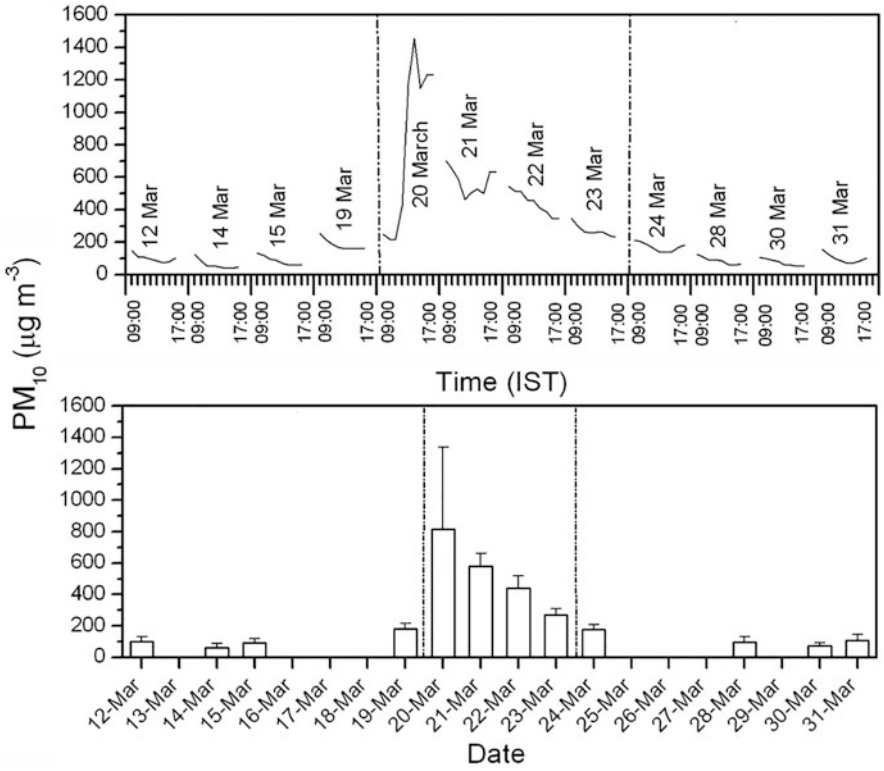

Fig. 4.8 Impact of a dust storm on the mass concentration of PM_{10}. (Adapted from Singh et al. 2016b)

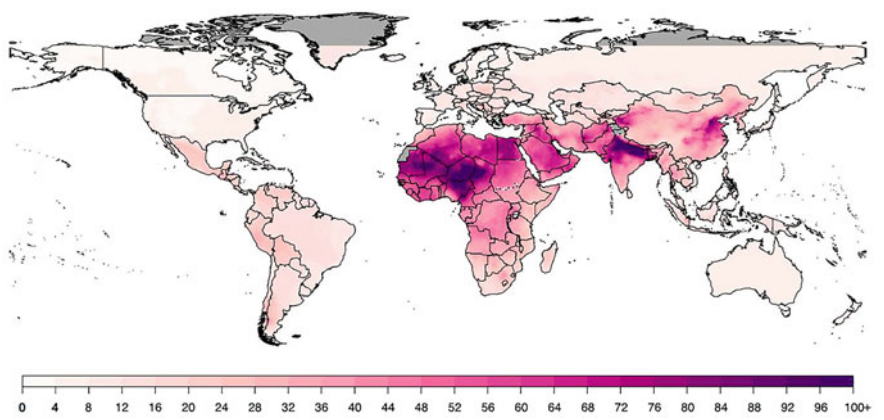

Fig. 4.9 Global distribution of $PM_{2.5}$ (in µg m^{-3}). (Adapted from Shaddick et al. 2020)

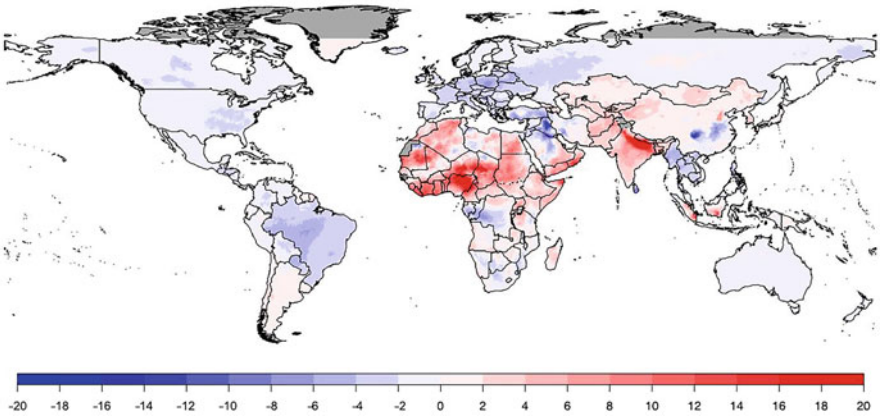

Fig. 4.10 Change in the mass concentration of $PM_{2.5}$ in 2016 as compared to 2010. (Adapted from Shaddick et al. 2020)

regions of Africa. The increase in $PM_{2.5}$ concentrations over sub-Saharan regions of Africa is due to enhancement in the contribution of fine dust aerosol due to climate change (Stanelle et al. 2014). In recent decades, emission control strategies for aerosol and its precursors have been adopted worldwide as aerosols have many negative effects on human health and the environment. This type of legislation leads to a gradual decrease in aerosol loading over various parts of the world, which is also reflected in the study made by Shaddick et al. (2020). They reported the change in $PM_{2.5}$ concentrations of 2016 relative to 2010 (Fig. 4.10). Despite decreasing $PM_{2.5}$ concentrations in 2016 as compared to 2010 over many parts of the world, around 50% of the world population were exposed to enhanced mass concentrations between 2010 and 2016. It is because regions having high population density showed an increasing trend in PM concentration. There is a reduction in $PM_{2.5}$ mass over the USA, North America, Europe, and some parts of East Asia between 2010 and 2016. However, there is an increasing trend in sub-Saharan regions of Africa, some parts of Southeast Asia, and the IGP region of South Asia. The reduction in PM mass over the USA, North America, Europe, and some parts of East Asia is attributed to the effective implementation of air pollution regulations by these countries.

The highest positive change in the PM mass is observed over the IGP (Fig. 4.10). It is one of the most polluted areas of the world due to numerous sources such as vehicular emissions, industrial emissions, power plant emissions, agricultural waste (biomass) burning, and biofuel burning. This region has the highest population density in the world. So, a relatively large number of people are affected by the same air pollution increase in this region as compared to other regions. The north-western part of the IGP experienced intense biomass burning emissions during October–November of every year. The intense biomass burning activities over this region are reflected in fire counts captured by NASA's satellite at the end of October (Fig. 4.11). During the biomass burning period, $PM_{2.5}$ mass concentration reached up to ~400 μg m^{-3} (8 h average) (Rastogi et al. 2014) and biomass burning

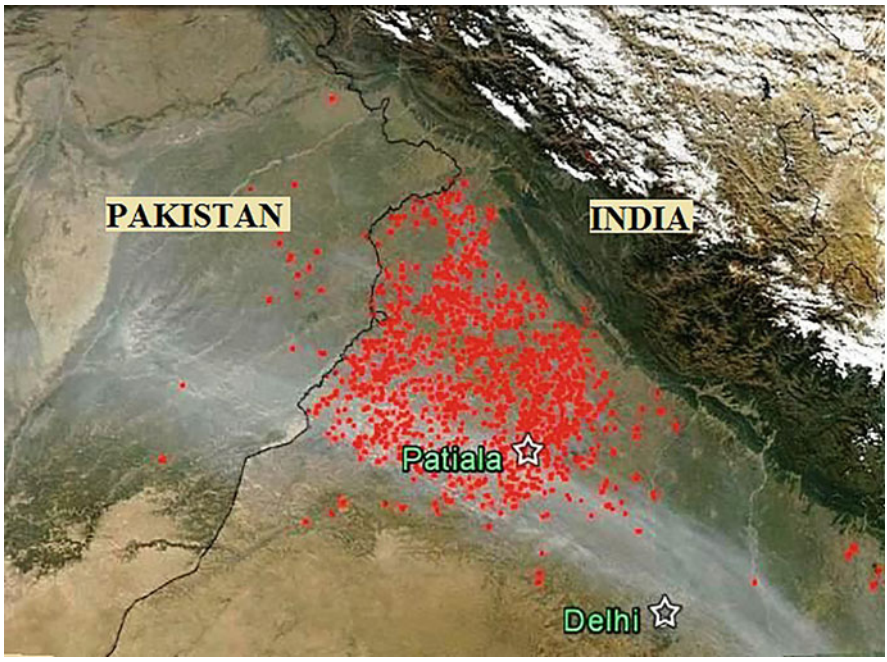

Fig. 4.11 NASA's satellite shows fire counts over northwestern IGP. (Adapted from Singh and Rastogi 2019)

emissions in this area contribute around 20% to the total global emission budget of carbonaceous aerosol (Rajput et al. 2014). The biomass burning affects the air quality of this region significantly. Singh et al. (2015) found that the annual $PM_{2.5}$ mass concentration over northwestern IGP is higher than that of the Indian National Ambient Air Quality Standards (INAAQs). The airborne particles also impact human health by producing reactive oxygen species (ROS) in the human respiratory system. Production of ROS causes oxidative stress due to an imbalance between oxidants and antioxidants in the body and leads to several cardiopulmonary diseases (Amatullah et al. 2012). Recently, Patel and Rastogi (2018) examined the oxidative potential (OP) of PM from the site of northwestern IGP during winter. They found that the mass normalized OP of this region is several times higher than that of reported from the various locations of Europe. They further found that the biomass burning-derived aerosol has more potential to enhance OP as compared to that emitted from fossil fuel combustion.

In addition to biomass burning emissions during a specific period, industrial and vehicular emissions from the big urban centers such as Delhi, India, of IGP contribute to air pollution throughout the year. The population-weighted $PM_{2.5}$ in 2015 for India was 74 μg m^{-3} and the life expectancy of Indians decrease by 1.5 years because of air pollution (Cohen et al. 2017; Apte et al. 2018). Delhi is the world's topmost polluted megacity as per the earlier report of WHO (WHO 2018). Recently, Gani et al. (2019) reported that the average concentration of $PM_{2.5}$ over Delhi

exceeds the daily average $PM_{2.5}$ INAAQs on more than 80% of the days of a year and 24 h of $PM_{2.5}$ WHO standards on all the days. Further, they highlighted the daily average concentration of $PM_{2.5}$ during winter remained above the INAAQs and WHO standard during almost all days. They showed that there is no clean air episode in Delhi during winter, in contrast to some other polluted megacities (e.g., Beijing), which also experienced clean air episodes along with polluted ones (Sun et al. 2013).

4.9 Air Pollutants in Indoor Environments

One of the most significant environmental risks faced by the people of the present era is the exposure of increased PM. The exposure to $PM_{2.5}$ lowers life expectancy worldwide as per the assessments of Global Burden of Disease (Forouzanfar et al. 2015). A maximum of PM exposure occurs indoor as most of the people spend a maximum of their time at home (Jenkins et al. 1992). About 3.8 million people die per year due to dirty air of indoor environments as per the WHO report. Pollutants in indoor environments are a mixture of aerosols that have infiltrated indoors and emitted indoors. Secondary aerosols also exist in the indoor environments that are produced through the reaction of gas-to-particle conversion. The indoor environments are generally dominated by the particles produced in activities such as cooking or indoor combustion, secondary aerosol formation, and dust resuspension (Wallace 1996; Waring and Siegel 2007; Waring 2014).

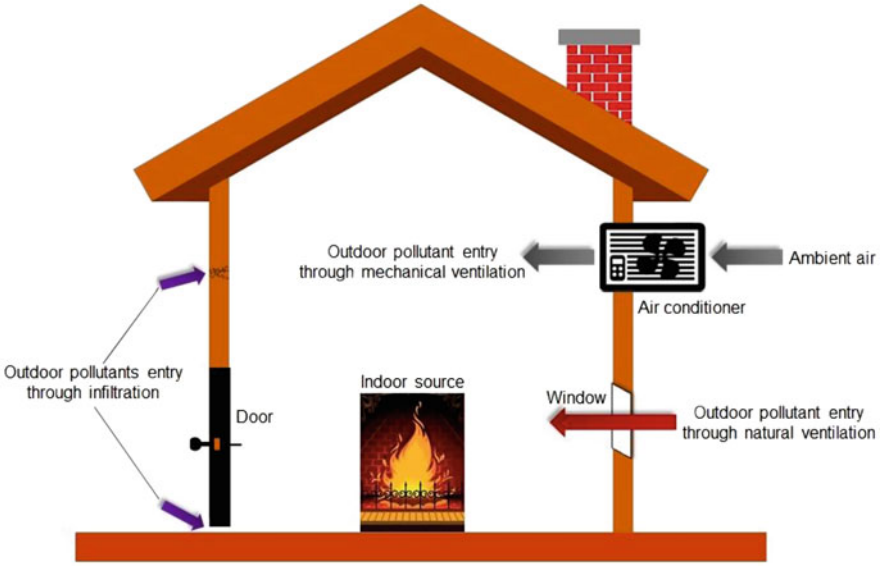

Fig. 4.12 Various pathways of infiltration of the outdoor pollutants to indoors. (Adapted from Leung 2015)

The exchange of air between outdoor and indoor alters the air quality of the indoors significantly. Figure 4.12 describes the outdoor pollutants mainly enter the indoor through mechanical and natural ventilation along with the infiltration process. The mechanical ventilation is responsible for the entry of the outdoor air into the indoor environments through fresh air intakes of ventilation fan and air conditioner system of the building. The outdoor air also flows into the indoors through the windows and doors of the house whenever they are opened (natural ventilation). The exchange of air between outdoor and indoor also occurs through the cracks and leaks in the building even when there is no mechanical and natural ventilation. This process is called infiltration and mostly occurs in the case of old buildings. Thus, the outdoor air enters the indoor through these ventilation processes and either dilute or add more particles to indoor air as per the ventilation condition. The natural ventilation system is used in enhancing sustainability in buildings by improving their energy efficiency and indoor air quality. It is one of the main objectives of the passive design of buildings. However, a hot and humid climate is one of the challenges in achieving energy efficiency and good indoor air quality. Another challenge for indoor air quality control is that of poor outdoor air quality. Although there are still some issues to achieve sustainable buildings, the focus on constructing the high-performance building will benefit us to achieve the goal in this direction (Persily and Emmerich 2012).

The ratio of indoor to outdoor (I/O) concentration is one of the widely used parameters in the literature to study the exchange between indoor and outdoor particles (Pekey et al. 2010). The I/O is defined as follows:

$$\text{I/O ratio} = \frac{C_{\text{in}}}{C_{\text{out}}} \tag{4.1}$$

where C_{in} and C_{out} are the particle concentrations in the indoor and outdoor environments, respectively.

The estimation of the I/O ratio is a simple method. In this method, two-particle monitor/sampler is installed in the indoor and outdoor environments, and the output of that two monitors is used to assess the I/O. In general, the high I/O ratio is observed for well-ventilated environments and is low recorded in the case of a closed window (Cyrys et al. 2004). The I/O ratio larger than unity is reported by Diapouli et al. (2008) related to indoor activities. They found I/O ratio > 1 for the PM_{10} and $PM_{2.5}$ classes and offices, and smaller than unity for a library. Similar results for indoors were found by Pagel et al. (2016). They reported the high I/O ratios ≥ 2 for total suspended particulates, $PM_{10,}$ and $PM_{2.5}$ in a research station at the Antarctic. In literature, the highest recorded I/O ratio is 30.40, which was observed during cleaning hours in an air-conditioned classroom in the presence of precipitation (Guo et al. 2008). The high I/O ratio > 3 is found due to indoor smoking and combustion sources, whereas low I/O ratio is observed when fewer indoor sources and building have good seals (Chen and Zhao 2011). The I/O ratio is also affected by the meteorological conditions. Figure 4.13 shows the I/O ratio of $PM_{2.5}$ reported from the various parts of the world (Chen and Zhao 2011 and references therein). All these studies suggested that the high I/O ratio is mainly related to indoor smoking.

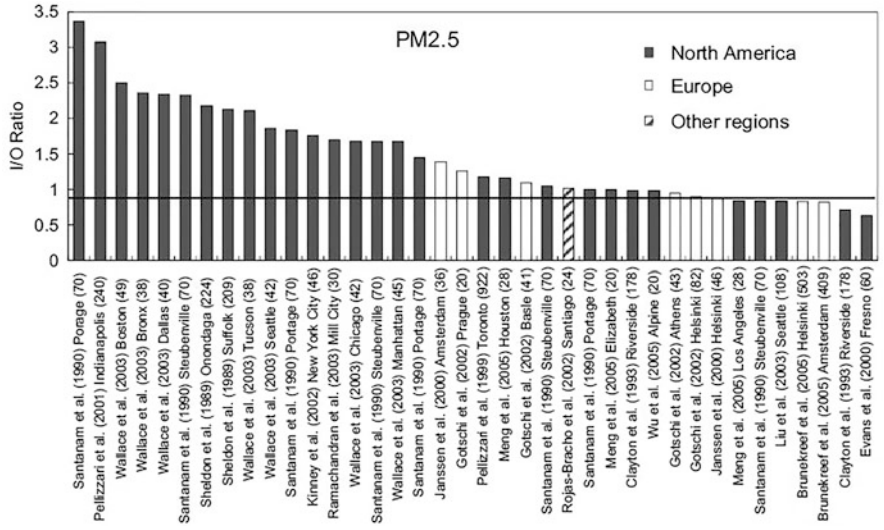

Fig. 4.13 I/O ratio from the different cities. The numbers in bracket denote the number of sample houses. (Adapted from Chen and Zhao 2011)

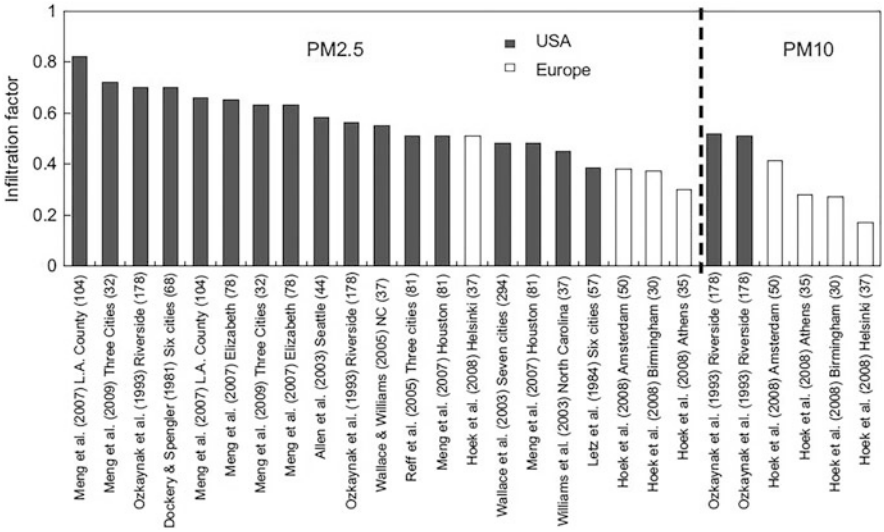

Fig. 4.14 IFs from the different cities. The numbers in bracket denote the number of sample houses. (Adapted from Chen and Zhao 2011)

The infiltration factor (IF) is another parameter used in establishing the relationship between outdoor and indoor particles (Meng et al. 2009). It characterizes the portion of outdoor particles that penetrates indoors and remains suspended. It does not consider the mixing of outdoor particles with indoor particles. The

literature-based IF varied from 0.3 to 0.8 for $PM_{2.5}$ and 0.2 to 0.5 for PM_{10} (Fig. 4.14; Dockery and Spengler 1981. Letz et al. 1984; Ozkaynak et al. 1996; Allen et al. 2003; Wallace et al. 2003; Reff et al. 2005; Wallace and William 2005; Meng et al. 2007, 2009; Hoek et al. 2008). These studies suggested that the IFs of $PM_{2.5}$ are higher than that of PM_{10} as coarse mode particles settled easily. As IF counts the fraction of outdoor particles entering the indoor without consideration of indoor sources, therefore, infiltration is pretty suitable for assessing the portion of the total indoor particles coming from outdoor environments.

To study the penetration of particles into indoor, the most appropriate parameter is the penetration factor (PF). It represents the portion of particles in the infiltration air that passes through the building shell. The PF is estimated in both real buildings and laboratories. Earlier studies showed that the penetration factor for real buildings varies from 0.6 to 1.0 for particles with diameters higher than ~0.05 μm and less than 2 μm. The penetration factor decreases as the diameter of particles increases because of the stronger gravitational setting of coarse mode particles (Chen and Zhao 2011 and references therein). Williams et al. (2003) found the penetration factor for $PM_{2.5}$ as 0.72, whereas it varied between 0.69 and 0.86 for PM_{10} (Tung et al. 1999). The outdoor particles are also carried by humans to the indoor environments in addition to the method discussed above. However, the fraction of outdoor particles flow to indoors in this way is unclear.

4.10 Impact of Outdoor and Indoor Air Pollution on Human Health

The high levels of outdoor PM have adverse health effects, e.g., increased risk of cardiovascular and pulmonary diseases. It is further found that fine PM (i.e., $PM_{2.5}$) is more significantly correlated with both mortality and morbidity due to their ability to penetrate deeply into the lungs (Pope et al. 2009; Goel et al. 2021). There are many premature deaths per year in the world due to air pollution. Cohen et al. (2017) estimated that there are more than four million deaths prematurely per year on a global scale due to air pollution in outdoor environments. The production of reactive oxygen species (ROS) in situ in the human respiratory system on inhalation is one of the most accepted mechanisms related to how aerosol affects human health (Pope et al. 2009). The imbalance between oxidants and antioxidants in the human body due to the production of ROS leads to several cardiopulmonary diseases (Amatullah et al. 2012). The capacity of aerosol to generate ROS and/or deplete antioxidants is called as their oxidative potential (OP). Although ROS production often displayed a good correlation with PM mass in literature, it is more complex than mass alone and may depend more on the physicochemical characteristics of PM (Akhtar et al. 2014; Charrier et al. 2015). A recent study by Patel and Rastogi (2018) over the northwestern IGP investigated the link between the chemical composition of outdoor PM and their OP (measured through dithiothreitol (DTT) assay). They reported that carbonaceous aerosols showed a positive correlation with OP where secondary inorganic aerosols displayed a negative correlation with OP. Further, they found that

carbonaceous aerosols emitted from biomass burning are found to be likely more DTT active than that derived from fossil fuel burning. Another study by Puthussery et al. (2020) found that the volume normalized OP over Delhi is found to be about five times higher than that observed in Illinois, USA. It is interesting to note that the average outdoor PM_1 concentration over Delhi was 13 times higher than the average outdoor $PM_{2.5}$ concentration over Illinois. But OP of outdoor PM over Delhi was only five times higher as compared to Illinois. It highlights the significance of measuring the PM chemical composition along with its mass concentrations for assessing the overall health impacts linked with aerosol exposure. The concentration of indoor PM can exceed health thresholds and cause life risks. Indoor PM produces a sense of discomfort that results in various cardiovascular and respiratory lung diseases and finally increases the morbidity and mortality (Goyal and Kumar 2013). The indoor air quality is mostly affected by outdoor pollution in addition to indoor sources as mentioned earlier. About 3.8 million people die per year due to dirty air of indoor environments as per the WHO report. Roy et al. (2016) studied the health risk associated with exposure to PM-bound metals in the indoors of the urban and rural sites of Pune City, India. The most likely sources of these metals include combustion of fossil fuels, coal, waste dumping, resuspension of household dust, candle burning, paint, and outdoor impacts. They found the high concentration of Fe among the metals in both fine and coarse mode PMs at both the locations that play a crucial role in the oxidant-generating activity. Further, they observed that fine mode PM is more oxidative in nature as compared to coarse PM and both fractions are responsible for the breakage of the DNA strand.

4.11 Summary

Air pollution is one of the biggest problems of modern society as it has various negative impacts on human health and has the potential to perturb the climate and agricultural production. Thus, it not only affects the people who lived in big urban centers but also impacts us all through climate change. There are more than four million deaths prematurely per year due to outdoor air pollution globally and outdoor air pollution also affects the indoor air quality, which is further responsible for 3.8 million deaths per year. The production of reactive oxygen species (ROS) in situ in the human respiratory system on inhalation is one of the important mechanisms through which aerosol affects human health. The capacity of particulate matter (PM) to produce ROS (termed as OP) is relatively more dependent on the chemical composition of PM rather than their mass concentrations. The global distribution of fine particulates indicates that high concentration is mainly observed over the middle east region, south and east Asia, and sub-Saharan regions of Africa. The reduction in fine particulates was observed over the USA, North America, Europe, and some parts of East Asia between 2010 and 2016 due to the implementation of emissions control strategies in these regions. The biggest reason for enhanced air pollution in the past few decades is utilizing the energy sources in an uncontrolled way to sustain our daily life activities. In recent years, most of the countries encourage the adoption

of renewable energy sources to tackle the air pollution problem, but it is not cost-effective. Thus, the coordination between the scientific community and policymakers should be required to address the problem of air pollution.

Acknowledgments We are thankful to the MODIS NASA scientific research team.

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High-Resolution Ambient Record of Aerosols over Delhi and Associated Typical Health Effects

5

Prashant Rajput, Jai Prakash, and Deepti Sharma

Abstract

Atmospheric aerosols, soon after their emission, may experience changes in its chemical composition, mass concentration, size, and its optical properties. These changes are dynamic in nature and occur over a short period of time. Since aerosols play a critical role in human health effects, cloud microphysics, hydrological cycle and climate perturbations, it is therefore of paramount importance to understand both qualitatively and quantitatively all the major changes, which an ambient particle could experience during its residence time in the atmosphere. High-resolution measurements (i.e. real-time measurements) are being carried out worldwide to capture any high-frequency changes in aerosol characteristics. In this study, we discuss the observations based on an open-access high-resolution data set retrieved from the Central Pollution Control Board (CPCB) for a location in central capital Delhi. Along with the particulate matter (PM) data, we also discuss some of the gaseous species owing to the reason that these gases influence the aerosol behaviour and its budget due to coating and secondary aerosol formation. The source strengths are highly variable (in both space and time) in Indo-Gangetic Plain (IGP) mainly due to industrial activities and seasonal influence of biofuels and biomass burning emission. This chapter presents a case study

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_5

highlighting some of the important observations on temporal variability and processes from high-resolution atmospheric data set of aerosols and reactive gases. We also present here a review on the health effects of outdoor and indoor aerosol pollution.

Keywords

Aerosols · Trace gases · Urban air pollution · Health effects

5.1 Introduction

Air pollution is the presence of any substance in the air at such concentrations, which are detrimental not only to the human beings, flora and fauna but also to the several components of the environment (Chakraborty et al. 2017; Choudhary et al. 2018). Air pollution is one of the major causes for degradation of environment (Yadav and Rajamani 2004). It occurs either from natural sources like volcanic eruptions, forest fires, sea spray, wind blown dust and pollen grains or can be as a result of various anthropogenic (human) activities like agricultural waste burning, vehicular emissions, power plants, and industrial emissions (Fig. 5.1). Air pollutants usually exist as tiny solid and liquid (e.g. dust, oil droplets and particulate matter), gases (e.g. NO_x, SO_2 and O_3) and semi-volatile species [e.g. PAHs: polycyclic aromatic hydrocarbons] (Rajput et al. 2014b). It has been widely realized that air pollution has

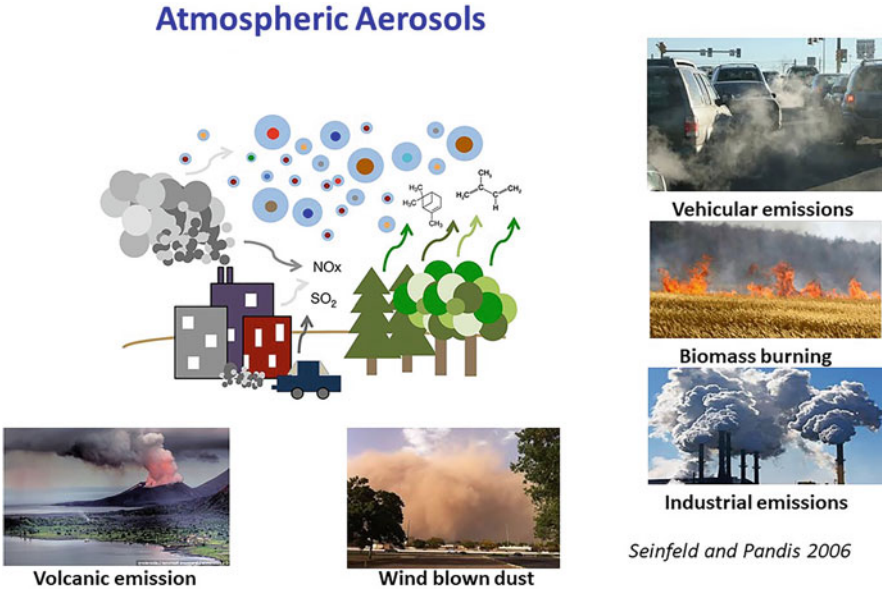

Fig. 5.1 Various sources (primary emissions and secondary formation) of ambient aerosols (also known as particulate matter: PM) (Senfield and Pandis 2006; Rajput et al. 2011, 2018a, b)

emerged not only as a local problem but also as a regional and a global problem (Izhar et al. 2018). Air pollution is widely being understood as one of the biggest environmental health risk factors of this century (Dockery et al. 1993; Rajput et al. 2014a; Schwartz 1995). Anthropogenic activities such as rapid industrialization, unrestricted population growth and increasing urbanization contribute increasingly to elevated emission rates of various air pollutants—among these, specifically higher levels of particulate matter (PM_{10} and $PM_{2.5}$), sulphur dioxide (SO_2), nitrogen oxides (NO_X), carbon monoxide (CO) and ozone (O_3)—leading to not only the degradation of the environment and climate change but also having a debilitating effect on human health (Dey et al. 2012; Pant et al. 2016). Simultaneously, over two-thirds of rural Indians caught in the 'chulha trap' use biomass fuels such as wood, twigs and dung cake to meet their cooking and heating needs, resulting in smoke-filled homes causing extremely high levels of exposure to the residents. Air pollution is especially severe in many developing parts of the world, which also happen to be very fast-growing urban regions contributing higher levels of pollution and are therefore subject to higher exposure. According to the World Health Organization's (WHO) figures, 97% of the cities in the low- and middle-income countries (LMICs), which have more than 100,000 inhabitants, do not meet WHO air quality guidelines (WHO 2018a). In the year 2016, ambient air pollution is estimated to have caused 4.2 million premature deaths worldwide, of which 91% occurred in LMICs (WHO 2016).

The atmospheric aerosol (aka particulate matter) ranges from 0.001 to 100 μm in aerodynamic diameter. Having various sources of origin and different chemical composition, they are an intricate combination of small and big particles (Kumar et al. 2017). They can mainly be sub-divided into two parts: primary and secondary. Primary aerosols are those that are directly produced and emitted into the atmosphere from identifiable sources like vehicles, industries, desert areas, construction activities, fossil fuel combustions, and road dust. They consist of black carbon (BC), crustal elements and organic compounds of high molecular mass released from combustion sources, etc. (Sorathia et al. 2018). *Secondary organic* aerosols (SOA) are those that form when condensation of volatile organic compound (VOC) oxidation products takes place (Rajput et al. 2013; Seinfeld and Pankow 2003). Secondary/aged aerosols are either organic or inorganic that affects the physico-chemical properties of the aerosols (Rajput et al. 2018a, b). Once produced, they grow to different sizes and can have different composition due to several physical and chemical modifications like coagulation, polymerization, photolysis, structural reorganization, and phase alteration and these processes are defined as atmospheric ageing (Fuzzi et al. 2006). SIAs (secondary inorganic aerosols) are formed from the chemical reactivity of gases like SO_2, and NO_2 and NO (collectively known as NO_X) leading to the formation of particulate sulphate and nitrate (Rajput et al. 2016). A recent study (Rajput and Gupta 2020), through causal modelling, has shown that for every 10-unit change in O3 concentrations the SOA formation increases by ~3.2% during daytime under prevailing long-range transport of biomass burning emissions from upwind IGP. Overall, the main composition of an atmospheric aerosols includes crustal matter (mineral dust); sea salt which includes sulphate, magnesium,

sodium and chloride; secondary particles like nitrate, sulphate and ammonium; trace metals like vanadium, chromium and lead; and carbonaceous material which includes both elemental and organic carbon and liquid water content (Senfield and Pandis 2006).

Also, depending upon the size of the particles, aerosols are classified into various categories. TSPs (total suspended particulate matters) are those whose aerodynamic diameter (d) is $\leq$100 μm (aerodynamic diameter of a particle is the diameter of a unit density sphere) ($\rho = 1$ g/cm^3) having the same terminal velocity as the particle of interest (Senfield and Pandis 2006), PM_{10} (coarse mode) whose aerodynamic diameter (d) is $\leq$10 μm and $PM_{2.5}$ (fine fraction) whose aerodynamic diameter is $\leq$2.5 μm. The fine fraction particles are further classified into nucleation mode ($d \leq 0.01$ μm), Aitken mode ($0.01 < d < 0.1$ μm) and accumulation mode ($0.1 < d < 1$ μm) (Raes et al. 2000). Coarse mode particles are formed from various mechanical processes like wind-blown dust, sea salt spray, cement dust, milled flour and pollen, but the fine particles are mainly formed from the various combustion processes (causing formation of black carbon, smoke, etc.) and condensation processes or secondary conversion of gases into the particulates (Rajput et al. 2016).

Aerosols influence the quality of life by affecting health, visibility and the environment at a very profound level (Posfai and Buseck 2010). Various epidemiological studies show that the mortality and morbidity rate in human beings increases with increase in the concentration of aerosols, especially correlated with the fine fraction particles (Geller et al. 2002; Srivastava and Jain 2007; Dockery and Brunekreef 1996; Peters et al. 2000; Neas et al. 1999; Schwartz 1995; Korrick et al. 1998). Among those most affected are the women, children, senior citizens, and the subjects with respiratory illness.

Aerosols play an important role in the climatic system of the Earth and the biogeochemical cycle of oceans (Mahowald et al. 2005). Aerosols affect directly the Earth's atmospheric radiative balance by scattering and absorbing incoming solar radiations, resulting in warming or cooling of the atmosphere. For instance, black carbon absorbs solar radiation and makes the global climate warm (Ramanathan and Carmichael 2008) and organic aerosols (net effect) scatter light, which led to reduction in incoming solar energy (Rudich 2003). Aerosols affect the climate indirectly by acting as CCN (cloud condensation nuclei) and IC (ice nuclei), i.e. act as nuclei for the condensation of water vapour and ice crystal (Novakov and Penner 1993; Spracklen et al. 2011). Indeed, if there were not any atmospheric aerosols, clouds would not be formed and would have resulted in no precipitation. Due to the increase in anthropogenic activities, burden on global mean aerosol concentration has changed considerably (Rajput et al. 2011). In order to enumerate these effects in a better way, a very good understanding of the formation, composition and transformation of aerosols is desired. Dry and wet scavenging processes are the two main removal pathways of aerosols from the atmosphere. Generally, the larger particles with $d > 1$ μm are removed by gravitational settling, but this process becomes less efficient as the particle size reduces. Particles with $d < 1$ μm can be removed efficiently by the wet deposition (Rajeev et al. 2016).

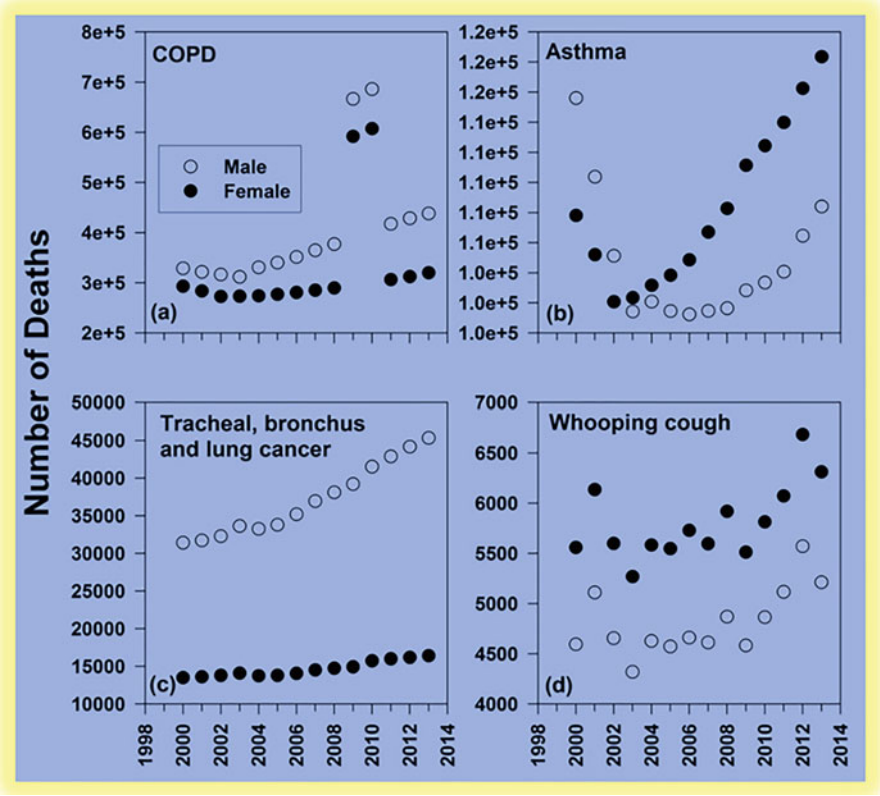

Fig. 5.2 Cause- and gender-specific mortality estimates for Indian region based on Global Burden of Disease data set (GBD 2015; Rajput et al. 2019)

Worldwide research on exposure assessment of ultrafine and fine particles has suggested severe human health impacts due to inhalation (Nazarenko et al. 2014; Singh and Gupta 2016; Asbach et al. 2017; Dandona et al. 2017). A near-continuous assessment on morbidity and mortality from major diseases, injuries and risk factors is being carried out through Global Burden of Disease (GBD) research programme (GBD 2015). GBD estimates (Fig. 5.2) suggest that number of mortalities in India is rising year by year due to COPD, asthma, TBL cancer and whooping cough, among others.

Integrating the data set on mortality (Fig. 5.2), it has been inferred that death of about one million people (including both male and female subjects) in 2013 year (in India) was caused due to respiratory diseases. Furthermore, decadal monitoring of GBD data set suggests that premature mortality of males is more pronounced due to COPD and TBL cancer (among the respiratory diseases), whereas higher deaths of females were found due to asthma and whooping cough (Fig. 5.2). One of the plausible reasons suggested for observing higher mortality due to asthma and whooping cough in females relate to the fact that most of the Indian women are

housewives and are therefore exposed for prolonged period to indoor air pollution and fresh emissions from biofuels as compared to the men (Parikh et al. 2001; Padhi et al. 2017).

5.2 Air Quality Guidelines

The air quality guidelines recommended by different organizations viz. World Health Organization (WHO), European Union (EU) and Indian region are listed in Table 5.1.

Air pollution kills an estimated seven million people worldwide every year. WHO data show that 9 out of 10 people breathe air containing high levels of pollutants. WHO is working with many countries to monitor air pollution and improve air quality. From smog hanging over cities to smoke inside the home, air pollution poses a major threat to health and climate. The combined effects of ambient (outdoor) and household air pollution cause about seven million premature deaths every year, largely as a result of increased mortality from stroke, heart disease, chronic obstructive pulmonary disease, lung cancer and acute respiratory infections. More than 80% of people living in urban areas are exposed to air quality levels that exceed WHO guideline limits, with low- and middle-income countries (LMICs) suffering from the highest exposures, in both indoors and outdoors.

5.3 Methodology

5.3.1 Air Pollution Monitoring in Delhi

Indian region, especially northern part, has experienced daunting challenges due to air pollution—according to several researchers, it kills every year more than one million in the country (Chatterjee 2019; Rajput et al. 2019). Many cities in India

Table 5.1 Air quality guidelines from World Health Organization, European Union and NAAQS (India)

Pollutant	WHO		EU		Indian	
	24 hr mean	Annual mean	24 hr mean	Annual mean	24 hr mean	Annual mean
$PM_{2.5}$ (μg/m³)	25	10		25	60	40
PM_{10} (μg/m³)	50	20	50	40	100	60

Interim targets(IT) by WHO aimed at promoting a gradual shift from high to lower concentrations.

IT for $PM_{2.5}$ (annual)

IT-1 – 35 μg/m³
IT-2- 25 μg/m³
IT-3- 15 μg/m³

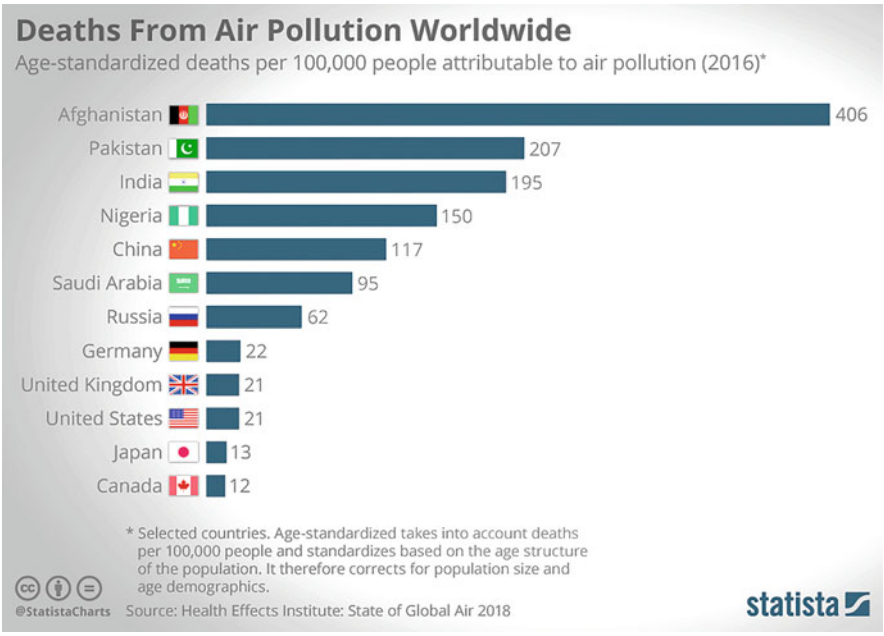

Fig. 5.3 A global scenario on air pollution caused mortality data from various countries (https://www.statista.com/chart/13575/deaths-from-air-pollution-worldwide/)

have exceeded over 5 times of the $PM_{2.5}$ level recommended by the WHO guidelines. Fine particulates ($PM_{2.5}$), comprising primarily of mineral dust, secondary aerosols and combustion products, are ~20 times smaller than a human hair, and they cause stroke, heart disease, chronic obstructive pulmonary disease, and lung cancer (WHO 2016, 2018b). In total, 90% of the world's population breathe harmful air (https://news.un.org/en/story/2018/05/1008732). A global scenario on air pollution led mortality from various countries is shown in Fig. 5.3.

India is making some progress in this area. The National Clean Air Programme aims to reduce air pollution levels by up to 30% by 2024. The country is also planning what it calls the world's largest expansion of renewable energy by 2022.

A recent 'world air quality report', published by AirVisual (2018), has reported a list of 20 most polluted cities in South Asia, and 16 of these are cities in India (Fig. 5.4). Delhi is the capital of India, and it is one of the most polluted cities in the world.

The heterogeneity in $PM_{2.5}$ levels and other gaseous pollutants is dependent on the location (Zikova et al. 2017). Many previous studies have been carried out to investigate the air pollution over Delhi through offline measurements. Since 2017, CPCB initiated continuous ambient air quality monitoring measuring air quality on a near-real time to hourly time interval resolution. The best part of these measurements by CPCB is that the data set is open source. The regulatory bodies and public organizations have deployed a series of instruments based on the federal reference

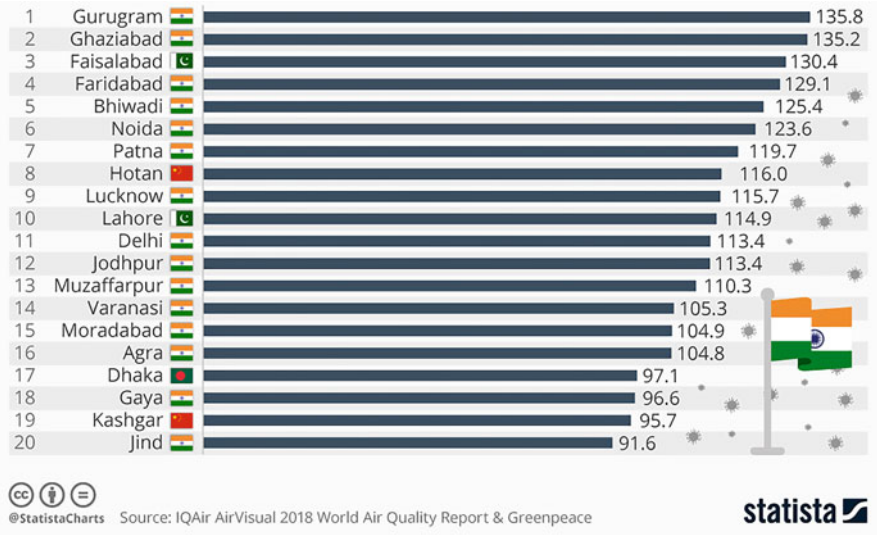

Fig. 5.4 Regional scenario of air pollution (annual average $PM_{2.5}$ in year 2018) in Delhi and nearby cities in India and in neighbouring countries. Source: AirVisual (2018)

method (FRM) and federal equivalent method (FEM) for an accurate and reliable air quality measurements in Delhi (DPCC 2017). A total of 26 Continuous Ambient Air Quality Monitoring Stations (CAAQMS) have been set up to help improve air quality data sets and assess the spatiotemporal variabilities in the abundance of pollutants and their source contributions (http://www.dpccairdata.com).

This chapter also embodies observations and discussions on the variability, effects and the understanding of criteria air pollutants. This work on detailed characterization of the air masses in Delhi documents on the following: (1) temporal variability of air pollutants on an hourly, weekly and seasonally basis; (2) abundance of primary and secondary pollutants and their relative abundances; and (3) application of conditional probability function (CPF) and potential source contribution function (PSCF) to look into the new insights of air pollution over Delhi.

5.3.2 Study Site

To assess the ambient air quality in urban area of Delhi, the Mandir Marg (MM) site was selected (Fig. 5.5).

MM is situated in the central part of Delhi, and it is 200 m away from the ring road, and the site has an influence from local emissions such as light duty/heavy duty vehicle activities. At MM site, a real-time beta-attenuation monitor (BAM, Ecotech, AECOM Group, Australia) and gases monitor (Ecotech, AECOM Group, Australia) are installed by the CPCB for measuring criterion pollutants.

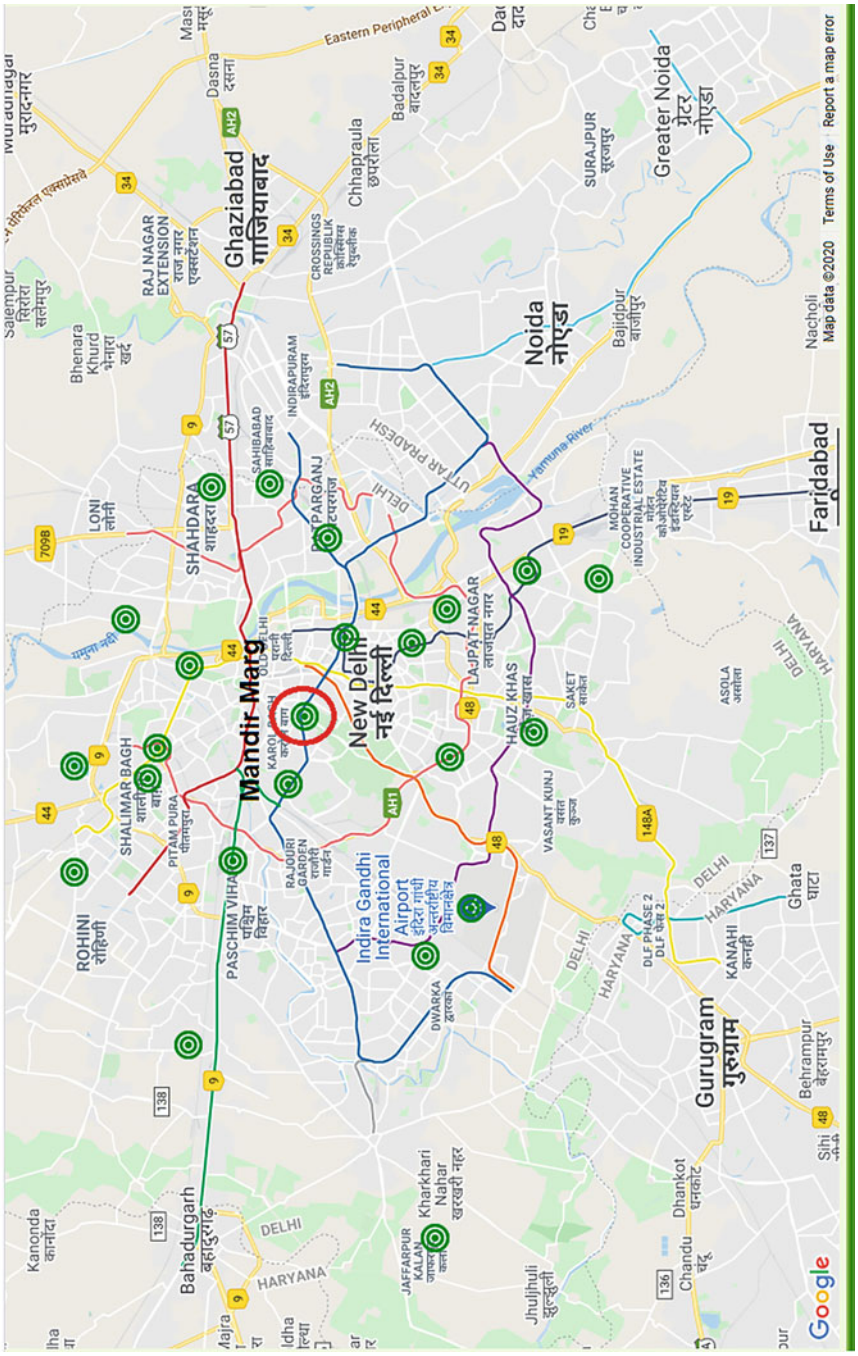

Fig. 5.5 Air quality data set in this work have been retrieved from CAAQM station (i.e. Mandir Marg: MM). Source: Real-Time Ambient Air Quality Data of Delhi (DPCC)

5.3.3 Data Source and Study Period

The hourly concentrations of particulate matter ($PM_{2.5}$ and PM_{10}) and other pollutants along with the meteorological parameters (wind speed, wind direction, temperature, and relative humidity) were obtained from the CPCB online portal for air quality data dissemination (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing). In this study, concentrations of these pollutants were analysed for the time period of 1 year from 01 January 2018 to 31 December 2018.

5.3.4 CBPF Analysis

In order to identify the local sources of pollutants, the conditional bivariate probability function (CBPF) analysis was performed. The CBPF was calculated using air pollutants by coupling of conditional probability function (CPF) with wind speed as a third variable, distributing, measured pollutant concentration to range of wind sector bins. CBPF is defined as follows:

$$\mathrm{CBPF}_{\Delta\theta,\Delta u} = \frac{m_{\Delta\theta,\Delta u} \downarrow c \geq X}{n_{\Delta\theta,\Delta u}}$$

where $m_{\Delta\theta,\ \Delta u} \downarrow c \geq X$ is the number of samples while wind is blowing in the wind sector '$\Delta\theta$' with wind speed interval 'Δu' having concentration 'c' greater than a threshold value, 'X'; and $n_{\Delta\theta,\ \Delta u}$ is the total number of samples observed in that wind direction for a given speed interval. The threshold criterion was chosen at the 50th or 75th percentile of pollutant concentration. CBPF analysis was performed by openair R package (Carslaw and Ropkins 2012) in R-studio (version 3.1.1; R Core Team, 2014) statistical software. More details about the method are described in Uria-Tellaetxe and Carslaw (2014).

5.3.5 PSCF Analysis

Air mass backward trajectories (AMBTs) were retrieved for each day at intervals of 3 h for the duration of 120 h during the study period in year 2018 using National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Rolph et al. 2017). The spatial resolution of the data is $1^\circ \times 1^\circ$, and the arrival heights of AMBTs were 500 m above the ground level. In this study, openair package in R has been utilized to download back trajectories. The functions and codes for downloading the monthly meteorological file from HYSPLIT PC model and merging every 3-h back trajectory end-point files (e.g. at MM site in this study) are discussed in openair R package manual. Furthermore, the potential source contribution function (PSCF) was also performed using the openair R package (Carslaw and Ropkins 2012).

5.3.6 Results and Discussion

Figure 5.6 shows the time-series plots (hourly variation) of PM_{10}, $PM_{2.5}$, CO, NO_2, NO, and SO_2 over the entire study period. The relevance of discussing here some of the gaseous species lies in the fact that they are connected with the emission source of PM and/or contribute to its burden through chemical reactivity (of these gases) and formation of secondary aerosols. The high concentrations of PM_{10} were observed in various episodes with frequent peaks in summer (March, April, May, and June 2018), and few peaks during the autumn season (November 2018). The PM_{10} mass concentrations exceeded over 75% of the National Ambient Air Quality Standards (NAAQS), attributable partially due to high load of mineral dust near the site. The highest mean ($\mu \pm 1\ \sigma$) concentration of PM_{10} was observed as $292 \pm 116\ \mu g\ m^{-3}$ in winter, followed by $218 \pm 126\ \mu g\ m^{-3}$ in autumn (post-monsoon), $182 \pm 101\ \mu g\ m^{-3}$ in summer and $126 \pm 86\ \mu g\ m^{-3}$ in monsoon, respectively.

In contrast, the elevated levels of $PM_{2.5}$ were observed during autumn (5 and 13 November 2018) and winter (22–24 and 29 December 2018) compared to summer and monsoon. The high concentrations of $PM_{2.5}$ during autumn and winter are attributable to the emissions from regional agriculture residue burning and local burning for space heating. The $PM_{2.5}$ concentrations exceeded over 55% as compared to NAAQS likely due to the anthropogenic sources (long-range transport of agricultural waste burning emissions, coal combustion, local biomass/waste burning, and vehicular emissions). The hourly mean $PM_{2.5}$ concentrations were observed as $192 \pm 92\ \mu g\ m^{-3}$ during the winter season, followed by autumn ($159 \pm 147\ \mu g\ m^{-3}$), summer ($79 \pm 55\ \mu g\ m^{-3}$) and monsoon ($49 \pm 32\ \mu g\ m^{-3}$), respectively (Fig. 5.6). The winter months are associated with low temperatures, low solar radiation, low mixing heights, and calm winds. All of these conditions are favourable for the accumulation of pollutants, and thus, leading to high concentrations of PM. The geographical setting of the region also plays a critical role in the dispersion/accumulation of air pollution.

High peaks of CO concentrations were found mainly during the winter (26–-31 January 2018). The highest mean CO level was observed as $2.6 \pm 4.8\ \mu g\ m^{-3}$ during the winter season, followed by autumn ($1.8 \pm 1.4\ \mu g\ m^{-3}$), summer ($1.1 \pm 0.8\ \mu g\ m^{-3}$), and monsoon ($0.5 \pm 0.3\ \mu g\ m^{-3}$) (Fig. 5.6). During winter and autumn seasons, local and regional source activities [burning of leaves and woods, and long-range transport of emissions from agricultural residue burning and the burning for heating purpose in winter] along with the lower boundary layer height could be the possible reasons for high concentrations of CO.

A near similar trend was observed for NO_2 and NO concentration during the study period at MM site. However, the highest NO_2 and NO concentrations were observed during night and early morning in winter and autumn season likely due to increasing heavy duty diesel vehicle emission, atmospheric chemistry and low mixing height. The highest mean NO and NO_2 concentrations were $96 \pm 146\ \mu g\ m^{-3}$ and $74 \pm 39\ \mu g\ m^{-3}$ during winter season of 2018, followed by autumn ($103 \pm 136\ \mu g\ m^{-3}$ for NO; $79 \pm 43\ \mu g\ m^{-3}$ for NO_2), summer

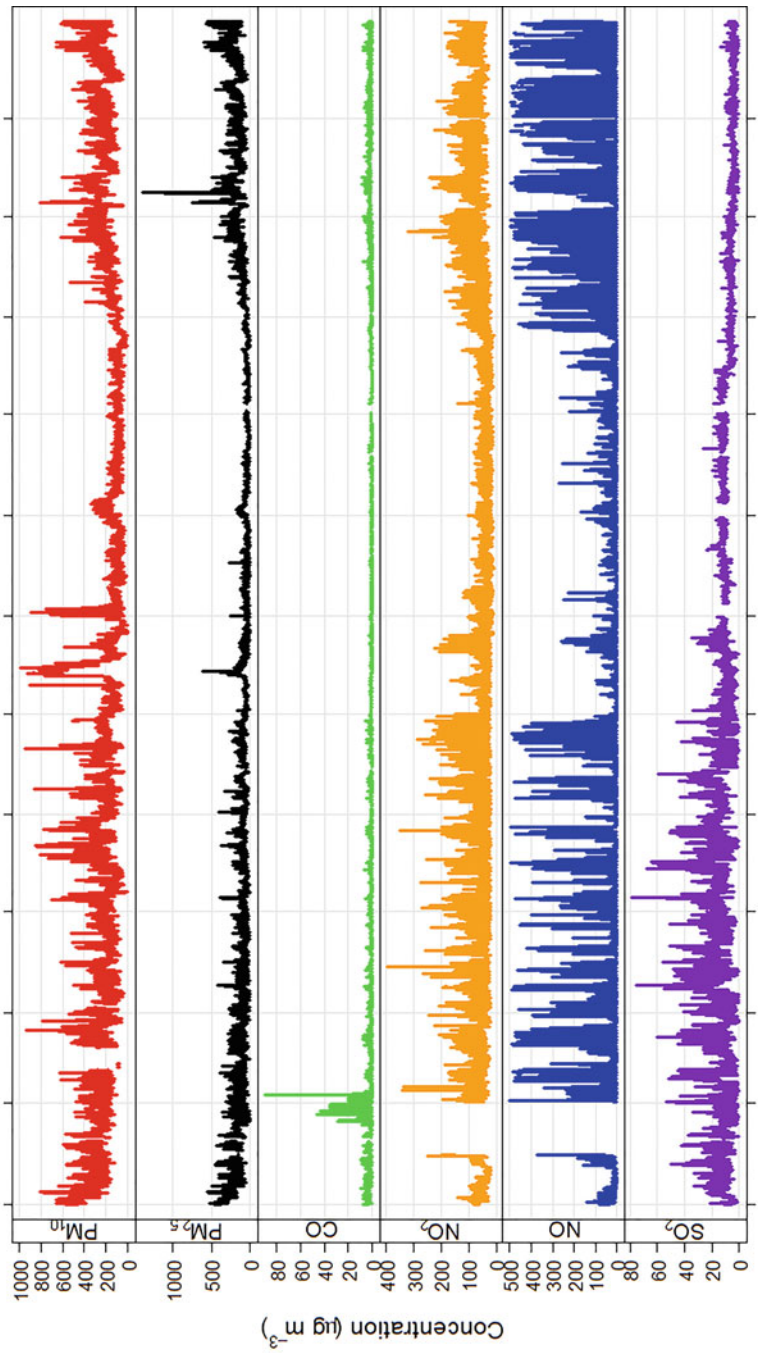

Fig. 5.6 Time series of PM_{10}, $PM_{2.5}$, CO, NO_2, NO, and SO_2 monitored over an urban site (Mandir Marg) of Delhi during the year 2018

(47 ± 93 μg m for NO; 65 ± 43 μg m for NO_2), and monsoon (21 ± 39 μg m^{-3} for NO; 38 ± 20 μg m^{-3} for NO_2) seasons, respectively (Fig. 5.6). Interestingly, it is noted that NO level is lower in summer and monsoon as compared to NO_2 level, which indicates the influence of photo-chemistry in regulating the abundance of NO_X species.

The elevated peaks of SO_2 were observed in winter through summer (March, April, and May), and then, declining levels are observed in monsoon and autumn seasons. The highest mean SO_2 concentration was observed as 16.2 ± 10.3 μg m^{-3} during summer, followed by winter (11.0 ± 9.1 μg m^{-3}), monsoon (10.9 ± 2.0 μg m^{-3}), and autumn (5.4 ± 1.7 μg m^{-3}) (Fig. 5.6).

5.3.7 $PM_{2.5}/PM_{10}$ Ratio

Figure 5.7 shows the calendar plot of hourly mean $PM_{2.5}/PM_{10}$ ratio at an urban site (MM) of Delhi. A high ratio of $PM_{2.5}/PM_{10}$ varying from 0.8 to 1.0 during the autumn and winter season has been observed in this study. The high ratios suggest the predominant impact of anthropogenic emissions and the intense atmospheric reactions leading to enhanced formation of secondary aerosol during the high $PM_{2.5}$ pollution episodes. Furthermore, the $PM_{2.5}/PM_{10}$ ratios were found in the range of 0.2–0.4 during the summer months at the study site, which plausibly indicates that coarse particles were more prevalent in the summer season. This observation has

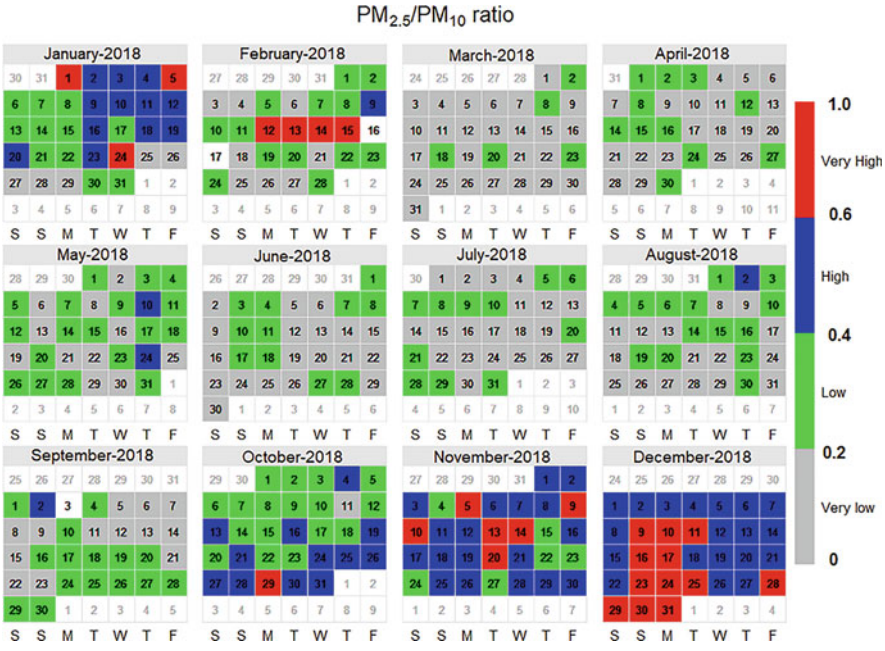

Fig. 5.7 Calendar plot of $PM_{2.5}/PM_{10}$ ratio over an urban site (Mandir Marg) in Delhi during 2018

linkage to enhanced mineral dust resuspension during the drier and hot summer season.

5.3.8 Influence of Meteorology

Besides atmospheric chemistry, the meteorological factors can also influence the level of air pollutants. Therefore, in order to understand the transport and the variabilities of criteria pollutants, conditional probability function (CPF) using wind speed and direction was analysed for the two high pollution witnessing seasons (winter and autumn). We plotted CPF by openair R package (Carslaw and Ropkins 2012) in R-studio (version 3.1.1; R Core Team, 2014) statistical software. More details about the functions are described in openair manual (Carslaw and Ropkins 2012).

The CBPF plots for diagnostic ratios ($PM_{2.5}/PM_{10}$, CO/NO_X and SO_2/NO_X) are shown in Fig. 5.8 for two different seasons [top panel (winter) and bottom panel (autumn)]. Concisely speaking, one of the unique features from CBPF plots for all the assessed pollutants or its ratios herein is that their variability pattern is by and large governed by the winds from south-west to the south-east direction.

5.3.9 PSCF Analysis

Further, the PSCF approach helps to establish the comparative importance of regional and local sources by determining the contributions of potential source regions influencing the air pollution at the receptor site. The PSCF analysis also segregates the relevant back trajectories along with species concentrations at the receptor site. The PSCF plots for the $PM_{2.5}$ are shown in Fig. 5.9 and the colour scale shown in each of these maps is a PSCF probability, indicating the possibility of source origin of a given species, which is measured at the receptor site. Threshold criteria were chosen at 75th percentile of pollutants for identifying the specific sources. For $PM_{2.5}$, PSCF analysis identified regional source locations in north-western region encompassing areas from IGP region such as Delhi, Punjab, Haryana and northern Pakistan, especially in winter and autumn seasons. Some parts of Uttar Pradesh also contributed $PM_{2.5}$ in autumn season (Fig. 5.9). It should be noted that the highest $PM_{2.5}$ was associated with low winds. In a recent study (Rajput et al. 2021), it has been shown that ~73% of the total PM pollution originates within the city cluster in IGP region and rest of the PM pollution is governed through long-range transport of pollutants from upwind region.

The PSCF maps of $PM_{2.5}/PM_{10}$ ratio identify potential source locations mainly in north-west directions such as Punjab, Haryana, with some contributions from Uttar Pradesh. This indicates that fine particles were transported predominately from regional source regions during autumn and winter season (Fig. 5.10a). In winter and autumn, the PSCF plots of CO/NO_X indicated that the probable locations

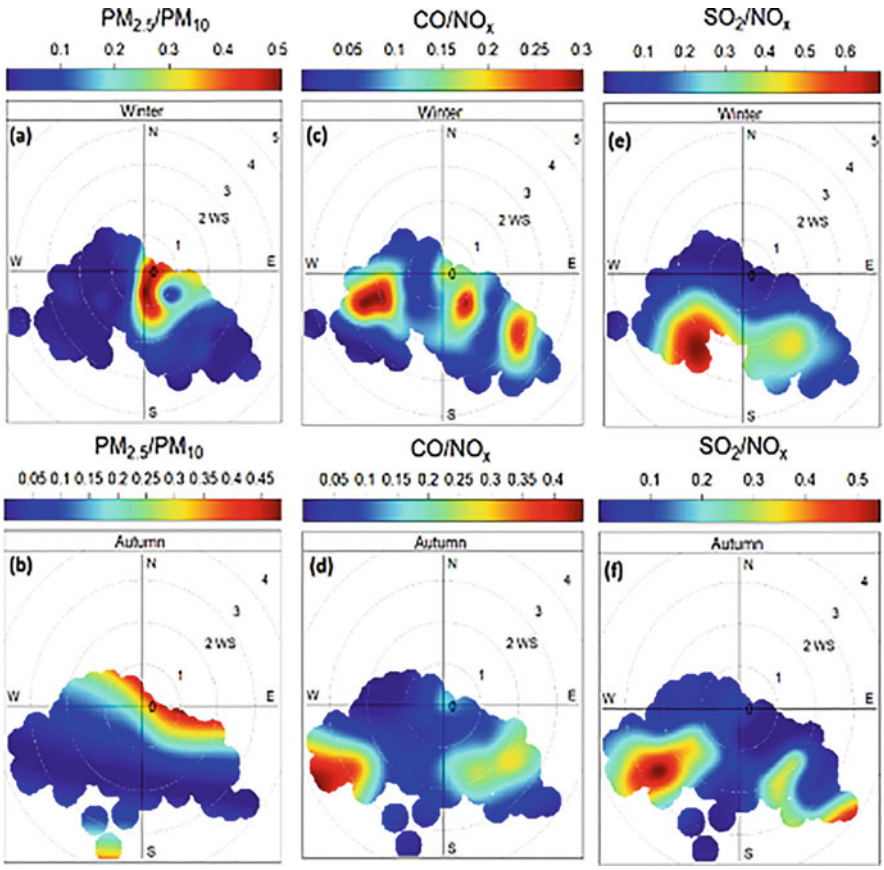

Fig. 5.8 CBPF plots of $PM_{2.5}/PM_{10}$, CO/NO_X and SO_2/NO_X in winter (top panel) and autumn (bottom panel) seasons over Mandir Marg in Delhi during year 2018. Threshold criteria were chosen at 75th percentile of species/pollutants

influencing their concentrations are situated in the south-east and east directions (Ghaziabad and Dadri from Uttar Pradesh) (Fig. 5.10b).

5.4 A Brief Review on Air Pollution and Public Health

5.4.1 Household Air Pollution (HAP) and Its Health Effects

According to the World Bank's '*The cost of air pollution: strengthening the economic case for action*', it is estimated that health and productivity loss in India due to air pollution, ambient and indoor combined, was about 5.7% of the GDP in 2013 (Balakrishnan et al. 2019). The same report also estimates that of this 5.7%, the 1.3% of GDP loss was due to indoor air pollution (IAP).

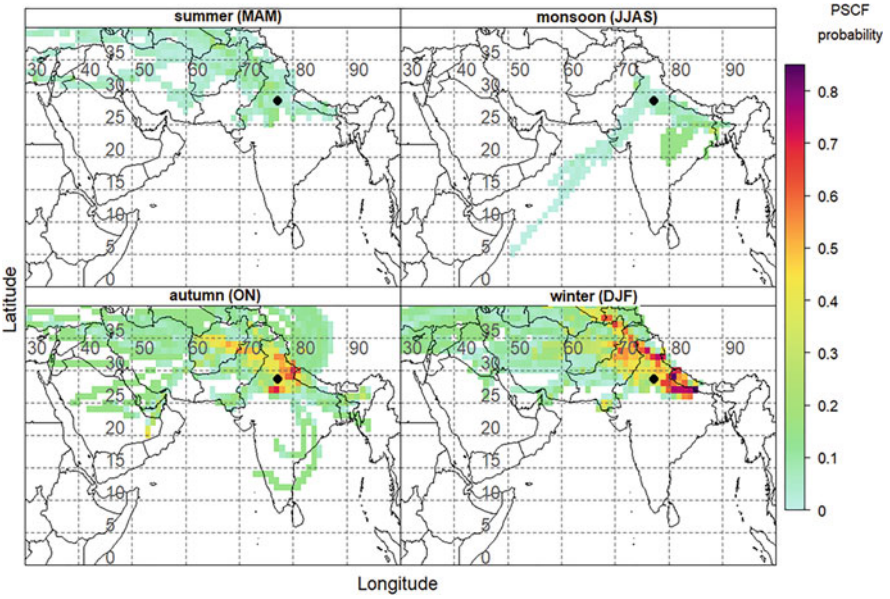

Fig. 5.9 PSCF plots of $PM_{2.5}$ using 5-day air mass back trajectories at Mandir Marg in Delhi (at 500 m above ground level). Threshold criteria were chosen at 50th percentile of pollutants

About IAP, the World Health Organization (WHO) asserts the rule of 1000, a rule which states that any pollutant released indoors is 1000 times more likely to reach into a person's lung as compared to the scenario when it is released outdoors (WHO 2007). As a result, IAP has been found to be 10 times more potent as ambient air pollution (Ching-Boon 2016). According to the WHO, IAP has directly been linked to increased cases of pneumonia, stroke, ischaemic heart disease, chronic obstructive pulmonary disease (COPD), and lung cancer in women and children (WHO 2018b).

Moreover, studies indicate that IAP disproportionately affects under-developed and developing countries (Kankaria et al. 2014). 4.5% of global daily-adjusted life year (DALY) and 3.5 million deaths in 2010 were attributed to indoor air pollution. The World Bank Study also reported that the total welfare loss due to premature death as a result of air pollution increased by 94% between 1990 and 2013, in which the contribution of IAP increased by four times to the final tune of $1.5 trillion (adjusted to 2011 PPP, purchasing power parity).

5.4.2 Sources and Pollutants

(a) Solid and biomass fuels—Incomplete combustion of biomass fuels generate pollutants like particulate matter (PM), carbon monoxide, polyaromatic hydrocarbons, polyorganic matter and formaldehyde. Combustion of coal, on the other hand, produces oxides of sulphur, arsenic and fluorine.

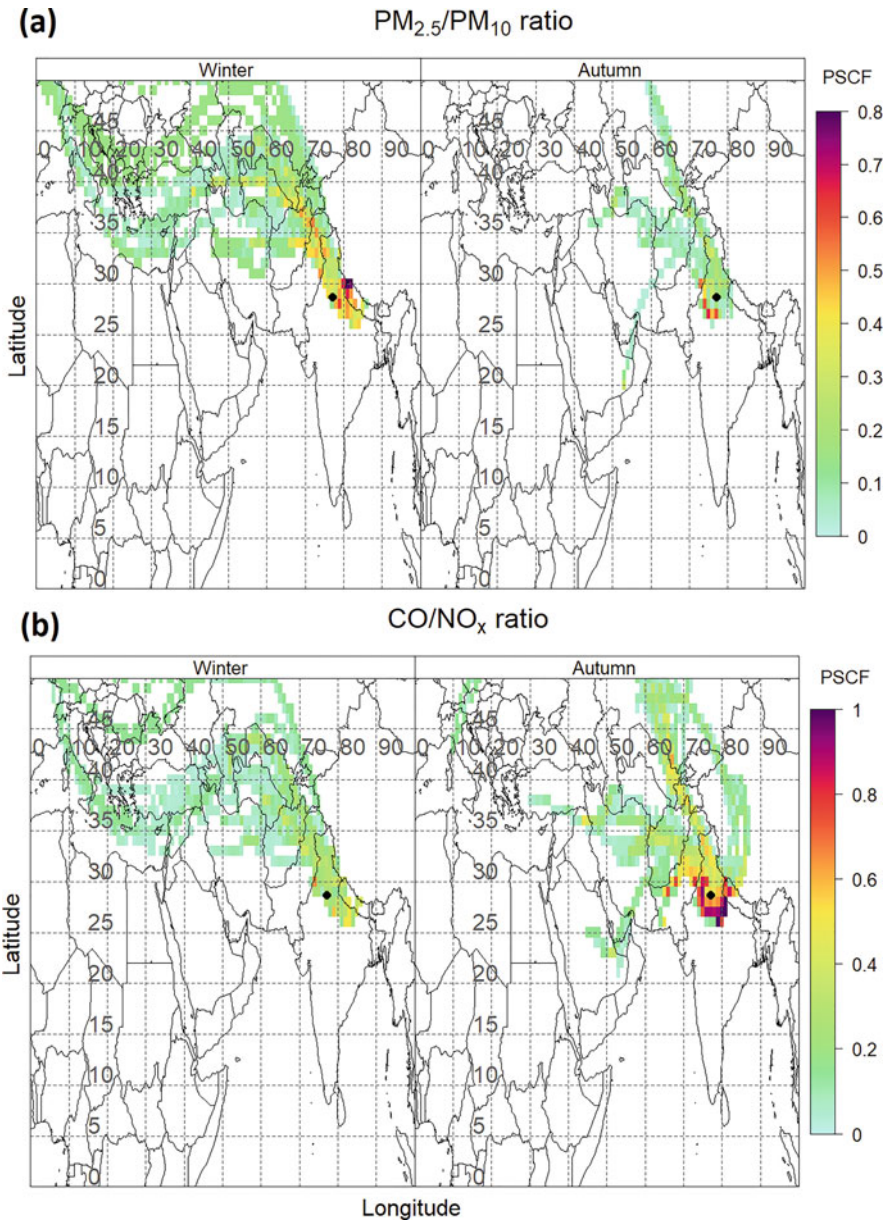

Fig. 5.10 PSCF plots of $PM_{2.5}/PM_{10}$ and CO/NO_X ratio at Mandir Marg in Delhi. Threshold criteria were chosen at 50th percentile of pollutants

Table 5.2 Indoor air polluting major cooking sources and associated emission impact from rural Indian region

Indoor pollution source	CO (mg m^{-3})	PAH (mg m^{-3})	HCHO (mg m^{-3})
Dung cake	144	3.56	670
Wood	156	2.01	652
Coal	94	0.55	109
Kerosene	108	0.23	112
LPG	14	0.13	68

Table 5.3 Indoor air quality in buildings within Delhi NCR

Pollutants	Average concentration
CO_2, ppm	1068
PM_{10}, μg m^{-3}	689
$PM_{2.5}$, μg m^{-3}	492
Benzene, ppb	150
Acetaldehyde, ppb	3125
Acetone, ppb	800
Toluene, ppb	275
Aerobic plate count, CFU	153
Fungal count, CFU	48

Here, *ppm* parts per million; *ppb* parts per billion; and *CFU* colony-forming units

(b) Bioaerosols—Airborne particles produced from microbial, viral, fungal and actinomycete, as well as microbes from organic materials, humidifiers, vaporizers, heating, ventilating and air conditioning systems (HVAC), lead to allergies, infections and poisoning.
(c) Volatile organic compounds—Pollutants such as aldehydes, volatile and semi-volatile organic compounds from resins, waxes, polishing materials, cosmetics and binders.
(d) Heavy metals like zinc, cadmium, chromium, mercury, lead and copper. Radon, pesticides, tobacco smoke and carbon monoxide.
(e) Biological pollutants like dust mites, moulds, pollen and infectious agents produced in stagnant water, mattresses, carpets and humidifiers too pollute indoor air.
(f) Infiltration of outdoor polluted air.

Additionally, indoor air quality (IAQ, Tables 5.2 and 5.3) gets further affected by

1. Building characteristics such as the air tightness and ventilation
2. Building occupancy and living space
3. Equipment used within the buildings (e.g. photocopiers, printers and heaters)
4. The customs, habits and tradition of the residents
5. The economic status of occupants

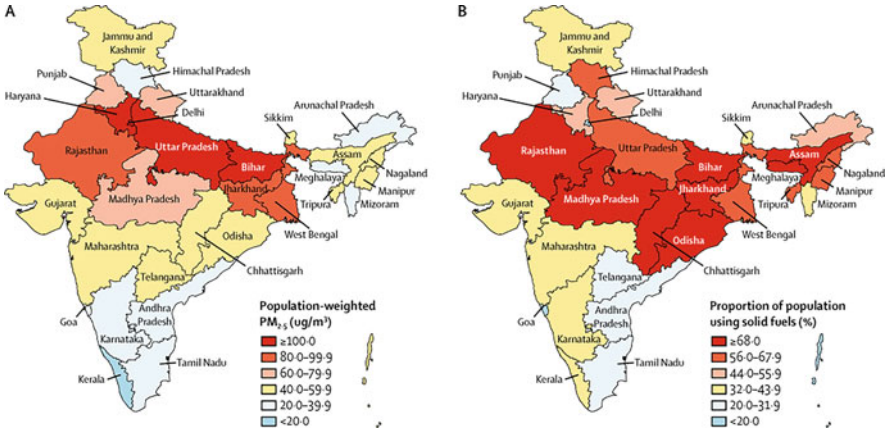

Fig. 5.11 $PM_{2.5}$ mass concentrations and use of solid fuels in the states of India, 2017: (**a**) Population-weighted mean ambient air $PM_{2.5}$ and (**b**) proportion of population using solid fuels. (Adapted from Balakrishnan et al. 2019)

In India, combustion of fuels is the largest contributor to indoor air pollution (IAP). Balakrishnan et al. (2019) find that IAP continues to wreak havoc in India due to excessive residential use of solid fuels (wood, dung, agricultural residue, coal and charcoal) for cooking and heating purposes (Fig. 5.11). Furthermore, more than half of India's population was exposed to IAP in 2017 (Balakrishnan et al. 2019).

5.4.3 Health Status

Of the 1.24 million deaths in India in 2017 due to air pollution (12.5% of all deaths in India that year), 0.48 million deaths were attributed to IAP (Balakrishnan et al. 2019). 8.1% of total DALYs in India (38.7 million in 480.7 million) for the same year were due to air pollution; 3.3% were due to IAP. Lancet report informs that 1 out of every 8 deaths in India in 2017 were due to air pollution (Balakrishnan et al. 2019). This indicates that air pollution puts a disproportionate health burden on India. This same fact also means that India has the most to gain by undertaking reforms. The same Lancet report informs that reduction in air pollution and bringing air quality level to minimum accepted level would add 1.7 years to the average life expectancy of Indian population.

According to the State of Global Air Report, 2019 (Health Effects Institute 2019), Indian region was observed to have the second highest concentration of indoor $PM_{2.5}$ averaging at 91 μg m^{-3} in South Asia (after Nepal's 100 μg m^{-3}) in 2017. Even in 2017, 56% of the population was still using solid fuels. A study done in rural areas of India found that PM exposure in a household that uses biomass for cooking averaged at 231 ± 109 mg m^{-3}, compared to households that used cleaner fuel where the daily average exposure stood at 82 ± 39 mg m^{-3} (Kankaria et al. 2014). The findings from the above-mentioned study are presented below:

A study conducted in Mumbai found that $PM_{2.5}$ average concentration from tobacco smoke was 363 μg m^{-3} at venues where smoking was allowed, compared to 97 μg m^{-3} where it was not (Raute et al. 2011).

Besides households, other settings where IAP is a cause of concern are schools, offices, and hospitals. A Greenpeace India report found that pollution levels in Delhi schools were five times higher than the safe limit recommended by WHO (Press Trust of India 2015). Other studies done in Delhi (Singh et al. 2017), Chennai (Nagendra and Harika 2010), Himachal Pradesh (Shree et al. 2019) and international experiences (WHO 2018b) all corroborate this finding and confirm that IAP level remains far worse inside the classroom than outside with exaggerated PM levels being the most threatening pollutant.

The Lancet (Stokel-Walker 2018) reports that 800,000 people globally die every year due to air quality issues at their workplace, and many more suffer due to the 'sick building syndrome' (EPA 1991), which includes headaches, cough, fever and chest pain caused due to contamination of air inside buildings. Lack of nationwide data in the Indian context makes it hard to comment on the corresponding figures for India, but a presentation given at Griha Summit summarizes the following with respect to buildings in NCR (Meattle 2016). Other studies in Rajasthan (Singhvi et al. 2019) support the finding of poor indoor quality in buildings.

The WHO reports that at any time 1.4 million people around the world are influenced with hospital-acquired infections (HAIs) and as many as 80,000 people around the world every year die due to HAI (Sidhu 2018). The IAQ and HAI incidence is dependent on factors like dimensional space, design features, cleaning and maintenance activities (Gola et al. 2019) and presence of bacteria, fungi, moulds and germs (Sidhu 2018). Emissions of pollutants ($PM_{2.5}$, PM_{10}, O_3 and NO) from nearby sources like road traffic and parking (Gola et al. 2019) also contribute to poor air quality in hospitals. A study done in hospitals in Chennai found high level of contamination of bioaerosols and pathogens in indoor air (Sudharsanam et al. 2008).

5.4.4 Health Effects

IAP disproportionately affects children, women and elderly (over the age of 60) because they spend most of their time at home and thus are exposed to pollutants for a longer period (Table 5.4). Sustained exposure of pregnant women has been reported to affect both the mother and the unborn. According to WHO factsheet, 3.8 million people globally die prematurely every year due to IAP. Among these, 27% are due to pneumonia, 18% due to stroke, 27% due to ischaemic heart disease, 20% due to COPD and 8% due to lung cancer (WHO 2018b).

Studies have found that the use of solid fuels causes acute respiratory tract infection and COPD, poor perinatal outcomes like low birthweight and stillbirth, cancer of nasopharynx, larynx, lung and leukaemia (Kankaria et al. 2014). PM and nitrogen dioxide have been found to cause respiratory infections. PM causes chronic bronchitis and COPD, while nitrogen dioxide affects lung function and causes wheezing. Sulphur dioxide too causes wheezing and exacerbates asthma, COPD

Table 5.4 Health effects of indoor air pollution (IAP)

Study and year	Important finding summary
Capistrano et al. (2017)	Found increased airway inflammation and oxidative stress when women are exposed to biomass smoke
Neogi et al. (2015)	HAP found to be strongly associated with neonatal mortality rate after adjustment ($\beta = 0.22$; 95% confidence interval [CI] = 0.09 to 0.35) for urban and rural areas combined. For rural areas, the association was significant ($\beta = 0.30$; 95% CI = 0.13 to 0.45) after adjustment
Sehgal et al. (2014a, 2014b)	Use of biomass fuel was associated with cataract 2.16 (1.42, 3.26) and stillbirths 1.26 (1.12, 1.43) in women
Burnett et al. (2014)	Risk estimate for male COPD incidence due to IAP $PM_{2.5}$ was 1.90 (95% CI: 1.56, 2.32) and for females was 2.70 (95% CI: 1.95, 3.75)
Bhat et al. (2012)	Use of any other fuel except LPG was found to be associated with acute lower respiratory tract infection (OR = 26.3, 95% CI: 10.5–65.7)
CPCB (2018)	Women chronically exposed to biomass smoke—high risk of developing upper and lower respiratory symptoms, lung function impairment, COPD, pulmonary and systemic inflammation, CVD, depression and increased risk of lung cancer
Johnson et al. (2011)	Biomass fuel use found to be associated with COPD (OR = 1.24, 95% CI: 0.36–6.64)
Sreeramareddy et al. (2011)	High exposure of pregnant women to IAP associated with low birthweight of newborns (OR = 1.41, 95% CI: 1.27–1.55)
Bassani et al. (2010)	Biomass fuel use associated with child mortality between ages 1 and 4 (prevalence ratio: boys = 1.30, 95% CI: 1.08–1.56; girls = 1.33, 95% CI: 1.12–1.58)
Tielsch et al. (2009)	Use of biomass fuels associated with increased probability (49%) of low birthweight
Behera and Balamugesh (2005)	Use of solid fuel among non-smoking women led to increased chances of lung cancer (OR = 3.04, 95% CI: 1.1–8.38)
Saha (2005)	Age-related cataract associated with wood burning (OR = 2.12, 95% CI: 1.03–4.34)

and CVD (Cardiovascular disease). Carbon monoxide (CO) has been found to lead to low birthweight and perinatal death, while polycyclic aromatic hydrocarbon (PAH) has been found to lead to cancers of lungs, mouth, nasopharynx and larynx. These PAHs are released by the combustion sources, which also produce metal ions, both of which cause cataract.

Incomplete combustion of biomass also produces formaldehyde, which has been known to cause acute irritation and bronchitis, reduce vital capacity and act as a carcinogen that can cause leukaemia and lung cancer. India-specific studies show that use of biomass combustion for cooking leads to active tuberculosis (odds ratio: OR = 3.66, 95% CI: 2.82–4.50). In fact, 51% of all cases of active tuberculosis in the age group of 20 years and above could be attributed to smoke from cooking. Users of biomass fuels were also found to be at 50% excess risk of stillbirths and 1.5 times more likely to have low birthweight babies. On average, these babies weigh 73 g lighter (mean birthweight 2883.8 g versus 2810.7 g, $p < 0.001$). There is also an

increased risk to asthma (Sehgal et al. 2014a, b). Besides this, the cognitive abilities and productivity levels of those exposed to higher level of indoor pollutions are severely hampered. Holding constant other risk factors, apart from LPG, all other cooking fuels were found to cause acute lower respiratory tract infection (adjusted OR = 4.73). In fact, the use of biomass fuels was found to significantly contribute to a prolonged nasal mucociliary clearance time (765.8 ± 378.16 s) when compared to the use of cleaner fuels (545.4 ± 215.55 s). Similarly, biomass use was also found to lead to higher cases of COPD (OR: 1.24), especially among those who spend more than 2 h a day for cooking. Additionally, the carcinogens (PAHs, HCHO, etc.) released by biomass fuels reportedly led to cases of lung cancer in women (Kankaria et al. 2014). Among women, the study conducted by Sehgal et al. (2014a, b) found that IAP contributes to 2.4 million of the 5.6 million cases of chronic bronchitis, 0.3 million of the 0.76 million cases of TB and five million of the 51.4 million cases of cataract. Her paper also corroborates aforementioned IAP health effects of COPD (OR from 1 to 3.04), lung cancer (OR from 1.5 to 3.8) and acute lower respiratory tract infections (OR from 1.5 to 3.7).

Studies that have been used to present above the health effects of IAP have been tabulated in table 5.4:

5.4.5 Vulnerable Population

IAP is more likely to affect rural and poor/low socio-economic status (SES) households compared to urban and richer households and women and younger children are the more vulnerable population compared to men (Kankaria et al. 2014). Since combustion of cooking fuels contributes to IAP the most, women get disproportionately affected due to household air pollution. According to the Global Burden of Disease programme, globally India records the highest number of deaths attributed to illnesses caused due to IAP from solid fuel burning. According to the World Health Organization's report 'Air Pollution and Child Health' in 2016, indoor air pollution led to the death of 66,890 children below the age of 5 years, out of which 36,073 were girls and 30,817 were boys. In totality, 101,788 children in India under 5 years of age died due to ambient and indoor air pollution combined, which roughly translates to around 12 deaths per hour in 2016. Besides women and children, it is the elderly (age ≥ 60 years) who are extremely vulnerable to IAP and studies show that the elderly in households that use biomass fuels more often suffer from asthma (as compared to households that use cleaner fuels, OR = 1.59; 95% CI: 1.30–1.94). The same study also confirmed that women are more vulnerable to asthma caused by IAP as compared to men.

5.5 Conclusions

We have presented here the current status of air pollution focusing over a typical urban site of Delhi and a brief overview of health effectsof air pollution. We report on detailed characterization of the air masses in Delhi and investigate the following aspects: (i) temporal variability of particulate matter ($PM_{2.5}$ and PM_{10}) on an hourly, weekly, monthly and seasonally basis; (ii) the primary and secondary pollutants and their relative abundances; and (iii) conditional probability function (CPF) and potential source contribution function (PSCF) are also discussed for the data set over Delhi. In Delhi, clear seasonal trends were observed for $PM_{2.5}$, PM_{10}, CO, SO_2 and NO_X. High abundance episodes of $PM_{2.5}$, PM_{10}, CO and NO_X were observed in winter and autumn due to emissions from local and regional sources and from the long-range transport. High $PM_{2.5}/PM_{10}$ ratio in autumn and winter is attributable to predominant impact from anthropogenic emission sources. CPF and PSCF analysis showed that besides local sources the long-range transport affected the local and regional ambient air quality in Delhi. Overall, the PSCF analysis has revealed that by and large the high concentration of air pollutants, mainly during the winter and autumn seasons, was associated with air masses arriving from north-west direction in Delhi. This study highlights the utility of other CAAQM stations in India for the exploration of air quality research, public health and awareness and policy framework.

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Characterization of Primary and Secondary Airborne Particulates

6

Saraswati

Abstract

This chapter presents a brief review on the characterization of primary and secondary airborne particulates. The atmospheric aerosols are complicated composition of various chemical species. As the chemical structure and size distribution of the aerosol particulates are linked to their origin and formation mechanisms, their natural or anthropogenic origin can be identified by chemical characterization. Other factors including regional atmospheric dynamics (responsible for transport and dispersion of pollutants), meteorological conditions and the presence of gaseous precursors (influencing gas-to-particle conversion) are also important. The purpose of this chapter is to present a brief outline of emission sources of primary and secondary particles from natural and anthropogenic sources with focus on characterization and to describe and analyse the main factors that characterize main sources of origin, chemical structure and size distribution. We begin with the primary and secondary particulates and their emission sources. We then discuss physical and chemical characteristics of the airborne particulate matter. The particle diameter, shape, density, size distribution, etc., are described in detail. We have also highlighted the different chemical and biological composition of PM. The formation and removal pathways of these species are also explained. The brief overview of different characterization techniques was also given in the last section of this chapter, which are used for the physical and chemical characterization of particulates.

Keywords

Primary and secondary particles · Emission source · Characteristics · Atmospheric particle formation and removal

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_6

6.1 Introduction

Atmospheric particles, also known as aerosols or particulate matter (PM), are a suspension of solid and liquid particles in the air (Baron and Willeke 2001; Koop et al. 2011). Atmospheric PM comprises a heterogeneous mixture of small particles and liquid droplets varying greatly in origin, size and composition (Kim et al. 2015) depending on the location and time. Airborne particulate matter represents a broad class of physically and chemically varied substances (Virtanen et al. 2010). Atmospheric PM is of considerable concern because it has pronounced effect on global climate, human health and visibility reduction (Seinfeld and Pandis 2016; Saxena and Sonwani 2019a). Particulate matter (PM) accounts for a complex group of air pollutants with properties and impacts that vary according to its composition and size. The mass and composition of airborne particulate matter are highly unpredictable in spatiotemporal terms and are considerably affected by meteorological and climatic circumstances. The emission rates, size and composition of PM emissions are challenging to determine since they depend not only on the sector considered, but also on the fuel properties, technology and other characteristics of the emission process. Aerosols in the atmosphere have different origins and largely varying physical and chemical properties. Atmospheric PM can be emitted by a wide variety of sources that influence its physical, chemical and biological compositions (Després et al. 2012; Saxena and Sonwani 2019b). Particles with diverse size fractions might distinct not only in framework and size but also in origin, formation technique and physical and chemical characteristics (Lee et al. 2006). Once emitted, particles may undergo various physicochemical transformations that may alter particle size and chemical characteristics. The atmospheric aerosol is very complicated, portraying a combination of primary and secondary species (Kanakidou et al. 2005). The emission sources, geographical location and corresponding atmospheric chemistry determine the characteristics of the primary and secondary aerosol (Karagulian et al. 2015). Sources of PM comprise both direct emissions and chemical conversion of precursor gases emanated from automobiles, power plants, wood burning, forest and agricultural fires, and natural sources (Sonwani and Kulshrestha 2018). The crustal elements (Fe, Ca, K, Mn, Si, Al, Ti, Sr) and their composite, soot, sea salt and a series of organic compound are main components of primary aerosol, while ammonium, nitrates, sulphates, chloride and carbonaceous material are important part of secondary aerosol (Cheung et al. 2011).

The presence of all these pollutants modifies the physicochemical characteristics of the atmosphere. The mass and number concentrations of particulate matter, their architecture and chemical content are also a crucial aspect to be considered along with size. It is necessary to understand what makes up the aerosol and how the chemical composition of the aerosol is temporally and spatially distributed in the ambient environment. The physical and chemical characterization of the particulates can determine their atmospheric behaviour and also provide the valuable information about the sources of particles. Unlike other pollutants, such as SO_2 or NH_3, PM describes a complex group of air pollutants with properties and impacts that vary according to their composition and size (Booth and Bellouin 2015). The composition

of PM is highly complicated and varies depending on local sources, source strength and atmospheric processes such as regional transport and gas-to-particle partitioning. The primary goal of the present chapter is to describe and analyse the main factors that characterize PM emissions, including main sources of origin, size distribution and chemical composition. Thus, understanding their sources and their associated physical, chemical and biological compositions can provide insight on exposure and possible mitigation strategies. Therefore, investigating the physico-chemical characteristics of PM is crucial in understanding its environmental and health effects for both policymakers and the general public (Sonwani and Maurya 2018; Saxena and Sonwani 2019c).

6.2 Primary and Secondary Airborne Particulate Matters

Atmospheric aerosol particles can be divided into two classes reflecting their major formation mechanisms as primary and secondary. The directly emitted particles from anthropogenic or natural sources are primary PM and those resulted from gas-to-particle conversion are secondary PM. The latter ones are produced through condensation processes of a semi-volatile component either on its own or on pre-existing particulate surfaces or volumes and via reactions of more than one gas forming a new particle (Maria et al. 2004).

Primary PM originates predominantly from combustion (e.g. vehicle engines) and high-temperature processes (e.g. smelting and welding industrial operations) (Fonseca et al. 2015; Maricq 2007) as well as from mechanical disruption processes and man or wind-induced events causing suspension of particles (e.g. resuspension of street dust) (Amato et al. 2014; Guevara 2016). Primary particulates are emanated from sources as particles and are dispersed in the atmosphere without any large chemical changes. Combustion emissions include directly generated carbonaceous material and trace elements, while hydrocarbons, SO_2 and NO_x released from natural and anthropogenic sources are oxidized within the atmosphere forming products, which may either form new particles or be removed by condensation onto the surfaces of existing aerosols. The great interest in atmospheric particles at present is result of their impacts on human health and climate. Primary particles generally have effects on local scales, whereas secondary particles affect regional and much broader areas, whereby the primary particles mostly exist in the coarse size fraction and the secondary particles generally in the fine fraction (Raes et al. 2000). The coarse fraction includes particles greater than 2 μm aerodynamic diameters (ADs), which are mainly directly introduced into the atmosphere with mechanical actions or from natural sources. The fine fraction contains primarily particulates with aerodynamic diameters (ADs) less than 2 μm, which originate from gas-to-particle conversion. The secondary PM in the atmosphere is the result of gas-to-particle conversion or condensation of gaseous compounds on pre-existing aerosol particulates, mainly involving NO_x, SO_x, NH_3 and VOCs, which may react with O_3, OH and other reactive molecules forming secondary inorganic aerosols (SIAs) and secondary organic aerosols (SOAs) (McMurry et al. 2004).

6.3 Emission Sources

The temporal variability and spatial variability in the structure of atmospheric aerosols on regional and global scales are controlled by different types of natural and anthropogenic emission sources. The sources of primary particulate matter (PM) are derived from both human (anthropogenic) and natural (non-anthropogenic or biogenic) activities. Secondary PM sources directly emit gaseous pollutant into the atmosphere, which forms or helps to form PM.

6.3.1 Natural Sources

Globally, natural sources of primary aerosol dominate the mass emissions of PM. Natural sources are mainly sea salt, soil erosion, volcanic eruptions, wildfires and biogenic sources (Lewis et al. 2004).

Sea salts, commonly known as sea spray, are particles arising due to the bursting of air bubbles on the surface of water due to the movement of waves (Lewis et al. 2004). The freshly generated sea salt particles from the sea possess the composition of the seawater. This composition is modified during their stay in the atmosphere due to the reaction with gaseous and acidic species such as NO_x, leading to chloride depletion. In general, they consist essentially of sodium chloride (NaCl), sodium, potassium or magnesium sulphates (Na2SO4, K2SO4 and MgSO4) (Bliefert and Perraud 2007). Hygroscopic properties of these compounds determine the particle size.

Soil erosion is another natural source of primary aerosol, generated primarily through wind action in dry conditions or in arid regions, which cover about a third of the surface of the continents (Mahowald et al. 2005). The natural mineral dust particles may result from physical and chemical weathering, soil dust resuspension or long-range transport (Tegen et al. 1997). **Mineral (soil) dust** is a primary component of the aerosol on a global scale and accounts for a large part of the natural primary particulate matter. The structure of these particles relies upon the geological characteristics of the area (Pietrodangelo et al. 2013). The chemical structure of atmospheric aerosols from soil erosion indicates that they are on the whole, consisting of characteristics of the crustal elements, mainly Al, Si, Fe, Ti, Ca, Na, Mg and K (Usher et al. 2003).

Volcanic eruptions are also sources of primary particles but in a limited time contribution. However, their contribution to the bulk PM levels in ambient air is limited in time and space (Andres and Kasgnoc 1998; Graf et al. 1997). The volcanic particles are mainly composed of glass and also contain pyroxene, feldspar, plagioclase and aluminosilicates. Two types of solid particles are formed, dust and fly ash, as well as gaseous emissions mainly SO_2, CO_2, H_2O, H_2S, etc. These compounds can act as a precursor gas at the gas-to-particle conversion.

Wildfires, as volcanic eruptions, have a limited spatial and temporal impact. The difference between natural and anthropogenic aerosols produced under these conditions is difficult to establish. The composition of smoke from forest fires varies

and this smoke is composed of primary particulates, in the variety of ash and soot and gases that may lead to the production of secondary particles by gas-to-particle conversion (Jain et al. 2021). The amount of the particles produced and their composition depends on the characteristics of the burnt plant timber (Alves et al. 2010).

The origin of the **biogenic particles** is variables such as pollens, spores, fragments of animals and plants, as well as bacteria, algae, protozoa, fungi and viruses (Després et al. 2012). Primary biogenic sources give rise to bioaerosols or biological residues, some of which are of potential risk to human health. These aerosols comprise mainly of plant debris and microbial particles such as bacteria and fungi, viruses, protozoon or algae, pollen and spores. Bacteria and viruses have sizes <2 μm, whereas the fragments of plants and spores exhibit sizes in the coarse fraction (Pósfai and Molnár 2013).

Sulphate, nitrate and organic matter are the main components of the natural secondary aerosols. The natural sources of **secondary particles** are the sources of precursors involved in the gas-to-particle conversion (Sonwani et al. 2016). Natural sulphate aerosols are generated in the atmosphere from the chemical reactions of gaseous precursors. The two main sulphate precursors are SO_2 from volcanoes and dimethyl sulphide ($(CH_3)_2S$; DMS) from biogenic sources. Nitrate is formed by the oxidation of nitrogen oxides (NO_x), and the soil transpiration and lightning are the main natural sources (Price et al. 1997; Roelle et al. 2001).

Secondary organic aerosols (SOAs) may be formed by oxidation of organic compounds emitted by forests and grasslands, volcanic eruptions and burning biomass. The main natural sources of the organic precursors for secondary aerosol formation occur in forested areas, where significant quantities of volatile organic compounds (VOCs), such as isoprene and monoterpenes, are released during plant transpiration. The oxidation of these organic vapours gives lower vapour pressure gases, which create new particles by nucleation or condense onto pre-existing particles (Claeys et al. 2004).

6.3.2 Anthropogenic Sources

Anthropogenic emissions of **primary particles** result mainly from the transportation sector, industrial waste, petroleum products, incineration sites and agricultural activities. Road transport contributes to particulate emissions not only through the exhaust gas, but also by the wear of tires and brakes, as well as the resuspension of dust covering the roads. It is responsible for many types of particles: fine carbon particles, coarse particles from road abrasion, particles from abrasion of tires and brake, characterized by their high copper (Cu) in the case of brakes or zinc for the tires (Davis et al. 2001). The industries are responsible for the issuance of a vast majority of heavy metals. The nature of industrial particulates relies upon utilization of process, but combustion particles generally are dominated by black or elemental carbon and heavy organic material such as polycyclic aromatic hydrocarbons (PAHs) (Sonwani et al. 2021a; Bond et al. 2007; Davis et al. 2001).

Anthropogenic particulate sources are mainly located in urban and industrial environments. With regard to traffic, primary coarse particles originate from the abrasion of brake linings (Al-Momani et al. 2005; Gietl et al. 2010) and tyres and resuspended road dust, whereas fine primary particles (soot and trace elements) are emitted by the vehicle exhaust. Manufacturing of bricks, cement and ceramics, building construction, coal combustion, mining, metallurgy, smelters and waste incineration are among the industrial and technical activities that also produce primary particles. The primary particles associated with some industrial sources consist mostly of coarse particulate matter of crustal composition. Smelters and waste incinerators emit fine primary particles (Pacyna and Pacyna 2001). Coal combustion is a large source of fly ash (primary PM) whose emission has been larger in the past, but currently in most industrialized countries, it has been reduced due to the progress replacement of coal by other fuels and the use of emission abatement technologies.

Anthropogenic secondary particles include sulphate, nitrate and organic particles. A large proportion of SO_2, which is the gaseous precursor of sulphate, originates from coal combustion, other industrial activities and vehicular traffic. The oxidation of SO_2 produces sulphuric acid (H_2SO_4), which is then neutralized by ammonia forming ammonium derivatives (NH_4HSO_4, $(NH_4)_2SO_4$) in the fine size fraction. However, sulphuric acid neutralized by calcium carbonate and sodium chloride can be found in the coarse fraction. Traffic emission in the urban environment and some industrial processes are the main anthropogenic sources of nitrogen oxides (NO_x), and gaseous nitric acid (HNO_3) is formed by the oxidation of NO_x and may be neutralized and transformed into particulate nitrate. Ammonium nitrate is present in the fine mode, while calcium nitrate and sodium nitrate (formed by neutralization of HNO_3 by crustal $CaCO_3$ and marine NaCl, respectively) occur in the course.

Secondary particles can be formed by anthropogenic emissions and gaseous compounds by gas-to-particle conversion (Pankow 1994). Anthropogenic emissions of sulphur-based compounds are totally due to SO_2 emissions. Sulphur is emitted from burning of coal and petroleum products, refineries and processing of non-ferrous ores. Nitrogen-based gases such as NO and NO_2 emitted into the troposphere by combustion processes (fossil fuels, biomass) and NH_3 emitted from the combustion of biomass, animal husbandry and agriculture are precursors of anthropogenic particles (Benson et al. 2011). Burning fossil fuels (transport, industry), waste incineration and combustion of wood and coal (cooking and heating) are sources of anthropogenic particles rich in organic compounds.

6.4 Characterization of Airborne Particulate Matter

The particles are mainly categorized based on their physical (size and shape) and chemical characteristics. The characterization of PM provides information important to the understanding of our environment and associated health risks. Understanding the size and shape of particles is very necessary to evaluate the impact of PM on human health and environment. Thorough description of physical properties like

shape, size, density and chemical and biological composition is given in the present section.

6.4.1 Physical Properties

6.4.1.1 Textural Properties

Whatever their chemical composition, the solid particles can be characterized according to their textural properties. The concept of texture includes the specific surface area (m^2/g), the specific pore volume (cm^3/g) and porosity, the shape of the pores, and the pore distribution or the pore volume distribution. The specific surface area (m^2/g) is the total surface area per unit mass of a divided solid, and it corresponds on one hand to the geometric surface of the grains, depending on the size distribution and shape (such as asbestos) of particles, and, on the other hand, to the surface made by the pore walls (Corn et al. 1971). The specific surface area promotes the adsorption or the attachment of molecules from the gas phase. In the solid–gas interface, the molecules from the gas phase can either bounce off or set on the surface of the solid for a longer or shorter time, causing an over concentration on the surface of the solid. Depending on the nature and intensity of the bonding forces in play, there are physical adsorption and chemical adsorption. The larger the specific surface area, the greater the capability to absorb the molecules is important.

The particles having a diameter less than 1 μm are generally characterized by a high specific surface value, which will promote the adsorption of gaseous molecules. The soot has a microporous and mesoporous structure that contributes to the total surface area, and it can exceed 100 m^2/g (Rockne et al. 2000). These particles are likely to have a higher number of sorption sites for different gaseous organic compounds in the troposphere, such as VOCs, light PAHs, PCBs and PCDD/F. These textural properties determine the penetration, retention and excretion of the particulates in the respiratory tract and are therefore responsible for their health effects (Novák et al. 2014; Wang et al. 2013; Sonwani et al. 2021b).

6.4.1.2 Particle Diameters

Particles come in many different shapes and sizes and are seldom spherical. Hence, their diameters have to be illustrated by an equivalent diameter. The type of equivalent diameter used depends on the importance of the physical process involved. For instance, while diffusion is the primary process for smaller particles (<0.5 μm), the larger particles are more strongly controlled by their gravitational settling behaviour. The former particles are best described by the Stokes diameter, while the aerodynamic diameter is a more useful quantity to characterize the latter. The two mentioned physical processes have a strong impact on particle transport, collection and removal processes, including deposition in the respiratory tract.

Stokes Diameter

The Stokes diameter (Ds) of a particle is based on its aerodynamic drag force, which it experiences when its velocity differs from that of the surrounding fluid. A smooth,

spherically shaped particle would have a Stokes diameter exactly equal to its physical diameter, while irregularly shaped ones have Ds of an equivalent sphere having the same aerodynamic resistance. Moreover, the Stokes diameter is independent of density (EPA 2004).

Aerodynamic Diameter (D_a)

Aerodynamic diameter (D_a) depends on the density of the particle and is represented as the diameter of a spherical particle having equal gravitational settling velocity with material density of 1 g/cm^3. D_a is the quantity of interest for particles that are larger than 0.5 μm.

The equivalent diameter is used in order to:

- Determine the properties, effects and fate of atmospheric particles.
- Investigate their atmospheric deposition rates and residence times.
- Establish the deposition patterns of the particles in the lung.
- To characterize their light scattering ability (EPA 2004).

6.4.1.3 Shape

Shape is another major physical property of PM, which determines its effect on human health (Davidson et al. 2005). Particle shape analysis and its effect on human health are rather new field of study, and many researchers are focusing on understanding the relationship between particle's shape and its effect on human health. The morphological structure of atmospheric particulates acknowledged substantial prominence recently as a result of the effect of particulate shape on their chemical properties. The researcher investigated the framework of particulates present in a bio-diesel bus and differentiated the particulates into 14 different shapes. Further, this study showed the relationship between particle shape and its chemical properties. For example, the smooth square particulates were observed to include Fe, Na, Cl, Mo, Ca, V, Al, Ti, S, Si, Ag, Pd, K and Mg. The semi-coarse square particulates contained K, Mo, Cl, Pd, Al, Si, Ca, S and Na, while the coarse square particulates had Pd, Al, Cl, Mo, Mg, Ca and Na (Shandilya and Kumar 2010). Understanding the size and shape of particles is very crucial to evaluate the effect of PM on human health and environment.

6.4.1.4 Density

The aerosol transport properties are determined by density. The dry deposition and cloud scavenging rely upon settling velocities and inertial characteristics, which depend on the aerosol particle density. The density of a practically spherical particle can be theoretically calculated with aqueous aerosol (Reid et al. 1977). The dry aerosol having low relative humidity results in irregular shape of particles, and the coagulation process of dry particles also results in production of irregular shape aerosol particles with non-uniform density. The theoretical assessment of the emerged densities is not currently accessible, and consequently, observation is needed for the precise calculation of the density of particles of complicated morphology.

6.4.1.5 Size

The PM size ranges exhibit differences in respiratory deposition, atmospheric formation and deposition mechanisms, composition of particles and their optical properties. Size of the particles is one of the crucial variables, which affect the transport and atmospheric deposition of aerosol through the environment. The attitude of an aerosol is determined by size, which generally represented the aerodynamic diameter.

Particle Size Distribution

Particulate matter (PM) comes in a broad range of sizes according to its aerodynamic diameter, including coarse particles (PM2.5–10; diameter between 10 and 2.5 μm), fine particles (PM2.5; diameter $\leq$ 2.5 μm), ultrafine particles (UFPs) (PM0.1; diameter $\leq$ 0.1 μm) and nanoparticles (PM0.05; diameter $\leq$ 0.05 μm) (Fig. 6.1). The size of particulate matter (PM) is directly associated with its potentiality for creating health problems since lower size particles penetrate further down the respiratory tract and even transfer to extrapulmonary organs, including the central nervous system. While most severe adverse health effects have been typically associated with PM2.5, other epidemiological studies suggest that PM1 may have a greater potential for adverse health impacts (Sullivan and Prather 2005). The relative amounts of particles present in each size are expressed by mass concentration in the case of PM2.5–10 and PM2.5 and by number concentration (PNC) in the case of aerosol particulates with diameters in the range of 0.1–0.05 μm owing to their negligible mass.

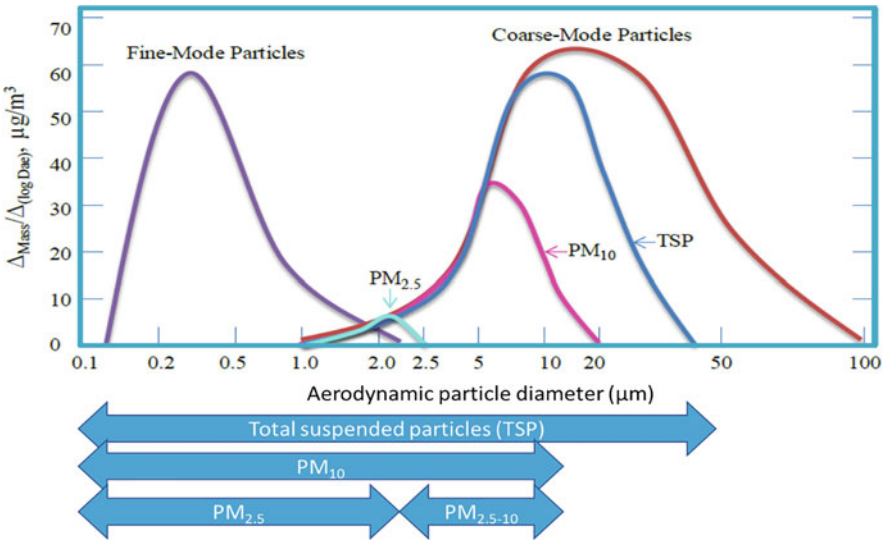

Fig. 6.1 Schematic representation of the size distribution of particulate matter in ambient air. (Modified from EPA 1996)

Coarse particles are commonly correlated with mechanical disruption processes (e.g. crushing, grinding and abrasion of surfaces) and the suspension of dust. The non-exhaust emissions (wear processes and resuspension) are assumed to be dominated by the PM2.5–10 fraction, although in some cases particles in the fine particle range have also been found (approximately 15%). Similarly, emissions derived from agricultural activities are mainly associated with the coarse size (Dzepina et al. 2009; Saxena et al. 2021) and the emissions related to handling, transport and storage of dusty raw materials (Sage et al. 2008). Regarding sea salt aerosols, approximately 95% of their total mass remain in the coarse mode (Laskin et al. 2012), although in Atlantic zones, its contribution to PM2.5 can be up to 11%. PM2.5–10 tends to have a local impact (1–10s of km) and to settle on the ground through dry deposition processes (e.g. gravitational sedimentation) in a matter of hours.

This is not the representation for coarse particles related to wind-blown desert dust, which can be transported over thousands of km. Primary PM2.5, UFP and nanoparticles are mainly formed from combustion and high-temperature processes and industrial operations. Road transport, in particular diesel engines, is the major source of primary PM0.1 and PM0.05 emissions in urban environments (Zauscher et al. 2011) with reported contributions of up to 97% of the total PNC (Laskin et al. 2006). Many of the PMs produced by RWC and maritime traffic are also below 1 μm (Platt et al. 2014). On the other hand, primary UFP and nanoparticle emissions from industrial processes such as tile sintering and laser ablation operations are also receiving increasing attention (Fonseca et al. 2015). As opposed to coarse particles, PMs in the accumulation mode (diameter varies amidst 0.1 and 2.5 μm) tend to have longer lifetimes (days to weeks) as they settle slowly and have low diffusivities and their travel distance being up to thousands of km (Sheppard et al. 2005). On the other hand, UFP usually presents lifetimes that go from minutes to hours owing to their tendency towards growth into the accumulation mode.

Size Fractions of PMs

The particle behaviour is governed by allocation of particles as according to size, which is a substantial physical parameter. Different approaches are used to categorize the size of particles: (1) modes, which are based on size distribution observations and mechanisms of formation; (2) dosimetry or occupational health sizes, as per the trespass into different chambers of the respiratory systems; and (3) cut points, generally based on the 50% cut point of the particular sampling instruments (EPA 2004).

Modes: The mass size distribution of PMs is commonly characterized by the three modes: nucleation, accumulation and coarse modes (Meng and Seinfeld 1994). The nucleation mode (or Aitken mode) is lowest in diameter, i.e. 0.1 μm, which is result of condensation of hot vapour emanated from combustion sources and gas-to-particle conversion in the air. Particles of this size have a high chance of deposition in the gas-exchanging (alveolar) part of the lung; they are comparably short-lived and grow into larger particles. This size range can be noticed with the presence of fresh emission sources adjacent to an observation site or with formation of new

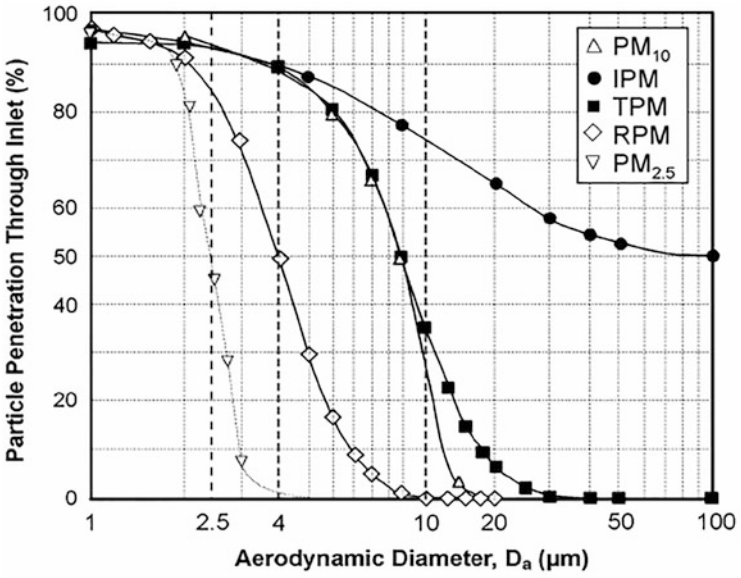

Fig. 6.2 Specific particle penetration (size-cut curves) with focus on inhalable (IPM), thoracic (TPM) and respirable particulate matter (RPM). [Source: EPA (2004)]

particles in the atmosphere (Watson et al. 1995). Conversely, the presence of nucleation mode in the measured atmospheric particle indicates local sources (Pakkanen et al. 2001). The accumulation range particles consist of those with diameters between 0.1 and about 1 μm. The coagulation of lower size particles, condensation of volatile species and gas-to-particle conversion result in formation of accumulation range particles. These particles remain drooped for up to several weeks in the air and are not quickly withdrawn by rain. The fine particle size fraction comes in the nucleation and accumulation ranges, and prominently ammonium nitrate, ammonium bisulphate, ammonium sulphate and elemental and organic carbon are observed in this size range (Bardouki et al. 2003).

The coarse mode consists of particles greater than about 1 μm in diameter. These PMs are commonly produced by mechanical break-up, including wind-blown dust, construction and sea spray. They make a disproportionate contribution to PM_{10} mass (relative to their numbers) when they are measured close to their sources. It is to be noted that a particle of 1 μm has mass one million times heavier than does a particle of 10 nm (assuming the same density).

Dosimetry or occupational health sizes: The size fractions are determined by the occupational health community in provision of their entry into different sections of the respiratory system. The upper size cut of the particles categorizes them into inhalable, thoracic and respirable. The entry of inhalable particles into respiratory tract occurred through head airways (EPA 2004). The subgroup of thoracic particles,

i.e. respirable particles, are more ostensible to approach gas exchange regions of the lung (Fig. 6.2).

Cut points: Another size fraction is usually specified by the 50% cut point size; e.g., $PM_{2.5}$ refers to particles collected by a sampling device that collects 50% of 2.5 μm particles and rejects 50% of 2.5 μm particles. Size-selective sampling is used to compute particle size division with some certain implication related to health and source apportionment studies, to measure mass size distributions or to collect size-segregated particles for chemical analysis. The particles are divided into smaller and larger fragments with collection on separate filters in dichotomous samplers. The multiple size-cut technique was used by cascade impactors for mass or chemical composition assessment.

Relative Humidity's Impact on Particle Size

Relative humidity influences the particle size distribution in both the accumulation and coarse modes (EPA 2004). The accumulation and coarse modes overlap in the intermodal region, which is in the range of 1.0–3.0 μm. High RH causes hygroscopic particles to grow in size as a result of the accumulation of particles, thus enabling initially small-sized accumulation mode particles to reach aerodynamic diameters above 1 μm. At RH of 100%, as in fog and clouds, these accumulation mode particles may even extend above 2.5 μm in aerodynamic diameter. Conversely, the coarse particles are disintegrated into lower size particles at very low RH and result in coarse mode particles having aerodynamic diameters below 2.5 μm (Environmen and Burton 1995). Misclassifications of accumulation and coarse mode particles can occur when neglecting the influence of RH.

6.4.1.6 Deliquescence

The single-component aerosol particle can be considered for observing the impact of relative humidity (RH) on the growth of particles. The atmospheric aerosol particles remain solid at very low relative humidity. The saturated aqueous solution is formed by absorbing atmospheric moisture by particles at the relative humidity, and the transition of phase represents the relative humidity of deliquescence (DRH). The thermodynamic equilibrium is further maintained with the increasing ambient relative humidity, which results in further water condensation onto the salt solution. Otherwise, evaporation of water occurs with the decreasing relative humidity (RH) over a salt solution. However, the crystallization of solution does not occur at the deliquescence relative humidity (DRH) as according to thermodynamic equilibrium. The crystallization finally takes place at considerably lower humidity.

6.4.2 Chemical Characterization

The composition of atmospheric particles is very heterogeneous and varies according to their emission sources, their physicochemical changes in the atmosphere and their size fractions (Thurston et al. 2011) and the location. The origin determines the chemical composition of aerosols. Chemical characterization is

widely used to identify the particulate matter components and their natural and anthropogenic origin.

6.4.2.1 Chemical Components of Airborne Particulate Matter

The atmospheric particulates are complicated combination of different chemical species. The major aerosol types (components) are carbonaceous materials (organic carbon, elemental carbon), ammonium, nitrate, sulphate, sea salt (chloride, sodium) and crustal matter (mineral dust) (Mazzei et al. 2008). Sulphates and nitrates are mainly secondary particles. Organic carbon is found in both primary and secondary forms. Elemental carbon and trace metals are usually emitted as primary particles.

Inorganic and Organic Fraction

The different components of atmospheric aerosols are as metals, ions and carbon: ammonium, sulphate, nitrate, sodium, chloride, crustal elements, trace metals and carbonaceous material.

Sulphates and nitrates are initially formed as H2SO4 and HNO3, but are further neutralized by atmospheric ammonia, which leads to formation of ammonium salts, NH4NO3, NH4HSO4 and (NH4)2SO4. NH3 can also react with hydrochloric acid (HCl) to form NH4Cl. The reaction of formation of NH4Cl and NH4NO3 is reversible: these salts are volatile and may lead to the reformation of their gaseous precursors at low pressures of NH3 or at elevated temperature. Chlorides are found adsorbed on the particulates as a result of neutralization of ammonia with HCl vapour, which is emanated from sources such as incinerators and power stations. In a marine and coastal atmosphere, the reaction of HNO3 with NaCl forms sodium nitrate (NaNO3) and releases HCl. In a calcium-rich atmosphere, HNO3 can react with CaCO3 to lead to the formation of $Ca(NO_3)$. During a dust transport from deserts, CaCO3 can react with H_2SO_4 to form CaSO4 and with NaCl and release HCl (Hwang and Ro 2006).

The trace elements: The trace elements such as Ce, Ba, Cd, Co, Ag, As, Cr, Cu, La, Mn, Nb, Ni, P, Pb, Sc, Se, Sn, Sr, Rb, V, Sb, Zn, Te and Ti are also adsorbed or condensed on the surface of the particles and may play an big part in the toxicity of the aerosol. Heavy metals are released during the burning of fossil fuels and wood, cement, agriculture, some industrial processes and waste incineration.

The carbonaceous fraction: The carbonaceous fraction of the aerosols comprises both organic carbon and elemental carbon. The combustion processes emit elemental carbon (EC) directly into the atmosphere. While particles containing organic carbon (OC) emanated into the atmosphere from primary sources such as biomass burning and combustion processes, they can also be imported by secondary organic aerosol (SOA) formation. The atmospheric oxidation reactions result in formation of products having low enough volatility, which leads to formation of aerosol via nucleation or gas-to-particle partitioning (Jaoui 2002). It is usually formed by the incomplete combustion of carbon-based fuels including wood, diesel and petrol from the combustion of natural (such as the terpene found in the essential oils of plants, especially conifers and citrus trees) and synthetic products such as

cigarettes. The main anthropogenic sources of OC are transport (diesel vehicles), industries and wood heating (Saxena et al. 2020; Sonwani et al. 2021a).

The organic fraction: VOCs are emitted as gases from certain solids or liquids; they can be adsorbed on PM. The anthropogenic and biogenic sources result in emission of VOCs into the atmosphere (Seinfeld and Pandis 2016). VOCs include diversity of components linking to diverse chemical groups (alkanes, ketones, aldehydes, alcohols and aromatic hydrocarbons). These include organic compounds having high vapour pressures, which evaporate immediately to the atmosphere. VOCs are emitted from the combustion of fuels, or by evaporation of solvents in certain products during their manufacture, storage or use.

PAHs are a group of over 100 compounds that are present in the atmosphere in very less amounts (ng/m^3 of air) but in a higher concentration than VOCs. They can appear in two varieties: adsorbed on suspended particles and in gas phase: low molecular weight PAHs which occur in the troposphere chiefly in the vapour phase, whereas high molecular weight multi-ringed PAHs are largely enslaved to particles. Intermediate molecular weight PAHs are distributed between the vapour and particulate phases, as it depends on the atmospheric temperature (Srogi 2007). In the atmosphere, the reaction of PAHs with pollutants such as ozone, nitrogen oxides and sulphur dioxide results in formation of diones, dinitro-PAHs and sulphonic acids, respectively. PAH formation can result from natural processes, but they are mainly formed by man-made sources: incomplete combustion process of carbonaceous materials at high temperature, fossil fuels and other organic material pyrolysis (tobacco or charbroiled meat), waste incineration and combustion of wood and coal (Ravindra et al. 2008; Sonwani et al. 2022).

PCDDs, PCDFs and PCBs are persistent organic pollutants (POPs) and share a similar base structure of two aromatic benzene rings with variable chlorine substituents. 'Dioxins' generally refer to a group of seven PCDDs, ten PCDFs and 12 'dioxin-like' PCBs, which are grouped together based on similar structural characteristics and mechanisms of action. The congener 2,3,7,8-TCDD is the most widely studied dioxin and is therefore often referred to simply as 'dioxin' (Safe 1990). The number and configuration of the chlorine compounds play a large role in determining properties of each PCDD, PCDF and PCB congener. PCDDs and PCDFs are not commercially produced or manufactured chemicals; rather, they are released into the environment as a by-product of combustion (burning) of organic matter in the presence of chlorine at high temperatures or other industrial processes such as waste burning incinerators. Natural combustion (forest fires, volcanic activity) are also anecdotal source of emission of PCDDs and PCDFs. The main human way of exposure to PCDD and PCDF is related to alimentation (90%). PCBs, on the other hand, were manufactured until 1979 for use in numerous commercial and industrial applications (insulating materials) (Ueno et al. 2005).

6.4.2.2 Biological Components of Airborne Particulate Matter

The biologically derived matter including virus, fungi and bacteria comes under category of biological aerosols. The bioaerosols can be categorized on the basis of size distribution. Pollen (5–100), fungal spores (1–30), bacteria (0.1–30) and viruses

(<0.3) can be differentiated with size ranges (Després et al. 2012). The structural arrangement and water up taking capacity of atmospheric particles are affected by the bioaerosol. These biological aerosols also exhibit a substantial portion of airborne PM and also portray a notable portion of the mass of coarse (PM10) and fine (PM2.5) particles. The physical characteristic like size and concentration ruled the dynamics of biological particles in the atmosphere and result in the presence of bioaerosols as individual particles or agglomerates of particles (Jones and Harrison 2004). The different sources of bioaerosol include biomass, soil and industries. The different components of bioaerosol like virus, fungi and bacteria attach to PM in the atmosphere and accelerate their accession into different compartments of the respiratory system (Sonwani et al. 2021b). For example, the pollen grain with size >10 μm is captured in the nasopharyngeal tract at the time of inhalation due to its larger size, whereas the presence of pollen allergens in $PM_{2.5}$ results in penetration into deeper parts of the lungs (Després et al. 2012). The different pulmonary and cardiovascular diseases aggravate due to cluster formation of bioaerosols and PM (Morakinyo et al. 2016).

6.5 Formation Pathways

The two major types of particulate matter, defined in section 2.0, not only differ in their chemical composition, but also differ in their pathway of formation. Primary coarse particles are generally produced by mechanical processes including wind-blown dust, road dust, sea salt and combustion-generated particles such as fly ash and soot. Primary fine particles can be emitted directly either as particles or as vapours that quickly condense forming nucleation mode particles. The soot from diesel engines, a large range of organic compounds from incomplete combustion or cooking and compounds of As, Se, Zn, etc., which condense from vapour formed during combustion or smelting, are included in this category.

Condensable vapours generated by chemical reactions of gas-phase precursors are the source of fine secondary particulate matter. Most sulphates and nitrates along with some of the organic compounds in atmospheric particles are formed in these chemical reactions. It is, however, much more difficult to trace ambient secondary species back to their origins, as the entire formation process relies upon numerous factors, such as the concentration of precursors and other gaseous reactive species and atmospheric conditions such as solar radiation and relative humidity (EPA 2004).

6.5.1 Mechanisms of Particle Formation

Atmospheric particle properties are not stable in the environment and they do not have a constant composition throughout their life, and both their size and chemical nature can be modified by various physicochemical processes. Although some particles get straight into the atmosphere from natural and anthropogenic aerosols,

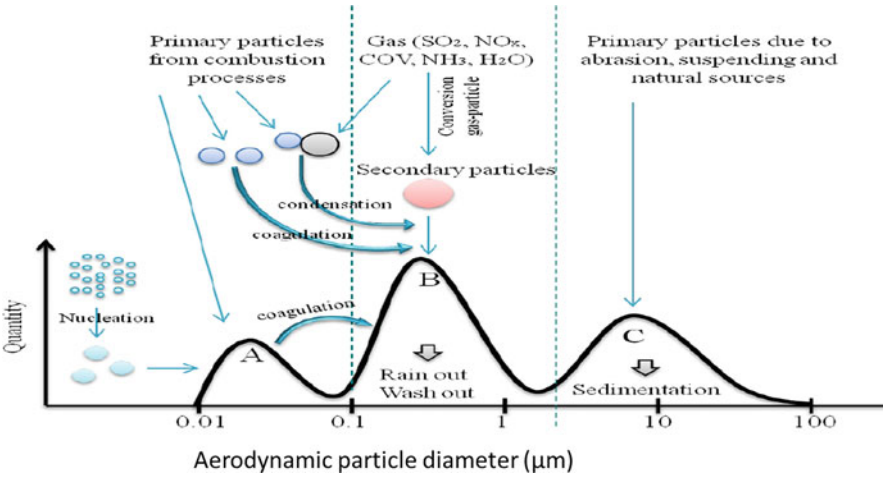

Fig. 6.3 Schematic representation of the particle size distribution of aerosols and their mechanisms of formation. (Modified from Whitby and Cantrell 1976)

a large number of particles are produced in the atmosphere (Metzger et al. 2010). The technique of formation of PM generally consists of three mechanisms: nucleation, condensation and coagulation as shown in Fig. 6.3. The nucleation leads to a notable fraction of particles (in number) in the atmosphere formed by the homogeneous nucleation from the gas phase; it is the genesis of particles. The condensation is a process where gas molecules condense on the particles. This mechanism increases the diameter of the particles while retaining their number. The coagulation is a process that increases the diameter of primary particles by reducing their number. This is the formation of a particle from the combination of two or more elemental particles. Due to the Brownian motion, the particles migrate permanently in the atmosphere and can collide with other particles. The rate of the coagulation depends on the concentration of particles, their composition, their speed of movement and their specific surface area. These mechanisms of formation of PM lead to different classes of particles according to their aerodynamic diameter. Chemical transformation corresponds to homogeneous or heterogeneous reaction of nucleation or condensation of gases naturally or anthropogenically emitted. This phenomenon is called gas-to-particle conversion that leads to the formation of small particles that will grow in size by physical transformation. Mainly oxidation reactions take place with three major classes: compounds based on nitrogen (NO_2 and NH_3), those based on sulphur (SO_2) and organic compounds.

6.5.2 Atmospheric Ageing

As soon as a soot particle leaves a car tailpipe or ship smokestack, it will undergo physical and chemical transformation, called atmospheric ageing. Atmospheric

ageing can result in condensation of material onto the soot aggregate, which alters the hygroscopic properties of the particle and consequently affects the cloud formation properties and lung deposition. Uptake of coating materials and potentially water will also change the morphology of the soot particle through restructuring into a more compact shape.

6.5.3 Gas-to-Particle Formation

The formation of secondary particulates is the result of atmospheric oxidation of SO_2 and NO_2 to sulphuric acid (H_2SO_4) and nitric acid (HNO_3), respectively. Both natural and anthropogenic sources generate sulphur and nitrogen gases. These precursors' gases undergo oxidation both in liquid droplets and in the gas phase and result in formation of non-volatile products either via condensation on pre-existing aerosol particulates or formation of new particulates. These processes lead to formation of aerosol predominantly in the fine size range (Langner and Rodhe 1991). The oxidation of SO_2 occurs via either gas phase or aqueous phase. The gas-phase oxidation includes the reaction of SO_2 with hydroxyl radicals (OH), and aqueous-phase oxidation includes the reaction of sulphur dioxide (SO_2) with hydrogen peroxide (H_2O_2), ozone (O_3), oxygen (O_2), hydroxyl radicals and hydroperoxyl radicals (HO_2) (Martin 1994). Nitrate is another main component of atmospheric aerosol along with sulphate. The gas-phase chemistry of NO_2 is ruled by hydroxyl radicals (OH) in the daytime and by nitrate (NO_3) radical chemistry in the night-time. The reaction of ammonia with nitric acid (HNO_3) and hydrochloric acid (HCl) is reversible, which leads to formation of ammonium salts:

$$\mathrm{NH_3(g) + HNO_3(g) \Leftrightarrow NH_4NO_3}(s) \tag{6.1}$$

$$\mathrm{NH_3(g) + HCl(g) \Leftrightarrow NH_4Cl}(s) \tag{6.2}$$

6.5.4 Secondary Organic Aerosol (SOA)

SOA is produced in the atmosphere through oxidation of volatile organic compounds and consequent partitioning of some oxidation products into the aerosol phase. The pathways for SOA formation can be gas-phase oxidation, in which VOCs are oxidized by species such as OH, O3 and NO3 (Seinfeld and Pandis 2016), and/or aqueous-phase oxidation in which SOA is formed in cloud and fog droplets (Blando and Turpin 2000). Secondary organic aerosol (SOA) particles originate in the atmosphere through the mass transfer of low-pressure products given by the oxidation of organic gases to the aerosol phase. Organic and carbonaceous aerosols are produced by g-to-p conversion of gases released from the biosphere and from volatile compounds. The organic gases are oxidized in the gas phase by species, such as ozone (O3), nitrate (NO3) and hydroxyl radical (OH), so that such oxidation

products gradually accumulate. Some of these products having low volatilities condensed on the available particles in an effort to establish equilibrium amidst gas- and aerosol-phase particles. The mass transfer flux of these products to the aerosol phase is directly proportional to the difference amidst their gas-phase concentration and their concentration in the gas phase at the particle surface. Thus, there are two separate steps involved in the production of SOAs: (1) the organic aerosol compound is produced in the gas phase during the reaction of parent organic gases, with rates closely depending on the gas-phase chemistry of the organic aerosol precursors, and (2) the organic compound partitions amidst the gas and particulate phases form SOA, occurring through variable interactions among the various compounds present in both phases. In the formation of photochemical smog, the OH radical can initiate a chain reaction, which attacks the hydrocarbon pollutants in urban air,

$$CH_4 + 2O_2 + 2NO \rightarrow H_2O + 2NO_2 + HCHO \tag{6.3}$$

$$CH_3COO_2 + NO_2 \rightarrow CH_3COO_2NO_2 \tag{6.4}$$

The chemical species on the right-hand side of the reaction represented in Eq. 4 is the vapour of a colourless and dangerously explosive liquid called PAN, an important component of photochemical smog and another major eye irritant.

6.6 Removal Pathways

6.6.1 Atmospheric Lifetimes

Atmospheric lifetime of particles depends on their size. The nucleation mode particles will rather quickly coagulate and hence grow into the accumulation mode, where no further growth into the coarse mode takes place. The fine particles from the accumulation mode remain in the air for a number of days and can travel over thousands of kilometres before they are deposited to surfaces. On the other hand, coarse mode particles do not remain suspended in the atmosphere for more than minutes to a few hours. As a consequence, the possible range they can travel is considerably shorter. The only exception arises during extreme weather events, such as strong dust storms, when coarse particles of smaller sizes can reach higher altitudes and be transported over longer distances (EPA 2004).

6.6.2 Dispersion

The local meteorological conditions play a crucial role in the fate of emitted particles and consequently in the extent of human exposure towards them. Therefore, the degree of dispersion, or in other words, the concentration of the atmospheric particles, will strongly depend on wind speed and atmospheric stability. Wind

speed and pollutant concentration (includes PM) are correlated reciprocally, i.e. low wind speeds will result in high pollutant concentrations and vice versa. This becomes very clear when considering a chimney that emits smoke at a steady rate. The volume of air into which the smoke is blown will increase with increasing wind speed. Thus, the pollutant concentration will be directly proportional to the rate of emission but inversely proportional to the wind speed. It is necessary to consider the prevailing wind directions as the pollution situation is worse downwind of the sources. In reality, however, the concentration of pollutants in urban areas usually does not drop as quickly as predicted by wind speed.

In addition to the direction and velocity of the wind, the vertical mixing of air in the planetary boundary layer of the troposphere also affects the concentration of the pollutants. The larger the surface roughness, the stronger the resulting turbulence, when wind blows across it, and as a result, the larger the vertical mixing of air. The roughness coefficient signifies the degree of surface roughness, which increases with an increase in obstacles in the pathway of the wind. Large-scale vertical mixing is dominated by the stability of the atmosphere, which in turn is largely controlled by the thermal buoyancy. An air package that is warmed at the ground will rise due to buoyancy, i.e. the surrounding air is colder and heavier. It will then ascend at a rate and to a degree given by the stability of the atmosphere. The rate at which it will cool and expand is called the adiabatic lapse rate, which is about 1 °C over 100 m for dry air and approximately 0.6 °C/100 m for moist air. This effect occurs because the pressure in the atmosphere decreases exponentially with height, and as the air cools, it expands. In the real atmosphere, the lapse rate can be smaller, almost equal to, or larger than the adiabatic lapse rate. This has consequences on the extent of vertical mixing.

6.6.3 Deposition

The deposition of suspended particles to surfaces occurs in several possible ways. Dry deposition describes the process in which the particles eventually settle down as a result of gravity. Turbulence may also cause particles to hit surfaces and be deposited. In contrast, wet deposition describes the atmospheric removal of particles via rain or snow (Harrison et al. 1999; Sonwani and Kulshrestha 2019; Sonwani and Saxena 2021). During occult deposition, named because it was previously hidden in measurements that determined the first two types, particles are being removed from the air via fog, cloud water and mist interception (EPA 2004). The dry deposition velocity reaches a minimum for particle sizes between 0.1 and 1.0 μm in aerodynamic diameter. Cloud processes are the predominant removal pathway for accumulation mode particles. Fine particles, in particular those containing a hygroscopic component, grow with increasing relative humidity into cloud condensation nuclei and; eventually into cloud droplets. When they have reached sizes larger than 100 μm, they form rain and fall out of the air. Falling raindrops also remove coarse mode particles by mechanical impact and ultrafine particles via diffusion. The cloud

processes are, however, much more efficient in removing accumulation mode particles than falling raindrops (EPA 2004).

6.7 PM Characterization Techniques

The physical and chemical components of PM determine the effect caused by PM on environmental and public health. This stimulated the interest in investing various evaluation techniques efficient in determining the shape and particles size distribution along with the analysis of chemical composition of aerosol particles. Some of these techniques are discussed below.

6.7.1 Gravimetric Approach

Gravimetric approach is a method for quantitative determination of chemical substances (Andrews et al. 2000). If the procedure is followed carefully, this technique provides precise quantitative analysis of chemical compounds present in the sample. The main disadvantage of this method is the chemical evaluation of single or limited group of elements only at a time.

6.7.2 Atomic Absorption Spectroscopy

Atomic absorption spectroscopy is the spectroscopic method of measurement, which characterizes the absorption of radiation and interaction with the sample. This technique is used to determine the chemical substance of a sample and also to quantify its amount. This technique is capable for the identification of metals present in the periodic table but is unable to ascertain shape or size of the particle (Seiler et al. 1994).

6.7.3 High-Performance Liquid Chromatography (HPLC)

The chemical components can be identified from a mixture with the help of HPLC as according to polarity (Sikalos et al. 2002). The outcomes are produced in very small time as it is an automated process. However, the operation of machinery required well-trained operator. Moreover, it can only be used for chemical characterization.

6.7.4 Gas Chromatography–Mass Spectrometry (GC-MS)

The aspects of both GC and MS are combined in gas chromatography–mass spectrometry for recognition of chemical components present in sample. The GC

works on the principle that a mixture separates into individual substances on heating. Then, MS identifies the separated chemical substances by measuring their mass.

6.7.5 Scanning Electron Microscope (SEM)

SEM with energy-dispersive X-ray (EDX) is ideally suited for the physical and chemical profiling of particulate matter (Van Malderen et al. 1995). The magnified images, better resolution and wider range of magnification are provided by SEM technique as compared to the conventional light microscope by using electrons (Laskin et al. 2006). The EDX analysis is an integrated feature of SEM. The EDX plots X-ray frequency for each energy level. These peaks depict highest frequencies of X-rays at corresponding energy levels. Each peak in a spectrum is unique for an atom, i.e. each peak represents the single element present in the filter paper. The concentration of element in the specimen is directly related to the peak in the spectrum. The different types of SEM/EDX method are discussed below.

6.7.5.1 Manual SEM

In this SEM technique (Heasman and Watt 1989), the filter paper is scanned manually, and whenever the particle is observed, the particle's shape and size are measured by drawing grids across the paper. For chemical characterization, EDX analysis is used. The main drawback of manual method is high computational time for analysing a single sample and continuous human intervention.

6.7.5.2 Computer Controlled SEM (CCSEM)

CCSEM is the process of automating the SEM technique for particle analysis (Mamane et al. 2001). The CCSEM technique carried out an automated analysis for the particles having fine spatial distribution. The numerous simultaneous measurements have been performed in an efficient manner for evaluation of individual particle shape, size and elemental composition. In CCSEM mode, the filter paper is divided into smaller grids and each grid is scanned automatically. CCSEM analysis is generally conducted by operating SEM in backscattered electron (BSE) mode (Lee and Kelly 1980).

6.7.5.3 SEM Integrated with Image Analysing Techniques

The latest technology for identifying and analysing the size of PM is computer vision-based image processing methods, which is started for particulate matter in the mid-80s, when custom systems were designed using conventional microscope and image analysing software written by the user (Mogireddy 2011). The advancement in this technique speeds up in the mid-90s, with rapidly enhanced computational power and improved microscopes. This use of modern image analysis systems for particle characterization has the capability of analysing large number of particles with size of less than 1 Gm in a matter of minutes. Imaging method integrated with SEM is a highly efficient and automatic technique for PM characterization (Nazar

et al. 1996). This method consists of two main steps, image acquisition and image analysis.

Image acquisition: It is the process of creating digital image from the physical scene. SEM is used to capture the images of filter paper by dividing the filter paper into smaller grids. The whole process can be automated by using commercially available SEM automation software such as smart particle investigator.

Image analysis: It is the process of extracting meaningful information from images. Image analysing software/techniques are used to analyse the particle images obtained from the SEM to find size, shape, area, etc., of individual particle present in filter images.

6.8 Conclusion

The important role played by aerosol in climate change and the detrimental effects of these airborne particulates on health result in increase in their study in recent years. Furthermore, these airborne particulates impact many atmospheric processes, including rain, fog, precipitation cloud formation and acidification of clouds. Aerosols are important in atmospheric chemistry, contribute to soiling and corrosion of buildings and structures, and have adverse impacts on the vegetation and on ecosystems. Most of the effects are driven by the physical and chemical characteristics of the aerosols, for example aerosol size, concentration and chemical composition, which varies from region to region depending on the sources of the aerosols. In order to assess and lower the impacts of aerosols, any programme aimed at regulating the levels of PM requires knowledge on sources of particles, size distribution and chemical composition.

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7 Toxicological Implications of Fine Particulates: Sources, Chemical Composition, and Possible Underlying Mechanism

Bhanu Pandey and Annesha Ghosh

Abstract

The effects of atmospheric fine particles on human health have become an utmost concern worldwide. Particulate matter is a complex and dynamic combination of a mixture of solid and liquid substances with several biological and chemical components. Various toxicological and epidemiological studies indicated that the fine particles create several health issues such as respiratory and cardiopulmonary disorders. The present chapter provides the information regarding regulations and standards set by various countries and organizations to regulate the atmospheric concentration of fine particles and discuss the primary and secondary sources of fine particulate pollution. This chapter demonstrated the biological and chemical components of fine particles that play a critical role in the toxicological implications of fine particulates. In addition, the justifications for the origin or sources of biological and chemical compositions and their impacts on human health become a concern in this chapter. The current chapter also aims to provide a brief overview of the molecular mechanisms connecting fine particulate exposure and health effects.

Keywords

Fine particles · Sources · Composition · Bio-aerosol · Toxicity · Health effects · Mechanism of action

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_7

7.1 Introduction

Troposphere, section of the atmosphere in which we breathe, is a complex mixture of aerosol particles and gases. An aerosol comprises particulate material suspended in a gas. The suspending gas is typically air, plus water vapor and any other gaseous contaminants. The particulate material consists of condensed matter, i.e., solid particles, liquids, or a mixture of both. The effects of particulate matter pollution are a subject of global concern because the size of these particles directly reflects their ability to cause a number of serious health and environment-related problems. The International Agency for Research on Cancer characterizes the ambient particulate matter as a group I carcinogen (IARC 2020). Particulate pollution represents the detrimental form of air pollution due to the ability of particulate matter to penetrate deep into the lungs and bloodstreams, causing respiratory disease, reduced lung function, nonfatal heart attacks, and early death (US EPA 2019). Particulate matter has been ranked as the sixth top risk factor causing death worldwide (Polk 2019).

Aerosols in the atmosphere impact climate and earth surface biogeochemistry and ecosystem after deposition (Pandey 2015; Pandey et al. 2019; Sonwani and Maurya 2018). Aerosols influence each layer of the earth's atmosphere. Atmospheric aerosols scatter and absorb incoming solar radiation. Aerosols that primarily scatter solar radiation exert a cooling effect, by intensifying the complete reflected solar radiation from the earth. Aerosols that absorb incoming radiation produce a warming effect. These aerosol–radiation interactions are described as radiation forcing. Radiative forcing is frequently used to measure and compare the potential climate impact of the different aerosol effects (Myhre et al. 2013; Wen et al. 2020). Aerosols represent a critical component in cloud formation because a subgroup of them can serve as cloud condensation nuclei and ice nuclei (Singh et al. 2018). Increased aerosols may increase the cloud condensation nuclei number concentration and lead to smaller and more cloud droplets for fixed liquid water content. In this manner, it increases the albedo of the cloud, causing an increase in reflection and a cooling effect termed the cloud albedo effect (Fiore et al. 2015). Aerosols additionally have the potential to modify clouds' properties by heating the air surrounding the clouds while reducing the amount of solar radiation striking the ground and also increasing the atmospheric temperature (Singh et al. 2017a, b). By altering the vertical temperature profile, absorbing aerosols develop atmospheric stability and the potential for pollutant accumulation (Fiore et al. 2015; Wen et al. 2020; Sonwani et al. 2021a). It is evaluated that anthropogenic alterations in aerosols add to a 40.0% change in shortwave radiative forcing and a 60.0% enhancement in the amount of cloud condensation nuclei on which small-sized water vapor condenses (Mukherjee and Agrawal 2017). Aerosols are also critically important, because greenhouse gases increase the energy retained by the earth for a long time; however, aerosols are short-lived so their radiative influence is simultaneous and clearer than greenhouse gases (Murphy and Ravishankara 2018; Pandey et al. 2017, 2018). However, at present, the consequences of particulate matter on human well-being and effect on visibility drive the current regulatory and research initiatives related to particulate matter, but

the impacts of particulate matter on functions of managed and natural ecosystems are equally important (Grantz et al. 2003; Pandey et al. 2014a).

Particulate matter occurs naturally in the environment as terrestrial dust, volcanic activity, sea spray, forest fire, and reactions between natural gaseous emissions. However, increasing anthropogenic interferences as fuel combustion, industrial processes, roadway dust from paved and non-paved roads, wind erosion of cropland, construction, and transportation sources have significantly augmented the environmental particulate matter burden (Saxena et al. 2017; Pandey and Choudhary 2019). Particles are described on the basis of their aerodynamic diameter, usually called particle size. Coarse particles, with aerodynamic diameters <10 μm (PM_{10}), are of concern for environmental problems. Aerosols with aerodynamic diameters <2.5 μm ($PM_{2.5}$) termed as fine particle are responsible for health hazards. Ultrafine particles are of aerodynamic diameters <1.0 μm (PM_1), contribute to visibility and radiation effects of degradation, and can get across deeper into the respiratory system (Pandey et al. 2014b).

Studies have shown that the smaller the diameter of particles, the greater the harm to human health. Particle size largely determines penetration depth into the airways, i.e., which region can be affected. Larger particles deposit mainly in the nasal region and are rapidly cleared. Ultrafine particle matter can enter cells and cause direct effect on macromolecules. $PM_{2.5}$, respirable fraction of particulate matter, is considered as an indicator of air pollution and supposed to be more harmful due to its capability of reaching the most distal regions of the lung, depositing and distributing in the bronchiolar and alveolar regions (van Berlo et al. 2012). The physicochemical properties of $PM_{2.5}$ samples reveal their complexities and heterogeneities related to its various natural and man-made emission sources. The principal source of airborne $PM_{2.5}$ is combustion emissions, i.e., combustion particles from motor vehicles, and burning of coal, wood, and fuel oil. Small quantity of fine particles also originates from finely pulverized road dust and soils. $PM_{2.5}$ emitted directly from combustion emission, road dust, and soils is primary fine particles (Saxena and Sonwani 2019a). Secondary fine particles are formed by the atmospheric conversion of gases, mainly SO_2, NOx, and hydrocarbons, into particles. In recent years, there has been a growing realization that fine particles are far more catalytically active than larger particles. Epidemiological and toxicological researches around the world have indicated an established link between exposure to fine particles and adverse effects on health (e.g., respiratory disease, lung cancer, cardiovascular disease, and premature mortality), although the specific sources and constituents responsible for these adverse effects have not been conclusively distinguished (Lippmann 2014; Sonwani and Kulshrestha 2016; Sonwani et al. 2021b). The fine particles in the environment are of particular research interest due to their impact on climate change and its detrimental consequences on human health. The vital goal of this chapter is to oppose information together on sources of emission, composition, mechanism of action, spatial variations in fine particulate matter concentrations, and their exceedances in various landmasses of the world. Since fine particulate matter is primarily responsible for negative health effects, health impacts of fine particulate matter were also reviewed.

7.2 Air Quality Standards for Fine Particulate Matter

As fine particles in the ambient air represent a grave concern for human health even at significantly lower concentrations and pose the greatest health risk, many national and international monitoring agencies have proposed guidelines and standards to curb the health effects caused by fine particulate matter. These national and international guidelines and standards value are set on the basis of various scientific evidences like emission sources, toxicity of specific pollutants, monitoring period, geographical location, and economic conditions. The primary target of these guidelines is to lessen or control the concentrations of fine particulate matter under explicit conditions accessible in a nation, as well as to advise the administrations of that country to bring the concentrations of pollutants to a safe or acceptable risk level. It has been suggested that concentrations higher than the standards can be toxic and cause severe negative consequences on the human respiratory system for both short and long durations; however, according to epidemiology studies, there is no mention of any particular value below which the effect of pollutants is unseen. Therefore, the possibility of adverse effects of fine particulates on health, even at levels below the standard values, cannot be ruled out (WHO 2006). Meanwhile, plenty of scientific studies also corroborate the improvements in air quality and public health benefits as a result of clean air policies (Brauer et al. 2016; Schikowski et al. 2013). Table 7.1 shows some selected national and international agencies' $PM_{2.5}$ guideline standard values for short term and long term.

Joss et al. (2017) compared various national ambient air quality guidelines of countries around the globe and reported that no standards were set by 53 (27%) countries for air pollution in any condition. This scenario is particularly in the Western Pacific (48%) that includes several small island states, the African region (45%), and the Americas region (37%). This research paper also reported that, in Europe, region of the Americas and the Western Pacific has lower percentages of countries without any knowledge (2, 6, and 7%, respectively). A report of population-weighted $PM_{2.5}$ concentrations positioned India as the fifth most polluted country in the world, with a yearly average concentration of 58.1 $\mu g/m^3$ (IQAir 2019). Table 7.2 shows the top ten most polluted nations arranged by average $PM_{2.5}$ concentration ($\mu g/m^3$), weighted with the population by country (IQAir 2019).

7.3 Sources of Fine Particulates

Atmospheric fine particles that are directly emitted into the atmosphere are primary particulate matter. Gas-to-particle transformation processes also result in the in situ formation of fine particles. The latter fine particles are called secondary particulate matter (Parvez et al. 2017). Although the sources of primary particles are both natural and man-made activities, anthropogenic sources of $PM_{2.5}$ are of higher priority than natural sources, as natural sources make just a little contribution to the total atmospheric concentration. Figure 7.1 demonstrated different sources and formation primary and secondary of atmospheric fine particles.

Table 7.1 $PM_{2.5}$ guideline standard values for 24 h and annual average of national and international agencies

Agency/ country	24 h (short term)	Annual average (long term)	Year of revised or published	Reference
Afghanistan	75	35	2011	ANSA (2011)
Australia	25	8	2008	Jackson et al. 2016
Bangladesh	65	15	2005	Rana and Biswas (2018)
Canada	28	10	2015	ECC (2013)
China	75 (class II)	35 (class II)	2016	GB 3095 (2012)
India	60	40	2009	CPCB (2009)
Iran	25	10	2011	Shaeri and Rahmati (2012)
Israel	37.5	25	2014	MoEP (2018)
Japan	35	15	2009	EQSJ (2009)
Jordan	65	15	2006	JAAQS (2006), Abu-Allaban and El-Khalili (2014)
Kuwait	35	15	–	KUEPA (2001)
Mexico	65	15	2005	NOM (2005)
Pakistan	35	15	2013	Pakistan Gazette (2010)
Republic of Korea	50	25	2013	ECOREA (2015)
Saudi Arabia	35	15	–	GAMEP (2017)
Singapore	25	15	2014	NEA (2016)
Sri Lanka	50	25	2008	MENR (2008)
Thailand	50	25	2010	PCD (2010)
US EPA	35	12 (primary)	2015	US EPA (2019)
		15 (secondary)		
WHO	25.0	10.0	2006	WHO (2006)
	75 (interim target 1)	35(interim target 1)		
	50 (interim target 2)	25 (interim target 2)		
	37.5 (interim target 3)	15(interim target 3)		

Among the natural sources liable for the emission of fine particles, wind-blown dust, volcanic action, biogenic outflow, and sea spray are significant. Generally, particles that are formed naturally by mechanical processes are coarse particles; however, a portion of these particles are sufficiently small to belong to the fine particulate category (Charron and Harrison 2005). Wind-blown dust represents a natural source of fine particles, despite the fact it is important to take note that terrestrial dust is also emitted as a result of anthropogenic activities, for example,

Table 7.2 Ten most polluted nations arranged by average $PM_{2.5}$ concentration ($\mu g/m^3$), weighted with the population by country (IQAir 2019)

S. No.	Country	$PM_{2.5}$ concentration ($\mu g/m^3$), weighted by population
1.	Bangladesh	83.3
2.	Pakistan	65.8
3.	Mongolia	62.0
4.	Afghanistan	58.8
5.	India	58.1
6.	Indonesia	51.7
7.	Bahrain	46.8
8.	Nepal	44.5
9.	Uzbekistan	41.2
10.	Iraq	39.6

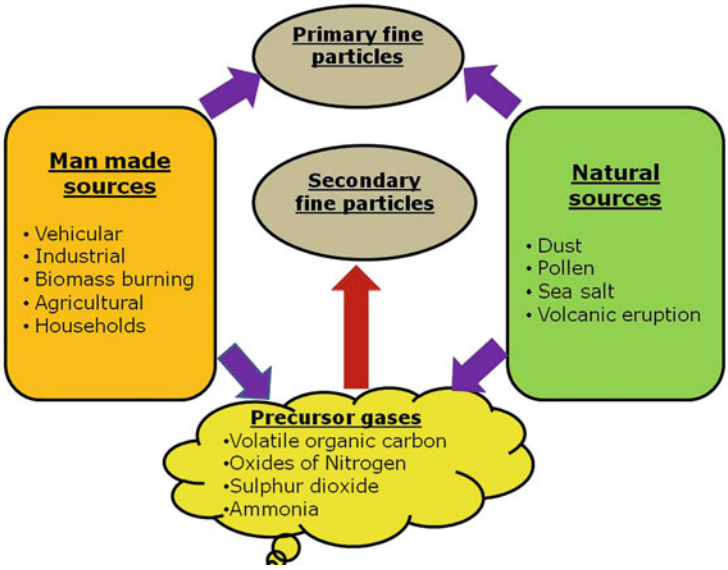

Fig. 7.1 Different sources and formation of primary and secondary fine particles

construction work, resuspension of dust during driving, or agricultural activities (Bloemen et al. 2008; Gupta and Mandariya 2013; Saxena et al. 2021). Smoke emanating from the natural fire in the forest, agriculture exercises, and other types of fire also contributes to the atmospheric fine particles (Long et al. 2002; Zhang et al. 2015).

The most important sources of primary anthropogenic particles include fuel combustion, various industrial processes, transportation, and various construction operations like fugitive dust from paved and unpaved roads or construction. Combustion of fuels such as oil, coal, or biomass brings about the emission of fine

particles. Fine particles emitted from various sources are of diverse compositions depending on the sources. Primarily in these particles, varying amounts of trace metals, carbonaceous substances, and sulfates are found (Park et al. 2018; Yang et al. 2005).

Most fine particulate mass found in the atmosphere is usually secondary particles, which are generated by gas-to-particle transformation (Wu et al. 2016). Generally, precursors of fine particles like oxides of sulfur, nitrogen, ammonia, and volatile organic compounds are emitted into the atmosphere in vapor form. At the point when these compounds are emitted in the atmosphere and undergo chemical changes, low volatility products are formed and after that the products are converted to the condensed phase (Saxena and Sonwani 2019b) quantification of $PM_{2.5}$ contributors is difficult due to the fact that considerable amount of the products formed can fluctuate between vapor and particulate states depending upon conditions. The extent to which these precursors react to form $PM_{2.5}$ depends on the environmental conditions and its various dimensions and the various drivers of complex chemical reactions (Liang et al. 2016). Sulfur dioxide is oxidized by hydroxyl radicals in the gas phase and by hydrogen peroxide, ozone, or oxygen inside the cloud droplets, finally resulting in the sulfate compound (Cox 1974). Nitric acid vapor is produced by the reaction between nitrogen oxides. Further nitric acid vapor reacts with the available ammonia to form ammonium nitrate, while this nitric acid vapor after reaction with sodium chloride from sea spray results in the formation of sodium nitrate, or react with carbonate in the dust, and results in calcium, potassium, or magnesium nitrate (Cox 1974). Most organic compounds and sometimes high molecular weight alkanes and alkenes, along with oxygenates additionally, form products with low volatility after photooxidation. These low volatility products condense on the available particles in the atmosphere to form secondary aerosols (Han et al. 2018). Albeit most secondary particulate matters are the consequence of anthropogenic activities, several studies have described that naturally occurring precursors equally contribute significantly to the formation of ambient fine aerosols. Some natural non-methane hydrocarbons produce a broad variety of secondary organic aerosol compounds when photooxidation occurs (Rattanavaraha et al. 2016). Dimethyl sulfide produced by plankton is the most abundant form in which the sea releases gaseous sulfur. Dimethyl sulfide generates sulfur dioxide and sulfate during atmospheric reactions with the hydroxyl radical (Ghahremaninezhad et al. 2019).

As is clear from the description up until now, gas-to-particle conversion processes form a considerable amount of particle mass; however, it is worth taking note that these reactions typically do not produce new particles (Singh et al. 2015). The products of these chemical changes are simply transferred to available particles. The generation of new ultrafine particles in the atmosphere can occur during the rapid formation of one or more compounds at exceptionally low vapor pressures. Nucleation of particles with a diameter of a few nanometers during the reaction of sulfuric acid and water is considered the most significant in situ source of aerosols (Kerminen et al. 2012). Through this nucleation, many new particles can be

produced in a brief time frame. However, due to the small size of these nuclei, the contribution of nucleation to atmospheric particulate mass is negligible.

Determination of specific sources of fine particulate matter is extremely complicated because of the fact that concentrations of various components are influenced by both primary emissions and secondary atmospheric reactions (Xu et al. 2020). It is an advantageous feature in the context of atmospheric primary fine particles that their sources can be distinguished by their chemical composition because their diverse sources have specific chemical markers (Ramli et al. 2020). Source apportionment techniques have been practiced to recognize the sources of fine particulate pollution, and the quantitative contribution of various emission sources as knowledge of the emission sources that make significant contributions to atmospheric $PM_{2.5}$ is necessary to evaluate potential risks to human health caused by fine particles and to support local authorities in limiting the effects of fine particulates. The emission inventories, the source-oriented model, and the receptor-oriented model represent three approaches for source apportionment that are used in most studies (Huang et al. 2017; Pio et al. 2020; Singh et al. 2017b; Nava et al. 2020).

7.4 Chemical Composition of Fine Particulate Matter

The composition of atmospheric particles is mostly extremely complex, and the reason for this is that its composition is influenced by the sources of emission of primary particles and the formation of secondary particles from the gas. Atmospheric particles especially particles with an aerodynamic diameter of less than 2.5 μm frequently absorb toxic pollutants like heavy metals, volatile organic carbons, and polycyclic aromatic hydrocarbons (Brüggemann et al. 2009). As indicated by Morakinyo et al. (2016), the particulate matters incorporate carbonaceous parts, consisting of carbonate carbon, natural carbon, and basic carbon. Remarkably, in addition it contains inorganic parts that incorporate crustal components, ionic species, and trace metals. Raes et al. (2000) have described that the chemical elements normally contribute 20% to the mass load of the overall particulate matter.

7.4.1 Organic Compounds

Polycyclic aromatic hydrocarbons are a broad group of organic compounds, consisting of two or more fused aromatic rings arranged in various arrangements (Kim et al. 2013). Polycyclic aromatic hydrocarbons are naturally found in coal, crude oil, and gasoline. Polycyclic aromatic hydrocarbons generated by burning coal, oil, gas, wood, waste, and tobacco can attach to or produce small atmospheric particles. Polycyclic aromatic hydrocarbons in the air are available in vapor and molecular phases as semi-volatile natural mixtures. Lighter polycyclic aromatic hydrocarbon species with two- and three-ring structures are typically found in the vapor phase, whereas heavier species, for example, five-ring polycyclic aromatic hydrocarbons, are in the molecular phase. Because of their predominantly small

respiratory size, i.e., $PM_{2.5}$, it increases the risk of exposure (Lu et al. 2008). It has been completely confirmed that polycyclic aromatic hydrocarbons are carcinogenic and toxic chemical compounds and the prime sources of polycyclic aromatic hydrocarbons include the incomplete combustion of fossil fuels and organic materials (Bootdee et al. 2016). As indicated by Evagelopoulos et al. (2010), the concentration of polycyclic aromatic hydrocarbons bound to $PM_{2.5}$ in samples collected in Kojani City of northern Greece in 2006 was almost three times higher than PM_{10}-bound polycyclic aromatic hydrocarbons.

Total polycyclic aromatic hydrocarbons were collected on PM_{10}, $PM_{2.5,}$ and $PM_{1.0}$ in outdoor and indoor conditions during a research study led by Hassanvand et al. (2015) in Tehran. In the study results, it was noted that complete particulate matter-bound polycyclic aromatic hydrocarbons were predominant up to 88% in $PM_{2.5}$. The level of the particulate phase of polycyclic aromatic hydrocarbons depends significantly upon the source and concentrations of the fine particulate matter (Duan et al. 2005). The principal source of particulate polycyclic aromatic hydrocarbons in urban conditions is typically traffic, but the role of traffic contamination in mechanical zones is decreased (Han and Naeher 2006). Villar-Vidal et al. (2014) studied polycyclic aromatic hydrocarbons in fine particulates in the Gipuzkoa Province of Spain, considering the contribution of traffic and described the significant role of industrial emissions. Benzo (a) pyrene, a polycyclic aromatic hydrocarbon, is frequently used as an indicator of carcinogenic risk. Polycyclic aromatic hydrocarbons have been seen as the reason for around approximately 1.6% of lung cancer cases in China (Zhang et al. 2009). In light of population studies and various animal experiments, it has been stated that at concentrations greater than 1 ng/m^3, benzo (a) pyrene can induce DNA damage. DNA damage is one of the significant stages of carcinogenesis. Therefore, research on the cancer risk due to benzo (a) pyrene bound to ambient $PM_{2.5}$ is extremely important at the present time (Chang et al. 2019). The correlation between total polycyclic aromatic hydrocarbons and the amount of benzo (a) pyrene is found to be higher during the winter season in a study that was conducted based on variability in season and time (Villar-Vidal et al. 2014). A powerful correlation between polycyclic aromatic hydrocarbons and benzo (a) pyrene levels confirms that benzo (a) pyrene is an appropriate marker compound to represent total polycyclic aromatic hydrocarbon levels (Villar-Vidal et al. 2014). Etchie et al. (2018) in a study conducted in Nagpur District of India concluded that humans are losing a significant amount of their healthy life because of exposure to ambient $PM_{2.5}$-bound polycyclic aromatic hydrocarbons. The significant findings of this study were also that ambient $PM_{2.5}$-bound polycyclic aromatic hydrocarbons brought about the highest cardiovascular impairments (55.1%), followed by cancer (26.5%) or lung cancer (23.1%), immunological abnormalities (18.0%), and reproductive health losses (0.4%).

7.4.2 Inorganic Compounds

The chemical composition of fine particles, typically trace metal components of $PM_{2.5}$, performs a critical role in the severity of the associated toxic effects (Wang et al. 2017; Pandey et al. 2016). Based on the study performed at Thessaloniki City of northern Greece, Samara and Voutsa (2005) noticed the presence of trace metals in most airborne particulate matter fractions of each aerosol volume. Trace metals, for example, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, arsenic, strontium, cadmium, and lead, are widely found in $PM_{2.5}$. The origin of trace metals is mainly attributed to soil dust formation, fossil fuel combustion, cremation, and metal processing at excessive temperatures. A recent study on $PM_{2.5}$ in Nanjing City, China, found strongly correlating magnetic properties of particles with trace metals derived from anthropogenic exercises, like industrial emissions, coal combustion, and traffic vehicle activities, while an inadequate relationship between particles emitted from natural sources and its magnetic properties is observed (Wang et al. 2017). A study conducted by Das et al. (2015) during 2013–2014 in Kolkata City of India found that metals, for example, Al, Ca, Fe, Mg, Mn, Sc, and Ti, were concentrated in the PM_{10} fraction, while toxic metals, i.e., Cd, Cr, Co, Cu, Mo, Ni, Pb, Sb, Sn, Zn, and V, were concentrated in the $PM_{2.5}$ fraction. Further, higher levels of Pb, Sr, Cd, and Cd in $PM_{2.5}$ were related to industrial emissions, though higher levels of Pb and Zn were related to coal burning and non-ferrous metal melting (Das et al. 2015). Traffic emissions include significant levels of Cr, Ni, and molybdenum (Das et al. 2015). Another study around Jharia coalfield, India, reported that the chief contributors of airborne metals were coal mining/active mine fires (57.7%), followed by emissions through traffic (17.8%) and wind-blown dust (7.5%) (Pandey et al. 2014b).

Water-soluble ions are commonly significant components of atmospheric aerosols. These chemical species are easily soluble in water in the reduced troposphere under certain circumstances (Ramli et al. 2020). Ammonium (NH_4^+), calcium (Ca^{2+}), chloride (Cl^-), magnesium (Mg^{2+}), nitrate (NO_3^-), potassium (K^+), sodium (Na^+), and sulfate (SO_4^{2-}) are water-soluble ions normally found in fine particulate matter that originates from different sources (Galindo et al. 2011). The water-soluble fractions found in atmospheric fine particulates are hygroscopic and contain numerous important compounds, which make them carry out a critically significant role in the number, size, density structure of aerosols, and the lifetime of aerosols also (Salam et al. 2015). In the study performed around heavy traffic area of Durg District in Chhattisgarh State, India, during 2009 and 2010, Deshmukh et al. (2011) found that out of the total $PM_{2.5}$ mass, water-soluble constituents add an average of 11.6% (7.5% anions, 4.1% cations). Deshmukh et al. (2011) further stated that K+, SO_4^{2-}, NO_3^-, and Ca^{2+} were the most prevailing species in $PM_{2.5}$, and the concentrations of NO_3^- and SO_4^{2-} were the highest in all size fractions. In another study, Galindo et al. (2011) reported that sulfate (4.2 μg m^{-3}, 24%), nitrate, and ammonium (1.5 μg m^{-3}, 9% each one) were major contributor to fine particulates mass.

7.4.3 Carbonaceous Species

Carbonate species found in ambient particulate matter incorporate carbonates, and natural and organic carbons (Yang et al. 2011). Of the over three, organic carbon represents a significant component of the ambient aerosol and makes up to 70% of the mass of fine particles (Sharma et al. 2018). He et al. (2001) found carbonaceous species have a significant contribution to the mass of fine atmospheric particles. Further, based on a study related to the characterization of carbonaceous aerosols in Tianjin, China, Li et al. (2012) reported that atmospheric particulate carbon consists of a complex mixture of substances consisting of two main fractions, i.e., elemental carbon and organic carbon. Organic carbon is emitted directly from biogenic and anthropogenic sources as primary organic carbon. Photochemical oxidation of gas-phase precursors produces low volatility organics and constitutes secondary organic carbon (Sahu et al. 2018; Sonwani et al. 2016). Atmospheric organic carbon consists of a mixture of many natural compounds of primary or secondary origin, like polycyclic aromatic hydrocarbons, polychlorinated dibenzo-p dioxins, polychlorinated biphenyls dibenzofurans, and other components with potential mutagenic and carcinogenic effects (Sonwani et al. 2022; Feng et al. 2018; Ram et al. 2008). Elemental carbon is sometimes referred to as black carbon (Singh et al. 2018). Elemental carbon is principally transmitted from anthropogenic burning sources and does not undergo chemical changes (Li et al. 2012).

7.4.4 Biological Components

Atmospheric fine particles consist of a mixture of liquid, solid particles, and chemical and biological fractions, and these biological fractions have a significant effect on the toxicity of fine particles. Bio-aerosols, fungi, bacteria, pollen, and endotoxins are significant biological components of atmospheric fine particles.

Bio-aerosols represent an important class of atmospheric particles that range from nanometers to about 0.1 mm in size and are emitted directly from the biosphere into the environment. Along with the occurrence of life-threatening respiratory viruses like COVID-19 (Gautam and Trivedi 2020), bio-aerosols are also reported to contain toxic substances and include living and dead organisms and other dispersions that occur through them, like bacteria, archaea, algae, fungal spores, plant pollen, and plant debris, are included (Tang et al. 2018). The above definition of organic aerosol incorporates all microorganisms, regardless of the viability or capacity of the culture to recover, and together with products of fractions, biopolymers, and all varieties of living organisms (Chithra, and SM, S. N. 2018). The origin, structure, intensity, and effects of biological constituents on aerosols have not been investigated to suit requirements and in view of this have not yet been well categorized. The lack of much information about the biological components in aerosols has led to a significant gap in life sciences and atmosphere conditions, interactions, and the evolution of the earth (Fröhlich-Nowoisky et al. 2009). By examining the chemical composition of fine particles, beneficial information can be accessed to distinguish the

specific sources contributing fine particles and to understand the characteristics of aerosols that influence human health, atmosphere, and environmental conditions (Snider et al. 2016).

Studies related to atmospheric processes in recent times have indicated that bio-aerosol is one of the largest emerging pollutants in the modern era (Humbal et al. 2020), posing a threat to the environment and global health standards, but at the same time, bio-aerosol is also an imperfectly understood pollutant (Urbano et al. 2011). Bio-aerosols contain living organisms or components directly released from living organisms (Wolf et al. 2010). The expulsion and settling of bio-aerosols carry out an instrumental role in transmitting pathogenic microbes (Kim et al. 2018a, b). Bio-aerosols are additionally considered responsible for economic losses such as medical expenses around about 21 billion US dollars globally, environmental degradation, material loss, and economic productivity loss, i.e., premature death and respiratory diseases (OECD, OCDE 2016).

The size distributions of bio-aerosols vary as per the type of bio-aerosol. The sizes of viruses, bacteria, fungal spores, and pollen are generally less than 0.3 μm, 0.1–10 μm, 1–30 μm, and 5–100 μm, respectively (Hargreaves et al. 2003). During his study on meta-proteomic analysis of the atmospheric aerosol collected at the roof of Max Planck Institute for Chemistry, Germany, Liu et al. (2016) observed a positive correlation of respirable bacterial fractions with fine particles and a positive correlation of the respirable fractions of fungi with coarse particles. Various factors, for example, physical attributes of bio-aerosols, environment temperature, relative humidity, and wind velocity, affect the transport of bio-aerosols and fine particles in the gas phase (Kalisa et al. 2019).

Bacteria commonly range from 0.5 to 2.0 μm in size with the levels of bacteria typically ranging between 104 and 106 cells m^3 (Lighthart 2000); however, in regions near point sources, for example, composting crops and wastewater treatment plants, these numbers might be higher (Rinsoz et al. 2008). These bacteria sometimes form clusters or can transport locally between aquatic, terrestrial, atmospheric, and artificial ecosystems that attach to particles (Smets et al. 2016). Bio-aerosol, especially its destructive microbial components, has dangerous effects on agriculture and human health due to its regional transport (Van Leuken et al. 2016). Human activities, mainly solid waste and sewage transportation, processing, and favorable wetlands, may increase the abundance of airborne bacteria cultured in urban conditions (Gangamma 2014). Cao et al. (2014) found that the representation of Streptococcus pneumonia, the most general reason for community-acquired pneumonia, within the entire bacterial community, was 0.012% in fine particles and 0.017% in coarse particle samples. During a study around cities in northern China, Wei et al. (2020) found bacterial aerosols are highest during moderate pollution. In severe pollution, the number of bacteria that adapt to harsh environments increases in aerosols. In moderate pollution, fine particles might harbor abundant bacteria, especially those of the family that contains opportunistic pathogens. To date, the features of most airborne bacteria, including pathogenicity, cell activity, resistance to adverse meteorological conditions, and biotransformation, have not been very evident. Research on the connection between pollutant concentration and bacterial

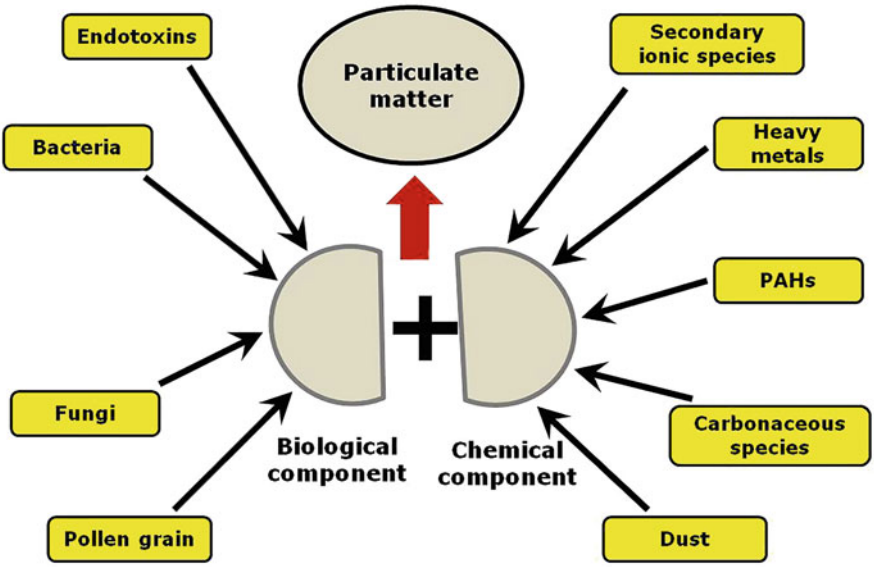

Fig. 7.2 Chemical and biological components of fine particulate matter

community composition in fine particles is restricted by several gaps in understanding and technology that could lead to contradictory results.

Zhang et al. (2010) discussed that fungal spores are the crucial biological component of airborne particles. This study further detailed that spore concentrations of Aspergillus and Penicillium are also found to increase as concentrations of fine particles increased (Yan et al. 2016). Fröhlich-Nowoisky et al. (2009), in view of research conducted from 2006 to 2007, stated that the capability of parasitic spores to tolerate adverse ecological conditions enables them to be ever-present in atmospheric fine particles. Based on morphological assessments, Telloli et al. (2016) recognized and distinguished pollen grains and fungal spores in fine particulate matters within a monitoring expedition of wheat plowing, threshing, and other agricultural operations. After examining the sampled organic particles with scanning electron and energy-dispersive X-ray spectrometer, Telloli et al. (2016) revealed that most of the particles collected during various agricultural exercises were fungal spores, flowed by pollen grains, bacterial colonies, and the plant fragments. The most frequent fungal taxa were the genus Aspergillus sp.

Endotoxin represents a complex and significant fraction of the biological components found in particulate matter, as well as it is ubiquitous in nature and has potent toxicity. Bacterial endotoxin is a lipopolysaccharide–protein complex derived from the outer membrane of Gram-negative bacteria; it is equally identified to produce symptoms, for example, airway inflammation, fever, and deterioration of lung function. Endotoxin remains stable even in adverse conditions of the environment, which is the reason endotoxin is available in modest quantities in atmospheric

particles. After comparing studies of endotoxin levels in coarse and fine particles, researchers have framed two conflicting perspectives. Allen et al. (2011) and Nilsson et al. (2011) point endotoxin levels in coarse particles are around three to ten times higher than fine particles, while Carty et al. (2003) and Mueller-Anneling et al. (2004) found that fine particles are positively associated with airborne endotoxins and pass through the lungs after breathing. Figure 7.2 shows the biological and chemical components of fine particulate matter.

7.5 Transport of Fine Particles

Fine particles can stay in the air for days or weeks after their formation and can travel many miles from their emitting sources through a complex transport and dispersal process (Marris et al. 2012). After several studies, it is observed that atmospheric temperature, wind speed, and relative humidity are the most significant factors affecting the dispersion of these particles (Zhou et al. 2018). The impacts of wind speed on the transport of fine particles can be seen in two different ways. The first and significant effect is that wind speed performs a critical role in deciding the movement time for fine particles to arrive at the receptors from their emission sources (Rasheed et al. 2015; Sonwani et al. 2021c). The other impact is the amount of pollutants dilutes in the windward direction (Meng et al. 2020). A positive correlation with the size and lightness of fine particles has been seen with wind speed. It has been observed in various studies that more air serves in the transportation of more particles over a larger area (Ediagbonya 2017). When there is a reduction in wind speed in the atmosphere, fine particles accumulate in the territory of their formation or emission sources (Pandey et al. 2014b). The fate and transport of fine particles in the environment are also highly dependent on the aerodynamic size of the fine particles. Fine particles have a longer residence time in the atmosphere because they are likely to have a gas-to-particle transformation process. The transport of fine particles into the atmosphere depends to a large extent on the mixing height and on the inversion temperature. At the time of favorable atmospheric temperature, a correlation between inversion temperature and transport of fine particles has been found. The transport of fine particles happens both horizontally and vertically. Because of the fact that fine particles are of a hygroscopic in nature, these particles absorb water vapor as the relative humidity in the atmosphere increases, which can increase their deposition and settling rate (Quinn and Bates 2005; Sonwani and Saxena 2021).

7.6 Deposition Processes of Fine Particles

For the deposition of fine particles, the process of scavenging fine particles in the atmosphere is a fundamentally essential step. The most prominent characteristics that affect the deposition of fine particles are primarily and aerodynamic properties of particles (Seinfeld and Pandis 2016).

There are mainly two different ways of deposition of atmospheric fine particles, one of which is dry deposition and the other is wet deposition. The term washout, rainout, is additionally utilized for wet deposition, while dry deposition includes gravitational settling, condensation sedimentation, and diffusion. The gravitational force exerted on suspended fine particles present in the atmosphere is responsible for gravitational settling, and this leads to fine particle deposition. The rate of settling of fine particulate matter is directly proportional to the aerodynamic particle size. Impaction, which is another strategy for deposition of fine particles, is because of the collision of particles in the atmosphere or the formation of a larger particle on another small particle wall. Fine particles are removed by impaction, forming large particles on the surface cover and aggregation, which are then removed from the atmosphere by either washout or settling (Seinfeld and Pandis 2016). The conversion of light particles into heavy particles occurs during the condensation process. While during sedimentation, heavy particles move from high atmosphere to low atmosphere. Brownian diffusion is the process in which collisions between gas molecules and fine particles happen, and this collision pushes the particle irregularly. The result of this process depends on the thermodynamic or diffusive diameter of the ambient fine particle rather than the aerodynamic diameter and that is why Brownian diffusion shows increment with the decline in particle size. The deposition of fine particles does not happen effectively through the dry deposition process. Precipitation is the most efficient scavenger of atmospheric fine particles (Ediagbonya 2017; Sonwani and Kulshrestha 2019; Sonwani and Saxena 2021). The raindrops accumulate atmospheric fine particles inside themselves that is why this procedure named as rainout rather than the washout. It is an established fact that atmospheric pollution has the potential to modify the precipitation forming processes. The effectiveness of the scavenging process depends on the size of the particles and has been confirmed in many studies to decrease with size. The scavenging effectiveness of ultrafine particles tends to be negligible (Seinfeld and Pandis 2016).

7.7 Health Effects of Fine Particulate Matter

Among atmospheric air pollutants, fine particles are globally viewed as the most responsible pollutant for the consequences on human health. The most significant effects of fine particulate matter to global health are believed to be on the ground that it can easily cross lung alveoli (Estol 2020). Subsequent to crossing the alveoli, it produces oxidative or inflammatory damage by entering the bloodstream and has an exceptionally drastic and lasting secondary impact on both the nervous system and the heart (Cho 2019). The effect of these fine particles on human health relies predominantly on climatic conditions, exposure concentrations, age, health conditions, lifestyle, and clinical courses of action.

During the study in Montreal, Quebec, Canada, Goldberg et al. (2001) found that daily mortality, in the more elderly individuals, increased linearly as concentrations of particles increased for persons who suffered from intense lower respiratory diseases, chronic coronary artery diseases, and congestive heart failure. Fine

particulate air pollution exposure has been linked with markers of the autonomic function of the heart including increased heart rate and decreased heart rate variability (Dockery 2001; Sonwani et al. 2021b). Several markers of increased risk for unexpected cardiac death have equally been related to fine particulates exposures. Respiratory demise because of chronic obstructive pulmonary disease, pneumonia, and the flu is additionally detailed in various epidemiologic studies, which indicate the early direction to potential pathways of particulate air pollution health impacts (Dockery 2001). Morris (2001), as indicated by his study, detailed that exposure to atmospheric fine particles and hospitalizations due to heart disease are related. Simultaneously, this study also stated the risk of exposure to airborne particles was on the specific disease category, the time interval used in the analysis, and the types and quantity of co-pollutants found with fine particles. Schwartz et al. (2002) observed the relationship of fine particulate matter with daily death in a hierarchical model in six US urban communities and they inferred that the extent of the connection between daily death and fine particulate matter suggests that controlling fine particle pollution would result in thousands of fewer premature deaths each year. De Hartog et al. (2003) led a study to explore the association between fine particulate air pollution and cardiorespiratory health of old individuals throughout the winter of 1998–1999 in Amsterdam, the Netherlands; Erfurt, Germany; and Helsinki, Finland. Not any association was observed between air pollution and chest pain. Increment in fine particulate matter concentration was positively connected with the incidence of shortness of breath. In conclusion, fine particulate matter was related to some cardiac symptoms in three panels of elderly subjects. De Hartog et al. (2003) further stated that fine particles were more strongly related to cardiorespiratory symptoms than ultrafine particles were.

Harrison et al. (2004) examined information presented in a review by the American Cancer Society Cohort and concluded that there is a significant correlation between mortality because of lung cancer problems and long-term exposure to fine particles. However, Harrison et al. (2004) in their study did not rule out the possibility that fine particulate matter is capable of affecting lung cancer even in the absence of known carcinogens. By utilizing a national database comprising daily time-series data on hospital admission rates for cardiovascular and respiratory outcomes and injuries of 204 US urban provinces, Dominici et al. (2006) explore about short-term impacts of fine particles on cause-specific hospital admission. Dominici et al. (2006) reported that the most significant association was with cardiovascular failure, which had a 1.28% increase in risk per 10 μg m^{-3} increment in same-day fine particulates. Miller et al. (2007) studied 65,893 postmenopausal women in 36 US metropolitan territories between 1994 and 1998 and also followed up for the next 6 years. These women exhibited no indications of heart disease previously. The conclusion of this study stated that long-term exposure to fine particulate air pollution is associated with heart disease and demise in postmenopausal women. The results of this study detailed there were a total of 1816 cardiac events including coronary heart disease, coronary revascularization, stroke, and death from myocardial infarction. They also found that each increment of 10 μg per cubic meter of fine particulate matter resulted in a 24% increase in the risk of a

cardiac event and a 76% increase in the risk of death from heart disease. Fuks et al. (2011) investigated the cross-sectional relationship of residential long-term PM exposure with arterial blood pressure and hypertension. They utilized the year 2000–2003 data from the Heinz Nixdorf Recall Study, a population-based prospective cohort in Germany. Fuks et al. (2011) observed a direct relationship between long-term urban background fine particulates and arterial blood pressure and hypertension, which may induce atherosclerosis. Performing a systematic review and meta-examination of short-term exposure to fine particles, Bell et al. (2013) put special emphasis on the elevated risk of death and hospitalization of old people by fine particles. Simultaneously, Bell et al. (2013) have additionally provided indicative evidence of substantial risk of fine particles for low education and death of persons belonging to the low-income group in their study. By the utilization of remote sensing data of satellites, Evans et al. (2013) determined global fine particulate matter exposure levels. During this study, Evans et al. (2013) reported that fine particulate matters are responsible for 8% of global adult mortality and for 9% of ischemic heart disease. Further, they also indicated the change in climate might affect more strongly than anticipated results. On the basis of their satellite-derived PM2.5 data, Evans et al. (2013) also showed that the man-made component of fine particles was exclusively accountable for approximately 13% increment in the lung cancer-related adult mortality globally (Evans et al. 2013). Association of one lakh global premature mortality increment with fine particulate pollution is the result of twenty-first-century climate change (Fang et al. 2013). Performing a study based on a systematic review of atmospheric particulate matter exposure and lung cancer risk, Hamra et al. (2014) proposed classifying ambient air pollution and atmospheric fine particulate matter as group 1 carcinogens. The examination on short-term relationship between fine particulate matter and mortality in nine French urban areas by Pascal et al. (2014) plainly showed that fine particles significantly affected cardiovascular mortality and the effect was most elevated during summer season. Fleisch et al. (2014) assessed the impact of fine particle exposure during middle 3 months of pregnancy in ladies of Boston, USA, and found fine particle exposure was altogether associated with impaired glucose resistance, however not with gestational diabetes mellitus, and demonstrated the immediate impact of fine particles in irregular glycemia during pregnancy. Ding et al. (2014) recorded alterations in 492 and 970 genes at higher and lower exposure were found when human bronchial epithelial cells were exposed to fine particulate matter samples collected from Wuhan, China. These alterations were typically connected with genes of inflammatory and immune responses, oxidative stress response, and response to DNA damage.

Atkinson et al. (2015) surveyed information on patients admitted to the hospital because of fine particulate matter pollution and daily mortality due to it, while Sun et al. (2015) performed a comparative assessment of the data of the relationship between pregnancy and preterm births and exposure to fine particulate matter, and demonstrated a direct correlation between exposure of fine particulate matter and preterm birth. In their systematic review of short-term exposure to $PM_{2.5}$ pollution and danger of myocardial infarction, Luo et al. (2015) observed an increment of 10.0 μg m^{-3} $PM_{2.5}$ concentrations was related to the risk of myocardial infarction.

Several epidemiological studies affirmed maternal exposure of fine particulate matter and various pregnancy outcomes and reported a positive association of an increase in $PM_{2.5}$ concentrations with an increase in the risk of preterm birth and low birthweight, whereas the association was non-significant for stillbirth (Zhu et al. 2015). Talbott et al. (2015) after their study in southwestern Pennsylvania detailed the effect of prenatal and postnatal exposure to fine particles on the risk of childhood autism spectrum disorder.

Morakinyo et al. (2016) recognized the role of biological and chemical segments of fine particles in their toxicity. Ajmani et al. (2016) detailed a significant association of the deterioration of olfactory function with exposure to fine particles based on studies on American adults aged 57–85 years. Mehta et al. (2016) and Kim et al. (2016) studied $PM_{2.5}$ exposure consequences on renal and depressive disorder separately and documented risk of decrease in renal function and significant risk of grave depressive disorder were positively associated with long-term exposure to fine particulate matter pollution. Meta-analysis performed by Flores-Pajot et al. (2016) obtained that per 10 μg m^{-3} ascent in the fine particulates exposure showed an augmentation of 1.3 instances of autism spectrum disorder. Yorifuji et al. (2016) in a short-term fine particulate matter exposure and newborn child mortality study in Japan found a positive correlation between infant mortality and post-neonatal mortality with the increase in fine particulate exposure. A study conducted by Wu et al. (2016) on Chinese men found fine particles are having an adverse effect on sperm concentration and its number, albeit fine particles have no impact on sperm motility. In light of the aforementioned study, the conclusion of the study was that due to the pollution of fine particles there is no effect on the growth of sperms; however, fine particles influence the quality of semen. During the study performed in the Chiayi City of Taiwan, Lu et al. (2017) confirmed a direct correlation between glucose homeostasis and fine particulate matter exposure in women during pregnancy, in spite of the fact that this study also found that the effect of short-term fine particulate matter exposure was non-significant. Chen et al. (2017) in another study reported a relationship between the atmospheric fine particles and incidence of influenza and detected an extremely strong relationship between exposure to fine particles and the relative risk of influenza incidence. The authors of this study estimated an increase in the incidence of influenza by approximately 11% due to exposure to fine particles.

Utilizing a dataset of community multi-scale air quality model simulations, Fann et al. (2018) assessed the change in the ambient level of fine particles all through the USA. They reported a 1.5% decrease in deaths because of a reduction in fine particulate pollution. An investigation by Fann et al. (2018) found that between 2005 and 2014 the level of concentrations of ambient fine particles decreased. The risk of premature death was diminished due to this decrease in the concentration of ambient fine particles between 2005 and 2014, and it was reduced throughout the USA and became more equitably distributed. After conducting a large literature survey, Miller and Xu (2018) detected a direct relationship between exposure to fine particles and total mortality, cardiovascular mortality, respiratory mortality, hypertension, lung cancer, the flu, and other adverse health outcomes. Miller and Xu

(2018) further proposed that future studies need to focus on long-term approaches to deal with check relationship between fine particulate matter and the health impacts resulting from them. More research endeavors ought to be given to seasonal patterns, sub-population susceptibility, and the mechanism by which exposure causes health effects. In addition, to get satisfactory exposure assessment at finer spatial resolutions, high-density sampling, satellite remote sensing, or models ought to be utilized. Fine particulate matter exposure may have frequent immunotoxic impacts on the immune system; however, the mechanism is incompletely understood (Wei and Tang 2018). Martins and da Graça (2018) emphasized understanding the origin of fine particles and predicting their predominance inbuilt indoor environments, which may allow the development of solutions that minimize the negative impacts brought about by fine particles, for example, an increase in the cardiovascular and pulmonary diseases that occur because of continued exposure to fine particulate matter, resulting in heightened health costs, work absence, and increased mortality, which influence impoverished communities more. Song et al. (2019) collected location-based service data and satellite-derived fine particulate concentrations to perform spatiotemporal assessments for 13 different urban areas in the Beijing–Tianjin–Hebei region, China. The results of this study demonstrated that around half of the total population live in the Beijing–Tianjin–Hebei region was exposed to the monthly mean fine particulate concentration higher than 80 μg/m^3 during 2015. In terms of total cause, and circulatory and respiratory ailments, the unexpected deaths were credited to fine particles and were estimated as 138,150, 80,945, and 18,752, respectively.

Chai et al. (2019) examined the impact of short-term exposure to fine particles of day-by-day outpatient visits for respiratory ailments on the basis of the information from the years 2007 to 2016, gathered from general medical clinics in Lanzhou, China. Chai et al. (2019) analyze the exposure–response relationship between the air pollutants, and the daily outpatient visits for respiratory ailments with the help of the distributed lag non-linear model, based on a gender and age groups, were applied According to this study, for every 10 μg/m^3 increment in the fine particulate concentration, the everyday outpatient visits for respiratory diseases increased by 0.53%. Individuals aged 18 years and younger were highly susceptible to fine particles. Furthermore, the impact of fine particle exposure was more critical for females than for males. Chai et al. (2019) assessed the effect of short-term exposure to fine particles of daily outpatient visits for respiratory diseases on the basis of the information from the years 2007 to 2016, gathered from general hospitals in Lanzhou, China. Chai et al. (2019) analyze the exposure–response relationship between the air pollutants, and the daily outpatient visits for respiratory ailments with the help of the distributed lag non-linear model, based on a gender and age groups, were applied. According to this study, for every 10 μg/m^3 increment in the fine particulate concentration, the everyday outpatient visits for respiratory diseases increased by 0.53%. Individuals aged 18 years or younger were most sensitive to fine particles, and the impact of fine particles exposure was more significant for females than for males. In light of a study headed by Wang et al. (2019), the risk of biogenic components on respiratory mortality was claimed to be higher than that of

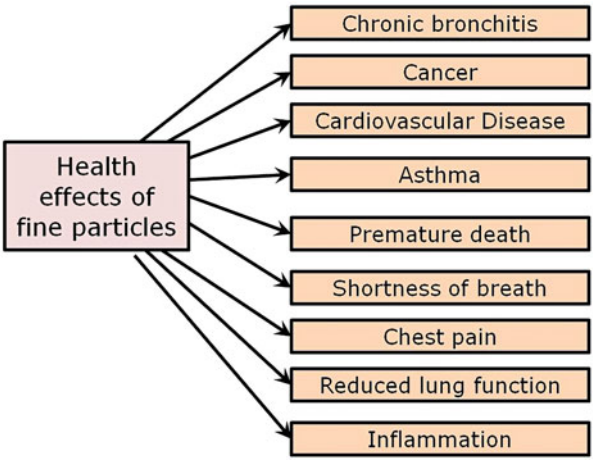

Fig. 7.3 Various effects of fine particles on the human health

circulatory mortality. A vast literature survey on researches conducted over 15 years demonstrated the presence of the direct positive relationship between exposure to fine particles and cardiovascular, hypertension, obesity and type 2 diabetes, cancer health risk, and mortality. The risk of exposure to fine particles is additionally connected with increased chances of hypertensive and diabetes issues in pregnancy and unexpected deaths. The ever-increasing hospital admission and mortality rate because of cardiovascular breakdown, diabetes, hypertension, and malignant growth might be because of long-term exposure to fine particles in various nations. Therefore, its impact ought to be conveyed for legal and scientific actions to lessen emissions from traffic sources (Alemayehu et al. 2020). A study by Wang et al. (2020) utilizing hybrid machine learning and Cox proportional hazard models to evaluate the relationship of long-term fine particulate matter exposures on explicit reasons of death for 53 million US medicare receivers of 65 years or more age inferred that Blacks, urban, and younger recipients were most vulnerable to the long-term effects of fine particulate pollution on mortality. Amoatey et al. (2020) conducted the study in Rome, Italy, and concluded that, during 2014, on average 1189, 348, 43, 301, and 387 instances of ischemic heart diseases, chronic obstructive pulmonary diseases, lung cancer, stroke, and working days lost, respectively, could be avoided in Rome if the annual average fine particulate matter concentration was diminished from 15.6 to 10.0 μg m^{-3}. On the basis of abovementioned studies, Fig. 7.3 shows the various health effects due to fine particles.

7.8 Host Responsiveness to Fine Particulate Pollution

The information on the health effects of ambient fine particulate matter focuses on specific host responsiveness. Increased mortality, morbidity, and respiratory symptoms and complaints (cough, irritation) are especially found in explicit subgroups of the general population. These risk groups may include (1) old

individuals, apparently with feeble physical conditions, (2) children, and (3) individuals with earlier cardiorespiratory ailments like congestive coronary illness, pulmonary hypertension, asthma, chronic bronchitis, emphysema, and airway infections. Exposure to fine particles is recommended to bring about an intensification of these diseases, possibly bringing about abundance morbidity and mortality. The mechanism underlying the finding that prior cardiorespiratory disease represents a significant hazard factor for the health effects of ambient PM fine particulate pollution might be partly based on biological sensitivity. Increased PM deposition in compromised airways, larger impairment of particle clearance from the lung, and a higher biological sensitivity of compromised lungs compared to healthy lungs have been suggested as contributing mechanisms. It is likely that the responses of the diseased or compromised cardiorespiratory system to inhaled fine particles are greater than those in healthy lungs. This may lead to a noticeable shift in the dose–response curve toward lower PM doses, bringing about an increased risk of morbidity and death in the most susceptible groups.

Most toxicology studies have utilized only healthy adult animals to find out about the impacts brought about by fine particles, and very few studies have been allowed to inspect the impacts of various disease states on the biological response to fine particles (Ibald-Mulli et al. 2004). Several studies have explored the impacts of lung disease on the deposition and clearance of inhaled particulates (Wei and Tang 2018). Changes in deposit sites and clearance pathways because of concurrent disease can have an effect on the dose delivered by inhaled particles, and consequently, influence toxicity.

Some work has been performed with fine particles using models of compromised hosts. McCreanor et al. (2007) selected 60 adult patients with mild and moderate asthma symptoms to take part in a randomized, crossover study and observed the impacts of particulates more prominent in adults with moderate asthma than in those with mild asthma symptoms. They further observed that these changes were accompanied by increases in neutrophilic inflammation and airway acidification. However, Mauderly et al. (1990) exposed young rats having elastase-induced emphysema to whole diesel exhaust. Various endpoints were examined after exposure, including pulmonary function, biochemical components of bronchoalveolar lavage, and histopathology and morphometry. There was no evidence that the diseased lungs were more susceptible to the particles from the diesel exhaust than were normal lungs.

Though several reports have shown that exposure to fine particles can increase the risk of cardiovascular disease (Brook et al. 2010; Wang et al. 2015), only a few studies have focused on the elderly people, who are the most susceptible subpopulation. Kan et al. (2008) found that the risk of cardiovascular disease because of exposure to particulate matter increased 0.26% in the age group 45–64 as compared with people of 5–44 years of age. Another Chinese investigation in Beijing showed ambient fine particles adversely influenced the cardiovascular capacity of elderly individuals with earlier heart diseases (Xu et al. 2013). Dominici et al. (2006) analyzed the acute impact of fine particulate air pollution on older individuals (age $>$ 65 years) and found the most significant association between particles and

congestive cardiovascular breakdown, a 0.72% increment in risk per 10 μg/m^3 rise in same-day particle concentration. This is more than the outcomes revealed by Brook et al. (2010) with an increment of 0.18% in the general population. However, annual average exposure to higher levels of black carbon (per 0.26 μg/m^3 elevation), a marker of traffic-related PM, was associated with a 1.1% increment in carotid intima–media thickness in a cohort of elderly men living in the Boston area (Wilker et al. 2013). Short-term PM exposure is strongly associated with increased cardiovascular mortality among older individuals (Sullivan et al. 2003). In an elderly population (aged 65 and older) across the eastern USA, researchers tracked down that both short-term exposure and long-term exposure were significantly associated with the risk of deep vein thrombosis (Kloog et al. 2015).

There has been growing interest in the assessment of gender differences in air pollution epidemiology (Clougherty 2010), while findings to date for effect modification by gender are far from consistent. A comparable PM-induced risk for all-cause emergency department visits between the two genders was reported in a study conducted by Zhang et al. (2020) in two metropolitan urban communities of southern China. A pooled analysis of 26 Chinese urban communities (Chen et al. 2017) reported relatively stronger effects between female's clinic visits and fine particles, while another national study in China (Tian et al. 2019) found males were at relatively more significant risk for all-cause hospitalization due to the impact of fine particle concentration. Two recent nationwide studies assessing the short-term relationship between $PM_{2.5}$ and mortality were revealed incongruities in outcomes, with no difference in China's urban communities (Chen et al. 2017), but higher vulnerability among females in many areas of the USA (Di et al. 2017). The findings of the study performed by Kim et al. (2019) suggest that, in metropolitan regions, the adverse impacts of increased exposures of particulate air pollutants on cognition were more prominent in females than in males. Given the wide lack of research consent, a debate is expected to continue over the next decade regarding whether females or males suffer severely from the health risks associated with PM.

7.9 Biological Mechanisms of Action of Fine Particulate Matter

Little is known about the health effects caused by ambient fine particles and the biological mechanisms underlying host response in specific subgroups of the population. Most of the studies reviewed earlier in this chapter were initiated to examine the biological mechanisms underlying health effects related to ambient air fine particles toxicity. From these studies and epidemiological studies focused on specific endpoints, a number of hypotheses on mechanisms can be put forth according to which these effects might occur.

Fine particles become confined in the lamina organelle subsequent to be absorbed into the targeting cells; however, fine particles have been observed without evident plasma membrane covering (Wang et al. 2013). The release of various components of fine particles, like polycyclic aromatic hydrocarbons and volatile organic compounds, activates the aryl hydrocarbon receptors of cells and bringing about

the increased expression of the aryl hydrocarbon receptor-regulated genes, including the phase I xenobiotic-metabolizing cytochrome P450 enzymes, the phase II enzymes, and aryl hydrocarbon receptor repressor (Feng et al. 2016; Richard et al. 2019). Afterward, the organic chemicals, released from fine particles, become metabolically activated by this xenobiotic-metabolizing enzyme system into reactive electrophilic metabolites, which cause various toxic effects to the target cells (Longhin et al. 2013).

Despite the fact that the mechanism underlying the relationship between exposure of fine particulate and adverse health impacts has not been completely clarified based on research up until this point. However, fine particulate-induced oxidative stress is considered as a significant mechanism of fine particulate-mediated toxicities (Deng et al. 2013). Various investigations on the impacts of fine particles have noticed that fine particulate exposure adds to systemic oxidative stress and makes extreme harm to animals and human cells (Abbas et al. 2019; Longhin et al. 2013). With atmospheric fine particles, and particularly with particulate matter emerging from the combustion process, there are environmentally persistent free radicals (Chen et al. 2020). On the other hand, many organic chemicals found in fine particles can be metabolically active and therefore form reactive electrophilic metabolites, which can increase the production of reactive oxygen species inside the cell (Holme et al. 2019). Oxidative stress resulting from fine particles mediated activation of inflammatory cells also possesses the potential to generate reactive nitrogen species and reactive oxygen species (Jan et al. 2020).

Alongside the above activities, fine particles have been appeared to have a negative effect on the antioxidant system of target cells and reduce the antioxidant capacity of target cells. Nuclear factor erythroid-2-related factor 2 is a transcription factor and essential intracellular defense mechanisms against oxidative stress. Particle-induced reactive oxygen species may work as signaling molecules to trigger translocation of nuclear factor erythroid-2-related factor 2 into the nucleus, resulting in altering transcription of antioxidant enzyme system (Feng et al. 2016).

Fine particulate exposure has been widely reported to be significantly liable for altering the expression of antioxidant enzymes and diminishing their activities (Wang et al. 2016). Several other studies have additionally reported the overexpression and suppression of some key transcription factors increased the production of particle-induced reactive oxygen species in target cells (Feng et al. 2016). Studies demonstrating a decrease in the activity of glutathione metabolic enzymes because of the effect of fine particles additionally notable. Decreased activity of glutathione metabolic enzymes represents the significant reason for the decline of total sulfhydryl groups in biological systems (de Paula et al. 2020). These reactive oxygen species, formed because of fine particulate exposure, have various adverse consequences on many macromolecules found in cells, impairing their structure and function, and thus increasing the damage to target cells and tissues. In certain studies, diverse markers generated by lipid and protein oxidation due to exposure to fine particles in the target cells have also been identified (Wang et al. 2016). In some other studies, significant information about oxidative DNA damage in cells due to exposure to fine particles can be seen. In these studies, increased

levels of some nucleotide oxides have been considered as the predictors of oxidative DNA damage (Tao et al. 2019). In addition, there is further proof of excessive reactive oxygen species activating multiple signaling pathways in biological cells, and finally, this phenomenon leads to a series of unfavorable effects on the cells. There are also studies providing substantial evidence that adverse impacts from exposure to fine particles are significantly restrained or weakened by antioxidants, and these studies have shown that antioxidants can represent a promising strategy to forestall or diminish the effects of fine particulate exposure (Feng et al. 2016).

The mutational properties of organic extracts found on fine particles have also been discussed in several research papers to find out the effects of exposure with fine particles. The principal cancer-causing agent transported with fine particles is polycyclic aromatic hydrocarbons and nitro-compounds (Badran et al. 2020). Apart from the aforementioned studies, fine particles are equally known to increase the frequencies of chromosomal anomaly in human cells. Some research papers also describe the effect of the heavy metal found with fine particles on the genotoxic potential of human cells (Feng et al. 2016).

Fine particulates induce DNA damage, which may in turn triggers an array of reactions causing alteration of cellular biochemistry and physiology, modification of genetic profiling, thereby affecting cellular fate and their functional aspects (Jin et al. 2019). Hence, the generative impact of fine particulates was observed to be significant to modify the overall expression of genes in cellular construct (Cheng et al. 2020). However, the underlying impacts of these particles on the repairing system of DNA are still elusive and require more detailed future research in this area to develop a better understanding of the underpinning mechanisms.

Fine particles have been observed to interact with alveolar macrophages, which cause activation of several transcription factors triggering the innate immune responses via generation of reactive oxygen species (Wang et al. 2020). On entry of these particles, activation of adaptive immunity is generally observed via manifestation of histocompatible class II complexes and alteration of T helper cell responses. Modification of immunity accompanied by inflammation and oxidative stress is some of the major respiratory impacts observed due to inhalation of fine particulates matters (Feng et al. 2016). Furthermore, such inflammation and oxidative stress in the hypothalamus may interfere with neuroendocrine functioning and eventually entail disorders in neuroendocrine systems. Feng et al. (2016) identified the particulates induced risk protruding toward pregnant women, which may induce detrimental effects on the baby in childhood or later, at mature stage. Moreover, similar study also reported the inflammatory impacts of fine particles on different organs viz. heart, spleen, liver, and kidney due to enhance manifestation of cytochrome P450 enzymes of phase I xenobiotic metabolites. Schematic representation of pathways and mechanism of toxicity and effects of PM exposure through inhalation are shown in Fig. 7.4.

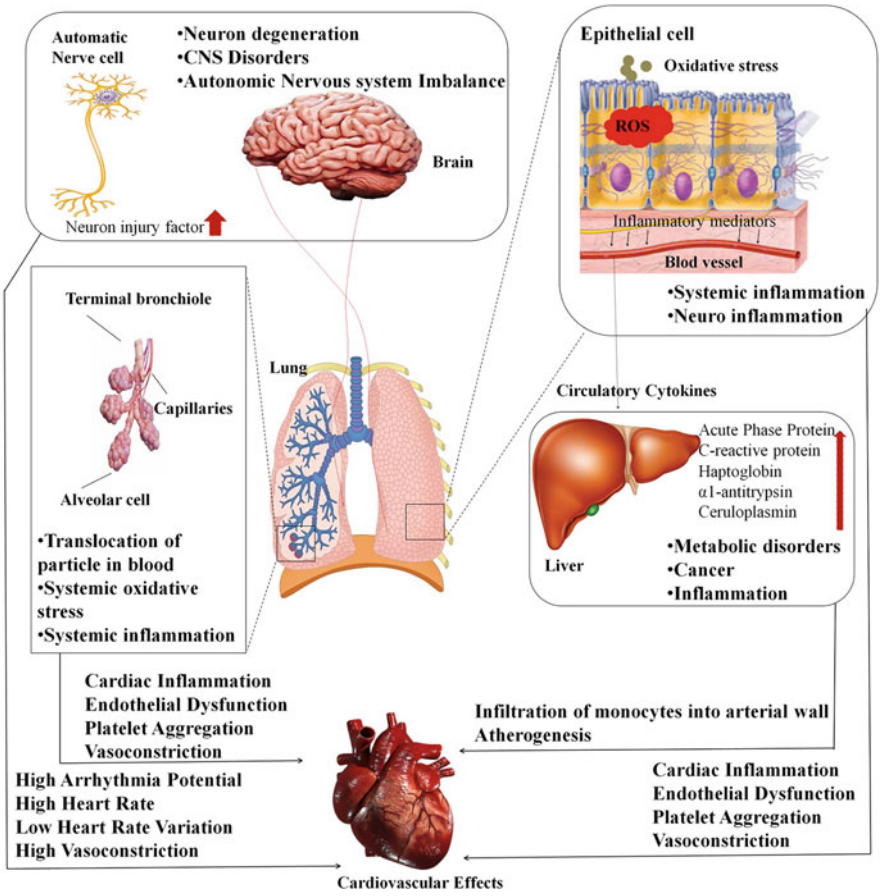

Fig. 7.4 Schematic representation of pathways and mechanism of toxicity and effects of PM exposure through inhalation

7.10 Conclusions

High population density and urbanization are the major drivers of poor air quality around the world. Traffic along with combustion activities is major source of fine particles. The chemical and biological components of fine particles lead to various health problems even at very low levels. Several studies indicated the carcinogenic or mutagenic nature of chemical constituents associated with fine particulate matter that have severe health consequences even at lower concentrations. Fine PM causes several health effects such as increase in inflammatory responses, lung cancer, heart rate variability, term low birthweight, and immune responses. Epidemiological studies provided evidence that there is an increasing trend of fine PM-related health

issues all over the world and children and pregnant women being most vulnerable. More scientific studies on gene and metabolic levels will further be able to discover the yet hidden health effects of fine particles. The physicochemical properties of fine particles and their components vary with spatial and seasonal factors and due to this dependence; there is a consistent uncertainty on the specific components of fine particles responsible for the specific detrimental effect and the intensity of these effects on human health. Due to this fact, there is a need for hours to do priority research on the molecular mechanism of action of fine particles on human health.

Acknowledgement The authors are thankful to Director, CSIR-Central Institute of Mining and Fuel Research, Dhanbad, for providing essential facilities.

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Bioaerosol and Its Impact on Human Health

8

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Abstract

Bioaerosols, a type of airborne pollutant, are biological components such as dead or animate bacteria and fungi, viruses, pollens and allergens along with several secondary metabolites such as mycotoxins, β (1,3)-glucans and endotoxins, which are mostly associated with particulate matter. They are ubiquitously present in the biosphere as they originate from both natural and manmade sources. Soil, damp surfaces of rocks, water bodies and living organisms like plants and animals act as the sources from where both active emission and passive emission of microorganisms take place. Various sampling techniques have been used to facilitate monitoring and characterising the bioaerosols. Owing to their omnipresence, concentration, size of particles and disease-causing capabilities depending upon their types, bioaerosols are potentially hazardous and are associated with numerous human health issues since decades. Bioaerosol transmission is the prime reason for some of the most infectious diseases, which include tuberculosis, severe acute respiratory syndrome and influenza. Pandemic outbreak of corona virus (2019) and H1N1 virus (2009) along with bioterror attacks (2001) is highly alarming. Hence, continuous monitoring and assessment of bioaerosol are of utmost importance for both identifying risks of exposure and establishing required threshold limits. Furthermore, as it is evident that bioaerosol does impose negative health impact on humans, hence along with assessment, appropriate measures are of utmost importance to control bioaerosol.

Keywords

Bioaerosol · Active and passive emission · Infectious and respiratory diseases · Pandemic outbreaks

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_8

8.1 Introduction

As a type of pollutants (airborne), 'bioaerosols' are biological components mostly associated with particulate matter. Such biologically originated aerosols are composed of all infectious or non-infectious, dead or animate bacteria and fungi, viruses, pollens and allergens along with several secondary metabolites such as mycotoxins, β (1,3)-glucans and endotoxins (Douwes et al. 2003). Although they are extremely variable and complex in nature, bioaerosols are ubiquitously present in the biosphere as they originate from both natural and manmade sources. Numerous bioaerosol particles of varied composition and size are significantly present in the air, which mostly fall within the respirable range with virus having the lowest size (0.003 μm), followed by bacteria (0.25–20 μm), fungi (up to 30 μm) and pollens (up to 58 μm) (Gregory 1973; Thomson 1951; Taylor 1988). Being inhalable in nature bioaerosol is of primary concern as they are susceptible enough to outreach inner parts of the respiratory system and infect deep down.

Historically, both the occurrence and dispersion of spores and fragments of microorganisms in the air were first monitored and assessed in early nineteenth century by Ehrenberg (1830) and Pasteur (1860). Since then, with the passage of time, long-term studies carried out by collecting air samples with the help of aircrafts, rockets, etc., revealed long-distance transportation of bioaerosols between continents and in higher altitudes irrespective of the fact that they were released from the terrestrial or oceanic surfaces (Gregory 1945; Griffin 2004; Hallar et al. 2011). Bioaerosols thus enact a significant role in the dispersion of reproductive parts from microbes and plants wherein the atmospheric circulation enables the transportation over geographic barriers. This eventually helps in spreading organisms, enabling genetic exchange between different biomes and habitats. Bioaerosols thus play a consequential function in the evolution and dynamism of ecosystems.

In the late nineteenth century, a study carried out in France by Miquel (1883) not only depicted seasonal variability in airborne bacterial spores but also reported a positive correlation between human mortality rate and bacterial bioaerosol concentration. Henceforth, the study of biologically originating airborne particulate matter, i.e. aerobiology, became an important scientific multidisciplinary research arena with special interactions with disciplines such as medical science, biology and physics. Different streams of medical research are highly concerned with the presence of bioaerosols and their types due to their linkage with various detrimental health impacts ranging from asthma, infections, allergies, acute and chronic toxic effects to cancer (Peccia et al. 2011; Sonwani et al. 2021). Innumerable negative impacts of bioaerosols on human respiratory system have been reported since decades (Verhoeff and Burge 1997; Lee et al. 2006). Considering the negative health impact of bioaerosols of critical importance, this chapter discusses and provides an overview on the various types of bioaerosols, their probable sources and related reported health impacts.

8.2 Bioaerosol Sampling Techniques

8.2.1 Impaction

This method is the most extensively used one, due to its economic feasibility. The prime advantages of this method include direct collection of microorganisms on to the growth medium, thus followed by reduction in any post-sampling processes. Innumerable samples can be collected without repeated sterilisation process. Few disadvantages are these impactions are based on culture-based enumeration method. In highly contaminated site, culture plates are overloaded with colonies, thus becoming difficult to distinguish. These samplings are also affected by wind speed.

8.2.2 Impingement

This technique is one very common technique, and a lot of data are available on its efficiency. This technique uses liquid media; thus, excess stress of microorganism is not an issue.

Post-collection quantification is a difficult task. Evaporation of liquid also stands problematic; it reduces the medium, and thus, loss may be encountered. Wind speed and wind frequency again stand as problematic in the sampling processes.

8.2.3 Filtration

Filtration is considered as one of the most economically feasible techniques to be used in the sampling. No restriction on the type of enumeration technique used subsequently includes the potential for size fractionation. There are some cons referring to quantification process, and filters become highly loaded in contaminated zones and may rise issue during dissolution process. Low recovery efficiency due to desiccation of microbes on filters can also be an issue.

8.2.4 Gravity

The advantages of this process start with economical feasibility. In most of the sampling scenarios, sampling can be done without being hindered by disturbing airflow. The results obtained in the experiment done using gravimetric methods are quite reliable.

Official guidelines have not always accepted this gravimetric technique. Air current biasness towards size plays a great role, which may be a source which can eliminate certain group of bioaerosol component.

8.2.5 Electrostatic Precipitation and Cyclone

Reduced stress used in the process gives a good recovery percentage. Low power requirement in its sampling makes it feasible to use, as well as in cyclone good collection efficiency because of reduced particle bounce and loss through re-entrainment. Sterilisation process is easy. Again, evaporation in the media causes problematic situation in the sampling process.

8.2.6 Thermal Precipitator

Thermal precipitator is widely used for smaller size particles on large scale and helps in determining all kinds of particles. Air flows freely through the sampler, and thus, pressure drops measured are very small and allied sources like vacuum are not needed. Collection rate is very low along with instrument area being small. Above all, the temperature affects the growth and viability of the microbes collected in the bioaerosol, thus disturbing the variability.

8.2.7 Condensation Technique

Ultrafine bioaerosol particles are mainly sampled and detected using this method. Viability of the microorganisms is maintained throughout. Skilled people are required to run this technique.

8.3 Types of Bioaerosol

8.3.1 Pollen

Pollens are very minute mostly microscopic bodies of different structures, sizes (in micrometre range) and shapes (such as peroblate, oblate and subspheroidal) (Sonwani and Kulshreshta 2018). These are formed in male structures of the flowers of seed-bearing plants which when in contact with a female gamete of the same plant or other plants of the same species, fertilisation is initiated. The transportation of these male gametes (pollen) to the female ones is carried out by water, insects, wind, etc. Anemophiles are plants that mainly use wind for the transportation and dispersal of pollen. All gymnosperms (like pine, cypresses and fir) and few angiosperm plants (like hazelnut, poplar and oak) are known anemophilous plants. Since pollen plays an integral part to facilitate fertilisation, enormous amount of these is produced by the plants during the flowering season. Thus, plenteous amount of pollens are found in ambient air.

Structurally, a pollen grain consists of two concentric coats that encircle one or many cells within. The inner layer or coat is composed of cellulose and is called

intine, while outer layer known as exine is composed of sporopollenin, arranged in a very complicated manner (Domínguez et al. 1999). Both the composition and the arrangement of the biopolymer (i.e. sporopollenin) in the exine have a natural resistant capacity towards any form of chemical and physical damage (Domínguez et al. 1999; Fraser et al. 2016). This eventually provides a long-term durability and endurance to the pollen.

The size of the pollens although differs depending upon the plant type, on average the aerodynamic diameter of pollens ranges between 17 and 58 μm (Stanley and Linskins 1974). The smallest pollen grain of lesser than 7 μm is known to be of the forget-me-not plant (*Myosotis spp*.), while the pollen grains of corn plants are as large as 90–100 μm (Pleasants et al. 2001). However, the actual geometric diameter of most of the pollen grains (e.g. *Pinus spp.*) is usually greater than the aerodynamic diameter due to the presence of systems like aerostats and air bladders that facilitates their floatation in the air. The pollen grains of different species also portray various types of pores and ridges on their outer surface. Thus, depending upon the shape, exine structure and size of the pollen, different species are identified microscopically (Weber 1998), while some specific ones (such as mulberry and pecan) are determined by utilising the fluorescence property of the pollens (Kiselev et al. 2013).

8.3.2 Fungi

Fungi are universally and ubiquitously found organisms in various environments such as both outdoor (soil, water bodies, plants, animals) and indoors. Till date, only 7% of 1.5 million estimated total species hypothesis (Costello et al. 2013) has been described as fungal species (Hawksworth 2004). As per the data obtained from recent molecular methods, around 2.2–3.8 million fungal species have been predicted to exist (Hawksworth and Lücking 2017).

Being majorly saprophytic in nature, most of the fungi survive on the organic contents of both the dead and decaying organisms (animal and plants) and on non-living organic materials such as leftover food materials, fabrics, furniture and paper. Several fungal species are also symbiotic in nature and play a major role in composting as they are mostly involved in the cycling of nutrients such as carbon and nitrogen, in the biosphere. Most of the remaining species of fungi are either parasitic or pathogenic in nature that survives on living organisms by extracting nutrients from the host. Few known parasitic fungal species causing various diseases are *Microsphaera spp. (powdery mildews)*, *Sporisorium spp. (smut)* and *Phakopsora spp. (rust) on plants, while Cordyceps*, Batrachochytrium and Candida are few among those on animals and humans. Thus, the presence of fungi in the air has innumerable consequences on ecology, agriculture and epidemiology, along with both direct and indirect meteorological impacts.

Fungi are eukaryotic microorganisms that can be both unicellular (such as yeasts) and multicellular filamentous microbes (such as *Fusarium spp.* and *Rhizopus spp.*) with hyphae or filaments, which aggregate to form a mycelium. The mycelium not only holds the fungus on to the substratum but also absorbs nutrients from the host.

Along with their growth during the vegetative phase, a simultaneous formation of spores (formed during the reproductive phase) and their release take place during the fungal life cycle. The varied shaped and sized (1–30 μm) (Gregory 1973) spores depending upon the type of species they are released from have naturally developed resistance towards various environmental stresses including desiccation as they are mostly dispersed through air. On deposition over suitable substratum with a high amount of cellulosic matter as nutrient supply whether indoor or outdoor, the spores naturally proliferate into a colony once favourable climatic conditions of temperature and humidity prevail (Ghosh et al. 2013; Dedesko and Siegel 2015). Eventually, enormous mass of spores is produced and released into the atmosphere due to natural and animal or anthropogenic activities under both humid and dry conditions depending upon the type of fungal species. In this process apart from the spores, several organic and inorganic molecules, hyphal fragments and infested particles (with adsorbed beta-glucans and mycotoxins) are also released into the air that acts as the biomarkers of the typical fungal species (Bauer et al. 2008; Hameed et al. 2012). In most cases, such infested particles are much smaller than and outnumber the intact spores that are released from the substratum (Górny et al. 2003; Namork et al. 2006). Since most of the airborne spores and mycelial fragments of fungus fall within the inhalable range (i.e. <8 μm) (Lal et al. 2017), their mere presence at the near-ground level is of serious concern as approximately 30–60% of the estimated airborne fungi are potentially allergic and toxic in nature (Adhikari et al. 2004). Approximately 10^3 to 10^7 m^{-3} of fungal spore are found at the near-ground level, with very high (i.e. $> 10^6$ m^{-3}) concentration existing indoors and outdoors such as treatment plants, farms, composting facilities or greenhouses (Durand et al. 2002; Radon et al. 2002), while lowest (approximately $\leq 10^3$ spores m^{-3}) at high altitudes (Marshall 1997; Pace et al. 2019). Thus, their concentration varies both temporally and spatially and is highly dependent on meteorological conditions (Jones and Harrison 2004; Ghosh et al. 2013; Pace et al. 2019).

Both culture-based and non-culturable methods are used for the assessment of airborne fungal species (Burge 1995; Zeng et al. 2006). The commonly found fungal species include Ascomycota (like *Aspergillus spp.*, *Alternaria spp.*, *Botrytis sp.*, *Cladosporium spp.*, *Fusarium spp.* and *Penicillium spp.*) and Basidiomycota (like Agaricus spp., *Cryptococcus* spp., *Dioszegia* spp., *Ganoderma spp.* and *Ustilago spp.*) are notably present in both indoors and outdoors (Radon et al. 2002; Ghosh et al. 2013; Oh et al. 2014; Lal et al. 2017; Pace et al. 2019). Table 8.1 represents the dominant fungal species found in various indoor and outdoor environments.

8.3.3 Bacteria

Bacteria are single-celled microorganisms. Similar to fungi, bacteria are also universal and ubiquitous. Although the global diversity of bacteria is still a subject of uncertainty, yet on an average approximately 10^{30} bacterial cells are estimated to be present on the earth, while nearly 10^{19} cells are aloft 3 km in the atmosphere (Whitman et al. 1998). Since bacteria require carbon and energy (i.e. electron) to

grow and propagate, they mostly utilise energy from either chemical compounds (inorganic or organic) or light. As a result, bacteria exhibit diverse trophic modes of utilising nutrients and energy from the environment and converting them into the biomass and internal biochemical energy. The various modes include both phototrophs and chemotrophs. Depending upon the source of carbon, the bacteria are either autotrophs (carbon dioxide is the source) or heterotroph (where carbon is absorbed from other organic compounds). Some bacteria are anaerobic methanogens that produce methane by utilising carbon dioxide and hydrogen as sources of carbon and energy, respectively, while few denitrifying bacteria utilise nitrate as their source of electron. Owing to this versatility, bacteria have been found in all the niches of the globe. This includes extreme habitats such as hot springs, deep down oceans, snow-covered polar regions and glaciers (Delort 2018). Due to their omnipresence, bacteria are known to have epidemiological, economic and environmental impacts (Brodie et al. 2007; Hervas and Casamayor 2009; Vaïtilingom et al. 2013).

Bacterial cells are prokaryotic having either very few or no organelles, with their genetic material not contained within a cell nucleus. Each cell is surrounded by a plasma membrane composed of phospholipid bilayer, which acts as a permeable barrier for majority of the molecules, while small channels present on the outer membrane also permit essential sugars, amino acids and ions to passively transport across. This passive transport eventually helps in the generation of biochemical energy within the cell. Surrounding the plasma membrane lies the cell wall mainly composed of peptidoglycan. The cell wall primarily protects the cell from both external mechanical damage and internal turgor pressure. Depending on the structure of the cell wall, bacteria are categorised into namely Gram-positive and Gram-negative bacteria. The difference between the two is established by Gram staining. Gram-positive bacteria (*Streptococcus spp.*, *Staphylococcus spp*., etc.) have thick cell wall with peptidoglycan constituting nearly 95%. On the contrary, Gram-negative bacteria (*Pseudomonas spp.*, *E. coli*, etc.) have a thinner cell wall (composed of only 5–10% of peptidoglycan) with an extra outer layer of lipid surrounding it.

This unicellular organism exists in various shapes, out of which the commonly found bacteria are either spherical (*Streptococcus spp*.), rod-shaped (*Bacillus spp*.), helical-shaped (*Spirillum spp*.) or curved rod-shaped (*Vibrio spp*.). Typically, majority of the bacteria fall within the size range of 0.2–2 μm, with few cells existing below 0.1 μm as well. Species such as *Arthrobacter spp*. and *Sphingomonas spp*. are the few below average-sized bacteria found in polar regions (Miteva and Brenchley 2005). In natural environment, bacteria are known to form biofilms (made up of exopolysaccharide matrix) on various surfaces including plants' surfaces. These matrices not only facilitate adherence to the surface but also provide protection to the bacterial cells from mechanical and meteorological impacts (Hall-Stoodley et al. 2004). Since several phytopathogenic and commensal bacteria are known to form biofilm on plants (Harrison et al. 2005; Fang et al. 2007), canopy cover emerges to be one of the important sources of outdoor airborne bacteria (Lindemann et al. 1982). Few bacterial species such as *Bacillus spp.* and *Clostridium spp.* are known to form spores in order to avoid extreme environmental conditions of oxidation, temperature,

etc. These undergo dormancy till they encounter favourable meteorological and nutrient conditions to germinate.

Typically, the range of near-surface airborne concentration is approximately between 10^2 and 10^6 bacterial cells m^{-3} (Harrison et al. 2005; Fang et al. 2007; Bowers et al. 2013). Similar to fungi, bacterial bioaerosol also displays large spatial and temporal variability with higher concentrations at human activity sites and indoors (Radon et al. 2002; Normand et al. 2011; Ghosh et al. 2013), while lowest in snow-capped mountains and glacial regions (Bowers et al. 2009; Pearce et al. 2009). Temporally among all the seasons, higher airborne bacterial concentration is reported during the summers and post-monsoon season (Bowers et al. 2013; Lal et al. 2017). Although meteorological parameters like temperature and humidity are known to have a considerable impact on the abundance of bacterial bioaerosol (Di Giorgio et al. 1996; Harrison et al. 2005), their influence is highly sampling site-specific. The most frequently found bacterial species outdoors are *Sphingomonas spp.*, *Pseudomonas spp.* and *Methylobacterium spp.*, belonging to the Proteobacteria group (Maron et al. 2005 ; Dueker et al. 2012). Among the various Pseudomonas spp., *P. syringae* is of notable interest in the field of aerobiology as it is a known plant and human pathogen (Lindemann and Upper 1985; Morris et al. 2008; Monteil et al. 2014). Other relatively frequently identified bacterial bioaerosols in urban settings and indoors are *Micrococcus spp*., *Bacillus spp.* and *Staphylococcus spp*. (Radon et al. 2002; Harrison et al. 2005; Brodie et al. 2007; Fang et al. 2007). Table 8.1 represents the dominant bacterial species found in various indoor and outdoor environments.

8.3.4 Virus

Viruses are obligate intracellular parasitic entities. They are acellular and highly infectious in nature. Unlike other microorganisms such as fungi and bacteria, viruses are usually extremely simple in structure. They contain either DNA or RNA (type of nucleic acid) as their genetic material is included in coat of protein called capsid. In order to replicate and multiply into new individuals, they always require a host cell. Generally, viruses exist in various shapes such as head and tail (mostly infect bacteria), filamentous (mostly plant virus such as tobacco mosaic virus), enveloped (such as HIV) and icosahedral (or isometric virus such as poliovirus). Although viruses do exist outside a host cell in a manner that they are dispersed by air and can be infectious, yet cannot multiply into new entities. Naturally, soil acts as one of the reservoirs of different types of viruses. Approximately 10^8 genome per gram of viral concentration is present in soil (Reynolds and Pepper 2000; Williamson et al. 2003). According to Griffin (2007), different types of viruses (such as bacteriophage MS2 and polio virus) are not only disseminated into the air from the soil but also transported and dispersed far away from the local arena. After multiplying in hosts such as humans, expulsion events such as sneezing and coughing of infected individual play an important role in aerosolisation of the virus (Mubareka et al.

Table 8.1 Bacterial and fungal bioaerosols identified in various indoor and outdoor environments

Country	Study site	Dominant fungal genus	Dominant bacterial genus	Reference
Central and Eastern Europe	Residence[I]	*Aspergillus* *Penicillium*	*Pseudomonas* *Micrococcus* *Aeromonas* *Staphylococcus* *Bacillus* *Nocardia*	Gorny and Dutkiewicz (2002)
China	Garden [O]	*Naganishia* *Candida* *Filobasidium* *Cystofilobasidium* *Alternaria*	*Planomicrobium* *Arthrobacter* *Acinetobacter* *Bacillus* *Sphingomonas*	Li et al. (2020)
China	Museum [I]	*Penicillium* *Alternaria* *Aspergillus* *Paecilomyces*	*Staphylococcus* *Arthrobacter* *Bacillus* *Pseudomonas* *Micrococcus*	Chen et al. (2010)
Hong Kong	Restaurant [I]	ND	*Bacillus* *Brevundimonas* *Micrococcus* *Moraxella* *Staphylococcus* *Kocuria* *Pseudomonas*	Chan et al. (2009)
Iran	Hospital [I]	*Aspergillus* *Cladosporium* *Penicillium*	*Staphylococcus* *Bacillus* *Micrococcus*	Hoseinzadeh et al. (2013)
India	University library [I]	*Aspergillus* *Cladosporium* *Rhizopus* *Curvularia*	*Bacillus* *Palisade* *Streptococcus*	Ghosh et al. (2015)
India	Agricultural field [O]	*Fusarium* *Aspergillus* *Mucor* *Candida* *Penicillium*	*Streptomyces* *Enterobacter* *Actinobacter* *Brevibacterium*	Krysinska-Traczyk et al. (2005)
India	Landfill site [O]	*Aspergillus* *Cladosporium* *Penicillium* *Alternaria*	*Bacillus* *Streptobacillus* *Coccus*	Madhwal et al. (2020)
Korea	Child day care facility [I]	*Penicillium* *Aspergillus* *Cladosporium* *Alternaria*	*Actinobacter* *Streptomyces* *Pseudonocardia* *Nocardiopsis*	Shin et al. (2015)
Poland	Sewage treatment plant [O]	*Geotrichum* *Penicillium* *Alternaria* *Cladosporium*	*Enterobacter* *Acinetobacter* *Pseudomonas* *Stenotrophomonas*	Prazmo et al. (2003)

(continued)

Table 8.1 (continued)

Country	Study site	Dominant fungal genus	Dominant bacterial genus	Reference
Texas	Poultry houses [I]	*Aspergillus* *Trematosphaeria* *Sagenomella* *Penicillium*	*Lactobacillus* *Staphylococcus* *Salinicoccus*	Nonnenmann et al. (2010)
Turkey	Cafeteria [I]	*Aspergillus* *Penicillium* *Mucor*	*Bacillus* *Staphylococcus* *Micrococcus*	Mentese et al. (2009)

Note: Superscript 'I' denotes indoor site and 'O' denotes outdoor site

2019). Once ejected, these infectious and active viruses remain in the ambient air, even when measured after an hour of release (Bischoff et al. 2013).

Several studies have revealed the presence of airborne viruses in different indoor environments such as dairy product manufacturing plants, day care centres, emergency medical clinics and residents (Cowling et al. 2009; Lindsley et al. 2010; Verreault et al. 2011; Yang et al. 2011). Public transport systems such as trains, subways and aeroplanes have been shown to transmit airborne viruses among humans (Cui et al. 2011; Yang et al. 2011; Coleman et al. 2018). Being the smallest in size among all the bioaerosols, viruses are found to be associated with wide-ranged particles. Along with co-existing with very small nanometre-sized particles, several viruses such as influenza A virus (IAV) and porcine epidemic diarrhoea virus (PEDV) are associated with larger particles ranging in several microns (Yang et al. 2011; Alonso et al. 2015; Sonwani et al. 2021). As per certain studies carried out in indoor environments such as health care facilities and day cares, nearly 64% of viral entities were associated with particle size less than 2.5 μm, while 46% adhered to >4 μm particles (Blachere et al. 2009; Yang et al. 2011).

On average, the concentration of virus ranges between 10^3 and 10^4 genomes m^{-3} in most indoors, which vary both temporally and spatially. Under extreme conditions, the viral concentration can reach down to $\leq 10^2$ genomes m^{-3} and soar up to 10^8 genomes m^{-3} (Yang et al. 2011; Alonso et al. 2015). Although no proper connection has been yet established between the infective characteristic of virus and the aerosol size, there is a hypothesis that airborne virus non-associated with particles would be more negatively affected by the ambient temperature and radiation rather than those aerosolised with particles (Donaldson and Alexandersen 2002). Since the particles are believed to protect the virus from environmental damage, the survival and activeness of the virus thus depend on the nature and composition of the particles in concern (Woo et al. 2012; Turgeon et al. 2014).

8.4 Sources of Bioaerosol

Microorganisms mostly dwell and propagate on soil, damp surfaces of rocks, water bodies and living organisms like plants and animals, as numerous as 10^4 to 10^8 cells are found to inhabit per cubic centimetre of surface area in different natural environments (Després et al. 2012). Hence, biosphere itself plays an important role by providing diverse sources for bioaerosol. However, the significance of these different sources is quite relative, and the factors that cause the variability are location, height, meteorological parameters and season (Brodie et al. 2007; Bowers et al. 2013). Although naturally both soil and plant kingdom act as near-surface air sources, the plants are dominant ones as the leaf surface area is almost four times that of the land surface area globally (Whittaker and Likens 1973).

Oceans cover major portion of the globe (roughly 70%) and provide shelter to various microorganisms such as algae, bacteria and fungi, in both living and decayed forms. Thus, microorganisms are also ejected or released into the air similar to other particles such as sea salt through bubble bursting mechanism (O'Dowd et al. 2004). Higher altitudes and polar regions (such as Antarctica and Greenland) covered with snow contain microorganisms (like bacteria) that settle due to precipitation. Thus, in wind-blown condition resuspension of these microbes takes place revealing the fact that snow-covered surfaces too play a powerful source (Pomeroy and Jones 1996). Similarly, wind-blown over arid and semi-arid regions known to contain an assemblage of microorganisms also produces small microscopic particles associated with biological entities into the near-surface atmosphere (Després et al. 2012).

Human population globally and their associated activities such as farming practices, livestock breeding, composting facilities and waste treatment plants are highly important and known sources of airborne microorganisms (Tsapko et al. 2011). In fact, depending upon the type of human activities the composition of the bioaerosol varies in both rural and urban settings. Bioaerosols originating from humans and other animals include debris of infected hair and skin parts along with their excreta, eggs, etc., dispersed into the air due to insects (Després et al. 2012; Bowers et al. 2013). Human activities such as talking, coughing or sneezing (expulsion events) of infected individuals also enact as an important source of aerosolisation of microorganisms (Bischoff et al. 2013; Mubareka et al. 2019). Along with outdoor air, the presence of bioaerosol in built environment has an important role as nearly 80–85% of the lifetime people stay indoors (Ghosh et al. 2015). Apart from outdoor sources and resuspension of settled dusts from surfaces and ventilation systems, human expulsion events and shedded particles of desquamated hair and skin cells influence the diverse indoor microbial composition (Ghosh et al. 2013).

8.4.1 Bioaerosol Emission Mechanism

Two major processes that are responsible for the emission of airborne microbes are passive and active release. Biological substances can be released by their respective

microorganisms by simply ejecting the materials into the ambient air by active mechanisms. Species-specific internal processes in response to meteorological parameters such as relative humidity and ambient temperature trigger such active release among several plant species and fungi. According to various studies, generation of convective processes or mechanical ejections due to the impact of dew or raindrops on the surfaces efficiently promotes release of large number of spores (such as fungal species namely *Fusarium graminearum*) and pollen (Trail et al. 2005; Kim et al. 2018). Unlike wet-initiated mechanism, dried condition can also initiate active release of spores from their respective microorganisms. Active release of bioaerosol can also be generated from other organisms like wildlife, livestock and humans. Along with shedding of hair and skin debris, expulsive events like coughing, sneezing or vomiting of humans and animals actively eject biogenic materials into the ambient air (Ghosh et al. 2013). Active release also takes place due to intended mechanical disturbance created by various waste-handling mechanisms in human-made systems such as waste water treatment and composting. The various operations that result in episodic active release include unloading, turning and grinding of compost piles and activities like aeration technique in wastewater tanks (Taha et al. 2005). As per a reported study, airborne actinomycetes and fungal concentration (*Aspergillus fumigatus*) were nearly 10^3 times greater during turning activity of green waste compost when compared to the ambient concentration through passive release from stagnant compost rows (Taha et al. 2006).

Passive release of bioaerosols on the contrary occurs when the bonding force existing between the source (like plants and mycelium structure of the fungi) and the biological material is disrupted by an external powerful force. Such passive release generally occurs due to the impact of dust storm or wind (Jones and Harrison 2004). The two notable mechanisms that facilitate this passive release are abrasive dislodgement and bubble burst.

8.4.1.1 Abrasive Dislodgment

The presence of a threshold force in the form of instantaneous or mean wind speed is required to damage, dislodge and erode away biological materials from their source surface (Soleimani et al. 2016). Along with the prevailing wind, other factors such as soil texture and available soil moisture also impact the rate of airborne suspension of bioaerosol. Aerosolisation of biological materials easily takes place from less humid sandy soil surface at a very lower wind speed (4–10 ms^{-1}) (Baertsch et al. 2007). Due to blowing air mass, along with individual movements of leaves, surface rubbing of leaves with their adjacent ones also results in dislodgment of biological materials from the plant family (Van Gardingen et al. 1991).

8.4.1.2 Bubble Burst

Bubble bursting is one of the major aerosolisation processes of bioaerosols from water bodies. Bubbles of air ubiquitously present on the surface of all forms of water systems on the earth are formed due to either impact of rain or wave breaking. The two types of droplets formed due to bubble bursting are film drops (0.1 μm to above

10 μm) and jet drops (up to 100 μm) (Veron 2015). Film drops are formed due to the cavity collapse of the thin water layer that detaches atmosphere from the trapped air bubble. As the layer collapses, the rising jet produces the larger jet drops. The droplets thus formed carry not only organics and salts but also good range of biological materials (O'Dowd et al. 2004).

8.5 Environment-Specific 'Bioaerosols'

Specific activity-prone area possesses high risk of bioaerosol and the types of diseases it causes. The severeness of the disease changes with 'nature of activities', 'confinement in areas' and 'aerosolised area'. The environments are also divided into three major categories on the basis of their location confineness, level of airborne microbes and endotoxin contamination. (a) Highly contaminated environments are of confined area with high biotoxin burden, e.g. agricultural settings and industrial composting facilities wastewater treatments plants with biological burden up to 10^9 total bacterial counts/m^3. This amount of toxin load can cause diseases such as rhinitis, asthma, chronic bronchitis and organic dust syndrome (ODTS) as well as hypersensitivity pneumonitis (HP). Environment with moderate airborne contamination are with biological load of 10^5 colony-forming units (CFU)/m^3. The weak contaminated environments represent contamination from humans mostly such as hospitals, schools, offices, libraries and homes. The bioload is around 10^2–10^3 bacteria/m^3. One such example of weak contaminated environments is associated with SBS (sick building syndrome). Increased in the rate of insulation in the buildings along with poor ventilation, building dampness resulting in increase in indoor mould exposure has been found to be associated with rhinitis and other symptoms of building-related illness (Wålinder et al. 2001; Heseltine and Rosen 2009). According to many studies, the factors associated with the prevalence of SBS symptoms are the floor covering, types of organic floor dust, architecture of the ventilation in use and the age of the building. Apart from the factors such as age of buildings (Skov and Valbjørn 1987) and various types of ventilation (Berglund and Lindvall 1986), other factors like amount of furry material used in the making of the building (Skov and Valbjørn 1987), temperature ranges within the room (Jaakkola et al. 1989) and existence of smoke (Jaakkola et al. 1989) also influence SBS symptoms.

8.6 'Bioaerosols': Pay-Off Human Health and the Environment

Bioaerosols prevalent in indoor and outdoor environments are the root cause of variety of diseases. The health problems that are prevalent due to bioaerosols include disease due to hypersensitivity, infectious and toxic ones, and there are even evidences where aerosolised bioaerosols (i.e. bioaerosols) are used in pernicious purposes. The important factors that stand as the main reasons behind the potential degree of hazardousness are (a) concentration and the nature of components present,

(b) size of the particles and their transport and (c) disease-causing capabilities, i.e. host vulnerability to the microbes. Bioaerosol transmission is the prime reason for some of the most infectious diseases, which include tuberculosis, severe acute respiratory syndrome and influenza (Ghosh et al. 2015).

Yet, there persists a lot of knowledge gap in exact role of bioaerosol and their component factors responsible for the mechanism for the diseases. Here, in this section we will discuss the infectious disease, non-infectious diseases, respiratory diseases, species-specific diseases, concentration size and genera-based bioaerosols and their related ill effects to health. We will also focus on bioterrorism related to bioaerosols and episodic outbreak of pandemics due to hazardous bioaerosols. Also, we present a comprehensive list of microorganisms and some of their major resulting diseases in Table 8.2.

8.6.1 Infectious Diseases (Species-Specific)

Infectious diseases break off mainly from exposure to microbial agents such as bacteria, viruses and fungi, and the transmission routes of these infectious agents can be in direct mode or indirect mode; direct mode includes touching, biting and licking, and eating, and indirect mode includes coughing and sneezing in passive way and vector-borne transmission (Liu et al. 2019).

8.6.1.1 Bacteria Caused Infectious Diseases

Bacterial infections can be the cause of different diseases with low even low concentration of bioaerosol as the infectious dose, and the predominant bacterial infections are anthrax, legionellosis and tuberculosis (Hussong et al. 1987, Ghosh et al. 2015). Anthrax spreading is in the form of inhaling of *Bacillus anthracis* spores, infected fly spores are the media of transfer for anthrax and disease anthrax is often linked with bioterrorism. The bacterial strain that causes human legionellosis is Legionella pneumophila, and the spread occurs by contaminated water. Tuberculosis is a very common health hazard in the underdeveloped and developing nations, and the transmission occurs through bacterial strain 'Tubercle *bacilli*' through inhalation of aerosolised droplets (containing bacilli) in expectorated sputum-positive tuberculosis patients during physical or passive contacts. Table 8.2 contains more details of aerosol-borne bacterial diseases.

8.6.1.2 Fungus Caused Infectious Diseases

Air borne fungal spore also reports to cause health disorders in many studies. Airborne fungi in a waste paper and cardboard recycling factory (Baghani et al. 2020), and industrial and solid waste regions emitting fungal spores for infections are common (Yang et al. 2018; Dehghani et al. 2018). Most common strains include *Penicillium sp*., *Cladosporium sp*. and *Aspergillus niger*, and transmission occurs orally, through inhalation or even dermal.

Table 8.2 Biological agents and their major resulting diseases

Microorganisms/species	Approximate size range of the microbes (length width)	Environment of occurrence	Disease to be developed	Transmission mode	References
Microsporum Trichophyton **(fungi)**	5–100 mm and 3–8 mm	Animal fingers and cattle bearers' skins and nails	Ringworm	Borne by humans, animals and formites can be transferred by direct and indirect contacts with infected skin and other parts of scalp lesion	Neves et al. (2018)
Legionella pneumophila **(bacteria)**	2 μm and 0.3–0.9 μm	Manmade air-conditioning systems	Legionnaires' disease	Inhaling of water-soluble aerosol	Kim et al. (2018)
Bacillus anthracis spore **(bacterial spore)**	3–5 μm and 1.0–1.2 μm	Dormant spore in soil for a long period of time	Anthrax	Breathing of anthrax spore (the carrier can be cattle, humans or mammals)	Kim et al. (2018)
Morbillivirus measles **(virus)**	125–250 nm and diameter-21 nm	Infected airspace with person coughed or sneezed	Measles, mumps and rubella	Body fluids: saliva droplets, mucus from the nose, coughing or sneezing, tears from the eyes, etc.	Kim et al. (2018)
Arenaviridae, Filoviridae, Bunyaviridae, Flaviviridae and *Rhabdoviridae* **(RNA virus, Ebola type)**	–	From wild animals	Haemorrhagic fever	Air borne transfer, sneezing or coughing contacts	Azad (2007)
Coxiella burnetii **(gammaproteobacteria)**	0.4–1.2 mm and 0.2–0.4 mm	Livestock's area	Q fever	Inhalation of air borne droplets	Kim et al. (2018)
Rickettsia prowazekii **(alpha-proteobacteria)**	–	Human body lice in optimal temperature transfer from one body to other	Typhus	Inhalation of air borne droplets	Ellison et al. (2009)
Alphaviruses **(alsuviricetes)**	_	Borne by mosquitoes, swampy environments are most common	Viral encephalitis	Inhalation of air borne droplets	Lim et al. (2018)

(continued)

Table 8.2 (continued)

Microorganisms/species	Approximate size range of the microbes (length width)	Environment of occurrence	Disease to be developed	Transmission mode	References
Bordetella pertussis **(beta-proteobacteria)**	40–100 nm, and dia: 2 nm	Transfer from one human to other in congested environment through cough	Whooping cough	Inhalation of particles in form of airborne droplets	Prussin II et al. (2015)
Mycobacterium tuberculosis **(bacteria)**	2–4 μm and 0.2–0.5 μm	Human infections spread occurs in case of direct contact to lungs or throat coughs, speaks	Tuberculosis	Air borne from one human to another	Jabir et al. (2018)

8.6.1.3 Virus Caused Infectious Disease

Viruses are the most dangerous and causes menace when airborne transfer is considered due to its swift transmission through air route. Severe acute respiratory syndrome (SARS) viruses (Asadi et al. 2020; Chavez et al. 2020), respiratory syncytial virus (RSV), hanta virus, which is spread through rodents and similar species, rubella viruses, zoster viruses, etc., are all airborne virus infections. The massive 2019–2020 pandemic the world is presently experiencing is caused by SARS virus, a novel strain of corona virus (novel coronavirus SARS-CoV-2). This strain is an extremely contagious and causes respiratory infection leading to breathing troubles and lung failures, thus significantly increasing the mortality and morbidity. Severe pneumonic conditions are also prevalent with corona virus infections.

8.6.2 Non-infectious Diseases

Allergic conditions, asthma and hypersensitive conditions are examples of non-infectious diseases that are caused due to bioaerosols. The composition of viable and non-viable microorganisms such as insect's debris, microbial toxins and allergic particles or non-pathogenic viruses causes non-infectious diseases (Peccia et al. 2008). Factors essentially responsible for non-allergic infectious diseases to cause are typically concentration along with duration of exposure (can be due to occupational exposure also). Some frequently identified non-infectious diseases to humans due to bioaerosols are allergic veolitis, asthma and organic dust toxic syndrome (Lacey 1991; Lacey and Dutkiewicz 1994).

8.6.3 Respiratory Diseases

The most common pathway for bioaerosols to cause infections is by increasing respiratory illness, and airborne fungi can lead to breathing problems more specifically allergic lung condition to atopic patients (Howard 1984). Atopy is the medical term used for individuals with allergic conditions producing high IgE in responses to allergens (air borne bioaerosols, e.g. pollens, food particles, house dust mites, spore moulds, cat dander) in this case. Other microbial allergen-causing threats are endotoxins (lipopolysaccharides), mycotoxins, β-glucans, allergens, lipopolysaccharides, etc. (Ghosh et al. 2015; Kim et al. 2018).

Endotoxins are characterised as lipopolysaccharides produced by Gram-negative bacteria that are the cause of airway and intestinal inflammation and pro-inflammatory symptoms. These symptoms can be even due to different occupational exposures (e.g. nose irritations, irritant-induced asthma). Fungal spore and fungi-related respiratory infections are due to the species-specific metabolism producing volatile compounds, which induce sensory irritations to the respiratory tracts. Indoor bioaerosols comprising of fungus such as Aspergillus (e.g. Aspergillus fumigatus, Aspergillus flavus) cause allergic bronchopulmonary aspergillosis (ABPA) and sinusitis.

8.6.4 Concentration Size and Genera-Based Bioaerosols and Their Related Ill Effects to Health

Different quantitative standards are given by government and private organisations (Kim et al. 2018), and various terminologies are used in numerous countries such as ' maximum acceptable values', ' orientation values', 'acceptable maximum values' and 'threshold limit values' (de Aquino Neto and de Góes Siqueira 2000; Becher et al. 2016; Jo and Seo 2005; ACGIH American Conference of Governmental Industrial Hygienists 2009). NOEAL or LOAEL has no dose–response approach for bioaerosol mass concentration, so toxicity calculation relating to bioaerosol and human or ecological health on the basis of data or even epidemiological observation is not made till date. However, different countries came up with different values of acceptable bioaerosol concentration in terms of microbes found; for example, in Korea fungal and bacterial concentration is 800 CFU/m^3; in Netherland, it is 10,000 CFU/m^3; Brazil (fungal concentration limit: 750 CFU/m^3), Germany (fungal concentration limit: 10,000 CFU/m^3), Portugal (fungal concentration limit: 500 CFU/m^3) and Switzerland (fungal concentration limit: 1000 CFU/m^3) (de Aquino Neto and de Góes Siqueira 2000; Pegas et al. 2010). On the other hand, the bacterial and fungal range differs for all the countries,for example limit of bacterial concentration in Netherland: 1000 CFU/m^3, Germany: 500 CFU/m^3 and Finland: 4500 CFU/m^3 (Nevälainen 1989; Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (IFA), 2004; Eduard 2009). Due to the existing data gap, researchers have given hypothesis that the health effects are dependent on three main factors: (a) genera of airborne microbes, (b) size ranges and the ability of them to penetrate deep into the respiratory and pulmonary system and (c) and their mass concentration in the specific environment (Roponen et al. 2002). However, all the 3 factors are responsible for estimating health effects, but there is hardly any study which had considered all the three factors together, mostly emphasising a single effects or combination of two is done. Allergic symptoms are seen to arise at different concentrations of bacterial spores (e.g. sometimes at 100 spores/m^3 for *Alternaria* or potentially sickening around 50 spores/m^3 for *Aspergillus sp.*) (Gravensen et al. 1986; Holmberg 1987).

8.6.5 Standards and Guidelines of Agencies Showing Concentration vs. Toxicity to Human Health

Different standards and guidelines for government and private agencies are (American Conference of Governmental Industrial Hygienists) (ACGIH) (<100 CFU/m^3—low risk, 100–1000 CFU/m^3—intermediate risk and >1000 CFU/m^3—high risk), American Industrial Hygiene Association (AIHA)—gave no safe limit for microorganisms, Indoor Air Quality Association (IAQ) (<300 CFU/m^3—common fungi are OK, <150 CFU/m^3—mixed fungi is OK), Ministry of Environment (ME), Republic of Korea (<800 CFU/m^3 is OK), Occupational Safety and Health Administration (OSHA) (>1000 CFU/m3 indicates contamination, >106 fungi/g of dust

Table 8.3 Standards proposed by different agencies for bioaerosol

Agency	Low risk	Intermediate risk	High risk
American Conference of Governmental Industrial Hygienists (ACGIH) (2004)	100 CFU/m^3	100–1000 CFU/m^3	>1000 CFU/m^3
American Industrial Hygiene Association (AIHA) (1986)	–	–	–
Indoor Air Quality Association (IAQA) (1995)	**No particular demarcation in the scale of risk.** (<300 CFU/m^3—common fungi is OK, <150 CFU/m^3—mixed fungi is permissible)		
Ministry of Environment, Republic of Korea (2010)	**No particular demarcation in the scale of risk.** (<800 CFU/m^3 is permissible).		
Occupational Safety and Health Administration (OSHA) (1994)	**No particular demarcation in the scale of risk.** (>1000 CFU/m^3 indicates contamination, >106 fungi/g of dust indicates contamination)		

indicates contamination), etc. (AIHA 1986; IAQA 1995; Ministry of Environment, Republic of Korea 2010; OSHA 1994) (Table 8.3).

8.6.6 Bioterrorism Related to Bioaerosols and Episodic Outbreak of Pandemics due to Hazardous Bioaerosols

Bioaerosol interestingly can be easily used as bioweapon. Bioterrorism by definition means deliberate spread of harmful microbes to cause diseases and induce mortality. On a broader note, bioterrorism can be caused by the use of pathogenic viruses, bacteria, fungi and microorganism produced toxins and their ill effects to human life, animal life and plants. The act of bioterrorism is subtle with invisible, silent, odourless and tasteless, which makes the detection scrupulous. Recent advances in biotechnology with more equipped use of biological weapons are threatening, and use of genetically modified organisms is an example. These acts have become a panicking reality, citing some incidences such as *Bacillus anthracis* spores mailing in envelopes in the year 2001 in the USA, which resulted in the outbreak of anthracis killing, sickening and contaminating several Senates, Post and Media officials (Klietman and Ruoff 2001). Botulism is another such example, caused by *Clostridium botulinum*, and the spread was manifested by canned food, spreading of the toxin through canned food and ensuring entry of the botulism toxins into the infants and adults blood stream, causing the spread of toxins throughout the body and causing neurological symptoms. These toxins are very powerful almost 40 million times powerful than cyanide (Lecours et al. 2017).

Variola viruses, which cause smallpox, *Francisella tularensis*, *Yersinia pestis*, *Brucella spp.*, *Variola virus* and *Coxiella burnetii* (Atlas 2002), are considered as potential bioweapons.

Bioweapons are considered as 'weapons of mass destructions', i.e. possess huge killing capacity and devastation on a massive scale (Henderson 1999).

8.6.6.1 Classification of Bioterrorism Agents

More than 250 potential agents were reported as bioweapons for bioterrorism. According to US Centre for Disease Control and Prevention, the agents of bioterrorism are classified into three distinct classes A, B and C. Class A includes dissemination and transmission of the potential agents from person to person and resulting in high mortality depending on the exposure rate (e.g. *Bacillus anthracis*). Class B represents where spreading is moderately difficult leading to moderate–low mortality rate (e.g. *Chlamydia psittaci*, *Coxiella burnetii*). Class C represents the emerging pathogens (e.g. Nipah and hanta virus) (Lecours et al. 2017).

8.6.6.2 Episodic Outbreak: Bioaerosol and Pandemic

Corona virus (COVID-19) has impacted several countries affecting more than 16.4 million people worldwide (December 2019–July 2020), making it a worldwide public threat with extreme mortality rate (Ge et al. 2020). Several aerosol scientists suggested that the routes of transmission are possible aerosol transfer through droplets or direct contact. The history and the spread of this virus or tracing the route of its origin are still sceptical. The spread of SARS-CoV is an accurate example of bioaerosol and its threat to human health. The regular symptoms of COVID-19 are upper respiratory tract illness sometimes severe to non-severe pneumonia and acute respiratory distress syndrome (ARDS).

8.7 Conclusion

Bioaerosols, owing to their sources and physical characteristics, are ubiquitous in nature and hence are omnipresent in both indoor and outdoor environments. Since in general, nearly 1.5 L of air is inhaled by human beings, and this results in the intake of 10^6 microbial fragments and cells approximately each day (Helmut 2011). Moreover, as bioaerosols are known to cause potential health impacts such as allergies, asthma, acute and chronic toxic effects, monitoring and assessing their type and concentration are of utmost importance. The presence of large number of bacterial cells and spores as well as numerous allergies causing fungi in different indoors exhibits an extremely allergic environment. Hence, along with assessment, appropriate measures are of utmost importance to control bioaerosol, especially in closed environments.

Although it is evident that bioaerosol does impose negative health impacts on humans, appropriate dose–response relationship depicting internationally accepted bioaerosol exposure limits is missing till date. The major reasons behind this absence can be attributed to the absence of proper dose–response data, insufficient

information of real time quantified and identified bioaerosol and deployment of different measuring and enumeration techniques in different studies for bioaerosol-producing incomparable results. Henceforth, suitable long-term study in different environments in various geographical locations with an unanimously accepted measuring technique should be carried out so as to conclude an appropriate exposure limits of bioaerosol as already done for other hazardous materials.

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Human Health Effects of Particulate Matter

9

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Abstract

With increased industrialization and number of pollutants, a large proportion of world population today is exposed to polluted air, especially the urban population. The particulate matter (PM) in the air is responsible for various respiratory and cardiovascular morbidity and mortality worldwide. It enters the lungs through the airways and settles in the alveoli inducing inflammatory response and surge in the pro-inflammatory biomarkers. The inflammatory and pro-inflammatory cytokines are released, which lead to systemic inflammation and oxidative damage causing various cardiopulmonary disorders. The polluted air contains PM of different sizes and constituents that are released in the air from different sources. The major health-related concern is from PMs that are less than 10 μm in diameter as they have larger surface area per unit volume and can easily penetrate through the airways, readily absorbed, go deeper in the circulation, and thus are more damaging than the larger size particles.

Evidence from multiple studies suggests that the exposure to increased PM in the air is the principal cause for increased respiratory and cardiovascular disorders like rhinitis, asthma, chronic obstructive pulmonary disease (COPD), hypertension, atherosclerosis, and lung cancer. All of these effects are mediated through

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_9

systemic inflammation and oxidative stress. Clinical studies based on dietary administration (mainly antioxidants to counter the pro-inflammatory response) have suggested some therapeutic approaches, but there is limited research in the area and variability in the data available so far. Therefore, further research is needed to identify the exact mechanism of damage caused to the cardiopulmonary and nervous system so that appropriate intervention and amelioration strategies may be offered.

Keywords

Particulate matter · Pulmonary disorders · Cardiovascular diseases · Blood–brain barrier

9.1 Introduction

For a healthy living, clean and safe air is the fundamental requirement. An adult requires around 10,000–20,000 L of air per day for survival. However, a vast majority of world population today is exposed to poor air quality. The WHO data indicate that 9 in every 10 people breathe air containing high levels of pollutants and results in approximately seven million deaths across the world every year (Campbell-Lendrum and Prüss-Ustün 2019). In addition, approximately 91% of global population live in places that have air quality levels exceeding the WHO guideline limit of 10 μg/m^3. Moreover, in this group, the predominantly exposed populations belong to the low- and middle-income countries (Cohen et al. 2005).

Particulate matters (PMs) are not just the key indicators of the air pollution, but they are also hazardous to human health, especially the lungs and heart, and the recent studies have indicated that they pose indirect but severe effect on the nervous system too (Saxena and Sonwani 2019; Sonwani et al. 2021a). It is the PM in the air that affects the human health most adversely as compared to any other pollutant (Campbell-Lendrum and Prüss-Ustün 2019). The adverse effects of PM on respiratory, cardiovascular, and neural systems are either induced by or lead to the systemic inflammation. These particles get inside human body through respiratory airways (primarily by inhalation), accumulate in the airways and alveoli, and eventually may penetrate the lung tissue over time. They are shown to be translocated to other organs of body by passing through the capillary walls and entering the circulatory system.

Fine and ultrafine PMs may translocate to pulmonary and extra pulmonary sites causing damage to the structural and functional integrity of the affected organs. Both the pro-inflammatory response and oxidative stress cause certain fundamental changes like cardiac remodeling, alterations in endothelial integrity and blood chemistry, autonomic nervous system modulation, and upregulation of inflammatory responses in the cardiovascular system (CVS). This in turn affects the parenchymatous, innate immune components, and the blood–brain barrier (BBB) that may result in predisposition for Alzheimer's and Parkinson's diseases (Miller 2020; Raftis and Miller 2019; Fiordelisi et al. 2017; Block and Calderón-Garcidueñas 2009). As per

estimate, even an exposure of less than 1 μg per capita per day can lead to serious health problems like impaired cognitive function and respiratory disorders, which includes asthma, chronic obstructive pulmonary disease (COPD), hypertension, autism, atherosclerosis, and various other cardiovascular diseases (CVDs) (Fiordelisi et al. 2017).

This chapter primarily focuses on the impact of respirable PM exposure on human body, especially cardiopulmonary and nervous system and related mortality. In addition, the epidemiological and experimental studies conducted globally to demonstrate the effects of PM on human health and the detailed mechanism of PM toxicity will be discussed.

9.2 Particulate Matter: Definition, Source, Composition, and Health Implications

PMs are the solid and liquid particles that may originate from diverse sources, differ in their chemical composition and size, and, generally, remain suspended in air. The main sources of PM may be natural phenomenon (volcanic eruptions, windblown dust, wild fires, seasonal variations bringing about pollen and allergens into the air) and anthropogenic like agricultural processes, construction, demolition activities, fossil fuel combustion by road transport, and power plants; industrial processes such as the production of metals, cement, lime, and chemicals; cigarette smoking; and wood stove burning (Fiordelisi et al. 2017; Kelly and Fussell 2012; Sonwani et al. 2021b). These are classified based on their origin, chemical composition, size, and many more criteria. Of these, the chemical composition and size play significant role in determining their toxicity (Valavanidis et al. 2008). The chemical components of PM may vary spatially and temporally owing to several natural and anthropogenic factors. Some of the main chemical components are minerals, ions, transition metals, materials of biological origin like microbes and pollens, endotoxins and allergens, organic compounds, and reactive gasses (Kelly and Fussell 2012; Sonwani and Saxena 2016).

Size makes an important factor in determining health impacts of PM as smaller particles have a greater surface area per unit volume and can absorb, adsorb, and retain more toxic substances. Airborne PMs are classified into three major categories depending on their size: (1) coarse (PM_{10}), (2) fine ($PM_{2.5}$), and (3) ultrafine or nanoparticles (see Box 1). Of the three, the subject of substantial speculation and research interest is nano-PM or ultrafine PM due to their origin (particularly diesel combustion and vehicular exhaust) and impact on health. Their composition, the high surface area-to-mass ratio, and the ability to penetrate in the body and interfere with the cellular components suggest that ultrafine PMs pose a remarkably greater health risk as compared to other PMs (Miller 2020; Raftis and Miller 2019). There are certain chemical constituents in the fine PM and ultrafine PM such as the vehicle exhaust and industrial hydrocarbon combustion byproducts that may potentially act as carcinogenic or mutagenic agents and affect most adversely.

Box 1 Classification of PM Based on Size

On the basis of particle size, the PM is classified in three categories:

1. **Coarse (PM_{10}):** The coarse PM are released in the atmosphere mainly from the agricultural and biomass burning and the forest fires. Their size ranges from 2.5 to 10 μm in diameter. These are usually deposited in the extra-thoracic airways, but these can trigger pulmonary inflammation. There are number of studies that have shown that coarse PM can activate neutrophils and eosinophils (Becker et al. 1996; Li et al. 1997; Shukla et al. 2000), increase the level of pro-inflammatory cytokines and cell-mediated immune response. (Ozturk et al. 2017; Brandt et al. 2017; McGee et al. 2015; Alexis et al. 2014).
2. **Fine ($PM_{2.5}$):** The vehicular dust, road dust and the biomass, industrial and waste burning are typical sources of $PM_{2.5}$. Their size ranges from 0.1 to 2.5 μm in diameter. These can go farther in the airways into the alveoli through simple diffusion and cause structural and oxidative damage in the lungs by triggering the varieties of inflammatory cell infiltration and smooth muscle thickening (Riva et al. 2011; Zhang et al. 2015; Wang et al. 2016, 2017).
3. **Ultrafine or Nanoparticles:** The main source of these particles is vehicle exhaust. Their diameter is less than 0.1 μm. Since nanoparticles are very small in size, therefore these are capable of crossing the capillary walls, go farther in the circulatory system, reach other organs, and can interact with cellular structures by crossing the cell membrane (Ozturk et al. 2017).

Among all PM constituents, the inhalable are the ones that draw major concern as these can easily penetrate the airways and lungs and then infiltrate the other organs via blood vascular system. A study utilizing Geophysical Fluid Dynamics Laboratory Atmospheric Model, version 3, to simulate the changes in air quality revealed that approximately 3% of cardiopulmonary and 5% of lung cancer deaths are attributable to PM worldwide (Fang et al. 2013).

Data from epidemiological and experimental studies (see Tables 9.1 and 9.2) indicate that exposure to PM is associated with increased hospital admissions and mortality due to respiratory and cardiovascular morbidities (Cohen et al. 2005; Künzli and Tager 2005; Sharma and Agrawal 2005; Pope III et al. 2004; Huang and Ghio 2006; Samet et al. 2000; Smith Jr et al. 2001). In a population, the most susceptible group comprises of old-aged people, pregnant women, and children, especially in the urban areas. According to WHO, around 4.2 million premature deaths were reported in 2016 due to ambient air pollution and a vast majority of them (around 90%) were from the low- and middle-income countries. The greatest burden of deaths due to air pollution is in the southeastern Asia and western Pacific countries (Campbell-Lendrum and Prüss-Ustün 2019). 24-h exposure to polluted air can result in uptake of almost 30 million particles in each lung acinus of which 50% is usually

Table 9.1 Major epidemiological studies across the countries showing the effect of PM exposure on pulmonary system

S. No.	Country/region and duration of study	Type of study	Study population	Major outcomes of the study	Reference
1.	Canada (1993–97)	Cross-sectional	Children diagnosed with conjunctivitis or rhinitis	10% increase in hospital visits for conjunctivitis or rhinitis due to increased fungal spores and pollen grains in the air	Cakmak et al. (2002)
2.	Germany (2003)	Cohort	General population	Risk of recurring wheeze increased significantly with high endotoxins in the air	Bolte et al. (2003)
3.	Japan (2005)	Cross-sectional	Adult population above 30 years in the Tokyo metropolitan area	When the long-term exposure to $PM_{2.5}$ was limited to 12 μg/m^3, 8% decline was observed in the deaths in Tokyo metropolitan area per year	Yorifuji et al. (2005)
4.	USA (2000–2003)	Cross-sectional	General population	Hospital admissions almost doubled for respiratory, CVD, and diabetes with a 10 μg/m^3 increase in $PM_{2.5}$ concentration	Zanobetti et al. (2009)
5.	Sweden, 2001–2002	Case–control study	Dust samples from the living rooms of 198 asthmatic and 202 controls, 1–6 years old	Association between endotoxins and the presence of respiratory disease was observed	Moniruzzaman et al. (2012)
6.	Poland (2014)	Prospective cohort study	4-year-old children; dust samples examined from bedroom	Increased wheezing was reported	Jedrychowski et al. (2014)
7.	China (2017)	Cross-sectional	Adult population in 7 clusters from 4 cities	Exposure to higher concentration of PM was found to be significantly associated with increased prevalence of COPD and declined respiratory functions	Liu et al. (2017)
8.	Netherlands (2018)	Cohort	Children and adolescents	Significant association was observed in decline of FEV1 function and with increased $PM_{2.5}$	Milanzi et al. (2018)
9.	India (2017)	Cross-sectional	Urban population across the country	Hospital admissions were found to be increased markedly in the metro cities during the peak PM concentration during	Manojkumar and Srimuruganandam (2019)

(continued)

Table 9.1 (continued)

S. No.	Country/region and duration of study	Type of study	Study population	Major outcomes of the study	Reference
				post-monsoon and winters. Around 1.27 lakh deaths occurred in 2017 due to increased $PM_{2.5}$ concentration in the air	
10.	South Korea (2015)	Cross-sectional	100,000 people examined in a national survey	Both outdoor activity and stress levels were worsened when the exposure time to a high PM10 (>80 μg/m^3) was more than 20 h	Jung et al. (2019)
11.	China (2016–2018)	Case–control study	Children (0–14 years old)	Increased exacerbation in children with asthma as compared to control group	Wu et al. (2019)
12.	Europe (2011–2013)	Cohort	Adults of average age 52 years	Long-term exposure to NO_2 found to be associated with increased severity of allergic rhinitis	Burte et al. (2020)

Table 9.2 Some major experimental and epidemiological studies to assess extrapulmonary effects of PM exposure on humans

S. No.	Country/region and duration of study	Type of study	Study population	Major outcomes of the study	Reference
1.	Harvard Six Cities Study	Cohort study	8111 adults living in six major US cities	Fine particulate matter contributes to increased mortality in the studied cities	Dockery et al. (1993)
2.	Boston, (June to September 1997)	Population	21 volunteers (53–87-year-old active Boston residents) from a housing community	The study reveals positive associations between ambient pollution levels and CVD	Gold et al. (2000)
3.	USA (1998 and 2003)	Data analysis study	798 participants from two clinical trials	The study provides the first evidence for strong association between CIMT, a measure of subclinical atherosclerosis, and long-term exposure to ambient air pollution	Künzli et al. (2005)
4.	Taipei, Taiwan (2006–2010)	Outpatient data analysis	Random one million patient samples from the cardiovascular disease data on outpatients using Taiwan's National Health Insurance Research Database (NHIRD)	This study demonstrates that only PM2.5 is significantly positively correlated with the number of daily outpatient visits for CVD during high air pollution events	
5.	Changchun China, (2014–2017)	Daily mortality count data	Elderly (≥65 years old) population non-accidental and circulatory diseases mortality	Results demonstrate that short-term exposure to $PM_{2.5}$ is associated with non-accidental and circulatory diseases deaths in elderly	Yangming Qu et al. (2018)
6.	211 county units in the 51 US metropolitan areas. (late 1970s and early 1980s), (late 1990s and early 2000s)	Data analysis study	General population	Improved life expectancy observed over the time period of study owing to reduced PM exposure	Pope III et al. (2009)

(continued)

Table 9.2 (continued)

S. No.	Country/region and duration of study	Type of study	Study population	Major outcomes of the study	Reference
7.	Belgium (2001)	Experimentation in human subjects	5 healthy, non-smoking male volunteers (24–47 years)	Experimentation involved inhalation of Technegas, i.e., an aerosol of technetium-99 m-labeled carbon particles to mimic the ultrafine fraction PM actual pollutants. Results indicate rapid diffusion of ultrafine PM into systemic circulation and hence implicated in causing CVS morbidity and mortality	Nemmar et al. (2001)
8.	USA (2000 and 2002)	Multi-ethnic study	3827 eligible participants (aged 45–84 years)	Results show that subjects living near major roadways are associated with chronic vascular end-organ damage due to traffic PM pollution	Van Hee et al. (2009)
9.	South Korea (2015)	Korean Community Health Survey (KCHS)	Approximately 100,000 people	The study highlights the indirect social costs of high PM levels in public mental health	Jung et al. (2019)
10.	Ontario (2019)	Cohort	Ontario Population Health and Environment Cohort (ONPHEC) comprising all residents in Ontario for 5 years or longer) as of April 1, 1996	Exposure to $PM_{2.5}$ was positively associated with acute myocardial infarction	Li Bai et al. (2019)

retained by airways and alveoli. The mortality is mainly attributed to fine PM (Brown et al. 2001).

As discussed earlier, the size of the PM plays a key role in determining its toxicity and degree of penetration into the lung and the consequent biological clearance or removal from the body (Donaldson and Stone 2003; Delfino et al. 2005; Ohlwein et al. 2019; Miller 2020; Goel et al. 2021). Coarse PM (PM_{10} and above) settles quickly due to its size and weight; hence, it is mostly collected in the nose and throat (Atkinson et al. 2010) and is generally expelled from the body through normal sneezing and coughing (Cadelis et al. 2014). The nasal deposition is about 20% for $PM_{2.5}$ in an adult at rest, but it can increase up to 40% during exercise (Becquemin et al. 1991). Smaller particles like fine and ultrafine PMs can penetrate deeper in the lungs and alveoli. $PM_{2.5}$ can cause respiratory illness like asthma, COPD, allergic rhinitis, inflammation of the airways, and lungs and are potentially associated with an increased risk of lung cancer (Samoli et al. 2005; Ostro et al. 2006; Sonwani et al. 2022).

9.3 Mechanism of Pulmonary and Extrapulmonary Damage by PM

It was in 1990s when effects of PM on health gained significant attention. A study conducted on healthy human subjects exposed to diesel exhaust particles for 1 h revealed that the number of alveolar macrophages, neutrophils, and T lymphocytes in the bronchoalveolar lavage (BAL) fluid was significantly increased (Rudell et al. 1990). Since then, several studies have been conducted worldwide to demonstrate the mechanism of damage caused by PM (Donaldson et al. 1996; Greenwell et al. 2002; Kelly 2003; Gripenbäck et al. 2005; Yoshizaki et al. 2010; Park et al. 2011; Fiordelisi et al. 2017; Miller 2020; Sonwani et al. 2021a).

Once inhaled, the particles deposit in the airways and lungs and eventually get accumulated in the alveoli where the gaseous exchange takes place. Deposition in the airways mainly depends upon the breathing pattern and size of particles. The deposition can be through **diffusion:** the primary process in which small particles deposit in the airways due to Brownian motion; **sedimentation:** larger particles simply fall out and deposit in the way due to their size and weight; or **inertial impaction:** particles slamming against the walls (Koenig 2000). Due to their larger surface-to-volume ratio, they can carry large number of toxicants and free radicals, thereby triggering the cellular immune response. However, the alveolar macrophages rapidly remove these particles by phagocytosis, but as the particle concentration increases, their phagocytic potential decreases. As a result, these particles remain in the lungs, accumulate there, and cause oxidative damage by different means. The oxidative damage triggers the release of pro-inflammatory cytokines and turn on the cellular immune response. As mentioned earlier, the ultrafine particles (UFPs) can penetrate even deeper into the interstitial spaces and interact with interstitial macrophages, which can further lead to CVDs. Three broad biological pathways namely systemic inflammation, translocation, and

neuroendocrine modulation via autonomic nervous system (ANS) have been described for PM exposure-based extra pulmonary morbidity, particularly in the CVS. These are explained in greater details as below.

(a) **Systemic inflammation:**
This includes free radical production and oxidative damage, inflammation, and cellular homeostasis impairment.

- *Free radical production and oxidative damage:* The surface of PM has various metals like iron, copper, zinc, manganese, and organic compounds like polycyclic aromatic hydrocarbons. These toxic compounds can trigger free radical production, which oxidizes the epithelial cells in the airways and lungs leading to injuries and inflammation (Donaldson et al. 1996; Rahman and MacNee 1996; Greenwell et al. 2002; Kelly 2003). On the other hand, these toxicants also consume the antioxidants creating an oxidant–antioxidant imbalance leading to oxidative stress. The reactive oxygen species (ROS) generated by these toxic substances like free $OH^{\cdot}$ radicals leads to oxidative damage of DNA and other biomolecules in the cells by altering their structure, which over longer period might lead to mutagenesis and even carcinogenesis (Mehta et al. 2008).
- *Inflammation:* The PM inhaled and deposited in the lungs triggers an inflammatory response leading to increased circulatory biomarkers of inflammation such as C-reactive proteins (CRP) and fibrinogen. Studies have reported increased neutrophils, eosinophils, T cells, and macrophage activity in BAL fluid with increased PM concentration (Gripenbäck et al. 2005), (Gordon 2003)**.** The UFP when encounters the epithelial cells in the lung, the cells phagocytose them and more pro-inflammatory cytokines are released, which aggravate the immune response (see Fig. 9.1). Increased production of inflammatory cytokines like interleukin (IL)-4, IL-10, IL-12, IL-13, and interferon (IFN)-γ has been found to be associated with levels of $PM_{2.5}$ and UFP by researches around the world (He et al. 2010; Yoshizaki et al. 2010; Park et al. 2011). These cytokines induce the neutrophils, eosinophils, T cells, and macrophages activity in the lungs and other tissues. Thus, the toxicants first induce the macrophage activity and release of pro-inflammatory cytokines, which in turn trigger the release of more cytokines and chemokines by increasing the cell activities consequently leading to epithelial damage and inflammation in the lungs leading to systemic inflammation (He et al. 2010; Yoshizaki et al. 2010).
- *Cellular homeostasis impairment:* Another mechanism suggested for damaging effects of PM is by damaging the cellular homeostasis by modulating the Ca^{2+}-mediated pathways. Increased ROS production induced by PM along with declined antioxidant level results in increased lipid peroxidation, which in turn increases the intracellular Ca^{2+} level. Researchers have suggested that intracellular modulation in Ca^{2+} level induced by increased ROS production might trigger cellular damage and even apoptosis and necrosis (Brown et al. 2004; Xing et al. 2011).

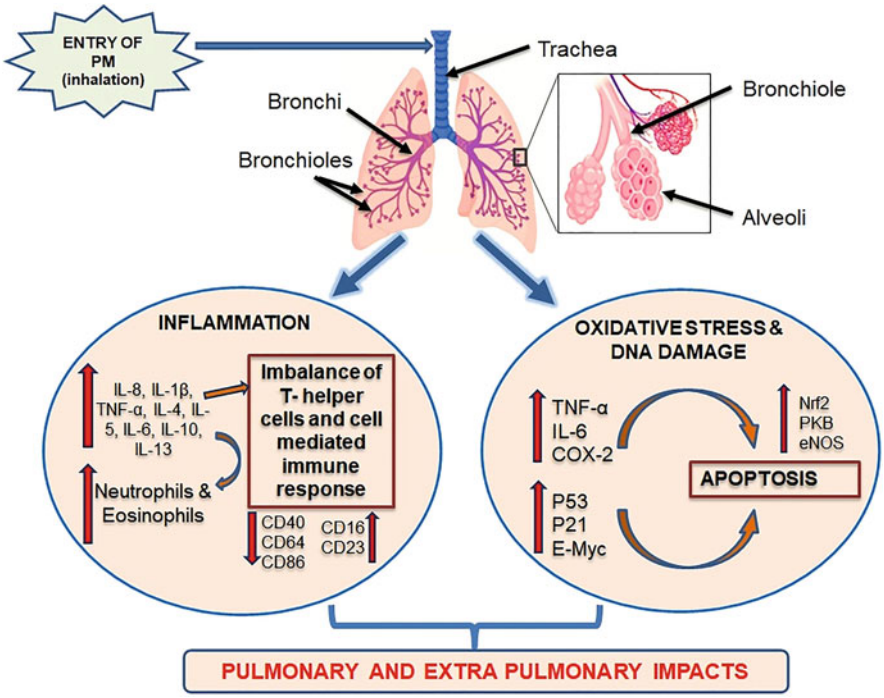

Fig. 9.1 Pulmonary implications of PM exposure: PM induces activation of neutrophils and eosinophils by triggering the pro-inflammatory cytokines interleukin (IL)-8, IL-1β, IL-5, and tumor necrosis factor (TNF)-α. These further induce release of more inflammatory biomarkers like IL-4, IL-6, IL-10, and IL-13, which aggravate the pulmonary inflammation and alter the immune response by altering the T-helper (Th) cells. PM also induces oxidative stress and DNA damage due to increased TNF-α, IL-6, and COX-2, which through various signaling pathways leads to apoptosis and necrosis. Increased ROS production and lipid peroxidation induced by PM cause increased intracellular Ca^{2+} conc., which impairs the cellular homeostasis and further leads to cell death

In the context of CVS, Ca^{2+} is established to be vital for excitation–contraction coupling and regulating the contractile strength of the cardiomyocytes. Studies have shown that oxidative stress induced by PM impacts the regulation of Na^{+}–Ca^{2+}exchange protein and L-type Ca^{2+}channel protein (Coetzee et al. 1994; Chiamvimonvat et al. 1995). These changes result in the enhanced levels of cytosolic calcium and hence the reduced SR stores of calcium ion. Consequently, there is reduction in cardiac contractility and increased Ca^{2+}-activated nuclear signaling potentially leading to cardiac hypertrophy (Fiordelisi et al. 2017).

(b) **Translocation**

PM has been found to cross the pulmonary epithelium and enter the blood circulation by various research groups using animal model studies (Miller 2020; Nemmar et al. 2001, 2002) conducted studies on hamsters and humans,

respectively, wherein the subjects were exposed to radioactively labeled experimental UFPs. The results demonstrate a rapid and statistically significant diffusion of experimental UFPs into the systemic circulation from the lungs. Oberdörster et al. (2004) performed another interesting study on rats to determine if the inhaled ultrafine PM translocated to extrapulmonary sites and demonstrated an effective translocation of ultrafine experimental particles to the liver within 1 day post-exposure by inhalation. These studies highlight the possibility that translocated particles may trigger responses in various extra pulmonary organs with devastating potentials in host depending on their chemical composition. Moreover, there have been speculations that if the pulmonary barrier can be crossed, what could be the implications for blood–brain barrier or mother-to-fetus transmission? Shou et al. (2019) have written an excellent review on impacts of blood–brain barrier crossing by PMs and its association with Alzheimer's disease. Interested readers can refer to this review for more details. Placental transmission is still under investigation, and nothing conclusive has yet been reported.

(c) **Neuroendocrine Modulation via Autonomic Nervous system (ANS)**
ANS plays a key role in controlling the cardiac functions such as heart rate (HR) and heart rate variability (HRV) that may act as predictors of cardiac death in the event of heart failure (HF). Incidentally, PM exposure is associated with impacts on HRV, resting HR, and blood pressure that are suggestive of activation of the sympathetic nervous system (Hoek et al. 2001). Pope et al. have demonstrated that PM exposure leads to rapid HRV decrease because of decreased parasympathetic input signal to heart (Pope III et al. 1999). This results in activation of sympathetic nervous system, increases events of cardiac arrhythmia, and consequently the probability of CV morbidity and mortality (Brook et al. 2004).

9.4 Impact of PM on Respiratory System: Experimental and Epidemiological Evidences

This section will primarily focus on the epidemiological and experimental evidences showing the effect of short-term and long-term exposure of PM on the airways and lungs. It is well established that PM exposure can cause serious respiratory illness, which includes allergic rhinitis, inflammation in the airways, asthma, and COPD. $PM_{2.5}$ exposure is associated with severe asthma exacerbations (Byers et al. 2016), number of wheezing episodes, increased risk of cough, shortness of breath, chest tightness (Dunea et al. 2016; Noh et al. 2016), and other respiratory symptoms. All these diseases are associated with airways and systemic inflammation and oxidative stress (Yadav and Saini 2016; Saini and Yadav 2019 a & b; Santus et al. 2014; Al-shair et al. 2011; Garcia-Rio et al. 2010; Sinden and Stockley 2010), which is the most common mechanism of damage caused by PM (refer to the section—mechanism of damage).

There are number of studies showing the increased incidences of respiratory illness and mortality with increased concentration of PM in the air. The epidemiological studies conducted worldwide in the past two decades have demonstrated a strong correlation between PM concentration in the air and respiratory illness and mortality (Brunekreef and Holgate 2002). In Canada and the USA, long-term exposure to $PM_{2.5}$ was observed to markedly decrease the life expectancy and raise the chances of cardiopulmonary morbidity and mortality and cases of lung cancer (Schwartz 2000; Sonwani and Kulshrestha 2016; Franklin et al. 2008). A study conducted in Estonia (Europe) in 2011 demonstrated that exposure to high concentration of PM decreased average life span (Orru et al. 2011). Data suggest that the correlation is even more in the elderly, pregnant women, infants, and patients with history of cardiopulmonary problems (Huynh et al. 2006; de Oliveira et al. 2012). Correia et al. (2013) in a 7-year study from 2000 to 2007 found that average life span was extended by 0.35 years for every 10 $\mu g/m^3$ drop in PM concentration.

Pope et al. in a large study on 500,000 adults in large and populous metro cities observed that, overall, cardiopulmonary diseases and lung cancer mortality increased by 4%, 6%, and 8%, respectively, for very 10 $\mu g/m^3$ rise in $PM_{2.5}$ concentration (Pope III et al. 2002). A large cohort study on 1.2 million American adults conducted from 1982 to 2008 by American Cancer Society revealed that mortality due to lung cancer increased by 15–27% when PM concentration raised by 10 $\mu g/m^3$ (Turner et al. 2011). Similarly, in Europe, an analysis of 17 cohort studies in 2013 revealed that lung cancer rates were significantly increased with increased PM concentration in the atmosphere (Raaschou-Nielsen et al. 2013). Burnett et al. in 2018 analyzed data from 41 cohort studies from 16 countries, which revealed strong association between $PM_{2.5}$ exposure and non-accidental mortality.

Regarding the Asian countries, multiple epidemiological studies demonstrated that Asian countries are probably the most affected due to air pollution, especially the developed and the developing ones. A study conducted on 63,500 people in Japan in 2011 observed increased incidences of mortality from respiratory illness, particularly pneumonia and lung cancer with long-term exposure to PM in the air (Katanoda et al. 2011). Studies conducted in China in past decade also demonstrate a strong correlation between ambient air pollution and increased mortality (Huang et al. 2009; Yang et al. 2012). In a recent study, Wu et al. (2019) reported increased exacerbation in children with asthma due to increased PM exposure. India is one of the most polluted countries in the world where most of the states do not meet the criteria of ambient air quality of less than 10 $\mu g/m^3$ as recommended by WHO (Cohen et al. 2005). According to an estimate, more than 70% of the population of India is exposed to poor air quality and higher PM concentration than recommended level. In 2017, 1.24 million deaths were caused due to air pollution, of which 0.67 million were due to ambient PM pollution. Around 8% of the total disease burden in India and 11% of premature deaths in people younger than 70 years could be due to air pollution, most of which can be attributed to PM (Balakrishnan et al. 2019). A timeline of major epidemiological studies conducted worldwide in the past two decades on PM-related respiratory illness and mortality is presented in Table 9.1.

Besides number of epidemiological studies demonstrating the adverse effects of PM on the human health, multiple experimental studies in vitro and in vivo have also described the specific impact on human respiratory system. Studies have reported increased macrophage tumor necrosis factor (TNF)-α expression in the alveoli macrophage cell lines with increased PM concentration (Jalava et al. 2007). Phipps et al. (2010) performed an experiment on two groups of mice for 5 weeks, exposing one group to the air (control) and the other to the cigarette smoke (exposed). The intra-tracheal injections of *Streptococcus pneumoniae* were given, and it was observed that bacterial counts in the lungs were 4 times higher in the exposed group after 24 h of exposure as compared to the control group. Increased innate and adaptive immune response both in vitro and in vivo induced by alveolar macrophage activity on exposure to ambient PM was observed by Miyata and van Eeden (2011). All these studies suggest a strong correlation between PM exposure and respiratory diseases. In the next section, various implications of different types of PM on respiratory disorders are summarized (Fig. 9.1).

9.4.1 Declined Pulmonary Functions

Edginton et al. (2019) conducted a systematic review and meta-analysis of major studies assessing the impact of outdoor PM and lung function in adults. They observed that a 10 μg/m^3 difference in short-term exposure to $PM_{2.5}$ was found to be associated with a decline of 7.02 mL in forced expiratory volume in 1 s (FEV_1). Similarly, a 10 μg/m^3 increase in long-term exposure to PM_{10} was significantly associated with a decline of 8.72 mL annual change in FEV_1. The findings infer that acute exposure and long-term exposure to outdoor PM are associated with decline in respiratory function in healthy adults. Gaffin et al. (2017) reported a 5% reduction in FEV_1/forced vital capacity (FVC) ratio for every 10 ppb increase in NO_2 concentration.

9.4.2 Activation of Neutrophils and Eosinophils in the Airways

Coarse PM ($PM_{2.5–10}$) exacerbate asthma and allergic rhinitis by inducing the pro-inflammatory cytokines IL-8, IL-5, IL-1β, and TNF-α in the epithelial cells of the airways (Ozturk et al. 2017). These pro-inflammatory cytokines induce the activation of eosinophils and neutrophils, which trigger the inflammatory response (McGee et al. 2015). In a cross-sectional study on 18 healthy human subjects, Loh et al. (2006) observed significantly raised levels of myeloperoxidase, neutrophil elastase activity, and IL-8 in the sputum due to inhaled endotoxins.

9.4.3 Severe Pulmonary Inflammation

The coarse PM induces pulmonary inflammation by triggering the neutrophils and eosinophils through pro-inflammatory cytokines as discussed earlier. The UFPs on the other side can trigger severe pulmonary and systemic inflammation as these can be detected in the blood immediately after inhalation due to their high absorptive power. These can even remain in the lungs for several hours after inhalation and thus can induce eosinophil and macrophage activation and trigger epithelial damage in the lungs (Li et al. 2009; Renwick et al. 2004) (refer to section inflammation in the mechanism of damage by PM for more details).

9.4.4 Activation and Alteration of T-Helper-Mediated Immune Response

Both the coarse and fine PMs are able to induce T-helper (Th)2 and Th17-mediated immune response (Burbank and Peden 2018). This is mediated by PM-induced suppression of IL-12 and IFN-γ and increasing IL-10 levels in the antigen-presenting T cells. Exposure of coarse PM was found to induce the Th2-mediated immune response by increased IL-10 secretion in the asthmatic mice in an experimental study conducted by Chan et al. (2006). The ultrafine PMs have also been shown to induce the similar kind of immune response by activating IL-4, IL-5, IL-6, IL-10, and IL-13 and proliferation of lymph node cells in the peri-bronchial region (de Haar et al. 2006; Huang et al. 2017).

9.4.5 Oxidative Stress, Apoptosis, Epithelial Damage, and Lung Dysfunction

Fine and ultrafine PMs trigger the production of ROS causing oxidative stress, which is also a cause and consequence of asthma, COPD, and rhinitis (Yadav and Saini 2016; Santus et al. 2014; Al-shair et al. 2011; Garcia-Rio et al. 2010). A study by Becker et al. (2005) found that fine PM triggers oxidative stress by inducing IL-6, TNF-α, and cyclooxygenase-2 (COX-2) in the bronchial epithelial cells and alveolar macrophages. Deng et al. (2014) revealed that apoptosis and epithelial damage leading to lung dysfunction are induced by fine and ultrafine PM through TNF-α and caspase signaling pathways. Other than that, p53, c-Myc, and p21 signaling pathways are also shown to be induced by PM exposure leading to cell death in lung epithelial cells leading to impaired lung function (Huang et al. 2014).

9.5 Impact of PM on CVS: Experimental and Epidemiological Evidences

Animal experiments and controlled human exposure studies have played a critical role in determining the impacts of PM (Miller et al. 2017). Although inhalation is considered as the most likely route of exposure to PM, the organs affected are associated with not only the pulmonary system but also extrapulmonary system. Of these, extrapulmonary effects on CVS attract special attention as highlighted in Table 9.2. Since all organs are interconnected with each other intimately by the circulating blood, studies on the extrapulmonary effects often require investigating the basic blood biochemical parameters and gross pathological indicators. In this context, studies have consistently shown nanoparticles to be capable of crossing alveolar barrier and to settle in extrapulmonary organs. In a landmark study, Miller et al. (2017) demonstrated translocation of inhaled gold nanoparticles using human subjects. The translocation of PM from the respiratory system to other organs has far-reaching implications in nanotoxicology (Raftis and Miller 2019). In this section, we focus on the prominent impacts of PM exposure on CVS (Fig. 9.2).

A significant study was carried out by Dockery et al. in 1993 to investigate the correlation between PM and the number of hospital admissions/deaths associated with CVD in six North American cities. The results of the study unraveled evidences

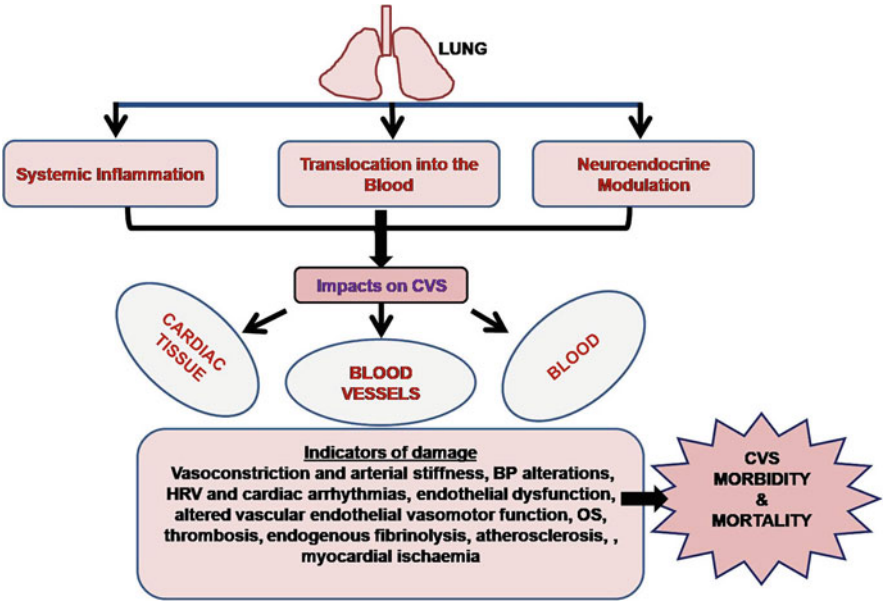

Fig. 9.2 A diagrammatic representation of PM exposure-associated impacts on cardiovascular (CVS) via the three major pathways. The major elements affected in CVS mentioned in circles in the diagram. All these effects ultimately increase the risk factors in CVS morbidity and mortality. *BP* blood pressure, *HRV* heart rate variability, *OS* oxidative stress

in support of a strong association between $PM_{2.5}$ levels and related events of CV morbidity and mortality. Hence, this study acted as an eye-opener for the ill effects of ambient air pollution. Interestingly, another study in the USA indicated an increase in life expectancy as the ambient fine PM levels decreased (Pope III et al. 2009). This observation is a ray of hope and encourages toward remediation measures to reduce ambient air pollution levels.

In addition to these, there have been several significant studies indicating a strong correlation between exposure to PM and CVD mortality (Pope III et al. 2004; Laden et al. 2006; Ki-Hyun et al. 2015). American Heart Association in its updated scientific statement titled "Particulate Matter Air Pollution and Cardiovascular Disease" in 2010 reinforces the observations of several research studies that there is a significant causal relationship between $PM_{2.5}$ exposure and the observed CVS morbidity and mortality. The mechanism occurs most likely through the systemic inflammation post-exposure and also by possible direct translocation of the PM into the blood circulation. The report reveals that $PM_{2.5}$ exposure ranging from a few hours to weeks is capable of triggering CVS-related mortality and related nonfatal events. It is further reported that long-term exposure (i.e., up to a few years) leads to a greater risk of cardiovascular mortality and also adversely affects life expectancy. CVS morbidities resulting from PM exposure can be measured by various indicators pertaining to the different structural and functional components, i.e., cardiac tissue, blood vessels, and blood. Below are the main parameters used for such studies.

9.5.1 Endothelial Dysfunction

On exposure to various stimuli, the endothelial cells undergo endothelial activation as a protective response to injury. One of the potent stimuli for endothelial activation is ambient PM exposure like cigarette smoke, diesel exhaust, and occupational fumes (Robbins Pathology, ninth Ed.). Brook et al. (2004) in their study on healthy adults have demonstrated impaired flow-mediated vasodilatation (FMD), after exposure to ambient PM. They also observed that the magnitude of BP alteration is significantly associated with the $PM_{2.5}$ carbon content. FMD is a technique that evaluates normal endothelial function by assessing the brachial artery vasodilatation in response to reperfusion after ischemia, a phenomenon predominantly driven by NO release from endothelial cells. Real-world studies indicate that even low concentrations of PM have negative association between FMD and ambient PM in human volunteers (Dales et al. 2007). Another study has demonstrated that diesel exhaust inhalation results in adverse impacts on vascular and endothelial function in humans as early as within 2 h of exposure. They also observed persistent negative impacts selectively on endothelium-dependent vasodilatation 24 h after exposure (Törnqvist et al. 2007). Animal and controlled exposure studies in humans have shown acute endothelial response measured as elevated plasma endothelin-1 levels due to diesel exhaust exposure (Vincent et al. 2001; Peretz et al. 2008). Another approach to study the effect of PM on endothelium is to assess changes in NO bioavailability. Animal studies have demonstrated that diesel exhaust inhalation

causes enhanced expression of endothelial NO synthase (NOS) and increased plasma nitrate and nitrite concentrations. These observations are indicative of impairment of the normal NO pathway in the exposed animals (Knuckles et al. 2011). A systematic review of literature by Yang et al. in 2018 revealed positive association between ambient air pollution and the observed increase in BP and hypertension in humans.

9.5.2 Vasoconstriction, Arterial Stiffness, and BP

Studies have shown an association of PM with increase in vasoconstriction wherein air pollution exposure in individuals was measured. Lundback et al. (2009) demonstrated that after exposure to dilute diesel exhaust, there is an immediate and transient increase in the central arterial stiffness along with an increase in arterial tone and vasoconstriction. On similar lines, real-world study in Italy has shown that children residing near major roads exhibit significantly higher central arterial stiffness than in those living farther away from the same (Iannuzzi et al. 2010). PM exposure has been regularly associated with small, but significant, elevations in blood pressure. Brook et al. (2010) demonstrated an increase in diastolic and mean arterial blood pressure strongly associated with the concentration of airborne PM within 2 h after the exposure (Urch et al. 2005; Brook et al. 2010). A case–control study in China, where the urban air pollution levels are high, has shown exaggerated increase in exercise-related blood pressure in healthy volunteers and in patients with coronary heart disease. Interestingly, this effect was capable of being reversed when subjects used an efficient facemask as a preventive measure from inhaling particulate air pollution (Langrish et al. 2009, 2011). Hence, all the above studies indicate that short- and long-term exposure to PM pollution can adversely impact the overall vascular function particularly the endothelial function, which governs other hemodynamic parameters.

9.5.3 Arrhythmia, Heart Failure, Cardiac Remodeling, and MI

The most common cause of arrhythmias is ischemic injury as it leads to biochemical alterations due to impairment of normal aerobic metabolism within a few seconds. As a result, there occurs inadequacy of high-energy phosphates like ATP and creatine phosphate (CP) and high levels of potentially noxious biochemical metabolites such as lactic acid. As a result of such events, functional loss potentially leading to heart failure typically precedes before the actual death of myocytes. Heart rate variability (HRV) is a parameter that indicates alterations in cardiac autonomic function and is derived from the detailed analysis of heart rhythm from electrocardiogram (ECG) recordings. Several epidemiological studies have indicated positive association between ambient PM exposure and increase in subject hospitalizations exhibiting conditions like MI, heart failure, and arrhythmias (Brook et al. 2010; Langrish et al. 2012). Also, several studies have demonstrated that exposure to PM

pollution (environmental or occupational) leads to a significant reduction in HRV and consequently the risk of sudden cardiac death (Pope III et al. 1999; Gold et al. 2000; Magari et al. 2001). Controlled human exposure studies have played a significant role in exploring this area further. One such study on healthy elderly subjects who were exposed for 2 h to concentrated ambient air pollution particles (CAPS) demonstrated reduced HRV immediately after the exposure and the impairment extended until 24 h post-exposure (Devlin et al. 2003). In a real-world study in Beijing, it was demonstrated that the use of an efficient face mask had protective effect against PM exposure as was indicated by the improvement in HRV in healthy subjects and subjects with coronary heart disease (CHD) (Langrish et al. 2009, 2011). On similar lines, Peters et al. in 2000 demonstrated that in patients with implanted cardioverter defibrillators exposure to PM particularly NO, CO, black carbon, and fine particle mass was associated with potentially life-threatening arrhythmias. Controlled exposure study in men with CHD revealed increased ST-segment depression and ischemic burden while performing a standardized physical exercise on bicycle, on exposure to diesel exhaust as compared to the experimental control exposure with filtered air (Mills et al. 2007). It has also been shown by studies that exposure to black carbon, which is a measure of traffic-derived PM pollution, causes an increase in ST-segment depression risk in elderly patients (Gold et al. 2000). A large-scale epidemiological study of approximately five million Canadian adults residing in Ontario shows that long-term exposures to $PM_{2.5}$ are positively associated with the increased incidences of congestive heart failure and acute myocardial infarction. This study also indicates that the positive associations of CHF with all the pollutants studied, i.e., $PM_{2.5}$, NO_2, O_3, and redox-weighted average of NO_2 and O_3 (O_x), were greater in magnitude in the elderly as compared to the young individuals. This observation may be explained by the generally reduced responsiveness to ANS stimuli in the elderly subjects between younger and older people. An epidemiological study on students in Taipei, Taiwan, revealed that PM in urban air pollution is associated with decrease in HRV parameters. The researchers in this study also recorded elevation in blood 8-hydroxy-2′-deoxyguanosine (8-OH-dG) and C-reactive protein (CRP). These observations are indicative of the presence of inflammation, OS, blood coagulation, and ANS dysfunction simultaneously in the subjects (Chuang et al. 2007). In a multiethnic study of adults wherein the subjects had no previous clinical cardiovascular disease, left ventricular mass index (LVMI), an indicator of hypertrophy, was measured by cardiac magnetic resonance imaging technique. The study revealed higher LVMI in subjects living close to major roadways, suggesting an association between cardiac damage from a traffic-related environmental exposure (He et al. 2010). Animal experiments have demonstrated that PM exposure leads to collagen accumulation in healthy rat hearts and caused vascular remodeling and right ventricular hypertrophy in mouse model of heart failure (de Oliveira-Fonoff et al. 2017). This finding highlights the heightened risk from air PM pollution to the heart patients. Wold et al. in 2012 carried out noteworthy in vitro and in vivo experimental studies to examine the long-term impacts of PM exposure in a mouse model of heart failure. In the in vivo study, mice were administered 9 months of exposure to $PM_{2.5}$ followed by assessment of

various parameters pertaining to cardiac contractility and remodeling. The results indicated cardiac dysfunction and related compensatory phenomenon such as cardiac hypertrophy, profibrotic gene expression upregulation, and Ca2+ reuptake reduction.

9.5.4 Thrombosis and Coagulation

Several new studies have shown the impact of PM exposure on hemostatic markers such as factor VII, fibrinogen, platelet count, and v-WF (Brook et al. 2010; Miller 2020). Epidemiological studies have indicated that PM exposure is associated with the occurrence of atherothrombosis, thrombotic stroke, and thromboembolism (Franchini et al. 2012)**.** Another study used a semi-experimental design wherein the subjects were exposed to five locations in the Netherlands for definite time periods to provide PM exposure contrasts. The exposure was followed by assessment of various biomarkers such as CRP, fibrinogen, platelet counts, v-WF, and TPA/plasminogen activator inhibitor-1 complex. The results revealed that the composition of PM affects thrombotic biomarker levels in the subjects (Strak et al. 2013). On similar lines, a literature review focusing on the relative prothrombotic impacts of inhalable airborne metal exposures resulting in lower limb venous thromboembolisms in humans demonstrates positive association. It concludes that such metallic PM exposure can activate or alter several prothrombotic and oxidative biomarkers (Signorelli et al. 2019). Controlled exposure studies in healthy human volunteers show that inhalation of PM (in the form of DE) is associated with increased blood coagulability (Lucking et al. 2008).

9.5.5 Atherosclerosis

For the study of atherosclerosis, measurement of carotid artery intima–media thickness (CIMT) is an effective and tested method (Robbins Pathology, ninth Ed.). Künzli et al. (2005) is reported to be the first study to determine the possible association between atherosclerosis and air pollution. The study included CIMT measurements of subjects with biomarkers (such as high LDL or homocysteine levels) that indicated predisposition to future CVDs. This study revealed that PM exposure led to a chronic vascular response and hence may be a powerful contributing factor in developing atherosclerosis in the long run. Further experimental data analysis has shown that here that PM exposure not only favors atherosclerosis, but it is also seen that the smaller-sized particles have greater proatherogenic properties as compared to coarse particles (Araujo et al. 2008; Araujo and Nel 2009).

Also, atherosclerosis is a pathological phenomenon that involves an intricate interplay of several factors (particularly the structural and functional aspects of endothelium and inflammatory components). Therefore, enhanced levels of biomarkers for oxidative stress and inflammation are strong indicators of atheroma formation as a result of cellular dysfunction. Hence, assessing oxidation levels in

blood by various techniques gives information regarding the relative role of certain key players in atherosclerosis (Kelly and Fussell 2017; Araujo and Nel 2009). Lund et al. (2011) in their controlled human exposure study report increased plasma-soluble lectin-like oxidized low-density lipoprotein receptor (LOX-1) levels on DE exposure. Enhanced LOX-1 levels can play a role in the accumulation of lipids within the vascular wall and hence have implication in the development of atherosclerosis. In another significant study, researchers have demonstrated that that exposure to concentrated ambient particles led to an increase in aortic atheroma in mice as measured by magnetic resonance imaging (Sun et al. 2005). In another animal model study, Suwa et al. (2002) demonstrated that in the Watanabe heritable hyperlipidemic (WHHL) rabbits exposed to repeated urban PM exhibited systemic inflammatory response and markers that are associated with atherosclerotic progression. Further, in a study on mice that were experimentally exposed to dilute DE an increase in oxidative stress markers was observed (Bai et al. 2011). In a real-world study in China, evidences have been found for the possible associations between chemical constituents of PM and alterations in oxidative stress biomarkers known to be characteristic of atherosclerosis (Wu et al. 2015). Some other studies have also reported that long-term exposure to ambient PM pollution (traffic-derived) may be a significant risk factor in causing CVS morbidity and mortality due to atherosclerosis (Hoffmann et al. 2007; Lambrechtsen et al. 2012).

9.6 Impact of PM on CNS: Experimental and Epidemiological Evidences

More and more experimental and epidemiological studies have strongly hinted that PM pollution is a source of neuroinflammation and hence is strongly associated with neuropathology, especially via ROS pathways. Translocation of PM to the brain tissue has been established by several studies. A review of experimental studies revealed various potential mechanisms for the entry of PM into brain tissue (Block and Calderón-Garcidueñas 2009; Illum 2000; Oberdorster et al. 2002). Significant to this context, several drug compositions have been found to reach the CNS after being administered through the nasal cavity. Three prominent pathways (Fig. 9.3) established for these observations are as follows:

1. **Across the blood–brain barrier (BBB):** The UFP deposited in the respiratory tract after translocating into the circulatory system reaches brain and crosses the BBB.
2. **Via olfactory nerve:** This path is specific for the UFPs that reach the olfactory bulb region of brain. The deposits in the nasal cavity olfactory mucosa can directly migrate into the olfactory nerve and finally reach the olfactory bulb in brain.
3. **Into CSF via olfactory mucosa and ethmoid bone:** This pathway is known to occur through the paracellular or perineural transport mechanisms across the olfactory mucosa and the ethmoid bone of skull into cerebrospinal fluid (CSF).

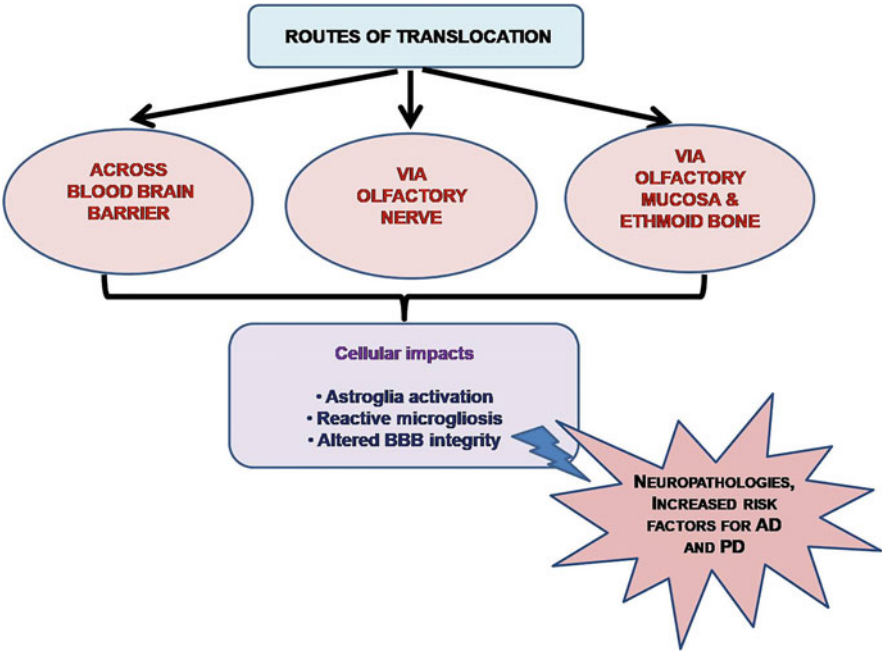

Fig. 9.3 Three major routes of translocation of PM into the CNS. Impacts on the cellular components of brain involve three major targets, i.e., astroglia, microglia, and the cells of blood–brain barrier (BBB). *AD* Alzheimer's disease, *PD* Parkinson's disease

These translocating PMs cause massive pathological consequences in the nose–brain barrier histology and CNS. In a prominent study in Mexico where pollution levels are high, ultrafine pollutant particles have been shown to cause inflammatory and neuropathological events in feral dogs (Calderón-Garcidueñas et al. 2002). This is reported to be one of the first studies to explore the implication of air pollution in neurodegenerative disease. The feral dogs that were naturally exposed to the high pollution levels in Mexico exhibited significant oxidative damage and enhanced DNA damage in the various regions of brain.

Epidemiological studies have indicated significant associations between air pollutant levels and the occurrence of ischemic stroke mortality. Such findings hint towards acute CNS neuropathogenesis potentially induced by PM (Hong et al. 2002). Another epidemiology study based on measurement of mRNA levels of indicators of pathological damage, namely cyclooxygenase-2, IL-1β, and CD14 in target human mortality brain samples, reported neuroinflammation, altered immune response in brain, and accumulation of markers for Alzheimer's and Parkinson's diseases (Calderón-Garcidueñas et al. 2008).

9.6.1 PM-Induced Neuropathology: A Cellular View

Over time, observations by various research studies resulted in speculations about the cell types that played prominent role in mediating the PM-induced CNS histopathology. The key players emerged to be astroglia, microglia, and the cells of BBB.

Astroglia has an important role in maintaining the structural and functional integrity in normal brain. Defects in astrocytes have been found to be implicated in several neurological disorders. Injuries to CNS result in astroglia activation (Seifert et al. 2006). Studies have revealed that chronic exposure to high air pollution levels cause activated astroglia as indicated by enhanced glial fibrillary acidic protein (GFAP) expression (Calderón-Garcidueñas et al. 2008).

Microglia are the brain's resident innate immune system cells and are also activated like astroglia in the conditions of neurodegeneration such as AD and PD (McGeer et al. 1988).

Elevated expression levels of CD14 observed in the human autopsy studies indicate infiltrating monocyte activation or that of microglia cells after exposure to air pollution. Block et al. (2004) reported in their in vitro study based on DE particles reported that microglia recognize and respond to PM. The activation was determined by assessing changes in cell morphology, superoxide production, nitric oxide (NO) levels, etc. The activation of microglia is a beneficial homeostatic phenomenon. However, on constant exposure to PM it may transform into a chronic pro-inflammatory response and oxidative stress in CNS and may consequently drive neurodegenerative leading to a condition called reactive microgliosis (Block et al. 2007).

The Blood–Brain Barrier is a unique physical and chemical barrier in brain that serves as a protection from external agents or insult such as toxins, small drug molecules, ions, and macromolecules. Essentially, it is composed of a network of capillaries in the brain parenchyma. Experimental studies have shown the detrimental impacts of Al nanoparticles on BBB measured as increased oxidative stress, reduced BBB endothelial cell viability, altered mitochondrial potential, increased oxidative stress, and reduced tight junction protein expression (Chen et al. 2008). In another in vitro study on whole brain rat capillaries, it was demonstrated that PM exposure leads to production of cytokines and ROS, and decreased expression of tight junction proteins (Hartz et al. 2008).

Hence, with compelling experimental evidences, the risk factor assessment of PM assumes much greater importance in light of the observed neuropathies, especially those linked to AD and PD.

9.7 Preventive Measures and Amelioration

It is a well-known fact that exposure to PM induces oxidative stress and inflammation, which further leads to DNA damage and apoptosis. Understanding the mechanism of damage is crucial for developing the effective therapeutic approaches. Once deposited in the lungs, most particles get removed through different clearance

mechanisms. Insoluble particles that get deposited on the ciliated airways are mostly removed by mucociliary activity within 24–48 h (Schlesinger 1990). The clearance from the pulmonary region is usually carried out by the action of alveolar macrophages, which act rapidly, but their removal from the lungs can take several weeks (Pepelko 1987). The remaining particles get deposited in the alveoli and trigger the endothelial inflammation and ROS generation, which further leads to DNA damage and various cardiopulmonary diseases.

Though different therapeutic approaches such as antioxidant therapy with N-acetylcysteine (NAC), superoxide dismutase (SOD), and glutathione peroxidase (Gpx) have been suggested by researchers after experimental studies on animals to counter the ill effects of PM on human health (Cui et al. 2015), it has also been revealed by studies that several nutritional supplements and antioxidant vitamins such as vitamin C, E, A, folic acid, β-carotene, and omega-3 fatty acids are capable of modulating the immune response generated by them (Erickson et al. 2000; Kris-Etherton et al. 2003; Singh et al. 2005). But, for concrete therapeutic approaches for the diseases caused by PM exposure, more research including long-term preclinical and clinical trials is needed.

Although absolute amelioration of the ill effects of PM is a long-term task and so is controlling the air pollution, several preventive measures have been suggested by various real life and epidemiological studies. Pope III et al. (2009) have indicated increased life expectancy in context of CVS diseases in instances of decreased PM exposure preventive measures to reduce PM exposure include staying indoors, reducing outdoor activities, or wearing a mask while going outside when the concentration of PM or smog in the air rises above the standard levels, for example, during severe winters, construction activity, or in case of natural or man-made disasters. Further, a healthy lifestyle, diet rich in antioxidants and vitamins and reducing indoor PM levels by using filters or chimneys during cooking can also help reducing the oxidative stress induced by PM. For a large-scale and long-term solution, important steps by way of updating government policies are required such as for reducing ambient PM levels by adopting eco-friendly measures (fuels and industrial processing practices) by public and private stakeholders worldwide. The urban pollution needs to be reduced to standardized levels for maintaining health standards of populations.

As is evident from the detailed account of the impacts of PM on various aspects of CVS function as discussed in the abovementioned sections, it is imperative that prevention is better than cure. There is clear evidence of the ill effects of PM exposure on human health from the animal model and the epidemiological studies mentioned under the specific sections of this chapter. Hence, there exists an urgent need to reduce the standard levels of PM, particularly the ambient PM by adopting suitable approaches for sustainable development by the public sector, private agencies, and all stakeholders.

9.8 Conclusion

Evidences from multiple studies depict that both short-term exposure and long-term exposure to the fine PM above the permitted standards have adverse health effects. PM enters the body through airways into the cardiovascular system and induces a series of pulmonary and cardiovascular events. In the absence of adequate clearance mechanism, it reaches other organs and influences the autonomic nervous system. As a result, the rate of worldwide cardiopulmonary and neural morbidity and mortality due to air pollution has increased significantly. Besides several scientific data and clinical studies, there is dearth of absolute therapeutic approaches to ameliorate the ill effects of PM. The major limitation with these studies is the variability in the data due to variation in the pollution levels and individual exposure to the PM. Due to such variability, the remarkable link between individual pollutant and health outcomes could not be established. To assess the health effects of individual pollutants, there is a need to develop methodologies and design the studies to further quantify the effects of exposure to different toxic combinations and individual pollutants. The antioxidant supplementation can prevent the effects to some extent as shown in various experimental studies in vitro and in vivo. But an effective therapeutic approach is still needed to be explored.

Albeit preventive measures to protect oneself from the detrimental effects of PM could be beneficial, but in large effective measures to control air pollution are pivotal. Governments worldwide in the recent decade have introduced automobiles with reduced pollutant emissions and electric vehicles. These interventions have been suggested to be significantly effective in mitigating the air pollution and its adverse effects on human health capping the incidences of hospital admissions and CVDs due to air pollution to some extent (EPA n.d.). Still, there is a need for effective emission reduction policies and their implementation combined with epidemiological studies to have appropriate control measures for PM mitigation. Further, a better understanding of the mechanism of damage induced by PM is also crucial for the development of improved therapeutic methods to treat the PM-induced diseases.

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Impacts and Responses of Particulate Matter Pollution on Vegetation

10

Priyanka Sharma and Pallavi Saxena

Abstract

Atmospheric pollution is one of the vital issues since last 10 decades due to rapid industrialization and urbanization. Among all the air pollutants, particulate matter (PM) is one of the major hazardous pollutants to both human and plant health. The significant variation noted in the ambient atmosphere because of particulate matter load in urban region has a great impact on the morphological, biochemical and physiological nature of plants and its responses. The present chapter reviews about the significant impact of PM pollution on vegetation and other plant species by taking the specific sections into consideration like morphological characteristics as leaf area, leaf number, stomata structure, flowering, growth and reproduction and some biochemical parameters like pigment content, enzymes, ascorbic acid, protein, sugar and physiological parameters such as pH and relative water content. Moreover, the role of plant species in biomonitoring studies to evaluate the tolerance and sensitivity will further help in greenbelt development and landscape planning.

Keywords

Plant species · Particulate matter · Morphology · Physiology and biomonitoring

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_10

10.1 Introduction

Particulate matter has been a pivotal part of earth's atmosphere and played important role in maintaining atmospheric processes like heat budget (Fuzzi et al. 2015; Plocoste and Pavón-Domínguez 2020; Sonwani et al. 2021a), acting as condensation nuclei for cloud formation (Spracklen et al. 2011; Brooks and Thornton 2018; Ching et al. 2019) and providing surface for chemical reaction (Vione et al. 2006). However, upcoming of modern civilization has disturbed the natural allowable limit of particulate matter and increased its concentration to dreadful levels. Other than natural sources like volcanic eruption, forest fire and seal salt spray, anthropogenic sources like industrial processes, thermal power plant, biomass burning, vehicular emission and construction activities (Zhang and Smith 2007; Gieré and Querol 2010; Guéguen et al. 2012; Guttikunda and Goel 2013; Saxena et al. 2021a) have contributed high level of particulate pollution at local and global scales.

Today, particulate pollution is a complex problem owing to its size segregation (coarse: $\leq$10 μm and fine: $\leq$2.5 μm) and chemical composition (sulphate, nitrate, metallic, biogenic, etc.). Due to various combustion and physical processes, the fine particles are released in the environment, which can be easily taken up by human respiratory system and result in various health implications like cardiorespiratory diseases, asthma, emphysema and bronchitis (Davidson et al. 2005; Bates et al. 2015; Kim et al. 2015; Sonwani et al. 2021b), whereas the chemical composition of particles like sulphate and nitrate results in acid rain and metallic particle after deposition contaminate water and soil environment (Yi et al. 2006; Connan et al. 2013; Luo et al. 2019; Sonwani and Maurya 2018). Also, urban particulate pollution is increasing the temperature forming the urban heat island (Pandey et al. 2012; Zheng et al. 2018; Yang et al. 2020). As increasing level of particulate pollution has become noxious to environment and human health, there is a need to search for a sustainable method to curb this problem.

Vegetation is a natural purifier of air pollution, and it is a known fact that vegetation cover and vegetation belt play a significant role in trapping gaseous and particulate pollution from atmosphere. Jim and Chen (2008) studied the ecosystem services of urban trees by removing air pollution in Guangzhou (China) and found that annual removal of SO_2, NO_2 and total suspended particulates by the forest is 312.03 Mg, and the benefits were valued at RMB 90.19 thousand (US \$1.00 = RMB8.26). Various studies have reported that vegetation can trap atmospheric particulate matter and improve air quality. For instance, in Beijing, the trees overall removed 1261 metric tons of air pollutants, 772 metric tons of which was PM_{10} (yang et al. 2005). Studies conducted in the UK reported that planting trees on one-fourth of the available urban area can reduce PM_{10} concentrations by 2 to 10% (McDonald et al. 2007). A study on attenuation of pollution by roadside greenbelt in Khulna City, Bangladesh, showed that green belt reduces both air and noise pollution and contributes significantly in reducing the level of total suspended particulate matter by as much as 65% (Islam et al. 2012).

The particle deposition on vegetation does not only depend on plant foliar and canopy characteristics but also depend on the particle size, concentration, deposition

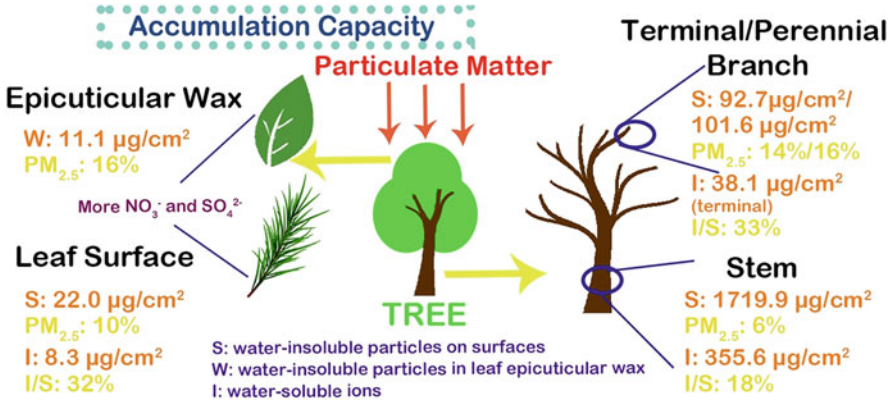

Fig. 10.1 Accumulation of particulate matter in different plant parts. (Source: adapted from Xu et al. 2019)

velocity, etc. Although particles are deposited through wet and dry deposition, certain physical processes like impaction, sedimentation, interception and Brownian diffusion influence particle deposition and retention on plant surface (Cavanagh 2006; Saxena et al. 2017). A study conducted by Xu et al. (2019) reported that the bark of a tree accumulates large portion of large particles, whereas branch surface and leaf epicuticular wax accumulate large amount of fine particles (Fig. 10.1).

Different types of tree species can have different particulate deposition and accumulation potential. Similarly, needle-leaved coniferous species capture more particles as compared to broad-leaved species (Chen et al. 2017). The dust capturing potential by the foliar surface of the plant primarily depends on its micro- and macro-morphological characteristics like leaf shape, roughness, trichomes and stomatal density (sgrigna et al. 2020). Study has reported that owing to their foliar characteristics certain tree species like *Ficus religiosa*, *Dalbergia sissoo* (Chaudhary and Rathore 2018), *Ficus benghalensis* (Rai and Panda 2014) and Sophora japonica (Zhang et al. 2020) can efficiently trap large amount of particles.

Other than trees that provide large canopy structure for the deposition of particles, roadside hedges with smaller height also play a significant role in PM reduction (Al-Dabbous and Kumar 2014; Gromke et al. 2016; Ottosen and Kumar 2020). Abhijith and Kumar (2019) measured the attenuation of PM by roadside hedge and found 43% reduction for black carbon, 30% reduction for particle number concentration, 15% reduction for PM_{10}, 14% reduction for $PM_{2.5}$ and 25% reduction for PM_1. Also, green spaces in urban residential areas like urban parks play important role in reducing particulate and noise pollution from nearby traffic areas (Silli et al. 2015; Mueller et al. 2020).

Although vegetation cover can play a significant role in abating atmospheric particulate matter, they in turn get affected by accumulating toxic chemicals on these particles, which trigger various physiological and biochemical changes within the plant cell. Once on the foliar surface, PM and its constituents can bring changes in

morphological attributes like leaf surface, stomatal density and trichome density and also on biochemical and physiological parameters such as pigment content, enzymes, protein, sugar, pH and relative water content (Rai 2016; Li et al. 2019a, b). To select certain plant species that are efficient in trapping dust load and are tolerant, scientists have used certain indices like air pollution tolerance index (APTI) and anticipated performance index (API) (Gupta et al. 2016; Javanmard et al. 2020; Rai 2020; Saxena et al. 2021b) to select such species, which can be recommended for designing better green spaces to remediate atmospheric particulate pollution.

As various factors influence the performance of vegetation in removing atmospheric particulate matter such as plant characteristics, sensitivity of plant to PM and its chemical constituent, vegetation belt or vegetation cover design, the chapter intends to undertake holistic review that put forward different aspects of PM remediation by vegetation and its impact. The chapter is designed in various sections, which will discuss (1) role of plants as a receptor of atmospheric particulate matter, (2) anatomical/morphological effect of PM on plants, (3) biochemical effect of PM on plants, (4) physiological effect of PM on plants and (5) chemical composition of particulate matter and its effect on plant system.

10.2 Role of Plants as Biofilter and Biomonitor of Atmospheric Particulate Matter

In urban areas dominated by high industrial polluted hotspot area, roadside plants can play an important role as a perfect trapping device of particulate matter (PM) and can act as bioindicator or biomonitor. The plant's foliar surface acts as a receptor site for atmospheric pollutants and plays an efficient role as a 'biofilter' for air pollution mitigation. Contaminants, transported through air mass movements, are deposited by dry and wet deposition and intercepted by plant canopies: the leaves absorb gaseous compounds or accumulate airborne particulates by the process of interception, impaction, Brownian motion or sedimentation (QUARG 1996; Cavanagh 2006). The deposition mechanism depends on particle size and deposition velocity. As shown in Fig. 10.1, for large particles sedimentation mechanism predominates and for fine particles Brownian diffusion predominates (Lovett 1984; Fowler 2002; Cavanagh 2006).

There could be different factors, which will influence the particle filtration and accumulative efficiency of plant species. The effectiveness of PM removal through plantation depends on particle size, speed of deposition and leaf surface properties (Harrison and Yin 2000; Mingorance and Oliva 2006; Qiu et al. 2009; Fuller et al. 2009; Petrova et al. 2014; Chen et al. 2017). Leaf morphology and the waxy components affect both airborne particle retention on the leaf surface and air-to-foliage gas transfer, which consequently affects the accumulation of particle-bound and gaseous contaminants in vegetation (Kömp and McLachlan 1997; Monteith and Unsworth 2013). Leaves with variant shapes and sizes have different particle retention capabilities (Smith 1981), and pubescent leaves have been shown to have

Table 10.1 Factors affecting filtration of particulate matter by plants

Factors	Impact
Wind speed	Significantly correlated with deposition rate
	Wind speed and flow inside tree canopy are negatively correlated with leaf area density
	Wind fluctuations significantly increase sub-micron (d p $<$ 1 μm) particle deposition
	Below 1 m/s, 30–80% of very fine particles (0.09 μm $<$ d p $<$ 0.26 μm) removed
	Vegetation with high surface area adequate to slow wind enhances PM removal rate
Vegetation characteristics	Canopies with large leaf surface area can allow significant airflow, which will increase deposition of small particles
	Pollutant uptake is directly proportional to canopy size
	Trees create more turbulent mixing than shrubs and herbs
	Tree bark can be a significant PM sink
Species selection	Longer life span, healthy, hardy trees that have high surface area are more beneficial
	Evergreen species are beneficial
	Conifers capture larger amounts of PM than broad-leaved trees
	Select low VOC-emitting trees
	Trees with the largest surface area have the greatest PM removal potential
Foliage characteristics	Needle-shaped leaves more beneficial than flat-shaped leaves for PM capture
	Increased stickiness promotes higher coarse PM capture
	Enhanced roughness (creates more turbulence) facilitates larger fine PM capture
Particle diameter	Diffusion accounts for most of PM removal for dp $<$ 0.1 μm
	Interception and impaction vital for PM where 0.1 $<$ d p $\leq$ 10 μm
	Gravitational sedimentation effective for PM where d p $>$ 8.0 μm
	As particle diameter decreases below 0.3 μm, deposition rate increases
	Smallest particles (d p = 0.001 μm) last for about 10 min in the atmosphere and then agglomerate to form accumulation size particles (0.05 $<$ dp $<$ 2.0 μm)
	Deposition efficiency (diffusion) increases as particle diameter decreases
	Impaction efficiency increases as deposition rate increases
Plot location	Greater particulate removal at more polluted sites
	PM removal effectiveness greatest when trees are close to the pollutant source

Source: Fuller et al. (2009)

greater scavenging efficiency than hairless ones for both inorganic and organic contaminants (Little and Wiffen 1977; Howsam et al. 2000). In addition, the roughness and integrity of the cuticle affect particle adhesion on the leaf surface (Neinhuis and Barthlott 1997; Rai et al. 2010; Chen et al. 2017; Barwise and Kumar 2020), and cuticular and epicuticular waxes play an important role in the sorption of

Table 10.2 Average dust capture on leaf of plant species at NCT—Delhi during summer and winter

Common name	Botanical name	Family	Average dust capture (gm/cm^2)	
			Summer	Winter
Indian rubber	*Ficus elastica*	Moraceae	0.1768	0.1768
Banyan	*Ficus bengalensis*	Moraceae	0.1331	0.2846
Amaltas	*Cassia fistula*	Caesalpiniaceae	0.0916	0.08
Woolly morning glory	*Argyreia roxburghii*	Convolvulaceae	0.0541	0.1209
Peepal	*Ficus religiosa*	Moraceae	0.0688	0.022
Teak	*Tectona grandis*	Verbenaceae	0.0524	0.0532

lipophilic compounds in leaves (Simonich and Hites 1994; Uzu et al. 2010). Some of the factors that affect the filtration capacity of plants are mentioned in Table 10.1.

Various kinds of leaves tend to have differences in several features of their surfaces. Some kinds of leaves have higher surface rigidity or roughness than other leaves, which may affect their stickiness or particle solubility (He et al. 2020). Stickier leaves are better for accumulating particles because large number of particles would stick to their surface. Thus, certain plant leaves may be highly advantageous for efficient dust capturing than other plants. Some of the plant species, which have been studied to be better remediator and monitor of atmospheric particulate matter, are *Ficus benghalensis* (Shrivastava and Sharma 2007), *A. stolonifera* and *F. rubra* (Speak et al. 2012), *Magnolia grandiflora* and *Platanus acerifolia* (Li et al. 2019a, b), *Pinus pinea* (Letter and Jäger 2019), etc. A study conducted by Shrivastava and Sharma (2007) analysed the dust capturing efficiency of various herbs, shrubs and tree species of Delhi and found that in tree species foliar surface of *Ficus benghalensis* (Banyan) showed maximum dust capture ranging from 0.133 gm/cm^2 to 0.2846 gm/cm^2 in summers and winters, respectively. Other than banyan, trees like *Argyreia roxburghii, Tectona grandis, Ficus elastic* and *Cassia fistula* also showed good dust capturing efficiency (Table 10.2).

Interestingly, recent researches have focussed on the influence of green belt design in improving particle deposition on plant surface. Chen et al. (2016) reported that rather than tree species selection design of planting configuration is practically an effective approach to attenuate ambient PM concentration. The study found that horizontal configuration of shrubs and tree grass could effectively reduce PM2.5 concentration. Another study by Weerakkody et al. (2019) examined the planting design of living wall to capture traffic generated PM and reported that heterogeneous topography of living wall with small and tall plants showed high PM density on the foliar surface as compared to homogenous topography (Fig. 10.2). Thus, other than studying the potential of plant species in capturing atmospheric dust, effective designing of green cover can too give us knowledge of how to use urban vegetation as a tool for pollution remediation.

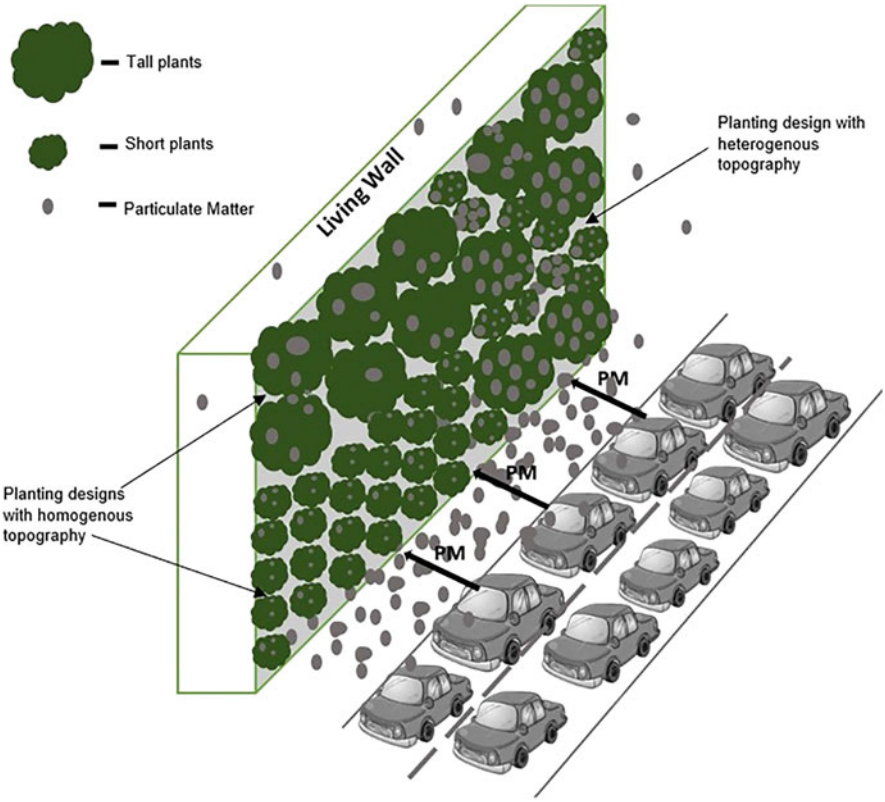

Fig. 10.2 Heterogeneous and homogenous planting design of living wall to capture traffic generated particulate matter. (Adapted from Weerakkody et al. 2019)

10.3 Anatomical/Morphological Effect of PM on Plants

Leaves are prime receptors for gaseous and PM pollutants present in the atmosphere. Prior the entry of pollutants inside leaf tissue, they interact with foliar surface and alter its configuration. Dust deposition on leaf surface, composing of ultrafine and coarse particles, reported decline in plant growth (Bender et al. 2002) due to its effect on leaf gas exchange (Ernst 1982), flowering and reproduction of plants (Saunders and Godzik 1986) and number of leaves and leaf area (Lambers et al. 1998). Decrease in leaf area and leaf number may be due to reduced leaf production rate and enhanced senescence (Seyyednejad and Koochak 2011). Due to alkaline cement dust pollution on pine and spruce, needle density and number of needle scars were larger for shoots formed in the period of higher pollution as compared with the shoots grown under a significantly lower pollution load (Ots et al. 2011). Dust deposition also affects the stomata causing occlude stomata (Hirano et al. 1995) as the particles make an entry inside the leaf by stomatal opening and their toxicity

alters the physiological activity of plants (Farmer 1993) like the inhibition of plant growth, rate of photosynthesis (Armbrust 1986), late flower and the hormonal imbalance (Farooqui et al. 1995). The inhibition of total photosynthesis would stop the assimilate translocation and consequently leaf area would decrease. It has been reported that cement dust-treated plants of *Brassica campestris* (mustard) observed a consistent decline in growth, photosynthetic pigments, yield and oil content over control plants (Shukla et al. 1990) and these factors together reduced the biomass of this plant. Earlier studies revealed that stomatal closure can help to protect plants against pollution damage (Mansfield and Majernik 1970). Other than PM, Mansfield and Majernik (1970) described the effect of CO_2 and SO_2 on stomatal behaviour in several plants. Black and Unsworth (1980) observed and described the *Phaseolus vulgaris* (Kidney Bean), and observed stomatal opening with respect to SO_2 fumigation. However, in general, there appear to be threshold concentrations above which all pollutants generally cause stomatal closure (Freer-Smith and Taylor 1992), which may be attributed to direct damage to the stomatal apparatus along with that of other leaf tissues. Krajickova and Mejstrik (1984) observed that in *P. vulgaris* (Kidney Bean), and *Zea mays* (corn), gaseous diffusion in stomata was increased on application of fly ash from power plant, but they were not plugged.

Particulate matter can decrease photosynthetically active radiation (PAR) by changing its optical properties, especially the surface reflectance in the visible- and short-wave IR range (Eller 1977; Hope et al. 1991; Keller and Lamprecht 1995), and increase the leaf temperature (Naidoo and Chirkoot 2004). The cement dust as the source of PM, suspended on the surface of plants and therefore producing harmful effect on the growth of plant species. Cement kiln dust decreased height, biomass and total productivity in plants (Prasad et al. 1991). Jahan and Iqbal (1992) showed reduction in leaf blade area of five tree species due to extensive dust and SO_2 pollution. The structure and morphology of epicuticular wax are reliable marker of plant health (Neinhuis and Barthlott 1997) by creating a hindrance between the plant and the environment and regulating the resistance to pollution stress. Deposition of road and cement dust containing large concentrations of MgO and PM causes degradation of epicuticular wax (Sauter and Pambor 1989; Bermadinger et al. 1988) by increasing the erosion rate of wax structure (Huttunen 1994) and produces changes in leaf wettability (Saneoka and Ogata 1987), inhibiting transpiration, which could have far-reaching physiological consequences, like prevention of gas exchange and photosynthesis (Saunders and Godzik 1986; Sauter et al. 1987) and loss of solutes from leaf cells (Bystrom et al. 1968). PM resulting from stone dust due to quarrying activities caused foliar anomalies and injury symptoms like tissue necrosis, brown and yellow patches, black spots and, in extreme cases, death of leaves (Saha and Padhy 2011). The presence of very high amount of heavy metals like copper and sulphur in the plants produces a number of physiological changes like symptoms of chlorosis (Bergman 1983), premature ageing and dying off of leaves. Changes in leaf morphology and anatomy as a result of PM pollution were also studied by Prasad and Rao (1981), Agrawal and Agrawal (1989), Verma and Singh (2006) and Rai et al. (2010). Acclimatization of plants to air pollutants might change their morphological structure like thicker epidermal cells and longer

trichomes (Rangkuti 2003). Once deposited on the leaf surface, some elements may be taken up into the leaf via the stomata (Reimann et al. 2001) affecting the overall plant development and reducing the resistance of plants to drought, frost, insect and fungi (Shanker et al. 2005). It has also been noted that shape of the leaves is also a vital factor for studying accumulation of PM like obovate and elliptic leaves, which are narrowest below the middle are highly affected by PM pollution in the atmosphere (Vogel 1989). Moreover, broader leaves and longer petioles are largely affected by PM as they are inefficient absorber of PM (Liu et al. 2015; Saxena et al. 2017). It has also been found that plant leaves with less hair are more susceptible to the effect of PM or they capture less PM because those leaves which are having high hair density not only enhance the surface area that can intercept PM but may also make it harder for PM to dislodge when leaves are moving (Neinhuis and Barthlott 1997; Qiu et al. 2009; Prusty et al. 2005). Moreover, by creating surface polarity, the hydrophobicity of some leaf hairs may help to attract charged particles including certain metal species generally found in PM (Fernández et al. 2014).

10.4 Effect of Particulate Pollution on Crop Health

With the increase in population, the demand for food is also increasing, and this is putting greater pressure on our existing food resources to have better crop yield and productivity. However, the pollution scenario today in urban and peri-urban areas has detrimental effect on the crop yield and quality. Unlike gaseous pollutants like ozone and $SO_{2,}$ very few studies have reported the effect of particulate pollution on the crop yield and health (Saxena and Sonwani 2019). PMs along with gaseous pollutant have negative effect on crop yield as reported by Chauhan and Joshi (2010). The higher concentration of pollutant such as SO_2, NOx, SPM and RSPM reduced the total chlorophyll, carotenoid, ascorbic acid, shoot fresh weight, root fresh weight, plant height and yield of wheat and mustard crops growing in the vicinity of the urban and industrial areas of Haridwar. Dust pollution from cement kiln can also adversely affect the productivity in black gram (*Vigna mungo)* as dust pollution reduced the height, phytomass, net primary productivity, chlorophyll content and number and size of flowers, which finally affected the yield of black gram (Prasad and Inamdar 1990). Study in China has observed that the heavy haze and aerosol pollution can severely reduce the yield of rice and wheat crop as solar irradiance reaching the most productive agriculture regions of China is estimated to reduce up to 28–49% under hazy climate. Reduction in solar irradiance in these regions can depress optimal yields of about 45% of rice and 75% of wheat growth in China (Chameides et al. 1999; Tie et al. 2016). Studies have reported that particulate matter will decrease the yields of crops like wheat, barley and chickpea (Yadav et al. 2019; Zhou et al. 2018). However, more studies are required to explicitly understand the morphological, physiological and biochemical response of crop plant to the particulate pollution and its associated risk to food security.

10.5 Physiological Effect of PM on Plants

1. **pH**
   The physiology of plants is highly affected by atmospheric PM on the basis of their physical and chemical nature. Dust pH may change the leaf extract pH of plants. The variation in leaf extract pH might affect the stomata sensitivity due to air pollutants. Cement dust on hydration emits calcium hydroxide, which can increase leaf surface alkalinity up to pH 12. This level of alkalinity can hydrolyse lipid and wax, and penetrate the cuticle, and denature proteins ultimately plasmolysing the leaf (Guderian 1986; Czaja 1960, 1961, 1962). Lower pH of leaf extract showed a perfect correlation with the kind of air pollution. The more acidic nature determines that the air pollutants, particularly SO_2 and NO_X, diffuse and form acid radicals in the leaf matrix by reacting with cellular water, having impact on the chlorophyll molecules (Türk and Wirth 1975). In the presence of an acidic pollutant, the leaf pH is reduced and this decline is higher in sensitive plant species. Alkaline property of cement dust decreases the absorption of mineral substances from the soil, producing variations in the plant physiology and morphology (Raajasubramanian et al. 2011). Alkaline nature of cement dust is accountable for change in leaf pH, as it causes chloroplast damage (Singh and Shrivastava 2002). Dusts with pH values of 9 may be responsible for producing direct injury to leaf tissues on which they are deposited (Vardaka et al. 1995) or indirectly by variation in soil pH (Hope et al. 1991; Auerbach et al. 1997) and dusts that contain toxic soluble salts will also have harmful effects on plants (Prajapati and Tripathi 2008a, b, c, d). Leaf extract pH may also be a good indicator as SO_2 entering the leaf is dissolved in inter-cellular water of mesophyll cells to produce sulphurous acid (H_2SO_3), which break down into $-HSO_3$ and $-SO_3$, resulting in acidification of the cell (Puckett et al. 1973). The exposure of SO_2 and NO_2 could reduce leaf extract pH as the plants with high susceptibility to SO_2 and NO_2 closed the stomata faster when exposed to the pollutants (Larcher 1995). Consequently, sensitive plants had higher leaf extract pH than tolerant plants.
2. **Relative Water Content**
   Water has a significant role in plant life. Relative water content determines the balance of plant water uptake and release (Jones 1994). Increased water content within a plant body may be responsible to maintain its physiological balance under the exposure of air pollution (Singh and Verma 2007). High relative water content favours resistance in plants (Dedio 1975). Plant with accurate water content still can expand the total leaf area as stated by Schuppler et al. (1998). If the leaf transpiration decreases due to the air pollution, plants cannot survive well due to losing its machinery that pulls water up from the root for photosynthesis. It has been shown that air pollutants increase cell permeability (Keller 1986), resulted in loss of water and dissolved nutrients, and early senescence of leaves (Masuch et al. 1988). Hence, leaf relative water content (RWC) is the perfect measure of plant water status in terms of physiological consequence of cellular water deficit (Joshi et al. 2011).

3. **Pigment content, photosynthesis and stomata**
   The photosynthetic pigment chlorophyll is a marker of productivity and called as photoreceptor. They are most likely to be damaged by air pollution (Prusty et al. 2005). This observation was also studied by a number of workers (Bansal 1988; Singh et al. 1990; Sandelius et al. 1995). Chlorophyll measurement is highly beneficial to determine the impact of air pollutants on plants. The decline in chlorophyll concentration is directly related to the reduction in plant growth. Chlorophyll pigments are found in highly organized state, and during stress conditions, they undergo various photochemical reactions like oxidation, reduction and reversible bleaching (Puckett et al. 1973); therefore, any change in chlorophyll concentration may alter the morphological, physiological and biochemical behaviour of the plant. Various pollutants play a vital role in inhibition of photosynthetic activity that may be due to the degradation of chlorophyll and carotenoid content of the leaves of different plants (Chauhan and Joshi 2008). Analysis of chlorophyll a (Chla) in photosystem II (PSII) is an efficient tool in the study of the physiological aspects of photosynthesis (Govindjee 2004; Bussotti et al. 2011) and has been widely used in plant stress studies (Maxwell and Johnson 2000; Adams and Demmig-Adams 2004; Bussotti et al. 2011). Bussotti et al. (2011) observed the effect of ozone stress in woody plants with chlorophyll a fluorescence. Leaves of *Viburnum tinus* showed reduced photosynthesis and gaseous exchange on the growth of black dust (Thompson et al. 1984). Moreover, limestone dust deposition reduced overall plant performance by loss of chlorophyll content, inhibition of CO_2 assimilation, uncoupling of the oxygen-evolving complex and reduced electron transport in Namib Desert shrub, *Zygophyllum prismatocarpum* (Tall zygophyllum) (Van Heerden et al. 2007).

Effect of simulated acid rain and iron ore dust deposition in *Eugenia uniflora* (Surinam cherry) resulted in degradation in net photosynthesis, stomatal conductance, transpiration, chlorophyll a content and electron transport rate through photosystem II (PSII) (Neves et al. 2009). Moreover, Neves et al. (2009) studied that catalase and superoxide dismutase activities were reduced by simulated acid rain. In *Schinus terebinthifolius* (Brazilian Pepper), deposition of iron ore PM elevates the chlorophyll content, the maximum quantum efficiency of photosystem II and ETR (Kuki et al. 2008). Zhang et al. (2010) demonstrated physiological responses of honeysuckle (Lonicera japonica Thunb.) and its autotetraploid cultivar to high ozone (O_3) exposure and found reduction in total photosynthetic rate and stomatal conductance. Because of O_3 exposure, chlorophyll loss, high membrane permeability, reduction in seed yield, loss of total sulphhydryl groups, decrease in soluble protein content and rise in guaiacol peroxidase activity were observed in leaves of soya bean cultivars (Chernikova et al. 2000). Coal-induced pollution produces inhibitory impacts of pollution stress on leaf pigments concentrations, nitrate reductase activity and the contents of reducing sugars and total N content, while stimulatory effects were given on stomatal index and nitrate and sulphur contents in A. indica (neem) (Iqbal et al. 2010a, b). Moreover, such emissions also adversely affected photosynthesis, nitrogen metabolism and growth characteristics of *Triumfetta rhomboidea*

(Chinese Burr), as studied by Iqbal et al. (2010a, b) at different flowering stages of plant growth. Pollutant gases like SO_2, NO_X and O_3 generate oxy-radicals in reactions with plant material (Shimazaki et al. 1980; Sakaki et al. 1983). These radicals produce broad damage to membranes and related molecules including the chlorophyll pigments (Sakaki et al. 1983; Malhotra and Khan 1984). The decline in chlorophyll concentration in the polluted leaves could be due to chloroplast damage (Pandey et al. 1991), inhibition of chlorophyll biosynthesis (Esmat 1993) or increased chlorophyll degradation. Simultaneously, SO_2 and NO_2 can reduce photosynthesis in *Betula pendula* (Silver Birch) and also change the gas exchange of woody plants *Fagus sylvatica* (common beech), *Populus deltoides* (eastern cottonwood) *X Populus nigra* (Black Poplar), *Picea sitchensis* (Sitka Spruce) and *Picea abies* (Norway spruce) (Freer-Smith and Taylor 1992). Impacts of NO and NO_2 on total photosynthesis have normally only been seen for exposure concentrations of higher than 500 ppb (Freer-Smith and Taylor 1992). Air pollutants, particularly PM, make their entry into the tissues via the stomata and cause partial degradation of the chloroplast and reduce the pigment contents in the cells of polluted leaves (Rao and LeBlanc 1966) and therefore the significant loss in total chlorophyll, in the polluted leaves exposed to air pollution stress supports the fact that the chloroplast is the main site of attack by air pollutants like SPM, SO_2 and NO_X (Tripathi and Gautam 2007). Rao and LeBlanc (1966) have also shown that decrease in chlorophyll content due to SO_2 might be due to their replacement of Mg2+ by two hydrogen atoms and reduction in chlorophyll molecules to phaeophytin, no longer, serves to trap the solar energy for photosynthesis. SO_2 diffuses and dissolves in mesophyll tissues and generates sulphite and bisulphite ions that in return photo-oxidized to less toxic SO_2^-–S involving free radical reactions (Asada and Kiso 1973). The excess free oxygen radicals may affect cellular components consisting of chlorophyll pigments (Shimazaki et al. 1980) and may inactivate enzymes contributing in chlorophyll synthesis. A number of studies where higher plants exposed to various SO_2 concentrations show decline in chlorophyll content (Inglis and Hill 1974; Hallgren and Huss 1975; De Santo et al. 1979; Agrawal et al. 1982), while most of the pollutants rises the total chlorophyll content, others decrease it (Agbaire and Esiefarienrhe 2009). A number of studies has imposed rise in chlorophyll content under air pollution, like Tripathi and Gautam (2007) reported that *M. indica* (Mango) leaves exposed to air pollution reported an increase in chlorophyll content (Tripathi and Gautam 2007). Seyyednejad and Koochak (2011) also showed the rise in chlorophyll content of *E. Camaldulensis* (Red Gum) leaves at polluted site as compared with control (Seyyednejad and Koochak 2011). Harmful impacts of dust and other air pollutants on plants with decline in photosynthetic pigments and yield have been demonstrated by various workers in different crops (Lerman 1972; Bytnerowicz et al. 1987; Farmer 1993; Saquib and Khan 1999; Rajput and Agrawal 2005; Lone and Khan 2007). Dusted leaf surface observed decreased photosynthesis and hence causing decline in chlorophyll content. Decline in chlorophyll content due to increased dust deposition was reported by Prajapati and Tripathi (2008a). Rajput and Agrawal (2005) and Joshi et al. (2009) observed that air pollution in urban areas highly affects total chlorophyll, carotenoid and ascorbic acid in wheat plants. Swami

et al. (2004) have reported a significant decline in chlorophyll content, carotenoid, ascorbic acid, pH and moisture content in the leaves of two species of trees viz. Sal (*Shorea robusta*) and Rohini (*Mallotus philippinensis*) exposed to roadside vehicular pollution. Sato et al. (1993) also showed that cement dust decreased the efficiency and concentration of chlorophyll in a number of crops. Cement kiln dust deposited on the leaf surface produces chloroplast damage resulting in reduced chlorophyll content. Decline in total chlorophyll has been found in leaves of different annual plants and conifers covered by cement dust (Pandey and Kumar 1996; Nunes et al. 2004). The shading effects because of deposition of suspended PM on the leaf surface might be responsible for the reduction in the concentration of chlorophyll in polluted area. It might block the stomata and therefore interfere with the gaseous exchange, which resulted in increase in leaf temperature which may subsequently decline chlorophyll synthesis. Decrease in chlorophyll content may be due to the interference of all the metals with chlorophyll synthesis and fat metabolism, reducing root shoot growth, photosynthesis, nutrient uptake, leaf area, biomass, etc. (Polacco 1977), as depicted by decreased chlorophyll content in *A. Procera* (Rubber bush), leaves with rising concentrations of metals (Pandey and Tripathi 2011). The successive decrease in metabolites like protein, amino acid, chlorophyll, carotenoid and total sugar is possibly due to decline in chlorophyll content (Prasad and Inamdar 1990). Darrall and Jager (1984) described chlorophyll as a marker for air pollution levels and its impacts. Carotenoids are a class of natural fat-soluble pigments found majorly in plants, algae and photosynthetic bacteria, where it plays a important role in the photosynthetic process. They act as accessory pigments in higher plants. Most of the researchers have shown decreased reduced carotenoid content under air pollution (Joshi et al. 2009; Tiwari et al. 2006). Carotenoid protects chlorophyll from photo-oxidative destruction (Siefermann-Harms 1987). The carotenoid contents of few crops were found to decrease in response to SO_2 (Pandey 1978; Singh 1981; Nandi 1984) as they are highly sensitive to SO_2 than chlorophyll (Shimazaki et al. 1980). Carotenoids play an important function, especially photoprotective agents within the chloroplasts. However, under stress condition, normal protective process may become overloaded and hence cellular destruction including pigment degradation occurs (Senser et al. 1990). Oxidation of carotenoids takes place by light-catalysed reactions resulting in the formation of epoxide, which is further reduced in dark by an enzyme-catalysed reaction (Calvin 1955).

10.6 Biochemical effect of PM on Plants

1. **Ascorbic acid**
   It is a natural antioxidant present in plants and has a crucial role in pollution tolerance (Chen et al. 1991). Ascorbic acid, also known as vitamin C, is one of the parameters that may determine the tolerance of plant to air pollution by assessing the chlorophyll content present in the leaf. It plays an important role in light reaction of photosynthesis (Singh and Verma 2007) and activates defence

mechanism (Arora et al. 2002), and in the presence of stress, it can replace water from light reaction II (Singh and Verma 2007). Ascorbate is called as an antioxidant molecule able to detoxify air pollutants (Smirnoff 1996; Joshi and Swami 2007) and able to control cell expansion and cell division (Loewus 1999; Conklin et al. 2000). It also has a significant role in cell wall synthesis, defence and cell division. It is a strong reducer and has vital role in photosynthetic carbon fixation, with the reducing power directly correlated with its concentration (Seyyednejad et al. 2011). Hence, it has been given utmost priority and used as a multiplication factor in the formula. High pH may accelerate the efficiency of conversion from hexose sugar to ascorbic acid, whereas low leaf extract shows good proportion with susceptibility to air pollution (Escobedo et al. 2008, Pasqualini et al. 2001; Conklin 2001; Liu and Ding 2008). Previous study has depicted that a strong correlation should exist between ascorbic acid content and resistance to pollution in plants (Varshney and Varshney 1984). Tolerant plants consist of large amount of ascorbic acid, whereas sensitive plants possess a low level of ascorbic acid. The concentration of this acid declines on pollutant exposure (Keller and Schwager 1977). Thus, plants maintaining high ascorbic acid level even under polluted conditions tend to be tolerant to air pollutants. Ascorbic acid being a strong reductant activates most of the physiological and defence mechanisms and its reducing power is directly correlated with its concentration (Lewin 1976). Table 10.3 summarizes the list of tolerant and sensitive plant species to particulate pollution.

Pollution load-dependent rises in ascorbic content of all the species possibly due to the higher rate of production of reactive oxygen species (ROS) such as SO_3^- HSO_3^-, OH^- and O_2^- during photo-oxidation of SO_3^- to SO_4^{2-} where sulphites are generated from SO_2 absorbed. The free radical production in the presence of SO_2 exposure would rise up the free radical scavengers, like ascorbic acid, superoxide dismutase and peroxidase (Pierre and Queiroz 1981). It also reacts with H_2O_2 and protects carotenes and tocopherols in plants which respond to different stresses in plants exposed to pollutants (Perl-Treves and Perl 2002). ROS like singlet oxygen, hydrogen peroxide and hydroxyl radical are generally very reactive molecules that consist of an unpaired electron, and under normal conditions, the balance between the generation and diminution of ROS is controlled by the antioxidant defence system. However, when ROS are not completely removed, an effect known as 'oxidative stress' may result. Excess ROS formed inside the cells can provoke oxidation and modification of cellular amino acids, proteins, membrane lipids and even DNA, creating oxidative injury that results in decline of plant growth and development (Hernández-Jiménez et al. 2002; Ogawa and Iwabuchi 2001). As per the earlier studies, there are controversial results about the impacts of individual pollutants on ascorbic acid contents of different plant species. In fumigation experiments with O_3 or SO_2 and in field experiments comparing trees growing in more or less polluted areas, various authors reported increases (Bermadinger et al. 1990; Härtling and Schulz 1995), while others decreases (Keller and Schwager 1977; Pandey and Agrawal 1994) and few of them reported about no alteration of the ascorbic acid contents

Table 10.3 Plant species tolerant/sensitive to particulate pollution

S. No.	Plant species	Tolerant/ sensitive	Reference
1	*Ficus benghalensis*	Tolerant	Bharti et al. (2018); Rai and Panda (2014); Thakar and Mishra (2010)
2	*Bauhinia variegate*	Sensitive	Rai and Panda (2014)
3	*Moringa oleifera*	Tolerant	Bharti et al. (2018)
4	*Acacia nilotica*	Sensitive	Bharti et al. (2018)
5	*Broussonetia papyrifera*	Tolerant	Noor et al. (2015)
6	*Ricinus communis*	Tolerant	Noor et al. (2015)
7	*Eucalyptus globules*	Tolerant	Noor et al. (2015)
8	*Dalbergia sissoo*	Sensitive	Gupta et al. (2016)
9	*Polyalthia longifolia*	Sensitive	Gupta et al. (2016)
10	*Mangifera indica*	Tolerant	Radhapriya et al. (2012); Thakar and Mishra (2010)
11	*Bougainvillea species*	Tolerant	Radhapriya et al. (2012)
12	*Psidium guaja*	Tolerant	Radhapriya et al. (2012); Thakar and Mishra (2010)
13	*Thevetia neriifolia*	Sensitive	Radhapriya et al. (2012)
14	*Saraca indica*	Sensitive	Radhapriya et al. (2012)
15	*Morus alba*	Tolerant	Khalid (2019)
16	*Ficus virens*	Tolerant	Chaudhary and Rathore (2019)

(Hausladen et al. 1990; Madamanchi et al. 1991) as a result of the impact of air pollutants. Few studies (Tanaka et al. 1985; Nouchi 1993) proved that there is action to O_3 may vary with pollutant dose, with less concentrations causing an increase and high-dose results in a loss of ascorbic acid.

2. **Enzymes**
   It is well known that ascorbate–glutathione cycle occurs in chloroplasts (Foyer and Halliwell 1976; Asada 1984; Dalton 1991; Foyer et al. 1991; Chernikova et al. 2000), which is accountable for scavenging toxic peroxide through SOD catalysis (Mehler 1951; Foyer et al. 1991). Lagriffoul et al. (1998) demonstrated that as compared to growth parameters, the measurement of enzyme activities may be included as early biomarkers in a plant bioassay to examine the phytotoxicity of Cd-contaminated soils on maize plants. Doğanlar and Atmaca (2011) observed decline in pigment and total soluble protein contents and increases in peroxidase enzyme activity in certain plants, e.g. *Acer negundo* (Boxelder), *Platanus orientalis* (Oriental Plane) and *N. oleander* (Oleander) when exposed to industrial and urban pollution in Turkey. It has been depicted

in *Pinus sylvestris* (Scotch pine) that enzyme scavenging and antioxidant system such as superoxide dismutase, guaiacol peroxidase and ascorbate peroxidase (Pukacka and Pukacki 2000) can respond with increased activity to signals from environmental pollution peroxidase (Pukacka and Pukacki 2000). ROS damage plant cells by oxidizing membrane lipids, consist of photosynthetic apparatus (Foyer and Harbinson 1994; Aranjuelo et al. 2008), inhibit protoplast regeneration (Marco and Roubelakis-Angelakis 1996; Aranjuelo et al. 2008) and damage proteins, chlorophyll and nucleic acids (Foyer and Harbinson 1994; Aranjuelo et al. 2008).

Singh et al. (2011) depicted that in mustard, the ozone exposure significantly increased oxidative stress resulting in significant losses of photosynthetic pigments and protein in leaves, whereas high antioxidative defence system plays a vital role in combating its impact. SO_2, one of the major airborne pollutants, can penetrate plant foliage through stomata and can produce metabolic or physical injury (Khan and Malhotra 1982). Sulphur fumigation as SO_3^{2-} and SO_4^{2-} inhibited RuBP carboxylase, but, last time, proved to be more inhibitory (Khan and Malhotra 1982). Ozone effects on the *Lamotte diana* were studied under controlled condition by Calatayud et al. (2011), and they marked decline in the in vivo CO_2 fixation capacity of Rubisco. Other marked effects were callose accumulation, formation of pectinaceous wart-like cell wall exudates and phloem alterations (Calatayud et al. 2011).

3. **Sugar Content**

Soluble sugar is a vital component and source of energy for every living organisms. Plants generate soluble sugar during photosynthesis and breakdown during respiration (Tripathi and Gautam 2007). Pollutants such as SO_2, NO_2 and H_2S in the presence of adverse conditions can result in excess degradation of soluble sugars in the plant leaves grown in polluted area. The decline in total sugar content of damaged leaves generally causes photosynthetic inhibition or stimulation of respiration rate (Tzvetkova and Kolarov 1996). Similarly, Bücker and Ballach (1992) determine the level of soluble carbohydrates decreased because of fumigation with mixture of O_3, SO_2 and NO_2 in both young and mature leaves, this results in decline in insoluble sugars that possibly arise due to increased metabolic consumption of energy under stress conditions. Increased respiration rate was reported in tree species tolerant to air pollution (Lorenc-Plucinska 1982). A higher inhibition of photosynthesis and photorespiration in the less resistant individuals was established in *P. sylvestris* (Scotch pine) by Lorenc-Plucinska (1982). Decline in sugar content of crop around the cement dust polluted area can result in increased respiration and decreased CO_2 fixation due to chlorophyll degradation (Tripathi and Gautam 2007). The decrease in total sugar reflects the interference of light absorption caused due to deposition of dust over the surfaces of leaf. The less sugar levels were possibly due to decreased synthesis or diversion of the metabolites to other synthesis processes. The reaction of sulphite with aldehydes and ketones of carbohydrates can also cause decline in carbohydrate content. The rise of soluble sugars was also determined following chronic exposure (Miller et al. 1969). The rise in soluble sugar was

reported in *Albizia lebbeck* (Siris) and Callistemon citrinus (Red Bottlebrush) cultivated in industrial land (Seyyednejad et al. 2009). Rise in quantity of soluble sugar is a protecting mechanism of leaves that has been shown in Pinto bean in exposure with various doses of ozone (Duccer and Ting 1970). It has been determined in milkweed that the variations showed in sugars, amino acids and phenols because of ozone exposure may change plant–insect relationships due to change in nutritional quality for insect herbivores (Bolsinger et al. 1991).

4. **Protein**

Protein is an important foliar biochemical component of plants and is needed for enzymatic activity in plant species. Protein amount in plants exhibits both rising and declining trends in response to pollution stress depending on the plant species and its inherent resistance against pollution. Decrease in protein content is possibly because of the increased rate of protein denaturation, which is also supported by the research of Prasad and Inamdar (1990). Constantinidou and Kozlowski (1979) observed increased protein degradation and breakdown of existing protein to amino acid as the major reason of decline in protein content. A decrease in the foliar protein content was also shown at the polluted sites. Kumar and Dubey (1998) have also summarized that pollutants emitted from auto-exhaust may result in inhibitory effect on protein synthesis. The foliar protein content was reduced may be due to either breaking down of existing protein and/or declined de novo synthesis of protein (Iqbal et al. 2000). Decrease in protein content could also be resulted in decreased photosynthesis (Constantinidou and Kozlowski 1979; Singh et al. 1988). Rana et al. (2000) observed impact of various levels of SO_2 on the quantity of free proline in the anthers of *Brassica juncea* L (mustard). The impacts of pollutants on plants consist of pigment destruction, degradation of cellular lipids and peroxidation of polyunsaturated fatty acid (Tiwari et al. 2006). The hazardous impacts of the pollutants are caused through the generation of reactive oxygen species (ROS) in plants, which produce peroxidative destruction of cellular constituents (Tiwari et al. 2006). Proline accumulation generally occurs in a different kinds of plants in the presence of various stresses, which act as a free radical scavenger to protect plants away from destruction by oxidative stress (Wang et al. 2009). There appears to be a relationship between lipid peroxidation and proline accumulation in plants subjected to different types of stress (Wang et al. 2009). If such a relationship exists, proline accumulation probably plays a vital role in inhibiting air pollution-induced lipid peroxidation. For instance, proline accumulation in leaves of plants exposed to SO_2 fumigation (Tankha and Gupta 1992), heavy metals (Wang et al. 2009) and salt (Woodward and Bennett 2005) stress has been reported (Tankha and Gupta 1992; Wang et al. 2009; Woodward and Bennett 2005). Seyyednejad and Koochak (2011) also showed that in the presence air pollution conditions, proline level of polluted leaves significantly risen up. Copper is a micronutrient for plants and a constituent of different proteins, especially those involved in both the photosynthetic (plastocyanin) ETC and the respiratory (cytochrome oxidase) ETC. Under extra conditions, the absorbed copper plays a cytotoxic role by producing ROS in Fenton-type reactions,

resulted in disturbance of metabolic pathways and macromolecular damage (Hegedüs et al. 2001). Protein synthesis declined because of the less chlorophyll and decreased leaf area surface, and similar findings were shown by Baszyński et al. (1980). Trivedi and Singh (1995) observed significant decline in protein content in some plants due to fly ash PM. Significant changes in photosynthetic pigments and protein content in foliar tissues due to auto-exhaust pollution were noticed by Verma and Singh (2006). Proline, a total free amino acid, accumulated in plants when they are exposed to moisture stress conditions and decrease on release of stress (Pokhriyal and Raturi 1985). Proline accumulation provides high stability in drought-induced stress. Heavy metals decreased crude proteins in crops, and in this study, the impact was much pronounced on forestry tree species relative to crops (Hemalatha et al. 1997). The decline in protein could be understood that metal in a likelihood would produce disturbance with sulphur-containing amino acid and crude protein resulted in declined protein content (Somasundaram et al. 1994). Amino acids play a significant role in plant primary metabolism. Being initial products of photosynthesis and nitrogen assimilation, they represent an important connection between nitrogen and carbon metabolism (Durzan and Steward 1989).

10.7 Chemical Composition of Particulate Matter and Its Effect on Plant System

Chemically, particulate matter could be nitrate, sulphate, metallic, organic or biogenic in nature. Not only size of the particles but also its chemical composition is important to infer its negative effect on the ecosystem. Foliar surface of plant that acts as receptor site for these particulate matter can also assimilate the chemicals enriched on particles, which leads to various biochemical and physiological stresses in plant. Gaseous exchange by leaf is generally done through stomatal opening, but chemical exchange from particle is little complex and influenced by various factors such as retention time of the deposited particle on foliar surface, chemical speciation, mobility of particle associated chemical, plant species and climatic factor (relative humidity, precipitation, temperature, solar radiation). There could be various foliar entry routes for the chemical bound on particles like soluble compound arising from deposited particle migrate to the cell and incorporate in the plant tissues. Mobilized component can penetrate through cuticular breaks, epidermal pores and aqueous pores (Kinnersley and Scott 2001). Two pathways aid the transfer of chemicals from the particles to the plant system, i.e. the **lipophilic** and the **hydrophilic** pathways (Schönherr 2006). Lipophilic pathway involve apolar or non-charged molecules, which majorly cross cuticle through diffusion from cutin and foliar wax, while the hydrophilic pathway involves uptake of ions and hydrophilic solutes from foliar aqueous pores, especially during high humidity condition. Stomatal pathway also exists that can diffuse fine particles or nanoparticles directly into apoplast (Simonich and Hites 1995; Eichert et al. 2008; Wang et al. 2013). Once the chemical has crossed cuticle barrier or stomata, it may remain in apoplasm or transported in cell

(Uzu et al. 2010). Post-internalization in the leaf cells the chemicals are loaded in phloem and transported into different plant parts (McLachlan 1999; Hao et al. 2007; Maillard et al. 2015; Liu et al. 2019). Once in the plant system, these chemicals can bring potential toxicity to the plant. The effect of various chemical composition of particulate matter on plant system is subsequently discussed.

Effect of sulphate aerosol: Sulphate aerosols are contributed in the environment by both natural and anthropogenic sources. The natural sources include volcanic eruption, forest fire and marine emissions (Ray and Kim 2014). Anthropogenic emissions come from industrial combustion, biomass burning and coal burning (Shikwambana and Sivakumar 2019). Sulphate particles like ammonium sulphate are also formed as secondary aerosol from gaseous sulphur dioxide or from heterogeneous reactions on mineral PM (Balasubramanian et al. 2013; Voutsa et al. 2014; Xu et al. 2019). Deposition of sulphate aerosols on leaf surface and in plant accumulation can seriously deteriorate plant health. Leaf chlorosis, necrosis and loss of turgor occur when plants are exposed to ammonium sulphate aerosols (Gmur et al. 1983). A synergistic effect of acidic sulphate aerosol along with ozone causes visible injury and chlorophyll loss in vegetation (Chevone et al. 1986). Deposition of ammonium sulphate particles on cauliflower increases the plant and insect herbivore interaction, where oligophagous diamondback moth (*Plutella xylostella) and* polyphagous Eri silk moth larvae (*Samia ricini*) feed on leaves deposited with ammonium sulphate (Agathokleous et al. 2019).

Effect of nitrate aerosol: The nitrogen-rich aerosols are deposited on plant surface as nitrate particulate (NO_3^-), ammonium (NH_4^+) or nitric acid vapour (HNO_3) (Bytnerowicz and Fenn 1996). Secondary nitrate aerosols are formed by the chemical reaction of gaseous nitrogen oxides in atmosphere (Riemer et al. 2003), whereas sources of atmospheric ammonia could be livestock management, fertilizer application, industry, power plants, traffic, human excreta, etc. (Fangmeier et al. 1994; Lee et al. 1997). A controlled nitrogen deposition can improve plant growth but high nitrogen deposition results in myriads of negative effects, including nutrient deficiencies, soil acidification, altered species composition, decreased mycorrhizal root symbiosis and increased vulnerability to environmental stresses (Bytnerowicz and Fenn 1996). Wet deposition of nitrogen-rich compound in the form of nitrate or ammonia on foliar or soil surface significantly affects tree nutrition by decreasing the foliar concentration of K, Mg and P (Wilson and Skeffington 1994). Studies have reported that deposition of ammonia on plants is more harmful than nitrate deposition. The adverse effect of ammonia on plants includes visible leaf injury, nutrient deficiency, increase attack of insects and pest, increased sensitivity to drought and frost stress (Krupa 2003). When ammonia is assimilated in roots, anions are taken up in preference to cations, whereas ammonia assimilation in leaves releases proton, which can cause cellular acidosis (Pearson and Stewart 1993). Thus, deposition of nitrogen-rich particles on foliar surface and its accumulation by plant system can greatly influence the plant nutrient pool, plant resistance to abiotic and biotic stresses and soil–plant interaction.

Effect of metallic particles: Atmospheric heavy metals are emitted in particulate form (Moldovan et al. 2002; Dai et al. 2014) and are present in almost all aerosol size

fractions, but mainly enrich in the smaller particles (Birmili et al. 2006; Venter et al. 2017). Various metals are constituent of particles in different size fractions, which largely depend on their source of emission (Song and Gao 2011; Tran et al. 2012). Heavy metals such as Fe, Ca, Al, Si and Ti are often found in coarse mode particles due to their high abundance in the crust, while metals such as Zn, Pb, Ni, Se, Sb and As are often observed in the fine mode particles since they are often released from high-temperature combustion processes (Moreno et al. 2013; Fomba et al. 2015; Pant et al. 2016; Sonwani and Kulshrestha 2018). These toxic PM can deposit on terrestrial ecosystem (Ma et al. 2010) and cause contamination of soil and plant species (Schreck et al. 2011; Luo et al. 2019). The effect of metal on plants depends on the presence of its bioavailable form in air, water and soil, which is ultimately taken up by the vegetation. Once metals are taken up by plants, they get accumulated into them (Bini et al. 2012). Metals get accumulated in cell walls by attraction to negative charges. Uptake of atmospheric metal by plants results in decreased photosynthetic activity, chlorophyll pigment and plant biomass (Liu et al. 2019; Luo et al. 2019). Plant growing in metal-rich environment also releases certain phytochelatins (PCs) and metallothioneins (MTs) (Cobbett 2000; Gawel et al. 2001; Hasan et al. 2017). It is known that metal produce toxicity by binding to important biomolecules and inactivate them, e.g. metals have high affinity for sulphur-containing ligands hence, they enter in cell and interact with many SH group, inactivate many enzyme and disturb their metabolism (Seregin and Ivanov 2001). Fourati et al. (2017) studied the effect of atmospheric deposition of trace metals on olive orchards and found decreased non-enzymatic and enzymatic activity and disruption of hormonal homeostasis. Heavy metals have been demonstrated to stimulate formation of free radical and reactive oxygen species (ROS) either by direct electron transfer involving metal cations or as a consequence of metal-mediated inhibition of metabolic reactions (Schutzendubel and Polle 2002; Shahid et al. 2014). Pinto et al. (2003) studied the heavy metal induced oxidative stress in algae. Algae respond to heavy metals by induction of several antioxidants, including diverse enzymes such as superoxide dismutase, catalase, glutathione peroxidase and ascorbate peroxidase, and the synthesis of low molecular weight compounds such as carotenoids and glutathione. Heavy metal toxicity induces increase in the pool of antioxidants (Pietrini et al. 2003; Clabeaux et al. 2013) out of which glutathione plays an important role in synthesis of phytochelatins (PCs) and providing metal tolerance (Noctor et al. 2011).

Effect of organic aerosols: Organic chemicals like volatile organic compound or semi-volatile organic compound include various classes of aromatic and aliphatic organic compounds such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCB), chlorinated dioxins, furans, dibenzofurans, biphenyls and pesticides (McLachlan and Horstmann 1998; Smith and Jones 2000; Qadir et al. 2013; Castro-Jimenez et al. 2017; Shen et al. 2019; Sonwani et al. 2016; Sonwani et al. 2022). The major sources of organic chemicals in atmosphere are from fossil fuel combustion, vehicular emissions, residential cooking and fugitive dust emissions (Kalaitzoglou et al. 2004; Wingfors et al. 2011; Zhao et al. 2019; Javed et al. 2019). These toxic organic chemicals can enter vegetation either through

gaseous deposition or through wet and dry particle deposition and taken up by leaves through waxy cuticular layer or stomata and further translocated by phloem (Simonich and Hites 1995; McLachlan 1999). Once in the plant system, organic compound affects different plant processes, for instance exposure to VOCs affects the flowering and seed production in plants (Cape 2003). Organic compounds like PAH affect photosynthetic process, plant growth, interfere with carbon allocation and root symbioses (Desalme et al. 2013). Wyrwicka et al. (2014) studied the effect of PCB-contaminated sludge on metabolism on cucumber plant and reported that exposure to PCB reduced the guaiacol peroxidise activity but increased the activity of glutathione S-transferase. As organic chemicals accumulate in plant body, they become part of food chain and great concern lies not only on plant health but also on human health as most of these chemicals are carcinogenic, teratogenic and mutagenic (Böhme et al. 1999; Bari and Kindzierski 2018; Tian et al. 2019; Li et al. 2020).

10.8 Conclusion

The present chapter concludes that plants or vegetation can be used as both sinks and bioindicators. Plants also possess stress-tolerant mechanisms and have the ability to cope up against damage resulted from PM or dust deposition leading inhibition of photosynthetic activities and protein synthesis as well as susceptibility to injuries caused by microorganisms and insects. Evaluation of morphological, physiological and biochemical changes in plants on exposure to PM pollution is an important step to isolate and screen tolerant plants from sensitive ones. Tolerant plant species are good sustainable step towards cost-effective measures for PM control and can also be applicable at wider scale. Such eco-friendly solutions always have win-a-win situation and can be used by policymakers to remediate or mitigate PM pollution.

Acknowledgments Pallavi Saxena wants to acknowledge Department of Science and Technology (DST) and Science and Engineering Research Board (SERB) for providing financial assistance in the form of research project (SR/FTP/ES-74/2013).

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Mitigation and Management of Ambient Particulate Matter

11

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Abstract

The mitigation of ambient particulate matter (PM) is motivated by its harmful effects on human health. In this chapter, we argue that successful management strategies need to consider the source of emissions of PM and precursor gases (magnitude and chemical composition of emissions, and configuration of the source), transportation and dispersion in the atmosphere, and the sensitivity and vulnerability of the receptor (population group or physical environment). This framework underpins impact assessment tools used to inform the siting and design of new developments, and policies and regulations for the management of existing sources. Emission control may be mandated through a command-and-control approach, for example emissions standards, or may be incentivised through market-based approaches like cap-and-trade schemes and congestion charges. Technically, mature technologies are available to reduce emissions of PM and precursor gases from most stationary and non-stationary point sources. Emission control may be implemented before combustion (e.g. by reducing the

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_11

levels of impurities in the fuel or substituting a cleaner fuel), by modifying the combustion process itself (as is often done to lower emissions of nitrogen oxides) and by removing pollutants from the flue gas stream after combustion with scrubbers or converters. Three case studies are presented of innovative initiatives to address ambient PM around the world: conversion of public transportation to compressed natural gas in New Delhi; the coal-to-gas project for residential heating in China; and emission trading programmes in the USA. Vegetation has the potential to be more effectively used to filter PM from the air via dry deposition on leaves. Challenges remain in financing abatement technologies in the developing world, in controlling emissions from uncontained fugitive sources and in addressing the residential burning of solid and liquid fuels that is often the cause of highest exposure to ambient PM levels in vulnerable population groups.

Keywords

Particulate matter · Emission sources · Management and mitigation

11.1 Introduction

Particulate matter (PM), also called aerosols, is a complex mixture of solid and liquid particles suspended in the atmosphere, originating from both anthropogenic and natural sources. PM affects atmospheric processes (such as the formation of clouds) (Booyens et al. 2015; Seinfeld and Pandis 2006) and the climate, resulting in localised heating of the atmosphere (absorptive particles) or cooling (reflective particles) (Bond et al. 2013; Sonwani et al. 2021a). PM constitutes a large portion of the uncertainty in the estimation of climate forcing impacts. In addition, there is evidence of PM having an impact on vegetation and plant phenology (Jochner et al. 2015).

The primary purpose of the management and mitigation of atmospheric PM is to minimise the impacts on human health (Cohen et al. 2017; Gakidou et al. 2017; World Health Organization 2014). Exposure to $PM_{2.5}$ is the fifth highest mortality risk factor and the most hazardous environmental risk factor globally (Stanaway et al. 2018). Ambient PM is estimated to cause 4.2 million premature deaths and 103.1 million disability-adjusted life years annually. This represents 7.6% of total global deaths and 4.2% of global attributed disability-adjusted life years (Cohen et al. 2017). The contribution that ambient air pollution (particularly attributed to PM concentrations) makes to adverse human health outcomes has increased recently due to population ageing, changes in the rates of non-communicable diseases and increasing levels of atmospheric pollution in low- and middle-income countries (Cohen et al. 2017). Furthermore, 4.3 million deaths were attributable to household (indoor) air pollution in 2012 (World Health Organization 2014). This all speaks to the importance of managing and mitigating ambient particulate matter.

The climatic impacts of PM are felt through two main processes. Firstly, the direct impact is through altering the albedo of the atmosphere or the land surface (Kloster

et al. 2008). Depending on the optical characteristics of the particles or the particle mixtures, the impact may either be an increase in albedo through light scattering particles such as sulphates, or be a decrease in albedo due to highly absorptive particles such as black carbon (Bond et al. 2013). The secondary aerosol effect on climate is through the impact that particulates have on the formation of clouds since they act as cloud condensation nuclei, and the subsequent impact on cloud properties (Kloster et al. 2008). These effects may be felt in different directions (less/more rain, cooling/warming), and the overall impact of PM on the climate is highly uncertain (Fuzzi et al. 2015).

Despite more stringent regulations, improved abatement technologies and widespread recognition of the way PM shorten lifespans and degrade quality of life, ambient PM concentrations remain at levels that are considered harmful to health in many parts of the world (Health Effects Institute 2019; World Health Organization 2016). Often, it is lower-income countries and communities that are subjected to highest PM exposure. Some PM in the atmosphere is inevitable due to natural processes such as aeolian dust generation (particularly in arid or semi-arid environments), the release of biogenic aerosols such as pollen or fungal spores, and the emission of biogenic precursors to secondary organic aerosols such as volatile organic compounds (VOCs) from natural biomass burning and dimethyl sulphide (DMS) from phytoplankton. Anthropogenic processes alter the magnitude, composition and distribution of atmospheric PM. Sources of PM and its precursors are widespread and linked to many activities integral to society and the economy, like energy use, transport, agriculture and home life. Our inability to reduce ambient PM levels to acceptable levels is sometimes due to the technical difficulty in controlling the emissions themselves (this is particularly true for widespread or fugitive sources, like agricultural activities, uncontrolled vegetation fires or non-exhaust emissions from roads from the wear of tyre and brakes and dust picked up by traffic). More often, however, technical solutions are available, but they cannot be implemented because of lack of resources, or the solutions are not well-tailored for implementation in a local context.

In this chapter, we review the tools, technologies and approaches that have been employed to manage and mitigate ambient PM. We propose a framework for the management of PM that considers the entire impact pathway of PM, from source to the receiving environment. We argue that the management of PM needs to be approached holistically, considering the initial design of new sources, the atmospheric conditions influencing the transport and transformation of PM and its precursors, and the susceptibility of the receiving environment. We critically evaluate the success of different approaches that have been employed to manage and mitigate ambient PM.

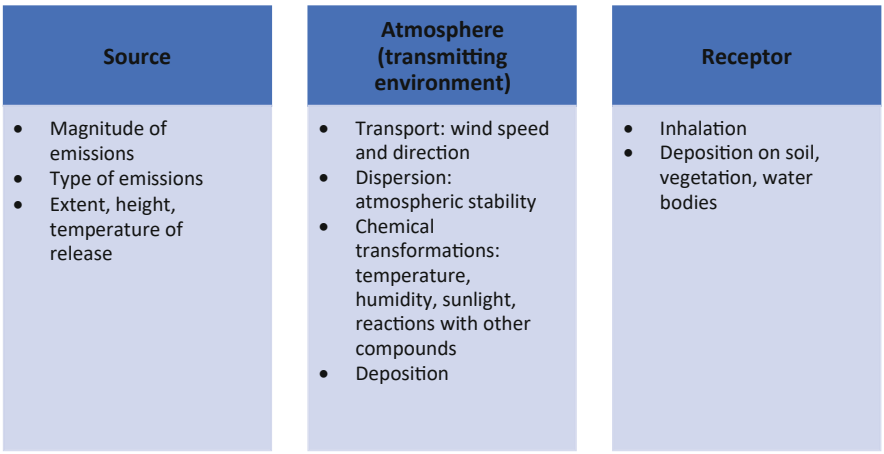

Fig. 11.1 Framework for the management of ambient particulate matter

11.2 Framework for the Management of Ambient PM

PM management typically focuses on the control of sources of PM and its precursor gases. However, there is not a linear relationship between source strength and magnitude of the impact, or even between emissions and ambient PM concentrations. A holistic approach to PM management is required. The nature of the source, the atmosphere that transports and hosts the formation of secondary PM, and the receiving environment all need to be considered (Fig. 11.1).

11.2.1 Source

The magnitude and type of emissions from a source and the configuration of that source affect the magnitude and geographical extent of the contribution that a source makes to ambient PM concentrations. PM is either emitted directly (known as primary or filterable PM when released by point sources) or is emitted as a gas and reacts to become a liquid or solid in ambient conditions (secondary or condensable PM). Direct emissions of PM are often mechanically generated and large in size (in the coarse mode). Emissions of PM precursor gases, commonly SO_2, NO_x, NH_3 and VOCs, are usually a product of combustion. These gases oxidise and then in the presence of water vapour form acidic solutions (sulphuric and nitric acid) and then particulates (sulphates and nitrates).

The chemical composition of PM affects their impact on human health, the climate and the environment. While most fine secondary particulates (like sulphates) reflect shortwave radiation before it reaches the earth's surface (and so have a localised cooling effect on climate), some compounds like clay minerals and black

carbon absorb shortwave radiation and warm the atmosphere, affecting local lapse rates. High concentrations of hygroscopic particles that absorb water vapour from the air (like ammonium sulphate and sodium chloride) can suppress the formation of raindrops when ingested into clouds. There is still considerable uncertainty about the health effects of the different PM components. Black carbon (from the incomplete combustion of biomass and fossil fuels) and organic carbon (from biomass burning and vehicle emissions) have been most decisively linked with all-cause and cardiovascular mortality and morbidity. There is also evidence that the inhalation of secondary aerosols (like sulphates, nitrates and ammonium) and metal elements (particularly K, Si, Zn, V and Ni) is linked to adverse health effects (Yang et al. 2019). In terms of impact on the environment, acid deposition of sulphates and nitrates is of particular concern (Vet et al. 2014). All hygroscopic particles contribute to haze (Gao et al. 2017).

PM sources can be classified as continuous, which is the case for many industrial processes, or intermittent, like blasting operations at a mine. PM sources are also classified either as point sources (which range from stacks at large power plants to exhausts of individual motor vehicles) or as non-point sources, also called fugitive emissions. Point sources are typically easier to control because there is only one point of release to the atmosphere. Emission control approaches for point sources are discussed in Sects. 11.3.1, 11.3.2 and 11.3.3, while approaches for fugitive emissions are discussed in Sect. 11.3.4.

11.2.2 Atmosphere: The Transmitting Medium

PM is transported and transformed between the source and the receptor in the atmosphere. Prevailing winds determine the direction in which emissions are transported. Winds can be a result of synoptic-scale processes, like the passing of a westerly wave, or local and regional airflows like mountain valley winds and land–sea breezes. Knowledge of prevailing winds should be used when siting new developments, to ensure that sources are downwind of areas where people live.

Dispersion of PM in the vertical is determined by the rate of change in air temperature with height, termed the stability of the atmosphere. Under unstable conditions, when temperature drops more rapidly with height than rising air cools adiabatically (due to expansion in lower pressure), vertical motion occurs freely. Under stable conditions, the most severe of which is an inversion when temperature increases with height, vertical motion is suppressed and pollution becomes trapped. Unstable conditions are common during the day when shortwave radiation heats the earth's surface, and stable conditions are common at night when there are no clouds, and wind speeds are low. The mixed layer through which PM and its precursors may be dispersed is typically much higher in the middle of the day (hundreds of metres), and it collapses to a few tens of metres at night. It is possible to schedule some emitting activities to maximise dispersion and minimise impact at the surface. Surface sources should ideally release emissions in the middle of the day when they are spread through turbulence and diluted throughout the mixed layer.

Conversely, emissions from tall stacks are unable to move to the surface during stable conditions at night (and so have a minimal impact) but may be carried to the surface in turbulent eddies during the day. High-emission episodes like the rapping of electrostatic precipitators should be scheduled for the night. Stacks can be configured to mitigate the impact of their emissions on the surroundings by increasing the height and temperature of the release. This allows for greater dispersion before a plume comes to the ground, but also increases the area of impact of the source.

The atmosphere also provides the medium for the formation of secondary PM. In non-cloudy conditions, the conversion of SO_2 to SO_4^{2-} occurs mainly during the daytime, by reaction with the OH radical. The conversion rate in the gaseous phase increases with increasing temperature and relative humidity and is estimated to vary between 1% h^{-1} and a maximum of 10% h^{-1}. The conversion of SO_2 to sulphates proceeds much more rapidly in the aqueous phase, with conversion rates of over 50% h^{-1} possible. The conversion of NO_x to the nitrate radical NO_3 and nitric acid HNO_3 occurs much more rapidly during the day than the SO_2 conversion does, by reaction of NO_2 with OH. Gaseous-phase conversion of NO_x at night and aqueous-phase conversion of NO_x proceed extremely slowly and are almost insignificant relative to the daytime rate of gaseous conversion. SO_2 and NO_x conversion rates are highly dependent on the composition of the atmosphere. NO_3 reacts relatively rapidly with a variety of organics, which are often available in polluted air. Conversely, SO_2 and NO_x conversion rates usually are lower in a plume and polluted air due to oxidant limitations, but higher in the background air. Sulphuric and nitric acids then react with alkaline substances to form salts, notably the ammonium compounds NH_4NO_3 and $(NH_4)_2SO_4$ (Hewitt 2004).

Secondary organic aerosols (SOAs) can also be formed from biogenic volatile organic compounds (BVOCs), which are produced by vegetation. Once BVOCs come in contact with atmospheric oxidants, they undergo photochemical degradation to form gas-phase oxidation products. As a result of various heterogeneous reactions of gaseous precursors, SOA is formed, i.e. called biogenic secondary organic aerosols (BSOAs) (Boy et al. 2019; Marais et al. 2016; Xu et al. 2015). There are lots of chamber studies and fieldworks done regarding BSOA, but understanding the dynamics of formation and characterisation of BSOA is still challenging (Mauree et al. 2019; Oberdorster et al. 2005).

Since direct PM emissions are usually in the coarse mode, they are deposited fairly rapidly after release under gravitational settling. As such, the impact of direct PM emissions (such as from agricultural activities or a discard facility) is usually confined to within a few kilometres of the source. Secondary PM in the fine fraction is most effectively removed from the atmosphere by precipitation, but may remain suspended in the atmosphere for many weeks in the absence of precipitation. This can lead to pollution being carried across national borders and between continents. In the Northern Hemisphere, for example, it was found that acidification of forests and lakes in Europe and North America in the 1960s was often due to emissions from another country or even another continent. Resolving transboundary air pollution requires cooperation between countries. The first international treaty to deal with

transboundary pollution was the United Nations Economic Commission for Europe (UNECE) Convention on Long Range Transboundary Air Pollution (CLRTAP). It entered into effect in 1983 and is currently supported by 51 states in Europe, Canada and the USA. Significant success has been achieved in reducing emissions of PM precursor gases since the CLRTAP came into effect, with SO_2 emissions in Europe reducing by around 80% and NO_x emissions reducing by roughly 50% since 1990. Ambient PM levels in Europe and the USA have decreased by around 33% between 2000 and 2012 (Maas and Grennfelt 2016).

The interplay between meteorology and atmospheric chemistry in particular environments can have a profound effect on ambient PM levels in that environment. Secondary PM contributes significantly to the severe winter haze episodes in China, for example (Gao et al. 2017). It has been found that both changing synoptic systems and general climatic conditions in different regions affect secondary PM production. The formation of secondary PM is enhanced ahead of a cold front due to the uplift of precursors and the elevated humidity that facilitate heterogeneous and aqueous-phase reactions (Wang et al. 2019). Secondary organic aerosol production is mainly caused by aqueous-phase processing in the northern regions of Guanzhong and Beijing–Tianjin–Hebei where relative humidity is higher during pollution events regions. In the Pearl River Delta region to the south, secondary organic particulates are formed preferentially by photochemical reactions in relatively higher temperatures and stronger solar radiation (Garland et al. 2009; Rose et al. 2011; Wang et al. 2019). Topography plays a controlling role in Mexico City, which is situated in a basin surrounded by high mountains. The high frequency of surface and temperature inversions and poor ventilation result in the accumulation of PM in Mexico City (Kretzschmar 1994), to the extent that monthly mean PM concentrations in winter exceed the World Health Organisation's 24-h limit value (WHO 2019).

The transmitting medium is not always the outdoor atmosphere but can also be the air indoors. In an indoor environment, the energy efficiency and ventilation of the dwelling control PM concentrations. More energy-efficient dwellings, such as are achieved through air sealing and insulation, are associated with lower emissions of PM and precursor gases, both at household level where less fuel is needed for space heating and at a regional level where demand for electricity from fossil fuel power plants reduces. However, the draft proofing lowers air exchange rates, resulting in the accumulation of pollutants indoors unless the ventilation is improved (Underhill et al. 2020). Effective ventilation lowers indoor PM levels in areas where ambient PM levels are lower than indoor levels (e.g. in sub-divided housing units in Hong Kong) (Cheung and Jim 2019), but may actually raise indoor PM concentrations in areas where ambient PM levels are high. In low-income housing in Mumbai, for example, indoor $PM_{2.5}$ concentrations have been found to be mainly determined by the infiltration of ambient $PM_{2.5}$ into the household environment. In areas where solid fuel burning for residential heating and cooking is common, indoor PM concentrations are often higher than ambient concentrations in the morning and evening when household stoves are in use, but lower than outdoor concentrations in the middle of the day when other sources of PM contribute to ambient levels

(Adesina et al. 2020). The differential between indoor and outdoor PM levels needs to be considered when designing ventilation. Initiatives that have been adopted to reduce emissions from residential burning and the impact thereof are discussed in Sects. 11.3.3 and 11.4.3.

11.2.3 Receptor

The primary motivation for ambient PM management initiatives is the negative impact of PM exposure on human health. The intake fraction, defined as the mass of the pollutant inhaled by the exposed population per unit mass released from a source (Bennett et al. 2002), is a useful metric for evaluating the impact of emissions from a source on a group of people. The intake fraction for an indoor source can be 2–3 orders of magnitude higher than for an outdoor source (Lai et al. 2000), and even indoors can vary by a factor of three depending on the proximity of the emission to the person inhaling it (Licina et al. 2017).

The impact of PM on a receptor also depends on the susceptibility of the receptor. When considering the impact on human health, foetuses, young children, older people and those with existing medical conditions like cardiovascular disease, high blood pressure and diabetes are particularly vulnerable to exposure to PM (Royal College of Physicians of London 2016).

Some environments are more susceptible to acid deposition than others. Towards the end of the twentieth century, serious ecological impacts such as forest dieback and acidification of freshwater bodies, with resultant biodiversity and productivity impacts, were attributed to the deposition of acidic species (acid rain). The control of acid deposition requires the management of the emissions of the precursor species such as NO_x, SO_2 and NH_3 (Conradie et al. 2016; Galloway 1995; Josipovic et al. 2009). Acidifying material is deposited primarily through wet deposition, although the dry deposition of particulates such as ammonium nitrate salts may play an important role in the acidification of soils. The impact on soils and subsequent productivity is dependent on a number of edaphic factors such as the buffering capacity of the soil.

A variety of mechanisms are employed to manage ambient PM levels. Impact assessment is usually conducted in the planning stages of a new development or facility and should inform the design of the development so that the impact of PM emissions on receptors is minimised. Regulations, whether they be of the command-and-control type like emission standards or market-based mechanisms, are usually informed by ambient PM measurements and compliance with national ambient standards or the WHO guidelines. Regulations may target behaviour or stipulate time of emissions, for example, through vehicle traffic management plans, but they more commonly focus on controlling emissions from sources. Emissions can be regulated either through specifying process inputs, for example through fuel standards, or emission limits (either as concentrations normalised to a stipulated percentage of oxygen or as mass per unit of production) at the point of release to the atmosphere. Social upliftment programmes may be initiated when a more coercive

approach is not appropriate. This mainly pertains to the use of solid or liquid fuels by low-income households out of necessity and may take the form of providing access to cleaner sources of energy or lower-emitting cooking devices, for example. Here, we first review technical PM source mitigation measures in Sect. 11.3 and then broader PM management approaches in Sect. 11.4.

11.3 Emission Control Approaches

Technical measures to reduce emissions of PM and its precursor gases may be implemented before, during or after combustion (Table 11.1). Pre-combustion measures are designed to reduce the impurities in the fuel that is burnt, either by removing the impurities through a beneficiation/purification process, or by substituting a cleaner fuel for a dirtier fuel. Combustion efficiency can be optimised to minimise the amount of fuel that needs to be burnt, and to reduce the formation of polluting compounds during combustion. For example, high-temperature combustion results in the formal of 'thermal NO_x' from the breakdown of N_2 and O_2 in the air into N and O atoms and subsequent formation of nitric oxide (NO). The formation of thermal NO_x can be reduced by ensuring a more uniform temperature distribution throughout a furnace and keeping combustion temperatures as low as possible (Skalska et al. 2010). Sorbents can also be used during the combustion process to remove pollutants directly from the furnace/combustion chamber. Post-combustion control technologies are mature and usually remove an extremely high proportion of the PM or precursor gas from the flue gas/exhaust stream. These technologies either transform the toxic/polluting emissions into less harmful compounds, or remove the PM and precursor gases from the flue gas through a scrubbing process.

Historically, the first emission control initiatives were directed at particulate emissions. In the fourteenth century, King Edward I of England banned coal burning in London when parliament was in session due to the smoke produced (Kouimtzis and Zouboulis 1995). Studies into sulphur removal started in the mid-nineteenth century, and the first large-scale flue gas desulphurisation unit was installed in 1931 at the Battersea Power Station in London (A History of Flue Gas Desulfurization Systems Since 1850 1977).

Table 11.1 Emission control approaches for pre-combustion, during and post-combustion

Pre-combustion	Combustion	Post-combustion
• Substitute cleaner fuel • Remove impurities from fuel	• Improve efficiency • Improve combustion conditions • Sorbent injection	• Transformation of pollutants • Scrubbing of pollutants

11.3.1 Stationary Point Sources

11.3.1.1 Pre-combustion Treatment

Fuel substitution and fuel cleaning before combustion are two approaches that can be employed to reduce emissions of PM and precursor gases. Examples of fuel substitution are using diesel in place of heavy fuel oil or converting a process to run on natural gas rather than coal. Globally, there has been a move from coal to natural gas for power generation and industrial activity. In the USA, for example, 121 coal-fired electricity generation units were repurposed to burn other types of fuel between 2011 and 2019 (Aramayo 2020). Most of these conversions were to natural gas (103), with 86 coal-fired boilers converted to burn natural gas, and 17 coal-fired units retired and replaced with new natural gas-fired combined cycle plants. A further 18 coal-fired units were reconfigured to burn other fuels, like petroleum coke, wood waste solids and waste materials from pulp and paper production.

For many applications, fuel can be treated before combustion to remove some of the sulphur, nitrogen and ash in the fuel that are converted to air pollutants during combustion. Coal beneficiation, for example, uses mechanical and washing processes to remove the mineral matter (ash) from the coal. Inorganic sulphur and trace elements like antimony, arsenic, cobalt, mercury and selenium are removed along with the pyrite. Beneficiated coal has a higher energy content (higher quality) than raw coal (Miller 2005).

Integrated gasification combined cycle systems join gasification, gas cleaning and gas/steam turbine technologies to produce electricity from coal at the efficiency of a gas turbine and with the emissions of a natural gas-fired power plant (Holt 2003; Wang 2017; Xia et al. 2020). Coal is gasified with oxygen or air to form a synthetic gas (syngas) of mainly carbon monoxide and hydrogen. The syngas is cooled, and impurities like sulphur species and PM are removed before being combusted in the gas turbine.

11.3.1.2 Combustion Modification

Of the pollutants discussed in this chapter, combustion modification is most commonly used to address NO_x formation, and can reduce NO_x emissions by 30–70% for boilers, and by 70–85% for gas turbines. NO_x production can be reduced through combustion modification by reducing the temperature of combustion (the formation of thermal NO_x becomes significant at temperatures of above 1033 K), creating oxygen deficient conditions, controlling the air and fuel mixing ratio and varying the residence time in the different parts of the combustion chamber. A number of measures are employed to achieve this. Limiting excess air in the furnace to below 2% reduces NO_x formation. Low NO_x burners reduce NO_x formation by 30–50% by controlling air and fuel mixing to achieve staged combustion. Over fire air can be used in conjunction with low NO_x burners and injects combustion air into the furnace above the normal combustion zone. This creates a fuel-rich primary combustion zone and fuel lean, cooler secondary combustion zone. Thermal NO_x formation can also be reduced by injecting water or steam near the burner flame to reduce the flame temperature and oxygen content. Flue gas recirculation involves

injecting no more than 30% of the flue gas back into the secondary air stream before entering the boiler to lower flame temperature and reduce oxygen concentration (Skalska et al. 2010).

Circulating fluidised bed (CFB) combustion controls both NO_x and SO_2 emissions. A CFB furnace comprises a bed of granular solids, including fuel, fuel ash, sorbent (limestone, lime or dolomite) and other inert bed materials like sand or gravel. The bed is supported by primary combustion air entering at the furnace floor. Bed solids are injected into the lower part of the furnace and are well mixed throughout the furnace. A lower temperature of combustion is sustained throughout the furnace, limiting NO_x formation. Long residence times and close mixing of fuel and air ensure complete combustion. The SO_2 released during combustion is removed by combining with the suspended limestone/dolomite particles. As they exit the furnace, coarse sorbent and unburnt coal particles are recovered in a cyclone or separator and recycled back into the combustor. Finer solid ash particles and spent sorbent exiting the furnace are collected downstream of the gas–solid separator by an electrostatic precipitator or fabric filter plant (Basu and Scott 1991; Sarkar 2015).

11.3.1.3 Post-combustion Treatment

PM

Particulate emission abatement technology is selected based on the nature of the process producing the emissions, the emission limit to which the facility needs to comply and the required removal efficiency of the technology. There needs to be a correspondence between the size range of particulates produced from different processes, and the size ranges over which emission control systems are effective. Particulates can be extracted/removed from a flue gas stream by several processes, including mechanical collection, centrifugal separation (in cyclones), filtration, electrostatic precipitation and scrubbing (Kouimtzis and Zouboulis 1995). Particles are removed from the flue gas stream to a collection space and then dislodged into a hopper, from where they are conveyed to a disposal facility. Disposal systems can be wet or dry. Even if a dry disposal facility is selected, the dust is usually conditioned with water to facilitate the conveying and handling of the material. A brief description of the main abatement technologies for filterable PM follows.

- Mechanical collectors make use of gravitational settling in a slow-moving gas stream or inertia. Since mechanical collection depends on the mass of particles, it is only effective for coarse material and is usually used in conjunction with other particulate removal devices (Kouimtzis and Zouboulis 1995).
- Cyclone separators use centrifugal force to collect medium-sized PM (15–40 μm). The flue gas enters a spinning cylindrical vessel through a tangential inlet. The particles are separated out through centrifugal acceleration, move to the outside wall of the vessel and are then collected in a cylindrical hopper at the base of the cyclone. Cyclones used to be the most widely used PM abatement system, but have been replaced with more efficient removal systems as legislated emission standards have become stricter (Kouimtzis and Zouboulis 1995).

- Fabric filters are highly efficient and capture even very fine particulates. The fabric used depends on the temperature of the gas stream. Fine particles are not able to be captured by the fabric itself, since the pores in the filter cloth are generally larger than the particles that need to be trapped, but rather by the dust layer or 'cake' that builds upon the filter. As dust accumulates on the filter, it causes a drop in pressure across the filter. The filter can be shaken, flushed backwards with air or given a sharp pulse with compressed air to dislodge the dust which then falls into a hopper and is removed to the disposal facility (Kouimtzis and Zouboulis 1995).
- In electrostatic precipitators, particles are ionised in an electric field between a discharge electrode wire and a collecting electrode plate. Particles are attracted to the collection plates by the electrostatic force, and the plates are then rapped to dislodge the collected particles. Particles with higher resistivity (typical of fly ash of low sulphur coal) take longer to become charged, which reduces the collection efficiency of the electrostatic precipitator. Flue gas conditioning plants inject small amounts of sulphur trioxide, ammonia, sodium salts or water into the flue gas to lower the resistivity and increase the collection efficiency of the particles (Shanthakumar et al. 2008).
- Wet scrubbers use a liquid to separate particulates from the flue gas stream. Atomised droplets collect particles by impaction and then agglomerate as they decelerate. The scrubbing liquid is then removed from the flue gas stream (Kouimtzis and Zouboulis 1995).

11.3.1.4 Precursor Gases: SO_2 and NO_x

SO_2 is mostly emitted from coal-fired power plants, waste incineration, sulphuric acid manufacturing, clay brick plants and nonferrous metal smelters. Some processes have low concentrations of SO_2 in the flue gas (like power plants and clay brick kilns), while others have high SO_2 concentrations (such as smelter operations) (Deng and Baeyens 2019). SO_2 removal systems are classified as either once-through or regenerable, depending on how the spent sorbent is handled. Once-through systems dispose of the by-product or use it for another application. Regenerable systems recycle the sorbent back into the FGD system (Romero and Wang 2019). Both wet and dry systems are used for post-combustion SO_2 removal. Wet systems produce a liquid slurry waste. Dry systems inject a dry sorbent, and a dry waste/by-product is produced (Romero and Wang 2019). Low SO_2 concentration removal usually relies on a disposable reactant, while high SO_2 concentration flue gases are water scrubbed and the resulting liquid is concentrated to a commercially saleable sulphuric acid (Deng and Baeyens 2019). Limestone-based once-through wet FGD is used on around 95% of installed capacity globally (Zhang et al. 2015). A limestone slurry is sprayed on the flue gas in the spray tower. The SO_2 reacts with the $CaCO_3$ in the slurry to produce gypsum, which is either disposed of or used in the construction industry if it is of sufficiently high quality (Deng and Baeyens 2019).

Two main approaches can be followed for post-combustion NO_x removal: removing the NO_x from the flue gas stream or transforming the NO_x to a non-toxic compound (Skalska et al. 2010). The most used NO_x removal technology for power plants is the selective catalytic reduction (SCR) by ammonia, which

converts NO to N_2 and H_2O, and which can reduce NO_x emissions by 80–90%. A catalyst is used to facilitate the reaction. Selective noncatalytic reduction (SNCR) achieves lower NO_x removal rates than SCR (between 30 and 75%) but is cheaper and easier to operate because a catalyst is not used. Physical processes involving adsorption on activated carbon and absorption in alkaline solutions can also be used but are not common in commercial settings. In the chemical industry, NO_x concentrations are higher in the exhaust gases, and the ratio of NO to NO_2 is highly variable. End-of-pipe NO_x removal is performed by absorption in alkali solutions, reduction with hydrogen, methane or ammonia, or scrubbing (Skalska et al. 2010).

Multi-pollutant abatement technologies are also emerging, like electron beam flue gas treatment that removes both SO_2 and NO_x. The irradiance of flue gas with fast electrons produces active radicals that react with SO_2 and NO_x to form sulphuric and nitric acids. These are then converted to ammonium sulphate and ammonium nitrate in the presence of ammonia and filtered from the flue gas (Skalska et al. 2010).

11.3.2 Non-stationary Point Sources

11.3.2.1 Vehicle Emissions

Vehicles contribute to ambient PM levels through the emission of NO_x formed during high-temperature combustion in internal combustion engines, SO_2 formed due to oxidation of sulphur in the fuel, and primary PM consisting of elemental carbon (EC) also known as soot, high and low volatility organics, ash from lubricants and metallic particles from wear (Johnson et al. 1994; Saxena et al. 2020; Sonwani et al. 2021b). Particulates are formed by a suboptimal fuel:air mixing ratio fuel inside the combustion chamber, mainly during the cold start and warm-up phases of the engine (Piock et al. 2011).

Significant progress has been made in removing impurities from liquid fuels prior to combustion, and levels of both lead and sulphur have been significantly reduced over the past decades. Tetraethyllead was added to gasoline from the 1920s to improve vehicle performance and fuel economy. After it was realised that elevated ambient lead concentrations are particularly harmful to children's developing brains, lead was phased out of gasoline from the 1970s (Needleman 2000). Sulphur compounds are removed from crude oil during the refining process to meet the legislated limits of allowable sulphur in fuels (Saleh 2020). Sulphur also reduces the effectiveness of vehicle emission control technologies such as catalytic converters and diesel particle traps. Sulphur concentrations in diesel were successively reduced and are now less than 15 ppm in most of the developed world (UNEP 2018). Blending ethanol with gasoline, such as has recently been mandated in China, reduces emissions of primary fine particulate matter (but increase emissions of NO_x) (Liang et al. 2020).

The formation of particulates during combustion is minimised by a number of measures. The warm-up of the engine is speeded up, and the air and fuel delivery into the combustion chamber is optimised to promote the mixing of air and fuel. Deposits of residues on combustion chamber walls are avoided (Piock et al. 2011).

In the exhaust system, particulate filters are used to minimise emissions of primary particulates. Three-way catalytic converters are installed on the exhausts of most gasoline engines to remove NO_x, CO and hydrocarbons. The primary reaction in a three-way catalytic converter is the reduction of NO by CO to produce N_2 and CO_2 (Skalska et al. 2010). Diesel and lean-burn gasoline engines cannot achieve NO_x reduction by means of a three-way catalyst. Instead, diesel oxidation catalyst (DOCs) and diesel particle filters (DPFs) are used to reduce emissions of hydrocarbons, carbon monoxide and soot from diesel engines. For NO_x removal, the selective catalytic reduction is preferred for most vehicles with large and mid-size engines. The NO_x storage catalyst method is preferred for small vehicles (Olabi et al. 2020). The NO_x storage catalyst technology works by oxidising NO over precious metals to NO_2, which combines as nitrates with NO_x storage compounds. Then, the nitrate ions released from the storage area are reduced to nitrogen through reactions with hydrocarbons, hydrogen and carbon monoxide (Skalska et al. 2010).

The movements of mobile emission sources can also be regulated to achieve ambient PM targets. Policies to reduce vehicle emissions include the design of new roads to accommodate buses, cyclists and pedestrians; improved traffic management and public transport services; a slowdown in roadway investment; and restrictions to motor vehicle use in congested city centres. The first congestion charging system was introduced in Singapore in 1975. Road charging schemes now take many forms across the world, including area-wide schemes and tolling. Low-emission zones only admit heavy goods vehicles, buses and vans that meet stricter emission standards (Beevers et al. 2016).

Case Study: New Delhi Transportation System

To minimise the health burden due to air pollution in National Capital Territory Delhi, the government over decades has imposed a range of vehicle emission control strategies. The most notable intervention is the court-mandated conversion of all public transportation fleet buses, three wheelers and taxis to compressed natural gas (CNG). This was initially scheduled to be completed in 2001; however, due to technical difficulties with retrofitting so many vehicles (and the limited number of natural gas fuelling stations) the process was only completed in 2003. It has been reported that these various interventions, especially the conversion to CNG, have improved Delhi's air quality (Chelani and Devotta 2005; Kathuria 2002; Kumar and Foster 2009; Narain and Krupnick 2007; Ravindra et al. 2006; Khillare et al. 2008a, b).

The odd–even number plate scheme for private vehicles was also implemented to reduce the number of on-road private cars running on petrol and diesel. Vehicles were allowed to be driven in two phases for 15 days each in January and April (Kumar et al. 2017). Heavy-duty diesel vehicles are only permitted in Delhi City only during night times, i.e. from 10:00 p.m. to 05: 00 a.m. The latest addition to the reforms in the transport sector is the introduction of electric and other alternative fuel vehicles.

11.3.2.2 Ship Emissions

Ocean-going ships generally use low-grade heavy fuel oil or marine diesel oil and make a large contribution to ambient PM, SO_2 and NO_x levels in ports and coastal areas (Ni et al. 2020). It is estimated that in 2010, NO_x from ships accounted for 15% of global anthropogenic NO_x emissions, while SO_2 from ships accounts for 4–9% of global anthropogenic SO_2 emissions (Tzannatos 2010). Emissions from ships are regulated by the International Maritime Organization's Regulations for the Prevention of Air Pollution from Ships. Regional ship emission standards have also been introduced by the USA, European Union and China, and Emission Control Areas declared near the coasts of North America and Northern Europe (Baltic Sea and North Sea) where stricter emission limits apply (Lindstad et al. 2017).

As with other point sources, emissions of PM and precursor gases from ships can be controlled by treating the fuel, improving combustion and treating the exhaust gas. Alternative cleaner liquid fuels suitable for ships include biodiesel, liquid natural gas and ethanol. Biodiesel reduces PM emissions, but NO_x emissions may increase. Natural gas and methanol can reduce both PM and NO_x emissions. All the alternative fuels have much lower sulphur content (Ni et al. 2020).

In terms of combustion improvement, water injected into the cylinders can reduce NO_x formation (although some technologies may increase PM emissions). High-pressure common rail fuel injection for marine diesel engines reduces NO_x and PM emissions by improving air/fuel mixing and optimising combustion (Ni et al. 2020).

Post-combustion, SCR is used to reduce NO_x emissions, and a scrubber installed on a large ship can reduce SO_2 emissions. There are several available technologies for reducing PM exhaust emissions, but they are still immature and not widely employed. A diesel particulate filter is one of the most effective technologies for PM removal (achieving PM emission reductions of more than 90%), but becomes clogged when used with high sulphur HFO (Ni et al. 2020).

The choice of emission control approach depends on many factors, including vessel size. For example, Lindstad et al. (2017) recommended that for control of sulphur emissions, fuels with less than 0.5% sulphur content (like desulphurised HFO, distillates (diesel) or LNG) are more cost-effective for smaller vessels, while sulphur removal scrubbers are a better option for larger vessels.

11.3.3 Residential Burning

The burning of solid and liquid fuels for residential heating and cooking is pervasive in many parts of the world. It is estimated that exposure to fine particulate matter from the use of solid fuels is responsible for 1.6 million premature deaths per annum (Stanaway et al. 2018). These 'dirty fuels' and inefficient cooking devices are often used either because households do not have access to cleaner energy carriers or because the cleaner alternatives are unaffordable. In such low-income areas, PMs from cooking and heating activities are often supplemented in the ambient environment by the burning of household waste (a consequence of inadequate waste removal services), PM generated on unpaved roads and a number of other sources.

The residential use of solid fuels is not restricted to low-income areas, however. Around 12.5 million homes in the USA used wood for space heating, at least some of the time, in 2015 (US Energy Information Administration 2018). In Europe, it was estimated that domestic wood stoves accounted for 25% of $PM_{2.5}$ emissions in 2005 and that wood burning emissions were contributing an increasing proportion of $PM_{2.5}$ with time (Amann et al. 2005; Sigsgaard et al. 2015). In the southern half of Chile, residential wood burning contributes up to 90% of ambient $PM_{2.5}$ concentrations (Boso et al. 2019; Villalobos et al. 2017).

In low-income communities, solid fuels are typically burnt over an open fire or in highly inefficient devices, like the *imbaula* (self-fabricated braziers) in South Africa and the stone and clay *chulhas* in India. Combustion is far from complete under such conditions, and the relatively low temperature of combustion results in the emission of toxic organic compounds, which adsorb onto particles and are particularly harmful to health (Park et al. 2018).

Emission reduction initiatives focus on switching to cleaner fuels (pre-combustion) and improving the efficiency and completeness of the combustion process. In areas where space heating is a driver of residential solid fuel use, improvements to the quality of housing may also reduce the need for solid fuel use.

Interventions to help households to transition up the energy ladder to cleaner energy carriers are often implemented as social upliftment programmes that more generally improve quality of life, and are discussed in Sect. 11.4.3. Devolatilised low-smoke coal formed during pyrolysis (char) is found to reduce emissions of PM, VOCs and SO_2 from a coal stove by 80%, 90% and 35%, respectively (Kühn et al. 2017), and has the potential to significantly lower ambient PM levels in coal-using residential areas (Engelbrecht et al. 2002). It has also been found that washing wood to mimic the natural rain leaching process before combustion can reduce total PM emissions by between 18% and 53%, depending on the type of wood. However, washing does result in an increased amount of the PM mass being emitted in the ultrafine range (<1 μm) (Schmidt et al. 2018).

Since incomplete combustion is the source of most PM and precursors, improved cookstoves have been touted as an obvious solution to mitigate emissions from household solid fuel burning. The improved cookstoves take many forms and use many fuels, for example microgasifying cookstoves and sawdust pellets in Zambia (Peša 2017; Sonwani and Prasad 2016), methanol stoves in South Africa (Makonese et al. 2020) and biomass updraft stove modified to use apple pruning waste (Rasoulkhani et al. 2018). Programmes have been rolled out in many countries for at least the last four decades, but success has been variable. Improved cookstoves have been most widely adopted in China, where it is estimated that over 100 million of the over 148 million cookstoves distributed from the 1980s onwards were still in use in 2010 (Sesan 2014). In contrast, very few solid fuel-using households in sub-Saharan Africa have improved cookstoves, and India's improved cookstove programmes have been deemed failures (Khandelwal et al. 2017). Peša (2017) argues that improved cookstove programmes need to consider all actors throughout the cookstove and fuel value chain. Social and economic context need to be considered in addition to the technical aspects of the stove. For improved cookstove

technologies in particular, the context of use is extremely important for implementation. Numerous reasons have been identified for the failure of the Indian cookstove programmes, including failure to substitute the full utility value of the traditional chulhas that are replaced, the disappointing performance of the cookstoves in a real-world context, and the additional labour and altered cooking practices that may be required (Khandelwal et al. 2017).

Case Study: Coal-to-Gas Project in China

The 'Air Pollution Prevention and Control Action Plan for Beijing, Tianjin, Hebei and Surrounding Areas' passed by the Chinese government in 2017, legislates a variety of comprehensive measures to improve ambient pollution levels in Beijing, Tianjin, and 26 other cities in northern China. The 'coal-to-gas' project entails replacing part of the coal-based central heating system with a gas-based system (Zhao et al. 2020). No coal combustion is allowed in designated coal-restricted areas, and households are provided with gas subsidies (Xu and Ge 2020).

At the end of 2017, there was a large-scale shortage of natural gas because of significant shortfalls in production from the Tianjin LNG terminal and the pipeline supply from Turkmenistan. This shortage has persisted in some areas. Gas supply is also interrupted by blockages in or shutdowns of the gas pipelines. Natural gas users also report that subsidies are insufficient and only support about 50% of residents' energy demand (Xu and Ge 2020).

Despite these implementation hiccups, it has been found in Xianghe County that concentrations of SO_2, PM_{10} and $PM_{2.5}$ decreased significantly between the winters of 2017 and 2018 (decreases of 47%, 21% and 13%, respectively), but NO_x levels increased by 48% and particulate nitrate concentrations also increased. The increased NO_x concentrations are ascribed to the increased use of gas for heating, and not meteorological factors or motor vehicles (Zhao et al. 2020).

11.3.4 Fugitive Emissions

There are a number of processes that result in broad-scale emissions of PM from the land surface. These include the aeolian production of dust when there is limited vegetation cover either as a result of low vegetation cover such as in arid or semi-arid regions with erodible soils, or where there has been a disturbance to the soil cover such as during construction, mining or agricultural processes (Marticorena and Bergametti 1995; Pierre et al. 2015; Pozzer et al. 2012). Control mechanisms primarily focus on either reducing the wind speed at the surface, such as by improving the surface cover or reducing the erodibility of the surface material through wetting the surface or applying a binding agent.

11.4 Management Approaches

11.4.1 Impact Assessment Tools

The effective management of ambient PM requires the integration of several different tools, which are often dependent on different groups of expertise, and therefore, a multi-disciplinary approach is required. The first part of the understanding is to quantify the emissions of both the primary PM and the PM precursors. These may come from very different sources, which may require different techniques and expertise to quantify the emissions. The emission profiles from large industrial point or multi-point sources typically require a detailed engineering understanding of the facility under consideration and either the use of continuous emission monitoring in the stacks or the use of emission factors based on the activity being carried out. There are a number of well-regarded documents of emission factors (e.g. the US-EPA Compilation of Air Emission Factors, or others that have been specifically developed for that industry). Spatially dispersed sources may require a different approach, typically the aggregation of multiple small-scale point sources into an area source, for example for domestic combustion within a residential area. Various types of emission models could be applied to broader areas, for example models of biogenic emissions for various vegetation units (Gonzalez-Abraham et al. 2015; Sonwani et al. 2016). The development and validation of these models typically require field-based measurements for their parameterisation and validation (Jaars et al. 2014, 2016).

Once PM and precursors have been emitted to the atmosphere, these particles undergo a variety of transformations, which need to be accounted for. These chemical processes are represented in various models at differing levels of sophistication. At the simplest level, Gaussian dispersion models like CalPuff have very limited chemical schemes and can only model a few reactions (Bruwer and Kornelius 2017). Other chemical transport models, however, have a much greater library of chemical transformations (Janhäll 2015; Kljun et al. 2015; Malcolm and Manning 2001; Schuhmacher et al. 2004; Zunckel et al. 2004) and can therefore model the atmospheric chemistry more effectively but at a considerably greater computational cost. The dispersion models or chemical transport models use a variety of modelling approaches to move the particulate matter through the landscape based on the surface and meteorological conditions, and from that an ambient concentration can be predicted at various points across the landscape of interest to predict the impact that this may have on communities or ecosystems.

11.4.2 PM Management Regulations

Regulatory approaches to air quality management typically have a two-pronged approach. Firstly, many jurisdictions have set ambient air quality standards. These

are the concentration limits that are stipulated for ambient air and are primarily based on the health impact for communities exposed to air pollution (Saxena and Sonwani 2019a). In the case of particulate matter, ambient standards are generally based on two size classes, those being $PM_{2.5}$ and PM_{10} and are issued for differing averaging periods, both an annual mean concentration and a 24-h mean concentration (Saxena and Sonwani 2019b). In some cases, a certain number of exceedances of the 24-h mean concentrations are allowed. The WHO (2006) has issued ambient annual and daily air quality guidelines, and also a number of interim targets. Each of the interim targets is associated with an increase in health risk compared to the guideline value.

A second level of control is applied at the source of emissions. For large industrial sources, the control may be through the setting of emission limits in order to legislate the maximum amount of pollutant that is released from the facility. With these larger sources, it is often appropriate and required to implement continuous emission monitoring. This is typically done in the emission stacks and is normalised to a standardised temperature and relative oxygen content. For smaller emission sources such as motor vehicles or small boilers, which would be near impossible to monitor continuously, the control point is through the emission limits applied to the specifications of the source. In some cases, regular testing of the emissions will be needed as part of the licensing conditions.

Case Study: Emission Trading Programmes

As an alternative to the command-and-control regulatory approach, market-based mechanisms are also employed in parts of the world for the control of PM precursor gases, SO_2 and NO_x. Emission trading programmes typically operate by setting a national (or regional) cap on emissions. This cap is then divided up between regions and ultimately between individual facilities or boilers as permits. The permits are allocated based on historical heat input, emissions or production. Permits usually need to be purchased from the allocating authority, and can then be traded between facilities at a market-based price. The emissions cap is usually reduced over time. Such a market-based mechanism is intended to achieve emission reductions at the least cost.

A sulphur emission trading scheme was implemented in the USA from 1995 under the 1990 Clean Air Act Amendments, initially what facilities. Initially this allowed the inclusion of substitute units in the trading scheme to allow flexibility in the range of emission reduction measures implemented. A NO_x Budget Trading Programme commenced thereafter in the USA between 2003 and 2007 for large stationary point sources in 19 states. Facilities are required to reduce their emissions from May to August each year when ozone levels are highest. China also introduced a sulphur dioxide emissions trading programme in 2007 in 11 provinces that accounted for just over 50% of industrial emissions (Ren et al. 2020).

(continued)

Analyses show that these cap-and-trade schemes are effective in lowering emissions (Ren et al. 2020). The ability to trade between facilities allows for flexibility in terms of the technologies and measures adopted by facilities to reduce emissions. In the USA, the preferred method for SO_2 emission reduction was initially to switch to or blend with low sulphur coal, and then to reduce emissions at a substitution unit that was voluntarily enrolled by the utility in the programme. Only a minority of the plants installed scrubbers (Ferris et al. 2014).

11.4.3 Social Upliftment Programmes

With the notable exception of China, where the 'coal-to-gas' project for residential heating in the Beijing–Tianjin–Hebei region is legislated (see case study), initiatives to reduce emissions from residential burning usually take the form of social upliftment programmes.

As households become more affluent, they tend to progress up the 'energy ladder', abandoning traditional and more polluting fuels like wood and dung in favour of cleaner gas or electricity, which enables many more utilities (Hosier and Dowd 1987; Leach 1992). Rapid and consistent progress has been made in connecting households to national electricity grids. In 2018, almost 90% of the world's population had access to electricity (World Bank 2020). A notable exception is sub-Saharan Africa, which is lagging the rest of the world and is now home to two-thirds of the world's people who do not have access to electricity (Ritchie 2019).

However, even when households have access to a convenient and less polluting energy carrier like electricity, they often resort to the use of solid fuels, called 'energy stacking' (Brouwer and Falcao 2004; Campbell et al. 2003; Leach 1992). The inability to afford the cleaner energy carrier is one reason for preferring solid/liquid fuels (O'Keefe and Munslow 1989; Wickramasinghe 2011). The multi-utility provided by a wood or coal stove, the more effective space heating provided by solid fuels and cooking preferences are other reasons for energy stacking (Masera et al. 2000).

Energy subsidies are provided in a number of ways to promote the use of cleaner energy carriers by low-income households. Certain types of fuel may be subsidised. For example, in India, kerosene is subsidised (Rao 2012). Kerosene is widely used for lighting and also as a back-up fuel for cooking and in the event of frequent electricity outages. These types of subsidies are often criticised for being inefficient and benefitting higher-income households more than lower-income households (Arze del Granado et al. 2012). Only 26% of the total value of India's kerosene subsidy reaches households, and rural households derive very little benefit from the subsidy because they only use a small fraction of their quota for lighting (Rao 2012).

Pricing structures in which the costs of energy increase with increasing consumption are another way of subsidising energy for low-income households. An increasing block electricity tariff has been in place for the residential sector in China since 2012, both to encourage the frugal use of electricity and to promote electricity use among low-income households (Liu and Lin 2020). The first 'block' of electricity is even free, for example in South Africa where at least the first 50 kWh per month is free for indigent households in terms of their free basic electricity policy (Ye et al. 2018). Unfortunately, it appears that many households are either not aware of electricity subsidies provided in this form or do not understand how they work (Liu and Lin 2020).

The provision of government housing and slum resettlement programmes also have the potential to reduce indoor PM concentrations through improving the ventilation and the energy efficiency of houses. More energy-efficient dwellings, achieved through air sealing and insulation, are associated with lower emissions of PM and precursor gases, both at household level where less fuel is used for heating and at a regional level where demand for electricity or heating from regional fossil fuel-fired plants reduces. The energy efficiency measures often have the unintended consequence of lower air exchange rates, resulting in the accumulation of pollutants indoors (Underhill et al. 2020). Effective ventilation lowers indoor PM levels in areas where ambient PM levels are generally low (as has been found for sub-divided units in Hong Kong, for example (Cheung and Jim 2019)), but may raise indoor PM concentrations in areas where ambient PM levels are high. In a slum resettlement scheme in Mumbai, it was found that initiatives to reduce indoor emissions, through improved cookstoves, for example, were not effective in lowering indoor PM concentrations because of the infiltration of ambient PM into the household environment (Lueker et al. 2020). In areas where solid fuel burning for residential heating and cooking is common, indoor PM concentrations are often higher than ambient concentrations in the morning and evening when household stoves are in use, but lower than outdoor concentrations in the midday and afternoon when other sources contribute to ambient PM levels (Adesina et al. 2020). This suggests that the ventilation needs to be designed so that emissions are effectively exited from the house when the stove is in use, but outdoor pollution cannot enter the house.

11.4.4 Vegetation Management

An increasingly feasible strategy to mitigate ambient PM pollution is to use the natural features of vegetation. Numerous researchers have shown that plants are natural air phytoremediators and have a higher potential to reduce ambient PM among the common air pollutants (Cai et al. 2017; Nowak 1994; Yli-Pelkonen et al. 2017). They act as air filters to capture large quantities of PM from the environment via dry deposition onto their surfaces, as can be seen from the scanning electron microscope (SEM) images in Fig. 11.2 (Kończak et al. 2021). However, the effectiveness of plants to retain PM on their surfaces is influenced by various morphological and anatomical leaf traits (e.g. plants type, leaf area index and leaf

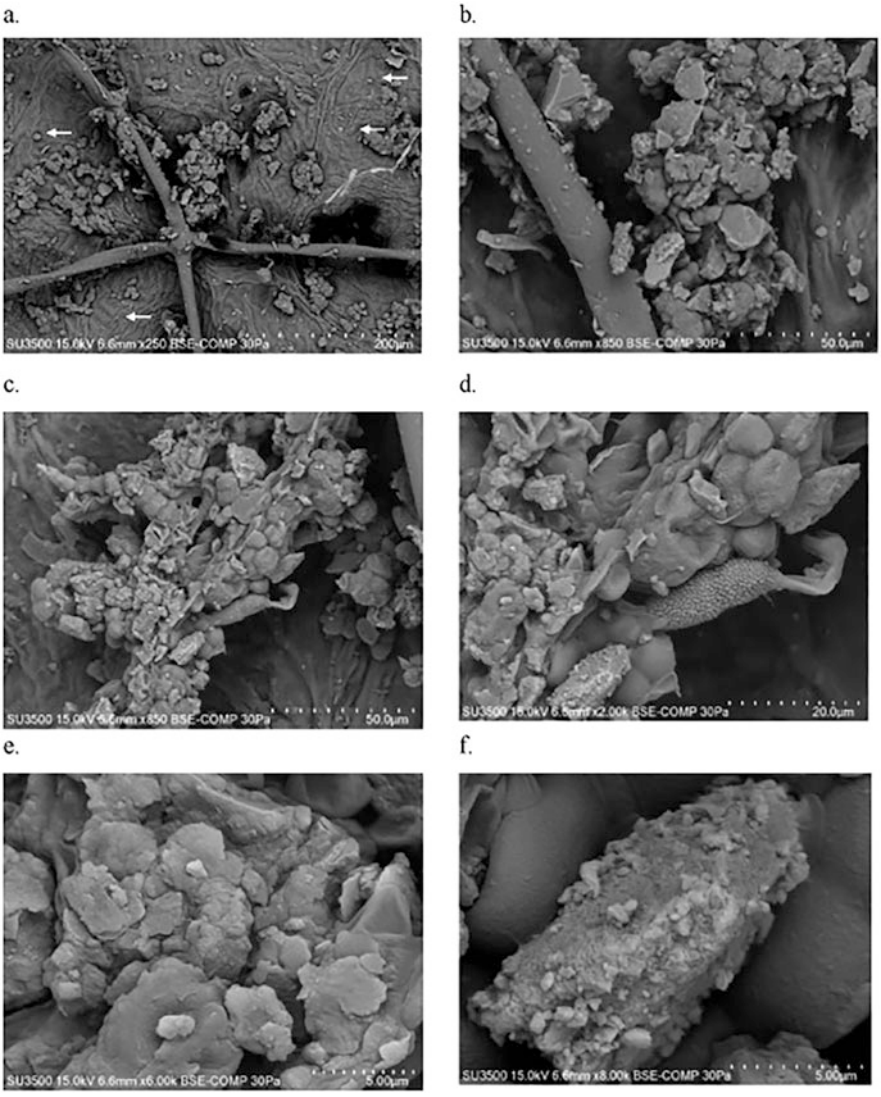

Fig. 11.2 Morphology of PM accumulated on the surface of leaves and in the corners of hair (SEM images): (**a**) surface of a leaf of the species Tilia cordata Mill with a layer of waxes and hairs (the arrow indicates anthropogenic particles immersed in wax); (**b**) PM accumulated near the hair; (**c**) geogenic particles together with particles of biogenic origin; (**d**) biogenic particle (plant fragment); (**e**) anthropogenic and geogenic particles; (**f**) geogenic particle (Kończak et al. 2021)

microstructure), accumulated within plant wax, resuspended to the atmosphere or washed off by rain, or dropped to the ground with leaf, needle or twig fall (Gakidou et al. 2017; Prusty et al. 2005; Przybysz et al. 2014; Räsänen et al. 2013; Song et al.

2015). Thus, vegetation may only be a temporary retention site for many atmospheric particles and can impact local air, water and soil quality.

Several studies have assessed the PM retention capacities across different species (Dzierzanowski et al. 2011; Lu et al. 2019; Mo et al. 2015; Mori et al. 2015; Zhou et al. 2020). A study conducted in the city centre of Beijing, China, over a year found that 772 tons of PM_{10} were removed by vegetation (Yang et al. 2005). Model studies conducted in Chicago, Illinois, used the iTree model and estimated that around 234 tons of PM_{10} would reportedly be removed if 11% of the city area were covered by trees (McPherson 1994; Nowak 1994). Also, approximately 215,000 tons of PM_{10} are removed by urban trees in the USA every year (Nowak et al. 2006). Still, more information in this area is needed to improve PM filtering performance of vegetation.

In general, eco-services provided by vegetation interventions assist in improving the health and well-being of the urban population in several ways (Abhijith et al. 2017; Sonwani and Maurya 2018; Kim and Miller 2019). Furthermore, vegetation could contribute to a range of other benefits such as urban heat island mitigation (Hami et al. 2019), storm water management (Dhakal and Chevalier 2017), CO_2 sequestration and noise abatement (Berardi et al. 2014; Gratani and Varone 2013), urban biodiversity (Borysiak et al. 2017) and climate change mitigation (Matthews et al. 2015). In this way, vegetation can contribute to achieving the United Nation sustainable development goal 3 'good health and well-being' and 11 'sustainable cities and communities'.

However, vegetation can also contribute to air pollution (an ecosystem disservice) through the emission of biological pollutants such as biogenic volatile organic compounds (BVOCs), pollen and fungal spores. BVOC emitted by vegetation, in particular trees, can play a crucial role in the biosphere–atmosphere interactions, which can contribute to photochemical ozone (O_3) production in the troposphere (Calfapietra et al. 2013).

11.5 Conclusions

Effective PM emission management considers the entire impacts pathway, from source to receptor. For point sources, consideration of the role that the atmosphere plays in transporting and transforming PM and its precursors should influence the siting of new sources relative to other sources and sensitive receptors. The atmosphere can only really be controlled in an indoor environment. Here, ventilation needs to be designed to maximise ingress of cleaner air from outdoors, but minimise airflow when ambient PM levels are higher than indoor levels. If possible, intermittent activities can be planned to coincide with times when dispersion potential is the greatest. For example, surface burning and vehicle traffic should be minimised between the evening and early morning, while emissions from tall stacks should be minimised at midday when turbulence can bring undiluted plumes to the surface.

Point source emission abatement technologies are mature and have effectively reduced emissions in areas where they have been implemented. Cost is a barrier to implementation in some parts of the world. More widespread/diffuse sources of PM and precursors are harder to control because technology needs to be specific to the local environment, and success depends on how it is implemented.

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Particulate Matter Regulatory Policies: National and Global Approach

12

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Abstract

Decreasing air quality has posed a great threat to humans health and environment. The rising concentration of particulate matter (PM) in the ambient air has made the condition even worse. PM includes smoke, fumes, soot, and other combustion by-products, and also natural particles such as wind-blown dust, sea salt, pollen, and spores. Rapid increase in the concentration of PM has been observed from different sectors, i.e., transport sector, household sector, and industrial sector. Various sectors have been dealt in different chapters of this book. In this chapter, various regulatory policies about particulate matter have been dealt in transportation sector. Various regulations, i.e., improved vehicle engines, fuel regulation, alternative fuels, traffic management activities, operating restriction and pricing, lane and speed management, traffic flow control, odd–even strategy, vehicle sharing systems, improved transit systems, and lane and speed management, are followed around the world. Standards play a crucial role in regulatory mechanism and need to be encouraged to reduce science–policy gap.

Keywords

Standards · Particulate matter · Air pollution · Source apportionment · Air quality

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S. Sonwani, A. Shukla (eds.), *Airborne Particulate Matter*,
https://doi.org/10.1007/978-981-16-5387-2_12

12.1 Introduction

Air pollution levels in most of the metropolitan cities and industrial zones around the world exceed the national and international air quality standards. Increased air pollution levels have direct impact on human health as recognized by scientific research. Various studies indicate that long- term exposures to air pollution lead to increased risk of illness and death from ischemic heart disease, lung cancer, chronic obstructive pulmonary disease (COPD), lower respiratory infections (e.g., pneumonia), stroke, and type 2 diabetes (Kim et al. 2011; Sonwani et al. 2021, 2022). Air pollution has contributed to approx. 6.67 million deaths worldwide, which are 12% of global total. Long- term exposures to ambient particulate matter ($PM_{2.5}$) pollution contribute to global burden of deaths of approx 4.14 million deaths accounting to 62% of all air pollution attributable deaths. This burden is largely borne by most populous countries, i.e., China (approx 1.42 million $PM_{2.5}$—attributable deaths) and India (approx 980,000 PM 2.5—attributable deaths) (SoGA 2020). Recent study by Dasadhikari et al. (2019) noted the change in premature mortalities due to air pollution. Between 2010 and 2015, excluding the effects of changes in population distribution or other social factors, sustained economic activity led to an estimated 99,000 additional premature mortalities annually primarily in India, Indonesia, and Bangladesh. This chapter is an attempt to understand the regulations of particulate matter (PM_{10} and $PM_{2.5}$) in major countries with major emphasis on transport sector.

12.2 Particulate Matter (PM): A Global Concern

Particulate matter (PM) is a widespread air pollutant, which consists of a mixture of solid and liquid particles suspended in the ambient air. PM is a mixture with physical and chemical characteristics depending upon the location and source of PM. Commonly, PM includes chemical constituents like sulfates, nitrates, ammonium, and inorganic ions such as sodium, potassium, calcium, magnesium, and chloride; organic and elemental carbon, metals like cadmium, copper, nickel, vanadium zinc, and particle -bound water, crustal material, and polycyclic aromatic hydrocarbons (PAHs) (Saxena and Sonwani 2019a). In addition to that, biological components such as microbial compounds and allergens are also found in PM (WHO 2016). Particulate matter (PM) consists of mixture of solid and liquid particles and widespread suspended in ambient air. Fine particulate, i.e., PM_{10} and $PM_{2.5,}$ majorly accounts for health damage. PM_{10} represents the particle mass that enters the respiratory tract, and moreover, it includes both the coarse (particle size between 2.5 and 10 μm) and fine (less than 2.5 μm) particles that are considered to contribute to the health effects observed in urban environments. Coarse particles are generally produced by mechanical processes like road dust resuspension, construction activities, and wind, while the fine particles originate primarily from combustion sources (Saxena et al. 2021). Coarse and fine particles are present in most urban environment, but the proportion of particles in these two size ranges is likely to vary significantly between different cities around the world, and it depends on the local

meteorology, geography, and source of specific PM sources. Emission from anthropogenic sources tends to be in fine fractions. However, some industrial and other processes that produce large amounts of dust, such as cement manufacturing, mining, and stone crushing larger than 1 micron and mostly large than 2.5 microns. In transport sector, the engines primarily emit PM with a diameter less than 2.5 micrometers ($PM_{2.5}$) (Zanobetti et al. 2014). Traffic -related emissions may make a substantial contribution to the concentration of suspended particulates in areas close to traffic. Some agro industrial processes and road traffic represent additional anthropogenic sources of mostly coarse particulate emissions. The largest stationary sources of particulate emissions include fossil fuel- based thermal power plants, metallurgical processes, and cement manufacturing (Saxena et al. 2017). The physical and chemical composition of particulate emission is determined by the nature of pollution sources. Most particles emitted by anthropogenic sources are less than 2.5 microns in diameter and include a larger variety of toxic elements than particles

Table 12.1 Sources of origin and main components of coarse ($PM_{10–2.5}$), fine ($PM_{2.5}$), and ultrafine ($PM_{0.1}$) primary particles (Source: Adapted from Guevara 2016)

PM fraction	Sources of origin	Main components	Contribution[a]
Coarse particles ($PM_{10–2.5}$)	Agricultural activities	Agricultural soil, OC	+++
	Traffic resuspension	Road dust	+++
	Wind-blown dust/construction and mining activities/industrial resuspension	Si, Al, Ti, Fe	+++
	Tyre and brake wear	Cu, Zn	++
	Combustion in energy and manufacturing industries (coal, coke, heavy oil)	EC	++
	Wind-land fires and volcanoes	Volcanoes' ashes, burned OC	+
	Biological sources	Plant debris and fungal spores	+
	Ocean spray	Na, Cl, Mg	+
Fine ($PM_{2.5}$) and ultrafine particles ($PM_{0.1}$)	Diesel-fuelled vehicle engines	BC	+++
	Biomass combustion	OC, PAHs	+++
	Maritime traffic	BC, OC, SO_4^{-2}	++
	Combustion in energy and manufacturing industries	Pb, Cd, As, Cr, V, Ni, Se, SO_4^{-2}	++
	Processes in non-metallic industries	Si, Al, Fe	+
	Metal processing activities	Pb, Cd, Cr, Zn	+

[a]+++ high contribution; ++ medium contribution; + low contribution

emitted by natural sources. Major sources of particulate matter and its main components are given in Table 12.1.

12.2.1 Understanding Standards

Each nation builds their own air quality standards[1] according to the approach adopted for balancing health risks, technological feasibility, economic conditions, and social and political factors. These standards are observed as a mechanism to share knowledge about a product and its design, its characteristics, and its impact (Brown et al. 2010). Standard is defined as a:

> *"[A]document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context* (ISO 2018)*"*.

While standardization is defined as

> *"[A]n activity of establishing, with regard to actual or potential problems, provisions for common and repeated use, aimed at the achievement of the optimum degree of order in a given context"*. (ISO/IEC Guide 2:1996, definition 1.1)

According to Brunsson and Jacobsson (2000) in their book, '*world of standards'* gave an interesting view about standards and standardization. According to them, standards generate a strong element of global order in modern world; they create control, homogeneity among producers, people, and organization. They are instruments of control and help in classifying things in standardized manner (p. 4). Standards are forms of rules similar to laws, documented in some manner but are voluntary in nature, while default rules are also argued to be similar to standards as they are voluntary and make non adherence difficult but at the same time they are different as they are invisible and users have lack of awareness surrounding them (Kerwer 2005). Even though standards are voluntary in nature, they are considered as significant governance mechanisms (Thévenot 2009; Brunsson and Jacobsson 2000). Moreover, they are powerful tool to challenge and alter institutionalized behavior and identities (Brunsson et al. 2012).

[1] Air pollution monitoring program started way back in 1968 by experts of World Meterological Organization (WMO), which formed the stepping stone of first global background air pollution monitoring network (Köhler 1988). Later transboundary movement of air pollution was observed, and need to protect people and environment from this transboundary movement of air pollution was emphasized. For reduction in transboundary movement of air pollution, convention on Long Range Transboundary Air Pollution (CLTRAP) was signed in 1979. Air quality guidelines using expert evaluation of scientific evidence was first produced by WHO in 1987, which was later updated in 1997.

Standards are directed at those actors, i.e., individual or organizers who are able to decide for themselves, whether to act according to standards or not. They act as actor only when they have choice to take a decision. When they have capacity to act and choose, the propensity to choose particular standard will depend on who they are and what is the situation (Brunsson and Jacobsson 2000, p. 131). Standards can also be seen as knowledge, generated by certain group (usually expert) or certain type of knowledge can readily be considered as standards. This knowledge is aimed generally to some categories and is directed toward potential adopters who have defined identity and situation (Brunsson and Jacobsson 2000, p. 133). The standards can be *product standard* (specification and criteria for the characteristics of products) and *process standard* (criteria for the way the products are prepared) (FAO website).[2] Standards can also be distinguished into *de jure* and *de facto* standards. *De jure* standards are "established through institutions involved in standards setting," while *de facto* are selected by the market between competing technologies and are developed outside the traditional standardization framework. They are also called as non-consensus standards (Aurelie and Throne-Holst 2012). This study would not be entering into the understanding of intricacies of abovementioned standards as it restricts itself to air quality standards. As a policy instrument, standards are noted to be inferior in reducing environmental externalities when compared to taxes. Taxes are considered as superior based on neo-classical model of rational consumer choice according to which when consumers face proper price signals,[3] they will make efficient choices. Pigouvian tax and standards can be considered as complementary instruments for higher social welfare rather than substitutes (Tsvetanov and Segerson 2013). Another critique about standards comes from Shove and Moezzi (2002), and they emphasized that standards often favor dominant designs. It brings expectation and convention in their wake (Shove and Moezzi 2002). As most of critiques are given from the perspective of developed countries, it is crucial to analyze how it shapes in different contexts, i.e., developing nations where air pollution patterns are different from their developed counterparts.

12.2.2 Standards for PM

The guidelines recommended by WHO include the heterogeneity and also recognize the scope of acceptance of these guidelines by different countries. WHO guidelines also acknowledge that different national governments can consider their local conditions of the country before accepting the guidelines. For particulate matter, WHO has notified following standard:

[2] Standards accessed from http://www.fao.org/3/Y5136E/y5136e07.htm

[3] Price signal is the information provided to consumers and producers, which is reflected through price charged from consumer or producers, which in turn gives a signal about the quantity of product to be produced or demanded.

$$PM_{2.5} : 10\ \mu g/m^3\ 24\text{-h}\ \text{annual mean}$$
$$25\ \mu g/m^3\ 24\text{-h mean}$$

$$PM_{10} : 20\ \mu g/m^3\ \text{annual mean}$$
$$50\ \mu g/m^3\ 24\text{-h mean}$$

As thresholds have not been recognized, therefore, identifying any standard or guideline value will not provide required protection against all possible adverse health effects of particulate matter. It is imperative to set standards, which reach the lowest concentration possible in context of local constraints, capabilities, and public health requirements. All countries try to adopt strict set of standards based on current scientific findings for PM according to their local context and global need. These standards can help reduce the adverse short- and long- term health impact of PM on human health and environment. Although PM_{10} is the more widely reported measure, and also the indicator of relevance to the majority of the epidemiological data, the WHO Air Quality Guidelines for PM are based on studies that use $PM_{2.5}$ as an indicator. The $PM_{2.5}$ guideline values are converted to the corresponding PM_{10} guideline values by application of a $PM_{2.5}/PM_{10}$ ratio of 0.5. A $PM_{2.5}/PM_{10}$ ratio of 0.5 is typical of developing country urban areas and is at the bottom of the range found in developed country urban areas (0.5–0.8). When setting local standards, and assuming the relevant data are available, a different value for this ratio, i.e., one that better reflects local conditions, may be employed (WHO 2018). For example, Air Quality Standards of European Union (EU) and USA are different from each other as they are formed as per their local criteria and political requirements, i.e., EU monitors more number of compounds as compared to WHO recommendations, whereas the National Ambient Air Quality Standards (NAAQS) of USA regulate nitrogen oxides, sulfur dioxide, carbon monoxide, ozone, lead, and particulates. It is important to note that particle pollution is regulated under two categories of particles based on established information on differences in sources, properties, and atmospheric behavior, to provide protection against potential health effects associated with short- and long- term exposure to particles. USA follows primary (health-based) and secondary (welfare- based) NAAQS for particulate matter.

The annual $PM_{2.5}$ NAAQS is set to address human health effects from chronic exposure to the pollutants. The 24-h standard is set to address human health effect from short -term or seasonal exposure to the pollutants. Current allowable $PM_{2.5}$ daily concentrations are set at 35 micrograms per cubic meter ($\mu g/m^3$), and annual concentrations are set at12 $\mu g/m^3$ (Liang et al. n.d.). In India, NAAQS were revised in 2009, which led to uniform standards for $PM_{2.5}$ concentrations across all regions. The standards of $PM_{2.5}$ and PM_{10} of various countries are given in Table 12.2 (Narita et al. 2019).

The State of Global Air Report (2020) report noted that highest annual average exposures of PM 2.5 that exceeded the WHO Air Quality Guidelines of 10 $\mu g/m^3$ were seen in Asia, Africa, and Middle East. This also relates to lower

Table 12.2 Standards of $PM_{2.5}$ and PM_{10} in select countries (Source: authors' compilation)

S. No	Country	Act	Agency	Year	$PM_{2.5}$ (24 h) μg/m^3	$PM_{2.5}$ (annual) μg/m^3	PM_{10} (24 h) μg/m^3	PM_{10} (annual) μg/m^3
1	India	Air (Prevention and Control of Pollution) Act, 1981	CPCB	2009	60	40	100	60
2	USA	Clean Air Act	EPA	1987	35 35	12 15	150 150	
3	E U	Directive 2008/50/EC[a]	European Parliament and Council	2008	20 (AEI)	na	50	40
4	China	GB 3095-2012[b]		2012	35 (C-I), 75 (C-II)	15 (C-I), 35 (C-II)	50 (C-I), 150 (C-II)	40 (C-I), 70 (C-II)
5	Thailand	National Environment Quality Act, 1992	Pollution Control Department	1995	50	25	120	50
6	Malaysia	Recommended Malaysian Air Quality Guidelines (RMG), 1989	Department of Environment	1996	35	15	150	50
7	Singapore	NA	National Environment Agency	2012	37.5	12	50	20
8	Australia	National Environment protection measure for ambient air quality	National Environment Protection Council	1998	25	8	50	25

[a]Directive 2008/50/EC introduced additional $PM_{2.5}$ objectives targeting the **exposure** of the population to fine particles. These objectives are set at national level and are based on the average exposure indicator (AEI). This is determined as a 3-year running annual mean $PM_{2.5}$ concentration averaged over the selected monitoring stations in agglomerations and larger urban areas, set in urban background locations to best assess the $PM_{2.5}$ exposure of the general population

[b]China's current air quality standards include two classes of limit values. Class 1 standards apply to special regions such as national parks. Class 2 standards apply to all other areas, including urban and industrial areas

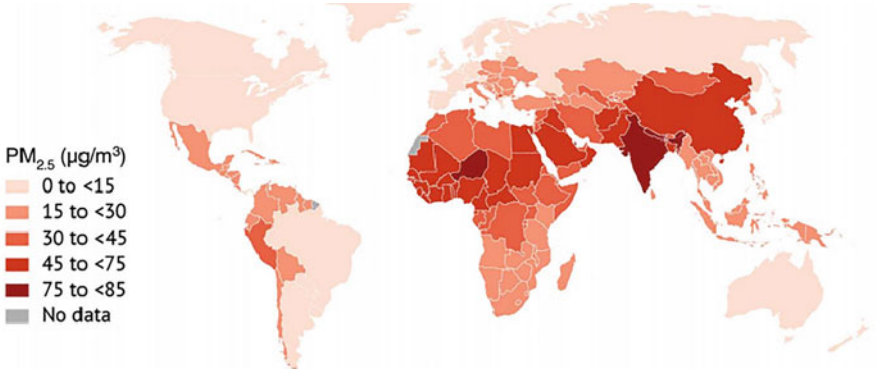

Fig. 12.1 Global map of population -weighted annual average $PM_{2.5}$ concentration in 2019. Source: State of Global Air Report (2020)

sociodemographic development and high exposures to $PM_{2.5}$ The countries with the lowest exposures (i.e., population-weighted annual average concentrations less than 8 µg/m^3) include Australia, Brunei Darussalam, Canada, Estonia, Finland, Iceland, New Zealand, Norway, Sweden, and the USA (Fig. 12.1).

12.3 Identifying PM Emission from Transport Sector

12.3.1 Road Dust

PM emission from road can be categorized into exhaust and non-exhaust components. Exhaust PM is emitted from tailpipe due to incomplete combustion of fuel in engine chamber, whereas factors affecting the total level of non-exhaust particulate emissions include ties and interaction with different road surfaces, brake pad/ shoe dust, operating characteristics of vehicles, type of road (paved and unpaved), and ambient weather conditions (temperature, rain, and wind) (Gwilliam et al. 2004). The primary particle emissions are emitted from exhaust along with emissions of gaseous particles precursors from combustion of fuels and lubricants from vehicles. Mechanical abrasion of brakes, clutch, tires, rotor, and muffler ablation also emits particles, which get deposited on to the road and then resuspend together along with mineral dust particles and road wear material (Amato et al. 2009; Correia et al. 2020; Cunha-Lopes et al. 2019). Non- exhaust particles from road traffic, domestic wood burning, cooking, and secondary organic aerosols are major contributors to air borne concentration of $PM_{2.5}$ (Harrison 2020). They mainly include trace elements (Ba, Cu, Mn, Pb, and Zn) from mechanical abrasion of brakes and ties and crustal species (i.e., Al, Ca, Fe, Mn, Si, and Ti) (Almeida et al. 2020).

12.3.2 Traffic

Heydari et al. (2020) in their recent study synthesized 155 studies on air pollution source apportionment for PM_{10} and $PM_{2.5}$ reported in World Health Organization (WHO) covering 169 cities worldwide. The study used Bayesian multi- level meta-regression, which allows capturing variations within and between studies with respect to their methods of estimations and study protocols. They found the traffic contribution to air pollution (PM) varies from 5% to 61% in cities worldwide (with average of 27%). The variability in traffic contribution estimates was found to be related to region of study, publication year, PM size fraction, and population. Average absolute $PM_{2.5}$ and PM_{10} concentrations due to traffic were noted to be lower in cities located in Europe, North America, and Oceania (5.43 μg/m^3 and 12.61 μg/m^3 vs. 17.689 μg/m^3 and 38.63 μg/m^3, respectively). Population was also directly found to be related to air pollution as $PM_{2.5}$ and PM_{10} concentrations were lower in cities with less than 500,000 people. The study also noted the increase in average absolute traffic-related concentrations globally after 2005. The $PM_{2.5}$ increased from 5.82 μg/m^3 before 2005 to 10.29 μg/m^3 after 2005 and PM_{10} increased from 14.13 μg/m^3 before 2005 to 20.41 μg/m^3 after 2005 due to rapid motorization of transport worldwide mainly in low- and middle -income countries. In another study, Karagulian et al. (2015) analyzed 419 source apportionment studies of 51 countries. They noted that in Central and Eastern Europe, main contributor of $PM_{2.5}$ is burning of biomass and fossil fuel for domestic use (32%), followed by traffic (19%), industry (17%), and other sources (16%). Table 12.3 identifies contribution of vehicle exhaust to ambient particulate concentrations in various studies:

12.4 Particulate Matter Regulation in Transport Sector

Various policies and programs have been introduced by countries for regulation of PM in transport sector in their respective regions to reduce its negative impact on environment and human health (Saxena and Sonwani 2019b). In transportation sector, various policies interventions are used to reduce the air pollution across nations, e.g., vehicle emission standards, traffic reduction methods, ban on polluting fuels, low -emission zones, congestion charging, innovation in public transport system, behavioral changes, and nudging the consumers by odd–even restrictions (Burns et al. 2019). East Asia including China and Japan has seen reduction of 76,000 additional premature mortalities due to electrification of railroads, newly introduced abatement measures, region-wide adoption of EURO standards complaint road vehicles, and enforcing fuel quality standards.

Road traffic is one of the major reasons of high concentrations of $PM_{2.5}$. Major regulation to reduce the $PM_{2.5}$ contribution from traffic includes improved vehicle engines, fuel regulation, alternative fuels, traffic management activities, operating

Table 12.3 Contribution of vehicle exhaust to ambient particulate concentrations (Source: Compiled by Authors)

Place	PM contribution	Technique/model	Time period	Source
Tianjin, China	21.1–23.5% of ambient PM 2.5	Positive matrix factorization (PMF)	Feb–Oct, 2016	Liu et al. (2020)
Delhi, India	14% of ambient $PM_{2.5}$	Various methods	2019	Singh et al. (2020)
16 cities of Europe and Central Asia	13% of ambient $PM_{2.5}$	Positive matrix factorization (PMF) receptor model	Jan' 2014–Dec' 2015	Almeida et al. (2020)
Asian residential community	38% of ambient PM_{10} and 40% of ambient $PM_{2.5}$	Lagrangian particle model (GRAL)	NA	Ling et al. (2020)
Athens, Greece	44% of ambient $PM_{2.5}$	Multi-linear regression (MLR)	June' 2017–Sept' 2017	Taghvaee et al. (2019)
Canada	16% of ambient $PM_{2.5}$	GEOS-Chem chemical transport model	2013	Meng et al. (2019)
New York	14.9% of ambient $PM_{2.5}$	High spatial resolution emission estimates	2010–2012	Kheirbek et al. (2016)
Delhi, India	21–55% of ambient PM_{10}	Analysis of emissions from on-road vehicles	1991–2011	Nagpure et al. (2016)
Los Angeles and Rubidoux	20% of ambient $PM_{2.5}$	Positive matrix factorization (PMF)	2002–2013	Hasheminassab et al. (2014)
Seattle	17% of ambient $PM_{2.5}$	Positive matrix factorization (PMF)	2000–2005	Kim and Hopke (2008)

restriction and pricing, lane and speed management, traffic flow control, odd–even strategy, vehicle sharing systems, improved transit systems, and lane and speed management (Bigazzi and Rouleau 2017; Holman et al. 2015). Various strategies are as follows:

(a) Traffic Management Strategies (TMS)
Traffic management strategies (TMS) are found to be crucial for mitigating emission, ambient concentration, and human exposure and health effects of traffic -related air pollution in urban areas. But effect of TMS on measured population exposure and public health outcomes has not been well studied. Moreover, lack of ex-post evaluations of implemented strategies, lack of studies of exposure and health impacts, and insufficient evaluation of spillover and indirect effects are acting as impediment to successful implementation of TMS (Bigazzi and Rouleau 2017).
(b) Harmonization of standards

Harmonization of standards reduces the production costs of vehicles and fuels and stimulates trade between various regions. Therefore, higher emphasis is given to harmonization of fuel quality standards worldwide by vehicle manufacturers, especially in the USA and EU. On the other hand, it is also important to note that various countries prefer regionally differentiated or city-specific standards, e.g., Brazil, Chile, India, and Mexico as harmonization is an expensive and complex process. With tightening of vehicle emission standards, fuel quality and vehicle technology have become integral part of regulation of air pollution in most of the nations and should be encouraged on a larger scale (Gwilliam et al. 2004).

(c) Emission regulation
Emission regulation (i.e., tier 3 in USA, LEV III in California, Euro 6 in EU, and BS-VI in India) resulted in lower vehicle emissions and further improvements in air quality. In USA, the federal tier 3 and California LEV III light duty vehicle (LDV) standards went into effect from 2015 till 2025. In EU, Euro 6 low duty vehicle (LDV) standard phased-in in 2015. In India, Bharat stage (BS) emission standards are enforced. BS standards are instituted by Central Pollution Control Board (CPCB), which is equivalent to Euro 6. Since April 1, 2020, Indian government has mandated that vehicle makers must manufacture, sell, and register only BS-VI vehicles. BS- VI grade auto fuel was introduced in 2018.

(d) Zero-emission vehicles (ZEVs)
Zero-emission vehicles (ZEVs) are vehicle that does not produce tail pipe emissions, which result in roadside emissions and improving local air quality. They can be pure battery electric vehicles (BEVs) or hydrogen fuel cell vehicles (FCVs) and plug-in hybrid electric vehicles (PHEVs also known as transitional ZEVs). Many countries are implementing ZEV programs, e.g., California, USA, and China (Winkler et al. 2018). India is also gradually moving toward adoption of electric vehicles in the transportation system to reduce its oil combustion, reducing pollution, and facilitate employment growth (NITI 2018). To reduce emissions, 200 low- emission zones (LEZs) have been established in 12 EU countries. They restrict the entry of vehicles based on the emission standards the vehicles were mainly constructed to meet.

12.5 Science–Policy Gaps in Regulation of Air Pollution

Strategies to reduce air pollution from mobile sources should be designed to be seen as in the private interests of the actors and social interest. Technological improvements and physical measures should be seen as complement to fiscal measures such as taxes, penalties, and subsidies. Special emphasis should be laid on developing countries as data sets are not available for them. Major reasons identified for lack of data sets are lack of personnel and technological assessment, and spatiotemporal and seasonal variations are not established. Lack of international emissions or source apportioned air quality data sets hinders the comparisons of effectiveness of urban strategies across cities (Heydari et al. 2020). Lastly, it is found

that it is important to increase public understanding of impacts of traffic on environment and population at large.

12.6 Conclusion

The air quality deterioration due to transport sector is on rise around the world. Developing countries and least developed countries are major contributors and sufferers due to lack of advanced and cleaner technologies in transport sector, inaccessibility to clean and green fuels, and absence of regulations. A standard for improving air quality is a crucial tool for regulation, especially for particulate matter. PM standards are not universal rather they are formulated to suit local conditions, which allow its better implementation. PM standards with major emphasis to transport sector are being explored in this study. The present chapter is an attempt to understand the policies and regulation related to PM in transport sector across the world.

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