DEVELOPMENT OF SPATIALLY RESOLVED AIR POLLUTION EMISSION INVENTORY OF INDIA

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Development of Spatially Resolved
AIR POLLUTION EMISSION INVENTORY OF INDIA

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CONTENTS

ABBREVIATIONS

g	Gram
kg	Kilogram (103 g)
Mg	Tonne or Million gram (106 g)
Gg	Kilo tonne or Gigagram (109 g)
Tg	Million tonne or Teragram (1012 g)
m	Metre
km	Kilometre
ha	Hectare (104 m2), 2.47 acre
km2	100 ha
PJ	Peta Joule (1015 Joule)
Mm3	Million metre cube
MMSCM	Million Metric Standard Cubic Metre
PM10	Atmospheric particulate matter < 10 m
PM2.5	Atmospheric particulate matter < 2.5 m
SOx	Oxides of sulphur (sulphur dioxide)
NOx	Oxides of nitrogen
CO	Carbon monoxide
NH3	Ammonia
VOC	Volatile organic compound
NMVOC	Non-methane volatile organic compound
APCD	Air pollution controlling device
ARAI	Automotive Research Association of India
CPCB	Central Pollution Control Board

EXECUTIVE SUMMARY

Broadly, air pollution includes the introduction of gases or particles to the ambient atmosphere that can have negative impacts on humans and/or the environment. Here, the ambient atmosphere is defined as the portion of the troposphere within 100 m of ground level. Important air pollutants include primary particulate matter (PM), both below 2.5 microns in diameter ($PM_{2.5}$) and below 10 microns in diameter (PM_{10}), and gaseous pollutants, such as carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2), volatile organic compounds (VOCs), and ammonia (NH_3). These pollutants are a major concern, particularly in a country with growing economies such as India (which has improved its global economic ranking from 10th to 6th between 2012 and 2016) because of its impacts on human health, agriculture, and economic growth. Delhi, the capital city of the country, is the focus of discussion around the world because ambient PM_{10} and $PM_{2.5}$ concentrations are significantly higher than most of the cities in the world (WHO, 2019). Apart from the capital city, several other cities in the country also violate the national ambient air quality standards (NAAQS) of PM_{10} and $PM_{2.5}$ concentrations almost throughout the year. Considering the dynamically changing energy landscape that reflects the economic growth of the country as well as recent interventions taken on reducing air pollution, there is a need to update the existing Indian emissions inventory.

In order to address air pollution issues, it is important to understand primary sources of major ambient air pollutants (e.g., PM_{10}, $PM_{2.5}$, CO, NO_x, SO_x, VOCs, NH_3) in the country. These sources range from those that arise due to fuel use (i.e., energy use sectors) to sectors from which pollution is emitted by other means (i.e., no energy use sectors). Here "energy use" sectors include the residential, power, industry, and transport sectors; "no energy use" sectors include open agricultural burning, refuse burning, crematoria, construction sector, and mining. For example, in the residential sector, poverty-driven issues related to energy access lead to the use of biomass-based fuels for cooking purposes. In the transportation sector, limitations in public transport and economic growth have led to unprecedented increase in the number of vehicles in the cities. Growing power demands and the dependence on coal also contribute significantly to emissions along with industrial pollution. Improper management of municipal and agricultural waste is also another key issue which eventually leads to emissions of pollutants, as significant quantities of these wastes are combusted for volume reduction and heating purposes.

To accurately reflect emissions for India, it is important to have indigenous source specific emission factors of different pollutants while estimating the emissions from the respective sources. Additionally, the emission inventory for pollutants such as ammonia (NH_3), which plays important role in secondary particulate formation is not yet established in India. TERI had undertaken this study to develop India-specific emission factors for agriculture residue burning, refuse burning and road dust resuspension in different categories of Indian roads vis-à-vis to develop an updated air pollutants emission inventory of different sectors in the country for the year 2016.

Importantly, when primary air pollutants are released into the ambient air they can transform through chemical reactions to form secondary air pollutants (e.g., gaseous SO_2 and NO_x can transform to ammonium sulphate and ammonium nitrate particles, respectively, by reacting with ammonia). Thus, while an emission inventory provides the amount of primary pollutants emitted, it is necessary to use a chemical transport model that takes into account atmospheric, meteorological and thermodynamic conditions to fully assess ambient concentrations of air pollutants. Both primary and secondary atmospheric pollutants together determine the ambient air quality of a region. This study also simulated the ambient concentrations of particulate matters (PM_{10} and $PM_{2.5}$) at 36 km × 36 km scale by integrating the meteorological variables based on the estimated emission inventory described in this report (of $PM_{2.5}$, PM_{10}, SO_x, NO_x, CO, NMVOC, and NH_3) and chemical reactions in the atmosphere. WRF-CMAQ simulation platform was used in the study to simulate the ambient concentrations of $PM_{2.5}$ at 36 km × 36 km scale using the gridded emissions inventory, meteorological parameters and the global air quality products of the National Centre for Atmospheric Research (NCAR), USA.

Considering emissions from different fuels, results (Table S1) of the emission inventory study show that PM_{10} and $PM_{2.5}$ emissions were higher from coal, CO emission was higher from the burning of fuelwood, while NO_x emission was higher from diesel. Sector-specific inventory of different pollutants are summarized in Table S2.

Table S1 Fuel-wise emissions (Gg) of different pollutants during 2016

Fuel	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	NMVOC	NH_3
Fuelwood	1538	1045	182	386	15,112	3611	0
Crop residue	628	417	51	132	4677	621	0
Dung cake	290	121	17	28	2168	665	0
Coal	5357	2719	6946	2844	5277	253	165
Kerosene	334	334	0	1	143	14	0
Diesel	311	245	741	3058	1736	124	1
Gasoline	11	10	1	285	1387	0	12
CNG	25	25	8	92	90	1	0
LPG	5	5	6	41	28	270	0
Total	8499	4921	7952	6868	30,618	5559	177

Table S2 Sectorial emission inventory of different atmospheric pollutants during 2016

	Emissions (Gg)						
Sector	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**NO_x**	**CO**	**VOCs**	**NH_3**
Energy use sectors							
Residential	2836	1941	331	598	22,421	5233	
Power	574	230	5437	2517	182	80	0.1
Industry	5386	2792	3886	1179	7978	177	165
Transport (Tailpipe)*	192	187	14	2228	2938	1033	14
Road dust*	*1001*	*242*					
Transport total	1193	429	14	2228	2938	1033	14
Diesel generator set	78	66	71	1110	239	91	
No energy use sectors							
Open burning	1325	937	158	527	6501	600	118
Refuse burning	880	655	127	332	2638	370	
Crematoria	47	23	1	6	235	131	
Construction	3291	197					
Mining	163	33	8	3			
Agriculture activities	87	13					5482
Total	15,806	7316	10,033	8500	43,132	7715	5779

* *The emissions from transport (tailpipe) and road dust are summed and presented as transport total.*

Based on our WRF-CMAQ modelling results, the simulated ambient concentration of $PM_{2.5}$ remained higher in Gujarat and northeastern region of the Indo-Gangetic plain (IGP) of India (Figure S1) compared to other parts of the country.

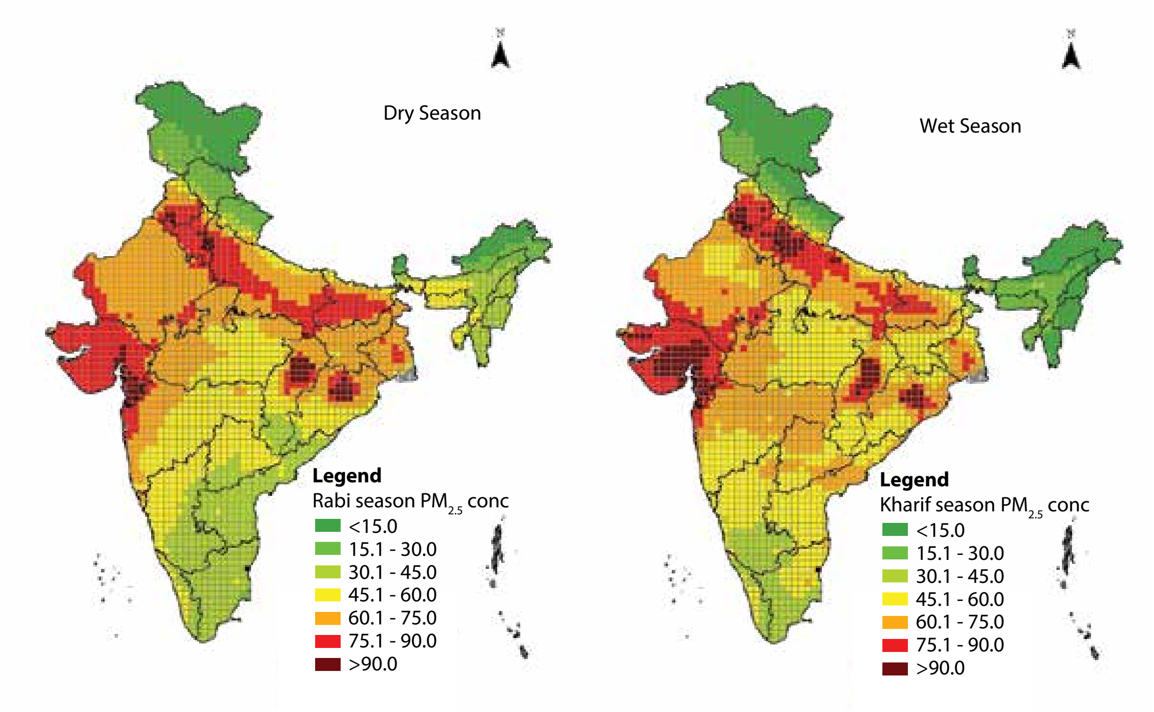

Figure S1 Simulated ambient $PM_{2.5}$ concentration (mg/m³) over India during 2016

1

INTRODUCTION

Air pollution is a global environmental issue with critical effects on human health and food security. The issue is of major concern in a developing economy such as India. There are many sources that contribute to the deterioration of air quality in India. Limitation to access of clean energy for domestic cooking and lighting, scarcity of convenient public transport facility, increasing power demand and increase in coal- based industries along with pollution related to industrial activities are the major challenges contributing to the air pollution issue in the country. Additionally, open burning of agricultural residues, road dust, operation of diesel generator sets (DG sets), construction activities, inadequate management of municipal waste/refuse, and indiscriminate use of fertilizers on croplands also contribute to deterioration of air quality in India.

The Indo-Gangetic Plain (IGP) of India shows the highest levels of air pollution due to the presence of large numbers of high-intensity emission sources, adverse meteorological condition, and high density of population. The government of India has taken several steps towards controlling air pollution vis-à-vis achieving its commitments to the Paris Agreement (COP21). Considering the dynamically changing energy use landscape in India as well as recent policy interventions taken to reduce air pollution, there is a need to update the air pollution emission inventories.

While developing emission inventories, it is always preferable to have country-specific emission factors of different air pollutants from various sector-specific activities. This helps to reduce uncertainty in estimating emissions of air pollutants from that sector. In this study, TERI has developed emission factors for open agriculture residue burning, refuse burning, road dust resuspension, and some industrial activities. Primary data was generated through the collection of samples across the country. TERI also derived emission factor for ammonia emission from different activities in India based on the secondary information available in published literature. A new indigenous emission factor database has been formulated using this new information.

The emission inventory of pollutants gives an idea of contributions in source emissions but does not reflect their shares in ambient concentration. Understanding of source contributions in ambient concentrations is important to understand the impact of air pollution—particularly on human health or agricultural activities. Again, different primary pollutants, such as NH_3, NO_x , SO_2, VOCs, etc., can react in the atmosphere to form secondary pollutants based on the meteorological and thermodynamic conditions. Thus, it is necessary to use meteorological parameters and pollutants inventories together in a chemical transport model to estimate the ambient concentration of different air pollutants. We have carried out a preliminary model run to assess pollutant concentrations in India based on the inventory prepared in this study. This project has the following objectives:

1. To update muti-sectoral emission inventory of PM, NOx, $SO_{2,}$ NMVOC, CO of India for the year 2016

2. To develop an inventory of ammonia emissions for India
3. To simulate pollutant concentration using chemical transport models for identification of hotspots.

2

METHODOLOGY

The basic equation (Eq. 1) followed in the study to estimate emission is:

$$E_p = \sum_R \sum_S \sum_F A_{R,S,F} \times EF_{R,S,F} \times (1 - \alpha_{R,S,F}) \times X_{p,R,S,F} \qquad (1)$$

where, E_p is the annual emission of a pollutant (p) (Kt); R is the region/state; S is the sector; F is the type of fuel; A is the activity data (fuel consumption or other emission-related data); EF is the emission factor (Kt per unit of fuel use) of the pollutant (p); α is the removal efficiency (%) of pollutant (p) with the installed pollution control technology and X is the actual application rate of the control technology (Klimont et al., 2002).

The activity data (A) of 2016 for different sectors was mostly collected from the published dataset of different ministries of the Government of India. However, some data gaps have been filled through published peer-reviewed literature survey and with the help of the MARKAL model (Annexure V).

The basic framework of the present study is summarized in Figure 1.

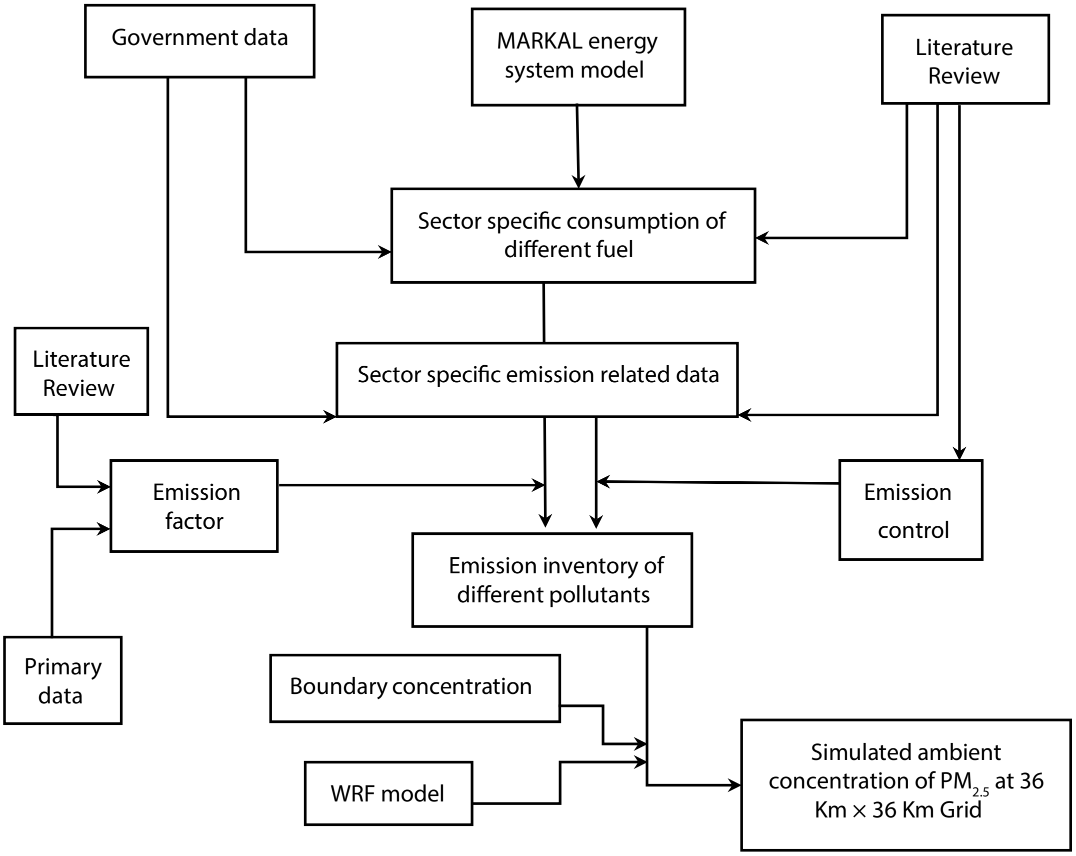

Figure 1 Framework of the study

2.1 Methodology to develop sector-specific emission inventory

Emission inventories of different pollutants, *viz.*, PM_{10}, $PM_{2.5}$, CO, SO_2, NO_x, non-methane volatile organic compounds (NMVOCs) and NH_3 were prepared during the period of the project, that is, 2016. Sectors involved in the emissions of different pollutants were broadly classified into two classes: A. Energy use sectors and B. Non-energy use sectors. The sub-classes under the former are: 1. Residential sector, 2. Power sector, 3. Industry sector, and 4. Transport sector. Sub-classes under the latter are: 1. Open burning of agricultural residues, 2. Refuse burning, 3. Crematoria, 4. Construction sector, and 5. Mining sector.

Sector-specific methodologies to develop emission inventory and detailed emission inventory of the respective sectors are provided in Chapters 3–13.

2.2 Methodology to simulate ambient concentration of $PM_{2.5}$

Atmospheric concentrations of PM are simulated by integrating the emission inventory and meteorological parameters using the WRF-CMAQ model in Chapter 14. India-scale emission inventory data developed here at a resolution of 36 km x 36 km was provided as input. To account for transport of pollutants from outside India, international boundary conditions have been adopted from global air quality products of the National Centre for Atmospheric Research (NCAR), USA. These global products are generated using the global chemical transport model MOZART. The contributions to the ambient air quality from neighbouring countries, such as Pakistan, Nepal, Bangladesh, etc., which fall within the Indian study domain were taken from ECLIPSE database (IIASA, 2014).

3

RESIDENTIAL SECTOR

The basic equation (Eq. 2) employed for emission estimation from the residential sector is:

$$[Ep]R = \sum_{(S=\ 1)}^{35} \sum_{(D=1)}^{n} \sum_{(f=1)}^{n} Pop_{(D,f)} \times C_{(f,S)} \times EF_{(f,p)} \tag{2}$$

where, $[E_p]_R$ is the emission of a particular pollutant (p) from the residential sector; $Pop_{(D)}$ is the population of a district using a particular fuel; $C_{(f'S)}$ = State specific per capita consumption of a particular fuel; and $EF_{(f,p)}$ = Emission factor of the particular pollutant (p) of the particular fuel type (f). We define rural areas following the 2011 India Census. Under the census, a rural area is any area that does not belong to a municipality, corporation, cantonment board or notified area and meets all of the following criteria: more than 75% of people are engaged in agricultural activities, area is not contiguous to a statutory town, area does not possess urban infrastructures (e.g., pucca road, streetlight, water tap, drainage, educational institution), and area is within the revenue limit of a village. All other areas were considered as urban areas in the present study.

The district-level population and household data (rural and urban area) were collected from the India census (2001, 2011) for the years 2001 and 2011. The population data of India census has an error of 2.3% (India Census, 2011). These data were used to derive the district-level annual population growth rate and growth rate of number of people living in one household. These growth rates were then used to project the population and number of households in 2016 based on the district-level respective data of 2011 following Eq. 3 and Eq. 4

$$Pop_{(2016)} = Pop_{(2011)} \, (1 + POP_{GR})^5 \tag{3}$$

$$HH_{(2016)} = \frac{Pop_{(2016)}}{HHPOP_{(2011)} \left\{1 + \frac{HHPOP_{(2011)} - HHPOP_{(2001)}}{10 \times HHPOP_{(2001)}}\right\}^5} \tag{4}$$

where, $Pop_{(2016)}$ is the projected population of 2016; $Pop_{(2011)}$ is the district-level (rural and urban) population in 2011 (Census, 2011); POP_{GR} is the annual population growth rate (Census, 2011); $HH_{(2016)}$ is the projected household number in a district (rural and urban) in 2016; $HH_{POP(2011)}$ is the average number of people in each district (rural and urban) living in each household during 2011; and $HH_{POP(2001)}$ is the average number of people in each district (rural and urban) living in each household during 2001. The annual population estimation using the method above can have an error as high as 16% based on the earlier available data from India Census (1991, 2001 and 2011). Thus, $Pop_{(2016)}$ and $HH_{(2016)}$ estimation using Eq. 4 has an error of estimation of 18.3%.

The number of households in a particular district (rural and urban area) that use a particular fuel for cooking and lighting energy during 2016 was calculated using the household amenity dataset of India census (2011). This was used to calculate the number of people using a particular fuel by considering the average household population in each district.

However, there is a significant annual growth in household electricity and liquefied petroleum gas (LPG) usages after 2011. State-level annual unelectrified village data for the years 2013 to 2016 were collected from the Central Electricity Authority (CEA, 2013 to 2016). State-wise annual electricity surplus data were also collected from the CEA (2011 and 2017). The number of unelectrified households in each district (rural and urban) during 2011 was calculated based on the household amenity data (Census, 2011). State-level annual rural electrification growth rate was calculated using the village electrification data of CEA. This was used to estimate the number of electrified households during 2016. The state- wise power surplus data (CEA, 2011 to 2016) were used to adjust the household kerosene use in both urban and rural areas using Eq. 5 and Eq. 6

$$\textit{Adj}\mathrm{HH}_{\mathrm{unelc}} = \mathrm{HH}_{\mathrm{unelc}} - (\mathrm{HH}_{\mathrm{elec}} \times \mathrm{E}_{\mathrm{GR}} \times \mathrm{P}_{\mathrm{Sur}}) \tag{5}$$

$$\textit{Adj}\mathrm{HH}_{\mathrm{K\_L}} = (\mathrm{HH}_{\mathrm{K\_L}} \times \textit{Adj}\mathrm{HH}_{\mathrm{unelec}}) / \mathrm{HH}_{\mathrm{unelec}} \tag{6}$$

where, $\textit{Adj}\mathrm{HH}_{\mathrm{unelc}}$ is the estimated number of households un-electrified during 2016; $\mathrm{HH}_{\mathrm{unelec}}$ and $\mathrm{HH}_{\mathrm{elect}}$ is the number of households unelectrified and electrified respectively in 2016 based on Census (2011); E_{GR} is the annual village electrification growth rate in a state; $\mathrm{P}_{\mathrm{Sur}}$ is the state-level change (%) in power surplus situation between 2011 and 2016 (CEA, 2011; 2017); $\textit{Adj}\mathrm{HH}_{\mathrm{K\_L}}$ and $\mathrm{HH}_{\mathrm{K\_L}}$ are estimated number of households using kerosene for lighting purpose during 2016 and calculated number of households using kerosene for lighting during 2016 based on census (2011). The $\mathrm{HH}_{\mathrm{unelec}}$ and $\mathrm{HH}_{\mathrm{elect}}$ were calculated from the India census (2011), which is having an error of 2.3%; thus there is an error of 2.3% in the estimation of $\textit{Adj}\mathrm{HH}_{\mathrm{K\_L}}$ in Eq. 6.

Similarly, the number of households using LPG for cooking fuel in 2016 was also estimated. State-level annual registered LPG consumers' data for the year 2013–2016 were collected from the database of Petroleum Planning & Analysis Cell, Ministry of Petroleum and Natural Gas, Government of India (PPAC, 2013; 2014; 2015; 2016). State- level rural and urban area-wise annual data of LPG distributors for the same years were also collected from the above source. These data were used to calculate the state-level annual growth of LPG consumers in rural and urban areas. The number of the LPG using households ($\textit{Adj}\mathrm{HH}_{\mathrm{LPG}}$) in rural and urban areas during 2016 was adjusted using Eq. 7

$$\textit{Adj}\mathrm{HH}_{\mathrm{LPG}} = \mathrm{HH}_{\mathrm{LPG(2016)}} + (\mathrm{HH}_{\mathrm{LPG(2011)}} \times \mathrm{GR}_{\mathrm{LPG}}) \tag{7}$$

where, $\mathrm{HH}_{\mathrm{LPG(2016)}}$ is the number of LPG using households in either rural or urban area of a district during 2016 using the household amenity data of the India census (2011) and the number of households in 2016 using the *eq. 4*; $\mathrm{GR}_{\mathrm{LPG}}$ is the district-specific calculated annual growth rate of LPG consumers' in rural and urban areas. The increase of numbers of households using LPG ($\textit{Adj}\mathrm{HH}_{\mathrm{LPG}}$ - $\mathrm{HH}_{\mathrm{LPG(2016)}}$) was then uniformly distributed to adjust the number of FW, CR and CDC using households during 2016. Thus, the estimation of consumption of different fuels in the residential sector during the year 2016 has an error as high as: 19% for FW, 19% for CR, 19% for CDC, 20% for kerosene, 19% for coal, and 20% for LPG.

The data related to the state-level per capita consumption of different fuel ($C_{(f,S)}$) used in the residential sector was collected from the National Sample Survey Office report (NSSO, 2014).

Apart from cooking, Fuelwood (FW) is also used in the residential sector for the purpose of water heating, space heating during the winter season and also for preparing animal fodder in several parts of India. The FW use for the residential water heating was separately accounted in this study. First, it was assumed that the households in the rural areas of districts with morning temperature below 18°C during the morning hours (6 AM to 11 AM) mostly use the FW for water heating. District-wise hourly ambient temperature data were collected from the Indian Meteorological Department (IMD). The ambient temperature in the rural areas of the districts was below 18°C for three months during the year (December to February). In these districts, the total FW use (kg/annum) was adjusted ($AdjPP_{FW}$) by including the FW use for water heating using Eq. 8

$$(AdjPP_{FW})_{Ru} = (PP_{FW})_{Ru} + (PP_{FW\_H})_{Ru} \times (C_{FW})_{Ru} \qquad (9)$$

where, $(PP_{FW})_{Ru}$ is the district-specific FW use (kg) in the rural area; $(PP_{FW\_H})_{Ru}$ is the district-specific number of people using FW for residential water heating and $(C_{FW})_{Ru}$ is the per capita use of FW in the rural area (NSSO, 2014). Fuel-specific emission factors of different pollutants ($EF_{(f,p)}$) were taken from Datta et al. (2016) and Pandey et al. (2014) (Table 1).

Table 1 Emission factors (g/kg) of different pollutants from different fuel types used in the residential sector

Fuel type	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	NMVOC
Fuelwood	6.8	4.6	0.8	1.7	66.5	15.9
Crop residue	8.6	5.7	0.7	1.8	64	8.5
Dung cake	10.5	4.4	0.6	1.0	78.6	24.1*
Coal	8.3	4.0	15.3	2.16	59.5	10.5*
Kerosene (for cooking)	3.6	3.0	0.4	1.3	43	17.0*
Kerosene (for lighting)	91. 3	91.3	NA	NA	29.3	NA
LPG	0.4	0.4	0.4	2.9	2.0	3.7*

* Pandey et al. (2014); others were adopted from Datta et al. (2016)

NA: Not available

Datta et al. (2016) have reported the error in the emission factors listed in Table 1 that may be attributed to an uncertainty of up to 25% in the estimation of individual pollutants emissions.

3.1 Estimated fuel consumption in residential sector

The annual consumption of different types of fuels in the residential sector of different states of India estimated using the methodology stated above is summarized in Table 2 and Table 3.

Table 2 State-wise annual consumption (Gg) of different fuels in the rural areas during 2016

State	FW	CR	CDC	Coal	Kerosene	LPG
Andaman & Nicobar Islands	70	9	0	0	1	3
Andhra Pradesh	7964	2785	27	3	107	268
Arunachal Pradesh	742	142	0	0	3	12
Assam	10,481	4186	12	10	149	148
Bihar	12,362	25,491	4369	211	477	209
Chandigarh	0	0	0	0	0	0
Chhattisgarh	6216	0	442	37	81	12
Dadra & Nagar Haveli	0	0	0	0	0	0
Daman & Diu	0	0	0	0	0	0
Goa	45	0	0	0	2	12
Gujarat	9089	2306	406	16	179	135
Haryana	2596	468	1214	3	28	161
Himachal Pradesh	1180	0	3	0	3	27
Jammu & Kashmir	3794	787	71	6	35	89
Jharkhand	6814	1863	499	995	134	263
Karnataka	13,137	1637	48	0	167	155
Kerala	6069	356	0	2	28	196
Lakshadweep	3	0	0	0	0	0
Madhya Pradesh	11,131	6019	2413	5	249	109
Maharashtra	13,241	5851	36	16	278	458
Manipur	479	168	1	15	5	19
Meghalaya	1016	0	0	9	8	6
Mizoram	310	0	0	0	1	7
Nagaland	620	48	0	0	1	18
NCT of Delhi	1	0	0	0	0	6
Odisha	12,825	959	324	110	157	49
Puducherry	3	0	0	0	1	8
Punjab	2754	809	1885	1	28	238
Rajasthan	20,207	609	1155	7	211	182
Sikkim	86	0	0	0	1	8
Tamil Nadu	8930	1622	8	0	153	439
Telangana	4969	1738	17	2	67	167
Tripura	1884	0	1	2	14	7
Uttar Pradesh	24,735	6035	11,161	63	652	348
Uttarakhand	3800	409	35	0	25	78
West Bengal	13,842	4328	1323	998	336	172
Total	201,395	68,625	25,452	2511	3583	4011

FW: Fuelwood; CR: Crop residue; CDC: Dung cake; LPG: Liquid petroleum gas

Table 3 State-wise annual consumption (Gg) of different fuels in the urban areas during 2016

State	FW	CR	CDC	Coal	Kerosene	LPG
Andaman & Nicobar Islands	2	2	0	0	1	4
Andhra Pradesh	599	124	4	15	32	399
Arunachal Pradesh	51	0	0	0	0	8
Assam	404	95	0	3	6	158
Bihar	833	335	248	102	9	301
Chandigarh	0	0	0	0	0	0
Chhattisgarh	672	150	71	215	6	99
Dadra & Nagar Haveli	0	0	0	0	0	0
Daman & Diu	0	0	0	0	0	0
Goa	22	0	0	0	2	40
Gujarat	1271	2012	36	153	86	622
Haryana	248	59	112	6	4	368
Himachal Pradesh	265	12	1	0	12	144
Jammu & Kashmir	241	52	2	6	9	127
Jharkhand	278	57	48	766	5	197
Karnataka	2156	0	10	5	91	622
Kerala	5860	284	0	8	10	509
Lakshadweep	17	0	0	0	1	1
Madhya Pradesh	1498	25	208	47	35	449
Maharashtra	1215	258	36	26	206	1502
Manipur	73	1	1	10	0	15
Meghalaya	53	0	0	3	1	15
Mizoram	38	0	0	1	1	19
Nagaland	179	0	0	0	0	18
NCT of Delhi	19	0	2	0	3	287
Odisha	1370	79	6	97	11	124
Puducherry	35	2	0	0	2	27
Punjab	270	42	154	4	20	340
Rajasthan	1242	24	77	23	11	416
Sikkim	1	0	0	0	1	16
Tamil Nadu	1904	310	1	1	165	1121
Telangana	601	124	4	15	37	400
Tripura	245	6	0	1	1	29
Uttar Pradesh	2623	248	924	47	29	1008
Uttarakhand	279	0	9	0	5	98

State	FW	CR	CDC	Coal	Kerosene	LPG
West Bengal	1283	151	175	875	84	718
Total	25,850	4453	2127	2428	887	10,200

FW: Fuelwood; CR: Crop residue; CDC: Dung cake; LPG: Liquid petroleum gas

The estimated fuel consumption in the residential sector (Table 2 and Table 3) was comparative with the estimated fuel consumptions in the residential sector reported in other studies (Table 4). The MARKAL model simulation is based on estimates of different energy use in the domestic sector, so there are possibilities of error in the simulation framework. The MARKAL simulation does not have any estimation of coal consumption in the residential sector of India. The reported coal consumption in the residential sector in the Ministry of Statistics and Programme Implementation (MoSPI) (2014) was of FY2012–13. In the present study, we estimated the coal consumption in the residential sector by projecting the population in Census 2011 to 2016 and also the number of households using coal based on India Census 2011 data adjusted with increase in the LPG using households during 2011 to 2016. This may attribute to estimation of higher coal consumption in the present study compared to MoSPI (2014). Pandey et al. (2014) have reported the biomass use during 2012–13, while in the present study the estimation was made for 2016. However, the fuel use in the residential sector in the present study was adjusted with increase in LPG use during 2011 to 2016 period. Thus, the estimated biomass use was lower in the present study compared to that reported in Pandey et al. (2014), although the estimated population was higher during 2016 than 2012–13. The PNGStat reports the consumption of kerosene through the Public Distribution System (PDS), India; the ~14% difference in kerosene consumption in the present study with the PNGStat may be attributed to higher estimation of LPG uses during 2016 in the residential sector or lower use of kerosene for lighting in the domestic sector. The ~24% lower estimation of LPG consumption compared to the PNGStat (Table 4), may be attributed to inclusion of commercial use of LPG in PNGStat.

Table 4 Comparison of estimated energy use in the residential sector with other reported studies

	Biomass (Gg)	Coal (Gg)	Kerosene (Gg)	LPG (Gg)
MARKAL estimates	339,409		2611	10,973
PNGStat, 2017[1]			5204	18,871
Pandey et al., 2014[2]	350,476			
MoSPI, 2014[3]		2682		
Present study	327,902	4939	4469	14,212

3.2 Emission inventory of the residential sector

The activity data of different fuels (Table 2 and Table 3) was fed into the *eq. 2* along with the fuel-specific emission factors of different pollutants ($EF_{(f,p)}$) to calculate the emission of different pollutants from the use of different fuel types in the rural and urban areas (Figure 2).

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1 PNGStat Indian petroleum and natural gas statistics 2016-17. Ministry of Petroleum and Natural Gas, Government of India.

2 Pandey, A., Sadavarte, P., Rao, A.B., Venkataraman, C. 2014. Trends in multi-pollutant emissions from a technology-linked inventory for India: II. Residential, agricultural and informal industry sectors. Atmospheric Environment 99: 341-352.

3 MoSPI 2014 Energy statistics 2014. National Statistical Organization, Ministry of Statistics and Programme Implementation, Government of India.

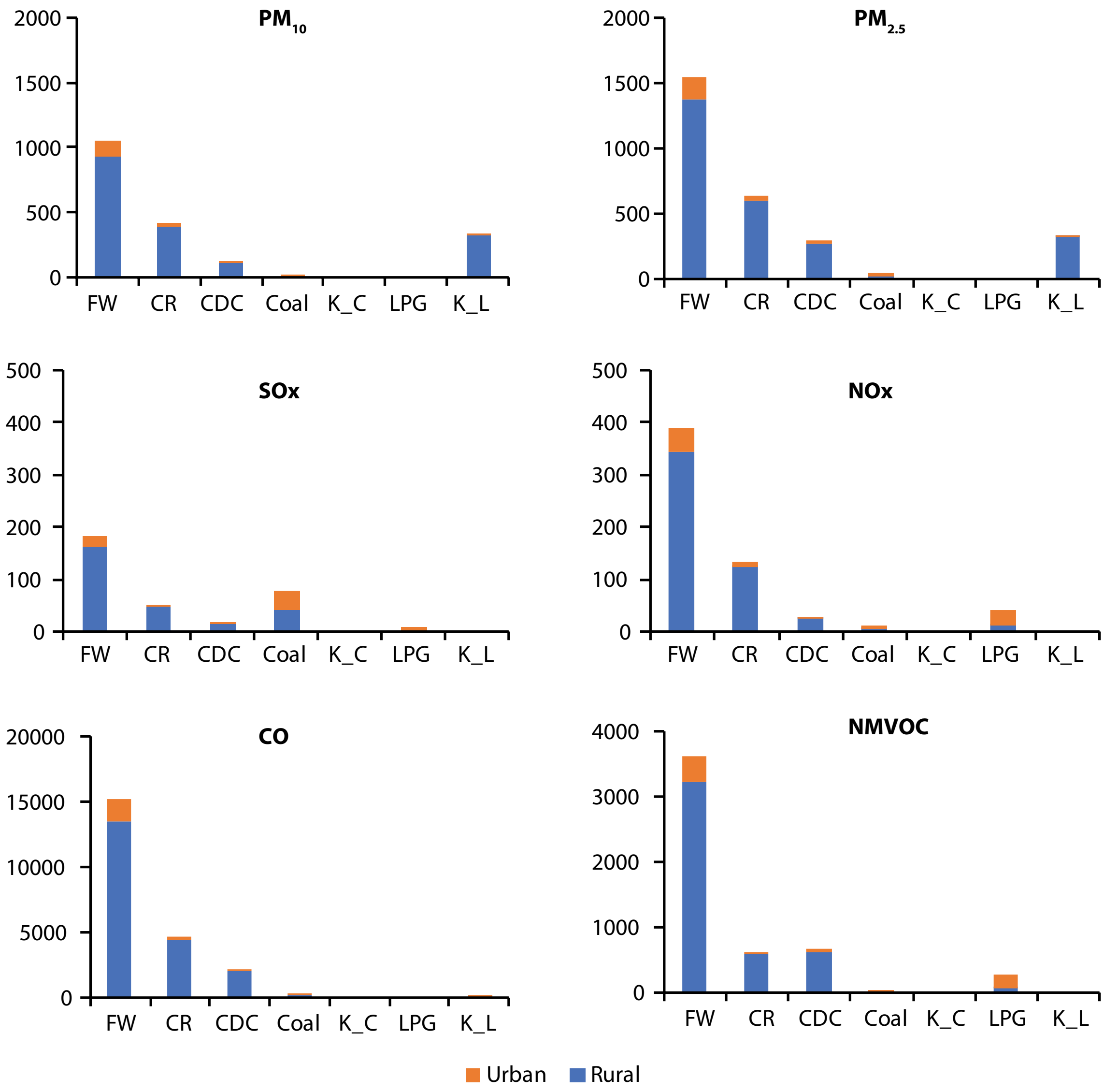


Figure 2 Fuel-wise emissions of different pollutants from the residential sector during 2016

The district-specific emissions of different pollutants were distributed spatially over 36 × 36 km2 grid (Figure 3) using the ratio of the area of each polygon and area of the respective district. However, if a polygon has higher population density in a district, it was not attributed through this method. This distribution method contains up to 5% error in spatial distribution of district-level estimated emissions of each pollutant.

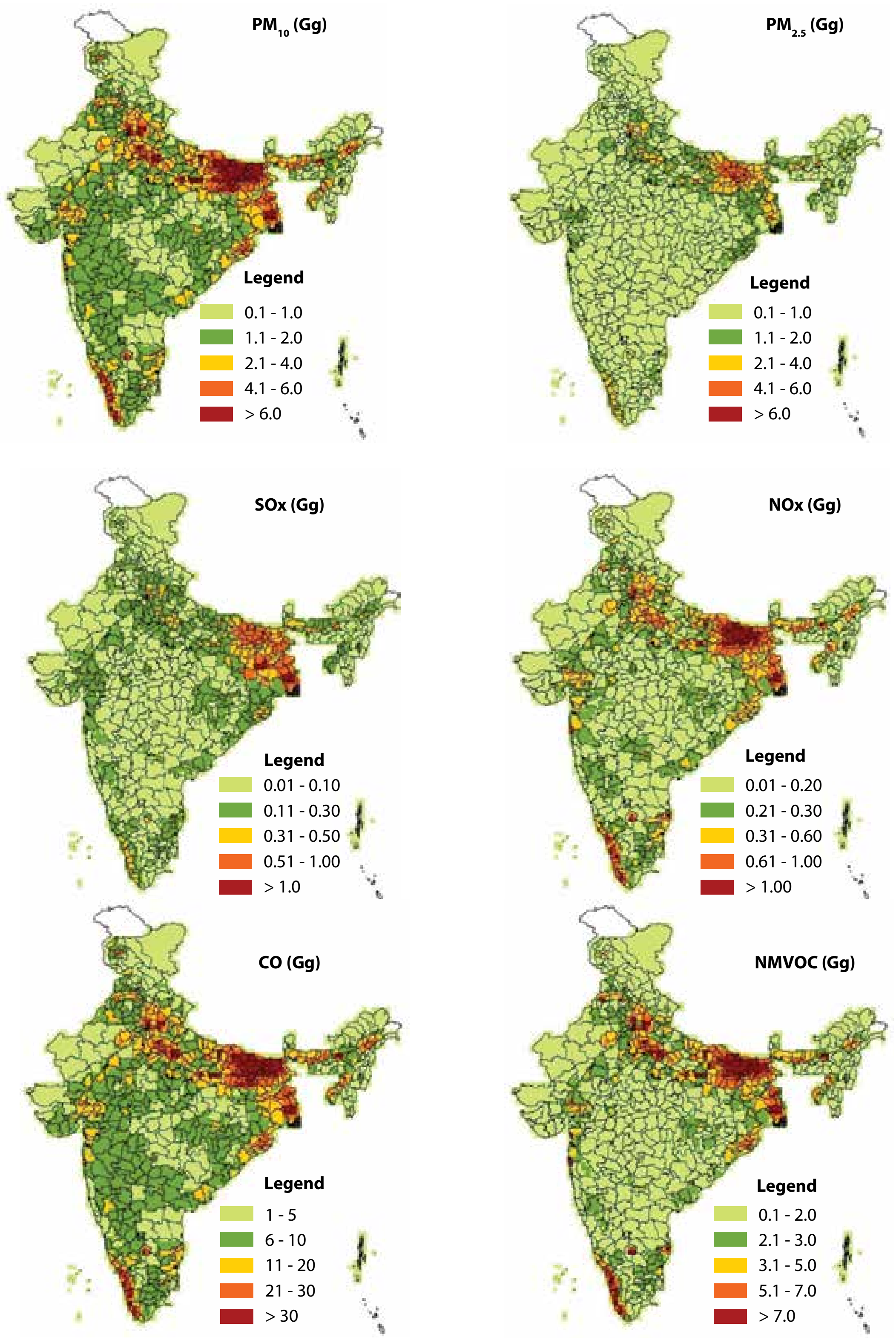


Figure 3 Spatial variations of emissions of different pollutants from the domestic sector

Total emissions of different pollutants from the residential sector are summarized in Table 5.

Table 5 Fuel-wise total emissions (Gg) of different pollutants from the residential sector during 2016

Fuel type	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	NMVOC
Water heating						
Fuelwood	28	41	5	10	402	96
Cooking						
Fuelwood	1510	1004	177	376	14,710	3515
Crop residue	628	417	51	132	4677	621
Dung cake	290	121	17	28	2168	665
Coal	41	20	76	11	294	52
Kerosene	3	3	0	1	37	14
LPG	5	5	6	41	28	270
Lighting						
Kerosene	331	331	0	0	106	0
Total	2836	1941	331	598	22,421	5233

FW: Fuel wood; CR: Crop residue; CDC: Dung cake; K_C: Kerosene used for cooking; K_L: Kerosene used for Lighting (Wicked Lamp); LPG: Liquid Petroleum Gas

Earlier studies have estimated 3236 Gg (ECLIPSE) to 3600 Gg (IEA, 2016) of emissions of $PM_{2.5}$ and 476 Gg (ECLIPSE) to 725 Gg (IEA, 2016) of emissions of SO_2 from the residential sector during 2015. Higher estimation of emissions of $PM_{2.5}$ and SO_2 in earlier studies may be attributed to the consideration of increase of LPG uses and simultaeneous decrease in biomass uses in households for the present study. Additionally, decreases in kerosene consumption for lighting and cooking purposes have also been accounted for in the activitiy data of the present study by using the growth of electrification and LPG usage in India; this might also have contributed to decreases in $PM_{2.5}$ and SO_2 emissions from the residential sector compared to earlier studies.

4

POWER SECTOR

4.1 Coal-based thermal power plants

In India, more than 50% of the electricity demand is met through coal-based thermal power plants (TPPs) (Singh and Siddique, 2013; TERI, 2015). Large quantities of coal is burnt annually in the TPPs, which leads to the production of fly ash and bottom ash. Particulate matter emissions from coal-based TPPs are linked to high ash content (which ranges between 20% and 40%) in Indian coal. Sulphur content in Indian coal (generally < 0.6%), leads to emission of SO_2 from TPPs. Emissions from coal-fired power plants are function of the quality of fuel (ash content and sulphur content), the type of boilers, and the types of air pollution control devices used and their efficiency. In addition to coal, natural gas is also used in power plants in India.

The equations (Eq. 9 and Eq. 10) used for estimation of emissions from coal-based power plants are:

$$[E_{PM}]_c = \sum_{a=1}^{n} [P_c]_a \times Ac \times (1-fb_r) \times M \times (1-RE_a) \qquad (9)$$

$$[E_{pg}]_c = \sum_{a=1}^{n} [P_c]_a \times EF_{pg} \times (1-RE_a) \qquad (10)$$

where, E_{PM} is the emission of particulates; E_{pg} is the emission of gaseous pollutants; $[P_c]_a$ is annual coal consumption in plant a; A_c is ash content of coal; fb_r is the ratio of bottom ash to total ash; M = particulate mass fraction (0.4 for $PM_{2.5}$ to PM_{10} and 0.75 for PM_{10} to total particulates following Mahtta et al., 2016); RE is the efficiency (%) of installed emission control equipment; and EF_{pg} is the emission factor of the particular gaseous pollutant (p).

Coal consumption (Pc) in each power plant for the year 2016 was taken from the CEA database. As per the CEA data, the total coal consumed by power plants in India for the year 2016 was 557,854 Gg. However, the MARKAL estimates of coal consumption in power sector during the year was 473,290 Gg, while MoSPI (2018) reported it as 527,256 Gg. The CEA (2016) reports plant-wise actual coal consumptions during January to December. However, MoSPI (2018) provides the data of total coal supplied to the power plant during FY2016–17. In general, power plants maintain a coal stock for three months, this attributes to variation in actual coal consumptions in power plants than supplied coal during a particular period. Plant-wise ash content (Ac) data was also taken from the CEA database. Expert consultations were organized to understand the type of boilers and efficiencies of air pollution control devices used in power plants. Ratio of bottom to total ash was taken as 20% because 20% of the total ash generated during combustion of coal is bottom ash and the remaining is fly ash (F.Bassetti et al., 2015; FHWA, 1998). It was understood after consultation from experts that all the coal- based TPPs in India are equipped with electrostatic precipitators (ESPs) to control PM emissions in order to meet the emission norms prescribed by the CPCB. A literature review was carried out to understand the efficiency of ESPs used by TPPs in India and based on that, ESP efficiencies for 40 units were adopted from Chandra (2008). For rest of the units, average efficiency of all ESPs used by different TPPs of that particular state was assumed. During 2016, there were only three power plants in India that have FGD (Wet flue gas desulphurization) units in operation to reduce SO_2 emissions. These power plants are: Trombay TPS, Udipi TPP and Jindal TPP—whose sulphur removal efficiency is 90%. NO_x emissions from coal-based power plants in India are not controlled.

Emission factors for gaseous pollutants namely, SO_2, NO_x, CO, NMVOCs and NH_3 were selected based on review of published literature and the selected emission factors are shown in Table 6.

Table 6 Emission factors for coal-based thermal power plants in India

Pollutant	Emission factor
SO_2 (kg/Mg)*	7.37
NO_x (kg/Mg)**	4.50
CO (kg/Mg)**	0.30
NH_3 (Mg/PJ) ***	0.01
NMVOCs (Mg/PJ) ***	15.00

Source: *Mahtta et al., 2016;** ARAI, 2010; ***GAINS Asia database

4.2 Gas-based power plants

The equation (Eq. 11) used for estimation of emissions from gas-based power plant is:

$$[E_p]_g = \sum_{a=1}^{n} [P_g]_a \times EF_p \times (1-RE_a) \qquad (10)$$

where, Ep is the emission of particular pollutant (p); [Pg]a is the annual gas consumption in power plant a; and EFp = Emission factor of the particular pollutant (p). Gas consumption (Pg) in each power plant for the base year was taken from the CEA database. The quantity of gas consumed for power generation in India for the year 2016 was about 11,067 MMSCM.

Fuel-specific emission factors (EFpg and EFp) of different pollutants were selected based on review of published literature. All the gas-based power plants in India are using selective catalytic reduction (SCR) for NO_x emissions reduction whose efficiency is about 85%. The selected emission factors for gas-fired TPPs in India are shown in Table 7.

Table 7 Emission factors for gas-based power plants

Pollutants	Emission factor	Pollutants	Emission factor
PM_{10} (kg / 10^6 m^3)	121.60	NMVOC (kg/ 10^6 m^3)	0.091
$PM_{2.5}$ (kg / 10^6 m^3)	121.60	NH_3 (Mg/PJ)	0.01
SO_2 (kg / 10^6 m^3)	9.60	HC (Mg/PJ)	1.00
NO_x (kg / 10^6 m^3)	4480.00	CO (kg / 10^6 m^3)	1344.00

Source: *ARAI, 2010; **GAINS Asia Database

4.3 Emission inventory of the power plant

PM_{10} emissions for the year 2016 are estimated to be about 572.5 Gg from coal-based power plants in India, out of which around 229 Gg are $PM_{2.5}$ (*Table 8*). For the same year, the estimated emissions of SO_2, NO_x, CO, and NMOVCs from coal-based TPPs in India are 5437, 2509, 167, and 80 Gg, respectively. However, NH_3 emissions from coal- based TPPs in India were estimated to be small (0.05 Gg).

Table 8 Emissions from coal-based power plants during 2016

Pollutants	Emissions (Gg)
PM_{10}	572
$PM_{2.5}$	229
SO_2	5437
NO_x	2509
CO	167
NMVOC	80
NH_3	0.05

The estimated emissions from gas-based thermal power plants in India are shown in *Table 9*. Emissions from both coal- and gas-based power plants were spatially distributed in 36 km × 36 km map based on actual coordinates of the thermal power plant.

Table 9 Emissions from gas-based thermal power plants during 2016

Pollutants	Emissions (Gg)
PM_{10}	1.35
$PM_{2.5}$	1.35
SO_2	0.11
NO_x	7.44
CO	14.87
NMVOC	0.001
NH_3	0.005

INDUSTRY SECTOR

5

Air pollutant emissions from industries are the result of different categories of manufacturing activities. Different air pollutants are released to the atmosphere through industrial chimneys/stacks. Emissions from industries can be broadly classified as: i) combustion-related emissions due to the burning of fuels, *viz.,* coal, petcoke, biomass, furnace oil, diesel and natural gas in different types of boilers, furnaces, etc., ii) non-combustion emission related to the use of naptha, natural gas, etc., as feedstock, and iii) fugitive emission related to manufacturing processes, storage, and handling of materials, etc.

Combustion-related emissions from industries are function of quality of fuel, boiler type, and emission controls. Emissions from industries are estimated based on the following equation (Eq. 12):

$$[E_p]_I = \sum_{a=1}^{n} \sum_{f=1}^{n} [C_f]_a \times EF_{(f,p)} \times (1-RE_a) \qquad (12)$$

where, $[E_p]_I$ is the emission of a particular pollutant (p) from the industry sector; C_f is annual consumption of a particular fuel in industry type a; $EF_{(f,p)}$ is emission factor of pollutant p of the fuel type f related to the boiler type; and RE_a is percentage removal efficiency of installed pollution control device in industry type a. $EF_{(f,p)}$ was developed based on review of published literature.

Fugitive emissions (*f*) from industrial arc furnace and induction furnaces was estimated using the following equation (Eq. 13):

$$f\,[E_p]_I = \sum_{u=1}^{2} [M_u]_a \times EF_{(p,u)} \times (1-RE_u) \qquad (13)$$

where, M is the amount of materials processed in a particular type of furnace (u); EF is emission factor for a particular pollutant p; and RE is the efficiency of the control device used. u=1 is arc furnace while u=2 is induction furnace in the above equation.

Emissions were estimated separately for large-scale industries, *viz.,* cement, iron and steel, fertilizers, paper, aluminium, and glass. For each category of large-scale industries, emissions due to process and combustion were estimated separately. Production capacity of each category of industry was taken from the MARKAL model (*Annexure V*). In order to estimate emissions due to the combustion of different fuel types, fuel-wise actual energy consumed data were taken from the MARKAL model. Based on the calorific value of each type of fuel, this actual energy consumed by each fuel type is then converted into fuel consumed. The remaining small- and medium-scale industries were clubbed into the 'Other industries' category. Actual energy consumed in these industries was taken from the MARKAL model. Emissions were estimated following Eq. 12 and Eq. 13. Apart from these emissions of different industries, the emissions from the brick kiln and mines were estimated separately. The estimation of emissions from each category of industry is explained in subsequent sections.

5.1 Large-scale industries

5.1.1 Cement industry

Cement manufacturing processes lead to emissions of PM and other gaseous pollutants. The emissions from cement manufacturing processes are:

- *Fugitive emissions*: Due to handling and storage of raw, intermediate, and final materials
- *Process emissions*: Due to operation of kiln, clinker coolers, and mills.

Major emissions occur in the kilns during production through physical and chemical reactions involving the raw materials and the combustion of fuels. Emissions were estimated based on the production, energy or fuel consumed, emission factor per unit of cement production, and efficiency of controls. The indigenous emission factors per unit of cement production were adopted from Infrastructure Leasing & Financial Services Limited (ILFSL, 2010) and CPCB (2007) (Table 10). Bag filter and ESPs are the common air pollution control devices used by cement industries to control stack emissions. The estimated emissions of different pollutants from the cement industries are shown in Figure 4. The emissions also include pollutants emitted during captive power generation activities.

Table 10 Emission factor (kg/Mg) for cement sector

	PM		NOx	SO_2	CO
	W/o APCD	APCD	W/o APCD	W/o APCD	W/o APCD
Dry Process					
Kiln	94	0.98			
Grinding	257	0.21			
Others	7	0.01			
Total	358	1.2	2.2	4.9	0.27
Fugitive		0.56			
Wet process					
Kiln	174	0.2			
Grinding	123	0.02			
Others	6	0.03			
Total	303	0.25	4	3.75	0.27

APCD: Air Pollution Control Devices; W/o APCD: without Air Pollution Control Devices

Source: ILFS (2010), CPCB (2007)

5.1.2 Iron and Steel industry

Production of coke, sinter and pellets, iron ore processing, making of iron and steel, steel casting, combustion of blast furnace and coke oven gases are the major processes involved in iron and steel manufacturing that result in the emissions of different pollutants. Emissions are estimated based on the production, energy/fuel consumed, and emission factors. The emission factors were adopted from the European Environmental Agency (EEA) and GAINS-Asia and are shown in Table 11. Generally, iron and steel plants in India are equipped with efficient air pollution control devices such as ESPs and wet scrubbers for reduction of PM and gaseous emissions. oHThe estimated emissions from iron and steel manufacturing process are shown in Figure 4.

Table 11 Emission factors (kg/Mg) for different pollutants from various processes in iron and steel making

Pollutant	Process		Steel making with ESP	
	Sintering	Pig-iron	Basic oxygen furnace	Electric arc furnace
$PM_{2.5}$	0.08	0.025	0.021	0.021
PM_{10}	0.1	0.04	0.024	0.024
NO_x	0.5		0.01	0.13
SO_2	1	0		0.06
CO	12	10	7	0.0017
NMVOC	0.138	0	0	0.046

5.1.3 Aluminium industry

Emissions from this sector were estimated using activity data (production and energy/fuel consumed) and emission factor. The emissions include pollutants emitted during captive power generation activities also. The emission factor for aluminium production was taken from EEA (2009), EPA (2012), and GAINS-Asia (Table 12). The estimated emissions are shown in Figure 4.

5.1.4 Glass industry

The glass industry is highly energy intensive, and the melting and refining process accounts for 60–70% of the energy consumed in production. Natural gas is the fuel used in India as the thermal energy source in this sector. The emissions from this sector are estimated based on the production data and emission factor. The production data for the year 2016 was taken from GAINS-Asia. About 4.54 Mt of glass was produced during the year 2016. The emission factors of different pollutants for glass manufacturing was adopted from EEA (2009) and GAINS-Asia (Table 12). The estimated emissions of different pollutants are presented in Figure 4.

5.1.5 Paper and pulp industry

The Kraft method is broadly used in India for paper production. Pollutants are emitted from different processes in paper and pulp manufacturing as well as from combustion of coal in boilers. Emissions from processes and combustion are estimated using activity data (production and energy/fuel consumed) and emission factors. The emission factors of different pollutants in the paper industry are taken from EEA (2009) and EPA (2012) and are presented in Table 12. The estimated total emissions from process and combustion in the paper and pulp industrial sector are shown in Figure 4.

5.1.6 Fertilizer industry

Emissions from fertilizer industry were estimated from activity data (production) and emission factors. The emission factors for different pollutants for estimation of emissions in the fertilizer industry is taken from AP 42 (USEPA, 1995). The emission factors used in this study for estimation of emissions from large-scale industries are presented in Table 12 and estimated emissions are shown in Figure 4.

Table 12 Emission factors (kg/mg) of different pollutants from various large-scale industries

Parameter	Aluminium production	Glass manufacturing industry	Paper & pulp industry	Fertilizer industry
PM_{10}	2.0	0.27	0.8	0.33
$PM_{2.5}$	1.0	0.24	0.6	0.22
NO_x	1.0	8.12	1.0	2.00
SO_2	6.0	1.74	2.0	0.04
CO	120.0	0.10	5.5	62.25
NH_3				8.37*
NMVOC			2.0	

* kg/mg of urea produced.

Source: USEPA, 1995.

5.1.7 Emission inventory of large-scale industries

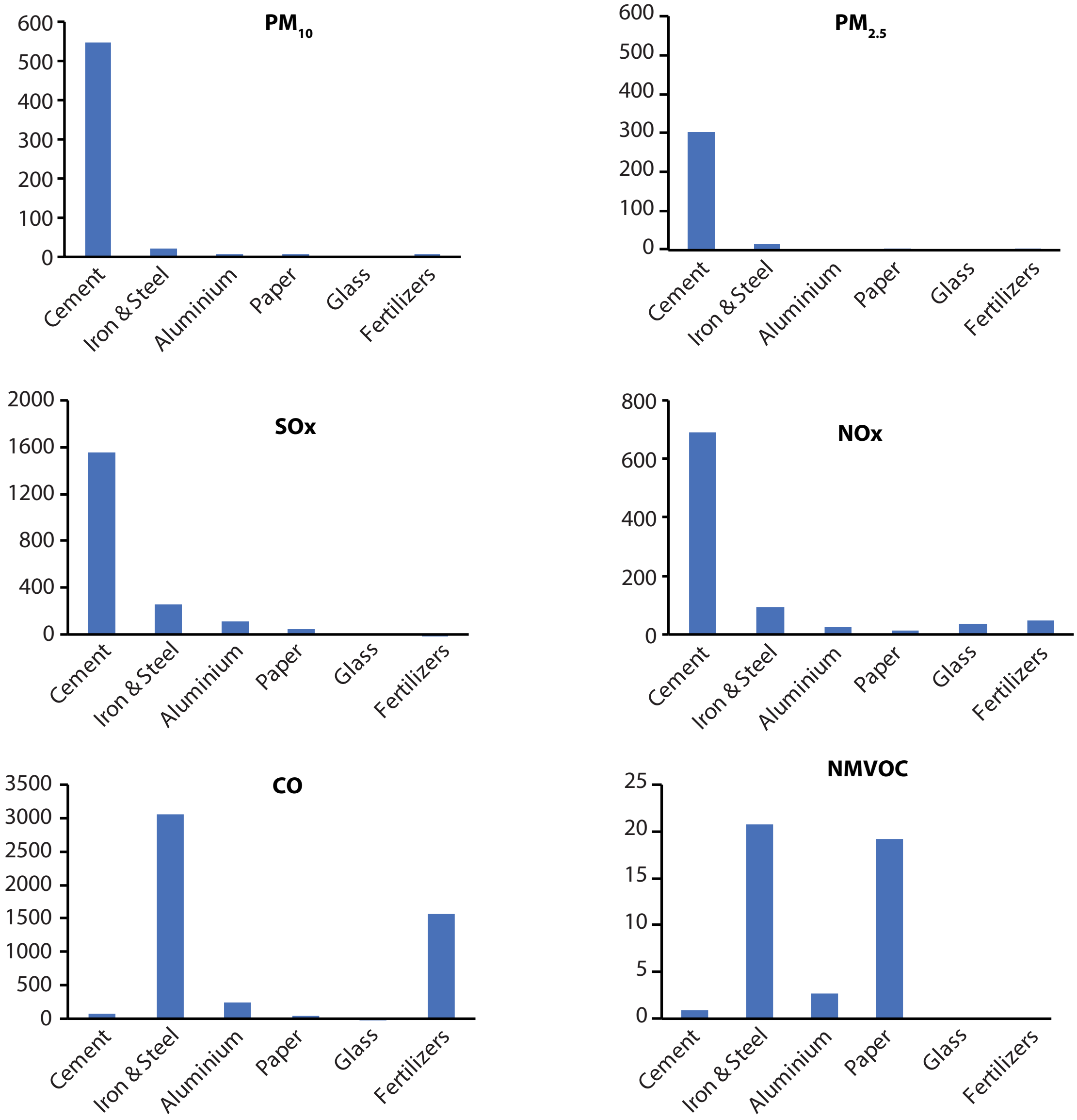
Estimated emissions of different pollutants from the large-scale industries during 2016 are summarized in Figure 4.

5.2 Micro-, small- and medium-scale industries

The energy consumed in the small- and medium-scale industry sector such as manufacturing of apparel wearing, food and beverages, sugar industry, pharmaceuticals, chemical, hosiery, textile, furniture making, plastic and paper-based industry, etc., was collected from the MARKAL model. PM_{10} and $PM_{2.5}$ emission factors for coal combustion in industries was calculated based on ash content and efficiency of air pollution control devices using Eq. 14:

$$EF_C = A_c \times R \times fPM \times (1- RE_a) \qquad (14)$$

where, EF_c is the emission factor of coal combustion; Ac is the ash content of the coal (***Table 13***); R is the ratio of fly ash and bottom ash during the combustion of coal; and *f*PM is the fraction of PM_{10} or $PM_{2.5}$ in total PM.



CEM: Cement industry; IRS: Iron & steel industry; ALU: Aluminium industry; GLA: Glass manufacturing industry; PAP: Paper & pulp industry; FER: Fertilizer industry.

Figure 4 Emissions of different pollutants from the large-scale industries during 2016

Table 13 Coefficient of coal combustion in small- and medium-scale industries

Coefficient	High control (e.g. ESP)	Medium control	Low control
Ash content (Ac)	35%	35%	35%
F/B ash ratio (R)	80:20	80:20	80:20
PM_{10}/PM (fPM_{10})	0.71	0.48	0.39
$PM_{2.5}/PM$ ($fPM_{2.5}$)	0.35	0.29	0.21
Efficiency of control (%)	99.90	70.00	40.00

Emission factors of other fuels used in the small- and medium-scale industries were taken from CPCB (2011) and GAINS-Asia (Table 14).

Table 14 Emission factors (Kt/PJ) of different pollutants from different fuels used in the small- and medium-scale industries

Fuel	PM_{10}	$PM_{2.5}$	NO_x	SO_2	CO	HC
Coal	3.75	2.03	0.13	0.57	0.01	0.02
Natural gas	0.002	0.002	0.07	0.02	0.04	
Biomass	0.12	0.11	0.03		0.30	0.80
Furnace oil	0.11	0.07	0.15	1.73	0.01	0.09
Diesel	0.77	0.26	0.08	0.94	0.04	
Light diesel oil	0.77	0.26	0.08	0.94	0.04	
Naptha	0.10	0.10	0.07	0.02	0.04	

5.2.1 Emission inventory of micro-, small- and medium-scale industries

Currently, in India only large-scale industries are equipped with high efficient equipment, *viz.,* ESPs and bag filters. Based on expert consultation and industrial survey during the present study, it was found that the efficiency of the control equipments varies from 10% (e.g., gravity settling chamber) to as high as 99% (e.g., ESP and bag filters), which are rarely used in small- and medium-scale industries. Most of these industries use cyclones (60%), multi-cyclones (80%) and dust collectors (10%) and a very good percentage of small- and medium-scale industries are running without APCDs and if at all they are using APCDs, then it is not properly maintained. Based on these, it was assumed that all micro- and small-scale industries were equipped with APCDs with efficiency of 40% and medium-scale industries were equipped with APCDs with efficiency of 70%. The estimated emissions from micro-, small- and medium-scale industries are shown in Table 15.

Table 15 Total emissions of different pollutants from the micro-, small- and medium-scale industries during 2016

Pollutant	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	VOCs	NH_3
Emission (Gg)	4126.1	2231.7	1551.6	283.9	44.1	56.9	0.29

Industries are mostly concentrated in different industrial zones of India. Industrial emissions were spatially distributed based on their locations all over the country (Figure 5).

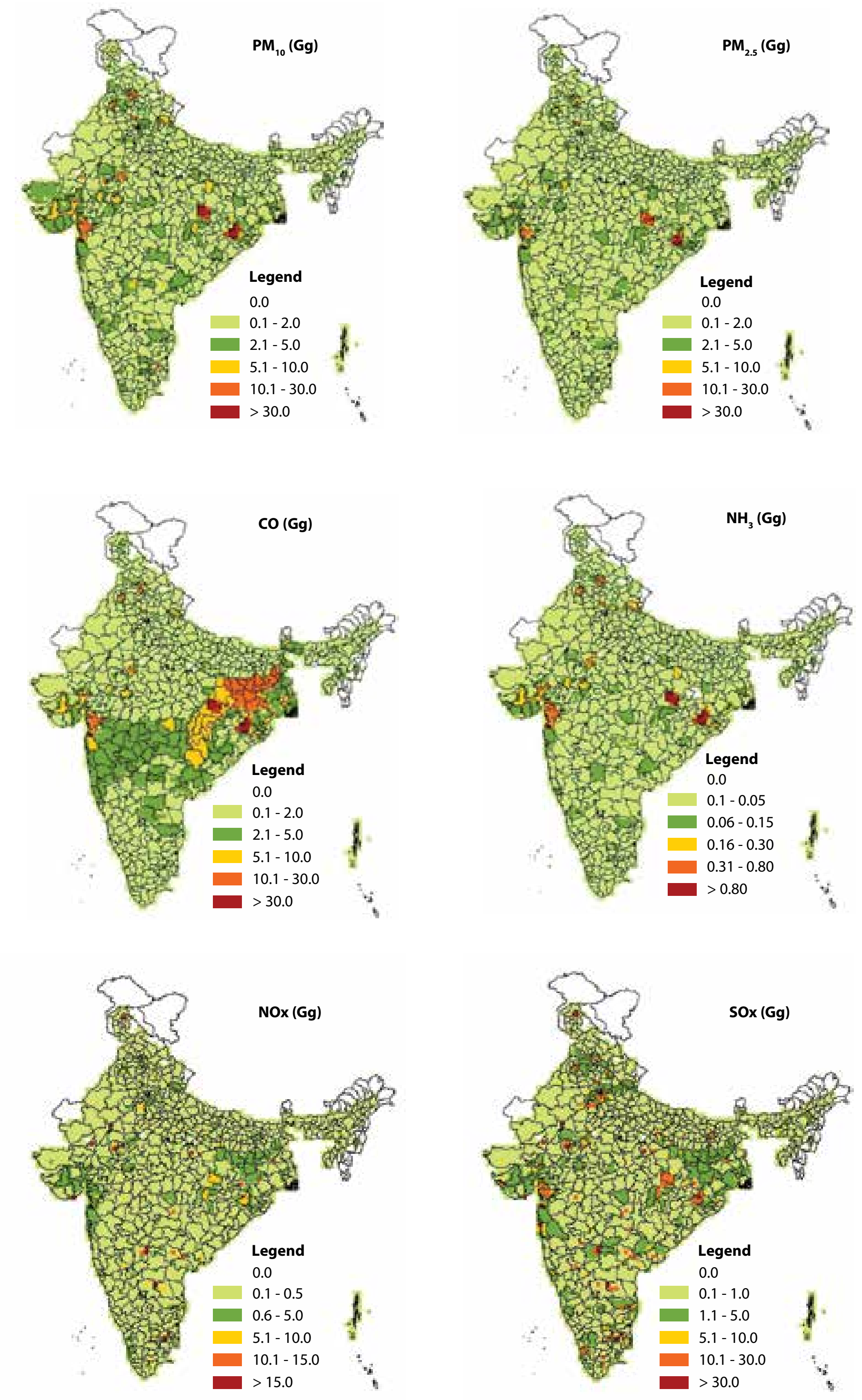


Figure 5 Spatial distribution of large-, micro-, small- and medium-scale industrial emissions during 2016

5.3 Emission inventory of brick kilns

Brick kilns are one of the largest consumers of coal in India. The brick industry in India consumed about 31 Mt of coal and 14 Mt of biomass for the year 2015 (Mahtta et al., 2016) which corresponds to a brick production of 236 billion for the same year. Bull's trench kilns (BTK) and clamp kilns are the two major brick firing technologies used in India. Other firing technologies, which are not significant in terms of brick production, are Vertical Shaft Brick Kiln (VSBK), Hoffman, Zig-zag, Down Drought Kiln (DDK), and tunnel kilns. Bull's trench kilns account for about 70% of total brick production in India (Rajaratnam et al., 2014). The brick manufacturing sector is an unorganized sector, using old technologies with low combustion efficiencies and limited control for air pollutants emissions. Due to rapid increase in brick production, the corresponding fuel consumption has also increased resulting in the emissions of pollutants such as PM, SO_2, NO_x, CO, metals, organic compounds, etc. The emissions from the brick kiln sector are estimated based on the state-wise technology-wise annual brick production data (TERI, 2016) and technology-wise emission factor. Emissions from the brick kilns were estimated using Eq. 15:

$$[E_p]_{bt} = \sum_{t=1}^{n} [W_b]_t \times EF_{pt} \qquad (15)$$

where, $[E_p]_{bt}$ denotes emissions of a particular pollutant p for fire technology t; $[W_b]_t$ is the total weight of the brick produced by a particular technology t; and EF_{pt} is the emission factor for a particular pollutant for the particular technology t. The total weight of the brick produced by a particular firing technology is estimated from the total number of bricks produced annually and weight of the fired brick. After consultation with experts, we have assumed the weight of the fired brick as 3 kg. Technology-wise emission factors for different pollutants are selected based on review of published literature (Rajarathnam et al., 2014) (Table 16).

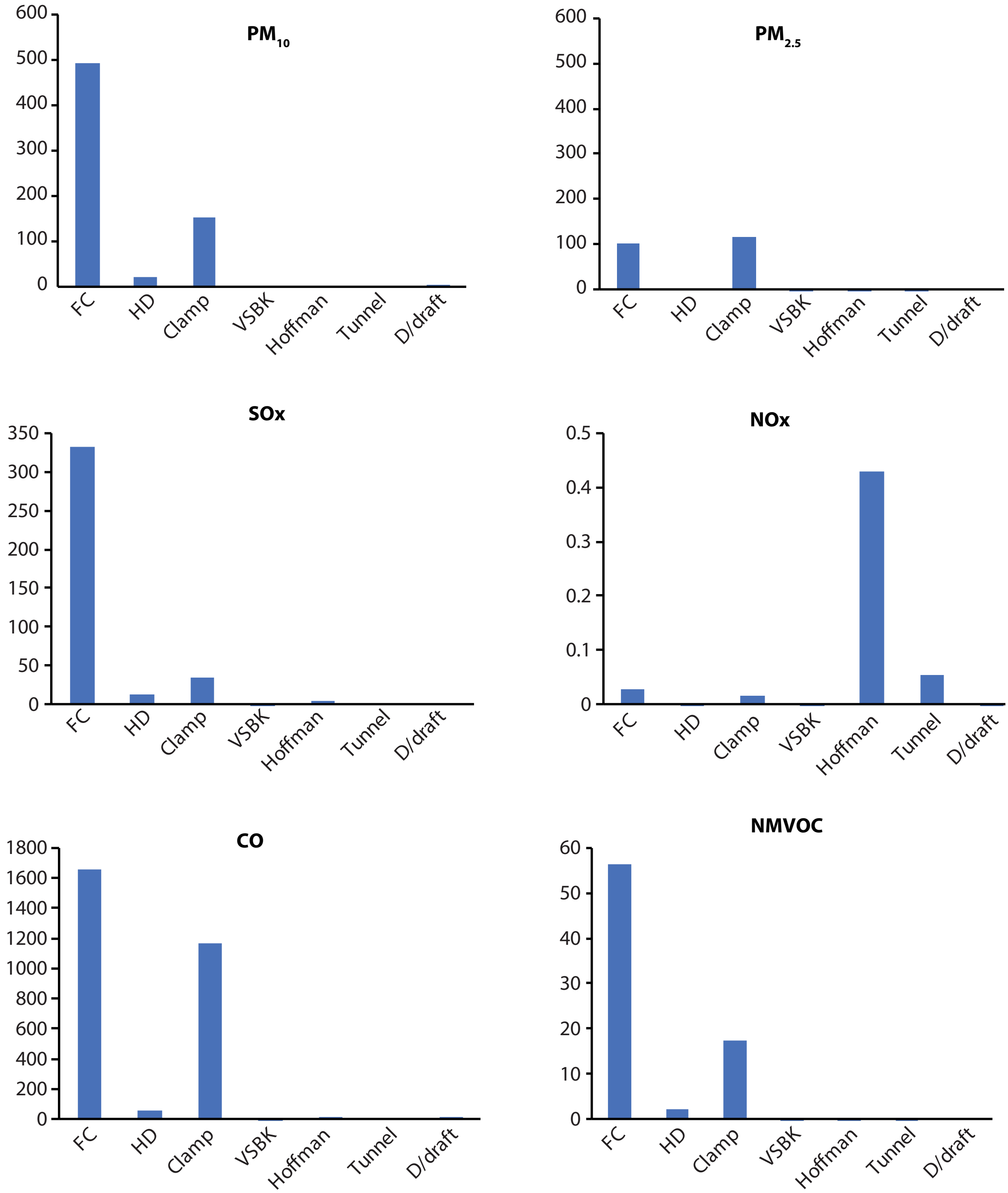
Table 16 Technology-wise emission factors for different pollutants of brick kiln

Technology	Emission factor (g/kg of fired bricks)					
	PM_{10}	$PM_{2.5}$	SO_2	NO_x*	CO	VOCs*
FCBTK	0.875	0.18	0.59	0.00005	2.94	0.1
HD	0.875	0.18	0.59	0.00005	2.94	0.1
Clamp	1.3*	1*	0.3*	0.00015	10*	0.15
VSBK	0.1	0.09*	0.32	0.01275	2.99	0.08
Hoffman	0.12*	0.08	0.72*	0.067	2.5*	0.013
Tunnel	0.31	0.18	0.72	0.018	2.45	0.016
DDK	1.56	0.97	0.00002*	0.0001	5.395*	0.15

Source: *GAINS Asia, rest: Rajarathnam et al., 2014

5.3.1 Emission inventory of brick kilns

The estimated total emissions from brick kilns in India are summarized in Figure 6.



A = FCBTK, B = HD, C = Clamp, D = VSBK, E = Hoffman, F = Tunnel, G = DDK

Figure 6 Estimated emissions of different pollutants from different types of brick kilns during 2016

Though there is wide variation in spatial distribution of brick kilns in India, most of the brick kilns are located in the Indo-Gangetic Plain region of India. Accordingly, the emissions from the brick kilns were spatially distributed (Figure 7).

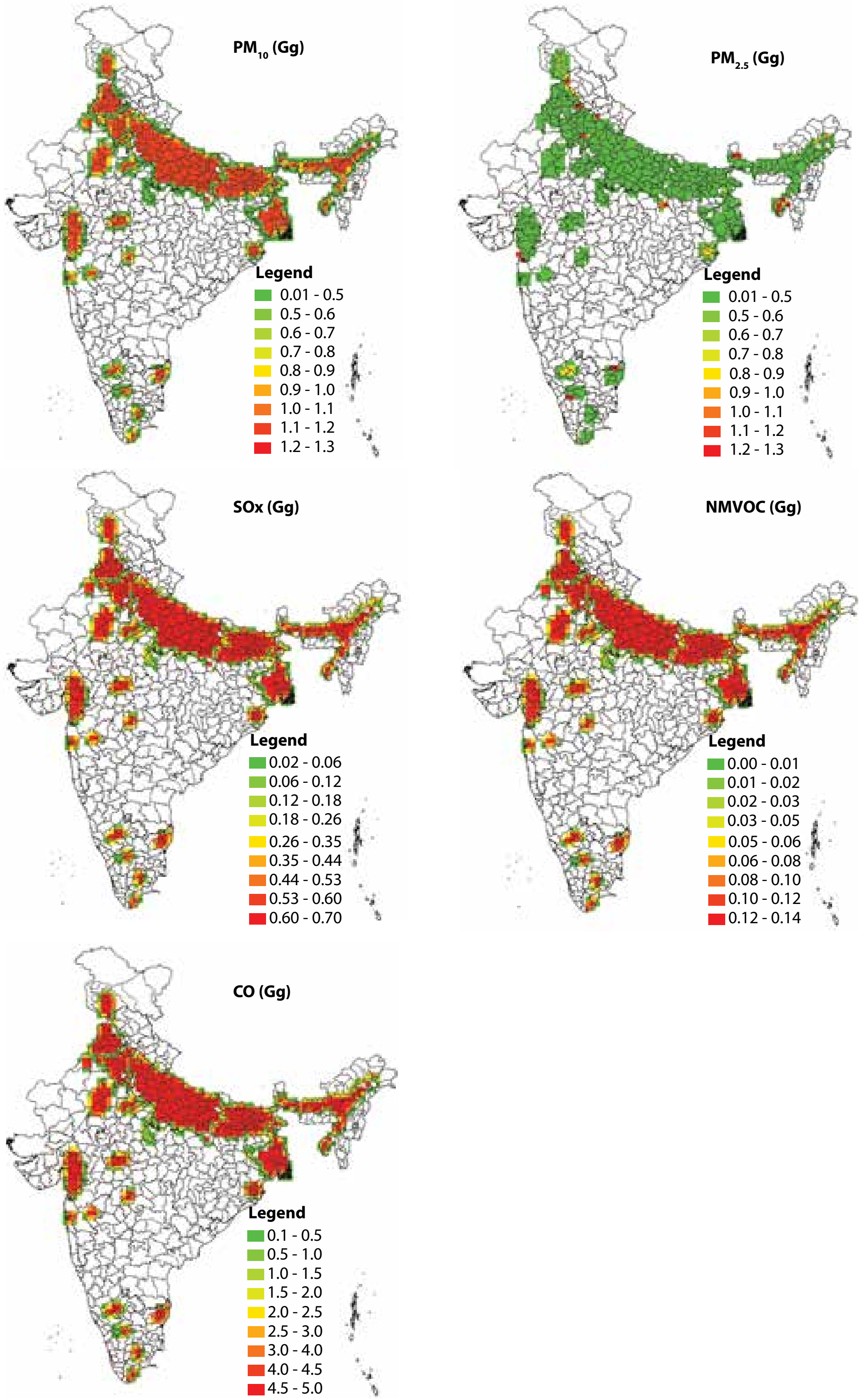


Figure 7 Spatial distribution of atmospheric particulate matter emissions from brick kilns during 2016

5.4 Total emissions from industry sector

In summary, the estimated total emissions from the industry sector are shown in *Table 17*.

Table 17 Total industrial sector emissions (Gg) in India during 2016

Sector	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	VOCs	NH_3
Large-scale industry							
Cement	547	304	1514	672	85	1	
Iron & Steel	21	16	261	94	3056	21	
Aluminium	6	3	118	26	252	3	
Paper	8	6	45	15	51	19	
Glass	1	1	8	37	0	0	
Fertilizers	8	5	1	50	1569	0	164.5
Sub-Total	591	335	1947	894	5013	44	164.5
Micro-, Small- and Medium-Scale industries							
	4126	2232	1552	284	44	57	0.3
Brick kilns	669	225	387	1	2921	76	
Total emissions	5386	2792	3886	1179	7978	177	164.8

Micro-, small- and medium-scale industries contributed to 74% of the total PM_{10} emissions from the industry sector in India during the year 2016. Brick kilns (12%) and cement industries (10%) (Table 17) were the highest emitting sectors. Most of these industries are not equipped with APCD, and even the efficiencies of the installed APCDs in these plants are much lower (40–60%) than those in large-scale industries. This contributes to the higher emissions of pollutants in micro-, small- and medium- scale industries compared to large-scale industries, which are mostly equipped with high-efficiency APCD.

The estimated emissions from industrial sector were spatially distributed to 36 km × 36 km grids based on the district-level industrial fuel consumption in different industries (MoSPI, 2016). However, for iron and steel and cement sectors, the emissions were distributed to the grid locations using the actual coordinates of plants. The emissions from the brick kilns were distributed spatially, based on Fixed Chimney Bull's Trench Kiln (FCBTK) identified using DigitalBoard Quickbird satellite data (at 2.62 m multispectral nadir).

6

TRANSPORT SECTOR

The equation (Eq. 16) to estimate the tailpipe emission of the transport sector is:

$$E_p = \sum_{c=1}^{n} \sum_{s=1}^{4} E_{c,s} \times EF_{c,s,p} \times \varepsilon_{c,s} \qquad (16)$$

where, Ep is the total emission of a pollutant (p); c is the category of vehicle; s is the emission control norm (BSI to BSIV); *E* is energy use; *EF* is the emission factor of pollutant p; and ε is the percentage of vehicle under an emission control norm.

The EF of PM_{10}, $PM_{2.5}$, NO_x, SO_x, hydrocarbon and carbon monoxide for this exercise was adopted primarily from Automotive Research Association of India (ARAI, 2010). ARAI has carried out a series of measurements to ascertain indigenous emission factors for different categories of vehicles in Indian conditions (Table 18). The EF of NH_3 was taken from the GAINS-ASIA simulation system. The estimated national level energy consumption (E) under different categories of vehicles during 2016 was adopted from the MARKAL energy system model (Annexure V).

Table 18 Tailpipe emission factors of different categories of vehicles

Fuel	Category	Vintage	g/km				
			PM	NOx	HC	CO	NH_3
Gasoline	**2W–2s**	1991–1996	0.07	0.03	3.29	5.82	0.87
		1996–2000	0.07	0.1	3.0	4.2	0.87
		Post 2000	0.05	0.05	2.10	2.51	0.87
		Post 2005	0.06	0.04	0.97	0.30	0.87
	2W–4s	1991–1996	0.01	0.23	0.78	3.12	1
		1996–2000	0.02	0.30	0.74	1.58	1
		Post 2000	0.04	0.50	0.52	1.50	35
		Post 2005	0.01	0.15	0.52	0.72	15
		Post 2010	0.003	0.25	0.42	1.17	15
	3W–2s	1996–2000	0.110	0.30	6.04	3.15	0.87
		Post 2000	0.045	0.20	2.53	1.37	0.87
		Post 2005	0.043	0.16	1.63	1.15	0.87
	3W–4s	Post 2000	0.011	0.61	1.57	4.47	35
		Post 2005	0.015	0.53	0.77	2.29	15
	LDV–4s	1991–1996	0.01	0.95	0.84	4.75	0.73
		1996–2000	0.01	0.75	0.66	4.53	0.73
		Post 2000	0.01	0.18	0.21	2.35	30
		Post 2005	0.00	0.09	0.12	0.84	12
		Post 2010	0.00	0.04	0.09	0.98	12

Fuel	Category	Vintage	g/km				
			PM	NOx	HC	CO	NH_3
Diesel	**3W–4s**	Post 2000	0.347	0.69	0.16	2.09	0.45
		Post 2005	0.091	0.51	0.14	0.41	0.4
		Post 2010	0.090	0.72	0.06	0.29	0.4
	LDT–4s	1991–96	0.57	1.70	1.39	2.49	0.45
		1996–2000	0.45	0.67	0.73	3.07	0.45
		Post 2000	0.24	0.97	0.29	1.13	0.45
		Post 2005	0.06	0.47	0.13	0.21	0.4
		post 2010	0.06	0.52	0.08	0.49	0.4
	LDT–4s	1991–96	1.00	3.03	2.28	3.07	0.45
		1996–2000	0.66	2.48	1.28	3.00	0.45
		Post 2000	0.48	2.12	1.35	3.66	0.45
		Post 2010	0.12	1.69	0.30	1.44	0.4
	HDT	1991–96	1.57	9.41	1.83	8.73	0.29
		1996–2000	0.88	12.85	1.05	6.43	0.29
		Post 2000	1.2	11.1	1.4	7.6	0.29
		Post 2005	0.42	8.64	0.29	4.14	0.25
		Post 2010	0.39	8.35	6.13	4.85	0.25
	HDT	1991–96	2.01	11.24	2.40	13.06	0.29
		1996–2000	1.21	15.25	1.46	4.48	0.29
		Post 2000	0.56	6.49	2.01	3.97	0.29
		Post 2005	0.30	6.53	0.16	3.92	0.25
		Post 2010	0.48	5.17	0.21	4.73	0.25
CNG	**2W–4s**	Post 2000	0.07	0.35	1.16	0.85	4.9
		Post 2005	0.18	0.20	5.56	1.29	4.9
		Post 2010	0.02	1.07	1.79	1.03	0
	LDV–4s	1996–2000	0.00	0.53	0.79	0.85	0.5
		Post 2000	0.00	0.38	0.41	0.33	4.9
		Post 2010	0.00	0.07	0.26	1.95	3
	HDB	Post 2000	0.04	6.21	3.75	3.72	10
		Post 2010	0.02	15.15	7.80	9.22	5
LPG	**2W–4s**	1996–2000	0.17	0.05	5.08	7.20	0
		Post 2000	0.13	0.04	1.03	1.70	0
	LDV–4s	Post 2000	0.00	0.20	0.23	2.72	0

2W: 2-wheeler; 3W: 3-wheeler; LDV: Light duty vehicle; HDB: Heavy duty bus; HDT: Heavy duty truck; 2s: 2-stroke engine; 4s: 4-stroke engine

National level energy consumptions in different categories of on-road vehicles were brought down to the district level on the basis of district-wise on-road number of vehicles. The data of district-wise on-road numbers of vehicles were obtained from the registered number of vehicles. District-level information on category-wise number of vehicles was obtained from Directorate of Economic and Statistics of different states. The National Green Tribunal (NGT), India has imposed a ban on diesel and gasoline vehicles older than 10 and 15 years, respectively in the Delhi-National Capital Region (NCR) in 2015. However, in the absence of an effective vehicle scrapping policy, these vehicles are still in use in the Delhi-NCR and in other parts of the country. Following this, we assumed 20 years as the average life time of a vehicle in India during 2016.

Fugitive emissions of PM from re-suspension of road dust due to movement of vehicles on paved roads was calculated using the following equation as provided in AP-42,

$$[E_p]_t = \sum_{r=1}^{3} VKT_r \times k \times w^{1.02} \times Mo^{0.91} \qquad (17)$$

where, $[E_p]_t$ is the fugitive emission of pollutant (p) from the transport sector; r is the type of road (1 arterial, 2 sub-arterial and 3 local); VKT is Vehicle Kilometre Travelled, k is function of particle size (0.62 for PM_{10} and 0.15 for $PM_{2.5}$); w is the average weight of vehicle travelling on the road; and Mo is road surface silt ($\leq 75\ \mu m$ in physical diameter) loading in unit area. The $[E_p]_t$ is directly proportional to the silt loading on the road surface and average weight of the vehicles plying on the road. The spatial variation of Mo was established during this study (Annexure III).

After estimating $[E_p]_t$ using the above equation, the effect of rainy days was considered to finalize the fugitive emission ($f[E_p]_t$) from road dust re-suspension using Eq. 18:

$$f\,[E_p]_t = [E_p]_t \times (1 - D_p) / (4 \times 365) \qquad (18)$$

where, D_p is the number of rainy days in a year.

6.1 Energy consumption in the transport sector

According to the MARKAL model, total energy consumption in on-road transport sector in the year 2016 was 4081 PJ. Buses and trucks are major consumers of energy in the transport sector followed by light commercial vehicles (LCVs), cars, 3-w and 2-w (Figure 8).

6.2 Tailpipe emissions of different pollutants

The tailpipe emissions of different pollutants from various categories of on-road vehicles were calculated using *eq. 16*. Higher PM emissions were calculated from the tailpipe emissions of heavy duty vehicles (Table 19) followed by light duty vehicles and passenger cars.

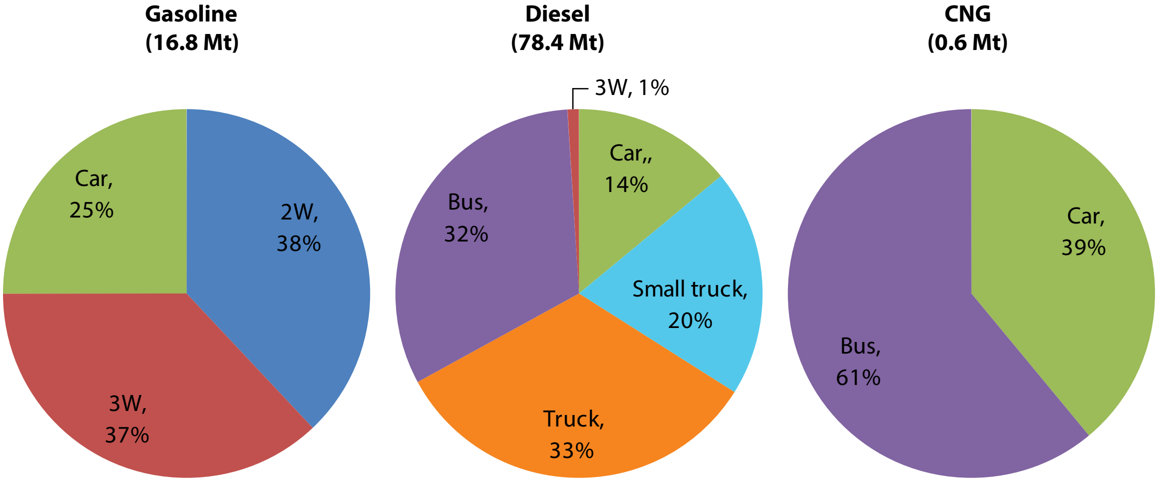


Figure 8 Energy consumption in different categories of vehicles during 2016 according to the MARKAL model

Table 19 Tailpipe emissions (Kt) of different pollutants during 2016

PM_{10}	6.86	9.07	24.28	36.47	53.80	61.97	**192.44**
PM_{25}	6.66	8.80	23.55	35.37	52.18	60.11	**186.67**
SO_X	4.69	5.35	2.74	0.28	0.43	0.29	**13.78**
NO_X	137.35	185.31	124.34	232.31	703.27	845.74	**2228.32**
CO	564.96	775.77	270.53	290.45	534.47	501.84	**2938.03**
NH_3	4.69	5.35	2.74	0.28	0.43	0.29	**13.78**

2W: 2-wheeler; 3W: 3-wheeler; LDV: Light duty vehicle; HDB: Heavy duty bus; HDT: Heavy duty truck

Earlier, Venkataraman et al. (2018) have estimated the emission inventory of the transport sector of India using the same emissions factors (ARAI, 2010) used in the present study. That study reported 286, 6078 and 105 Gg of $PM_{2.5}$, NO_x and SO_2 emissions respectively from the transport sector during 2015 with reported uncertainties of -54% to +91%, -63% to +122%, and -71% to +157%, respectively.

6.3 Inventory of road dust resuspension

The silt and clay content of the road dust samples were higher in the states of Odisha (Annexure III). Re-suspension of road dusts due to movement of the vehicle contributes to PM_{10} and $PM_{2.5}$ concentrations in the atmosphere. The contribution of road dust suspension to PM_{10} and $PM_{2.5}$ was calculated using Eq. 18. Among other states, higher road dust resuspension in the state of Maharashtra (Table 20) is mainly attributed to comparatively higher road length in the state (MoSPI, 2017) apart from average vehicle weight and silt concentration on the road.

Table 20 State-wise contribution of road dust suspension to atmospheric PM_{10} and $PM_{2.5}$ during 2016

State	$PM_{2.5}$ (Kt)	PM_{10} (Kt)
Andhra Pradesh	5.91	24.44
Arunachal Pradesh	0.01	0.06
Assam	0.70	2.88
Bihar	1.73	7.15
Chhattisgarh	1.98	8.18
Goa	0.08	0.32
Gujarat	31.76	131.26
Haryana	1.14	4.71
Himachal Pradesh	0.18	0.74
Jammu & Kashmir	0.29	1.22
Jharkhand	1.21	5.01
Karnataka	13.62	56.30
Kerala	9.68	40.02
Madhya Pradesh	4.89	20.21
Maharashtra	77.13	318.80
Manipur	0.01	0.06
Meghalaya	0.11	0.44
Mizoram	0.00	0.02
Nagaland	0.06	0.25
Odisha	3.17	13.09
Punjab	4.82	19.92
Rajasthan	12.58	52.01
Sikkim	0.00	0.00
Tamil Nadu	30.45	125.88
Telangana	2.82	11.67
Tripura	0.01	0.04
Uttarakhand	0.19	0.79
Uttar Pradesh	32.90	135.97
West Bengal	2.97	12.26
Andaman & Nicobar Islands	0.0008	0.0031
Chandigarh	0.0518	0.2141
Dadra & Nagar Haveli	0.0006	0.0026
Daman & Diu	0.0004	0.0018
NCT of Delhi	1.6544	6.8380

State	$PM_{2.5}$ (Kt)	PM_{10} (Kt)
Lakshadweep	0.0000	0.0000
Puducherry	0.0207	0.0858
Total	242.14	1000.83

District-level total tailpipe emissions of each pollutants and emissions from the road dust resuspension were distributed to grid based on i) the ratio of polygon area to the district area using Eq. 19 and ii) the ratio of the length of national highways in a polygon to the length of national highway in a district using Eq. 20.

$$G_{Pol} = \sum_{p=1}^{n} \sum_{d=1}^{n} \frac{A_p}{A_d} \times (E_{pol,d} \times 0.6) \qquad (19)$$

$$G_{Pol} = \sum_{p=1}^{n} \sum_{d=1}^{n} \frac{LN_p}{LN_d} \times (E_{pol,d} \times 0.4) \qquad (20)$$

where, G_{Pol} is the emission of a particular pollutant (Pol) in the Grid (G); A and LN are the area and length of national highway respectively in a polygon (p) and d (district); and $E_{Pol,\,d}$ is the estimated emission of the pollutant (Pol) in the district (d). Spatial variations of different pollutants emissions from the transport sector were distributed over a 36 km × 36 km gridded map after adding the gridded values derived from Eq. 19 and Eq. 20 (Figure 9).

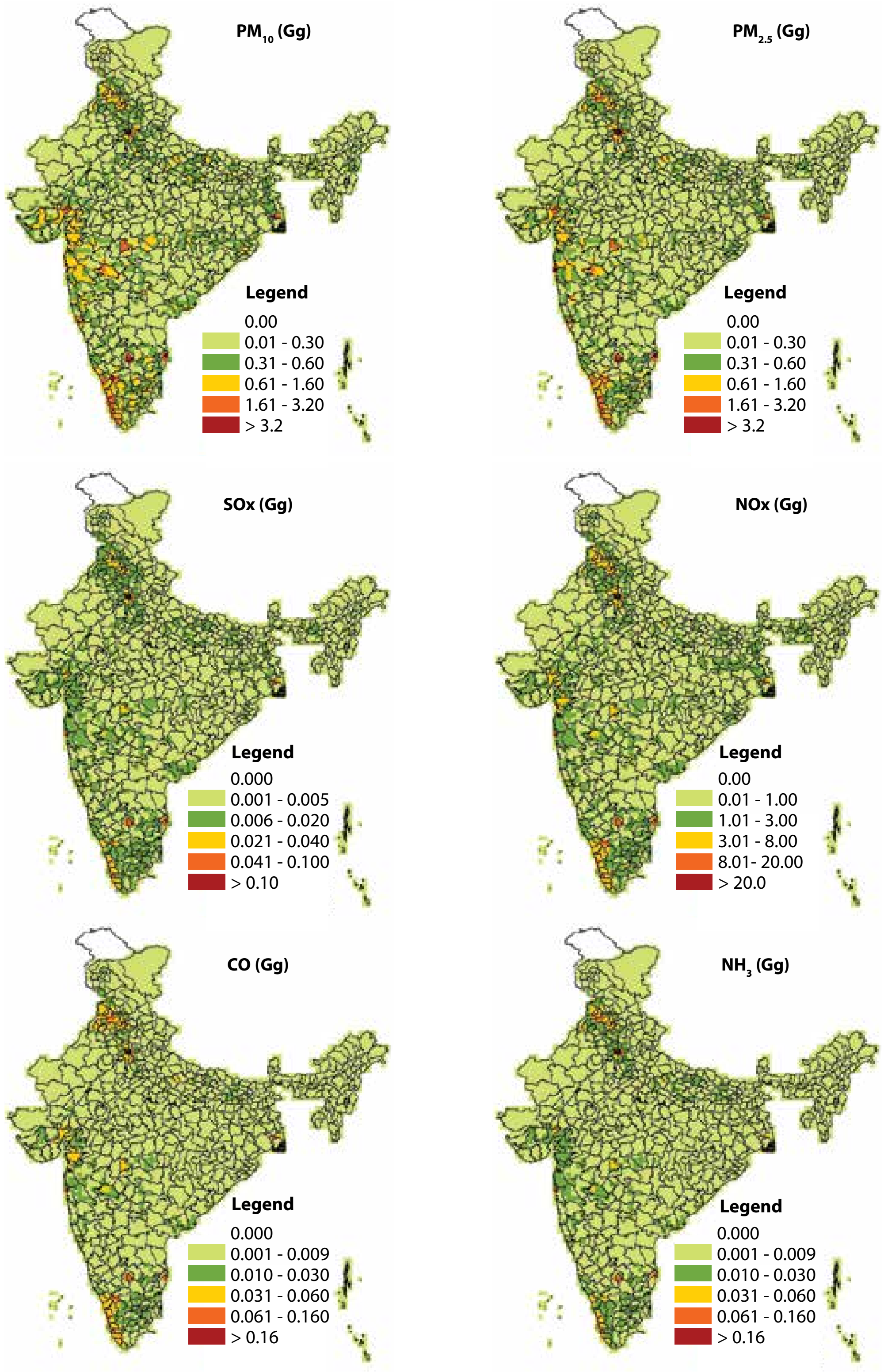


Figure 9 Spatial variations of emissions of different pollutants from the transport sector during 2016

DIESEL GENERATOR OPERATION

7

The current installed electricity generating capacity of India is 275 GW, which is significantly higher than the peak demand of 140 GW (NITI Ayog, 2017a). Despite installed electricity generation capacity exceeding the peak power demand, some parts of the country face acute power shortages. The critical reasons are: coal supply shortages, high levels of transmission and distribution losses, and poor financial health of utilities. Distribution companies (DISCOMs) that buy electricity generated with imported coal face significant and unpredictable upward pressure on tariffs. These fundamental problems in the power sector are hampering the efficient use of the existing system to even meet the grid-connected demand. Rampant load-shedding and low-voltage power supply forces people to resort to private, localized solutions such as diesel generators (DG). The total capacity of diesel generators in India is estimated at 72 gigawatts, about 25% of the installed capacity of power plants, and growing at the rate of 5 GW per annum (Economic Survey, 2016). The data from the CEA suggests that large industries with electricity consumption greater than 1 MW own about 14 GW of DG sets. A substantial portion of the rest (58 GW) may be contributed by micro and small industries, with load capacities of less than 1 MW (Economic Survey, 2016).

The emissions from DG sets are estimated based on the population, per-capita diesel consumption, percentage distribution of diesel consumption in different sectors using DG sets and emission factor by using Eq. 21:

$$E_x = EC \times \%DC \times EF_x \qquad (21)$$

where, Ex = Emissions of pollutant x; EC = District-wise energy consumption, which is estimated based on district-wise fuel consumption and calorific value of diesel. For estimating district-wise fuel consumption, district-wise projected population for the year 2016 (based on census 2011 data set) and per-capita fuel consumption were used. State-wise high speed diesel (HSD) consumption and population of that particular state were used to estimate state-wise per capita fuel consumption. This state-wise per capita fuel consumption was assumed for each district falling in that particular state and was used to estimate district-wise fuel consumption. State-wise diesel consumption was obtained from Indian PNG statistics 2018.

%DC = percentage distribution of diesel used in different sectors using DG sets, such as agri pump sets, industries, mobile towers, and other purposes. The relevant state-wise percentage distribution of diesel consumption in different non-transport sectors was referred Petroleum Planning & Analysis Cell (PPAC, 2013). This state-wise percentage distribution was assumed for all the districts falling in that particular state. In the absence of state-wise percentage distribution, zone-wise percentage distribution was assumed.

EFx = Emission factor of pollutant x

The pollutant-specific emission factors for DG sets were adopted from USEPA, 2015 (Table 21) and the estimated emissions for different pollutants are shown in Table 22. The state-wise emissions of pollutants from DG sets indicated that Uttar Pradesh contributes around 16.6% to the overall DG sets emissions from all over India followed by Haryana in North and Tamil Nadu and Karnataka in the south.

Table 21 Emission factors for DG sets

Pollutants	EF (ng/J)
PM_{10}	133.3
$PM_{2.5}$	113.305
SO_2	124.7
NO_x	1896.3
VOC	154.8
CO	408.5

Table 22 Emissions (Gg) from the operation of diesel generators during the year 2016

Pollutant	Agriculture Pumpsets	Industry	Mobile Tower	*Others	Total
PM_{10}	16.1	21.9	8.9	20.4	**67.3**
$PM_{2.5}$	13.7	18.6	7.6	17.4	**57.2**
SO_2	15.0	20.5	8.3	17.4	**61.2**
NO_x	228.5	311.6	126.8	290.8	**957.7**
CO	49.2	67.1	27.3	62.7	**206.3**
VOC	18.7	25.4	10.3	23.7	**78.2**

*others include residential and commercial use

The total emission of each pollutant emitted during the operation of the DG set was distributed over 36 km × 36 km grids following Eq. 22:

$$G_{Pol} = \sum_{p=1}^{n} \sum_{d=1}^{n} \frac{A_p}{A_d} \times E_{pol,d} \qquad (22)$$

where, G_{Pol} is the emission of a particular pollutant (Pol) in the Grid (G); A is the area of a polygon (p) in a district (d); and $E_{pol,d}$ is the emission of a particular pollutant in the district(d).

OPEN BURNING OF AGRICULTURAL RESIDUES

8

Emission inventory of different pollutants from the burning of different crop residues in the cropland is being developed following the IPCC (2006) inventory preparation guideline. The primary crops considered for inventory preparation are rice, wheat, maize, sugarcane, and cotton, as mentioned in different published literature. Emission from the in-situ burning of crop residue was calculated using Eq. 23:

$$\mathrm{Epol} = \sum_{S=1}^{35} \sum_{D=1}^{n} \sum_{C=1}^{n} Pa \times Ra \times fDa \times fBa \times EFpol \qquad (23)$$

where, Epol = Emission of a particular pollutant (pol) (g); Pa is the total production of a particular crop (C) in a particular district (D) of the state (S) in kilograms; Ra is the fraction of residue generated for the production (Pa) of the particular crop (a); *f*Da is the fraction of dry matter in the residue of the particular crop (a); *f*Ba is the combustion efficiency of crop residue that is burnt; and *EFpol* is the emission factor of the particular pollutant (g/kg). During the course of the present study, crop residue samples were collected from different parts of the country to develop the *EFpol* of different pollutants emission while burning the crop residues (*Annexure I*). VIIRS dataset of the Fire information for Resource Management System (FIRMS) of NASA was used to identify the crop residue burning locations all over the country while collecting the crop residue samples. The VIIRS sensor is placed aboard the joint NASA/NOAA Suomi National Polar-orbiting Partnership (Suomi-NPP) satellite. The 375-m active fire product of VIIRS was used for this study. The 375-m data complements Moderate Resolution Imaging Spectroradiometer (MODIS) fire detection; they both show good agreement in hotspot detection but the improved spatial resolution of the 375-m data provides a greater response over fires of relatively small areas and provides improved mapping of large fire perimeters using pixel-integrated Fire Radiative Power (FRP). The VIIRS 375-m FRP dataset of the year 2016 was overlaid on the seasonal cropland map of India to extract the crop residue burning activities during the harvest seasons of Kharif (wet) and Rabi (dry) seasons crops.

The seasonal (wet season and dry season) production data (Pa) of different crops were collected from the Department of Agriculture Cooperation and Farmers' Welfare (DAC&FW), Ministry of Agriculture, Government of India for the year 2016. Crops were categorized into the following six groups in the present study, a) rice, b) wheat, c) cotton, d) maize, e) sugarcane and f) others based on the field observation of crop residue burning. The 'others' group includes, tur, mustard, cassava, tiger grass, and jute. The state-level production of different crops is given in Table 23.

Table 23 State-level production (Mg) of different crops during dry and wet seasons of 2016

State	Rice	Wheat	Cotton	Maize	Sugarcane	Others
Andaman & Nicobar Islands	0	0	0	352	2338	1
Andhra Pradesh	557,500	52,547	413,780	256,422	129,225	258,379
Arunachal Pradesh	264,433	144,521	0	201,452	197,795	0
Assam	0	129,083	144,707	186,996	121,575	517
Bihar	0	4,736,448	0	2,288,789	11,914,615	0
Chandigarh	206	5060	0	80	0	0
Chhattisgarh	5,154,328	142,329	94	237,676	46,895	0
Dadra & Nagar Haveli	29,598	302	0	99	51,300	220
Daman & Diu	3600	0	0	0	0	0
Goa	115,068	28,800	700	65,200	11,022,477	0
Gujarat	1,584,355	2,315,849	7,542,431	608,511	10,947,109	563
Haryana	3,941,000	11,117,000	1,783,500	26,000	7,500,000	13,863
Himachal Pradesh	114,648	602,102	0	707,890	37,516	0
Jammu & Kashmir	646,362	544,889	1	523,609	290	0
Jharkhand	222,218	113,828	0	115,255	9140	31,910
Karnataka	2,713,089	128,988	1,152,047	3,310,473	0	148,704
Kerala	0	0	196	74	13,813	1845
Lakshadweep	0	0	0	0	0	0
Madhya Pradesh	3,246,000	15,705,000	738,000	2283,000	3,980,000	0
Maharashtra	2,517,100	952,551	3,913,230	1,594,670	58,271,000	128,700
Manipur	0	0	0	0	0	0
Meghalaya	62,901	875	8928	41,242	356	0
Mizoram	37,746	0	77	10,295	51,270	0
Nagaland	439,460	5950	80	136,360	190,200	0
NCT of Delhi	0	0	0	0	0	0
Odisha	5,874,000	0	0	110,977	577,157	0
Puducherry	31,070	0	271	0	213,968	0
Punjab	11,823,022	16,077,185	39,3000	42,4637	6,607,000	0
Rajasthan	369,780	10,468,161	206,448	1,156,675	531,267	0
Sikkim	19,687	346	0	68,310	0	0

State	Rice	Wheat	Cotton	Maize	Sugarcane	Others
Tamil Nadu	7,374,681	0	326,659	2,532,330	25,508,824	0
Telangana	3,047,289	16,902	3,733,072	1,751,074	2,404,655	937
Tripura	575,826	407	1365	12,177	40,492	0
Uttar Pradesh	12,434,053	26,874,361	2658	1,303,866	145,384,798	20,143
Uttarakhand	591,755	790,370	0	38,208	5,656,014	0
West Bengal	15,948,254	788,503	1326	662,434	1,327,805	4960
Total	79,739,030	91,742,357	20,362,570	20,655,132	292,738,893	610,742

DAC&FW, Ministry of Agriculture, Government of India

The residue to crop fractions (Ra) of different crops was replicated as in Datta and Sharma (2016). The dry matter fraction in different crop residues () were replicates as reported by Jain et al. (2014). The combustion efficiency (*f*Ba) of different crop residues were used as reported in Turn et al. (1997). Table 24 summarizes different coefficients used to estimate the emissions of pollutants from burning of crop residues using *eq. 23*.

Table 24 Coefficients of different crop residues to estimate the emissions of different pollutants

Co-efficient	Rice	Wheat	Cotton	Maize	Sugarcane	Others
Residue to crop ratio (Ra)[1]	1.59	1.70	0.40	3.00	2.00	2.00
Dry fraction of residue (*f*Da)[2]	0.86	0.88	0.80	0.90	0.80	0.90
Combustion efficiency (*f*Ba)[3]	0.89	0.86	0.90	0.92	0.68	0.91

[1]Datta and Sharma (2016); [2]Jain et al. (2014), [3]Turn et al. (1997)

The VIIRS dataset of the FIRMS was also used to identify the crop residue burning locations at 36 km × 36 km grid over the country boundary during the dry (April–May) and wet (October–December) crop harvesting seasons of 2016 (Figure 10). All districts were divided into different polygons based on the 36 km × 36 km grids. Total number of fire event in each polygon was calculated. Each polygon was allotted a weighted value based on the number of fire events. The weighted values of each polygon were; 0.1 if number of burning events were >0 and <10, 0.3 if number of burning events were >10<=50; 0.6 if number of burning events were >50<=100; 0.8 if number of burning events were >100<=1000, and 1 if number of burning events were >1000.

Each polygon area was divided with the harvested area of each crop in a district (DAC&FW, Ministry of Agriculture, Government of India, 2016) to calculate a factor to allot the amount of crop residue available in a polygon using Eq. 24:

$$[B_{Poly}]_C = \frac{APoly}{Ac} \times [Pa]_C \times [Ra]_C \times [fDa]_C \times [fBa]_C \qquad (24)$$

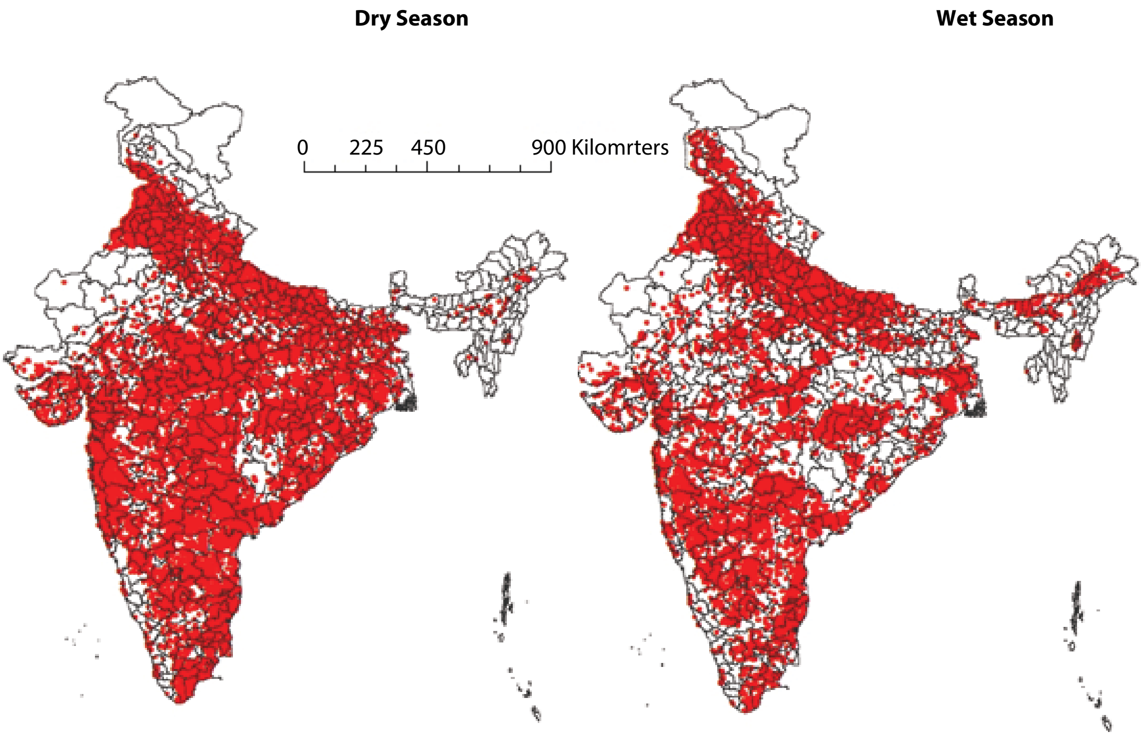


Figure 10 Locations of crop residue burning at the agriculture field during the harvest period of dry and wet season crops during 2016. Data source: MODIS-VIIRS

where, $[B_{Poly}]_C$ is the burnable fraction (Mg) of crop type C in a polygon; A*Poly* is the area of the polygon (ha); A_C is the total harvested area (ha) of crop C in the district; $[Pa]_C$, $[Ra]_C$, $[fDa]_C$ and $[fBa]_C$ are the district-level production (Mg), residue to crop ratio, dry fraction of residue and combustion efficiency of the crop C. $[B_{Poly}]_C$ was multiplied with the respective number of fire weighted values of respective polygon to estimate the amount of each crop residues burnt (Mg) in each polygon during a crop harvest season. Accordingly, it was estimated that about 17% of total crop residues generated during 2016 were burnt in the field (Table 25).

Table 25 Estimated amount of different crop residues and burnt amount during 2016

Crop type	Residue generated (Mg)	Residue burnt (Mg)
Rice	126,785,058	30,637,767
Wheat	155,962,007	11,134,512
Cotton	61,087,709	8,127,676
Maize	41,310,265	5,019,477
Sugarcane	117,095,557	32,018,180
Others	1,221,483	141,327
Total	503,462,079	87,078,939

The emission factors of different pollutants (Table 26) as measured using the method described in *Annexure I* was used to calculate the emissions of different pollutants in each polygon using Eq. 25:

$$\mathrm{Epol} = [B_{Poly}]_C \times W_i \times EF_{Pol} \tag{25}$$

where, E_{pol} is the emission of a particular pollutant (pol) in kg; W_i is the weighted value of number of fire; and EF_{Pol} is the emission factor of a pollutant (pol) in kg/Mg.

Table 26 Emission factors (kg/Mg) of different pollutants during the burning of crop residues

Crop	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	NMVOC	NH_3
Rice	14.60	9.26	2.12	5.70	79.61	6.49	1.30
Wheat	11.33	8.51	1.14	5.98	97.96	7.43	1.30
Cotton	11.78	9.78	0.37	6.41	123.22	6.86	1.30
Maize	13.64	11.18	0.38	6.82	47.81	9.87	1.30
Sugarcane	18.28	11.98	0.52	6.05	62.93	5.91	1.30
Others	24.96	15.05	0.79	8.90	130.27	8.24	1.30

* NH_3 emission factor was taken from GAINS-ASIA.

8.1 Emission inventory of different pollutants during the open burning of crop residue

Seasonal emissions of different pollutants from the burning of different crop residues were estimated using Eq. 23.

Figure 11 shows the seasonal emissions of different pollutants from the burning of different types of crop residues.

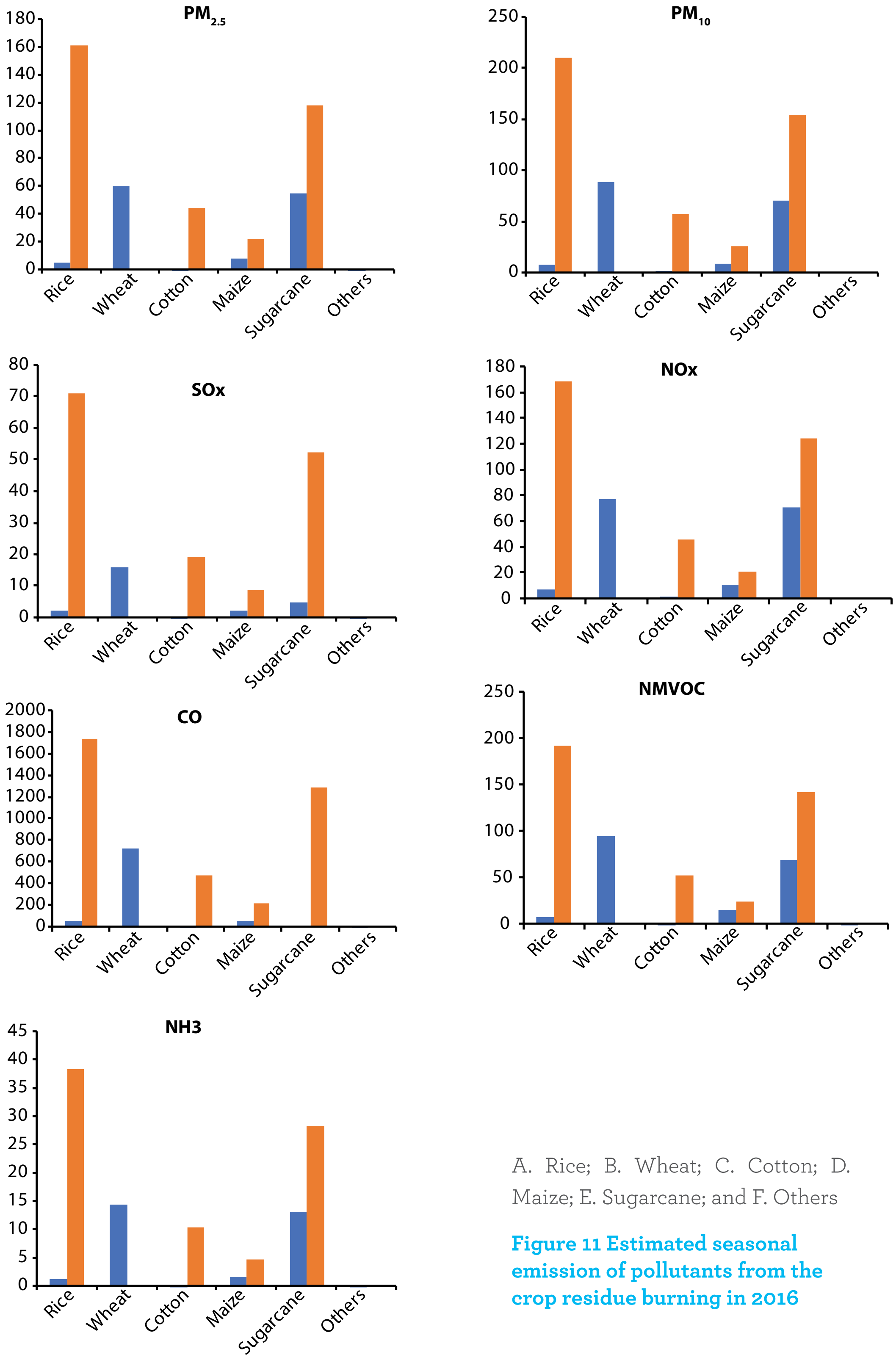
Table 27 summarizes the emission of different pollutants from the burning of different types of crop residues in respect of the crop production.

Table 27 Estimated emissions (Gg) of pollutants per unit production (Tg) in different seasons

Crop	PM_{10}		$PM_{2.5}$		SO_x		NO_x		CO		VOC		NH_3	
	D	W	D	W	D	W	D	W	D	W	D	W	D	W
Rice	0.22	5.91	0.14	3.75	0.03	0.86	0.09	2.31	1.20	32.24	0.10	2.63	0.02	0.53
Wheat	1.59	-	1.19	-	0.16	-	0.84	-	13.70	-	1.04	-	0.18	-
Cotton	0.00	5.84	0.00	3.91	0.00	0.85	0.00	2.28	0.05	31.87	0.00	2.60	0.00	0.52
Maize	1.07	3.47	0.87	2.66	0.03	0.50	0.53	1.35	3.73	18.92	0.77	1.54	0.10	0.31
Sugarcane	10.33	2.15	6.77	1.77	0.29	0.31	3.42	0.84	0.57	11.75	3.34	0.96	0.73	0.19
Others	1.36	3.55	0.82	3.66	0.04	0.52	0.49	1.39	7.11	19.38	0.45	1.58	0.07	0.32

D: Dry season; W: Wet season

Seasonal emissions of different pollutants due to the open burning of the crop residues in the agricultural fields were distributed to 36 km × 36 km grids (Figure 12) following Eq. 24.



A. Rice; B. Wheat; C. Cotton; D. Maize; E. Sugarcane; and F. Others

Figure 11 Estimated seasonal emission of pollutants from the crop residue burning in 2016

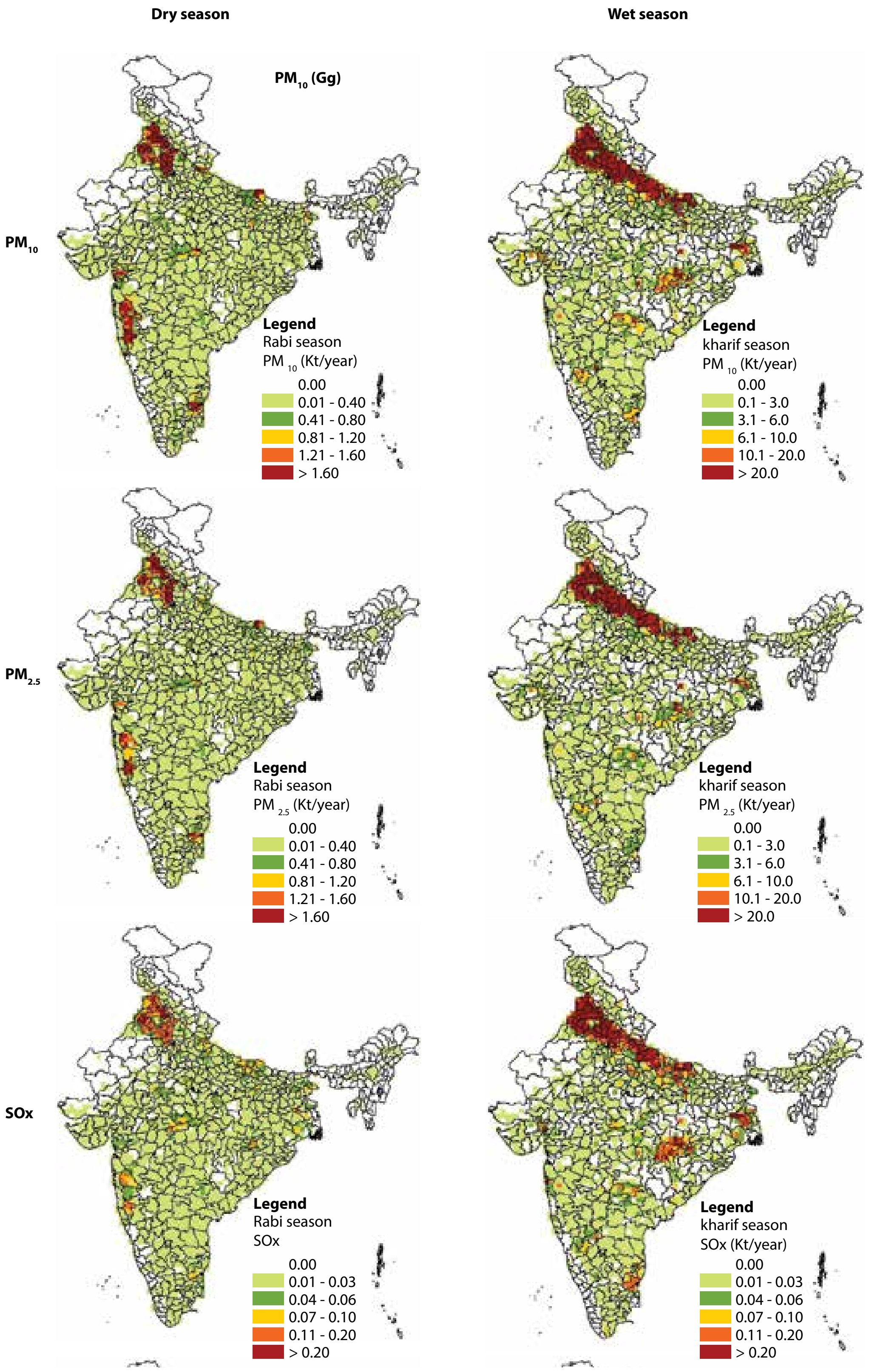


Figure 12
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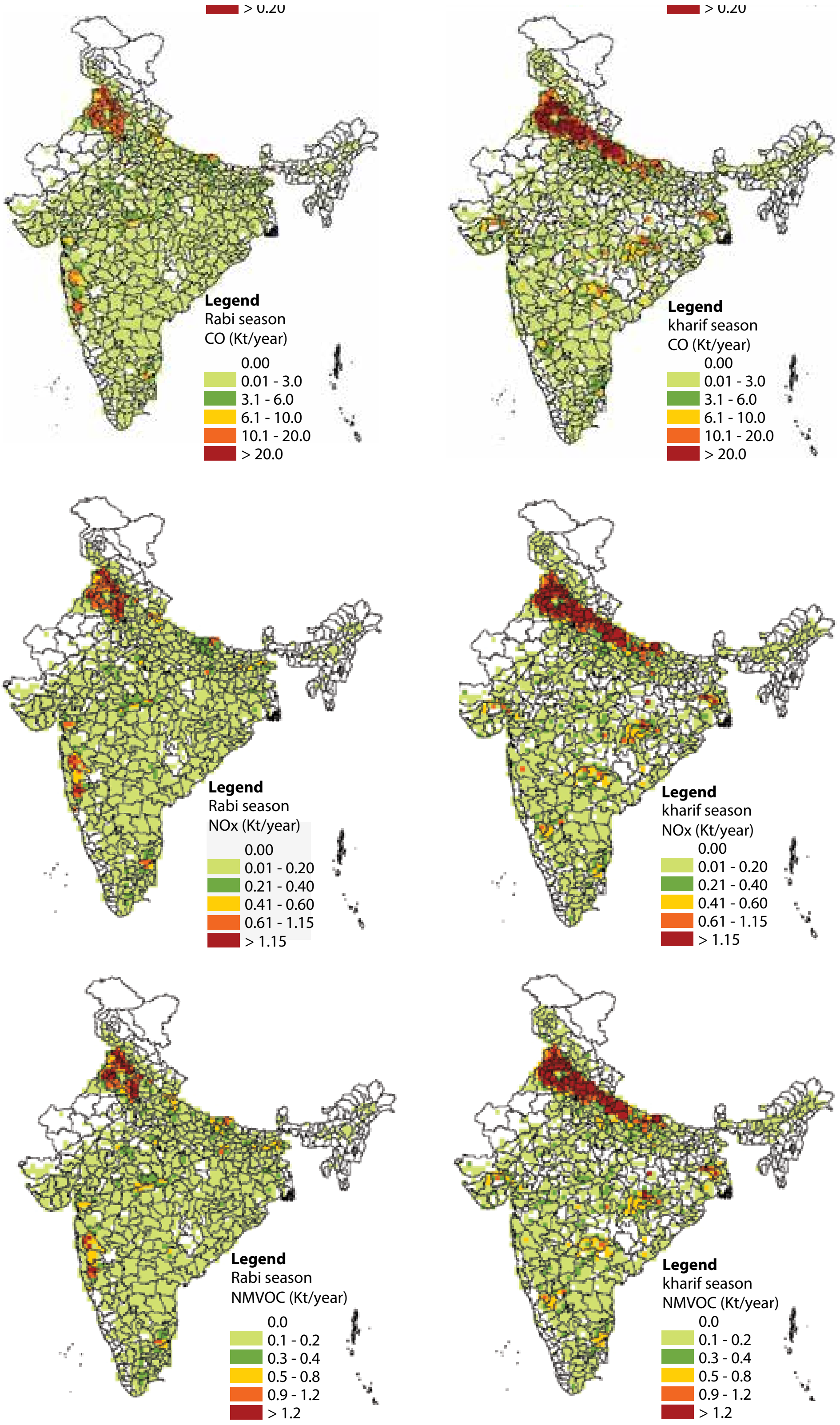

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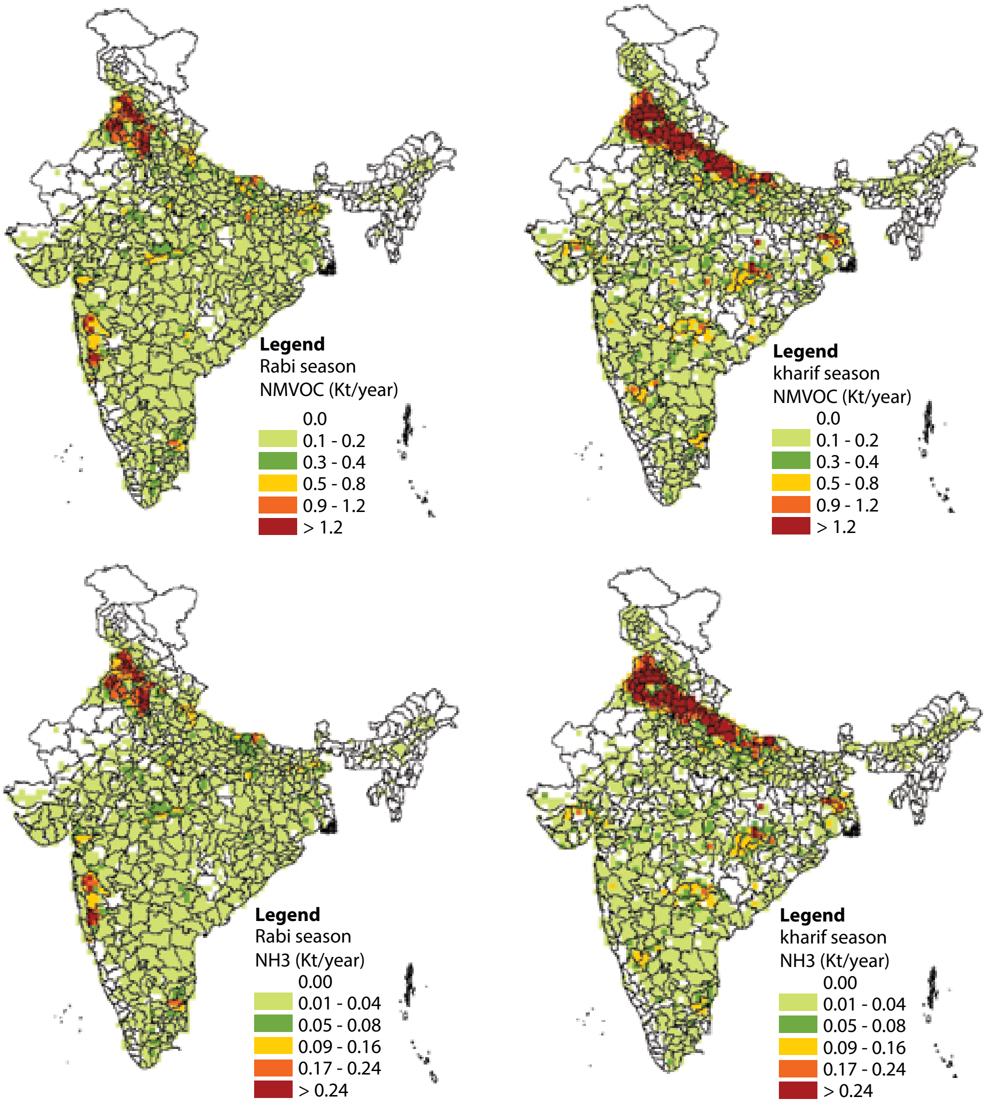


Figure 12 Spatial variation of emissions of different pollutants due to burning of crop residues in agricultural field during different crop harvesting periods

Annual emissions of PM_{10}, $PM_{2.5}$, SO_x, NO_x, CO, NMVOC and NH_3 due to burning of crop residues are 1325, 937, 158, 527, 6501, 600, and 118 Gg, respectively (Table 5). Annual emission of PM_{10} and $PM_{2.5}$ was higher from the burning of sugarcane residues (934 Gg) all over the country compared to other crop residues burnt in the field during 2016. While, SO_x, CO and NMVOC emissions were recorded higher from the burning of rice crop residues in the entire country compared to other crop residues (Table 28).

Table 28 Annual emissions (Gg) of different pollutants from the burning of crop residues in the croplands during 2016

Crop	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	VOC	NH_3
Rice	450	285	65	176	2453	200	40
Wheat	145	109	15	77	1257	95	17
Cotton	119	80	17	47	655	53	11
Maize	76	59	8	32	370	40	7
Sugarcane	533	402	52	195	1752	211	44
Others	3	2	0	1	14	1	0
Total	1325	937	158	527	6501	600	118

9

REFUSE BURNING

Scrape materials, garbage, biomass materials, etc., those are burnt anthropogenically in the open area are considered as refuse in the present study. The amount of waste generation depends on the population and livelihood of residents in a particular place. The basic equation (Eq. 26) followed to estimate the emissions of different pollutants from the burning of refuse materials is:

$$\text{Epol} = \sum_{S=1}^{35} \sum_{a=1}^{2} \sum_{i=1}^{n} fWb_{a,i} \times EF_{i,S} \qquad (26)$$

$$\text{Epol} = \sum_{S=1}^{35} \sum_{a=1}^{2} \sum_{i=1}^{n} fWb_{a,i}$$

where, E*pol* is the emission of a particular pollutant from the burning of the refuse material; *f*Wb is the fraction of waste materials burnt in an area (a); i is the type of waste material burnt; and EF is the state specific (S) emission factor of the particular pollutant (*pol*) from the burning of the waste material (i) (Table 29). The area (a) is classified as rural and urban.

Table 29 Region-wise emission factors (g/kg) of different pollutants

Refuse type	$PM_{2.5}$	PM_{10}	SO_2	CO	NO_x	VOC
Rubber	70.50	88.13	47.78	69.65	12.58	16.45
Plastic	5.11	6.26	1.94	39.61	2.62	15.00
Paper	2.28	3.13	0.47	44.29	4.76	3.79
Biomass	14.73	20.42	0.39	64.25	8.68	5.58

It is required to estimate the total waste generation to calculate the *f*Wb. The population of the year 2016 was estimated using the *eq. 3*. The CPCB (2000) has reported average waste generation in different urban areas based on the population of the area (*Table 30*). On the other side, Sharholy et al. (2008) have suggested average solid waste generation in the range of 0.21 to 0.50 kg/capita/day in India. Based on this, the average solid waste generation in the rural areas of India was taken as 0.21 kg/capita/day.

Table 30 Waste generation in relation to population in urban areas of India

Population	Waste generation (kg/capita/day)
> 2,000,000	0.43
1,000,000 – 2,000,000	0.39
500,000 – 10,000,000	0.38
100,000 – 500,000	0.39
<100,000	0.36

The composition of waste (biodegrable, plastic, paper and rubber) was segregated following Selvan and Palanivel et al. (2015) for different areas. The average value of different types of area was assumed as the composition of waste in the country (*Table 31*).

Table 31 Average composition of refuse materials in India

Type of waste	Commercial area (%)	Residential area (%)	Dump yard (%)	Mean (%)
Biodegradable	60.3	52.64	76.95	63.30
Plastic	12.3	17.56	5.5	11.79
Paper	10.5	3.36	0.6	4.82
Rubber	1.5	3.32	0.55	1.79

However, most of the cities and towns in India have a well-defined waste collection facility, which prevents the burning of entire waste generated in these areas. State-level waste collection efficiency data was collected from the MoSPI (2016) (Table 32). Conversely, there is no structured waste collection facility in rural areas of India.

Table 32 Urban waste collection efficiencies of different states of India

States/UTs	Collection efficiency	States/UTs	Collection efficiency	States/UTs	Collection efficiency
Andaman and Nicobar Islands	100%	Himachal Pradesh	75%	Odisha	89%
Andhra Pradesh	98%	Jammu and Kashmir	74%	Puducherry	98%
Arunachal Pradesh	85%	Jharkhand	100%	Punjab	100%
Assam	54%	Karnataka	84%	Rajasthan	49%
Bihar	0%	Kerala	49%	Sikkim	100%
Chandigarh	97%	Lakshadweep	NA	Tamil Nadu	98%
Chhattisgarh	90%	Madhya Pradesh	65%	Tripura	89%
Daman and Diu, Dadra	100%	Maharashtra	100%	Telangana	94%
Delhi	99%	Manipur	71%	Uttar Pradesh	100%
Goa	89%	Meghalaya	84%	Uttarakhand	100%
Gujarat	100%	Mizoram	50%	West Bengal	85%
Haryana	100%	Nagaland	56%	**India**	91%

NA Not available

We assumed that 60% of total uncollected wastes in both rural and urban areas get burned to reduce the volume of the waste following IPCC (2006). Accordingly, the *f*Wb was calculated following Eq. *27*.

$$fWb_{a,i} = \{P_a \times C_\omega \times Com_i \times (1 - \varphi)\} \times 0.6 \qquad (27)$$

where, P_a is the population of the area (rural or urban); C_ω is the per capita waste generation (Table 30); *Com* is the fraction of the waste (*i*) (*Table 31*); and φ is the waste collection efficiency (Table 32).

9.1 Emission inventory of different pollutants due to refuse burning

Estimated region-wise emissions of different pollutants due to the burning of different refuse materials are given in Figure 13.

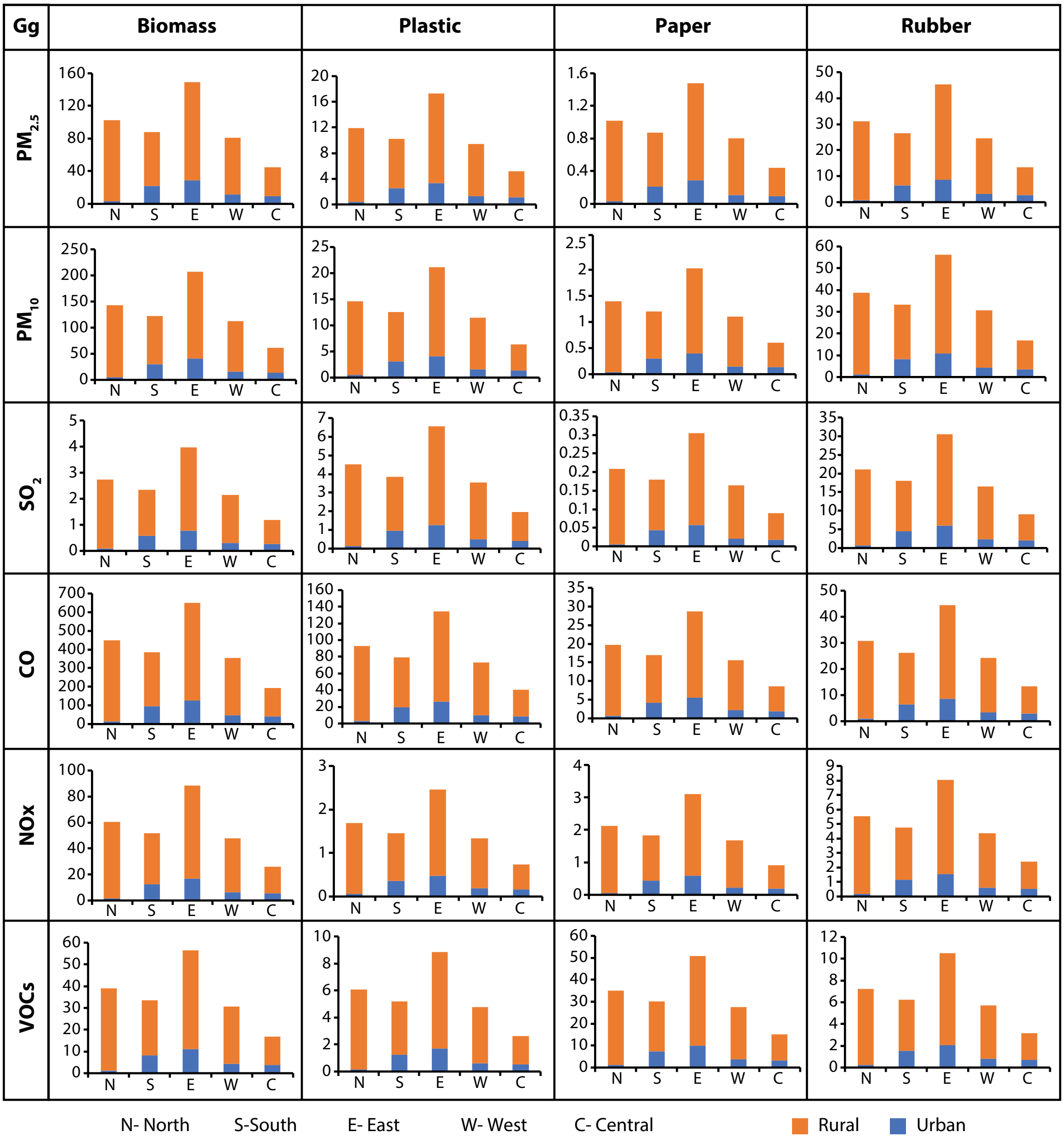


Figure 13 Emissions of different pollutants in the rural and urban areas due to the burning of various refuse materials

Total emissions of atmospheric PM_{10} and $PM_{2.5}$ due to refuse burning were estimated as 862 and 632 Kt during 2016 respectively (*Table 33*). Burning of biomass waste material was the major source of almost all estimated pollutants emission.

Table 33 Emissions of different pollutants (Gg) due to refuse burning during 2016

State	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	VOC
Andhra Pradesh	30.49	22.68	4.40	11.49	91.36	12.80
Arunachal Pradesh	1.06	0.79	0.15	0.40	3.19	0.45
Assam	30.33	22.56	4.38	11.43	90.89	12.74
Bihar	109.30	81.30	15.78	41.17	327.50	45.89
Chhattisgarh	19.81	14.74	2.86	7.46	59.36	8.32
Goa	0.67	0.50	0.10	0.25	2.00	0.28
Gujarat	31.11	23.14	4.49	11.72	93.22	13.06
Haryana	14.81	11.02	2.14	5.58	44.38	6.22
Himachal Pradesh	4.61	3.43	0.67	1.74	13.81	1.94
Jammu and Kashmir	11.06	8.22	1.60	4.16	33.13	4.64
Jharkhand	23.57	17.53	3.40	8.88	70.61	9.90
Karnataka	42.74	31.80	6.17	16.10	128.08	17.95
Kerala	39.96	29.72	5.77	15.05	119.73	16.78
Madhya Pradesh	65.39	48.64	9.44	24.63	195.95	27.46
Maharashtra	55.25	41.10	7.98	20.82	165.57	23.20
Manipur	2.32	1.73	0.34	0.87	6.96	0.98
Meghalaya	2.53	1.89	0.37	0.95	7.59	1.06
Mizoram	0.99	0.74	0.14	0.37	2.96	0.42
Nagaland	1.77	1.32	0.26	0.67	5.32	0.75
Odisha	34.16	25.41	4.93	12.87	102.35	14.34
Punjab	15.43	11.48	2.23	5.81	46.23	6.48
Rajasthan	68.45	50.92	9.88	25.79	205.10	28.74
Sikkim	0.38	0.28	0.05	0.14	1.14	0.16
Tamil Nadu	34.54	25.69	4.99	13.01	103.49	14.50
Telangana	20.95	15.58	3.02	7.89	62.77	8.80
Tripura	2.57	1.92	0.37	0.97	7.71	1.08
Uttar Pradesh	144.89	107.78	20.92	54.58	434.16	60.84
Uttarakhand	6.30	4.69	0.91	2.37	18.88	2.65

State	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	VOC
West Bengal	63.91	47.54	9.23	24.07	191.49	26.83
Andaman and Nicobar Islands	0.20	0.15	0.03	0.08	0.60	0.08
Lakshadweep	0.14	0.10	0.02	0.05	0.41	0.06
NCT of Delhi	0.33	0.24	0.05	0.12	0.98	0.14
Puducherry	0.37	0.28	0.05	0.14	1.12	0.16
National emission (Gg)	880	655	127	332	2638	370
Contribution of different type of refuse materials (%)						
Biodegradable	73.4	71.2	9.7	82.8	77.1	47.8
Plastic	7.5	8.2	16.1	8.3	15.8	42.8
Paper	0.7	0.7	0.7	2.9	3.4	2.1
Rubber	20	21.5	75	7.6	5.3	8.9

The state-level emissions of different pollutants due to burning of the refuse materials were spatially distributed following the weighted value of each polygon in a state. The weighted value of each polygon was derived based on the ratio of the polygon area and the area of the state (Figure 14).

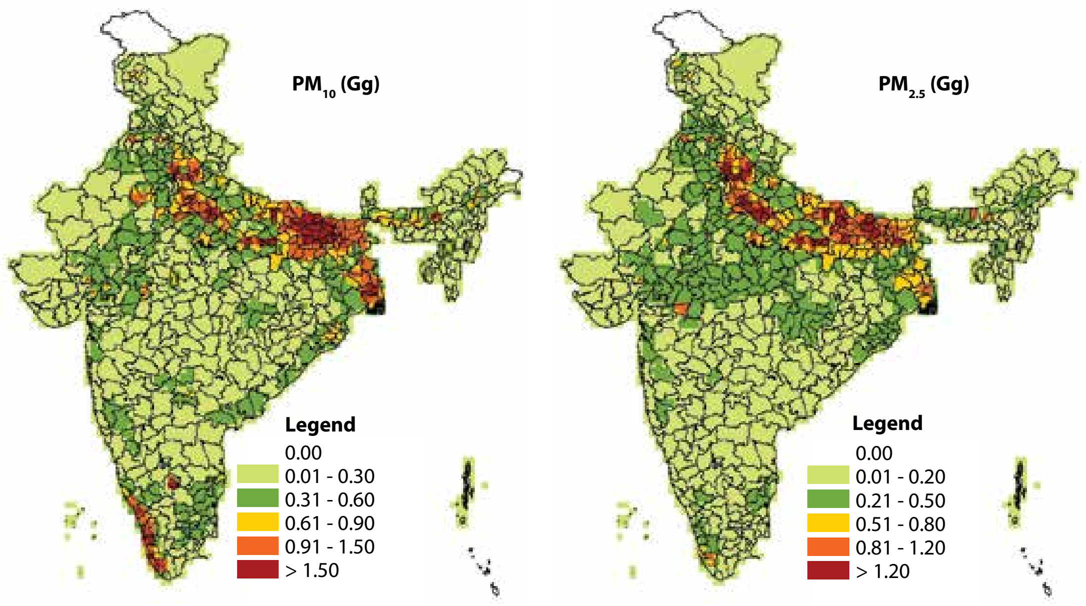


Figure 14 Contd...

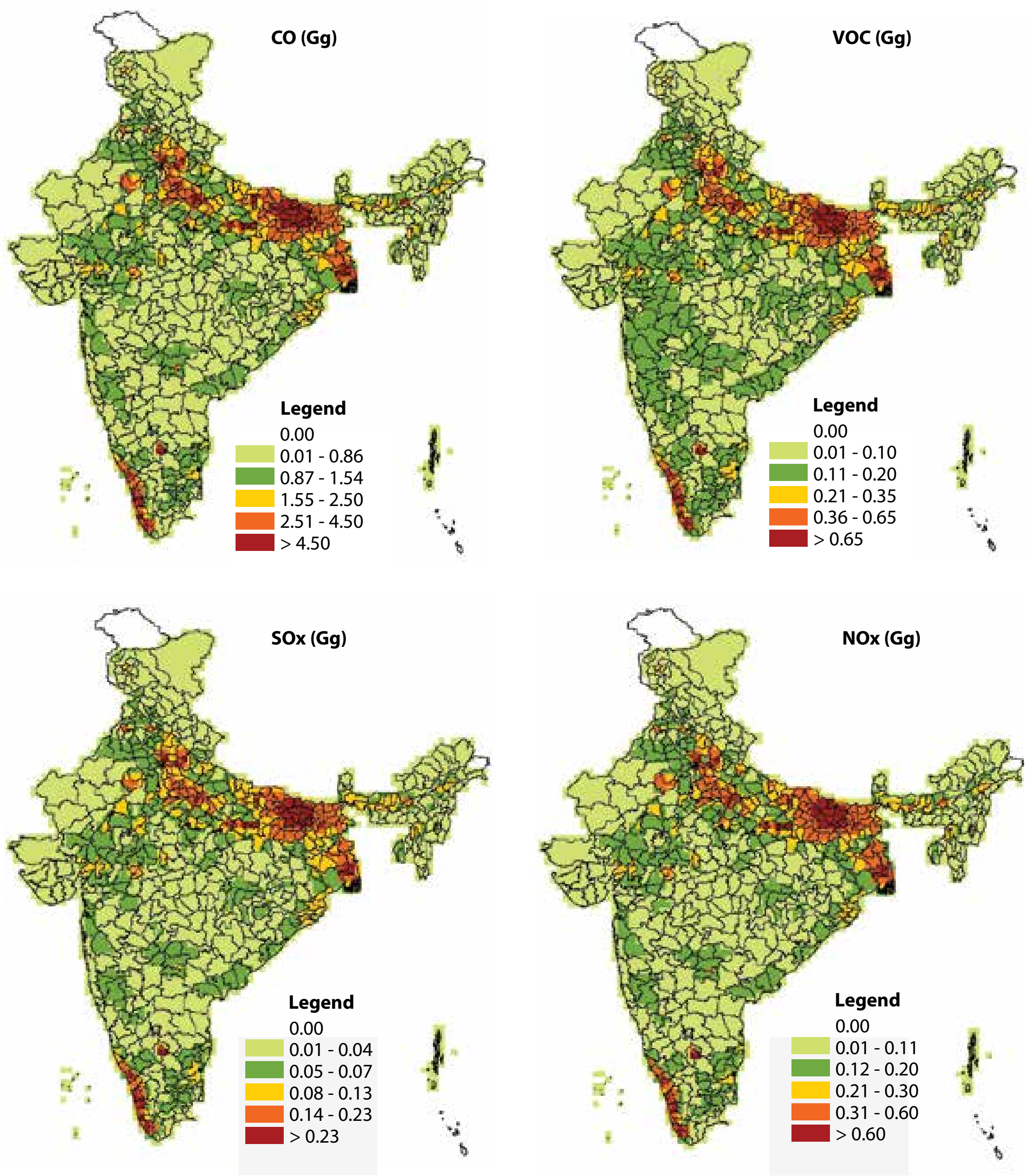


Figure 14 Spatial distribution of emission of different pollutants due to the burning of the refuse materials

CONSTRUCTION SECTOR

10

According to the World Bank, the Indian GDP has progressed from 10th largest in the world during 2012 to 6th largest during 2017 in spite of being the second most populated country in the world. This is associated with large growth in the construction sector during this period. Emissions of the construction sector depend heavily on the area of construction activity. Thus, it is important to estimate the emission of atmospheric pollutants due to the construction activities in the country.

10.1 Estimation of the construction area

It is a difficult task to identify the construction areas in different parts of the country using any reliable data source. We have estimated state-specific construction area using the GSDP and share of construction sector to GSDP of each state during the year 2016. The data of area on active construction sites in the states of Delhi and Gujarat during 2016 were identified by using high-resolution satellite images. The criteria used for demarcating these construction sites is its perimeter, i.e., sites of perimeter of 300 m and above have been taken into account. Further, all the construction sites have been labelled on the basis of the nature of construction. For example, residential, commercial, institutional such as schools, and others. Average construction cost per unit area in these two states during 2016 was calculated (C_a). The construction area (A_C) in each state (S) was estimated using Eq. 28:

$$A_{C,S} = \frac{GDP_S \times GDP_{C,S}}{C_a} \qquad (28)$$

where, GDP_S is GSDP of the state (S) during 2016; $GDP_{C,S}$ is the percentage share of construction sector in state(S) GSDP during 2016. C_a was calculated as INR 8,718,000 per acre of construction. The state-specific GDP values were collected from the Reserve Bank of India for the year 2016. Accordingly, the construction area of each state ($A_{C,S}$) was estimated in acre using Eq. 28 (Table 34). This suggests that an estimated 4109 km^2 area was under construction during 2016.

Table 34 Estimated area under construction in each state during 2016

State/UT	Area under construction (Acre)	State/UT	Area under construction (Acre)	State/UT	Area under construction (Acre)
Andhra Pradesh	48,118	Jharkhand	17,613	Puducherry	3248
Arunachal Pradesh	1773	Karnataka	62,168	Punjab	24,407
Assam	19,244	Kerala	68,366	Rajasthan	55,799
Bihar	33,213	Madhya Pradesh	41,700	Sikkim	836
Chandigarh	1506	Maharashtra	108,024	Tamil Nadu	122,872
Chhattisgarh	20,233	Manipur	2189	Telangana	28,250
Goa	1881	Meghalaya	1273	Uttar Pradesh	112,676
Gujarat	60,746	Mizoram	1793	Uttarakhand	12,102
Haryana	38,318	Nagaland	1300	West Bengal	63,237
Himachal Pradesh	9145	NCT of Delhi	19,365		
Jammu and Kashmir	8780	Odisha	25,174	**Total**	**1,015,349**

10.2 Estimation of emissions from construction activities

Emissions of PM_{10} and $PM_{2.5}$ due to the construction activities were estimated using Eq. 29:

$$EPM = A_{C,S} \times EF_{PM} (12 - R_S) \qquad (29)$$

where, E_{PM} is the emission of PM (Mg/acre); EF_{PM} is the emission factor of PM (1.2 Mg/acre/month); and R_s is the number of month in state (S) received total rainfall higher than 100 mm during 2016. According to USBR (2002), PM_{10} emissions from overburden removal and bulldozing activities during construction activity is 35% of the total PM emission. Again, Muleski et al. (2005) have reported the ratio of $PM_{2.5}$ to PM_{10} was varied between 0.2 to 0.46 at the construction sites. Based on these, it was assumed that 35% of the PM (E_{PM}) was PM_{10} and 6% was $PM_{2.5}$. Estimated PM_{10} and $PM_{2.5}$ emissions due to construction activities during 2016 were 3291 Gg and 197 Gg, respectively (*Table 35*).

Table 35 Emissions of pollutants due to construction activities in different states during 2016

State	PM_{10} (Gg)	$PM_{2.5}$ (Gg)	State	PM_{10} (Gg)	$PM_{2.5}$ (Gg)
Andhra Pradesh	142	9	Manipur	5	0
Arunachal Pradesh	3	0	Meghalaya	3	0
Assam	49	3	Mizoram	4	0
Bihar	98	6	Nagaland	3	0

State	PM_{10} (Gg)	$PM_{2.5}$ (Gg)	State	PM_{10} (Gg)	$PM_{2.5}$ (Gg)
Chandigarh	6	0	NCT of Delhi	73	4
Chhattisgarh	68	4	Odisha	85	5
Goa	6	0	Puducherry	16	1
Gujarat	230	14	Punjab	103	6
Haryana	145	9	Rajasthan	211	13
Himachal Pradesh	31	2	Sikkim	2	0
Jammu and Kashmir	30	2	Tamil Nadu	413	25
Jharkhand	89	5	Telangana	107	6
Karnataka	131	8	Uttar Pradesh	426	26
Kerala	115	7	Uttarakhand	41	2
Madhya Pradesh	140	8	West Bengal	159	10
Maharashtra	363	22	Total	3291	198

11

MINING SECTOR

Emissions from mining activities are estimated based on the empirical formula derived by Chakraborty et al. (2002). The formula is used to estimate emissions of different pollutants from coal and iron ore mining. The empirical formulae (Eq. 30, 31, and 32) used for estimating the emission rates of different pollutants are:

$$E_{PM} = [u^{0.4}a^{0.2}\{9.7+0.01p+b/(4+0.3b)\}] \quad (30)$$

$$E_{SO_2} = a^{0.14}\{u/(1.83+0.93u)\}\times[\{p/(0.48+0.57p)\}+ \{b/(14.37+1.15b)\}] \quad (31)$$

$$E_{NOx} = a^{0.25}\{u/(4.3+32.5u)\}[1.5p+\{b/(0.06+0.08b)\}] \quad (31)$$

where, E_{PM}, E_{SO_2} and E_{NOx} are emissions rate of pollutants PM, SO_2 and NO_x respectively from mining activities. u = wind speed (m/s); a = area of pit (km^2); p = mineral production (Mt/year); b = Overburden (OB) handling (Mm^3/year)

The production, overburden removal and number of mines for each coal mining company for the year 2016 have been taken from the *Coal Directory of India 2016–17*. Since the data on mining area of all mines in India are not available, the ratio of coal production to area of production (0.039 Mt/km^2) calculated for the state of Odisha is used for other states also. Wind speeds of respective states have been taken from Climatological tables of India published by Indian Meteorological Department (IMD). The ratios of PM_{10} and $PM_{2.5}$ in the total PM were assumed to be 0.5 and 0.1, respectively (GAINS-ASIA). Emissions estimated in this method was also validated using the emission factor method developed by Ghose (2004). Due to lack of detailed data on mine-wise area and location of each mine for iron ore mining, emissions from iron ore mining were estimated using the emission factor developed by Ghose only. Emission factors for mining operations developed by Ghose (2004) are shown in Table 36.

Table 36 Emission factors for mining operations

Mining activity	Material	Emission factor for PM (g/kg)
Overburden (topsoil removal)	Overburden	0.029
Dumper loading of overburden (by power shovel)	Overburden	0.018
Unloading	Overburden	0.001
Total EF for OB removal	Overburden	0.048
Transportation in haul road	Overburden	2.25*
Loading	Coal	0.014
Unloading	Coal	0.033
Total EF for coal mining	Coal	0.047

Transportation in haul road	Coal	2.25*

Using Ghose's emission factor, emissions from both coal and iron ore mining activities are estimated based on the production, overburden removal, and number of mines using Eq. 33 and Eq. 34:

$$E_{OBR} = OBR_T \times EF_{OBR} \quad (33)$$

$$E_M = P_T \times EF_M \quad (34)$$

where, E_{OBR} and E_M are emissions from overburden removal and mining respectively and OBR_T is the total overburden removal; P_T is the total production; and EF_{OBR} and EF_M are total emission factors for overburden removal and mining, respectively. Emissions are also estimated due to transportation of both overburden and coal/iron ore in haul road. The emissions due to transportation of overburden and coal/iron ore in haul road are estimated using Eq. 35:

$$E_{Tr} = VKT_M \times EF \quad (35)$$

where, E_{Tr} is the emissions due to transportation of overburden and coal/iron ore in haul road; VKT_M is the vehicle kilometer travelled; and EF is the emission factor. VKT_M was calculated using Eq. 36:

$$VKT = h \times c \times Q_{MT} \quad (36)$$

where, h is the average length of haul road which is 0.5 km for overburden and 0.7 km for coal/iron ore; c is the average capacity of the dumper used to transport which is 85 tonne and 58 tonne respectively for overburden and coal/iron ore, respectively.

The data for production, overburden removal and number of mines in coal mining sector is taken from the *Coal Directory of India 2016–17*, whereas the corresponding data for iron ore mining sector is taken from the *Ministry of Mines Annual Report 2017–18*.

The estimated emissions from open cast coal mining and open cast iron ore mining are shown in Table 37.

Table 37 Emissions of pollutants (Gg) from open cast coal mining and iron ore mining during 2016

Pollutant	Open cast coal mining		Iron ore mining	Total
	Chakraborty (2002)	Ghose (2004)		
PM_{10}	100.01	132.78	46.31	279.1
$PM_{2.5}$	20.00	26.56	9.26	55.82
SO_2			8.46	8.46
NO_x			3.04	3.04

As per the emissions estimated based on the methodology developed by Ghsoe (2004), 74% of PM emissions are contributed by coal mining and remaining 26% PM emissions are contributed by iron ore mining. Out of this, for both coal mining and iron ore mining, 65% emissions are caused by overburden removal, 11% by mining activities and 24% due to transportation of overburden and coal/iron ore mine in haul road.

The emissions from coal mining sectors in India were allocated spatially using mining data of coal and iron ore in different districts. For iron ore mining also the emissions were distributed on the basis of production of iron ore from various states. In India, there are mainly ten iron ore producing states, i.e., Karnataka, Andhra Pradesh, Rajasthan, Tamil Nadu, Goa, Chhattisgarh, Odisha, Maharashtra, Madhya Pradesh, and Telangana. State-wise production of iron ore for the year 2014–15 was collected from Indian Bureau of Mines and was considered for emissions distribution. After that emissions from states to grid level were distributed using ArcGIS software (Figure 15).

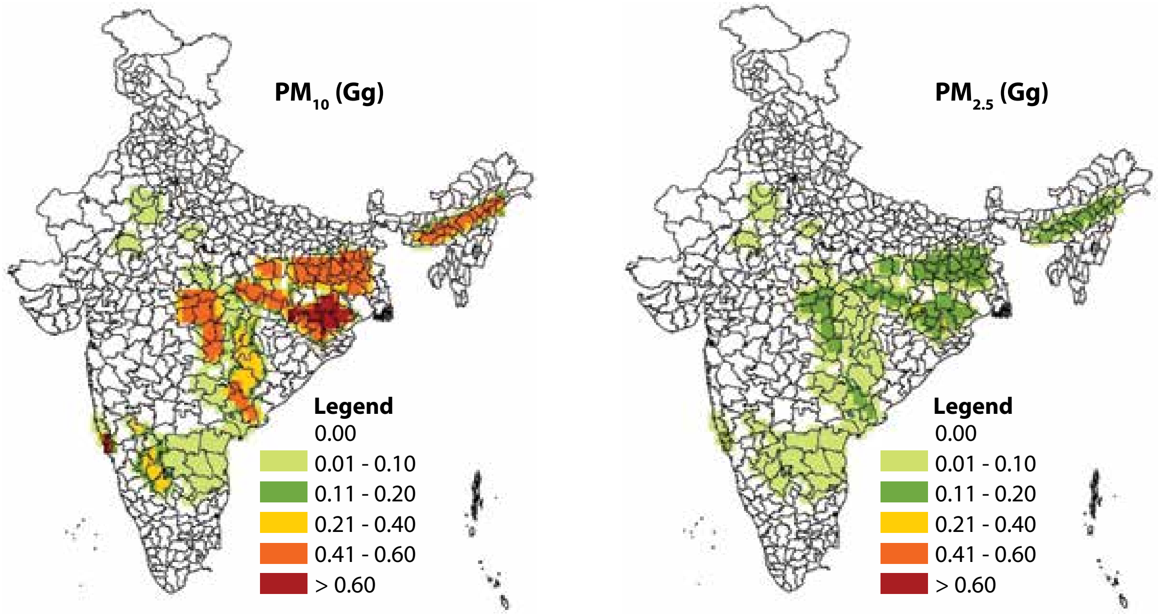


Figure 15 Spatial variation of emissions of particulate matters from the mining sector

12

CREMATORIA

The cremation of body is a religious ceremony performed for final disposition of dead body mainly by Sikhs, Jains and Hindus in India. This involves open air funeral pyre made of wood on which dead body is laid and burned. The process results in deforestation and air pollution. In this study, we have estimated the crematoria emissions from wood burning activity only. Earlier studies in India have also reported the emission from the crematorium based on the wood burning activities; however, these studies are mostly based on the city-specific emission inventory, e.g., Delhi, Kanpur. Malik and Sharma (2016) reported less than 1% of total emissions of PM_{10} and $PM_{2.5}$ from the wood burning activities in crematorium. However, TERI (2018) has reported 1% annual PM_{10} and $PM_{2.5}$ emissions in Delhi-NCR from the wood burning in crematoria.

In this study, we calculated the emissions from crematoria at rural-urban level in each district of India. For this we used the 2011 census projected population for 2016 at the rural-urban level of each district. Further, the fraction of Hindus and Sikhs in each district was calculated by using district-wise religious population data of 2011 census. Here the assumption was made that the fraction remained constant from 2011 to 2016. The data of death rate by residence of each state (NITI Ayog, 2017b) was used for each district of respective state in combination with the fraction of Hindu and Sikh population, for estimating the deaths of Hindus and Sikhs in each district in rural-urban areas.

The amount of wood burnt in crematoria of a district is calculated using Eq. 37:

$$TW_d = \sum_{i=1}^{2} P_i \times F_i \times DR_i \times W \tag{37}$$

where, TW is the total amount of wood burned in kg; P is the total population; F is the fraction of Hindu and Sikhs in the population; DR is the death rate (Table 38); and W is the amount of wood required for each cremation. Different literature has reported the amount of wood required for each cremation in the range of 200 kg to 600 kg (Patel, 2018; Bedge et al., 2016; Sharma, 2016; Kermeliotis, 2011; Sharma, 2010); based on TERI survey during 2016 at fifty crematoria in Delhi, we have taken the value of W as 350 kg in this study; i: Represents rural-urban area of each district.

Table 38 Death rate (percent of total population) by residence for the year 2016

State	Death Rate	State	Death Rate
Andhra Pradesh	6.8	Mizoram	4.2
Arunachal Pradesh	6.2	Nagaland	4.5
Assam	6.7	Odisha	7.8
Bihar	6.0	Punjab	6.0
Chhattisgarh	7.4	Rajasthan	6.1
Delhi	4.0	Sikkim	4.7

State	Death Rate	State	Death Rate
Goa	6.7	Tamil Nadu	6.4
Gujarat	6.1	Telangana	6.1
Haryana	5.9	Tripura	5.5
Himachal Pradesh	6.8	Uttar Pradesh	6.9
Jammu and Kashmir	5.0	Uttarakhand	6.7
Jharkhand	5.5	West Bengal	5.8
Karnataka	6.7	Andaman and Nicobar Islands	5.2
Kerala	7.6	Chandigarh	4.5
Madhya Pradesh	7.1	D&N Haveli	4.0
Maharashtra	5.9	Daman & Diu	4.6
Manipur	4.5	Lakshadweep	6.0
Meghalaya	6.6	Puducherry	7.2

Source: NITI Aayog (2017b)

Further, the emissions were calculated by Eq. 38:

$$E_p = \sum_{s=1}^{n} \sum_{d=1}^{n} TW_d \times EF_p \qquad (38)$$

where, EF: Emission factors (Table 39); s: number of states; and d: number of districts.

Table 39 Emission factors of different pollutants due to open burning of wood

Pollutant	PM_{10}	$PM_{2.5}$	SO_2	NO_x	NMVOC
g/kg	18.5	9.1	0.4	2.5	51.9

Source: Malik et al. (2016) and Akagi et al. (2011)

12.1 Emission inventory of different pollutants from crematoria

The resultant values from crematoria burning shows expected results with NMVOCs being emitted most followed by particulate matters (PM_{10} and $PM_{2.5}$) as compared to other pollutants (Table 40). The results show more emission from states with higher population and lower emissions are seen from states where Hindu-Sikh population is less (Figure 16).

Table 40 Emission of different pollutants from the crematoria in different states during 2016

State	PM_{10} (Gg)	$PM_{2.5}$ (Gg)	SO_2 (Gg)	NO_x (Gg)	CO (Gg)	NMVOC (Gg)
Andaman and Nicobar Islands	0.009	0.005	0.000	0.001	0.046	0.026
Andhra Pradesh	2.159	1.062	0.047	0.298	10.853	6.057
Arunachal Pradesh	0.011	0.005	0.000	0.001	0.054	0.030
Assam	0.896	0.441	0.019	0.124	4.505	2.514
Bihar	3.911	1.924	0.085	0.539	19.659	10.971
Chhattisgarh	1.317	0.648	0.028	0.182	6.622	3.696
Goa	0.049	0.024	0.001	0.007	0.245	0.137
Gujarat	2.492	1.226	0.054	0.343	12.526	6.990
Haryana	1.039	0.511	0.022	0.143	5.222	2.914
Himachal Pradesh	0.311	0.153	0.007	0.043	1.562	0.872
Jammu and Kashmir	0.154	0.076	0.003	0.021	0.777	0.433
Jharkhand	0.875	0.430	0.019	0.121	4.400	2.455
Karnataka	2.627	1.292	0.057	0.362	13.207	7.371
Kerala	1.054	0.518	0.023	0.145	5.297	2.956
Lakshadweep	0.000	0.000	0.000	0.000	0.000	0.000
Madhya Pradesh	3.506	1.725	0.076	0.483	17.627	9.837
Maharashtra	4.055	1.995	0.088	0.559	20.387	11.377
Manipur	0.037	0.018	0.001	0.005	0.187	0.104
Meghalaya	0.011	0.006	0.000	0.002	0.057	0.032
Mizoram	0.000	0.000	0.000	0.000	0.002	0.001
Nagaland	0.004	0.002	0.000	0.001	0.020	0.011
NCT of Delhi	0.218	0.107	0.005	0.030	1.096	0.611
Odisha	2.198	1.081	0.048	0.303	11.047	6.165
Puducherry	0.057	0.028	0.001	0.008	0.285	0.159
Punjab	1.122	0.552	0.024	0.155	5.638	3.146
Rajasthan	2.801	1.378	0.061	0.386	14.083	7.859
Sikkim	0.014	0.007	0.000	0.002	0.070	0.039
Tamil Nadu	3.085	1.517	0.067	0.425	15.506	8.653
Telangana	1.379	0.678	0.030	0.190	6.933	3.869
Tripura	0.108	0.053	0.002	0.015	0.544	0.304
Uttar Pradesh	8.388	4.126	0.181	1.156	42.164	23.530
Uttarakhand	0.444	0.218	0.010	0.061	2.231	1.245
West Bengal	2.367	1.165	0.051	0.326	11.901	6.642
Total	47	23	1	6	235	131

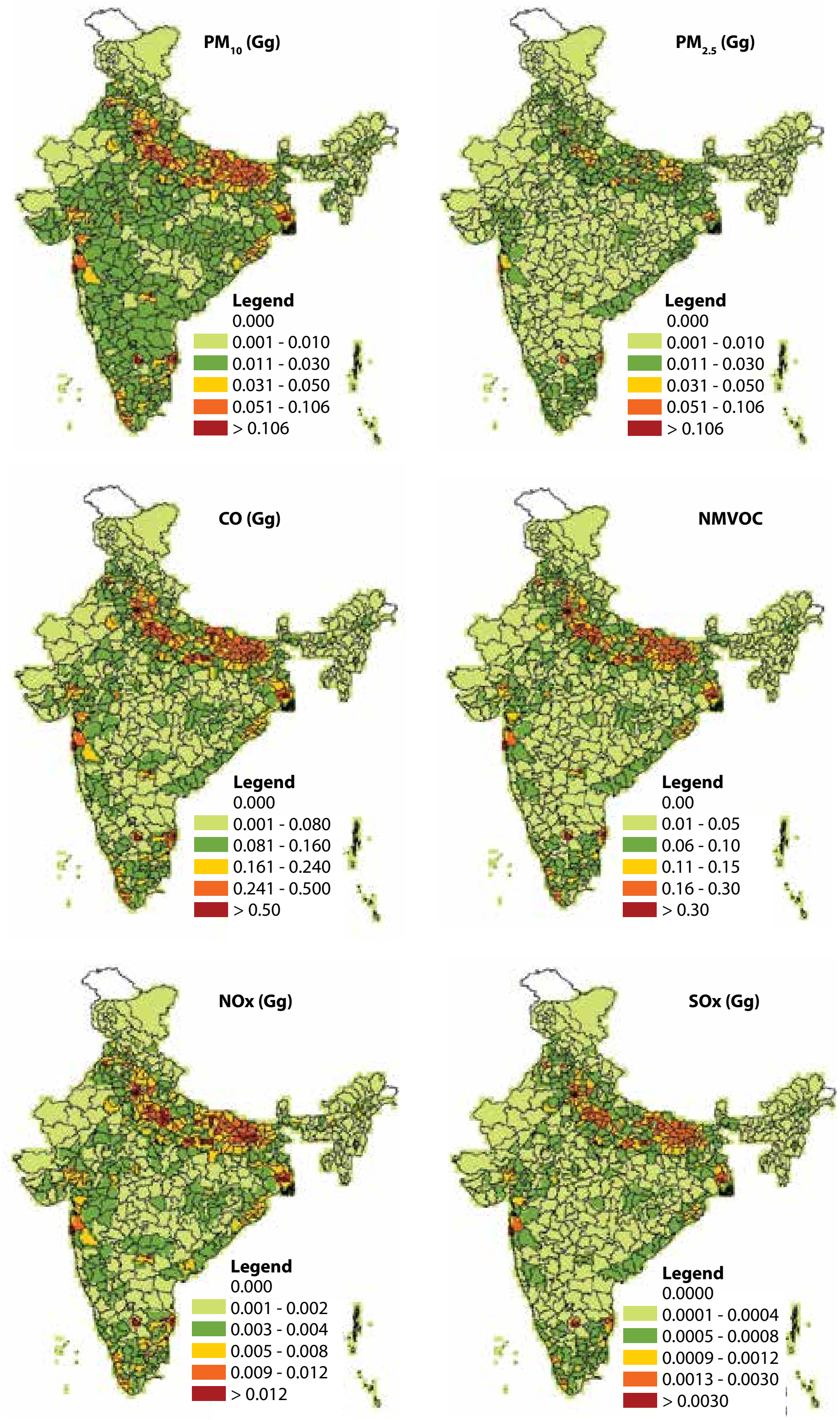


Figure 16 Spatial variations of atmospheric particulate emissions from crematoria during 2016

ESTIMATED ATMOSPHERIC CONCENTRATIONS

13

The modelling framework for this study consists of a meteorological model, an air quality model and an emission inventory database which were integrated to simulate the local and regional atmospheric circulation and predict the pollutant concentrations on national level. Ambient $PM_{2.5}$ concentrations were simulated in this study using the WRF-CMAQ modelling combination. Models-3/CMAQ modelling system has been used in the study to assess chemical transport of different pollutant species under prevailing meteorological conditions (Byun and Ching, 1999). The CMAQ system is based on multi-pollutant and one atmosphere approach and is a leading air quality model used for assessment of ozone (O_3) and aerosols (Byun and Schere, 2006). CMAQ is known to have certain advantages over the traditional Gaussian-based models (ISCST3, AERMOD), which have been generally used in India in source apportionment studies. CMAQ is Eulerian model as compared to Gaussian approach followed in AERMOD/ISCST3 and includes many more atmospheric processes than traditional models. CMAQ deals with chemical reactive species such as ozone, NO_x, hydrocarbons, and secondary particulates (sulphates, nitrates) and can be used on a range of spatial scales—continental to local, and accounts for long- and medium-range transport of pollutants. The model can deal with multiple pollutants together rather than individually and also takes into account the photochemistry which is not accounted for in traditional models.

A number of studies have shown satisfactory performance of the Community Multi scale Air Quality Modelling System (CMAQ) to predict urban- and regional-scale concentrations of a variety of pollutants (Marmur et al., 2009; Jose et al., 2013; Liu, 2013). The model has been extensively used for policy and research evaluations across the world (Paza et al., 2013 (Mediterranean Basin); Sokhi et al., 2006 (London); Chen et al., 2007 (Beijing); Khiem et al., 2010 (Japan); Simon et al., 2012 (USA). Sharma et al. (2014) have applied the CMAQ model to predict NO_x concentrations for Bangalore city and ozone concentrations in India (Sharma et al., 2016). Based on the widespread applicability and requirements of multi-pollutant prediction, WRF (ver 3.1.1)-CMAQ (ver 5.0.2) combination have been chosen for carrying out the assessment in the present study (*Figure 17*).

WRF model runs have been carried out to generate three-dimensional meteorological fields over the study domain which acts as an input to the CMAQ model along with emissions inventory. ECMWF and USGS datasets have been used for running the WRF model, the output of which are the three-dimensional meteorological inputs that are fed to the CMAQ model.

India-scale emission inventory data at a resolution of 36 km x 36 km has been prepared in this study and has been provided as input to CMAQ model. To account for transport of pollutants from outside India, international boundary conditions have been adopted from global air quality products of NCAR (National Centre for Atmospheric Research, US). These global products are generated using the global chemical transport model MOZART. The emissions in neighbouring countries, such as Pakistan, Nepal,

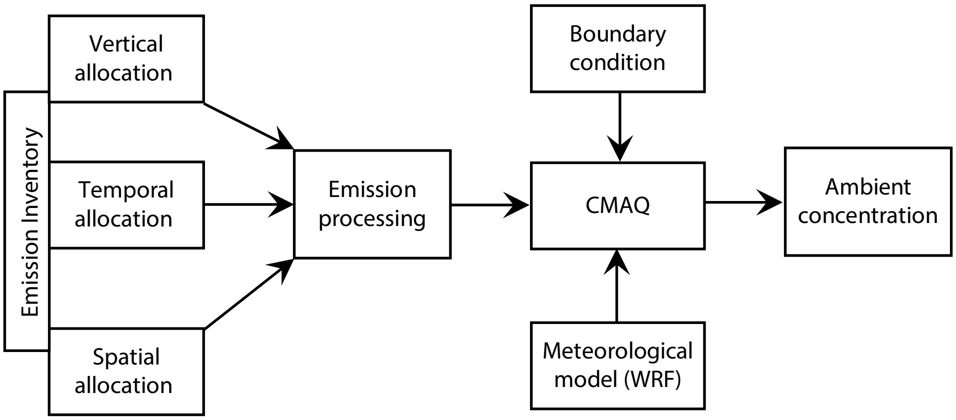


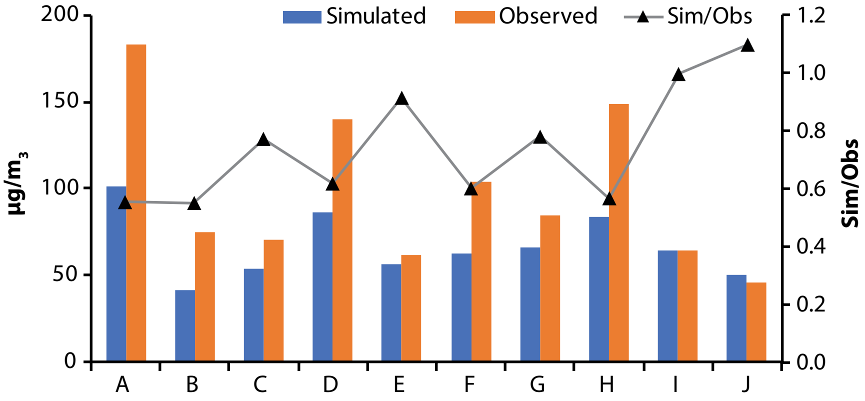
Figure 17 Framework of ambient air quality simulation

Bangladesh, etc., which fall within the Indian study domain are taken from ECLIPSE database of IIASA (2014).

With these inputs, the model was run for the year 2016. The simulated ambient air concentration of $PM_{2.5}$ was validated with the selected annual automatic air quality monitoring stations data from the CPCB (www.app.cpcbccr.com). The validation of this model established that the model is able to reproduce physical and chemical processes which define pollutant concentrations, and it can be further utilized for running sensitivities of different sources.

The simulated results were validated against the observed measurements collected from the CPCB in the year 2016 with annual average concentration measured in major cities across India. The average ratio of simulated to observed values was found to be ~ 0.74 (*Figure 18*), which can be considered quite satisfactory. City wise variations in simulated and observed results attributed to, a) variations in landuse land cover pattern in different cities; b) the simulated value represents a single value over 36 km ×36 km area; whereas, observed values are generally the average of n numbers of monitoring locations in the specific city. These factors affects city wise variations in observed and simulated ambient $PM_{2.5}$ concentrations.

The spatial and temporal variation of simulated ambient $PM_{2.5}$ concentration over the Indian domain during 2016 (Figure 19) suggests dominance of internal sources during winter months which can be attributed to mainly two factors: i) agriculture residue burning, practised mainly by farmers of Punjab, Haryana and western Uttar Pradesh in the months of October and November. The ambient concentration of $PM_{2.5}$ over the region increased from the month of September to November and starts to dissipate in the month of December; ii) the meteorology, the wind conditions prevailing in winter are not conducive to dispersion due to slowdown in horizontal wind along with decrease in planetary boundary layer due to fall in ambient temperature (TERI, 2018). Further, burning of biomass is also prevalent for maintaining warmth in winter season both inside and outside of houses in the region, which also contribute significantly to ambient $PM_{2.5}$ concentration.



A. Ahmedabad, B. Bengaluru, C. Chennai, D. Delhi, E.Hyderabad, F. Jaipur, G. Nagpur, H. Patna, I. Pune, J. Visakhapatnam.

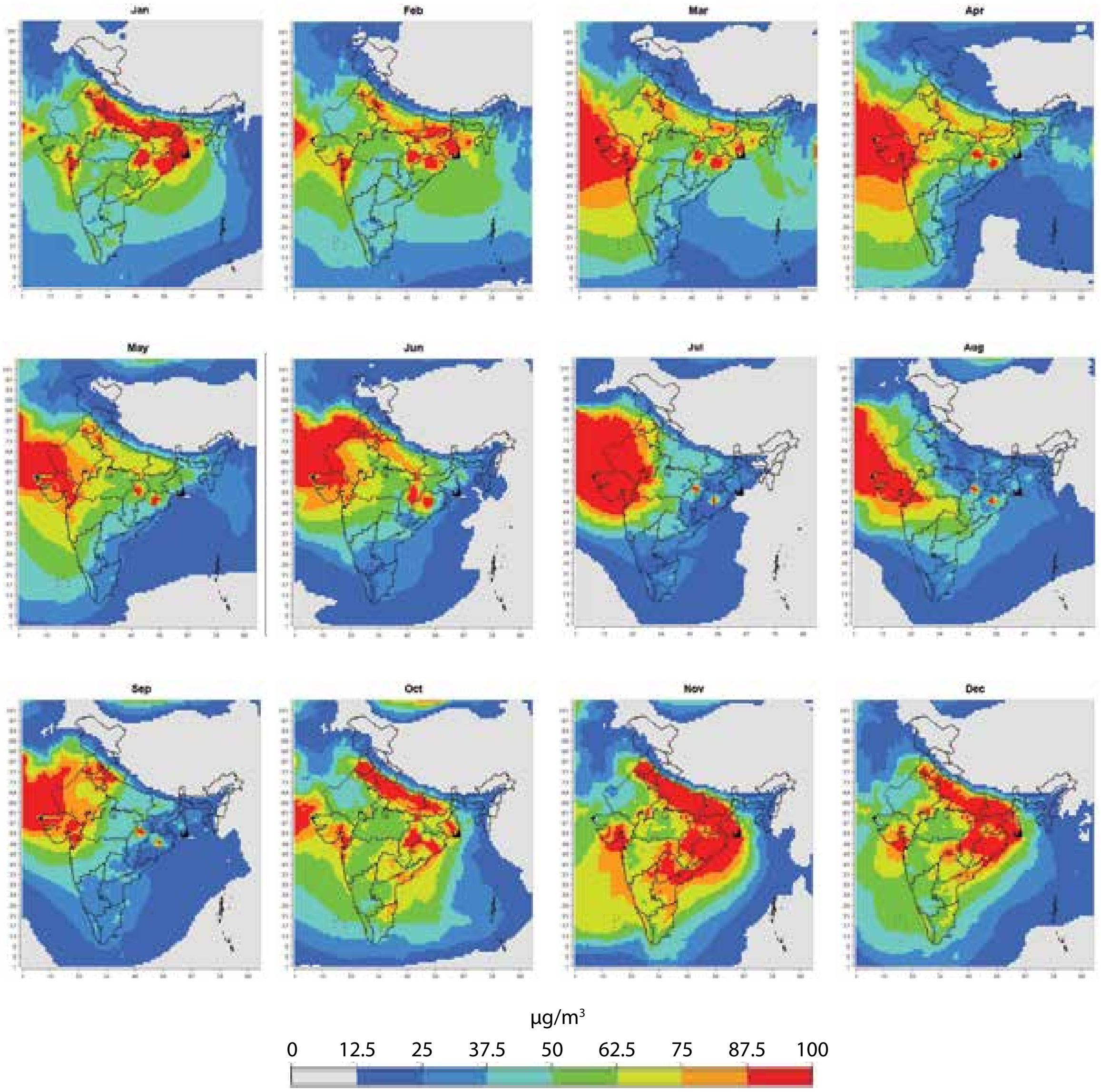
Figure 18 Validation of simulated concentrations of PM2.5 with observed results from the CPCB National Ambient Air Quality Monitoring Stations of different cities in India

However, during the summer months the dominance of contribution from the western region outside the political boundary of India can be observed (Figure 19). This is attributed to the prevailing wind direction and higher wind speed compared to the winter months. Further, higher concentration of $PM_{2.5}$ is visible all over the year over the IGP region. This $PM_{2.5}$ concentration is washed down in the monsoon months, i.e., June and July.

The simulated monthly data also suggests that the PM2.5 concentrations in most of the locations in India are above the annual average National Ambient Air Quality Standard of 40 µg/m3 prescribed by CPCB (Figure 19). This is mainly high in the densely populated regions of India, such as Indo-Gangetic belt, Maharashtra-Gujarat region and parts of Orissa-Andhra Pradesh-Telangana-Karnataka-Tamil Nadu. This high concentration may be attributed to the sectors which are driven by the presence of people in any area, such as waste generation, crematoria, transport, residential, etc. While in scarcely populated regions, such as north east and Jammu and Kashmir, low level of PM2.5 concentration is simulated round the year.

A few hotspots of ambient $PM_{2.5}$ concentrations (Figure 20) over Chhattisgarh and Odisha may be attributed to the presence of major thermal power plants and industries in this part of the country. The power and industry sectors remain in operation throughout the year, resulting in the release of high level of $PM_{2.5}$ levels in the region.

The regional variations in ambient $PM_{2.5}$ concentration during 2016, requires further study to know the seasonal variation of the sources in different regions to develop appropriate regional air quality management plan.



A. January, B. February, C. March, D. April, E., May, F. June, G. July, H. August, I. September, J. October, K. November, L. December

Figure 19 Spatiotemporal variations of simulated ambient $PM_{2.5}$ over the Indian subcontinent during 2016

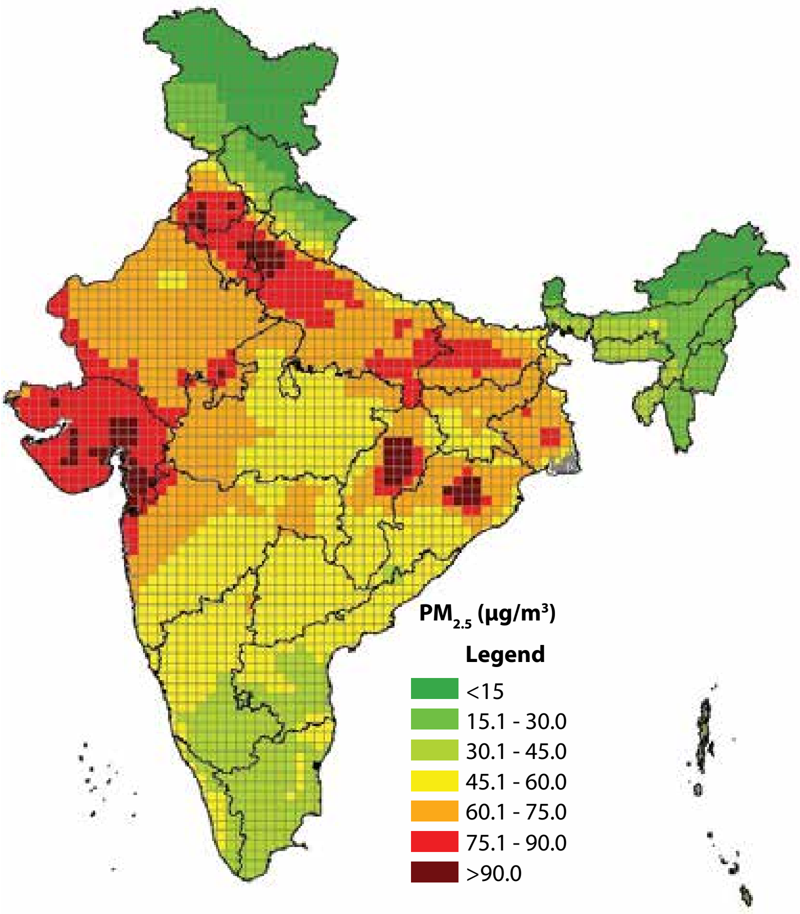


Figure 20 Simulated annual average ambient PM$_{2.5}$ concentration (µg/m^3) in India during 2016

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