Estimation of Contribution of Sources to Ambient $PM_{2.5}$ Concentration in Lucknow City & District

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The Energy and Resources Institute

Darbari Seth Block, India Habitat Centre, Lodhi Road, New Delhi – 110 003, India

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Team Members

Principal Investigator – Dr. Anju Goel

Co – Principal Investigator – Dr. Prateek Sharma

Team Members - Dr. Sumit Sharma, Mr. Suresh Ramasubramaniyam Iyer, Dr. Arindam Datta, Mr. Nimish Singh, Md. Hafizur Rahman, Mr. Justin Jacob, Mr. Prabhat Sharma, Mr. Dheeraj Mehra, Ms. Seema Kundu, Ms. Shivani Sharma, Ms. Varsha Gupta, Mr. Mrinal Alexander Emmanuel, Mr. Ved Prakash Sharma

Secretarial Assistance – Ms. Valsa Charles

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Executive Summary

One of India's critical environmental complications today is air pollution, which is caused due to anthropogenic activities and overconsumption of fossil fuels. Air pollution has harmful health consequences. Growing urbanization and more significant economic activity contribute to higher levels of pollution and thus greater exposure. The problem is restricted to cities and has a widespread influence outside the city boundaries. People continue to depend on burning solid fuels such as wood, charcoal, coal, and dung in their homes for cooking and heating. Exposure to ambient $PM_{2.5}$ has increased a person's risk of contracting a disease such as lung cancer, stroke, heart disease, and chronic bronchitis. Air pollution is a health risk and a drag on development. By causing illness and premature death, air pollution reduces the quality of life. The Government of India and the state governments have recognized the adverse effect of air pollution and are keeping no stone unturned to control the situation.

This report has quantified the emissions of particulate matter (PM_{10} and $PM_{2.5}$) and gaseous pollutants (SO_x, NO_x, CO, NMVOC) from various sources of air pollution existing within Lucknow district boundaries. These emissions were then fed into a dispersion model to estimate the contribution of different sources in PM_{10} and $PM_{2.5}$ concentrations of Lucknow city. In total, 13 sectors have been inventoried based on fuel consumed in these sectors or the extent of activity being carried out. These sectors are industries, transport, road dust re suspension, agriculture residue burning, residential; refuse burning, brick kilns, diesel generator sets, aviation, construction, crematoria, landfills, and hotels and restaurants. The data for some sectors have been collected by conducting a primary survey, while UPPCB provided some sectorial data. While these emissions are from traditional sources, some are subject to considerable uncertainties, and the usual care must be taken in their interpretation.

Following are some of the key findings from the study –

- Emission inventory results for Lucknow city for 2019 reveal that in the case of particulate matter pollution, road dust re-suspension is the primary source of PM_{10} and $PM_{2.5}$. Construction activities contributed about 5% and 3% of PM_{10} and $PM_{2.5}$ emissions, respectively.
- In the case of gaseous pollutant emissions, industries account for about 58% of the total SO_2 emissions, followed by the transport sector with 21%, aviation sector with 13% and diesel generator sets with 5% in the city.
- NO_x is majorly emitted by the transport sector and accounts for 98% of the total emissions inside the city, followed by diesel generators sets which emit about 2% of the total emissions.
- In district inventory, road dust re-suspension accounts for 74% of PM_{10} emissions and 52% of the total $PM_{2.5}$ emissions. In the case of gaseous pollutants, brick kilns account for 64%, and the residential sector accounts for 14% of the total SO_2 emissions. The transport sector account for 98% NOX, 86% CO and 96% NMVOC's in the district.
- The yearly averaged ambient $PM_{2.5}$ concentration remains above the CPCB's air quality standard in the whole study domain.

- In the summer season, the overall $PM_{2.5}$ concentration is low in most parts of the study domain compared to the post-monsoon and winter seasons.
- The residential sector emerges as one of the major contributor in all the seasons, with a yearly average contribution of about 23% in $PM_{2.5}$ concentrations. In comparison, the maximum contribution of 27% is observed in the winter season.
- Road dust with 26% contribution emerges as the top contributor of the $PM_{2.5}$ concentration in Lucknow during summer season due to increase in wind speed coupled with prevailing dry conditions in the region causing re-suspension of dust particles in the atmosphere.
- The contribution in ambient $PM_{2.5}$ concentration is dominated by secondary particulates (including both secondary organic and inorganic particulates), which vary from 42% in monsoon to about 70% in post-monsoon seasons.
- The high contribution of primary particulates is observed in summer and monsoon seasons of 41% and 58%, respectively.
- In yearly averaged terms, about 19% contribution to ambient $PM_{2.5}$ concentration comes from sources falling within the city's boundaries and rest 81% from outside the city boundary.
- The maximum contribution of 11% in $PM_{2.5}$ concentration have been attributed to sources emitting within the political boundary of the state of UP during winter months, which can be attributed to calmer wind speed, resulting in a fall in contributions from distant sources.

With this source apportionment as a guiding path, we aim to update the existing clean air action plan for Lucknow district and recommend suitable interventions which can be achieved in short and long duration of time.

1. Background

Constituents of the atmosphere are changing as a consequence of continuous emissions due to human activities resulting into critical environmental issues like air pollution. Atmospheric concentration of pollutants are found to be much above its natural background concentration which has resulted in undesirable effects on humans and environment in last few decades. In India also, air pollution has now become an issue of serious concern with more than 70% of cities violating the prescribed standards of (particulate matter with aerodynamuc diameter less than 10μm) PM_{10} concentrations (NAAQS 2020). Consumption of fossil fuels, increasing transportation needs, traffic congestion, inefficient use of biomass as energy source and seasonal agricultural crop residues burning are primary sources of air pollution in the country. Increase in population coupled with rapid growth of industries and urbanization have acted as the primary drivers leading to severity of the issue. The levels of $PM_{2.5}$ and PM_{10} are found to be extremely higher than the WHO guidelines in allcities in India.

Lucknow is one of the non-attainment cities identified in the National Clean Air Program (NCAP) of India as the levels of particulate matter, especially during winters, violated the prescribed (National Ambient Air Quality Standards) NAAQS. In order to better understand the atmospheric chemistry, air quality, and its impact on human health, more accurate data of spatially and temporally distributed emissions is required. It is essential to estimate the impacts created by such the pollution sources, and hence apportionment of different sources towards prevailing pollution levels becomes essential. This is especially important for the policy makers to formulate effective emission control strategies and air quality management plans.

Emission inventory is an important tool for quantitatively expressing sources of pollution load in a defined area at a particular time. Furthermore, the estimation of shares of contributing source to ambient pollution concentrations at any receptor location is referred to as source apportionment, and is one of the most powerful technique to strengthen the process of air quality management planning. Emission of pollutants from sources and their effects on ambient pollutant concentrations can be related using dispersion modeling techniques.

TERI, in collaboration with Uttar Pradesh Pollution Control Board and Lucknow Municipal Corporation, has conducted this study on Source apportionment of particulate matter pollution in Lucknow city. This is supported by the Swiss Agency for Development and Cooperation (SDC) to assist the Government of India in accomplishing some of the important objectives of NCAP. This report provides information on prevailing PM_{10} and $PM_{2.5}$ levels and establishes sources of ambient PM10 and PM2.5 in Lucknow city using established scientific methodologies.

a) Study Region – Lucknow District

Lucknow is located at 26.8467°N, 80.9462°E, and is the capital city and administrative headquarters of the Indian state of Uttar Pradesh (Figure 1). The city is located in the Awadh region, known as India's granary. It is ranked twelfth-most populous urban agglomeration in India. Lucknow district covers an area of 2,528 square Kilometres (976 sq mi). It is surrounded on the eastern side by

Barabanki, on the western side by Unnao, on the southern side by Raebareli and on the northern side by Sitapur and Hardoi districts. Lucknow sits on the north-western shore of the Gomti river, which flows through the city. Some of the tributaries of this river are Kukrail, Loni, Beta etc. Sai river flows 5 from the south of the city and in the east enters district Raebareli. There are four tehsils in Lucknow districts; Bakshi ka Talab, Lucknow, Mahilabad, Mohanlalganj. The Lucknow Municipal Corporation area is part of the Lucknow tehsil (Figure 1).

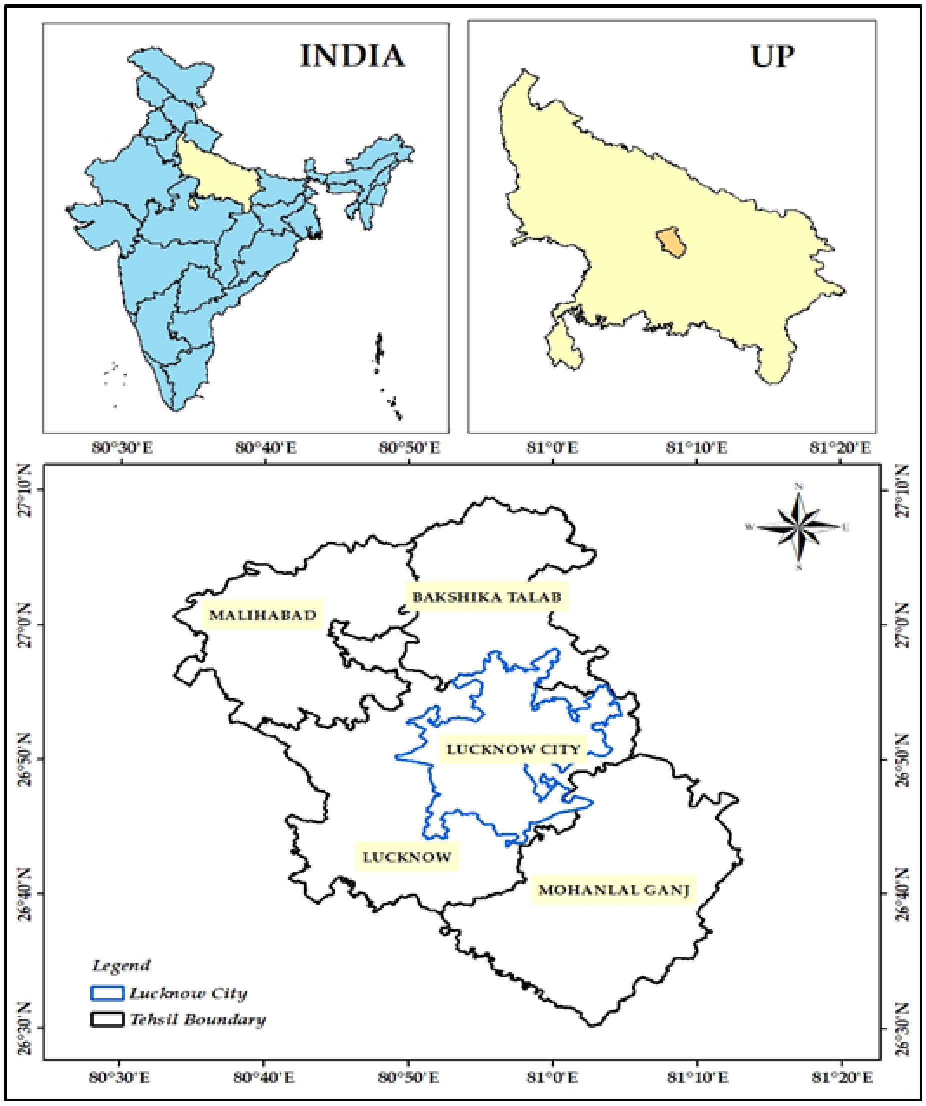


FIGURE 1: District map of Lucknow

b) Demographics

Lucknow district rank 5th in the state with a population of 3.7 million. The population of Lucknow city (Nagar Nigam) as per 2011 census is 2.8 million. The decal population growth rate in Lucknow city during 2001-11 is 28.81%.The average increase in population of the city from 1971 to 2011 is 3.22% per year (Figure 2). This has caused the expansion of city from 600 sq. km to 980 sq. km within a span of 10 years since 1999. According to census 2011, Lucknow has population density of about 8049 persons/Km^2. The city has 609 slums with 148117 households.

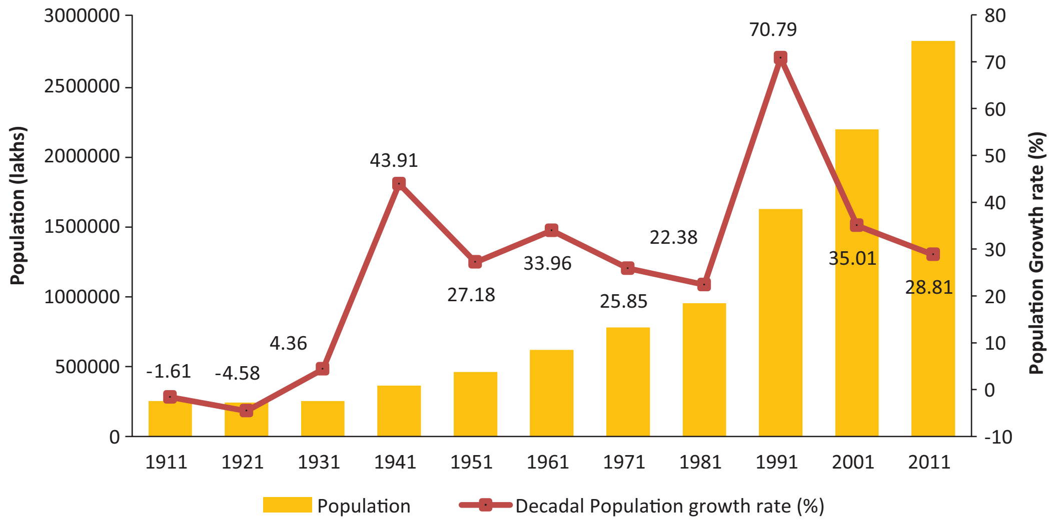


FIGURE 2: Population trend of Lucknow city form 1911–2011

c) Climate

Lucknow has an extreme tropical climate with very cold and dry winters from December to Mid-February and dry, hot summers from April to Mid-June. The rainy season is from mid-June to mid-September, when it gets an average rainfall of 1000 mm mostly from the south-west monsoon winds. During extreme winter the maximum temperature is around 25° Celsius and the minimum is 3 - 4° C. Summers are extremely hot with temperatures rising to the 40 to 45° Celsius range. The average wind speed in Lucknow is 2.6 m/s with a maximum wind speed of around 10 m/s. The average ambient temperature remains 25.3°C, varies from 6.2°C to 41.9°C. The average relative humidity remains around 68.6%, varies from 17.5% to 99.7%. In Lucknow district, predominantly wind blow from the WNW - about 24.75% of all wind directions.

d) Land use and land cover

Rawat A. *et al.*, 2020 reveal an increase in built-up areas in Lucknow city comprising human habitation developed for non-agricultural uses like building, transport, and communications since 1999. There was a significant decrease in agricultural land used for paddy, food, and vegetables. Large amounts of agricultural land have been converted into settlements and other urban development activities (Figure 3).

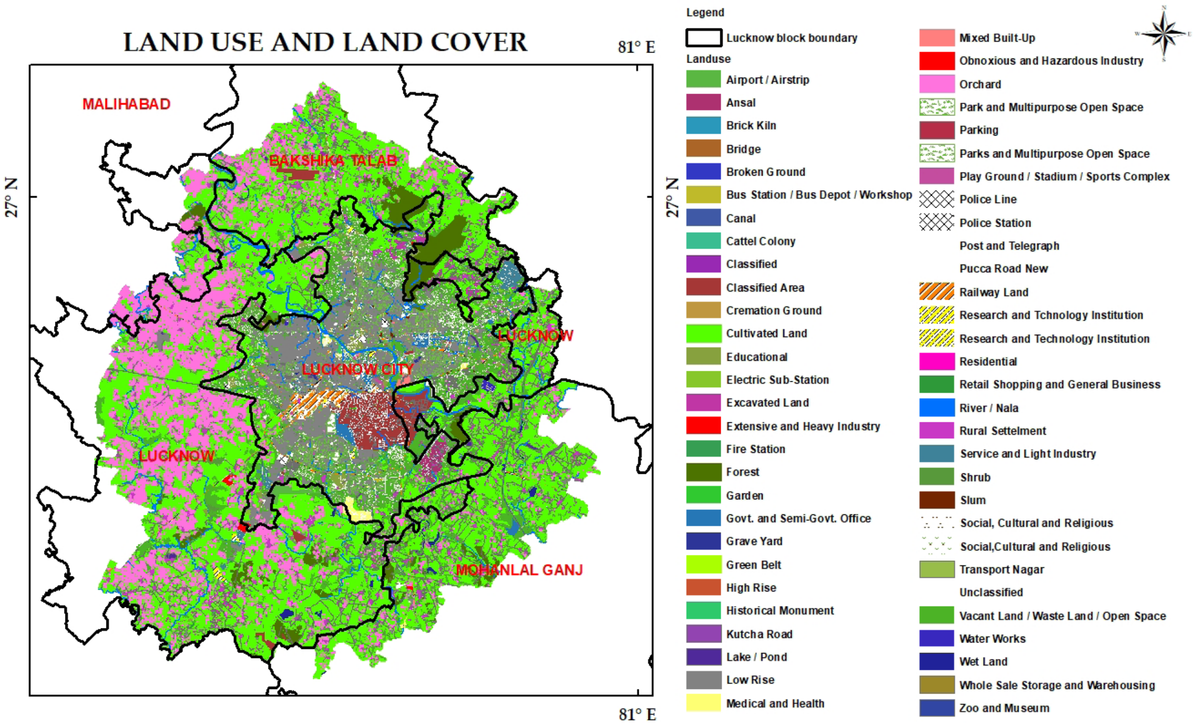


FIGURE 3: Land use land cover map of Lucknow city

Water distribution zones, including manufactured and natural water structures such as rivers/ streams, dams and lakes, have declined from 37 sq. km in 1999 to 12 sq. km in 2019, with a net decrease of 25 sq. km. The built-up area is substantially increased. On the other side, agriculture, and water body areas are diminishing.. At the same time, vacant land increased in first decade of the study period and declined in the next decade (Rawat A., et. al., 2020). Lucknow district reports a very low proportion of area under forest. The total area under forest (4.66%) is much less as compared to state average which is barely around 7%. The forest area is negligible in the district. The main crops grown in Lucknow are wheat, paddy, sugarcane, mustard, potatoes.

e) Vehicular population and road network

With city's expansion, road traffic has increased manifold around the peripheral areas. The road network of Lucknow city accounts for 3387 Km of road length, and road density is around 10.2 Km of road/Km^2 of land area. Figure 4 shows the increase in registered vehicles from 2001 till 2015 in Lucknow city. The city has seen a growth of about 8% in the vehicular population from 2004-2016. Moreover, the construction of small-scale industries, residential buildings, and commercial centers near highways is common practice in Lucknow due to easy connectivity. Lucknow has a well-connected system of roads and five national highways pass through the city. The National Highway (NH) NH24, NH28, NH24B, NH25, and NH56 connect Lucknow city to Bakshi ka Talab, Chinhat, Sisendi, Bijnaur, and Gosainganj respectively. Other than National Highways, major roads run through the district connecting towns. Road network of the Lucknow district is shown in the Figure 5. As per a study carried out by MSME- Development Institute in 2010, the length of railway network in Lucknow district is 188 kms, and the length of National Highways is 113 kms. The length of State Highways is 101 kms and major district highways conclude to 154kms length. Other district and rural roads comprise of about 2508 kms length.

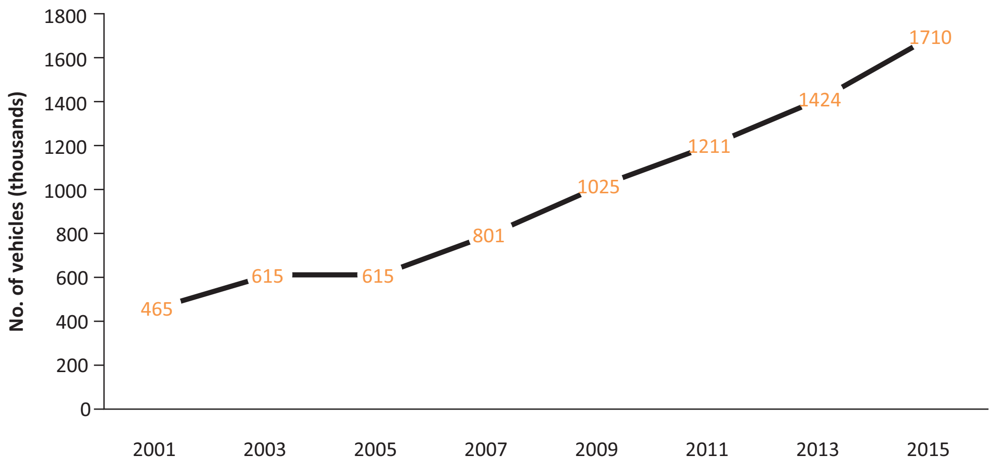


FIGURE 4: Annual number of registered vehicles during 2001 to 2015

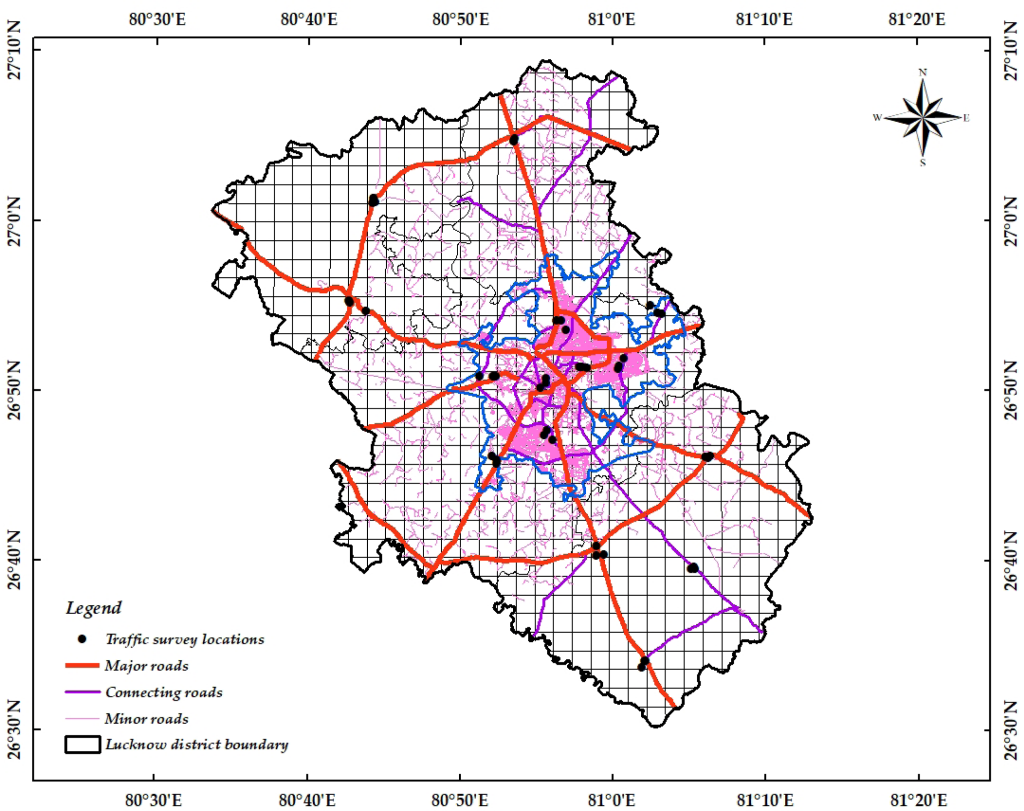


FIGURE 5: Road network map of Lucknow district

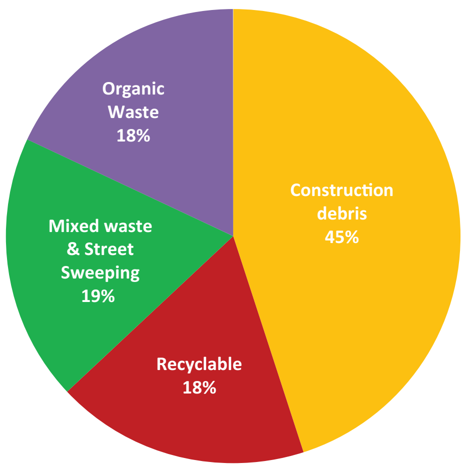
2. Economic Status of Lucknow

Industrial Establishment

Being the capital of India's highest populated state, Lucknow has always been centre of art, culture, heritage, and trade. Hence industrial development and growth have always been the utmost priority. Lucknow has been famous for small and medium scale industries. There are mainly four industrial clusters situated in Talkatora, Chinhat, Amousi, Sarojini Nagar, which acquire around 100 hectares of land accounting for 6% of the proposed land in the master plan. The main types of industries situated in Lucknow are agro based, cotton, woollen, jute, readymade garments, paper products, leather goods, and embroidery works.

Solid Waste Management

Lucknow Municipal Corporation governs the Municipal Solid Waste (MSW) management in the city. Lucknow city generates around 114.7 TPD (Archana et al., 2014). The average rate of per capita generation of MSW in Lucknow is 0.48 kg/capita/day. The constituents of solid waste consist of paper, leather, synthetic material, glass, metals, rubber, compostable or biodegradable, and inert materials, and Figure 6(a) shows the composition of waste produced in Lucknow. Composition of waste varies from place to place, depending on the sources. In Lucknow, solid waste management has improved as the collection efficiency and treatment has improved. Primary collection of waste is done through rickshaw trolleys, hand carts & other carrier vehicles, and the MSW collection efficiency of Lucknow is 89%. The overall process of waste collection, treatment, and dumping is shown in Figure 6(b).



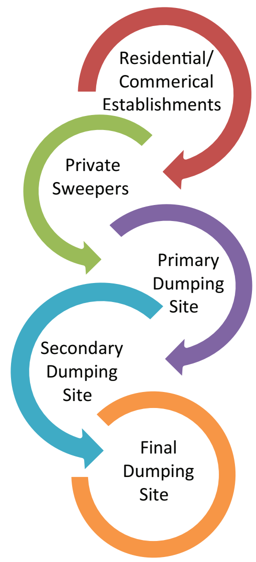


FIGURE 6 (a): Characterisation of Municipal solid Waste

FIGURE 6 (b): Distribution of Solid Waste and waste collection, dumping & treatment in Lucknow

Source: Archana et al., 2014

3. Ambient air quality of Lucknow City

Air quality monitoring stations have been set up at seven locations under National Air Quality Monitoring Programme (NAMP) viz. Aliganj, Chowk, Mahanagar, Hazratganj, Aminabad Talkatora, Ansal Technical campus, and Vikas Khand. One Continuous Ambient Air Quality Monitoring Stations (CAAQMS) is located at Gomti nagar. Out of eight monitoring stations, four are located in commercial, two in residential, and two in industrial locations. Figure 7 shows the annual average air quality trends in Lucknow city. The particulate matter concentration has consistently violated the national ambient air quality standards (NAAQS) from 2012-20, while NO_2 has violated the standard occasionally and SO_2 is well within the standard at all the locations. Figure 8 shows the PM_{10}, SO_2, NO_2 concentration during the year 2020 at 8 monitoring sites in the city.

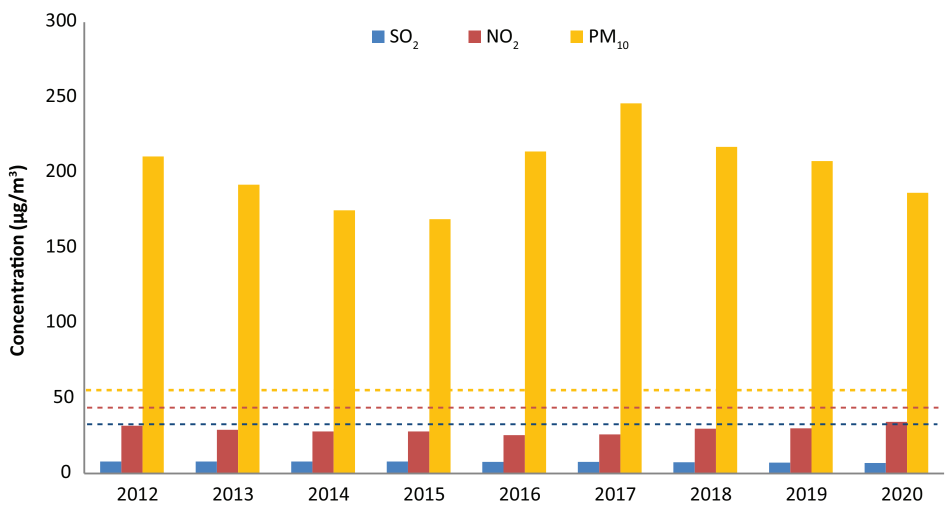


FIGURE 7: Annual average PM_{10}, SO_2, NO_2 concentrations in Lucknow city during 2012 to 2020

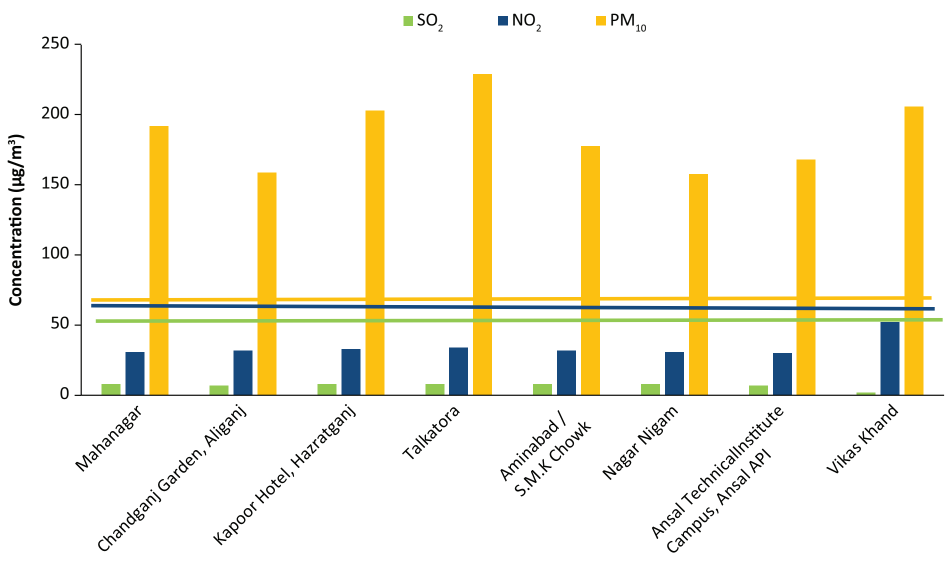


FIGURE 8: Annual average PM_{10}, SO_2 and NO_2 concentrations as recorded at different monitoring locations of Lucknow city in 2020

4. Emission Inventory

Developing an emission inventory arose from the need to improve air quality across the region and prevent adverse effects on the health of humans and ecosystems. A systematic emission inventory is significant for planning pollution control programs, particularly in a densely populated city like Lucknow, where environmental situations are of growing concern owing to their typical meteorological conditions. The pollution sources broadly classified as point, line, and area sources in a systematic way (Figure 9).

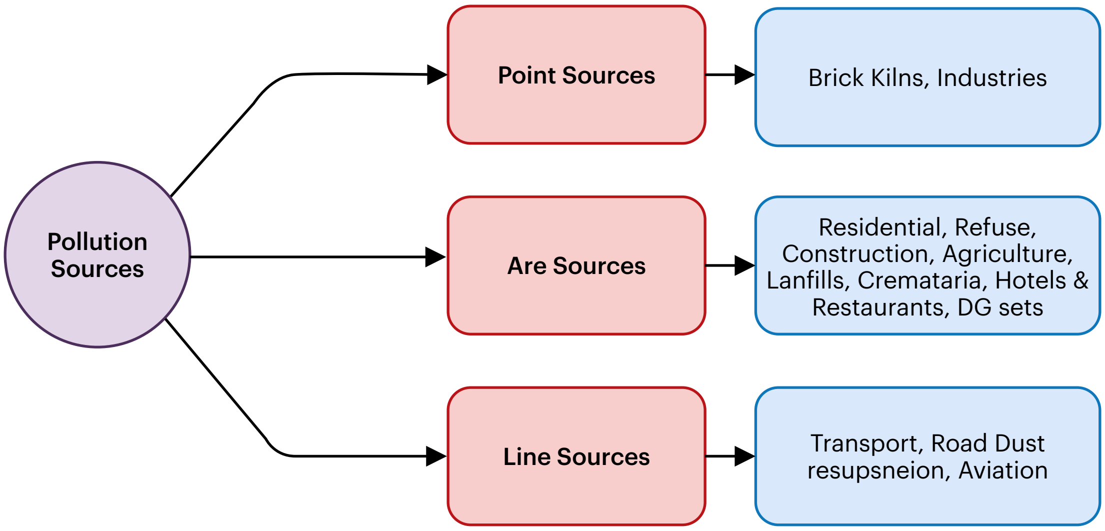


FIGURE 9: Types of Sources of Air Pollution

Quantification of air pollutants is done using basic formula for each source determined on the basis of activity data and emission factors and formula described in the Eq. 1. Activity data is described as the measure of the scale of activity producing the emissions and emission factors are the average emission rate of a given pollutant from a given source, relative to the intensity of a specific activity such as burning of fuel. The formula to deduce the emissions from a source are -

$$\textbf{\textit{Emissions = Activity Data × Emission Factor}} \qquad \textbf{\textit{(1)}}$$

Data was collected from different secondary sources to establish a baseline profile for the study area. The data for developing emission inventory of industries and brick kilns was provided by the UPPCB, while the required data sources for residential, transport, refuse burning, DG sets and construction activities was obtained from effective and rigorous literature review. The respective emission factors adopted from various international institutions were used to estimate the emissions are stated along the emission inventory of the sectors. The inventory is prepared at a resolution of 2X2 km² for the year 2019 (Figure 10). The number of study area grids in Lucknow city and district are 129 and 898 respectively (Figure 11).

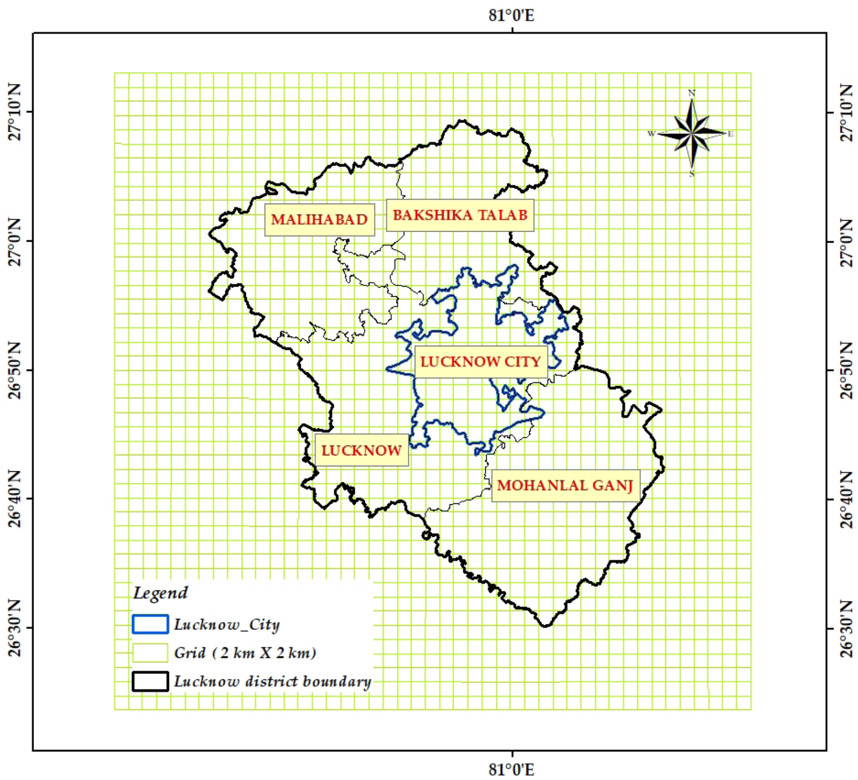


FIGURE 10: Study Domain

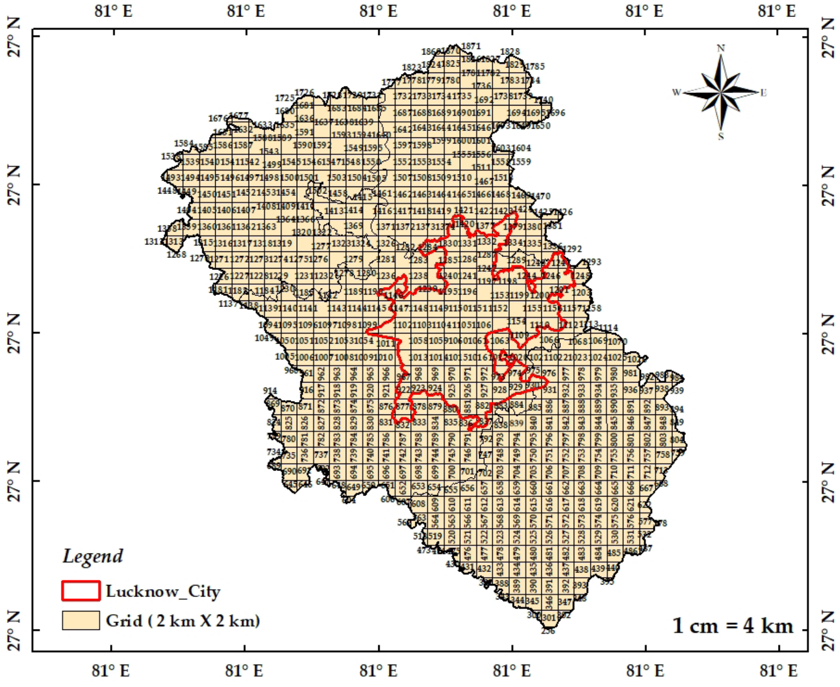


FIGURE 11: Gridded map of Lucknow District

a) Industry Sector

Activity data regarding industries and their locations was provided by UPPCB (Uttar Pradesh Pollution Control Board). Lucknow has a total of 75 industries out of which there are 29 red category industries (Large – 15, Medium - 5, Small - 9) and 46 small industries lie in orange category. The approach towards estimation of emissions from industrial sector is based on the quantity of fuel consumed in the industries, type of fuel used and the type and respective efficiency of the air pollution control device (APCD) installed. In most of the industries wet scrubber and dust collector are installed as an APCD. Major types of fuel used in industries are coal, biomass, HSD (High speed Diesel), LDO (Light Diesel Oil) & Natural gas. Type of fuel used and their quantities are shown in Table 1.

Table 1: Fuel type and quantity of fuel consumed in industrial sector in Lucknow district

Type of Fuel	Consumption
Biomass	21294 MT/yr
HSD	965100 Ltr /yr
Natural Gas	750 Nm3/yr
Coal	104107Mt/yr
LDO	679000 Ltr/yr

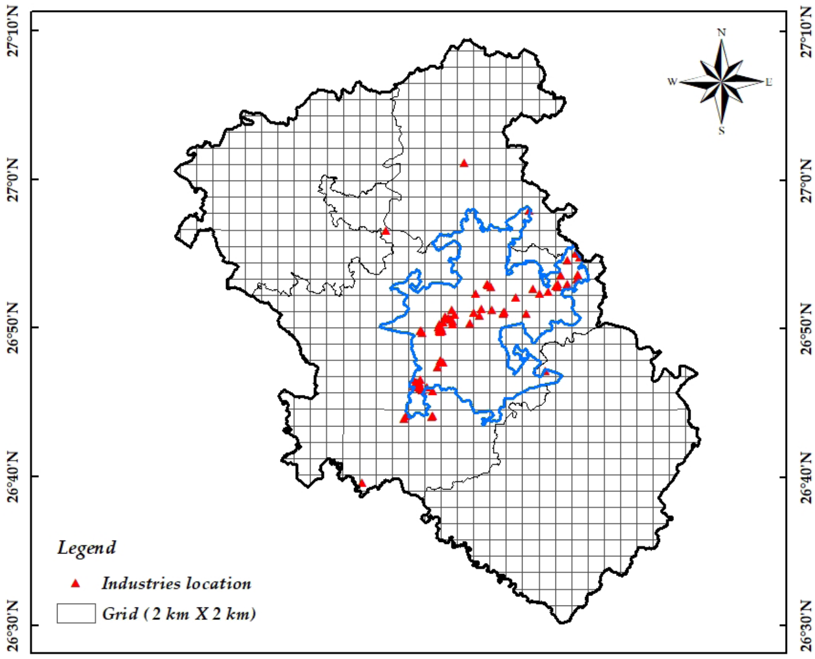


FIGURE 12: Industrial locations in Lucknow District

The emissions from industrial sector are estimated using the equation:

$$E_P = F_c * (1 - \eta_{ds}) * E_f \qquad (2)$$

Where, E_p is industrial emission of pollutant P, F_C is the fuel consumption, is efficiency of APCDs (Air Pollution Control Devices) installed in the industry, E_f is the emission factor. Emission factors used for estimating emissions is shown in Table 2. The estimated emissions from industries in Lucknow city are shown in Table 3. Figure 13 shows the spatial distribution of PM_{10} emission from industry sector.

Table 2: Emission factors for different fuels used in industrial sector

Fuel	PM_{10}	$PM_{2.5}$	SO_2	NO_2	CO	NMVOC
Wood (g/Kg)	17.3	15.7	0.2	1.3	126.3	26.5
HSD (g/L)	0.2	0.2	9.4	1.2	0.6	-
FO (g/L)	2.5	1.7	37.6	6.6	0.6	0.09
Natural Gas (kg/m^3)	$121.6*10^{-6}$		$9.6*10^{-6}$	$1.6*10^{-3}$	$1344*10^{-6}$	-
LPG (g/Kg)	2.1		0.4	1.8	0.2	88
Bagasse (g/Kg)	7.8	5.0	0.1	0.6	12.3	-
Coal (g/Kg)	187.6	65.6	9.7	4.5	0.3	-
Lignite (g/Kg)	187.6	65.6	9.7	4.5	0.3	-
LDO (g/Kg)	0.2	0.2	0.3	1.2	0.6	-

Source: CPCB, 2008, Source apportionment of six cities. Central Pollution Control Board, New Delhi

Table 3: Fuel wise emissions of different pollutants from industry sector in Lucknow district

Fuel	Emissions (Kg/day)					
	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	NMVOC
Biomass	238.4	224.7	5.5	38.4	3832.9	802.7
HSD	0.3	0.3	24.4	3.0	1.6	0.0
Coal	3265.8	1328.8	561.6	260.3	17.3	0.0
LDO	0.5	0.3	0.5	2.2	1.1	0.0
Total	**3505.0**	**1554.0**	**592.1**	**303.8**	**3852.9**	**802.7**

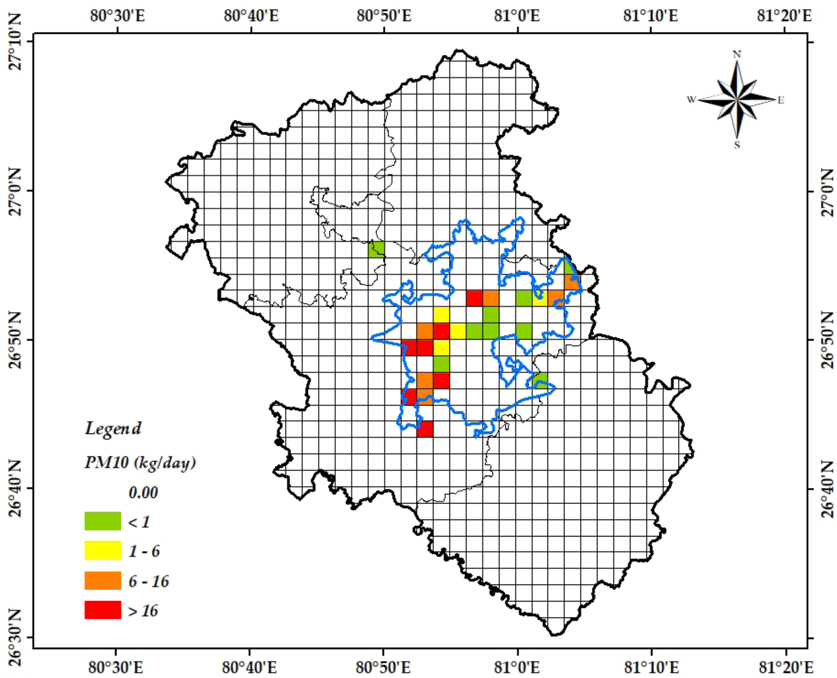


FIGURE 13: Spatial distribution of industrial PM_{10} emissions in Lucknow city and district

The spatial distribution of emissions from industrial sector to the grid locations were done by using the actual coordinates of industries. The distribution map clearly shows that the major industrial cluster is present in the city. Highest gridded emissions were observed more around the Lucknow municipal corporation area due to presence of large number of air polluting industries.

b) Brick Kilns

Brick is the major building block used in the construction of any infrastructure project. As reported by UPPCB, there are about 264 brick kilns located in Lucknow district out of which there are about 216 Fixed Chimney Bull's Trench Kiln (FCBTK's) and 48 Zig zag brick kilns. Locations of brick kilns in the study domain are shown in the Figure 14.

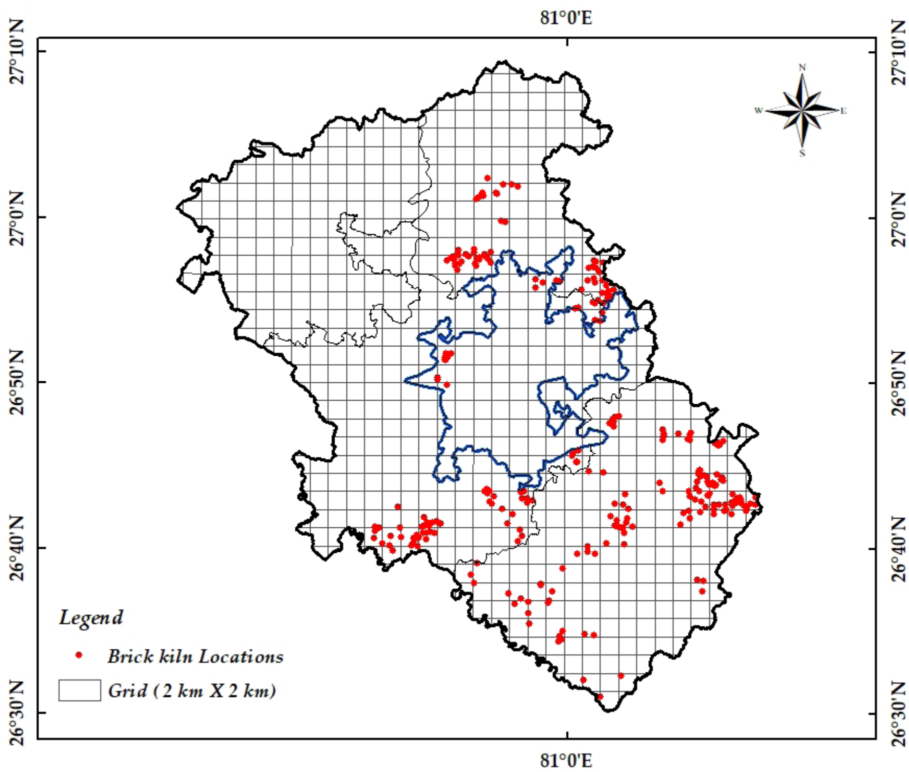


FIGURE 14: Locations of brick kilns in Lucknow district

During the manufacturing of bricks, coal is used in the furnace chamber as fuel. For estimation of emissions from brick kilns, production based approach was used. The approach is based on the total weight of bricks produced which is derived by considering average weight of a single fired brick (assumed as 3kgs) and a total production of 25000 bricks/day / kiln based on expert consultation and TERI's experience in the sector. Considering the number of working days of brick kilns as 180 days (February- July), total brick production is calculated. Emissions from brick kilns were calculated using equation 3.

$$E_p = TW_b * E_f \qquad (3)$$

Where, E_p is the emission of pollutant p, TW_b is cumulative weight of bricks produced annually from each kiln and E_f is the production based emission factors (Table 4). Total emissions for Brick kilns and the associated emission factors used for emission estimation in Lucknow district are summarized respectively in Table 4 and Figure 15 shows spatial distribution of PM_{10} emissions from brick kilns.

Table 4: Emission factors and Emissions of different pollutants from brick kilns

Pollutant	Emission factors (g/kg fired brick)		Emissions (Kg/day)		
	BTK	Zig-Zag	Zig-Zag	BTK	Total
PM_{10}	0.86	0.26	465.8	6931.5	7397.3
$PM_{2.5}$	0.18	0.13	219.2	1452.1	1671.2
SO_2	0.66	0.32	575.3	5315.1	5890.4
NO_X	0.00005**	0.00004**	0.1	0.4	0.5
CO	3.63	1.47	2602.7	29260.3	31863.0
NMVOC	0.1**	0.1**	164.4	794.5	958.9

Emission factors Sources: GAINS Asia, Rajaratnam et.al 2016, Maithel, S., et al. 2012*

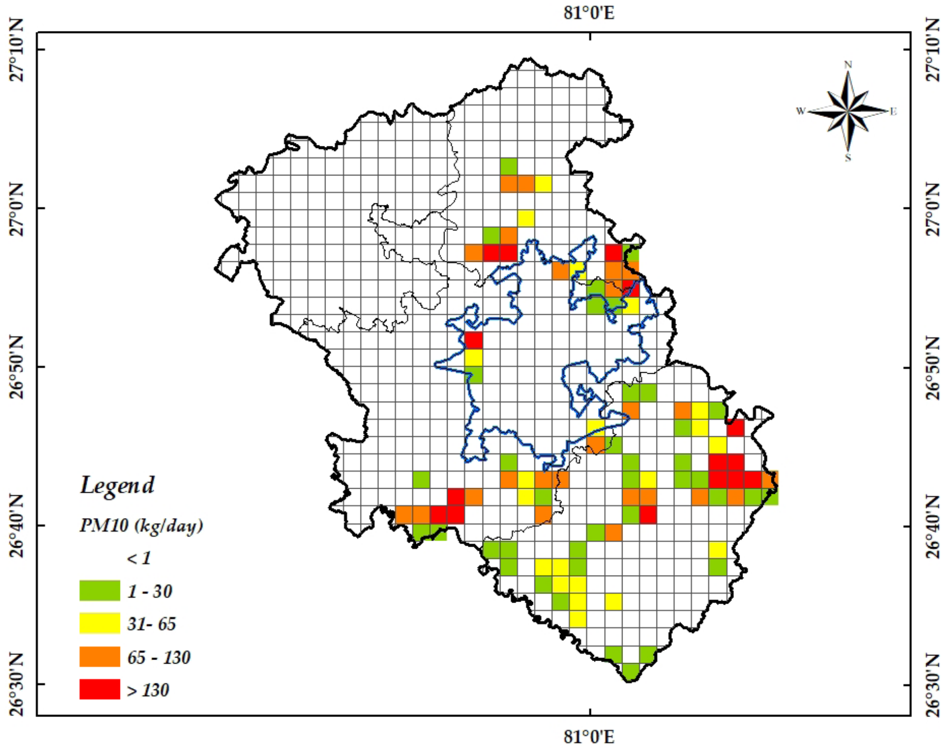


FIGURE 15: Spatial distribution of PM_{10} emissions (kg/day) from Brick kiln sector during the year, 2019

The emissions from brick kilns were distributed spatially to the grid locations, based on the kilns identified by mapping on high resolution images using Google Earth. Most of the identified kilns were in the city outskirts and the most polluted grids are in the south east direction of the district.

c) Transport sector

Vehicular pollution is a major issue in context of air quality problems faced by Indian cities. Road transport sector has grown at a very massive pace in recent times, mainly due to increasing population, economic growth, and technological and financial flexibilities. Diesel vehicles emit huge quantities of PM and NO_X whereas gasoline vehicles are known to emit other gaseous pollutants such as CO and VOCs. NO_X and VOC's released from transport sector become precursors for the secondary pollutants such as ground level ozone (O_3), and secondary particulate which are also known to cause several respiratory diseases. Transport sector emissions in Lucknow district has been estimated using the on road vehicle kilometres travelled approach (i.e. VKT) which is based on traffic count survey and parking lot surveys at different locations in Lucknow. Broad approach used to quantify tailpipe emission for the transport sector is,

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

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) and CNG penetration; VKT is the Vehicle Kilometer Traveled; EF is the emission factor of pollutant p and ε is the percentage of vehicle under an emission control norm and n is the total number of vehicle in category c. The EF of PM_{10}, $PM_{2.5}$, NO_X, SO_2, hydrocarbon and CO for this exercise are adopted from ARAI (2016). ARAI has carried out series of measurements to ascertain indigenous emission factors for different categories of vehicles in Indian conditions. Both VKT and ε are considered on the basis of primary survey results obtained from both traffic count survey and parking lot survey within the district, details of which are explained below.

Traffic count survey and parking lot survey

Traffic count survey has been conducted in Lucknow to analyse the behaviour of vehicular population plying on the roads. This was done by counting number of vehicles and their variation on different roads (Arterial, Sub-Arterial and Local) of the study domain. For conducting traffic count, total of 47 roads were selected in the entire district, comprising of 14 major (arterial) roads, 14 sub-arterial (connecting) roads, 14 minor (local) roads and 5 highways which interconnects Lucknow district with neighbourhood cities. These roads were chosen in different grids of the study domain representing different land use pattern - residential colonies (high, medium and low density), commercial areas, industrial hubs or mixed settlements etc.

In order to analyse the diversity in different types of vehicles on roads, manual method of traffic counting was used. A representative sample of traffic count in a period of time is collected from major, minor and connecting roads in the different land use regions in the Lucknow district. Figure 16 shows the road network density and traffic count locations in Lucknow city and district. The traffic count survey was carried out for 24-hours excluding weekends and holidays and the results of survey for different road locations is shown in Figure 17.

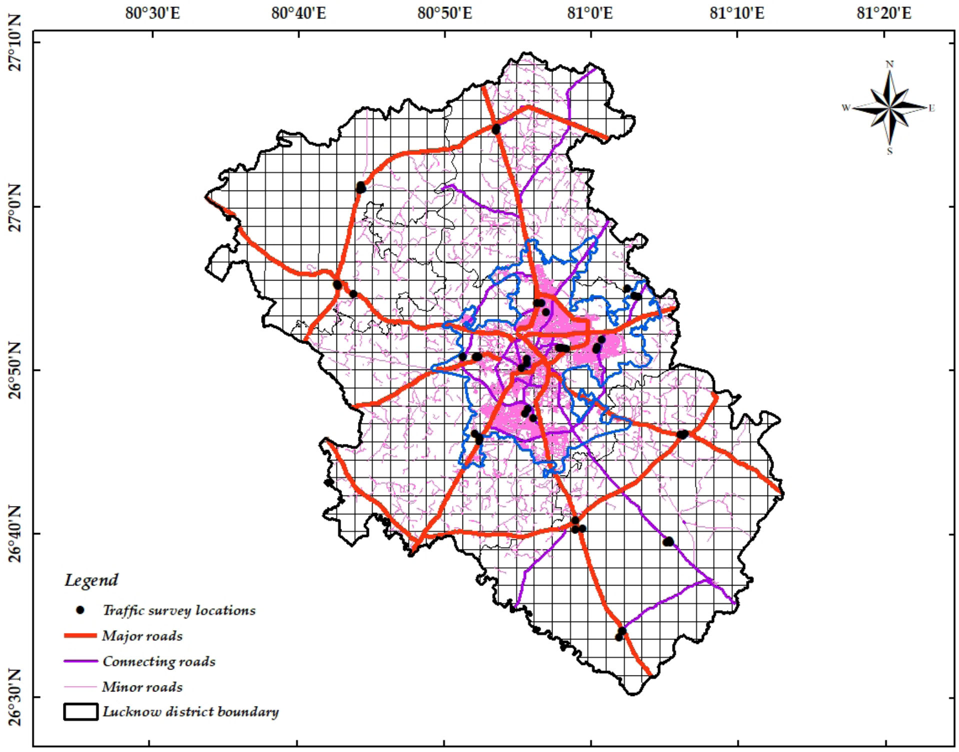


FIGURE 16: Traffic count survey locations in Lucknow District

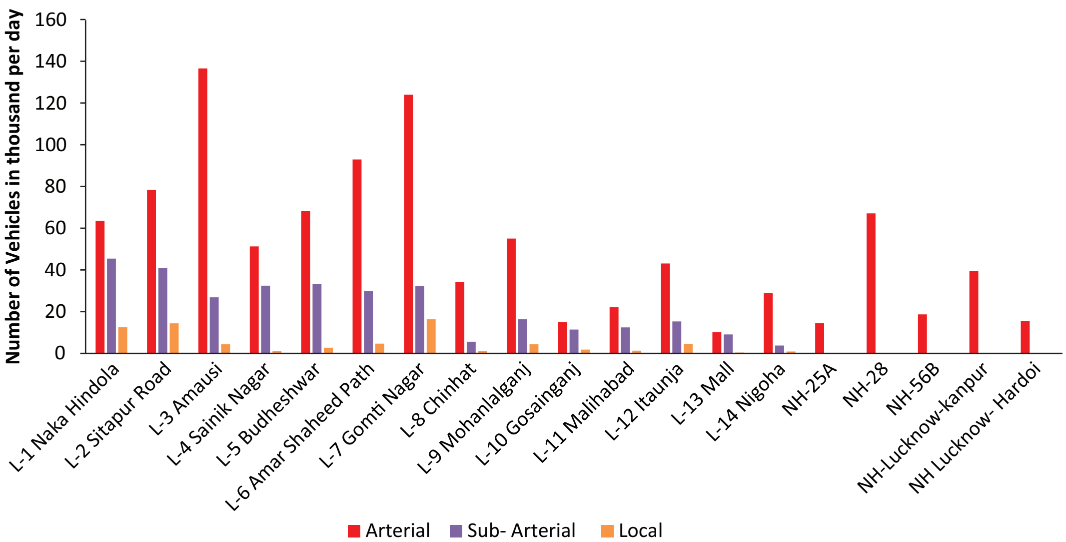


FIGURE 17: Traffic count statistics at arterial, sub-arterial and local roads in Lucknow District

Based on the traffic count results, it is derived that traffic count at arterial road is around 3 times that of sub-arterial road and about 14 times of that at local road. Parking lot surveys were also conducted to understand the type of existing fleet of vehicles and their distributions in the district by collecting information such as model, vintage, technology, fuel mix, average daily distance travelled occupancy and mileage. This information is required for application of appropriate emission factors to each vehicle category. In all, a sample size of about 9000 different categories of vehicles is taken to carry out the questionnaire based parking lot surveys in Lucknow district. The surveys are random for each category of vehicles without any bias to fuel, age, model or any other factor. It is observed that there is no difference in parking lot survey conducted within city and outside the city (district). Results of parking lot surveys in terms of vintage distribution are shown in Figure 18.

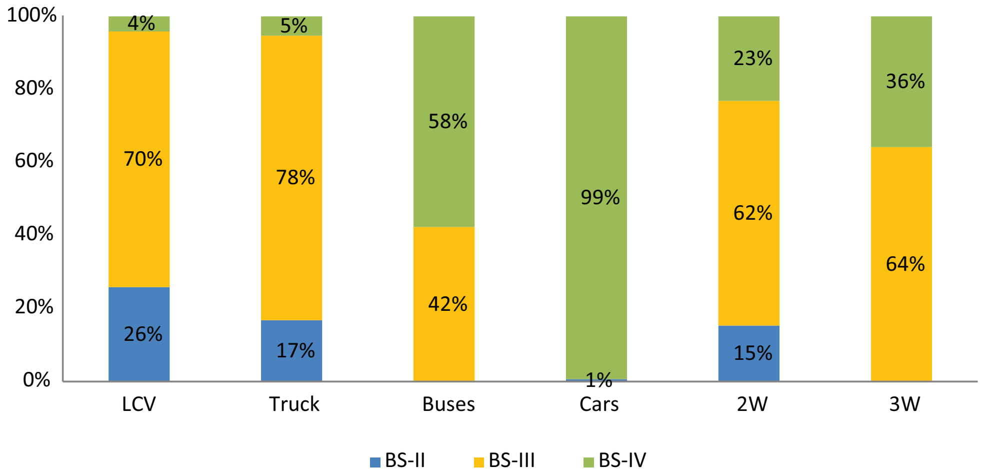


FIGURE 18: Vintage distribution for different categories of vehicles based on parking lot survey in Lucknow city

It can be clearly seen that in all categories, majority of vehicles follow BS III norms. However, within the city most vehicles especially cars are found to be following the BS-IV norms as these norms were ordered to be implemented in earlier in 2010 in 13 cities including Lucknow city.

Technological distributions of different vehicle categories are shown in the Figure 19. Petrol cars greater than 1400 cc accounted for 38% and 1000-1400 cc accounted for 56% of the total petrol cars surveyed. On the other hand, diesel cars less than 1600 cc accounted for 74% of all diesel cars surveyed in Lucknow district. 2-stroke and 4–stroke two wheelers (2W) accounted for 17% and 83% respectively. 2W greater than 100 cc accounted for 27%, greater than 200 cc accounted for 4% and 100-200 cc accounted for 69% of the total 2W surveyed.

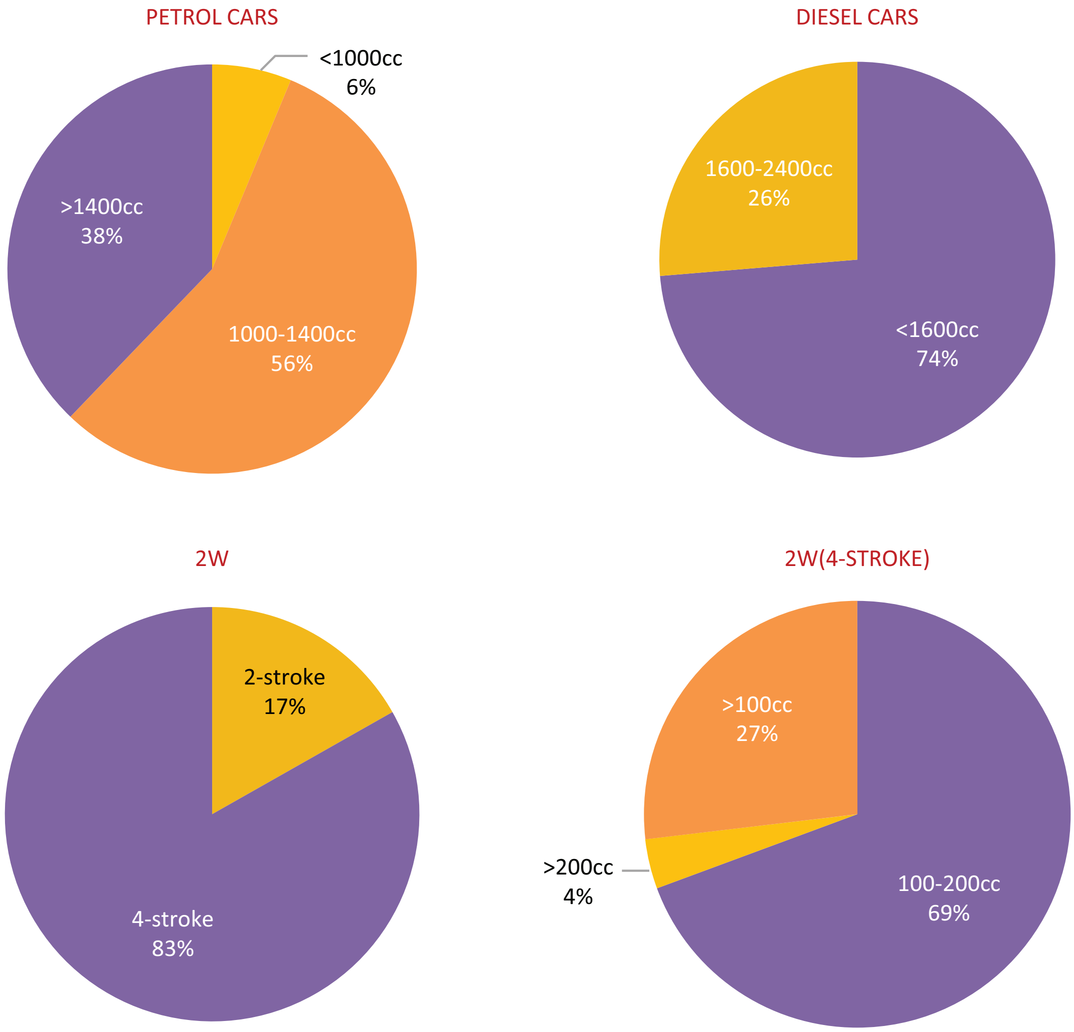


FIGURE 19: Technology wise distribution of cars in Lucknow based on parking lot survey

Tailpipe emission of different pollutants

Tailpipe emission for the road transport for various pollutants is estimated using Eq. 4

VKT were estimated by using the Eq. 5

VKT = Traffic count on road (in a given location) × road length (of the given grid) (5)

Road length in each of the grid was estimated using GIS. Emission factors play a vital role in computing the emissions from a typical vehicle category. In the current study, indigenous emission factors developed by ARAI, 2016 are used. Emissions from the transport sector are estimated following the methodology briefly illustrated in Table 5.

Table 5: Methodology for emission estimation

S. No	Protocol	Approach
1.	Assessment of the number of vehicles plying on roads	Traffic counts
2.	Analysing the distribution of vehicles based on vintages, technologies, and fuel types	Parking lot surveys
3.	Computation of vehicle kilometre travelled (VKT) for all sub-categories of vehicles	Traffic counts and road length
4.	Selection of emission factors for each sub-category	ARAI, 2011
5.	Emission Computation	VKT x Emission factor

The traffic count information of the 47 road locations is used to extrapolate emissions for the whole study domain (Figure 20). By estimating traffic intensities in the surveyed grids, traffic intensities were allocated to other grids based resemblance to the land use categories. Finally, VKTs in the remaining grids were estimated using allocated traffic intensities, and their respective road lengths. VKTs were finally multiplied with emission factors to estimate emissions for all the grids in the area.

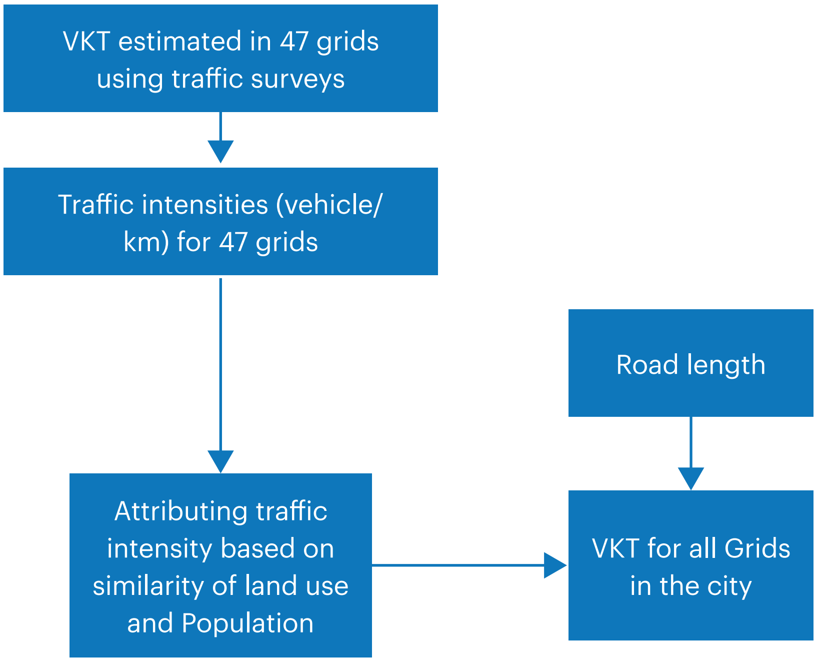


FIGURE 20: Method used for emission assessment of transport sector in the study area

Estimated emissions of different pollutants from the transport sector in Lucknow city are shown in the Table 6 and Figure 21. As seen in Figure 20, trucks are responsible for majority of the PM_{10} emissions and contributed 33% of the total PM_{10} emission load followed by 2Ws (26%), LCVs (21%) and 3Ws (5%). LCVs (28%) are the major contributor to NO_X emissions in the study domain, followed by 2Ws (21%) and Trucks (18%). Also, 97% of PM_{10} emissions from vehicles are $PM_{2.5}$ which account for 2.82 kt/year of $PM_{2.5}$ emissions from vehicular sector in the city of Lucknow. In total, 2.91 kt/year of PM_{10} and 42.64 kt/year of NO_X are released from transport sector in Lucknow city.

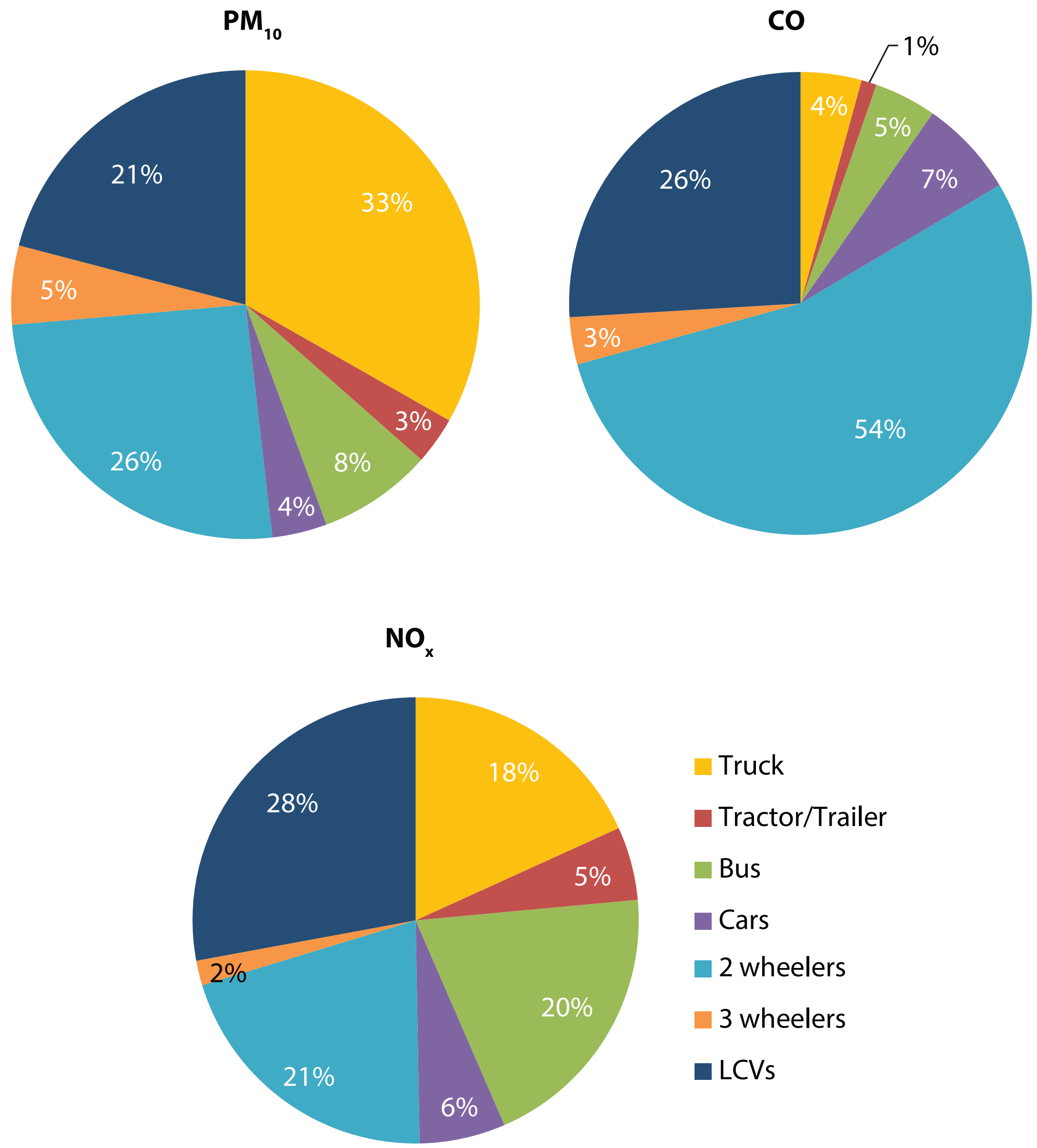


FIGURE 21: Distribution of PM_{10}, NO_X and CO emissions in Lucknow City

Table 6: Emission estimates in Kg/day of Lucknow City

Pollutants	Truck	Tractor/ Trailer	Bus	Cars	2W	3W	LCVs	Totals
PM_{10}	2640	260	636	329	2022	439	1663	7989
$PM_{2.5}$	2561	253	617	320	1962	426	1613	7752
SO_2	19	2	14	69	58	11	42	215
NO_X	21040	6147	23170	7526	24636	2080	32233	116832
CO	24611	6155	25166	39303	364356	19082	150097	628770
HC	28084	3687	22195	8106	174463	33120	22637	292292

District level assessments of transport sector

Estimated PM_{10} and NO_X emissions from the transport sector in Lucknow district are shown in the Figure 22. In total, 8.2 kt/year of PM_{10} and 113 kt/year of NO_X are released from transport sector in Lucknow district. Emission estimates for other pollutants are provided in the Table 7. Also, 97% of PM_{10} emissions from vehicles are $PM_{2.5}$ which account for 8.0kt/year of $PM_{2.5}$ emissions from vehicular sector in the Lucknow District (Table 7).

The emissions from transport sector are generally underestimated using emission factors which are developed at laboratory scale. Real world conditions are highly different from laboratory best test driving cycles. Ligterink (2017) shows the difference in emission factors of various types of vehicles in real world conditions in cities with prominence of congestion levels. In this study, we have accounted for real world conditions, and hence the final transport emissions have been estimated by multiplying with real world adjustment factors given by Ligterink (2017). Additionally, high emitters have also been accounted in estimation of emissions from transport sector. Grided distribution of particulate matter emissions from transport sector is shown in the Figure 23.

Table 7: Emission estimates in Kg/day of Lucknow District

Pollutant	Truck	Tractor/ Trailer	Bus	Cars	2W	3W	LCVs	Totals
PM_{10}	13242	787	1639	596	3090	627	2633	22614
$PM_{2.5}$	12845	763	1590	578	2998	608	2554	21936
SO_2	60	3	24	95	72	13	56	323
NO_X	156318	23111	73359	15011	41978	3292	68967	382036
CO	100335	14197	50901	63149	486704	24353	236628	976267
HC	170701	11142	57146	14260	265388	47273	42614	608524

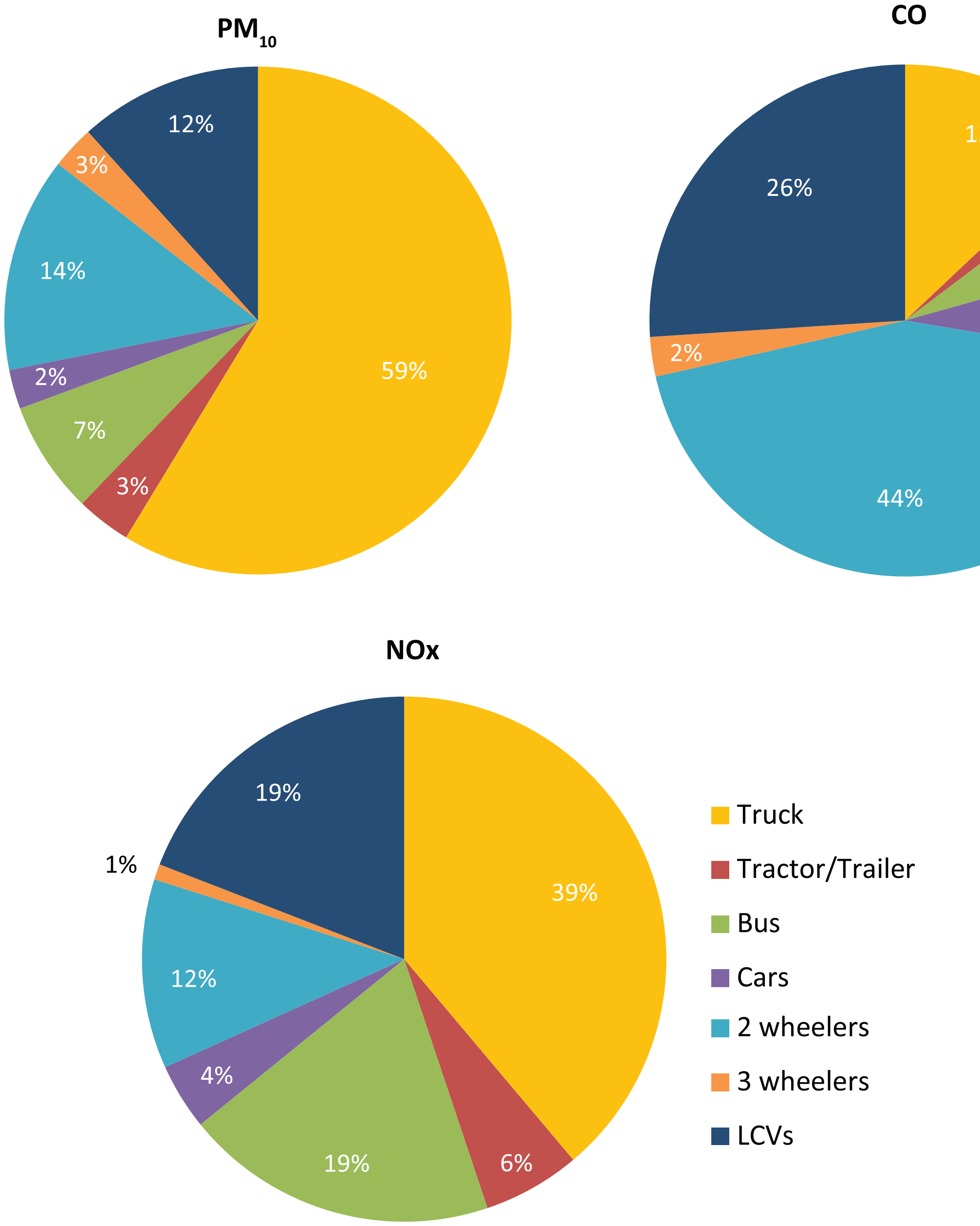


FIGURE 22: Distribution of PM, NO_x and CO emissions in Lucknow District

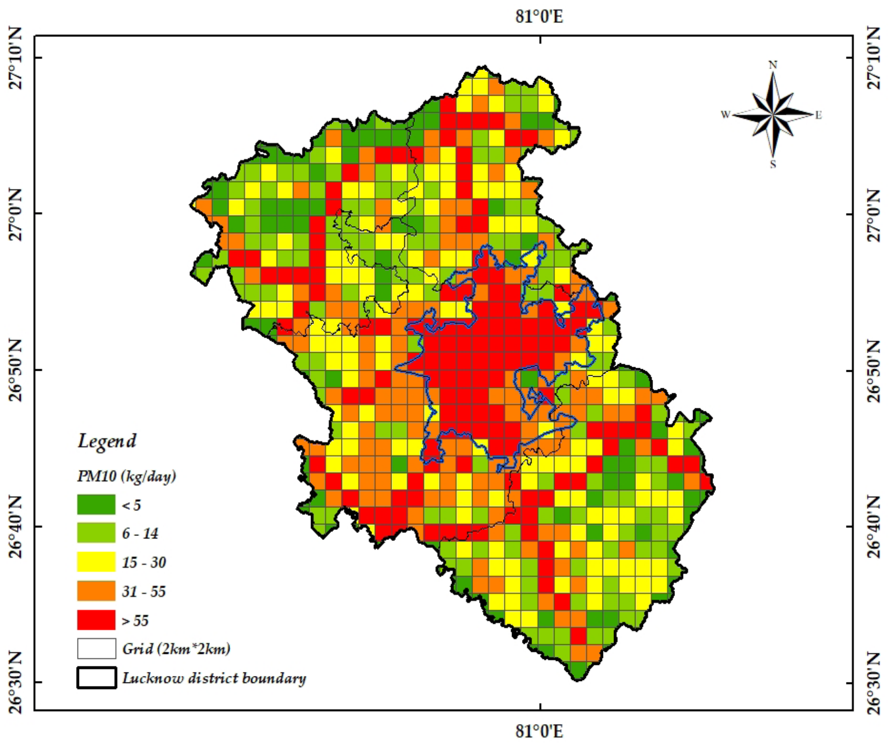


FIGURE 23: Spatial distribution of tail-pipe emissions from transport sector in the study domain

d) Road Dust Re-suspension

Though re-suspended dust is not resultant of vehicular tail-pipe emission, however, it is generated due to movement of vehicles on dusty roads. Emissions from road dust re-suspension due to movement of vehicles are calculated using USEPA (AP-42) method. These dust emissions due to movement of vehicles are found to be varying with the silt loading on the road surface and also with the average weight of the vehicles plying on the road. The term silt loading refers to the mass of the silt-size material (equal to or less than 75 μm in physical diameter) per unit area of the travel surface.

FIGURE 24: Road dust sampling in Lucknow district

Dust samples are collected from the selected roads in the study area as per USEPA AP42 method and are tested for their silt content and then converted into silt loading (g/m^2), which is used for estimation of emissions from the sector. A portable vacuum cleaner was used for the collection of samples from a designated area in the middle of the road (Figure 24). Filter bag of the vacuum cleaner was emptied and weighed before the sampling. Sampling material is collected only from the portion of the road over which the wheels and carriages travel routinely. Collected sample were weighed and stored in a clean and labelled container. After collecting the sample, sieve analysis was performed for 10 minutes by stacking the sieves of mesh no. 20, 28, 60, 100 and 200. The material collected underneath the mesh no. 200 is then collected and weighed as it represents the silt content of the sample.

Road dust samples were collected from the roads (covering arterial, sub arterial and minor roads) identified for carrying out the traffic count survey. Therefore a total of 47 road dust samples were collected from the study region and its silt contents are estimated. Particulate matter emissions from re-suspension of road dust due to movement of vehicles on paved roads are calculated using following equation 6 as provided in AP-42,

$$[E_p]_t = \sum VKT_r \times k \times w^{1.02} \times Mo^{0.91} \qquad (6)$$

where, [Ep]t is the fugitive emission of pollutant (p) from the transport sector; r is the type of road (arterial, sub-arterial and local); VKT is Vehicle Kilometer 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 (≤ 75 µm in physical diameter) loading in unit area. The [Ep]t is directly proportional to the silt loading on the road surface and average weight of the vehicles plying on the road. Based on k factor, 15% of the [Ep]t is considered as $PM_{2.5}$, while 62% is considered as PM_{10}.

For Lucknow district, average value of silt loading is found to be 2.36, 1.57 and 4.32 g m-2 on arterial, sub-arterial and local roads, respectively. The VKT for Lucknow district is estimated by using the method explained in the transport sector emission estimation. After estimating [Ep]t using the above equation, the effect of rainy days was considered to finalize the fugitive emission (f[Ep]t) from road dust re-suspension using the equation 7,

$$f\,[E_p]_t = [E_p]_t \times (1-D_p)/(4\times365) \qquad (7)$$

Where, Dp is the number of rainy days in a year. Total of 45 days are considered as rainy days in a year based on the meteorological conditions in Lucknow district. The estimated PM_{10} and $PM_{2.5}$ emissions from road dust re-suspension in Lucknow city are 116733 and 28242 kg/day respectively. The estimated PM_{10} and $PM_{2.5}$ emissions from road dust re-suspension in Lucknow district are 165768 and 40105 kg/day respectively. Gridded distribution of road dust emission is shown in the Figure 25.

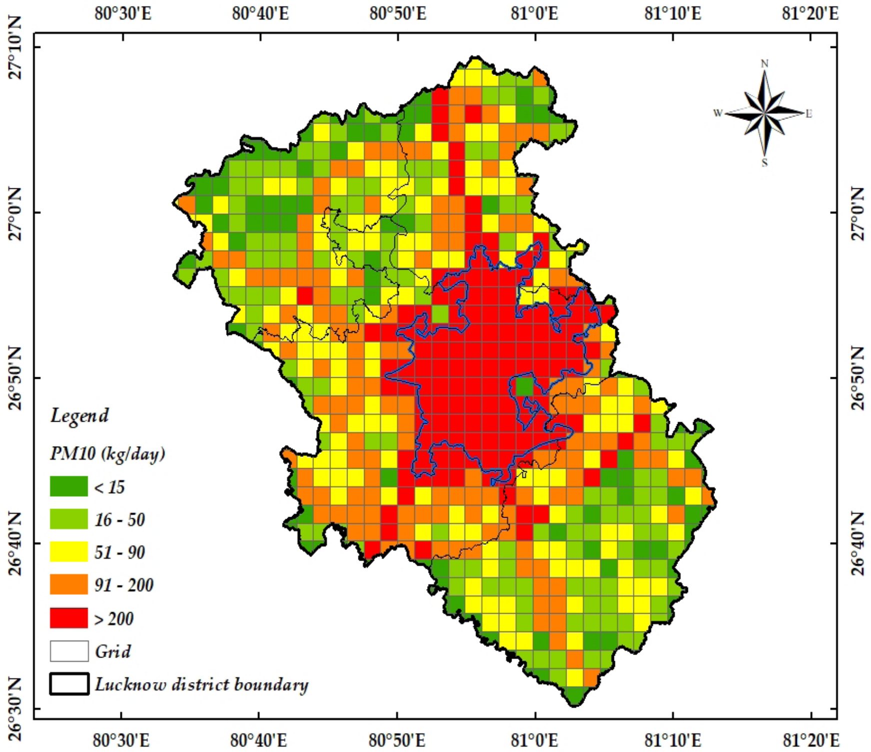


FIGURE 25: Spatial variations of PM10 emissions from the Road dust re-suspension

e) Refuse Burning

Emissions of different air pollutants from the burning of refuse materials are estimated by using the Eq. 8:

$$[E_p]_R = \sum_{a=1} Wba \times EF_{(f,p)} \quad (8)$$

Where, Epol is the emission of a particular pollutant from the burning of the refuse material, Wba is the quantity of refuse material burnt in Rural (a=1) and Urban (a=2) areas of a particular block in the district, EF is the emission factor of the particular pollutant (pol) from the burning of the refuse material.

$$Wb_a = \{P_a \times C\omega \times (1 - \phi)\} \times Bf \quad (9)$$

Where, Pa is the population in Rural (a=1) and Urban (a=2) areas of a particular block in the district, Cω is the per capita waste generation, ϕ is the waste collection efficiency and Bf is the burning faction of refuse material. Block level population of Lucknow district during 2019 is estimated following the population growth equation based on the population of 2011 and block level population growth rate in rural and urban areas of the district (India Census, 2011).

$$Pop_{2019} = Pop_{2011} [1+R\%]^{t} \qquad (10)$$

Where, is estimated population, is the population during 2011, district specific annual population growth rate (either in rural or urban areas) and t is the time period (year) between 2011 and 2019. The Pop_{2019} was estimated at rural and urban level in each tehsil of Lucknow district.

A primary survey was conducted at tehsil level in Lucknow district to collect daily household level waste generation information. The survey was conducted at 95% CI with 2% to 3% ME and 50% of population proportion. The calculated sample size was distributed among rural and urban areas based on the household ratio in each area of each tehsil. Ten villages in the rural areas of each tehsil were selected randomly and calculated survey household numbers were distributed according to total household number (as per India Census, 2011) in the selected village. Similarly, in the Lucknow Municipal Corporation area, the calculated survey households (N = 4853) were distributed in ten wards which were randomly selected at different parts of the city. In Bakshi ka Talab tehsil 715 households were surveyed at rural areas and 839 households were surveyed at urban areas of the block. 1357 households were surveyed at rural areas of Lucknow tehisil. 1049 rural and 226 urban households were surveyed in Mahihabad tehsil,. In Mohanlalganj tehsil, 552 rural and 413 urban households were surveyed.

During the course of survey, a set of questions were designed. including quantity of waste generated from household per day, availability of waste collection facility , type of available waste disposal system (door to door collection, community bins or on the roadside), frequency of waste collection facility etc. Information pertaining to waste burning incident and frequency (once a week, twice a week etc) of burning incident taking place in surrounding area of the surveyed household were also collected during the primary survey. Waste collection efficiency in a particular block was calculated based on the number of households have door to door collection facility and number of households disposing off their waste in community bins out of surveyed households. Similarly, the burning fraction of waste material was calculated based on the number of households witnessed waste burning incident in a particular tehsil/ward. The households those who disposed of their waste on the roadside were assumed to be completely burned. On the other hand, the households those having the collection facility but have witnessed the waste burning incident was also taken into account for calculation of burning fraction. Sampling marginal error in rural area is 26% at 95% CI, sample marginal error in Towns is 18% at 95% CI and sample ME at Lucknow Mucipal Corporation area was 8.6% at 95% CI.

The emission factor of various pollutants considered in present study is illustrated in Table 8.

Table 8: Emission factor for different pollutants from burning of refuse materials

Emission Factor (g/Kg)	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	VOC
	11.9	9.8	0.5	3.74	38	15.5

Source: Pappu et al. (2007)

Collection efficiency in a particular block

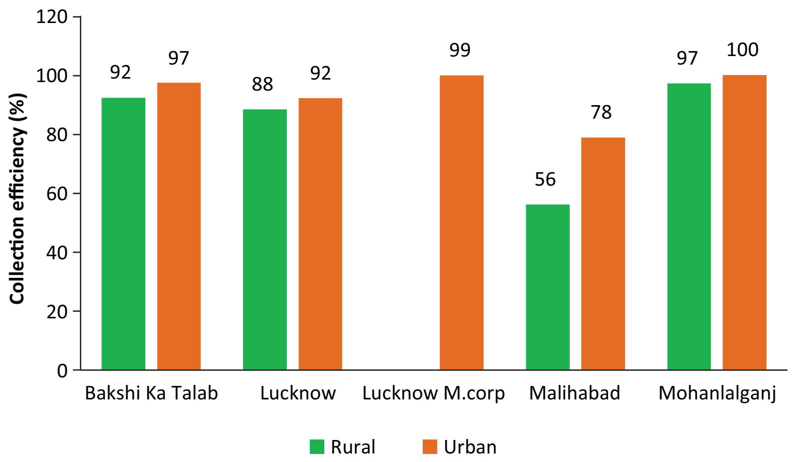


FIGURE 26: Collection efficiency of refuse material in a particular block of Lucknow district during 2019

Calculated Burning fraction in a particular block

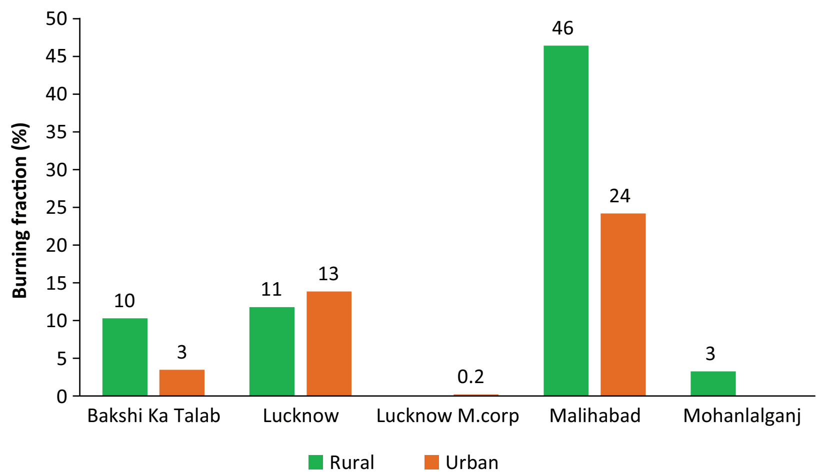


FIGURE 27: Tehsil wise burning fraction of refuse material in Lucknow district during 2019

Table 9: Emissions (Kg/day) of different pollutants from burning of refuse materials in Lucknow district during 2019

Block	Type	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	NMVOC
Bakshi ka Talab	Rural	16.4	13.7	0.0	5.5	49.3	19.2
Bakshi ka Talab	Urban	0.0	0.0	0.0	0.0	0.0	0.0
Lucknow	Rural	38.4	30.1	2.7	11.0	117.8	49.3
Lucknow	Urban	2.7	2.7	0.0	0.0	8.2	2.7
Lucknow M. Corp	Urban	0.0	0.0	0.0	0.0	0.0	0.0
Malihabad	Rural	402.7	331.5	16.4	126.0	1287.7	526.0
Malihabad	Urban	5.5	5.5	0.0	2.7	16.4	8.2
Mohanlalganj	Rural	2.7	2.7	0.0	0.0	8.2	2.7
Mohanlalganj	Urban	0.0	0.0	0.0	0.0	0.0	0.0
Total		**468.5**	**386.3**	**19.2**	**145.2**	**1487.7**	**608.2**

Table 10: Emissions (Kg/day) from refuse sector from rural and urban areas of Lucknow district

Type	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	NMVOC
Rural	460.3	378.1	19.2	142.5	1463.0	597.3
Urban	8.2	8.2	0.0	2.7	24.7	11.0

Spatially distributed PM_{10} emission due to burning of refuse materials from different blocks of Lucknow district is represented in Figure 28. The PM_{10} emission was estimated based on population of particular block. Highest PM_{10} emission was observed from Lucknow Municipal Corporation area due to presence of larger population and high per capita waste generation in this region. Also, the PM_{10} emission in the remaining blocks remained higher due to low waste collection efficiency and higher burning fraction of uncollected waste.

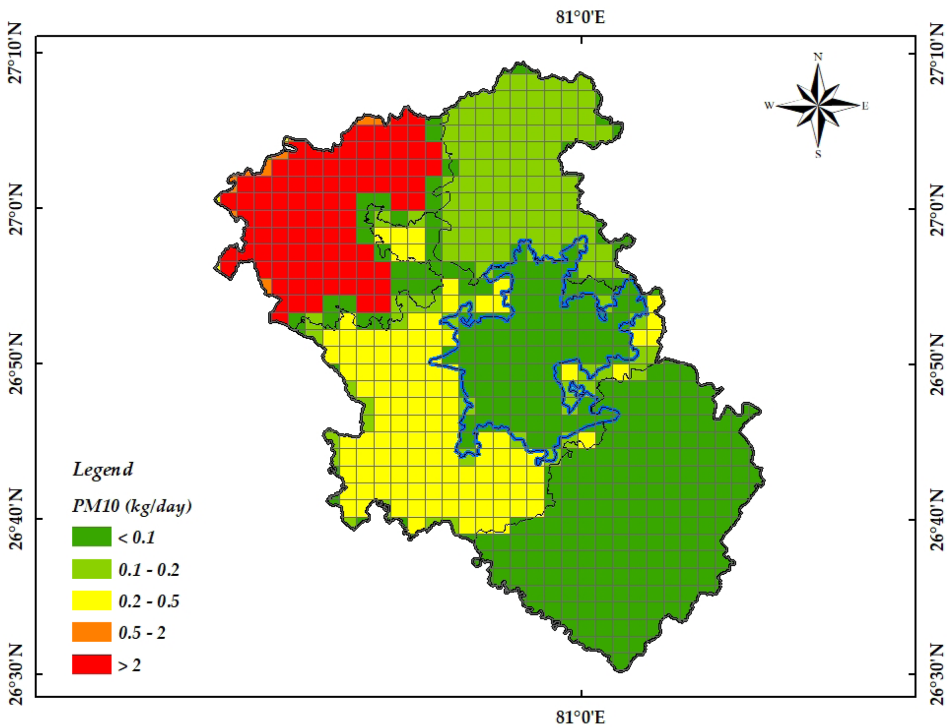


FIGURE 28: Spatial distribution of PM_{10} emissions from Refuse sector

f) Residential Sector

The basic equation employed for emission estimation from the residential sector is,

$$[E_p]R = \sum_{a=1}^{L} \sum_{f=1}^{6} Pop_{(a,f)} \times C_{(a,f)} \times EF_{(f,p)} \qquad (11)$$

where, $[E_p]_R$ is the emission of a particular pollutant (p) from the residential sector, $Pop_{(a,f)}$ is the population of Rural (a=1) and Urban (a=2) areas at block level of Lucknow district using a particular type of fuel (f), $C_{(a,f)}$ = Block level per capita consumption of a particular fuel, $EF_{(f,p)}$ = Emission factor of the particular pollutant (p) of the particular fuel type (f).

Thesil level population of Lucknow district during 2019 is estimated by using the Eq. 10.

A primary survey was conducted to gather specific information related to household cooking activities at tehsil level in Lucknow district. A defined set of survey questionnaires was prepared to gather specific information related to cooking activities in the households. The collected information includes household size, type of fuel used for cooking, monthly consumption of cooking fuel etc. Also, information pertaining to household electrification, daily/monthly power cut etc. was collected during the survey.

The survey was conducted at 95% CI with 2% to 3% ME and 50% of population proportion. The calculated sample size was distributed among rural and urban areas based on the household ratio in each area of each tehsil. Ten villages in the rural areas of each tehsil were selected randomly and calculated survey household numbers were distributed according to total household number (as per India Census, 2011) in the selected village. Similarly, in the Lucknow Municipal Corporation area, the calculated survey households (N = 4853) were distributed in ten wards which were randomly selected at different parts of the city. In Bakshi ka Talab tehsil 715 households were surveyed at rural areas and 839 households were surveyed at urban areas of the block. 1357 households were surveyed at rural areas of Lucknow tehisil. 1049 rural and 226 urban households were surveyed in Mahihabad tehsil. In Mohanlalganj tehsil, 552 rural and 413 urban households were surveyed.

Six major fuels those are used in the residential households for cooking and lighting purposes were included in the emission inventory preparation – a) fuel wood, b) dung cake, c) crop residue, d) coal, e) kerosene and f) LPG. Fuel specific emission factors of different pollutants ($EF_{(f,p)}$) were taken from Datta and Sharma (2014) and Pandey et al. (2014) (Table 11).

Table 11: 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
Fuel wood	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	2.9*

** Pandey et al. (2014); others were adopted from Datta and Sharma (2014)*
NA: Not available

Table 12: Consumption of different fuels (Kt/yr) in Rural and Urban areas of Lucknow district

District	FW	CR	CDC	COAL	LPG	KER
Rural	335.7	9.9	10.8	8.2	0.2	5.8
Urban	59.1	0.5	1.4	0.0	0.5	0.4
Total	**394.8**	**10.5**	**12.3**	**8.2**	**0.7**	**6.2**

Household consumption of different fuels in Lucknow district revealed that fuel wood, crop residue, cow dung cake and kerosene are the major fuel types being consumed in the rural areas. Fuelwood used for cooking is highly consumed in rural areas (335.7 Kt) and urban area (59.1 Kt) of the district during 2019. However, the estimated LPG consumption is higher in urban area with about 71% (0.5 Kt) consumption as compared to 29% (0.2 Kt) consumption in rural areas of the district during 2019.

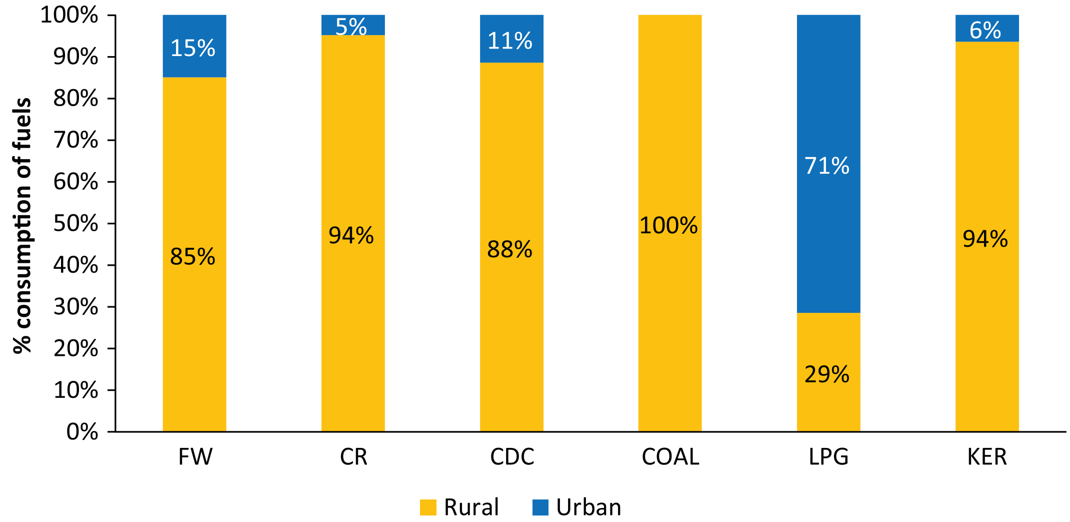
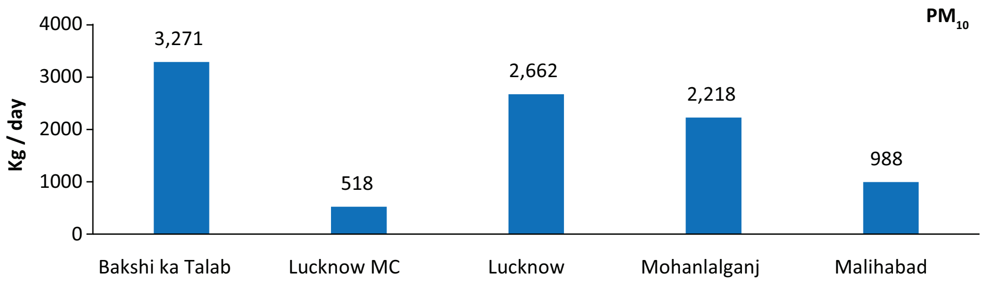


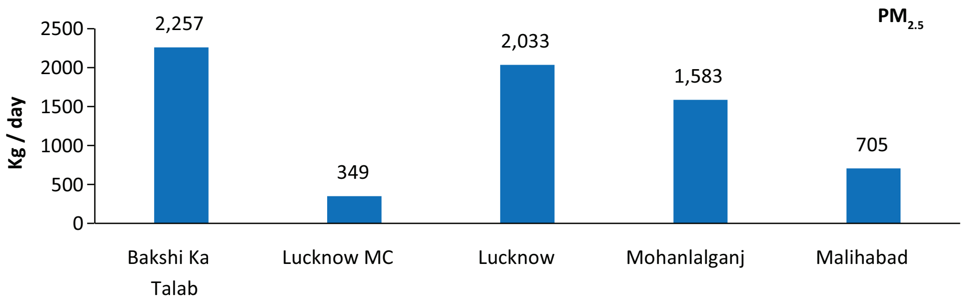
FIGURE 29: Share of different fuel consumption in urban and rural areas of Lucknow district

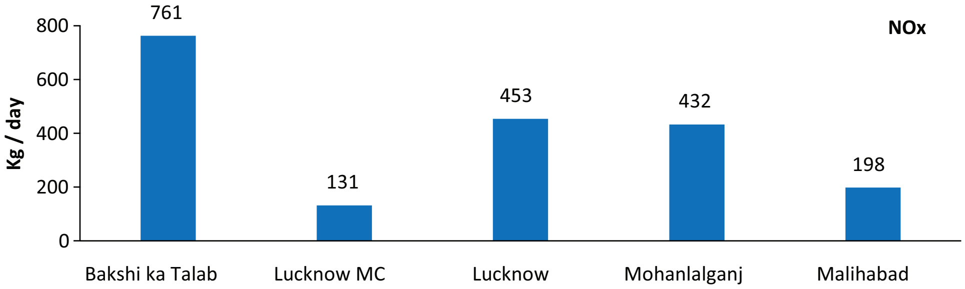
Emission inventory of the residential sector

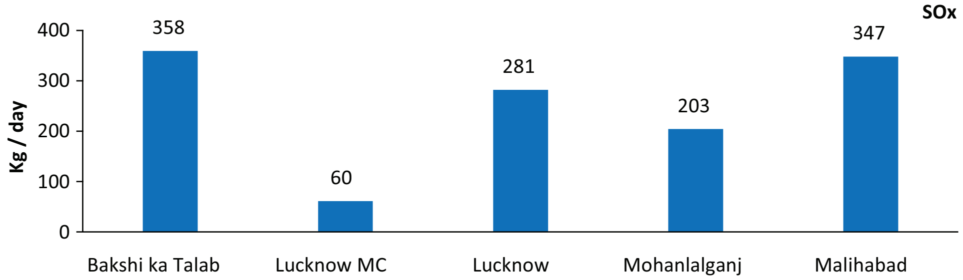
The activity data of different fuels along with the fuel specific emission factors of different pollutants ($EF_{(f,p)}$) (Table 11) is used to calculate the emission of different pollutants from the use of different fuel types in rural and urban area of Lucknow district.

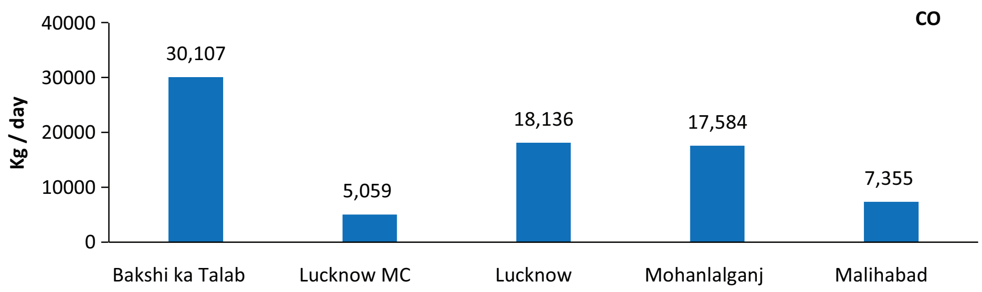
The estimated pollutant specific emission revealed higher PM_{10} (3271 Kg/day) and $PM_{2.5}$ (2257 Kg/day) emission in Bakshi ka Talab compared to other tehsils of the Lucknow district. In terms of gaseous pollutants i.e. SO_x, NO_x, CO and NMVOC the emission at Bakshi ka Talab were relatively higher compared to other tehsil of the Lucknow district. Higher emission of particulate and gaseous pollutants from Bakshi ka Talab tehsil could be attributed to higher fuelwood consumption (390462 Kg/day) compared to other tehsils. The emission of various pollutants remained relatively less at Lucknow Municipal Corporation area due to lower consumption of non-efficient fuels. The higher SO_x emission was observed from Bakshi Ka Talab and Malihabad block due to higher coal consumption in these regions. Similarly, higher NO_x, CO and NMVOC emission was also observed from residential households of Bakshi ka Talab block compared to other blocks. On the contrary, least particulate and gaseous pollutant emission was observed from Mahilabad block and Lucknow Municipal Corporation area. Lesser air pollutant emission from these regions could be attributed lower consumption of biomass fuels or higher LPG consumption for cooking activity.


PM10
Kg / day
4000
3000
2000
1000
0
3,271
518
2,662
2,218
988
Bakshi ka Talab
Lucknow MC
Lucknow
Mohanlalganj
Malihabad


PM2.5
Kg / day
2500
2000
1500
1000
500
0
2,257
349
2,033
1,583
705
Bakshi Ka Talab
Lucknow MC
Lucknow
Mohanlalganj
Malihabad


NOx
Kg / day
800
600
400
200
0
761
131
453
432
198
Bakshi ka Talab
Lucknow MC
Lucknow
Mohanlalganj
Malihabad


SOx
Kg / day
400
300
200
100
0
358
60
281
203
347
Bakshi ka Talab
Lucknow MC
Lucknow
Mohanlalganj
Malihabad



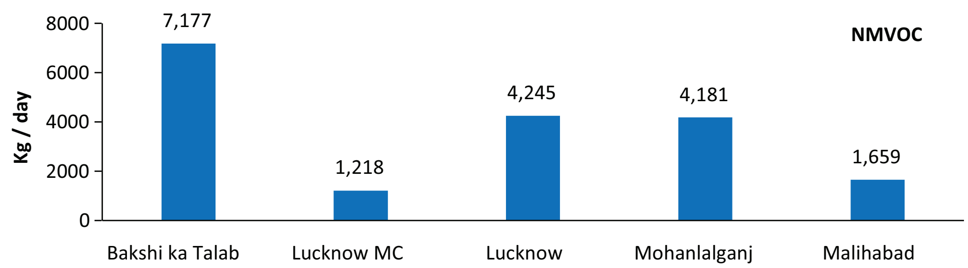


FIGURE 30: Emissions of different pollutants from block level household of Lucknow district during 2019

Table 13: Fuel-wise emissions (kg/day) of different pollutants at block level of Lucknow district during 2019

PM_{10}	FW	CR	CDC	COAL	LPG	KER	Total
Bakshi ka Talab	2951	58	84	0	0	178	3271
Lucknow MC	505	0	13	0	0	0	518
Lucknow	1677	67	84	39	0	795	2662
Mohanlalganj	1578	97	167	0	0	378	2218
Malihabad	611	26	5	147	0	199	988

$PM_{2.5}$	FW	CR	CDC	COAL	LPG	KER	Total
Bakshi Ka Talab	2005	38	35	0	0	178	2257
Lucknow MC	343	0	5	0	0	0	349
Lucknow	1139	44	35	19	0	795	2033
Mohanlalganj	1072	64	70	0	0	378	1583
Malihabad	415	17	2	72	0	199	705

Table 13: Fuel-wise emissions (kg/day) of different pollutants at block level of Lucknow district during 2019

SO_x	FW	CR	CDC	COAL	LPG	KER	Total
Bakshi ka Talab	349	5	5	0	0	0	358
Lucknow MC	60	0	1	0	1	0	61
Lucknow	198	5	5	73	0	0	281
Mohanlalganj	186	8	10	0	0	0	204
Malihabad	72	2	0	273	0	0	347

NO_x	FW	CR	CDC	COAL	LPG	KER	Total
Bakshi ka Talab	741	12	8	0	1	0	762
Lucknow MC	127	0	1	0	4	0	132
Lucknow	421	14	8	10	0	0	454
Mohanlalganj	396	20	16	0	0	0	433
Malihabad	153	5	1	38	1	0	198

CO	FW	CR	CDC	COAL	LPG	KER	Total
Bakshi ka Talab	28989	432	629	0	0	57	30107
Lucknow MC	4964	0	94	0	3	0	5060
Lucknow	16473	495	630	283	0	255	18136
Mohanlalganj	15497	719	1247	0	0	121	17584
Malihabad	6003	191	41	1058	0	64	7356

NMVOC	FW	CR	CDC	COAL	LPG	KER	Total
Bakshi ka Talab	6927	57	193	0	1	0	7178
Lucknow MC	1186	0	29	0	4	0	1219
Lucknow	3936	66	193	50	0	0	4245
Mohanlalganj	3703	96	382	0	0	0	4181
Malihabad	1434	25	12	187	1	0	1659

Gridded emission distribution of air pollutants from residential households of different blocks of Lucknow district is represented in Figure 31.

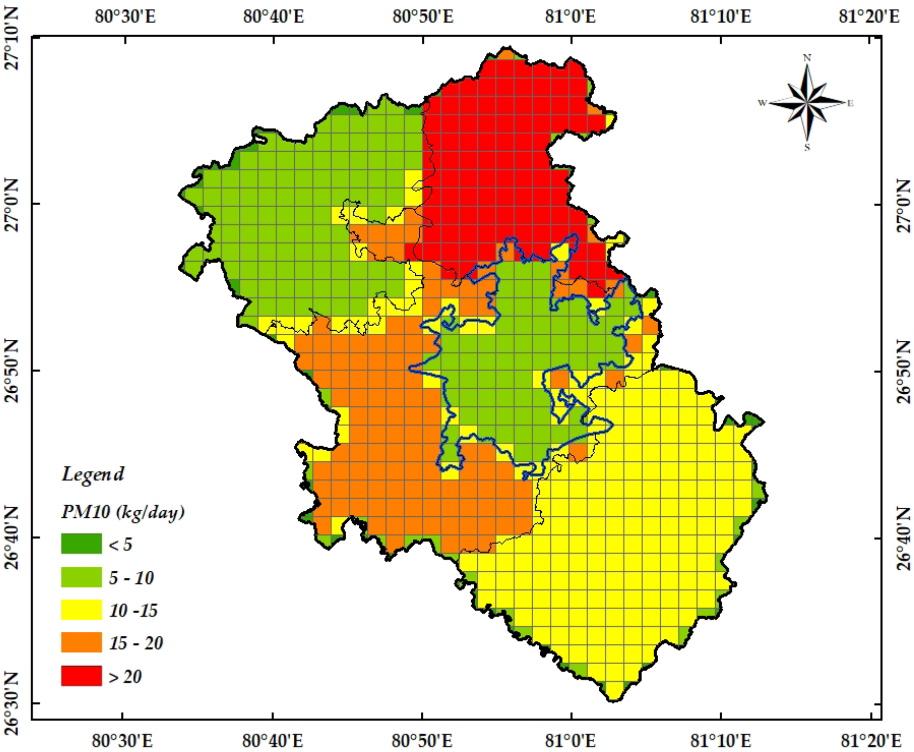


FIGURE 31: Gridded emission distribution map of PM10 from residential households in Lucknow district

g) Agriculture

Emission inventory of different pollutants from the burning of different crop residues in the agriculture field has been developed by following the IPCC (2006) inventory preparation guideline. The primary crops that will be considered for inventory preparation will be based on the primary survey of the district as well as literature survey of the studies conducted in the study area. Emission from the in-situ burning of crop residue will be calculated using the equation below,

$$\text{Epol} = \sum_{a=1}^{x} \text{Pa} \times \text{Ra} \times \text{fDa} \times \text{fBa} \times \text{Bf} \times \text{EFpol} \qquad (12)$$

Where, Epol = Emission of a particular pollutant (pol) (g); Pa is the total production of a particular crop (a) in kilogram and (x) will be number of crops selected for estimation of emission; Ra is the fraction of residue generated for the production (Pa) of the particular crop (a); fDa is the fraction of dry matter in the residue of the particular crop (a); fBa is the combustion efficiency of crop residue that is burnt, Bf is the burning fraction of the crop estimated on the basis of MODIS FRP data (has been explained below) and EFpol is the emission factor of the particular pollutant (g/Kg). The emissions have been projected based on the percent decrease in the net FRP value (for

2019) of the study with respect to the FRP value for which emissions were estimated based on the available production data i.e. for the year 2016. The residue to crop fractions (Ra) of different crops has been replicated as in Datta and Sharma (2014). The dry matter fraction in different crop residues (fDa) replicates as reported by Jain et al. (2014). The combustion efficiency (fBa) of different crop residues was used as reported in Turn et al. (1997) (Table 14).

Table 14: 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 (fDa)[2]	0.86	0.88	0.80	0.90	0.80	0.90
Combustion efficiency (fBa)[3]	0.89	0.86	0.90	0.92	0.68	0.91

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

The burning fraction (B_f) has been calculated from the MODIS Fire Radiative Power (FRP) data. The FRP dataset of the NASA's MODIS (aqua and tera) satellites was also used to identify the crop residue burning locations at 2 Km × 2 Km grid over the study region. This will be further employed to spatially allocate the emissions.

The MODIS active fire products provide fire detections at the satellite overpass times. Terra and Aqua respectively cross the equator at approximately 10:30 a.m. and 1:30 p.m. local time during daytime and 10:30 p.m. and 1:30 a.m. during night-time. The MODIS Level 2 active fire products (abbreviated MOD14 for Terra and MYD14 for Aqua) contain for each fire pixel the detection time, geographical coordinate, confidence (low, nominal, and high), fire radiative power (units: MW per pixel), brightness temperature at the MODIS band 21 (3.660–3.840 μm) and band 31 (10.780–11.280 μm), and average brightness temperature of the surrounding non-fire pixels at bands 21 and 31 (Giglio, 2015). The FRP estimates in MODIS Collection 6 (C6) active fire product are retrieved following the method developed by Wooster et al. (2003).

The FRP products retrieved from MODIS C6 datasets will be plotted on GIS along with LULC (land use and land cover) for each studied year. The FRP's detected over agricultural land use area was extracted for further analysis, as it is assumed that rest of the FRP's being detected may represent some other form of biomass burning being detected. This extracted data has been used to estimate seasonal FRP being detected in each district of the country.

The maximum FRP value detected in any district of the country will be assumed where almost 75% of the residue is being burnt. The assumption of 75% has been taken based on the field surveys where it has been found that some parts of the residue is always used by farmers and villagers for some allied activities that range from cattle food to building temporary huts. The added district wise FRP dataset for all the years since the launch of satellite (i.e. from 2001 to 2019) has been used to obtain the best fit. The resultant distribution was applied and the results were scaled between 0 & 0.75 i.e. from 0% (where no burning activity has been observed) to 75% (where maximum burning activity has been detected). The fraction obtained from this exercise was used as Bf in estimation of agricultural residue burning emission.

The emission factors applied in process have been shown in Table 15 while, the final agriculture residue burning emissions form the Lucknow district estimated have been tabulated in the Table 16. Figure 32 shows the spatial distribution of PM_{10} emissions from crop residue burning.

Table 15: Emission Factor (g/Kg) of different pollutants for each crop type

Crop	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	NMVOC
Rice	7.1	5.45	2.4	0.45	58.9	6.3
Wheat	8	5.4	1.45	0.5	65.5	0.5
Cotton	10	5.5	0.5	1.7	28.1	19.1
Maize	6.6	6	1.8	0.2	46.4	4.5
Sugarcane	6.9	5.4	0.5	1.5	28.1	0.5

Source: Datta and Sharma et al., 2016

Table 16: Annual emission (kg/day) for 2019 of different pollutants for Lucknow district

Pollutant	PM_{10}	$PM_{2.5}$	SO_x	NO_x	CO	NMVOC
Emissions (Kg/day)	3863	2658	795	2411	31342	795

The emissions of different pollutants due to the open burning of the crop residues in the agricultural fields were distributed to grids based on a fraction for each grid, estimated by taking the ratio of the total FRP observed in the particular grid to the total FRP observed in the study domain. The spatially distributed map presents no specific pattern but shows that majority of agriculture fires happened in the south east part of Lucknow district with almost all the observed fire events happening outside the Lucknow city.

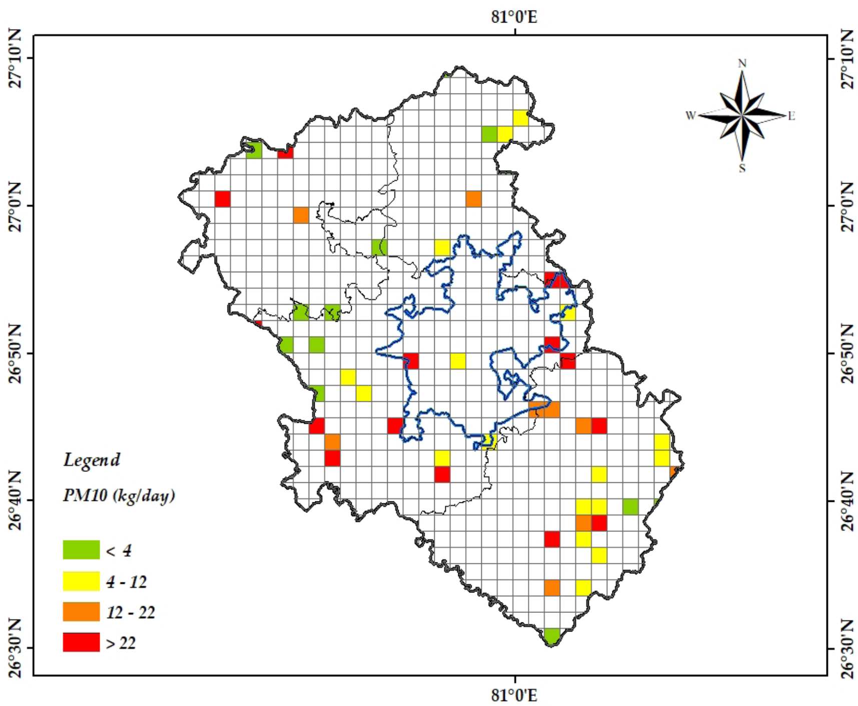


FIGURE 32: Spatial distribution of annual PM_{10} emission from open burning of crop residues in Lucknow district

h) Construction

The pollutant mainly emitted from construction sector is PM and it depends on the scale of activity i.e. excavation, demolition or construction of the site till the completion of the building. For the estimation of emissions we solely depend on the area of construction as the emission factor is comprised of area and duration of the activity. The methodologies followed for the estimation of emission inventory includes data on construction activity which was obtained from high resolution images using Google earth tools used in the identification of different construction sites (Google Earth) and to calculate the area of construction (Arc GIS) and is shown in Figure 33.

FIGURE 33: Constructed or demolished area in Lucknow during 2019 (marked in red)

Emissions of particulate matters (PM_{10} and $PM_{2.5}$) due to the construction activities were estimated using the eq. 13

$$E_{PM} = EF_{PM} * A * D_{12-Rm} \qquad (13)$$

Where, EPM is the emission of particulate matter (Ton/acre); EFPM is the emission factor of particulate matter (1.2 ton/acre/month) (USEPA – 42); A is the area of construction site in acres; Rm is the number of months of total rainfall higher than 100mm during 2019 which were assumed as no construction months. The ratios of PM_{10}/TSP and $PM_{2.5}$/PM_{10} are important because these ratios were used to project PM_{10} and $PM_{2.5}$ emission from the TSP estimates. According to Chow & Watson., 1998, about 35% of the particulate matter was assumed as PM_{10} and 6% is $PM_{2.5}$. Accordingly, estimated PM_{10} and $PM_{2.5}$ emissions due to construction activities from Lucknow district during 2019 were 9315 Kg/day and 1589 Kg/day respectively.

Grid wise distribution of total PM_{10} emissions from construction sector is done on the basis of grid wise construction/demolition mapping on high resolution images using Google Earth and Arc GIS. It is clear from Figure 34, most of the high emissions grids are represented in outskirt of the city in south east direction which represents more number of construction sites are there due to city expansion or nearby urban areas development. Most of the emissions can be seen in city and its adjacent areas.

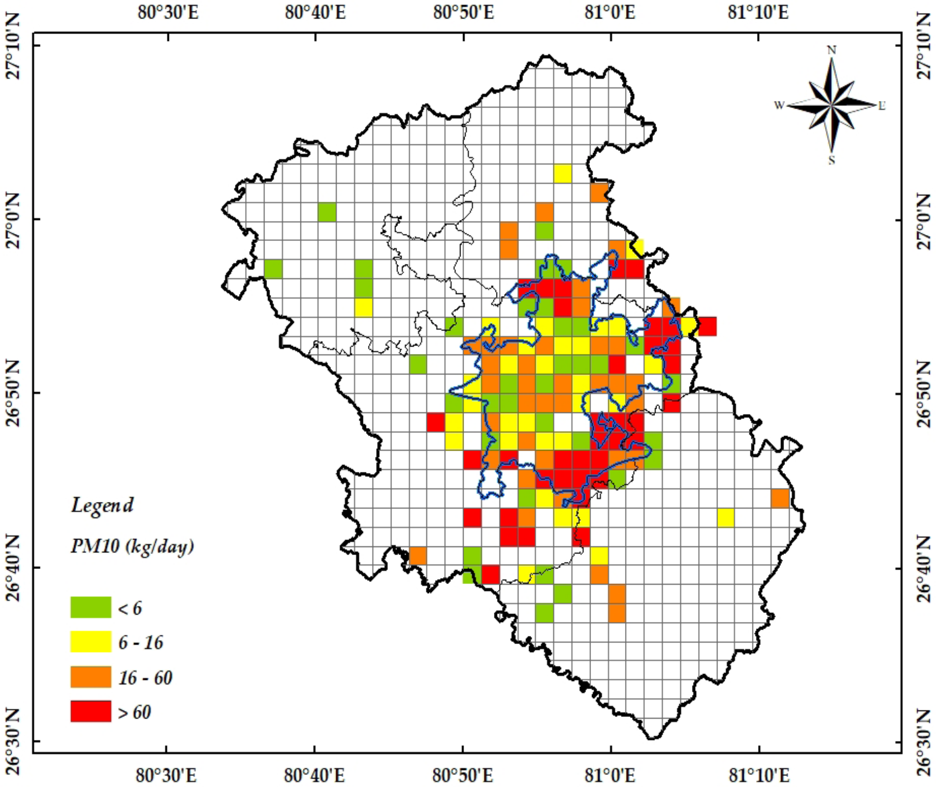


FIGURE 34: Spatial distribution of PM_{10} emissions from construction sector

i) Diesel Generator Sets

The use of diesel generator (DG) sets for power backup at various places like malls, shopping centres, industries, offices buildings or any other commercial or non-commercial places etc. increases the air pollution levels in the cities and causes severe health and environmental problems.

The basic equation employed for emission estimation from the DG sets sector is:

$$Ep = C \times t \times 36 \times 10^5 \times E_f \qquad (14)$$

Where, Ep is the emission of pollutant p, C is the capacity of DG set installed (KWh), t is the operating time in hours, 36 x 10^5 is the conversion factor to convert total energy produced into joules. The emissions from DG sets are estimated based on primary survey carried out in 19 different grids (Figure 35). The survey locations covered residential areas, industrial locations, commercial hubs, transport congested areas in the district to capture the actual scenario of DG sets usage and emissions. In order to inventorise emission from DG sets, the information on number of DG Sets, their capacity, operational hours and fuel consumption were collected by primary survey at 19 different locations in the Lucknow district (each location representing a grid of 2 X 2 km^2) and further the estimated emissions were extrapolated for all grids using grid wise population details. Based on the sample survey we have carried out in the study domain, it was understood that the average operating/working hours of DG set is 2 hours/day.

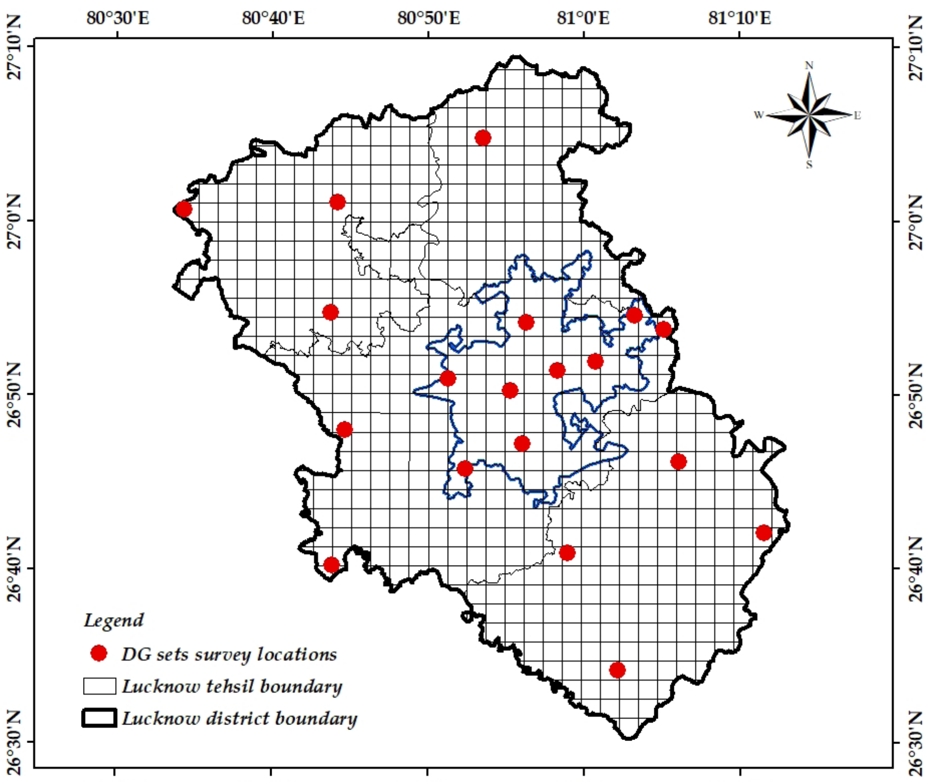


FIGURE 35: DG Sets Survey location map

Emissions factors are taken from AP-42, USEPA and shown in Table 17 along with estimated emissions.

Table 17: Emission factors and estimated emissions from DG Sets

Pollutant	Emission factor (ng/Joule)	Emissions (Kg/day)	
		City	District
PM_{10}	133.3	51.3	148.8
$PM_{2.5}$	113.31	41.9	125.4
SO_2	124.7	53.1	138.0
NO_X	1896.3	756.0	2099.4
CO	408.5	157.7	452.2
NMVOC	154.8	64.0	170.9

Figure 36 shows that most of the emissions are coming out from city and its outskirt, having high population density along with higher number of DG sets in this region. The emission distribution maps of particulate pollutant showed higher PM_{10} emissions from Lucknow city followed by Mahilabad and Bakshi Ka Talab. On the other side, least particulate emissions were observed from Mohanlalganj block.

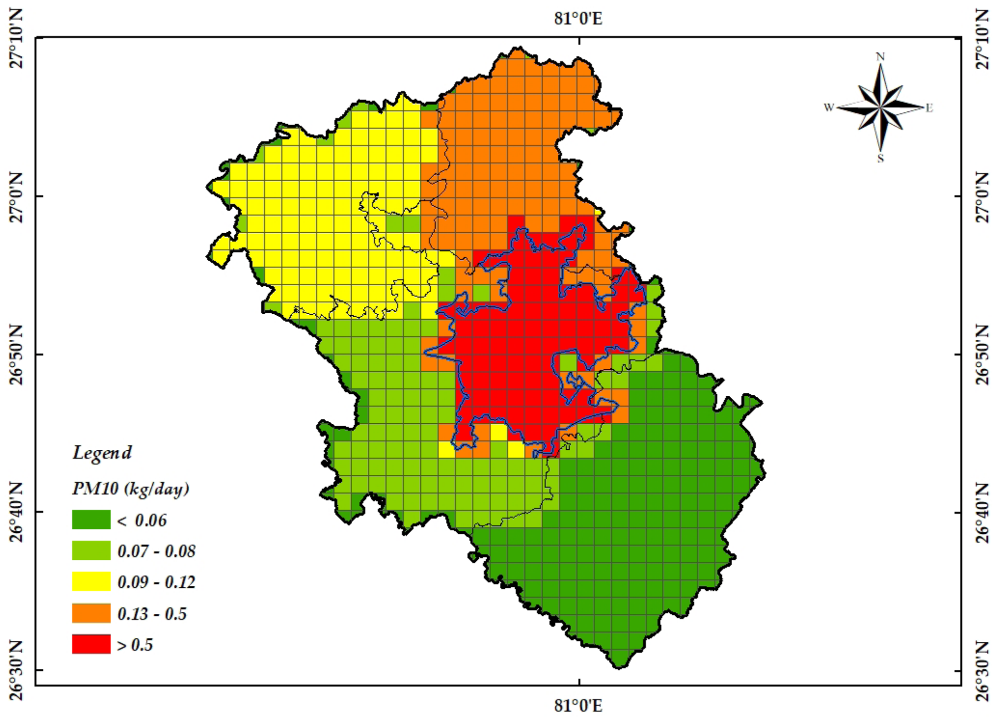


FIGURE 36: Spatial distribution of PM_{10} emissions from DG Sets

j) Landfills

Emissions from landfills are estimated on the basis of the municipal waste generated and collected by the authorities. Some of the collected waste is treated by using different treatment methods. The waste left untreated finally lands into open sites or landfills. Currently, Lucknow city generates about 1147 t/d of waste, out of which 516.7 t/d of waste is collected and transported through primary and secondary collection techniques. Primary collection techniques include sweeping during day time, door to door collection, night scrapping etc. The uncollected waste in Lucknow city is finally disposed in three landfill sites which accounts for about 631.7 tons/day. In Lucknow city, there are three active landfill sites that are loaded regularly by MSW Emissions from landfill sites are estimated based on the fact that 2% of waste is burnt at dumpsite by rag pickers and landfill fires. Eq. 15 employed for the emission estimation is –

$$E_p = 2\% \times W_L \times E_f \qquad (15)$$

Where Ep is the emission of pollutants p, W_L is the waste collected at landfill site and E_f is the emission factor adopted from USEPA – 42. Emission factors and emissions from the landfill sites are shown in Table –18. It can be seen that CO accounts for maximum emissions from the landfills followed by VOC emissions.

Table 18: Emission factors and emissions from landfill sites in Lucknow

Pollutant	Emission Factor (g/Kg)	Emissions (Kg/day)
PM_{10}	8	137
$PM_{2.5}$	5.44	82
SO_X	0.5	0
NO_X	3	55
CO	42	658
NMVOC	21.5	329

k) Crematoria

In India, religions are following distinct set of rituals towards their own socio-cultural system and spirituals activities. Cremation is one of the last rituals performed towards the deceased person in Hinduism, Jainism and Sikhism. In this ceremony a significant quantity of wood is burned. The estimation of emissions from cremation is done on the basis of total wood burnt during the ceremony.

As per census 2011, there are about 77.08% Hindus, 0.09% Sikhs and 0.11% Jains are residing in Lucknow district and projected population of the district for the year 2019 and percentage distribution of these three religions is accounted for emission estimation. For each cremation, on an average 350 kg wood is consumed (NEERI, 2010). Throughout the district, total wood burnt over the year 2019 was estimated based on accounted population and crude death rate (total number of deaths per year per 1,000 people) which is found to be 8.3 for rural area and 5.8 for urban area. Emissions are calculated using Eq. 16.

$$E_p = (Pop_{2019} \times F \times R_D \times 350) \times Ef \qquad (16)$$

Where E_p is the emission of pollutant p, Pop_{2019} is the population projected for 2019, F is the fraction of Hindus, Sikhs and Jains in Lucknow district and R_D is the crude death rate in Lucknow. Emissions from Lucknow city and district and emission factors are represented in Table-19.

Table 19: Pollutant wise emission factor and annual emissions in Kg/day

Pollutant	Emission Factor (g/Kg)	Emissions (Kg/day)	
		City	District
PM_{10}	18.5	279	501
$PM_{2.5}$	9.1	137	247
SO_2	0.4	5	11
NO_X	2.55	38	68
CO	93	1405	2526
NMVOC	51.9	784	1411

Grid wise emission distribution of PM_{10} is represented in Figure 37. Emission distribution has been done on the basis of geographical location of crematoriums. The emission distribution maps revealed that the high emissions were observed from crematoriums situated within the city and on the outskirt of the city where most of district population resides.

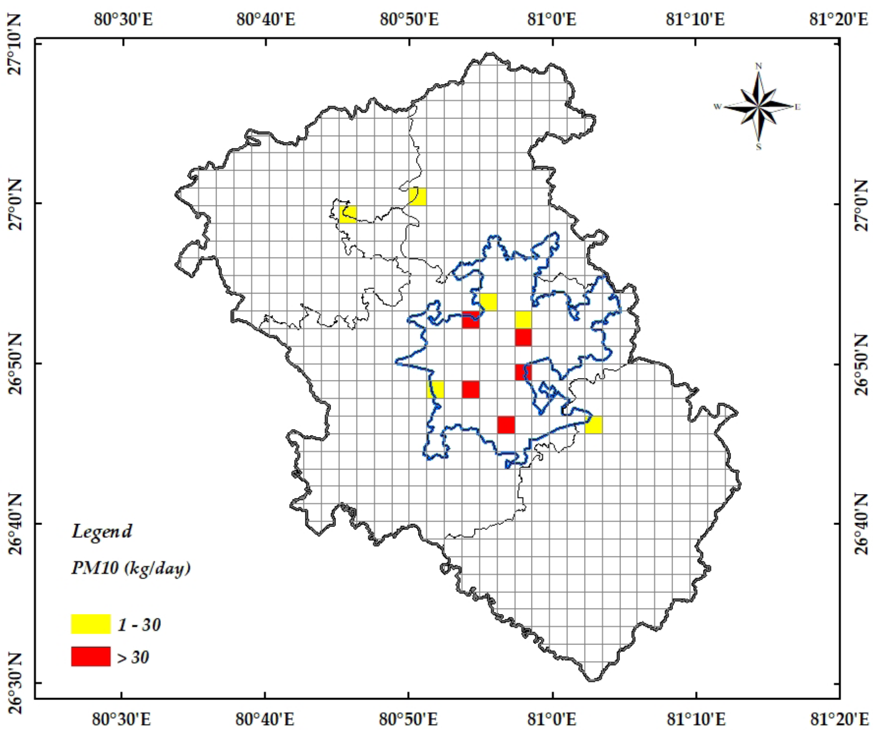


FIGURE 37: Spatial distribution of PM_{10} emissions from Crematoria sector

l) Hotels and Restaurants

As a result of tremendous growth of hotel & restaurant industry in India during last few decades, emissions from this industry have been growing. Use of different cooking fuels for cooking (liquefied petroleum gas (LPG), charcoal and wood) in tandoors/barbeques in hotels and restaurants generates emissions of different pollutants. In order to inventorise emission of various pollutants from hotel and restaurants, a primary questionnaire-based survey was carried out at nineteen locations (at 19 different grids) in Lucknow district to gather information on type of fuel consumption in restaurant/hotels. Based on the survey, charcoal and LPG were identified as the major fuels used in eateries in addition to wood and coal.

Estimation of emissions from this sector has been carried out using equation

$$Ep = C_f \times E_f \qquad (17)$$

Where, Ep is the emission of particular pollutant p, C_f = Fuel consumption by the hotel/ restaurant, E_f = Emission factor of different fuels used in cooking. Emission factors and annual emissions from Hotels and Restaurants sector are summarized in Table 20. Emissions estimated in these 19 grids were extrapolated for other grids in the study domain based on population density and land use pattern. Grid wise emission distribution of PM_{10} is represented in Figure 38. It can be seen that the emissions are low but significant from restaurant and hotel sources.

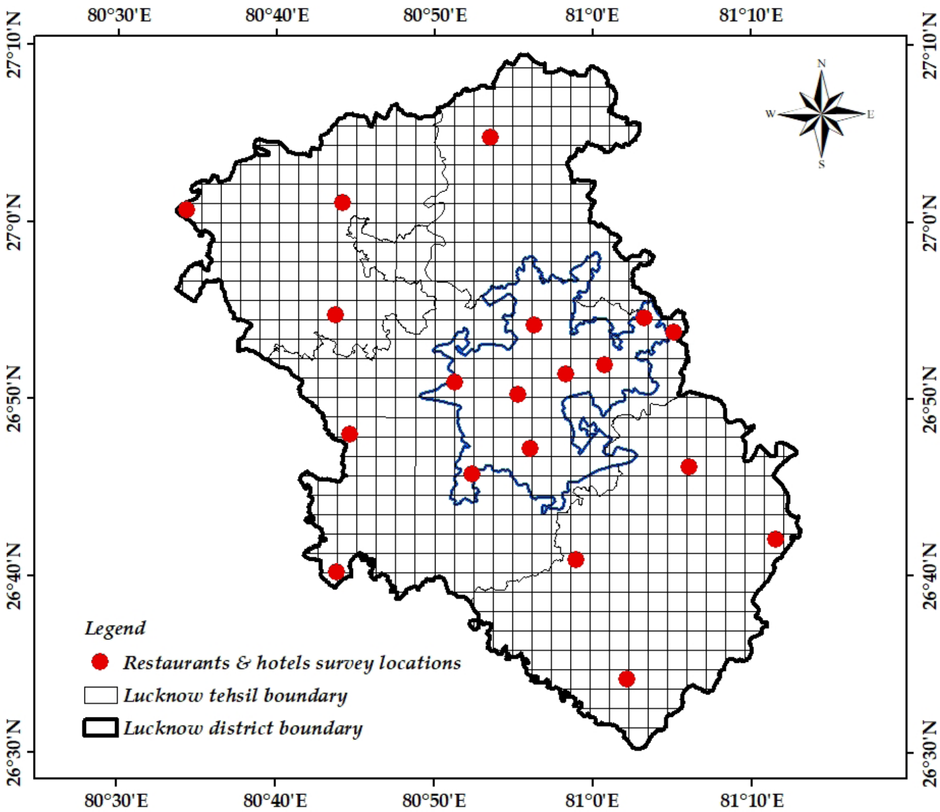


FIGURE 38: Survey location map of Restaurants

Table 20: Pollutant wise emission factor and annual emissions in Kg/day

Pollutant	EF - Wood (g/Kg)	EF - Charcoal (g/Kg)	EF - LPG (g/Kg)	Emissions (Kg/day) (Wood + charcoal + LPG)	
				City	District
PM_{10}	15.3	20	0.35	28.7	84.2
$PM_{2.5}$	12.1	12	0.35	18.8	54.0
SO_2	0.2	13.3	0.4	17.0	56.5
NO_X	1.4	3.99	2.9	16.5	45.9
CO	115.4	24.92	2	150.4	393.8
NMVOC	26.5	10.5	3.7	51.4	137.5

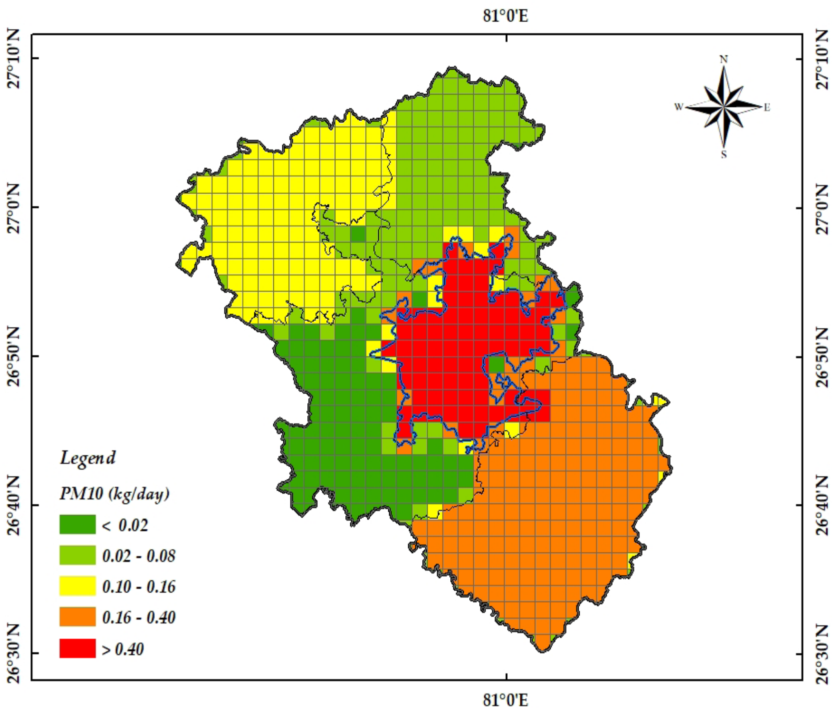


FIGURE 39: Spatial distribution of PM_{10} emissions from Restaurants

As presented, most of the emissions are coming out from city and its outskirt having high population density along with higher number of restaurants situated in this region. The emission distribution maps of particulate pollutant showed higher $PM_{2.5}$ and PM_{10} emission from Lucknow city followed by Mahilabad and Mohanlalganj. On the other side, least particulate and gaseous pollutant emission was observed from Lucknow block excluding Municipal Corporation area.

m) Aviation Sector

The pollutants emitted by aircrafts mainly come from the combustion of aviation turbine fuel (ATF) that is used as fuel for the aircraft engine. In the entire flight duration, initial to final destination of the aircraft has been categorized into three phases. These phases include take-off, cruise and landing phase. The Landing/Take-off (LTO) cycle includes all activities near the airport that take place below the altitude of 3000 feet (1000 m). Cruise phase includes travelling above 3000 ft (1000m) above the ground level. However, emission of pollutants in the cruise phase does not add to the emission loads as these emissions occur quite above in the atmosphere. Furthermore, the cruise emissions will be dependent on the length of the flight. Emission inventory of pollutants emitted from aircrafts is dependent on the number of LTO's conducted and the emission factors for pollutants per LTO are taken from TERI analysis. The emissions are evaluated using the eq. 18.

$$E_p = N_{LTO} \times E_F \qquad (18)$$

Where, Ep is the emission of pollutant p; N_{LTO} is the number of landings and take-offs conducted by the aircrafts in certain period of time (s); E_F = Emission Factors (TERI analysis). The emissions from aircrafts along with emission factors are shown in Table 21. As evident, CO emissions are the prominent emissions from the aviation sector followed by NMVOC's and NO_X.

Table 21: Emission Factors and total emissions from Lucknow aviation sector

Pollutants	Emission Factors (Kg/LTO)	Emissions (Kg/day)		
		International	National	Total
PM	0.3	3	25	28
SO_X	1.5	16	118	134
NO_X	19.1	222	1501	1723
CO	39.5	458	3104	3562
NMVOC	20.4	236	1603	1839

n) Total Emissions

In total 13 sectors has been inventoried in Lucknow city and district which are found to be contributing towards deteriorating air quality of Lucknow. In this section, we have summarized the entire findings of the emission inventory and deduced most polluting sector in district and city in terms of percentage share of emissions.

1. Lucknow District

Table 22 shows the emission of various sectors in Lucknow district and Figure 38 is the graphical representation of the percentage emissions contributed by each source.

Table 22: Overall emissions from all the sectors in Lucknow district

Sector	Emissions (Kg/day)					
	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	NMVOC
Brick Kilns	7397	1671	5890	1	31863	959
Transport	22614	21936	323	382036	976267	608524
Road Dust Re-suspension	165768	40105				
Agriculture	3863	2658	795	2411	31342	795
DG sets	149	125	138	2099	452	171
Residential sector	9657	6927	1251	1979	78243	18482
Refuse Burning	469	386	19	145	1488	608
Hotels & Restaurants	84	54	57	46	394	138
Crematoria	501	247	11	68	2526	1411
Landfills*	137	82	0	55	658	329
Construction	9315	1589				
Aviation*	27		134	1721	3562	1838
Industry*	3505	1554	592	304	3853	803
Total	**223486**	**77334**	**9210**	**390865**	**1130648**	**634058**

**Following sectors has been inventoried for city scale.*

It is evident from the Figure 38 that CO is the majorly emitted pollutant in Lucknow district followed by non-methanic volatile organic compounds (NMVOC). Both of these pollutants are mainly emitted from transport and residential sector. In terms of percentage share of emissions from different sectors, road dust re-suspension shares major emission load for PM_{10} and $PM_{2.5}$ in Lucknow district. Around 74% of the total PM_{10} and 52% of total $PM_{2.5}$ are emitted as re-suspended dust due to vehicular moment on district roads. Transport sector emits about 10% PM_{10} and 28% $PM_{2.5}$ to the total pollutant emissions. Brick kilns are major source of gaseous pollutant SO_2 and emits 64% SO_2 to the total emissions. Second major polluter of SO_2 is the residential sector and emits about 14% of the total SO_2 pollutant emissions. Gaseous pollutants, NO_x is majorly emitted by transport and shares about 98% of the total NO_x emissions followed by DG sets which shares about 1% of the total NO_x emissions. 86% of the total CO is emitted by transport sector followed by 7% emission loads from residential sector and 3% CO from the brick kilns. In case of NMVOC emissions, transport sector emits about 96% of the total NMVOC's while residential sector emits about 3% of the total NMVOC.

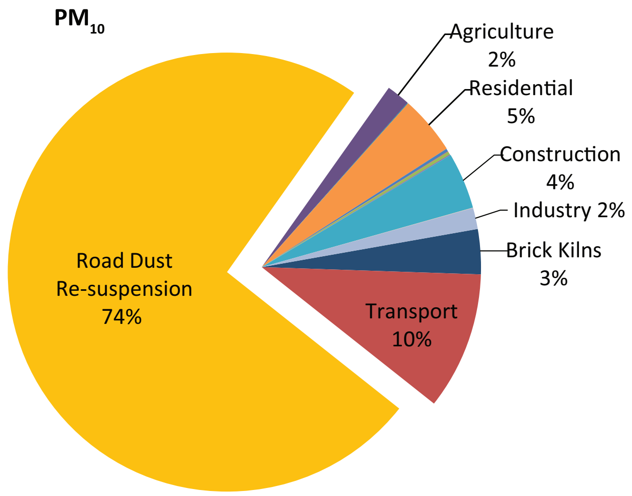


FIGURE 40: Percentage contribution of PM_{10} emissions in Lucknow district

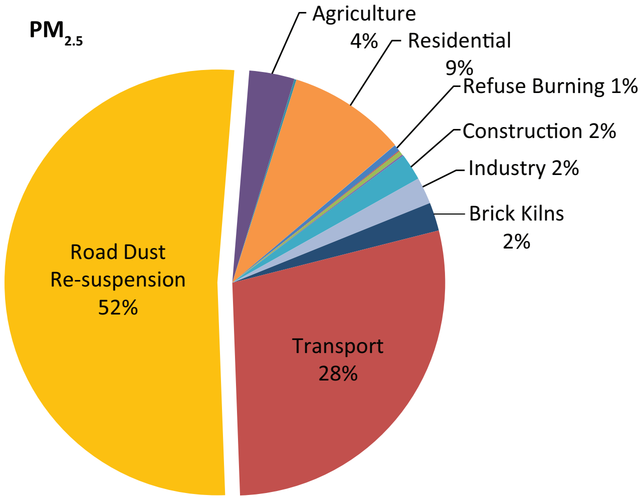


FIGURE 41: Percentage contribution of $PM_{2.5}$ emissions in Lucknow district

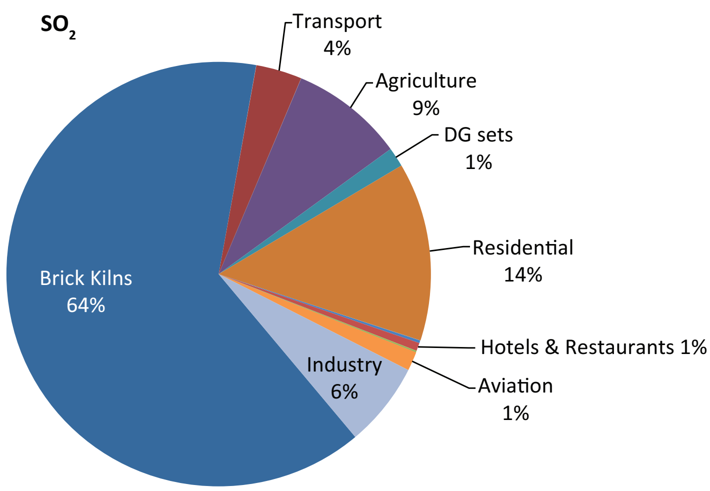


FIGURE 42: Percentage contribution of SO_2 emissions in Lucknow district

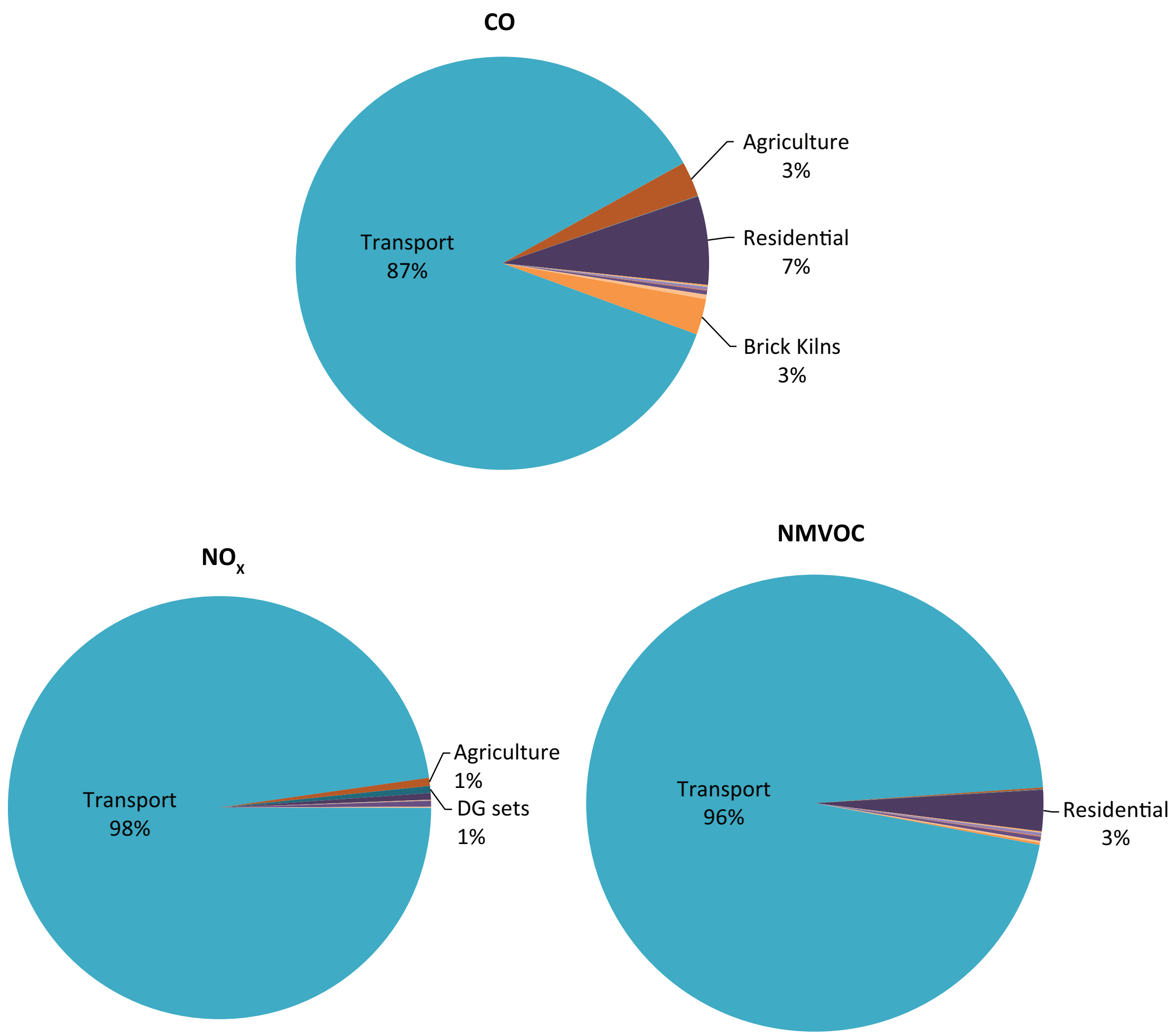


FIGURE 43: Percentage contribution of NO_x, CO and NMVOC emissions in Lucknow district

2. Lucknow City

In Lucknow city, around 49.7 and 14.2 kt/year of PM_{10} and $PM_{2.5}$ is released in the year 2019. Share of emissions from different sectors shows that major source of particulate pollution is from the road dust re-suspension which emits about 86% of the total PM_{10}, and 72% of the total $PM_{2.5}$. However, transport sector is the major emitter of gaseous pollutants and emit about 98% of the total NO_X, 98% of the total CO and 99% of the total NMVOC. Industries emits about 58% of the total SO_2, transport shares about 21% of the total SO_2 and diesel generators emits about 5% of the total SO_2. Overall emissions from all the sectors in Lucknow city are shown in Table 23 and percentage contribution of different pollutants in the Lucknow city is shown in Figure 42.

Table 23: Overall emissions from all the sectors in Lucknow city

Sector	Emissions (Kg/day)					
	PM_{10}	$PM_{2.5}$	SO_2	NO_X	CO	NMVOC
Transport	7989	7752	215	116832	628770	292292
Road Dust Re-suspension	116733	28242				
DG sets	51	42	53	756	158	64
Residential sector	59	1	1	0	1	0
Refuse Burning	8	8	0	3	25	11
Hotels & Restaurants	29	19	17	17	150	51
Crematoria	279	137	5	38	1405	784
Construction	7457	1278				
Landfills	137	82		55	658	329
Aviation	27		134	1721	3562	1838
Industry	3505	1554	592	304	3853	803
Total	**136274**	**39115**	**1017**	**119726**	**638582**	**296172**

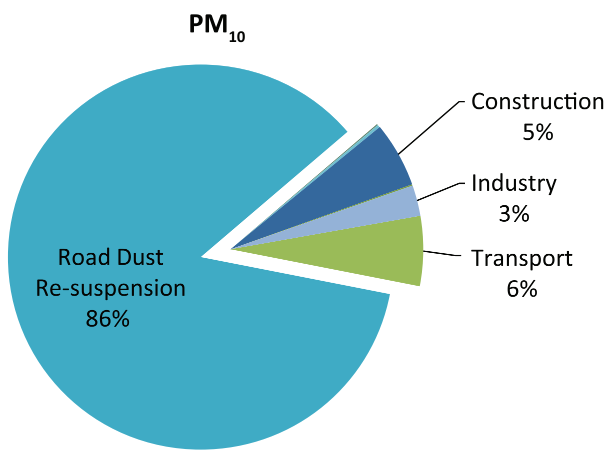


FIGURE 44: Percentage contribution of PM_{10} emissions in Lucknow city

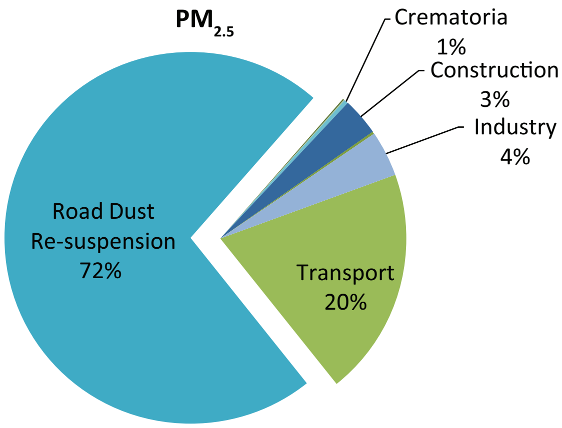


FIGURE 45: Percentage contribution of $PM_{2.5}$ emissions in Lucknow city

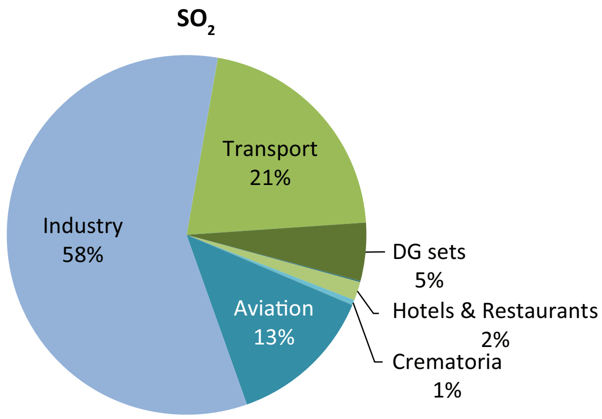


FIGURE 46: Percentage contribution of SO_2 emissions in Lucknow city

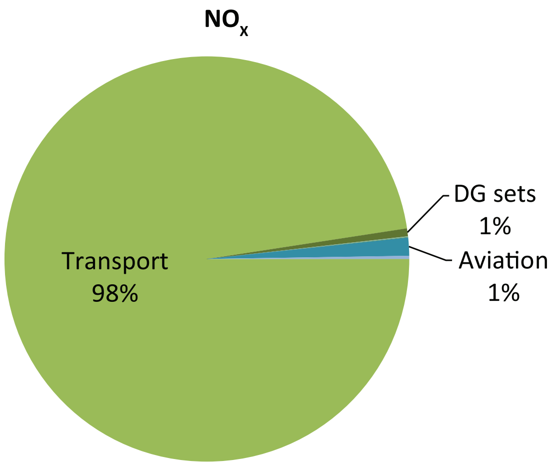


FIGURE 47: Percentage contribution of NO_X emissions in Lucknow city

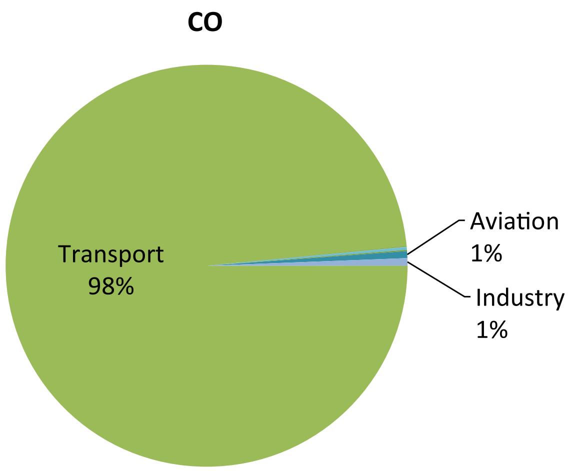


FIGURE 48: Percentage contribution of CO emissions in Lucknow city

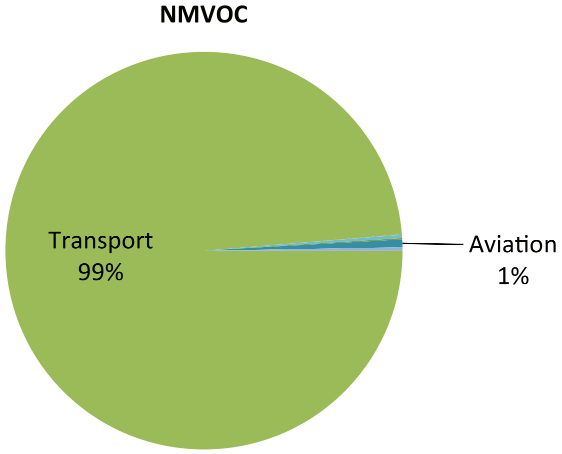


FIGURE 49: Percentage contribution of NMVOC's emissions in Lucknow city

o) Spatial distribution of pollutant emissions load over Lucknow district

Emission estimated for different pollutants from all the sectors have been spatially distributed using ArcGIS over grids of 2 × 2 km². Different parameters were used for spatial distribution of emissions from various sectors. Figure 50 shows the spatial distribution of different pollutants in Lucknow district during 2019. PM emissions are found to be more in Lucknow city mainly due to high population density, dependence of biomass for cooking and high vehicular density. Other than the city, PM_{10} intensities are higher in the district due to vehicular influences.

NO_X emissions are mainly concentrated at urban centres and highways, mainly due to vehicular and industrial activity. SO_2 emissions are found to be higher at locations of industrial and brick kilns clusters i.e. cement plants, iron steel manufacturing units, and other industries burning coal.

CO emissions are primarily driven by incomplete combustion in rural households and hence show higher intensities in district. NMVOC emissions are also dominated by biomass burning in district, followed by emissions in urban centres due to vehicles and solvent use.

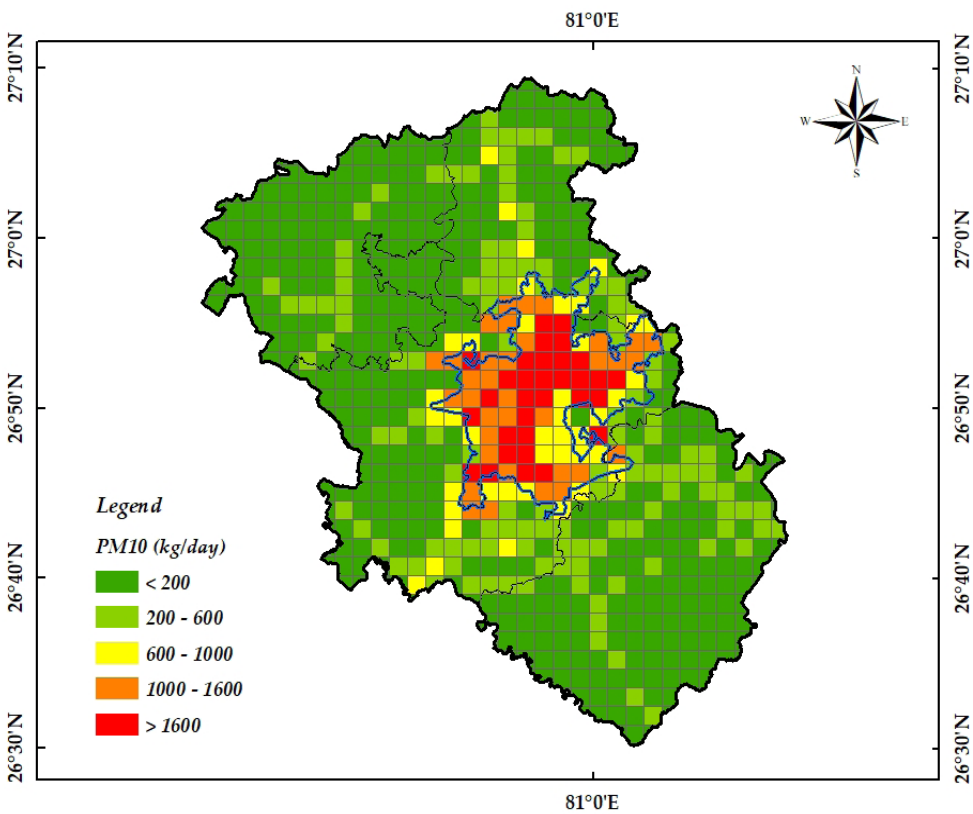


FIGURE 50: Spatial distribution of total PM_{10} emissions in Lucknow district

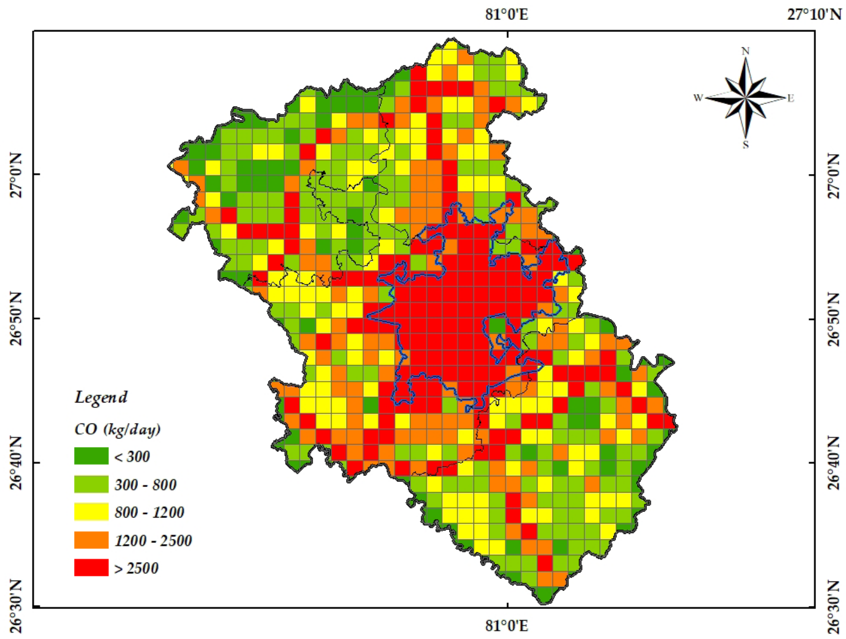


FIGURE 51: Spatial distribution of total NMVOC emissions in Lucknow district

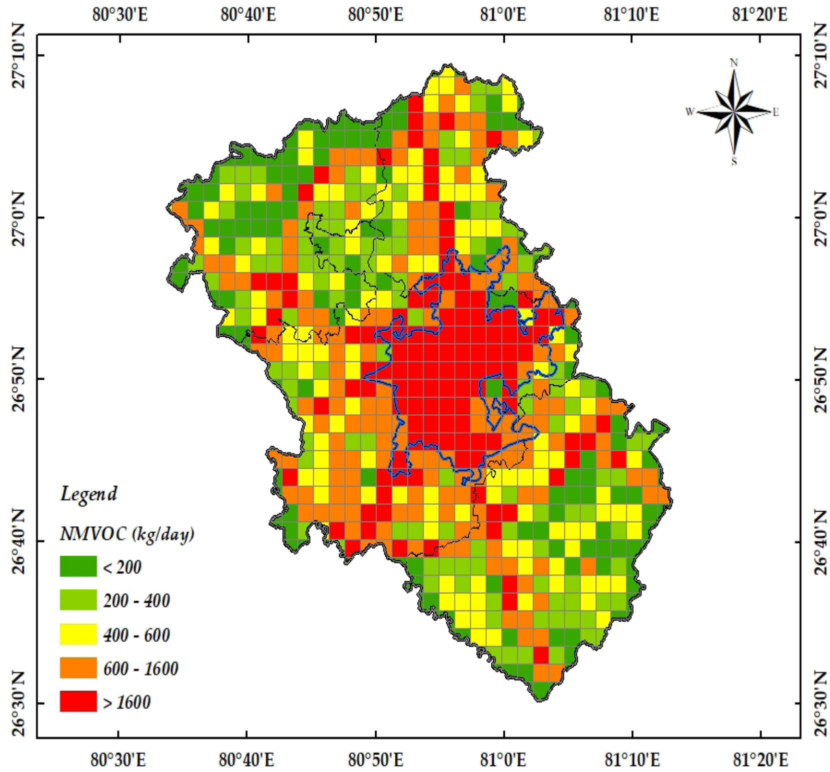


FIGURE 52: Spatial distribution of total NO_X emissions in Lucknow district

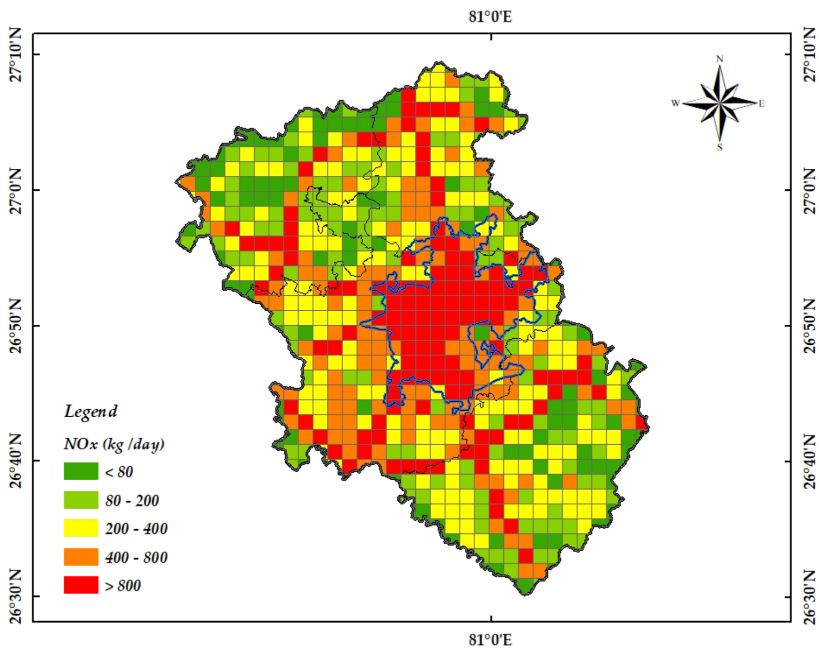


FIGURE 53: Spatial distribution of total SO_x emissions in Lucknow district

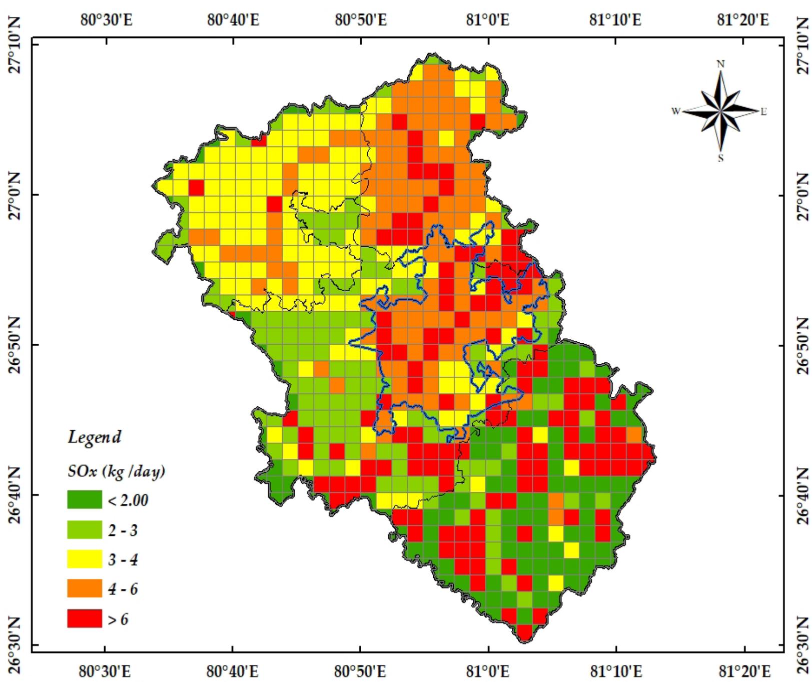


FIGURE 54: Spatial distribution of total CO emissions in Lucknow district

5. Comparative analysis with IIT Kanpur Emission inventory for Lucknow city - 2014

IIT Kanpur created emission inventory for Lucknow city in 2014, results of which are shown in Table 24 and representation is shown in Figure 55.

Table 24: Emission inventory results from 2014 IIT Kanpur study

Source Category	Emissions (Kg/day)				
	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO
Industries	2233	1981	225	134	15655
Transport	7115	6567	1447	68436	116559
Road Dust	119496	46195	0	0	0
Refuse Burning	2879	1959	181	1079	15121
Residential	2447	1712	329	978	11896
Construction/Demolition	1808	452	0	0	0
DG Set	192	173	178	2707	584
Crematoria	71	63	8	19	430
Aircrafts	5	5	41	455	386
Hotels/Restaurants	893	447	605	255	1589
Total	**137140**	**59553**	**3014**	**74063**	**162219**

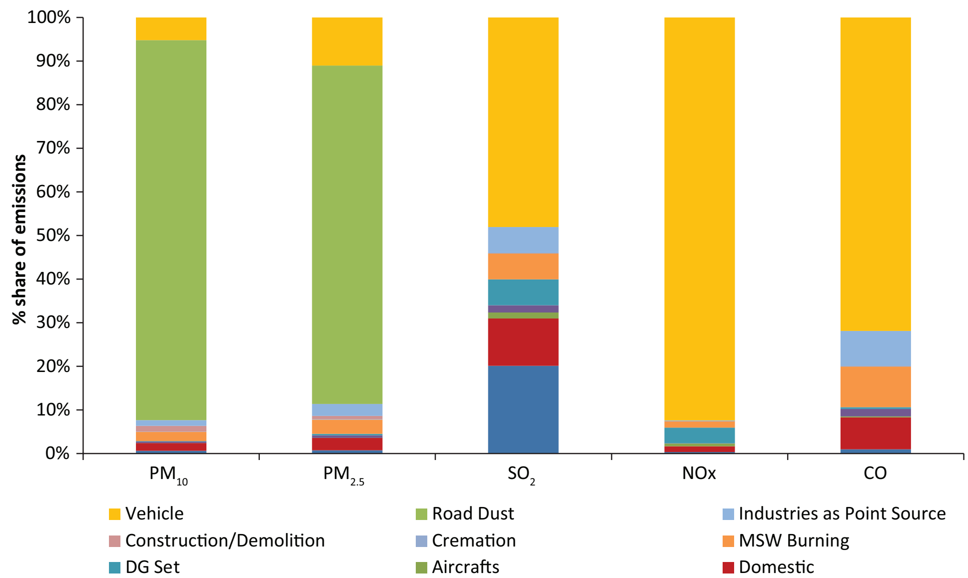


FIGURE 55: Percentage share of different sectors in inventory for Lucknow city as prepared by IIT Kanpur 2014

A comparative analysis from IIT Kanpur study conducted in 2014 is shown in Figure 55. It is clearly visible that the particulate matter emissions (PM_{10} and $PM_{2.5}$) from the road dust re-suspension in Lucknow city in 2014 were quite predominant at that time. Road dust re-suspension accounts for 87% share in the total PM_{10} emissions while $PM_{2.5}$ accounted for 78% emissions.

Gaseous pollutants like NO_X, SO_2, and CO were also majorly emitted by transport sector. As compared to the present inventory a marginal difference in the emissions from all the sectors is observed. The $PM_{2.5}$ emissions has shown a decrease of about 7% while only 2% decrease in the PM_{10} emissions is observed in the last 5 years. In case of gaseous pollutants a significant drop of 36% has been seen in the SO_X emissions. However, there has been increase in the NO_X emissions by 59% and increase of mainly because of the increase in the vehicular fleet and diesel generators activity since 2014.

Differences in estimated emissions in two studies

The main differences in the emission inventories developed by IIT Kanpur for 2014 and TERI for 2019 pertains to the variation in methodology and sectorial assumptions and emissions factors which are as follows;

a. For industrial sector, both IIT Kanpur and TERI obtained the fuel consumption data from UP-PCB. Moreover, TERI, assumed the APCD efficiencies and incorporated it in determining the emissions.

b. For transport sector, IIT Kanpur obtained activity data from primary conducted earlier. While TERI conducted parking lot survey and traffic count survey.

c. For construction sector, IIT Kanpur obtained data on constructed area from local government agencies like PWD, CPWD and Lucknow development authority and Lucknow municipal rail corporation and obtained constructed area for large construction structures while TERI used Google earth to mark the constructed/ demolished area.

d. For crematoria, IIT Kanpur assumed wood consumption for 1 corpse as 216 Kg (Sharma, 2010) while TERI referred wood consumption of 350 Kgs referred from Akagi et al., 2011.

e. For diesel generator emissions, IIT Kanpur obtained specific information on installed DG capacities from UPPCB and obtained power cut time as 2.5 hours from primary survey conducted. Emissions derived by TERI are based on the primary survey conducted in the different grids of Lucknow district and city.

f. For residential sector, activity data used and assumptions considered to prepare emission inventory is not mentioned in detailed by IIT Kanpur. Under TERI analysis, a primary survey was conducted at tehsil level which included both rural and urban areas. During the survey, a defined set of questionnaires was prepared to gather specific information pertaining to cooking activities. Household size, type of fuel used for cooking, monthly consumption of cooking fuel etc. Also, information pertaining to household electrification, daily/monthly power cut etc. was collected during the survey. Six major fuels those are used in the residential households for cooking and lighting purposes were included in the emission inventory preparations which are fuel wood, dung cake, crop residue, coal, kerosene and LPG.

g. For refuse burning sector, data used and assumptions considered to prepare emission inventory is not mentioned in detailed by IIT-Kanpur, TERI has prepared the inventory by conducting primary survey which was conducted at tehsil level which includes both rural and urban areas. Information pertaining to waste burning incident and frequency of burning incidents taking place in a particular area (once a week, twice a week etc.) were also asked in the primary survey. Waste collection efficiency in a particular tehsil was calculated based on the number of households have door to door collection facility and number of households disposing off their waste in community bins out of surveyed households. Similarly, the burning fraction of waste material was calculated based on the number of households witnessed waste burning incident in a particular tehsil.

6. Atmospheric Concentrations

The emission inventory developed from the data collected from primary and secondary sources is incorporated for dispersion modelling to estimate the apportionment of various air polluting sources, contributing to ambient air quality w.r.t. PM_{10} and $PM_{2.5}$. This emission inventory of various sectors along with meteorological datasets is fed into the Community Multi scale Air Quality (CMAQ) air quality model to assess pollution concentrations and contribution of different sources at both urban and regional scales. CMAQ model set up has been used to estimate the share of various sources contributing towards the total ambient $PM_{2.5}$ concentrations in the Lucknow city as well as the district.

The CMAQ model set up employed in this study consist of emission inventory database, a meteorological model (WRF 3.9.1) and an air quality dispersion model (CMAQ 5.3.1). Together this setup was used to simulate local and regional atmospheric pollutant circulation in Lucknow, along with estimating the ambient pollutant concentration in the city and district. The CMAQ system employed in the study assesses level of air pollutants following multi-pollutant and one atmosphere approach (Byun and Schere, 2006). The version 5.3.1 of CMAQ model also takes into account the formation of secondary organic particulates which are responsible for significant amount of ambient $PM_{2.5}$ concentrations in the cities lying within the Indo-Gangetic plain (IGP) region.

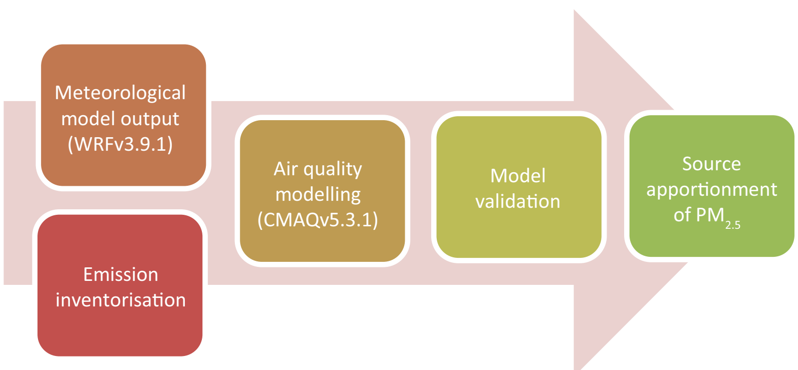


FIGURE 56: Modelling methodology

The overall approach followed in the study has been outlined in Figure 56. The WRF version 3.9.1 meteorological model was used over Lucknow district to generate 3-dimensinal meteorological fields using ERA5 and 6-hourly dataset of ECMWF.

Further the emission inventory estimated at 2x2 km resolution is spatially, temporally and vertically allocated into CMAQ compatible emission files to carry out simulations for the year 2019. India scale simulations were performed using the 36x36 km resolution emission inventory prepared by TERI, in order to account for pollutants outside the Lucknow district. In these national level simulations, atmospheric transport of pollutants from international boundaries were accounted for using global air quality products of National Centre for Atmospheric Research, U.S. (NCAR). The global product used in this study was generated from results of Community Atmosphere Model with Chemistry (CAM-chem) model. The pollutants entering from neighbouring countries like Pakistan, Nepal, Bangladesh etc., and fall within the national study domain were taken from ECLIPSE database of the International Institute of Applied Systems Analysis (IIASA, 2014). The hourly meteorological files generated using WRF model along with the CMAQ compatible emission files are used as input to chemical transport model of CMAQ along with the boundary files generated from India level run. The model set up has been used to simulate air quality of Lucknow for the year 2019. The estimated ambient $PM_{2.5}$ concentration has been validated with the actual observations monitored at four locations in Lucknow city (Gomti Nagar, Lalbagh, Nishant Ganj and Talkatora District Industries Centre). The validated model has been further used to estimate seasonal and yearly sectoral contribution of the ambient $PM_{2.5}$ concentration in Lucknow district. Additionally, contributions of secondary and primary particulates to the total $PM_{2.5}$ have been estimated in the city of Lucknow. The simulated ambient $PM_{2.5}$ concentrations for different season are shown in Figure 57.

The concentrations in the months of April, May and June were averaged to estimate summer seasons concentrations while July and August averaged for monsoon season, Oct-Nov for post monsoon and Jan, Dec and Feb were averaged for winter season. The yearly map represents the averaged concentration of all the months from Jan to Dec 2019. From the Figure 57 (a) it can be inferred that in summer season the overall $PM_{2.5}$ concentration is low in most part of the study domain compared to post monsoon and winter season.

This happens due to increase in wind speed coupled with increase in PBL (Planetary Boundary Layer) height which create conducive conditions for dispersion of pollutants. While the conditions are reversed during winter months that is slower winds along with shallower PBL resulting in high concentrations of ambient $PM_{2.5}$ concentrations in Lucknow district and surrounding regions (Figure 57 (d)). Rainfall causes down wash of pollutants suspended in the air resulting in least the ambient concentration of $PM_{2.5}$ in the study domain in the monsoon months (Figure 57 (b)). The open burning of agriculture residues in the Indo-Gangetic belt in the post monsoon seasons causes the ambient concentration to rise by many folds of the national ambient air quality standards (Figure 57 (c)). The yearly averaged ambient $PM_{2.5}$ concentration remains above the CPCB's air quality standard in the whole study domain Figure 57 (e).

The simulated values were validated with the observed ambient $PM_{2.5}$ concentrations at Gomti Nagar, Lalbagh, Nishant Ganj and Talkatora District Industries Centre stations (Figure 58). The simulated/observed ratio (simulated by observed $PM_{2.5}$ concentration values) of yearly averaged simulated concentration (90 $\mu g/m^3$) and observed concentration (102 $\mu g/m^3$) was found to be 0.88 which can be considered quite satisfactory. The seasonal concentrations of Lucknow city simulated by the model and measured at monitoring stations are shown in Table 25.

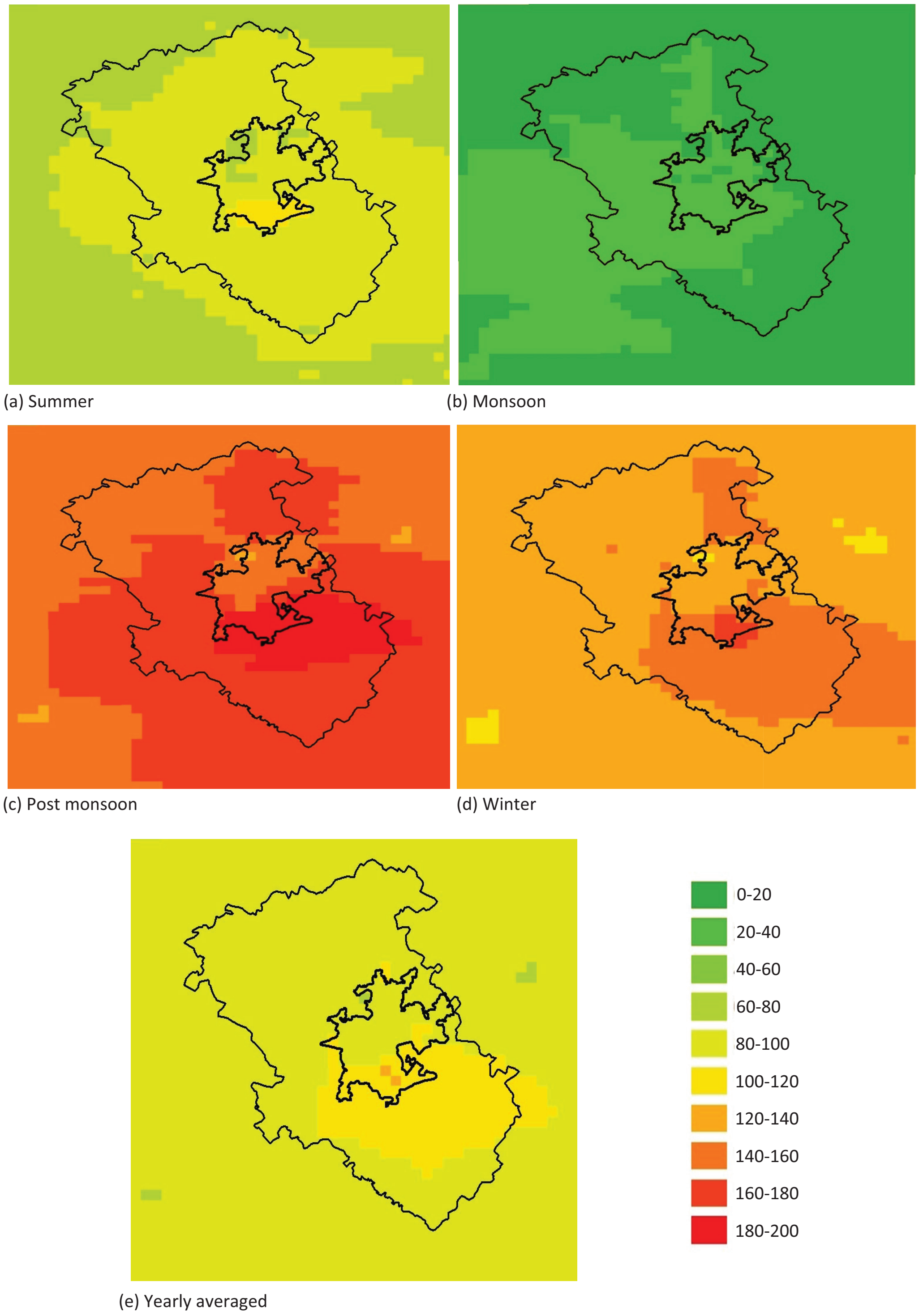


FIGURE 57: The simulated ambient $PM_{2.5}$ concentration; (a) summer season, (b) monsoon season, (c) post monsoon season, (d) winter season and e) annual averaged

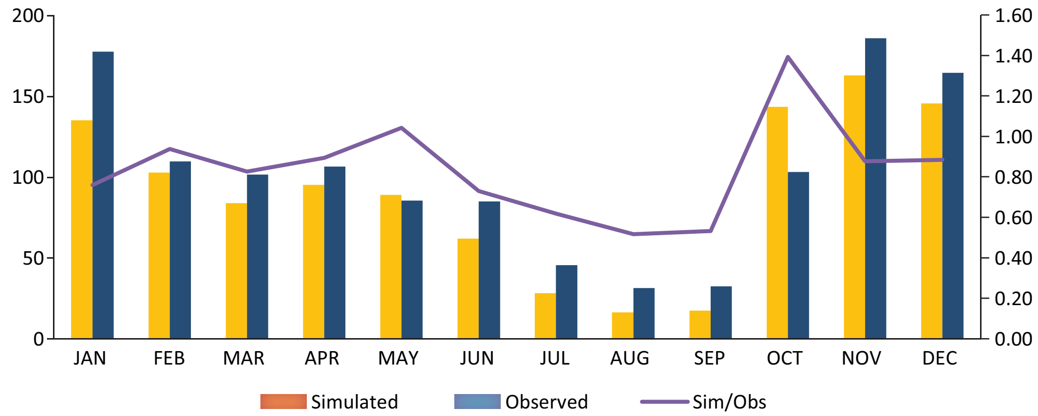


FIGURE 58: Simulated and observed monthly averaged value of Gomti Nagar, Lalbagh, Nishant Ganj and Talkatora District Industries Centre stations

Table 25: Simulated and observed average PM2.5 concentration (in µg/m3) in Lucknow city

	Winter	Summer	Post monsoon	Monsoon	Yearly
Simulated	128	82	153	22	90
Observed	150	92	144	38	102

The validation of model established that the model is able to reproduce ambient pollutant concentration satisfactorily and it can be further utilized for running sensitivities of different sources in order to derive source apportionment and impact from various interventions on the air quality of Lucknow city.

Source apportionment of ambient $PM_{2.5}$ in Lucknow city

The source sensitivity analysis was performed of the validated WRF-CMAQ model to quantify the contributions from different sources of ambient $PM_{2.5}$ in Lucknow.

Residential sector emerges out to be one of the major contributors in all the seasons with yearly average of about 23% while the maximum contribution of 27% is observed in winter season. The winter season of the Indo Gangetic plains is quite cold, the PBL height becomes shallower and wind speed are very slow resulting in increase in contribution of local sources. The next top contributor in Lucknow city is the road dust sector with yearly averaged contribution of 22%. The contribution rises to 26% in summer season due to increase in wind speed coupled with prevailing dry conditions in the region causing re-suspension of dust particles in the atmosphere. Similarly in winter months very dry conditions prevail causing re-suspension of loose dust particles on the road resulting in 19% contribution from road dust in the season.

From Table 25 and Table 26, we can infer that even though the contribution from road dust rises to 32% in monsoon season but the absolute ambient $PM_{2.5}$ contributed from the sector remains quite low (about 7µg/m^3) compared to 21 µg/m^3 ambient $PM_{2.5}$ concentration contributed in summer season.

The third biggest contributor towards ambient $PM_{2.5}$ concentration comes from international sources followed by transport, industry, open agriculture residue burning, power, others, construction and DG sets sectors.

Table 26: Sectoral contributions in different seasons and yearly average of $PM_{2.5}$ in Lucknow city

Sectors	Winter	Summer	Post monsoon	Monsoon	Yearly
Residential	27%	20%	21%	21%	23%
Transport	16%	7%	12%	11%	12%
Industry	8%	5%	7%	6%	7%
Brick kilns	5%	3%	5%	0%	4%
Power	8%	5%	6%	4%	6%
Construction	1%	1%	1%	2%	1%
Open agri residue	0%	12%	19%	0%	7%
Road dust	19%	26%	15%	32%	22%
Others	5%	4%	4%	5%	4%
DG sets	0%	1%	0%	0%	0%
International sources	11%	17%	11%	20%	14%

The contributions from transport sector vary from 7% to 16% with maximum contribution of 16% in winter months. Similar trend is observed in industry and power sectors with contributions varying in the range of 5% to 8% and 4% to 8% respectively with maximum contribution observed in winter months. It is quite evident from Table 26 that agricultural burning is not a year-round prominent sector in deteriorating the air quality of Lucknow with contribution varying from 0 to 19%. The agriculture residue burning happens in the harvesting seasons which fall in the months of Apr-May (summer season) and Oct-Nov (post-monsoon months) resulting in contribution of 12% in summers and 19% in post monsoon. The higher impact from open burning of agriculture residues is observed in post monsoon months due to calmer wind speed, shallower planetary boundary height and high relative humidity coupled with wind direction aiding the movement of particulate matter produced by burning in eastern Indo Gangetic plain (mostly Punjab and Haryana regions) towards the western Indo Gangetic plains.

The stable atmospheric conditions prevailing in winter season result in more contributions from local sources present inside the city boundary like transport and road dust while fall in contributions from long range sources like international is observed. The 17% contributions from international sources in summer months is when there is long range transport of particulate matter (anthropogenic and natural) which is aided by high wind speed and dry conditions.

The contribution from brick kiln sector goes from as low as 0% due to closure of brick kilns in monsoon months to as high as 5% in winter months. The others sector which includes waste burning, crematoria, and restaurants contribute about 4% to 5% across different seasons.

Primary and secondary particulate matter contribution in Lucknow city

The basic components of ambient $PM_{2.5}$ concentration include primary particulate matter (PMPRIM), secondary inorganic (SIA) and secondary organic aerosols (SOA). The variation of atmospheric chemistry, emitting sources and meteorological parameters from season to season result in seasonal variation of $PM_{2.5}$ species (i.e., PMPRIM, SIA and SOA). The knowledge of seasonal contribution of these species will provide policy makers more detailed cause and effect relationship between emitting sources and ambient $PM_{2.5}$ concentration.

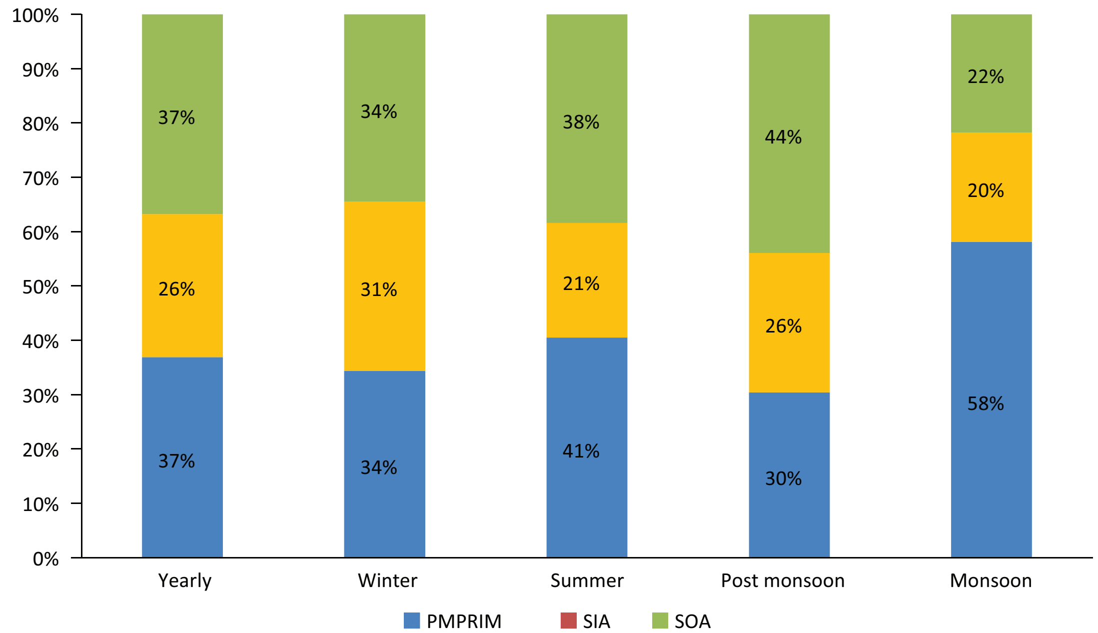


FIGURE 59: Primary (PMPRIM), secondary inorganic (SIA) and secondary organic (SOA) particulate matter contribution in ambient $PM_{2.5}$ in Lucknow city

The results of simulated values have been plotted in Figure 59 which shows contribution of primary, secondary inorganics and organic particulate matter in ambient $PM_{2.5}$ concentration of Lucknow city. The results show high contribution of primary particulates in summer and monsoon season of 41% and 58% respectively. This can be attributed to high re-suspension of road dust particulates in the summer months due to prevailing high wind speeds and dry conditions. Further due to downwash of precursor pollutants in the monsoon months cause lower formation of secondary particulates (21% from secondary inorganic aerosols and 38% from secondary organic aerosols) resulting in higher contribution from primary particulates (58%) even though the total ambient $PM_{2.5}$ concentration remains quite low in the season. The contribution in ambient $PM_{2.5}$ concentration is dominated by secondary particulates (including both secondary organic and inorganic particulates) which vary from 42% in monsoon to about 70% in post-monsoon seasons. Higher contribution of secondary particulates can be attributed emissions from residential sector using solid fuels prevalent in the region, agricultural biomass burning, transport, industry and power sector. While the individual contributions from secondary organics and inorganics vary seasonally. The SIA's contribution in ambient $PM_{2.5}$ concentration peaks to 31% in the winter months while it reaches its lowest values in summer and monsoon season with contribution of 21% and 20% respectively. The contributions in ambient $PM_{2.5}$ concentration from secondary organic aerosols vary from 22% in monsoon season to 44% in post monsoon months. The increase in contribution to ambient $PM_{2.5}$ concentration during post monsoon months from secondary organic aerosol can be attributed to open burning of agriculture residues in the Indo Gangetic plain observed during this season.

The results of the study present significant contribution of secondary particulates (including both SOA and SIA) in the ambient $PM_{2.5}$ concentration of Lucknow city. These results suggest that the air quality policy actions should not be just aimed to control ambient $PM_{2.5}$ concentrations of the city but should include precursor pollutants like NO_X, SO_X, and VOCs also which are emitted from anthropogenic sources and are responsible for formation of SOA and SIA in the city.

Geographical contributions in Lucknow city

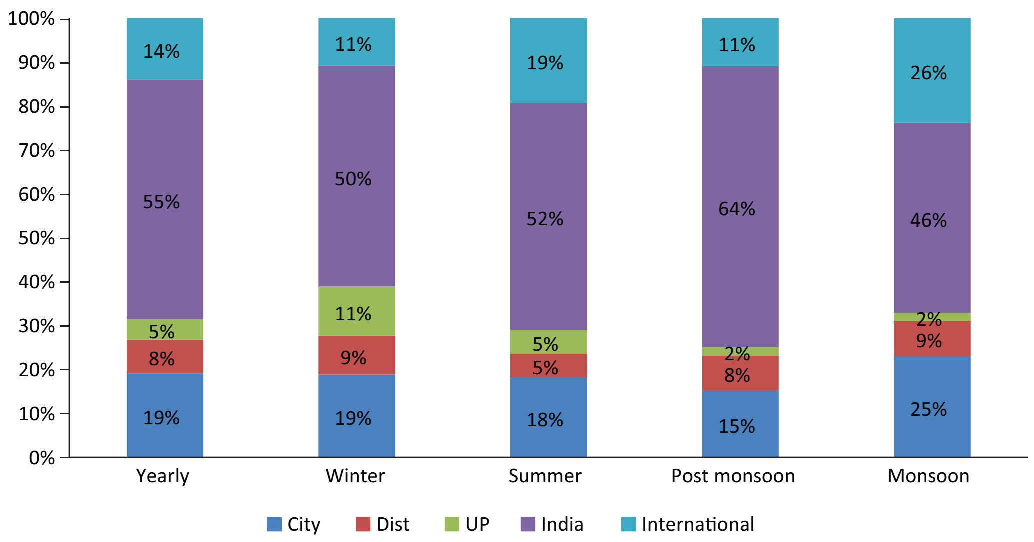


FIGURE 60: Geographical contribution of $PM_{2.5}$ concentrations in the Lucknow city

Yearly averaged contribution of 19% has been estimated in which city's own sources responsible towards city's ambient $PM_{2.5}$ concentrations rest 81% comes from outside the city boundary out of which about 8% is contributed from sources within the Lucknow district but falling outside the city boundary. The contribution from sources within the state of Uttar Pradesh, excluding Lucknow district, vary between 2% to 11%. The maximum contribution of 11% from state sources is observed in winter months which can be attributed to calmer wind speed which result in fall in contributions from distant sources. Maximum contribution of 64% from sources in India, excluding sources within state of UP, district and city of Lucknow, is estimated in post monsoon months. This increase is attributable to $PM_{2.5}$ concentrations resulting from open burning of agriculture residue in the Punjab, Haryana and adjoining regions during the post monsoon months. The maximum contribution of 19% from international sources is observed during the summer seasons when the high wind speed aids the flow of particulate matter over long distances. In the post monsoon months, the contribution in percentage terms decreases to 11% due heavy contributions from national sources but the absolute concentration between summer and post monsoon months remain somewhat same (16-17 $\mu g/m^3$).

So, it can be inferred from the analysis that major contribution in the city's ambient $PM_{2.5}$ concertation comes from outside the city's boundary with majority contributions attributable to national sources.

7. Conclusion

In recent times, air pollution has become a complicated issue as it negatively impacts the health of citizens as well as the economy of the country. A systematic shift towards renewable energy is the pragmatic approach towards reducing the dependency on fossil fuels as well as provides clean energy to households, vehicles, industries, brick kilns etc. It is suggested that comprehensive, integrated and long-term action plan, involving coordinated and coherent efforts from central & state government, NGO's stakeholders and most importantly citizens should be the pressing priority to address this growing concern.

Present work is an attempt for the bottom-up approach to develop the best possible source contribution estimates for the all the polluting sectors in Lucknow city and district. For this purpose sharing and systematic review of the activity data has been done in collaboration with UPPCB officials. Relative share of each sector varies considerably for different pollutant which has been discussed in detailed in this report. As evident from the above stated facts and figures, transport sector and road dust re-suspension is major concern in city while road dust and construction and residential sector are a major concern in district. Road dust re-suspension holds the maximum share in the particulate matter emissions. This is majorly because of the increasing transport in the city which has increased over time.

Annexure

Annexure 1: Survey identified grid details

For the entire study area, we have taken representative samples at 2 km × 2 km grids, seven locations within the city and seven locations outside the city boundary within the district boundary of Lucknow were selected for conducting surveys. In addition grid surrounding five highways entering/leaving the city was also selected for primary survey thereby a total of 19 grids were surveyed. These grids were selected based on different land use land cover pattern representing residential, commercial, industrial, and kerbside locations.

The overlay of landuse map over the study domain identified the predominant land-use of different grids. Based on this, all the grids in the study domain were categorized in to different land-use land cover (LULC) classes, which are:

1. Residential
    a) Highly populated (RH)
    b) Moderately populated (RM)
    c) Less populated (RL)
2. Commercial (C)
3. Industrial (I)
4. Mixed (M)
5. Public purposes (PP)
6. Others (O)

Considering higher number of grids falling in the residential land use category, it is sub-divided into three types based on their population densities (RM, RH, and RL). All the selected locations represent a type of land use category for the study domain.

In all the selected grids, traffic count survey, parking lot survey, DG set survey, hotel/restaurants survey were carried out using structured questionnaires. Traffic count survey in all the selected grids was carried out for three different categories of roads (Details of the selected locations are listed below). In addition survey was carried out at highways entering/leaving the city. Ideal sample size for parking lot is estimated using standard methodology (using Cochran's formula). Also the estimated fuel consumption based on survey was validated with the actual fuel consumption collected from oil companies.

For residential sector, primary survey was conducted to gather specific information related to household cooking activities at tehsil level in Lucknow district. A defined set of survey questionnaires was prepared to gather specific information related to cooking activities in the households. The collected information includes household size, type of fuel used for cooking, monthly consumption of cooking fuel etc. Also, information pertaining to household electrification, daily/monthly power cut etc. was collected during the survey.

The survey was conducted at 95% CI with 2% to 3% ME and 50% of population proportion. The calculated sample size was distributed among rural and urban areas based on the household ratio in each area of each tehsil. Ten villages in the rural areas of each tehsil were selected randomly and calculated survey household numbers were distributed according to total household number (as per India Census, 2011) in the selected village. Similarly, in the Lucknow Municipal Corporation area, the calculated survey households (N = 4853) were distributed in ten wards which were randomly selected at different parts of the city. In Bakshi ka Talab tehsil 715 households were surveyed at rural areas and 839 households were surveyed at urban areas of the block. 1357 households were surveyed at rural areas of Lucknow tehisil. 1049 rural and 226 urban households were surveyed in Mahihabad tehsil. In Mohanlalganj tehsil, 552 rural and 413 urban households were surveyed.

The same methodology for survey was followed in earlier SA study carried out different cities across the country. Based on TERI's past experience in this field and also based on earlier SA studies carried out at different parts of the country, this survey is sufficient enough to represent the study area.

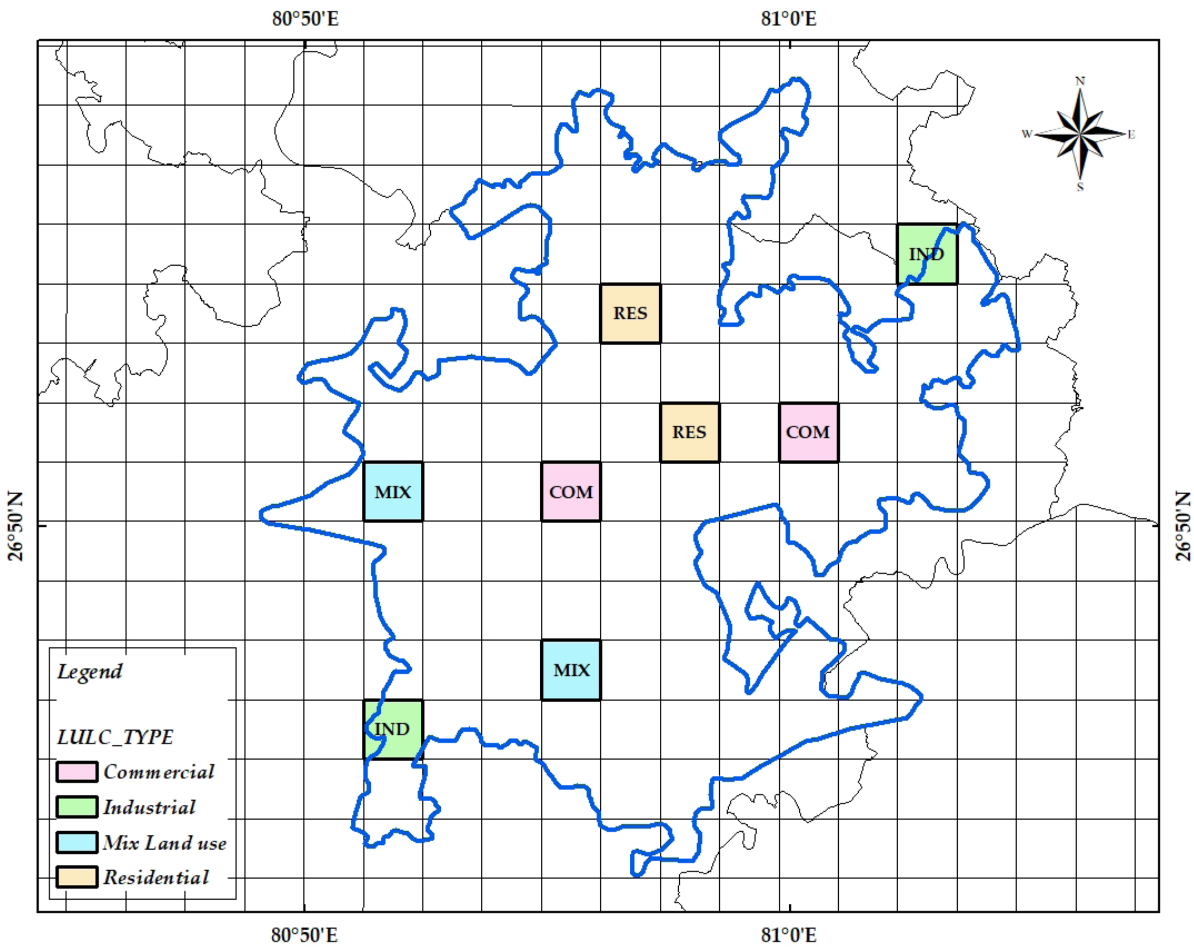


FIGURE 1 (ANNEXURE): Grids selected for Survey in the city.

Location Code	Location name	Road type
L-1	Naka Hindola Police Station, Guru dwara road	Major_road
	Buddha Dharmankur Sabha, Gautam Buddha marg	Connecting_road
	Netram Ajay Kumar Restaurant, Shri Ram Road, Near aminabad police station	Minor_road
L-2	St Joseph school, sitapur road	Major_road
	Sector Q park, near sector Q bus stop, sector Q road, Aliganj	connecting road
	In front of LDA football and cricket ground/ stadium, sector L aliganj	minor road
L-3	Institute Of Tool Room Training,A-1, Kanpur Rd, Gindan Khera, Nadarganj, Amausi, Lucknow, Uttar Pradesh 226008	Major_road
	Nadarganj Industrial Area Rd, Amausi bus depot,	connecting road
	Fire brigade building, UP govt, Nadarganji, Amausi	minor road
L-4	National Bureau of Fish Genetic Resources, Canal Ring Road, P.O, Dilkusha Marg, Lucknow, Uttar Pradesh 226002	Major_road
	Indian Oil Retail Outlet, Jail Rd, Eldeco Udyan-1, Bangla Bazar, Lucknow, Uttar Pradesh 226002	connecting road
	Pioneer Montessori School, Primary Section, 831, Eldeco Udyan-1, Bangla Bazar, Lucknow, Uttar Pradesh 226012	minor road
L-5	Near DBL Lawn, Near Railway Overbridge, Kanpur, Hardoi Bypass Rd, Budheswar, Lucknow, Uttar Pradesh 226017	Major_road
	Pal Tiraha, T (Intersection) point of Almannagar road and Luv Kush road	connecting road
	Near Rajajipuram lake	minor road
L-6	Amar shaheed path, Bus Station, Vibhuti Khand, Gomti Nagar, Lucknow, Uttar Pradesh 226010	Major_road
	TC Eye Centre,B-5/36, Railway Station Rd, Vinay Khand 5, Gomti Nagar	connecting road
	near mini stadium, Vinay Khand 4, Gomti Nagar, Lucknow,	minor road

Location Code	Location name	Road type
L-7	UPTRON Building, Gomti Barrage, Gomti Nagar, Lucknow, Uttar Pradesh 226010	Major_road
	Baikunth Dham, Butler Rd, Butler Colony, Lucknow, Uttar Pradesh 226001	connecting road
	Kalyan Bhavan, Prag Narayan Rd, Butler Colony, Lucknow, Uttar Pradesh 226001	minor road
L- 8 (Vill)	Tata motors main gate, Deva Rd, Chinhat, Lucknow, Uttar Pradesh 226016	Major_road
	in front of AVG Engeering Works, Dhawa, Uttar Pradesh 226019	connecting road
	Entrance of Goila village	minor road
L- 9 (Vill)	Mohanlalganj bus stop, Rai Bareli Road, Mohanlalganj, Uttar Pradesh 226301	Major_road
	village near railway track	minor road
	Bus stop to railway track	connecting road
L-10 (Vill)	Near Vijaya Bank, SULTANPUR ROAD connecting to NH towards lucknow, GOSAIGANJ, LUCKNOW	Major_road
	Lala Mahadev Prasad Verma Balika Mahavidyalaya, Main Market, Gosainganj, Lucknow, Uttar Pradesh 226501	connecting road
	near talab, GOSAIGANJ	minor road
L- 11 (Vill)	Shri Siddhi Vinayak Filling Station, SH 25, Mahilabad, Uttar Pradesh 226102	Major_road
	Chaudrana road, connecting to NH 25 , Mahilabad	connecting road
	Masjid Kuvedaan sahab, Mahilabad	minor road
L- 12 (Vill)	Petrol Pump, Sitapur Rd, NH25, Itaunja, Uttar Pradesh 226203	Major_road
	road connecting to NH 25, Itaunja	connecting road
	Itaunja	minor road
L- 13 (Vill)	outskirts of mall town, NH, (near pond) towards mahilabad side	Major_road
	Virangana uda devi girls inter college, Jehta mall road	connecting road
	new masjid , near pond, road connecting to major road	minor road

Location Code	Location name	Road type
L- 14 (Vill)	police station Nigoha, NH 36, Lucknow road	Major_road
	Sameer Prince Shu Haus Hotel, road to nigoha town	connecting road
	Annpurna Mandir, Nigohan Lucknow,	minor road
Highway-1	Lucknow Rasulabad Highway	
Highway-2	Lucknow Barabanki Highway	
Highway-3	Lucknow Sultanpur Highway	
Highway-4	Lucknow Kanpur Highway	
Highway-5	Lucknow Hardoi Highway	

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