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Nature of air pollution, emission sources, and management in the Indian cities

Sarath K. Guttikunda [a, b, *], Rahul Goel [a], Pallavi Pant [c]

[a] Transportation Research and Injury Prevention Program, Indian Institute of Technology, New Delhi, 110016, India
[b] Division of Atmospheric Sciences, Desert Research Institute, Reno, NV, 89512, USA
[c] Division of Environmental Health and Risk Management, School of Geography, Earth and Environmental Studies, University of Birmingham, Birmingham, B15 2TT, UK

HIGHLIGHTS

- Air quality monitoring in Indian cities.
- Sources of air pollution in Indian cities.
- Health impacts of outdoor air pollution in India.
- Review of air quality management options at the national and urban scale.

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ABSTRACT

The global burden of disease study estimated 695,000 premature deaths in 2010 due to continued exposure to outdoor particulate matter and ozone pollution for India. By 2030, the expected growth in many of the sectors (industries, residential, transportation, power generation, and construction) will result in an increase in pollution related health impacts for most cities. The available information on urban air pollution, their sources, and the potential of various interventions to control pollution, should help us propose a cleaner path to 2030. In this paper, we present an overview of the emission sources and control options for better air quality in Indian cities, with a particular focus on interventions like urban public transportation facilities; travel demand management; emission regulations for power plants; clean technology for brick kilns; management of road dust; and waste management to control open waste burning. Also included is a broader discussion on key institutional measures, like public awareness and scientific studies, necessary for building an effective air quality management plan in Indian cities.

1. Introduction

Air quality is a cause for concern in India, particularly in cities and air pollutants including particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), and ozone (O_3) often exceed the National Ambient Air Quality Standards (NAAQS). According to the World Health Organization (WHO), 37 cities from India feature in the top 100 world cities with the worst PM_{10} pollution, and the cities of Delhi, Raipur, Gwalior, and Lucknow are listed in the top 10 (WHO, 2014). A similar assessment by WHO, in 2011, listed 27 cities in the top 100. More than 100 cities under the national ambient monitoring program exceed the WHO guideline for PM_{10}.

In India, the national ambient standard for CO is better than the WHO guideline. The NO_2, SO_2, and O_3 standards are at par with the guidelines. However, the standards for PM_{10} (Aerodynamic diameter <10 μm) and $PM_{2.5}$ (aerodynamic diameter <2.5 μm) are lagging (comparative details in Supplementary Material).

As cities are increasing in size and population, there is a steady demand for motorized vehicles in both personal and public transport sectors. This puts substantial pressure on the city's infrastructure and environment, particularly since most Indian cites have mixed land use. For 40 cities highlighted in Census-India (2012), the key urban characteristics are presented in Table 1. The

* Corresponding author. Division of Atmospheric Sciences, Desert Research Institute, Reno, NV, 89512, USA.
E-mail addresses: sarath.guttikunda@dri.edu, sguttikunda@gmail.com (S.K. Guttikunda).

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Table 1
Cities at a glance.

City	AR	Pop	A	B	C	D	E	F	PM_{10} (μg/m^3)	SO_2 (μg/m^3)	NO_2 (μg/m^3)
Hyderabad	500	7,749,334	155	50%	14%	32%	70.82 (40)	No	81.2 ± 34.0	5.0 ± 2.4	22 ± 7.0
Vijayawada	79	1,491,202	189	26%	4%	21%		No	79. ± 14.9	4.6 ± 0.5	13.5 ± 3.1
Vishakhapatnam	159	1,730,320	109	36%	8%	21%		Yes	91.2 ± 34.8	11.9 ± 12.7	29.1 ± 13.8
Guwahati	145	968,549	67	10%	3%	80%		No	132.6 ± 89.9	8.1 ± 3.3	16.6 ± 5.3
Patna	86	2,046,652	238	32%	10%	29%		No	138.8 ± 84.4	5.3 ± 2.8	32.9 ± 18.8
Korba	39	365,073	94	43%	8%	56%		No	116.9 ± 17.	13.3 ± 0.7	21.3 ± 0.8
Raipur	95	1,122,555	118	38%	9%	48%	65.85 (63)	No	272.2 ± 43.3	17.8 ± 3.7	45.9 ± 2.7
Delhi	669	16,314,838	244	39%	21%	9%		No	260.1 ± 117.1	6.5 ± 4.2	51.1 ± 17.2
Ahmedabad	275	6,352,254	231	51%	13%	24%	75.28 (22)	No	94.3 ± 21.8	15.9 ± 3.5	20.9 ± 4.0
Rajkot	86	1,390,933	162	60%	10%	33%	66.76 (59)	No	105.6 ± 27.	11.3 ± 2.1	15.4 ± 2.6
Surat	155	4,585,367	296	44%	9%	28%	57.9 (79)	No	89.1 ± 13.1	18.6 ± 3.9	26.3 ± 3.2
Vadodhara	145	1,817,191	125	60%	14%	20%	66.91 (57)	No	86. ± 34.6	16.2 ± 5.8	30.2 ± 13.1
Vapi	37	163,605	44	44%	11%	32%	88.09 (2)	No	78.3 ± 8.1	16.4 ± 1.9	23.9 ± 1.7
Yamuna Nagar	41	383,318	93	42%	13%	24%		No	281.5 ± 132.3	12.7 ± 2.7	27.1 ± 3.3
Dhanbad	45	1,195,298	266	31%	5%	72%	78.63 (13)	No	164. ± 95.5	16.6 ± 3.5	41. ± 8.9
Jamshedpur	119	1,337,131	112	49%	12%	38%	66.06 (61)	No	171.7 ± 13.4	36.4 ± 2.2	49.3 ± 3.9
Ranchi	106	1,126,741	106	43%	13%	36%		No	178.9 ± 67.9	18.1 ± 2.2	31.6 ± 3.0
Bangalore	556	8,499,399	153	46%	18%	20%		No	109.4 ± 92.6	15. ± 3.1	37.5 ± 6.0
Jammu	123	651,826	53	48%	25%	13%		No	118.2 ± 37.4	8.2 ± 4.4	12.7 ± 3.4
Trivandrum	108	1,687,406	156	34%	17%	43%		Yes	62.9 ± 17.8	9.7 ± 5.2	26.1 ± 5.2
Bhopal	178	1,883,381	106	48%	15%	30%		No	118.5 ± 73.2	7.1 ± 2.4	17.5 ± 5.9
Gwalior	78	1,101,981	141	45%	8%	29%	54.63 (83)	No	227.7 ± 84.6	8.6 ± 1.9	16.8 ± 4.1
Indore	102	2,167,447	212	50%	13%	17%	71.68 (38)	No	160.6 ± 73.4	9.4 ± 4.3	16.4 ± 6.5
Jabalpur	104	1,267,564	122	46%	8%	34%		No	135.7 ± 13.0		24.3 ± 2.1
Ujjain	33	515,215	156	40%	6%	26%		No	78.4 ± 42.0	10.9 ± 3.4	11.9 ± 3.1
Shillong	46	354,325	77	9%	16%	42%		No	78.8 ± 31.0	19.4 ± 19.0	12.5 ± 5.4
Amritsar	90	1,183,705	132	50%	15%	21%		No	188.7 ± 24.2	14.8 ± 2.2	35.1 ± 3.1
Chandigarh	115	1,025,682	89	47%	26%	27%		No	79.9 ± 32.6	5.8 ± 0.5	15.4 ± 7.8
Ludhiana	167	1,613,878	97	50%	19%	19%	81.66 (10)	No	251.2 ± 21.9	8.4 ± 2.3	36.2 ± 7.0
Chennai	426	8,917,749	210	47%	13%	17%		Yes	121.5 ± 45.5	12.1 ± 3.5	20.8 ± 7.0
Agra	129	1,746,467	135	48%	12%	27%	76.48 (19)	No	184.1 ± 95.9	6.6 ± 3.5	20.8 ± 12.1
Allahabad	71	1,216,719	171	54%	11%	26%		No	165.3 ± 70.7	3.6 ± 1.0	23.7 ± 15.9
Firozabad	21	603,797	288	25%	4%	40%	60.51 (75)	No	195.6 ± 78.2	21.6 ± 4.8	32.1 ± 4.9
Kanpur	150	2,920,067	195	11%	3%	42%	78.09 (15)	No	211.5 ± 25.3	7.5 ± 1.2	31.3 ± 4.9
Lucknow	240	2,901,474	121	52%	15%	20%		No	200.4 ± 28.4	8.4 ± 1.0	36.1 ± 2.6
Varanasi	102	1,435,113	141	40%	7%	29%	73.79 (29)	No	125.3 ± 8.4	17.2 ± 0.7	19.6 ± 0.7
Asansol	49	1,243,008	254	27%	4%	61%	70.2 (42)	No	162.7 ± 98.7	9.4 ± 3.1	61.8 ± 18.5
Durgapur	56	581,409	104	27%	4%	61%	68.26 (52)	No	172.5 ± 107.1	9.8 ± 3.2	63.9 ± 18.6
Kolkota	727	14,112,536	194	12%	9%	34%		No	160.8 ± 109.3	17.3 ± 15.4	59.7 ± 27.8

Notes: AR = build-up area (in km^2) is estimated from Google Earth maps; A = population density (per hectare); B = % households with a motorized two wheelers; C = % households with a four wheeler; D = % households with a non-gas cookstove; E = CEPI rating (rank); F = is the city coastal.

urban population varies from 1.5 million to 17 million. The data shows that regardless of population size, 30 cities are densely populated with 100 persons per hectare or more, 30 cities have at least 30% of the households with a motorized two wheeler (MTW), and 19 cities have at least 10% households with a four-wheeler (a car or a utility vehicle). While most cities are supplied with liquefied petroleum gas (LPG) for domestic use, there is still a significant portion of households using other fuels – such as kerosene, biomass, and coal. Of the 40 cities in Table 1, 20 have at least 30% of households with a non-LPG cookstove.

In 2010, the Central Pollution Control Board (CPCB) developed the Comprehensive Environmental Pollution Index (CEPI), a methodology to assess air, water, and soil pollution at the industrial clusters in the country (CPCB, 2009). While industries typically rely on the grid electricity for operations and maintenance; frequent power cuts often necessitate the use of in-situ electricity generation (using coal, diesel, and heavy fuel oil), which adds to the industrial air pollution load. The study identified 43 clusters with a rating of more than 70, on a scale of 0–100, and listed them as critically polluted for further action. Most of these clusters are in and around major cities – most notably Korba (Chhattisgarh), Vapi (Gujarat), Faridabad and Ghaziabad (outside of Delhi), Ludhiana (Punjab), Kanpur and Agra (Uttar Pradesh), Vellore and Coimbatore (Tamil Nadu), Kochi (Kerala), Vishakhapatnam (Andhra Pradesh), Howrah (West Bengal), and Bhiwadi (Rajasthan). The CEPI ratings, where available, are listed by their ranking in Table 1.

The global burden of disease (GBD) assessments, listed outdoor air pollution among the top 10 health risks in India. The study estimated 695,000 premature deaths and loss of 18.2 million healthy life years due to outdoor $PM_{2.5}$ and ozone pollution (IHME, 2013). Among the health risk factors studied, outdoor air pollution was ranked 5th in mortality and 7th in overall health burden in India. Household (indoor) air pollution from burning of solid fuels was responsible for an additional one million premature deaths. A substantial increase was observed in the cases of ischemic heart disease (which can lead to heart attacks), cerebrovascular disease (which can lead to strokes), chronic obstructive pulmonary diseases, lower respiratory infections, and cancers (in trachea, lungs, and bronchitis). Several other studies have estimated premature mortality rates due to outdoor PM pollution for several Indian cities, using similar methodologies and are summarized in Table 2.

While the field of air pollution and atmospheric science is gaining ground in India and there has been a surge in the published research, much of the knowledge is widely scattered. While reviews in the past have provided scientific recommendations (Pant and Harrison, 2012; Krishna, 2012), there has been no concerted effort towards addressing the various aspects of the air pollution (source to impacts), and providing a global summary as well as gaps in current knowledge. Existing local (and international) knowledge can be leveraged in designing effective interventions in India, where pollutant sources are often complex. In this paper, we aim to present an overview of the emission sources and control options for

Table 2
Estimated premature mortality due to outdoor air pollution in India.

City/region	Study year	Pollutant	Premature mortality	Reference
All India	1990	PM_{10}	438,000	IHME (2013)
Delhi	1990	Total PM	5070	Cropper et al. (1997)
Mumbai	1991	PM_{10}	2800	Shah and Nagpal (1997)
Delhi	1993	PM_{10}	3800–6200	Kandlikar and Ramachandran (2000)
Mumbai	1993	PM_{10}	5000–8000	Kandlikar and Ramachandran (2000)
Delhi	2001	PM_{10}	5000	Nema and Goyal (2010)
Kolkata	2001	PM_{10}	4300	Nema and Goyal (2010)
Mumbai	2001	PM_{10}	2000	Nema and Goyal (2010)
Chennai	2001	PM_{10}	1300	Nema and Goyal (2010)
Ahmedabad	2001	PM_{10}	4300	Nema and Goyal (2010)
Kanpur	2001	PM_{10}	3200	Nema and Goyal (2010)
Surat	2001	PM_{10}	1900	Nema and Goyal (2010)
Pune	2001	PM_{10}	1400	Nema and Goyal (2010)
Bhopal	2001	PM_{10}	1800	Nema and Goyal (2010)
Pune	2010	PM_{10}	3600	Guttikunda and Jawahar (2012)
Chennai	2010	PM_{10}	3950	Guttikunda and Jawahar (2012)
Indore	2010	PM_{10}	1800	Guttikunda and Jawahar (2012)
Ahmedabad	2010	PM_{10}	4950	Guttikunda and Jawahar (2012)
Surat	2010	PM_{10}	1250	Guttikunda and Jawahar (2012)
Rajkot	2010	PM_{10}	300	Guttikunda and Jawahar (2012)
All India	2010	$PM_{2.5}$ + ozone	695,000	IHME (2013)
Delhi	2010	$PM_{2.5}$	7350–16,200	Guttikunda and Goel (2013)
Delhi	2030	$PM_{2.5}$	22,000	Dholakia et al. (2013)

air quality improvements in Indian cities, with a particular focus on key sectors such as transportation, dust, power plants, brick kilns, waste, industries, and residential. Also included is a broad discussion on key institutional measures necessary for building an effective air quality management plan.

2. Air quality in Indian cities

2.1. Air quality data

The national ambient monitoring program collects 24-h averages of key air pollutants 2–3 times per week at 342 manual stations in 127 cities. This program is managed by CPCB. However, only a limited number of cities operate continuous monitoring stations, measuring the full array of criteria pollutants and access to the monitoring data is limited. A summary of the measurements for PM_{10}, SO_2, and NO_2 for 2009–10 is presented in Table 1. Delhi and Pune also have citywide monitoring networks outside the national framework (SAFAR, 2013).

To supplement the data generated at on-ground monitoring stations, several studies have utilized satellite data to derive global ground-level ambient $PM_{2.5}$ concentrations (Van Donkelaar et al., 2010). These were utilized for the GBD assessments (IHME, 2013). An extract of this data, covering India, is presented in Fig. 1. Since the satellite extractions are available at 0.1° resolution (~10 km), there is some uncertainty associated with these derivatives and these retrieval methods are being improved every year, to complement the on-ground measurements. For example, most of southern India in Fig. 1 seems to comply with the WHO guideline of 15 $\mu g/m^3$. However, the urban pollution levels here are some of the highest in the country including Chennai and Coimbatore (Tamil Nadu), Hyderabad and Vishakhapatnam (Andhra Pradesh), Kochi (Kerala), and Bengaluru (Karnataka).

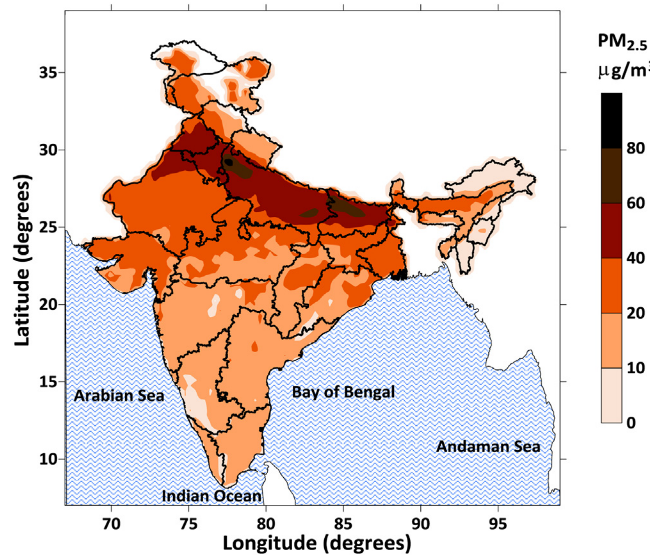

Fig. 1. Ambient $PM_{2.5}$ concentrations derived from the satellite observations.

Table 3
Number of receptor modeling studies conducted between 2000 and 2013 in India.

City	A	B	C	A&B	D	Total
Delhi	4	1		1	5	11
Mumbai	3	1		1	2	7
Kolkata	2	1			1	4
Chennai	1	1		2		4
Hyderabad		1		1		2
Agra				1	1	2
Kanpur			1			1
Ahmedabad				1		1
Chandigarh					1	1
Tirupati	1					1
Talcher	1					1
Dhanbad	1					1
Jorhat		1				1
Virudhanagar				1		1
Mithapur					1	1
Bhubaneshwar					1	1
Multi-city		1		1		2
Raipur	1				5	1

Notes: A = PM_{10}; B = $PM_{2.5}$; C = PM_1; D = mixed size fractions.

The Indo-Gangetic plain has the largest number of brick kilns, with old and inefficient combustion technology, using a mix of biomass and coal for combustion needs (Maithel et al., 2012). The states of Bihar, West Bengal, Jharkhand, Orissa, and Chhattisgarh harbor the largest coal mines in the country, and a cluster of power plants around the mines (Guttikunda and Jawahar, 2014). Several large power plants also exist in the states of Punjab, Haryana, Delhi, and Uttar Pradesh, making the north and the north-eastern belt the most polluted part of the country. The cities in the north are also landlocked, which are also affected by the prevalent meteorological conditions, unlike some of the Southern cities with the privilege of land-sea breezes (Guttikunda and Gurjar, 2012).

Besides $PM_{2.5}$ concentrations, the satellite observations can also help estimate the concentrations of SO_2, NO_x, and CO, and help analyze the severity of on-ground anthropogenic and natural emission sources (Streets et al., 2013).

2.2. Sources of air pollution

For city administrators, regulating air pollution is the primary concern and accurate knowledge of the source contributions is vital to developing an effective air quality management program. The contribution of various sources to the ambient PM pollution is typically assessed via receptor modeling and this methodology has been applied in many Indian cities (CPCB, 2010; Pant and Harrison, 2012). However, between 2000 and 2013, 70% of the known studies were conducted in five big cities – Delhi, Mumbai, Chennai, Kolkata, and Hyderabad and very limited number in other cities, which are also listed as exceeding the ambient standards and WHO guidelines (Table 1 and WHO, 2014). The number of studies in various cities is presented in Table 3, with limited number of studies on $PM_{2.5}$ size fraction.

The most commonly identified sources are vehicles, manufacturing and electricity generation industries, construction activities, road dust, waste burning, combustion of oil, coal, and biomass in the households, and marine/sea salt. A multi-city study was conducted by CPCB for six cities – Pune, Chennai, Delhi, Mumbai, Kanpur, and Bengaluru, at an approximate project cost of US$6 million (CPCB, 2010). A summary of this study is presented in Fig. 2. Unlike the popular belief that road transport is the biggest cause of urban air pollution, the CPCB (2010) results showed that there are other sources which also need immediate attention and the road transport is only one of the major contributors to the growing air quality problems in the cities. In the six cities, the share of road transport ranged 7% in Pune to 43% in Chennai. Along with Mumbai, Chennai harbors one of the largest commercial ports in India, which means a large number of diesel fueled heavy duty trucks pass through the city, to and from the port, and thus increasing the share of road transport in ambient PM pollution.

However, a vital limitation of the receptor modeling approach is the spatial representation of the contributions, i.e., the results are representative of the sampling location and its close vicinity (~2–3 km radius from the sampling location). Hence, in order to understand the source contributions in a city, it is important to conduct detailed analysis at multiple locations. The receptor modeling studies also require detailed chemical characterization of emission sources (either as an input or for validation). While several source profiles have been created in India, there is scope for further addition and improvement (Pant and Harrison, 2012).

2.3. Emissions inventory & dispersion modeling

While the receptor modeling approach is ideal to ascertain the source contributions, it is an expensive method and has limited spatial coverage. This limitation can be overcome by complementary source modeling. This relies on availability of data such as vehicle activity on the roads, fuel consumption in the domestic, industrial, and electricity generation sectors, waste collection and waste burning, silt loading on the roads for resuspension, and geography, population, and meteorology of the city. Since the analysis includes spatial dispersion modeling, there is a need for computational facilities to input, analyze, and output geo-referenced emissions inventories and concentration fields. Several studies have been carried out in India since 2000 and are summarized in the Supplementary Material, together with known emission factor databases and key requirements to conduct dispersion modeling. An example of gridded vehicle exhaust emissions from Pune, Chennai, and Ahmedabad at 1 km grid resolution is also presented in the Supplementary Material. Most of the studies have focused on PM pollution and fewer studies on ozone pollution.

The source modeling results are driven by user inputs and rely on measurements to test their validity, before they can be used for any policy dialogue. It is also important to note that the dispersion

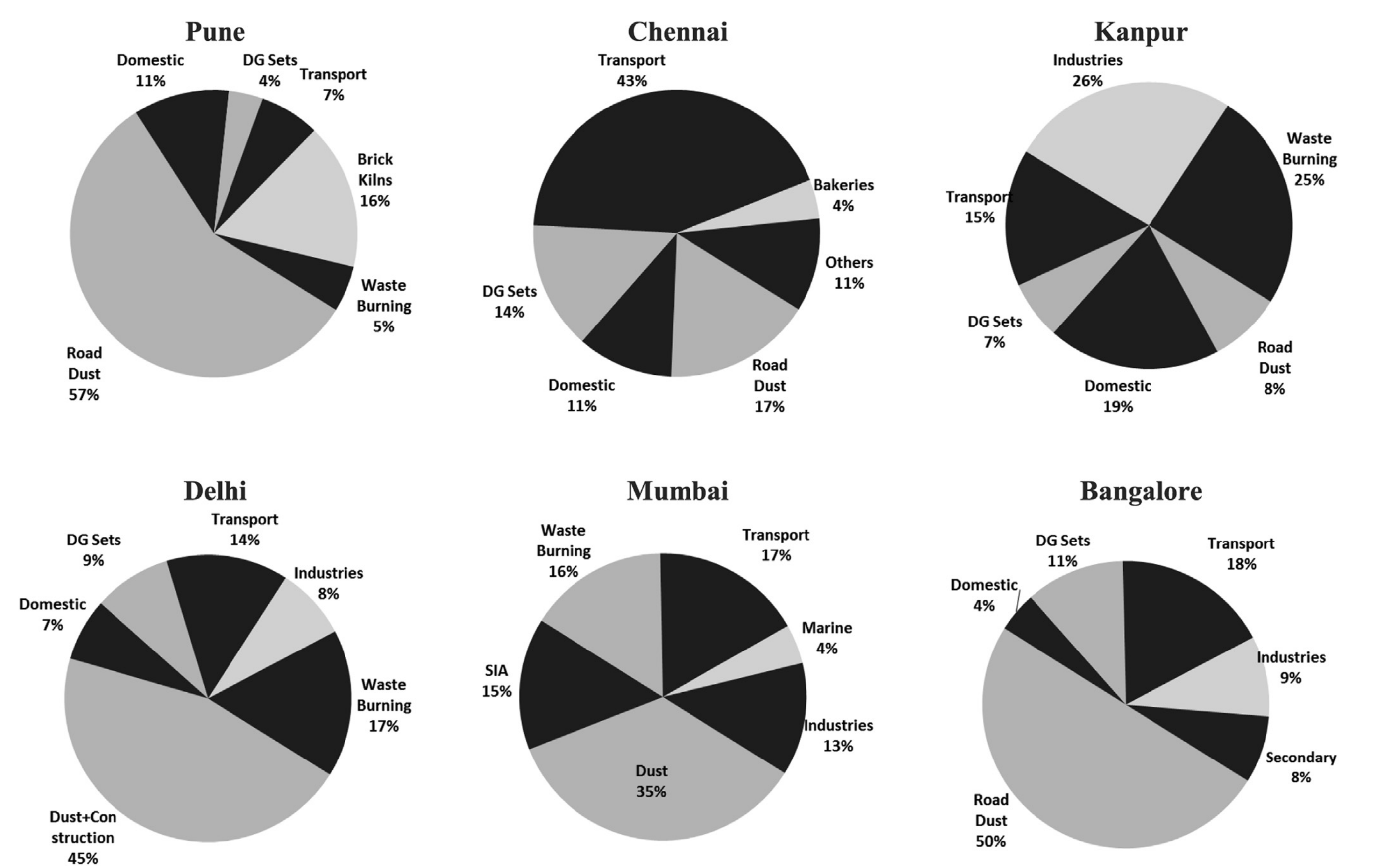

Fig. 2. Average percent contributions of major sources to PM_{10} pollution (CPCB, 2010).

and receptor models should not be used as substitutes for each other and they provide best results when used complementarily.

3. Potential for air pollution control

In most Indian cities, SO_2 is the only pollutant that complies with NAAQS. Interventions such as introduction of Bharat-4 diesel (with 50 ppm sulfur) in the cities and Bharat-3 diesel (with 350 ppm sulfur) for the rest of the country and relocation or refurbishing of industries consuming coal and diesel with better efficiency norms have led to this compliance. However, the same is not true for PM_{10}, CO, and NO_2 concentrations, as their emissions from combustion processes have significantly increased, regardless of the improvements in fuel quality and technology. While most of the industrial equipment and the on-road vehicles individually adhere to their respective emission norms; collectively, they emit enough to register ambient concentrations beyond the standards (Table 1).

There is a vast potential for pollution control in the cities, which can be achieved through the twin approach of stringent regulations technological interventions. The following sections provide an overview of the potential measures, some under implementation and some which need urgent attention.

3.1. Vehicle fuel standards and alternative fuels

Road transport plays a vital role in India's growing economy and the contribution of vehicular emissions is only expected to increase (Ghate and Sundar, 2013). Fuel emission standards in India lag behind the global emission standards (Table 4). It is essential to implement and enforce Bharat-5 (equivalent of Euro-5) or higher standards nationwide by 2015 or sooner, in order to maintain a balance between the energy demand and the growing emissions (Guttikunda and Mohan, 2014). Any delay in implementation or staggered implementation (as is the case currently), will result in a delayed response for improving air quality in Indian cities.

While the staggered introduction of the fuel standards is beneficial for the cities in the short run, the overall benefits are lost in transition. For example, the heavy duty vehicles operating on diesel contribute significantly to PM emissions and often run on lower grade fuel, which can lead to failure of catalytic converters. It is therefore imperative that "*one nation, one fuel standard*" norm is mandated for better air quality in the cities.

There is an increasing focus on shifting the public transport and para-transit vehicles to run on compressed natural gas (CNG). In Delhi, buses, three-wheeler rickshaws, and taxis were converted to operate on CNG and a steady supply of fuel coupled with lower prices is encouraging private car owners also to switch. The number of CNG outlets in Delhi increased from 30 in year 2000 to 300 in 2013, and according to the Ministry of Petroleum & Natural Gas of India, there will be 200 cities with CNG network by 2015 (PIB, 2013).

Table 4
Chronology of Bharat emission standards.

Standard	Date	Region
India 2000	2000	Nationwide
Bharat-2 (Ref: Euro-2)	2001	NCR, Mumbai, Kolkata, and Chennai
	2003.04	NCR + 13 cities
	2005.04	Nationwide
Bharat-3 (Ref: Euro-3)	2005.04	NCR + 13 cities
	2010.04	Nationwide
Bharat-4 (Ref: Euro-4)	2010.04	NCR + 13 cities
	2012.03	NCR + 13 cities + 7 cities
	2015	50 + cities

NCR is the national capital region of Delhi, including Delhi and its satellite cities.
13 cities are Mumbai, Kolkata, Chennai, Bengaluru, Hyderabad, Ahmedabad, Pune, Surat, Kanpur, Lucknow, Sholapur, Jamshedpur and Agra.
7 cities are Puducherry, Mathura, Vapi, Jamnagar, Ankaleshwar, Hissar and Bharatpur.

3.2. Urban travel demand management

As the cities are growing in geography and inhabitants, there is also a push to promote safe and clean public transport systems. In bigger cities like Delhi, Mumbai, Hyderabad, Kolkata, Chennai, Ahmedabad, and Bangalore, there is an established formal public transportation system and they also benefitted from Jawaharlal Nehru National Urban Renewal Mission (JNNURM) programs to better and increase the fleet (MoUD, 2012). Since 2009, more than 14,000 new buses were delivered under this program. However, most of these cities need to at least triple or quadruple the current fleets, in order for the 4-wheeler and 2-wheeler passengers to shift to public transport systems.

In urban India, implementation of dedicated bus corridors, known as "bus rapid transport (BRT) system" is among the priorities. International examples from Bogota (Colombia) and Curitiba (Brazil) serve as models with bus modal share of 62% and 45% respectively (LTA Academy, 2011). The cities of Delhi, Ahmedabad, Jaipur, Pune, and Indore have implemented BRT projects with varying corridor lengths and the cities of Rajkot, Surat, Bhopal, Vijayawada, and Visakhapatnam have approved BRT projects (Mahadevia et al., 2013). Since the projects are not fully integrated into the public transport systems, the results and the public response has been mixed.

For smaller cities, the definition of the public transport is changing. Most of these cities do not have an organized public transportation system; rather, they are supported by informal para-transit systems, mostly plying on the dominant corridors of the city. Among the para-transit systems, most common are the traditional three-wheeler auto-rickshaws (to seat up to 4 people), a larger version of the auto-rickshaws (to seat up to 10 people), and mini-buses. With their ability to negotiate the tiny by-lanes and weave through mixed traffic, these vehicles form an integral part of passenger and freight movement and in most cities is also a popular mode of mass transport for school children. An example is the city of Alwar (Rajasthan) where para-transit system "Alwar Vahini" was successfully formalized with regulations, as well as dedicated routes reaching various parts of the city. The para-transit systems have also benefited from the use of alternative fuels like CNG and LPG. In response to a Supreme Court mandate, the Delhi Government converted the entire three-wheeler fleet to CNG between 1998 and 2002, followed by similar initiatives in other cities.

Most Indian cities have a majority share of trips by walk and cycle (Mohan, 2013). This is because of low vehicle ownership (compared to the cities of the United States and the European Union) as well as traditional mixed-use design of the cities, which leads to shorter access to work, school, and other activities. In big cities with higher population density, in the absence of dedicated NMT infrastructure, motorized vehicles also pose serious risk of injury, because of which, people owning two-wheelers and cars are encouraged to use their vehicles, even for walkable distances. In the context of growing cities, the measures to improve air quality should include NMT policies as an integral part.

Some economic measures are also designed to force the use of public transport. One such measure is the congestion pricing – where the motorists are charged to use a network of roads during periods of the heaviest use. Its purpose is to reduce automobile (mostly car) use during peak congestion periods, thereby easing traffic and encouraging commuters to walk, bike, or take mass transit rail/bus as an alternative. Congestion pricing programs were successfully implemented in Singapore, London, and Stockholm (Eliasson, 2009; Menon and Guttikunda, 2010; Litman, 2011). On average, in London, congestion pricing is estimated to have reduced 20–30% of the downtown passenger car traffic and promote the non-motorized transport, whereas Stockholm experienced an immediate reduction of at least 20% in the daily car use. In Singapore, the average traffic speeds increased by at least 15 km/h. In all three cities, 10–20% reduction in eCO_2 emissions was estimated, along with health benefits of reducing air pollution.

A major reason for its success in Singapore, London, and Stockholm was the availability of widely accessible public transport system (road and rail), which can support the shift to a car-free environment. If implemented, there will be immediate benefits in big cities like Delhi, Mumbai, and Chennai. However, the public transport system is still not at par with those in Singapore, London, and Stockholm for effective implementation of this option.

While congestion pricing policies are difficult to replicate in the Indian context, at least for the foreseeable future, there is an important lesson. With increasing costs for private vehicles linked with their usage (fuel and other operational expenses), it is possible to achieve a shift to public transport, if combined with the provision of an adequate, reliable, and safe public transportation. One such measure is the increased parking cost. Currently, parking in most cities is either free or priced very low. Increased parking cost, if coupled with the parking locations, so that they are as far as the bus and the rail stops, will make public transportation an attractive option (Barter, 2012; CSE, 2012).

While the congestion pricing and parking policies target reduced vehicle usage, some countries have used regulatory measures to reduce the growth of private vehicles. For instance, a Chinese national regulation enacted in September, 2008, raised taxes on big cars and reduced on smaller ones. Car owners with engines above 4-L capacity have to pay a 40% tax; 15%–25% for cars with engines above 3-L capacity; and 1%–3% for cars with engines below 1-L capacity (Murad, 2008). China also introduced a policy to limit the number of licenses issued every year, where the license plates are auctioned in the cities of Beijing, Shanghai, and Guangzhou. Similar to congestion pricing, for the time being, such measures are difficult to implement under democratic political context of India.

3.3. Regulations for coal-fired power plants

In 2011–12, there were 111 coal-fired power plants in India with a combined generation capacity of 121 GW (CEA, 2012). The emissions and pollution analysis for these plants, resulted in an estimated 80,000–115,000 premature deaths and more than 20.0 million asthma cases from exposure to total $PM_{2.5}$ pollution annually (Guttikunda and Jawahar, 2014). While Indian coal has a low sulfur content in comparison with other coals, ash levels are reported to be quite high and can contribute to coarse PM emissions (Pant and Harrison, 2012).

Despite the volume of coal used in the power generation sector, there are very few regulations in place to address these environmental and health costs. To date, for PM emissions, the emission standard in India lags to those implemented in China, Australia, the United States, and the European Union (Table 5). For other key pollutants, there are no prescribed emission standards despite the fact that India is a relatively dense country and several power plants are in close proximity to residential areas. Aggressive pollution control regulations such as mandating flue gas desulfurization, introduction of tighter emission standards for all criteria pollutants, and updating procedures for environment impact assessments are imperative for regional clean air and to reduce health impacts. For example, a mandate for installation of flue gas desulfurization systems could reduce the $PM_{2.5}$ concentrations by 30–40%, by eliminating the formation of the secondary sulfates and nitrates (Guttikunda and Jawahar, 2014).

Besides flue gas PM emissions, fugitive dust from coal-handling plants and ash ponds (after the disposal from the plants) is also a problem. According to Central Electrical Authority, after the combustion and application of control equipment, ash collection at the power plants range 70–80% of the total ash in the coal. In 2003, an amendment notification from MoEF mandated 25% bottom ash in all brick kilns within 100 km radius of the power plant and all building construction within 100 km to use 100% ash based bricks, blocks, and tiles. To date, percentage of ash utilized in the construction industry is low.

3.4. Power shortages and diesel generators

In 2011, the peak electricity demand was approximately 122 GW and the peak electricity supply was approximately 110 GW (CEA, 2012). The gap between the supply and the demand is crucial to understand India's power generation sector. In India, a third of the population in rural areas does not have access to electricity and those areas on the grid are not assured of uninterrupted supply. The blackout in July, 2012, that paralyzed 600 million people in 22 states in the Northern, Eastern, and Northeastern India, is testament to how tenuous power situation is in the country.

In the urban areas, power cuts are severe in the winter and the summer months, when heaters and air conditioners are in full service, respectively. These needs are usually supplemented by in-situ large, medium, and small diesel generator (DG) sets at hotels,

Table 5
Summary of emission standards for coal-fired power plants.

Country[a]	PM	SO_2	NO_2	Mercury
India	350 mg/Nm^3 for <210 MW 150 mg/Nm^3 for >210 MW	None	None	None
China	30 mg/Nm^3 (proposed all) 20 mg/Nm^3 for key regions	100 mg/Nm^3 for new 200 mg/Nm^3 for old 50 mg/Nm^3 for key regions	100 mg/Nm^3	None
Australia	100 mg/Nm^3 for 1997–2005 50 mg/Nm^3 after 2005	None	800 mg/Nm^3 for 1997–2005 500 mg/Nm^3 after 2005	In discussion based on USA standards
European Union	Pre-2003 100 mg/Nm^3 for <500 MW 50 mg/Nm^3 for >500 MW Post 2003 50 mg/Nm^3 for <100 MW 30 mg/Nm^3 for >100 MW	Pre-2003 Scaled for <500 MW 400 mg/Nm^3 for >500 MW Post 2003 850 mg/Nm^3 for <100 MW 200 mg/Nm^3 for >100 MW	Pre-2003 600 mg/Nm^3 for <500 MW 500 mg/Nm^3 for >500 MW Post 2003 400 mg/Nm^3 for <100 MW 200 mg/Nm^3 for >100 MW	In discussion
USA[b]	6.4 g/GJ	640 g/MWh	720 g/MWh for old 450 g/MWh for new	0.08 g/MWh for lignite 0.01 g/MWh for IGCC

[a] Source: Guttikunda and Jawahar (2014).
[b] In official units; mercury as 12 month rolling average.

hospitals, malls, markets, large institutions, apartment complexes, cinemas, and farm houses and form an additional source of air pollution to an already deteriorating air quality in the cities. Telecommunication towers stand out, which with more than 500 million mobile phones in the country, are heavily dependent on DG sets. According to the Telecom Regulatory Authority of India (TRAI), 310,000 towers consumed over 2 billion liters of diesel in 2010 (TRAI, 2011). The mobile subscriber base is expected to reach 800 million by the end of 2013 with an additional 100,000 telecom towers in service.

For Chennai, Pune, Indore, Ahmedabad, Surat, and Rajkot, up to 10% of the modeled PM_{10} concentrations were found to originate from diesel generator sets (Guttikunda and Jawahar, 2012). In case of Delhi, the contribution went up to 15% (Guttikunda and Calori, 2013; Guttikunda and Goel, 2013). The use of generator sets is even higher in the rural areas, where they are mostly utilized for the pumping water in the agricultural lands.

An alternative to DG sets is not simple. One option is to increase the number of power plants to meet the electricity demand and reduce the transmission losses or provide alternatives like renewable energy. On the other hand, tightening of the emission standards for DG sets, at par with the heavy and light duty vehicles can help control some emissions.

3.5. Domestic fuels

The issue of indoor air pollution is also critical because of the high magnitude of population getting exposed to such pollution every day (Venkataraman et al., 2010; Grieshop et al., 2011; Smith et al., 2014). According to GBD 2010 assessments, household air pollution has been a persistent health hazard in India and has retained its position as the 2nd highest risk factor for disability life years lost and resulting in 1.0 million premature deaths annually (IHME, 2013). Several studies have characterized the impacts of household air pollution and health risks due to indoor solid fuel use in India (Balakrishnan et al., 2011).

In 2011, Non-LPG fuels are used in 35% of urban and 89% of rural households in India, compared to 52% and 94% respectively in 2001 (Census-India, 2012), with little improvement for the rural households. Keeping in view, the magnitude of the health risks, the Ministry of Petroleum & Natural Gas of India aims to provide LPG connections to up to 75% of households in India by year 2015 (PIB, 2013). For the rural areas, the program is also proposing to set up community kitchens with LPG connections, where users can pay as per usage. Alternatives like electric (induction) stoves are cleaner (with pollution generated somewhere else), but their usage is dependent on power supply in the rural communities. The use of electric stoves, in the urban centers, is increasing and currently limited by the cost of stoves.

3.6. Emerging technologies for the brick kilns

The traditional building construction in India believes in the fired clay bricks. The construction is one of the fastest growing sectors, contributing approximately 10% of the national GDP and has a growth rate of 9%. Overall, there are more 100,000 brick kilns in India, producing 150–200 billion bricks annually, employing 10 million workers, and consuming 25 million tons of coal (Isabelle et al., 2007; Maithel et al., 2012). Within a radius of 20–30 km, one can spot 500–1000 brick manufacturing kilns in the big cities of Delhi, Chennai, Kolkata, Pune, Ahmedabad, Hyderabad, Kanpur, and Patna (Guttikunda and Jawahar, 2012; Guttikunda and Calori, 2013).

Brick manufacturing includes land clearing for sand and clay, combustion of fuel for burning, operation of diesel engines on site, and transport of the end product to various parts of the city. Traditionally, the rectangle shaped clay bricks are sun dried and readied for firing in "clamps" – a pile of bricks with intermittent layers of sealing mud, and fuel. A significant amount of energy is lost during the cooling with no possibility of recycling. These are mostly located in Central and Northeast India. In the Indo-Gangetic plains, some advanced manufacturing technologies with a 50 m fixed chimney (FCK) are in practice. The chimney supports further dispersion of the emissions and is noted for its low cost of construction. A major disadvantage of these kilns is associated with weather – an open cast kiln means they can be operated only in the non-monsoonal season.

The emerging technologies and their operational features are summarized in Table 6. Between the available technologies, the newer technologies such as vertical shaft brick kilns (VSBK), zigzag, and Hoffmann, could result in at least 40% reduction in the PM emission rates compared to the currently in use FCK technology. VSBK design and construction details are presented as a manual in World Bank (2010) with some pilots in India, Bangladesh, and Nepal.

3.7. Construction

Construction activities emit particles during various activities including block cutting, excavation, demolition, mixing, road building, drilling, loading and unloading of debris etc. In addition, movement of vehicles (especially trucks) in and around construction sites increases the amount of particles by crushing and pulverizing the particles on the road surface. Several studies have highlighted the importance of construction as a PM source, though in receptor modeling studies, the source is combined with sources such as road dust (Pant and Harrison, 2012). For six cities, construction accounted for up to 10% of the annual emissions (Guttikunda and Jawahar, 2012; CPCB, 2010). There is a window of opportunity for the establishment of best practices in the construction industry.

3.8. Resuspended/road dust

Dust is a major concern for many cities in India (Fig. 2) and comprises of particles emitted due to wear and tear of tires and brakes and materials from the roads, pavements, and street furniture. Dust loadings increase even further, if the roads are not paved (CPCB, 2010).

Traditionally, all the streets, sidewalks, and public areas are swept manually and depending on the resources, poor or marginal areas receive reduced or inadequate service, or no service at all, while wealthier, commercial, or tourist areas receive extensive service. However, often in manual street sweeping, most of the dust swept is left on the side of the roads, which gets re-entrained when the vehicle movement resumes during the day. A better alternative is heavy-duty or light-duty trucks with vacuum cleaners to suck up dust from the roads and/or water sprinklers, so that the resuspension of any leftover dust is suppressed. The operational costs of mechanized sweeping could be similar to manual sweeping – given the latter is a labor intensive exercise. Since the road dust accounts for up to 30–40% of the PM_{10} pollution in most cities (CPCB, 2010; Guttikunda and Jawahar, 2012), an immediate intervention for this source is considered to be the lowest hanging fruit.

3.9. Open waste burning

There is no reliable national-level data on the technical or financial aspects of solid waste management, and figures are

Table 6
Comparison of technical and operational benefits and constraints of current and alternative brick manufacturing technologies.

Technology	Fuel consumed per 100,000 bricks	Investment and operational costs (million USD)[f]	Brick production capacity (million/kiln)	Number of kilns required to produce 3.5 billion bricks	Average tons of CO_2 produced per 100,000 bricks	Average reduction in PM emissions compared to FCK
FCK[a]	20–22 tons coal	1.7	4.0	1000	50	
Zigzag[b]	16–20 tons coal	1.6	4.0	1000	40	40%
Hoffmann[c]	15,000–17,000 m^3 NG	5.7	15.0	270	30	90%
Hoffmann[d]	12–14 tons coal	5.7	15.0	270	30	60%
VSBK[e]	10–12 tons coal	1.6	5.0	800	25	60%

[a] FCK = fixed chimney bull trench kiln; NG = natural gas; VSBK = vertical shaft brick kiln.
[b] Some zigzag pilot kilns are in operation, listed as medium performance. Any improvement in the efficiency of operations can lead to further reductions in coal consumption.
[c] Manufacturing period for Hoffmann kilns is round the year, compared to the current non-monsoonal month operations for the other kilns; thus increasing the land and raw material requirements; Link to natural gas grid and continuous fuel supply is a major constraint.
[d] Initial investments are higher for Hoffmann kilns.
[e] Operational models are available in India and Kathmandu.
[f] Costs include initial investment, land, building, operational, and taxes estimates (World-Bank, 2010).

therefore approximations. The country's annual generation of municipal solid waste is in the range of 35–45 million tons; likely to quadruple by 2030, at which time, the waste generation will be over 150 million tons a year (World-Bank, 2006; Annepu, 2012). The scale is perhaps more comprehensible at the city level – the national capital region of Delhi generates 10,000 tons/day and Mumbai 7000 tons/day. The waste collection efficiency in the cities is 50–90%, depending on the commercial and residential activities in various parts of the city. The waste not collected is eventually burnt. The best option for reducing the waste burning is to implement an efficient solid waste management program across the country. Currently, only a few cities operate landfills and manage waste collections. The waste management falls under the jurisdiction of the municipal corporation and according to Toxics Link (New Delhi, India), the municipalities spend an estimated INR 1500–2000 per ton of solid waste for collection (60–70%), transportation (20–30%), and treatment and disposal (5–10%).

The open waste burning problems are particularly worse in the medium and small scale cities, with very limited or no waste collection and no landfill facilities. Emissions of criteria pollutants from garbage burning are hard to quantify and are accompanied by large uncertainty. The toxic chemicals released during burning of paper, plastic, and biomass includes NO_x, SO_2, volatile organic chemicals (VOCs), and dioxins.

4. Policy implications

According to the 2011 census, 2774 rural settlements are now reclassified as urban settlements, pushing the total to 3894, primarily based on the definition of an urban settlement – population exceeds 5000, population density is above 400 per km^2, and more than 75% of the male workforce is employed outside of agriculture (Census-India, 2012). The population in urban areas is expected to grow from 30% to 50% by 2030 (MoUD, 2011). By 2030, the expected growth in industrial, transportation, domestic, and power generation sectors will consequently result in an increase in emissions and air pollution for almost all the cities listed in Table 1 and many more cities which are medium and small today. There are growing concerns about the impact of air pollution on human health and general well-being, which requires a multi-pronged approach for better air quality. Some key institutional measures which can lead the way are the following.

4.1. Monitoring and data dissemination

Before the GBD 2010 assessments (IHME, 2013), the 2008 Olympic Games in Beijing resulted in raising significant awareness on the urban air pollution problems. In Beijing, stringent measures were introduced to achieve blue skies rating for the Games and this included shutting down 50% of the on-road vehicles (based on their registration numbers) and shutting major coal-fired industrial estates in the vicinity of the city. These measures not only raised the awareness on the air pollution and benefits of pollution control measures, but also showed the level of commitment necessary from the public and the government to achieve such a result.

The city of Delhi hosted the 2010 Commonwealth Games, which raised some awareness on air pollution in the city. The number of official monitoring stations tripled during the Games. The national bodies established variable messaging systems and also disseminated the monitoring data on web (Beig et al., 2013). However, the emission control programs did not involve any stringent measures like those practiced during the Beijing Olympics (Streets et al., 2007; Wang et al., 2010) and the implemented measures were found to be ineffective during the Games (Beig et al., 2013). While such mega events help raise awareness intermittently, more efforts are necessary to prioritize air pollution and health into long term policy planning.

There is an acute need to not only increase the monitoring programs across all cities, but also to publicly disseminate the information. While the monitoring stations can be established, legislations amended, and standards improved, these efforts will be a waste, if the regular dissemination of the information is not practiced to raise the awareness for pollution control.

4.2. Scientific studies

The array of air quality studies in India (listed in Supplementary Material) points to significant need for information on spatial and temporal resolution of emissions inventories and pollution dispersion characteristics in the cities. It is important to build the necessary capacity of the state pollution control boards (SPCBs) to undertake focused analysis as well as scrutiny of intervention programs to improve the air quality.

Much of the past and current work focuses on PM_{10} and there is a growing trend towards analysis of $PM_{2.5}$ (Table 3). Due to the negative health impacts, there is a growing need for assessment of particles in the smaller size ranges (PM_1 and less). Very little is known in terms of spatial and temporal distribution of air pollutants and parameters such as particle size distribution (mass/number/volume). Semi-volatile and volatile organic species have also not been analyzed in much detail (Krishna, 2012; Ram et al., 2014). Some recent work focused on unique sources such as funeral pyres (Chakrabarty et al., 2013) and festive biomass burning

(Deka and Hoque, 2014) and specific chemical components of PM such as brown carbon (Srinivas and Sarin, 2014).

One of the key missing pieces is the personal exposure and toxicological analysis which is an important input for the assessment of health impacts of outdoor and household air pollution (Clark et al., 2013). This includes assessment of indoor and outdoor concentrations of various pollutants and integrated physio-chemical characterization (Wong et al., 2008; Massey et al., 2012; Balakrishnan et al., 2013; Chithra and Shiva Nagendra, 2013; Habil et al., 2013).

4.3. Conceptualizing combined-benefits

All the combustion sectors are interlinked, which leads to the concept of co-benefits for better air quality in the cities. There are many definitions for co-benefits and one of them is "a single activity or policy that can generate multiple benefits across varying sectors or fields". For example (a) a program in the solid waste management where the wet waste is collected and used to generate biogas, can support the domestic energy needs and thus reduce the load at the local power plant (b) a program designed to increase the energy efficiency of industries can lead to the supply of the excess power to areas plagued with frequent outages, and thus resulting in lesser usage of DG sets.

The definition of co-benefits can also be extended to pollutants. For example, programs to control pollutants like PM, SO_2, NO_x, and CO, can also reduce greenhouse gas emissions, and vice versa. For example (a) a program to improve the fuel economy of the vehicles by increasing vehicle speeds by reducing the number of cars and motorcycles on the roads, will result in a systematic reduction of all pollutant emissions (b) a program to encourage LPG and electricity usage for domestic cooking and heating, will result in lesser usage of the conventional fuels like coal, biomass, and kerosene, and can result in reduction of all pollutant emissions.

5. Conclusions

Ground measurements, computational studies, and satellite measurements, are all pointing towards changing pollution trends in India. Today, India has the unique opportunity to further the air pollution abatement measures, at the urban and the regional scale, but these depend on effective inter-sector and inter-ministerial collaboration. This is primarily due to the fact that all the sources contributing to the air pollution are interlinked. Among the sectors, transportation is the most critical and most connected.

Following the review, two challenges have emerged for better air quality in Indian cities (a) the need to secure greater public awareness of the problems and commitment to action at civic, commercial, and political levels (b) to ensure that action to tackle air pollution is seen in the context of wider social and economic development policies. For example, how much can these interventions help reduce the local challenges, like providing safer and reliable public transportation systems; cleaner and efficient waste management; dust free roads; and pollution free industries and power plants.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2014.07.006.

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