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EMISSION INVENTORY AND POLLUTION REDUCTION STRATEGIES FOR BENGALURU

Emission Inventory and Pollution Reduction Strategies for Bengaluru

Center for Study of Science, Technology and Policy

February 2022

Designed and edited by CSTEP

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This report should be cited as: CSTEP. (2022). Emission inventory and pollution reduction strategies for Bengaluru. (CSTEP-RR-2022-4).

February 2022

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Foreword

"Emission inventory and Source Apportionment Study conducted by Centre for Study of Science, Technology & Policy (CSTEP) has helped to identify the polluting sources and hotspots in the city of Bengaluru.

The recommendations suggested in the study will help to modify the action plan developed under National Clean Air Program (NCAP) for effective implementation.

This will help to plan and prepare the futuristic strategies to make Bengaluru a model city in the Country for improving the Quality of Life of the Citizens, Environment and Ecology".

04/02/2022

(Dr. Shanth A. Thimmaiah)
Chairman
KSPCB

Date: 04.02.2022
Place: Bengaluru.

Acknowledgements

We are thankful to the Shakti Sustainable Energy Foundation and Bloomberg Philanthropies for supporting this study.

We would like to extend our sincere gratitude to the Forest, Ecology, and Environment Department (DoFEE), Government of Karnataka and Karnataka State Pollution Control Board (KSPCB)—without them the study would not have been possible. The study was conducted under the guidance of Shri Vijay Kumar Gogi, former Principal Secretary to Government (Environment and Ecology) and various KSPCB officials who have provided immense support in information gathering. Various organisations and departments including Bruhat Bengaluru Mahanagara Palike (BBMP), Bangalore Electricity Supply Company Limited (BESCOM), Transport Department, Department of Civil Supplies, Indian Oil Corporation Limited (IOCL), Karnataka Industrial Areas Development Board (KIADB), Department of Electrical Inspectorate, Bengaluru International Airport Limited (BIAL), and district administrations have supported data collection for various activities to make this emission inventory a robust one.

We thank Dr Sreekanth Vakacherla, Anantha Lakshmi Paladugula and Riya Rachel Mohan from the Center for Study of Science, Technology and Policy (CSTEP) for their critical review of the project. Expert inputs from our external reviewers— Dr Tirthankar Banerjee [BHU, India], Dr Sumit Sharma [TERI, India], and Prof Chandra Venkataraman [IIT Bombay, India]—have helped us frame the research and its findings in a meaningful manner. We express our profound gratitude to them.

We would also like to thank Dr Jai Asundi (Executive Director, CSTEP) and Mr. Priyavrat Bhati (Sector Head—Climate, Environment, and Sustainability, CSTEP) for their constant support and motivation for conducting this research.

Finally, we would like to extend our sincere gratitude to the Communication and Policy Engagement team at CSTEP for editorial and design support.

Executive Summary

Growing air pollution poses a serious health risk in India. The National Clean Air Programme (NCAP), was launched by the Ministry of Environment, Forest and Climate Change (MoEFCC) in 2019, with the target to reduce particulate matter concentration level by 20-30% in several non-attainment cities in India. These non-attainment cities do not meet the National Ambient Air Quality Standards (NAAQS). Bengaluru has been identified as one of the non-attainment cities of India under NCAP. Considering this, the Government of Karnataka has been trying to generate scientific evidence on the causes of air pollution and to identify sectoral control measures to improve the quality of air in the city. As part of its efforts to generate scientific evidence on air pollution, the Department of Forest, Ecology and Environment (DoFEE) along with the Karnataka State Pollution Control Board (KSPCB) invited the Center for Study of Science, Technology, and Policy (CSTEP) in 2018 to conduct an emission inventory (EI) study for Bengaluru.

An EI is a sector-specific accounting of pollutants emitted by different activities over a specific period. CSTEP developed the EI for the air-shed area (an area of 60km × 60km) of Bengaluru. The activities from different sectors (transportation, industry, diesel generator sets, construction and demolition, waste burning, domestic and commercial fuel use, etc.) that contribute to air pollution in Bengaluru were identified. Emission load for various polluting sectors was estimated based on Central Pollution Control Board (CPCB) and the United States Environmental Protection Agency (USEPA) methodology. The EI study estimated particulate matter (PM_{10} and $PM_{2.5}$), oxides of nitrogen (NOx), and sulphur dioxide (SO_2) emissions for 2019. Based on the sectoral trends, CSTEP also projected the emission inventory till 2024.

Domestic fuel consumption:

Emission from domestic fuel consumption was estimated for cooking and heating activities. In Bruhat Bengaluru Mahanagara Palike (BBMP) area, emission from domestic fuel combustion was estimated to be 584 tonnes/yr PM_{10} (2% of total PM_{10} emission load) and 326 tonnes/yr $PM_{2.5}$ (2.2% of total $PM_{2.5}$ emission load). This emission load can be reduced significantly by incentivising liquefied petroleum gas (LPG) use in low-income households.

Commercial fuel consumption (eateries):

Eateries were found using coal/charcoal (for tandoor) in huge quantities along with LPG and piped natural gas (PNG) within the BBMP area. Emission from eateries in the BBMP area was estimated to contribute to around 1,026 tonnes/yr PM_{10} (around 4.2% of total PM_{10} load) and 549 tonnes/yr of $PM_{2.5}$ (3.7% of total $PM_{2.5}$ load). Though coal /charcoal constitutes only 0.3% of total fuel consumed in the eateries, it contributes to 97% of PM_{10} emission load from eateries. Emission from coal/charcoal consumption can be reduced through the mandatory installation of high-efficiency air pollution control devices in restaurants.

Diesel generator (DG) sets:

The BBMP area has around 8,700 DG sets installed with a cumulative installed capacity of 28,01,180 KVA. High installed capacity with an average load-shedding (scheduled + unscheduled) of 2 hours daily resulted in 2,187 tonnes/yr PM_{10} (around 8.9% of total PM_{10} emissions) and 1,601 tonnes/yr $PM_{2.5}$ (10.9% of total $PM_{2.5}$ emissions) emissions from DG sets. Bellanduru ward (no. 150) alone contributed to around 11% of PM_{10} emissions from DG sets. Other than PM emissions, DG sets were also major contributors to gaseous pollutants (NO_x – 37%, SO_2 – 51%). Rooftop solar photovoltaic cells/cleaner fuel-based generators can help reduce emissions from DG sets.

Municipal solid waste burning:

Waste burning contributed to around 1,456 tonnes/yr (6% of the total PM_{10} emission) and 1,412 tonnes/yr of $PM_{2.5}$ (10% of the total $PM_{2.5}$ emission) in the BBMP area. A more efficient solid waste management is needed to reduce emissions from this sector.

Construction and demolition:

During 2018-19, a total of 235 new construction projects were being built in and around the BBMP area. Emissions from these constructions contributed to around 2,702 tonnes/yr PM_{10} (11% of total PM_{10}) and 450 tonnes/yr of $PM_{2.5}$ (3% of total $PM_{2.5}$). Due to data unavailability, emissions from infrastructure development (road paving, metro, and bridge constructions) and demolitions were not estimated.

Airport:

As part of the air-shed area, emissions from Kempegowda International Airport (KIA) were estimated and found to be 248 tonnes/yr (PM_{10}) and 214 tonnes/yr ($PM_{2.5}$).

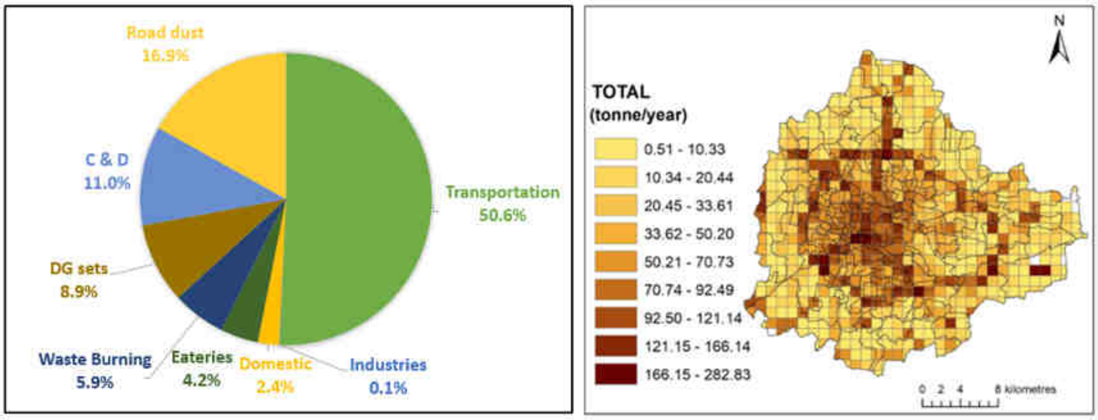
Industrial fuel consumption:

During the last couple of years, industrial plants within the BBMP area were either shifted to nearby industrial areas or closed down. Still, the gaseous emissions from industrial fuel consumption contributed to 25% of the total SO_2 emission.

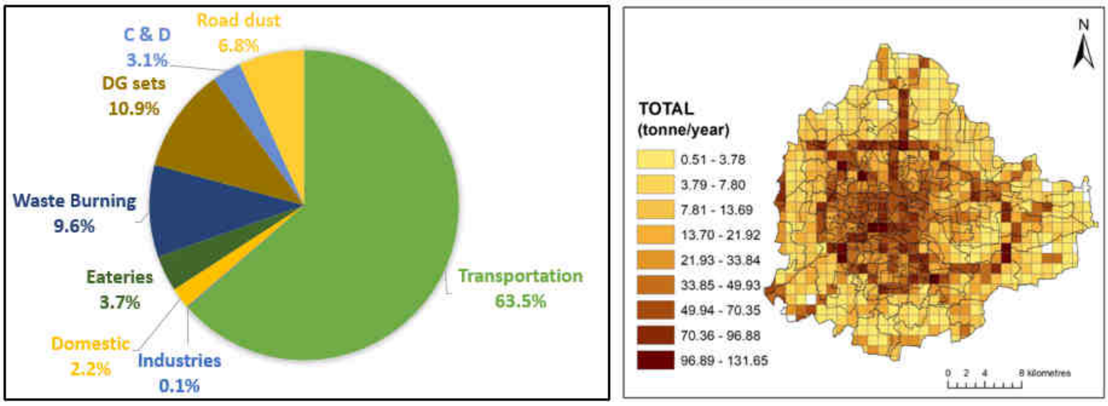
Road transportation:

Emissions from the transportation sector – tailpipe emission (51%) and re-suspension of dust (17%) – comprised 68% of the total PM_{10} emission and 60% of NO_x emission. Just 3% of commercial vehicles contributed to 84% of PM_{10} emissions from transportation. Emission from diesel cars was estimated to be 9% of PM_{10} emissions from the transportation sector. Affordable and clean fuel-driven public transport (CNG/EV) with end-to-end connectivity will reduce the usage of private vehicles and emissions from the sector.

The sectoral emission loads of PM_{10} and $PM_{2.5}$ and their spatial distribution over the BBMP area are depicted below.



Sectoral PM_{10} emission load and its spatial distribution over BBMP



Sectoral $PM_{2.5}$ emission load and its spatial distribution over BBMP

Based on this comprehensive emission inventory, we carried out dispersion modelling. The measured annual average of $PM_{2.5}$ (PM_{10}) over Bengaluru was 41.34 (88.86) μg/m^3 and the model-simulated annual average was 44.82 (86.01) μg/m^3. We validated the simulations against KSPCB observations. The error percentage (E) between the model-simulated annual average and KSPCB observation was 10% for $PM_{2.5}$ and 8% for PM_{10}. From the simulated annual concentration maps of Bengaluru, Nayanda Halli and Bapuji Nagar emerged as PM_{10} hotspots, whereas Nayanda Halli, Bapuji Nagar, Rayapuram, and Majestic turned out to be $PM_{2.5}$ hotspots.

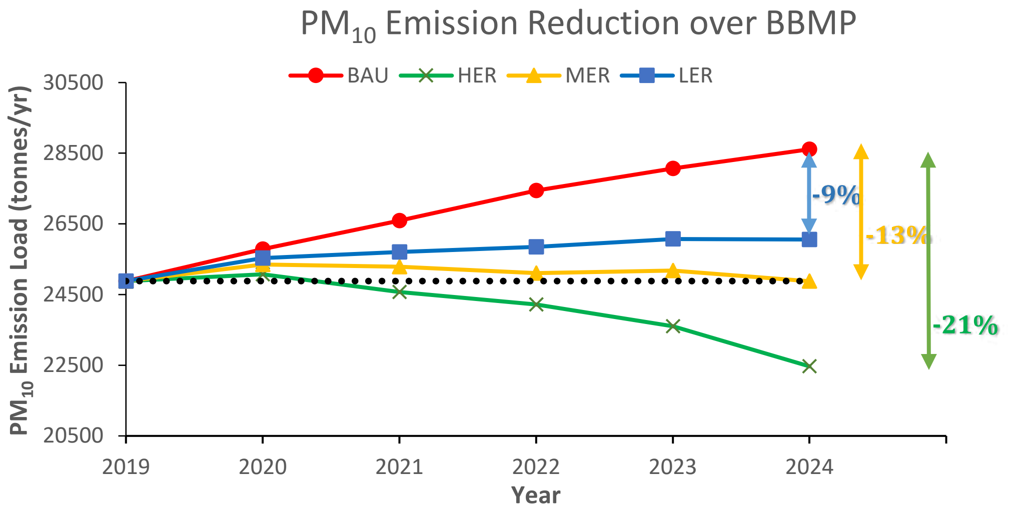
Further, we estimated the percentage share of individual sectors. In 2019, the transportation sector accounted for 55.3% and 67.2% of the total annual PM_{10} and $PM_{2.5}$ concentrations, respectively. Road dust along with re-suspended road dust accounted for 23.8% and 8.3% of the total annual PM_{10} and $PM_{2.5}$ concentrations, respectively.

The study estimated that the total PM_{10} emission load for BBMP would reach around 28k tonnes/year by 2024, a 15% increase from 2019 levels under the business-as-usual scenario (BAU). Transportation and dust remain the key polluting sectors in 2024 as well.

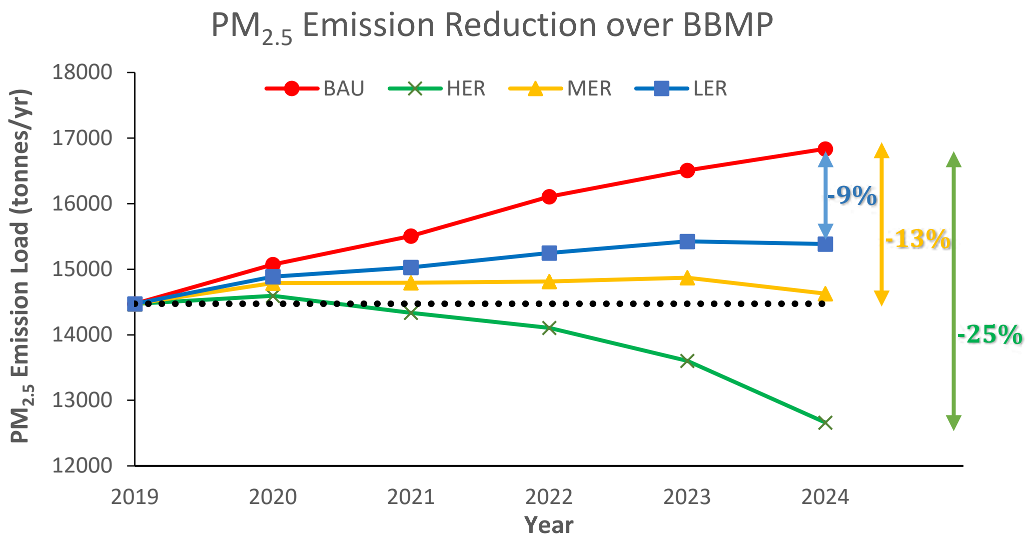
In the BAU scenario, the projected PM_{10} concentration increased from 86.01 μg/m^3 in 2019 to 108.01 μg/m^3 in 2024, which is a 25.5% increase with respect to the base year (2019). $PM_{2.5}$ concentration increased from 44.82 μg/m^3 in 2019 to 56.59 μg/m^3 in 2024, which is a 26.3% increase with respect to the base year.

The study also performed a techno-economic assessment to identify efficient technologies for curbing air pollution. A scenario analysis was carried out with three scenarios, based on high priority measures suggested by KSPCB. Some of the recommended measures include the installation of diesel particulate filters (DPFs), conversion of two-stroke autos to petrol-LPG hybrid autos, effective solid waste management, reduction in solid fuel usage, etc. These measures were clubbed with varying levels of compliance/targets to form high-, medium-, and low-emission-reduction (HER, MER, and LER) scenarios. Under the high-, medium- and low-emission reduction scenarios, the city would achieve an emission reduction (PM_{10}) of 21%, 13%, and 9% w.r.t 2024 emissions (BAU scenario), respectively.

The study also lists a strategic roadmap for all control measures considered by KSPCB. The roadmap includes the targets to be achieved year-on-year till 2024 while identifying the departments responsible for its implementation. The study also evaluates the costs likely to be incurred by the government to implement these measures. Some of the control measures under the HER scenario are already part of city implementation strategy and will help to prevent 800-1200 deaths annually. The implementation cost which only includes the capital cost for technological installations, incentives by the government, carrying out capacity building programmes for the departments and improving the monitoring infrastructure will be around 3230 crores.



Emission Reduction (PM_{10}) due to mitigation measures



Emission Reduction ($PM_{2.5}$) due to mitigation measures

All three scenarios show a reduction in the concentration of pollutants with respect to the respective year's BAU scenario. Possible concentration reductions from BAU for both PM_{10} and $PM_{2.5}$ are ~26.5%, ~13.5%, and ~9.6%, respectively, for high-, medium-, and low-emission reduction scenarios by 2024.

That said, effective on-ground implementation of any plan involves the cooperation of citizens. Hence, it is important to create awareness about the health and environmental impacts of air pollution so that citizens make conscious lifestyle choices that drive sustainable transitions.

Contents

Tables

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Abbreviations

BAU	business as usual
BBMP	Bruhat Bengaluru Mahanagara Palike
BESCOM	Bangalore Electricity Supply Company Limited
BIAL	Bangalore International Airport Limited
BMTC	Bengaluru Metropolitan Transport Corporation
BPCL	Bharat Petroleum Corporation Ltd
BS-VI	Bharat Stage VI
CAMQ	Community Multiscale Air Quality Model
CAMx	Comprehensive Air Quality Model with Extensions
CPCB	Central Pollution Control Board
DG	diesel generator
DoT	Department of Transportation
DPF	diesel particulate filter
ECMWF	European Centre for Medium-Range Weather Forecasts
EDGAR	Emission Database for Global Atmospheric Research
EF	emission factor
EI	emission inventory
ERA5	ECMWF atmospheric re-analyses
FO	fuel oil
GAIL	Gas Authority of India Limited
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GHS	Global Human Settlement
GIS	geographic information system
GoK	Government of Karnataka
HCV	heavy commercial vehicle
HER	high emission reduction
HPCL	Hindustan Petroleum Corporation Limited
IMD	India Meteorological Department
IOCL	Indian Oil Corporation Limited
IT	information technology
KIADB	Karnataka Industrial Area Development Board
KSPCB	Karnataka State Pollution Control Board
KVA	kilovolt ampere
LCV	light commercial vehicle
LER	low emission reduction
LPG	liquefied petroleum gas
LTO	landing and take-off
LULC	land use land cover
MCV	medium commercial vehicle
MoEFCC	Ministry of Environment, Forest and Climate Change
MER	medium emission reduction
MOZART	Model for Ozone and Related chemical Tracers
MSW	municipal solid waste
NAAQS	National Ambient Air Quality Standards
NCAP	National Clean Air Programme
NHAI	National Highways Authority of India
PBLH	planetary boundary layer height
PM_{10}	particulate matter 10
$PM_{2.5}$	particulate matter 2.5

PNG	piped natural gas
PDS	public distribution system
R^2	coefficient of determination
RDF	refuse-derived fuel
RERA	Real Estate Regulatory Authority
RH	relative humidity
RMSE	root mean square error
RTPV	rooftop solar photovoltaic
SA	source apportionment
SAFAR	System of Air Quality and Weather Forecasting and Research
TOMS-OMI	Total Ozone Mapping Spectrometer Ozone Monitoring Instrument
VKT	vehicle kilometre travelled
VOC	volatile organic compound
WRF	Weather Research and Forecasting

1. Introduction

India's National Clean Air Programme (NCAP) was launched by the Ministry of Environment, Forest and Climate Change (MoEFCC) in 2019 to develop an air quality management framework for various cities in India. Across the country, 132 cities were identified as 'non-attainment cities', where the ambient particulate matter (PM_{10}) concentration level does not meet the National Ambient Air Quality Standards (NAAQS). Under NCAP, these cities are required to reduce PM concentration by 20%–30% by 2024 with 2017 considered the base year. However, to frame effective pollution reduction strategies and achieve NCAP targets, scientific evidence on various polluting sources and their activities is essential. Source apportionment (SA) and emission inventory (EI) studies can help identify polluting sources, their share, and spread in a city's total emission.

Bengaluru, the capital of Karnataka, is one of the identified non-attainment cities. The last EI study for the city was conducted in 2008. In a rapidly growing city such as Bengaluru, it is essential to study the emission trends once every 5 years for introducing effective control measures in keeping with the changing dynamics. The Center for Study of Science, Technology and Policy (CSTEP), under the aegis of the Karnataka State Pollution Control Board (KSPCB), developed an EI for Bengaluru to identify efficient air pollution control strategies for the city. CSTEP examined the various polluting sectors and their activities and estimated their contribution and share in the city's total emission load. We used this information to estimate the spread of pollutants in the city. Finally, we identified prioritised control measures for each polluting sector.

1.1. General Description of the City

Bengaluru is spread across an area of approximately 800 km^2. The city is situated at an elevation of 900 m above sea level. In 2011, the population of Bengaluru was around 8.4 million (*Census of India: Primary Census Abstract*), making it the third-most populous city in India. Over the years, the city has witnessed tremendous growth in several aspects. Bengaluru is also called the 'Silicon Valley of India' because of the huge presence of information technology-related companies. Bengaluru city is part of the Bengaluru Urban district, and Bruhat Bengaluru Mahanagara Palike (BBMP) is the administrative body of the city.

Population Growth: Bengaluru transformed from a quaint little town in the 1990s to a bustling city in the 2010s because of the IT boom in the late 1990s. In just 20 years (1991–2011), the population density of Bengaluru doubled from 4130 per square kilometre to 8749.44 per square kilometre. The city has witnessed a population growth of 47% in the last decade (2001–2011) (Verma et al., 2017).

The population growth in the city (from the year 1901 to 2011) is shown in Figure 1-1.

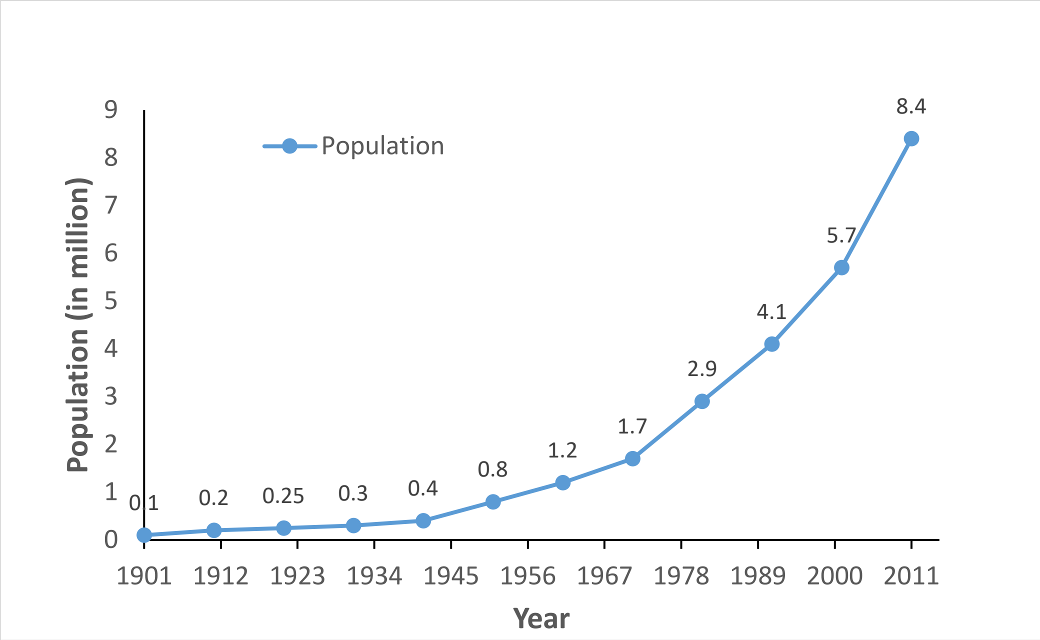


Figure 1-1: Population growth in Bengaluru (year 1901–2011)
Source: Census of India (1901–2011) (Verma et al., 2017)

Climate: Under the Köppen climate classification, the climate of Bengaluru is classified as tropical wet and dry climate. The temperature ranges from 26°C to 32°C throughout the year, except for the months of March, April, and May when the temperature varies from 34°C to 40°C. Bengaluru receives rainfall from May to October. Humidity ranges from 40% to 80% throughout the year.

Vehicular Growth and Road Network: As of 2018, Bengaluru had almost 7.2 million vehicles registered for private and public use. Bengaluru has the second-highest number of two-wheelers in the country, after Delhi. As per the national vehicle registry VAHAN and the transport department, the number of private vehicles in Bengaluru increased from 2.1 million in 2005 to 7.2 million in 2018 (Transport, 2020). Figure 1-2 depicts the year-wise vehicle registration numbers from the year 2012 to 2019. Vehicle categories such as two-wheeler, auto, car, light commercial vehicle (LCV), and heavy commercial vehicle (HCV) have been considered in this chart. The slow growth in public infrastructure has led to an increase in the number of private vehicles on roads in a city that has seen rapid growth in population during the same period. From 2012 to 2019, a prominent increase in the registration of two-wheelers can be observed. From 2014 to 2018, two-wheeler registrations increased by around 50%. Further, from 2014 to 2018, two-wheeler ownership increased by 10%, whereas car ownership increased by 9.5%. In the last few years, the registrations of HCVs, LCVs, and cars have decreased. In contrast, the registrations of two-wheelers and autos increased from 2012 to 2019.

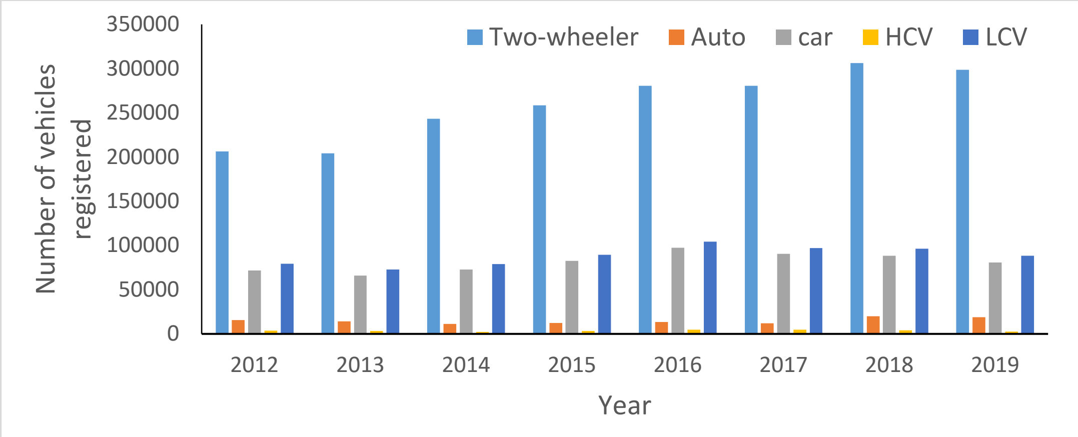


Figure 1-2: Vehicle registration data for Bengaluru (2012–2019)

Bengaluru has a road network of 14,000 km that includes ring roads, arterial and sub-arterial roads, and tertiary roads (Figure 1-3). The road network in the city is mainly radial, converging at the city centre. The main roads of the city include Bellary Road in the north; Tumkur Road and Mysore Road in the west; Kanakpura Road, Bannerghatta Road, and Hosur Road in the south; and Airport Road and Old Madras Road in the east. Of the 14,000 km road network, arterial roads constitute 923 km; sub-arterial roads, 1,017 km; Outer Ring Road (a road that runs around most of the perimeter of the city), 60 km; Inner Ring Road (arterial city road), 10 Km; and other major roads and residential streets, around 12,000 km (IDECK, 2019). Bengaluru faces the challenge of highly congested and overcrowded road corridors, leading to vehicular pollution. The Outer Ring Road is the most affected, as commuters from Doddaballapur Road, Bellary Road, Old Madras Road, Sarjapur Road, and NICE Ring Road use this road daily to reach their destinations in and around the city. To ease congestion on the Outer Ring Road, a peripheral ring road with an overall length of 116 km has been proposed by the state authorities. The burgeoning traffic congestion, vehicular pollution, and overcrowded corridors have greatly harmed the city's environment.

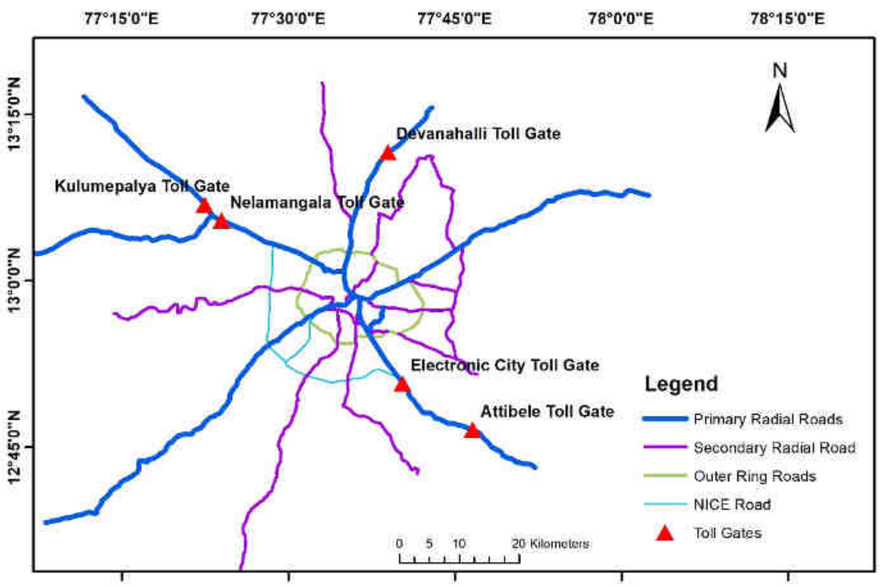


Figure 1-3: Bengaluru's road network

Land Use: Bengaluru, like most Indian cities, does not have proper segregation between commercial and residential areas. Figure 1-4 presents the land use and land cover map of Bengaluru. The majority of the area is built-up area. The city once known as the 'Garden City of India' is now overcrowded, resembling a concrete jungle. This change in the landscape will have serious environmental concerns.

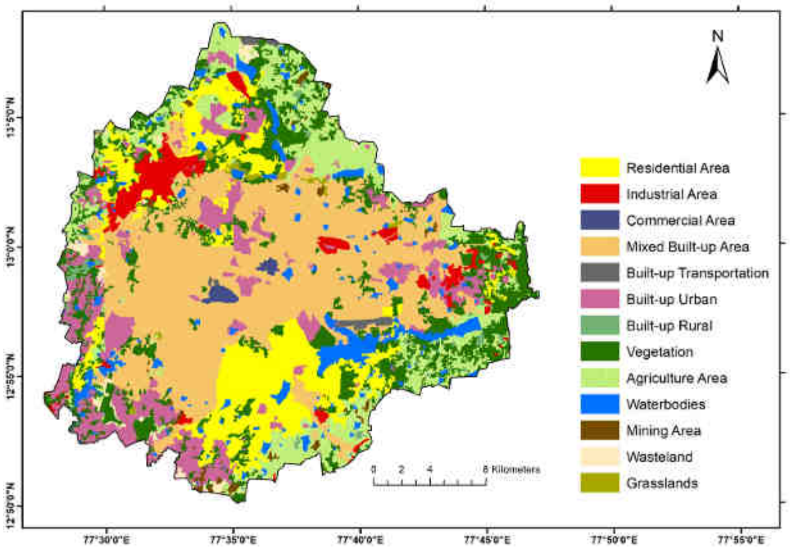


Figure 1-4: Land use and land cover map for Bengaluru
Source: Karnataka State Remote Sensing Applications Centre

Figure 1-5, the concentrations of pollutants PM_{10} and $PM_{2.5}$ have exceeded the NAAQS levels of 60 µg/m^3 and 40 µg/m^3, respectively, over the years. The exceedance factors of increased PM_{10} and $PM_{2.5}$ were calculated as the ratio between the pollutants' annual mean concentration and their respective standard.

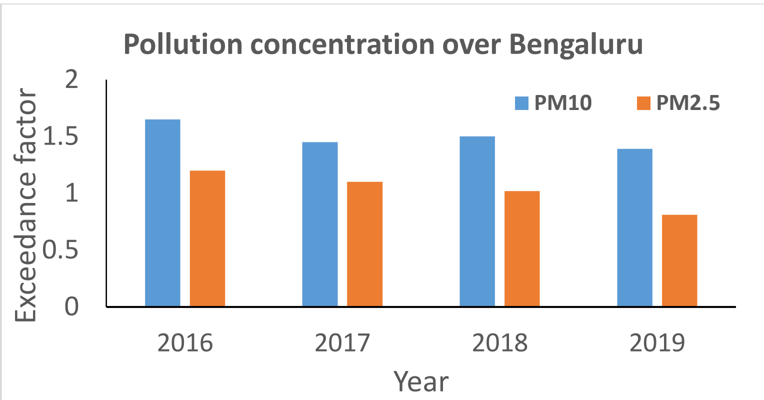


Figure 1-5: PM10 and PM2.5 pollutant concentration over Bengaluru
Source: Karnataka State Pollution Control Board (KSPCB)

1.2. Study Domain and Study Objectives

The EI for Bengaluru is developed for an air-shed area of 60 km × 60 km spread across six districts—Bengaluru Urban, Bengaluru Rural, Ramanagara, Kolar, Chikkaballapur, and Krishnagiri (in Tamil Nadu). The EI is developed with a horizontal resolution of 1 km × 1 km. Thus, the considered area consists of 3600 grids overlaid over the study area. Figure 1-6 (a) depicts the air-shed area used for developing the EI, and panel (b) shows the BBMP area with various wards.

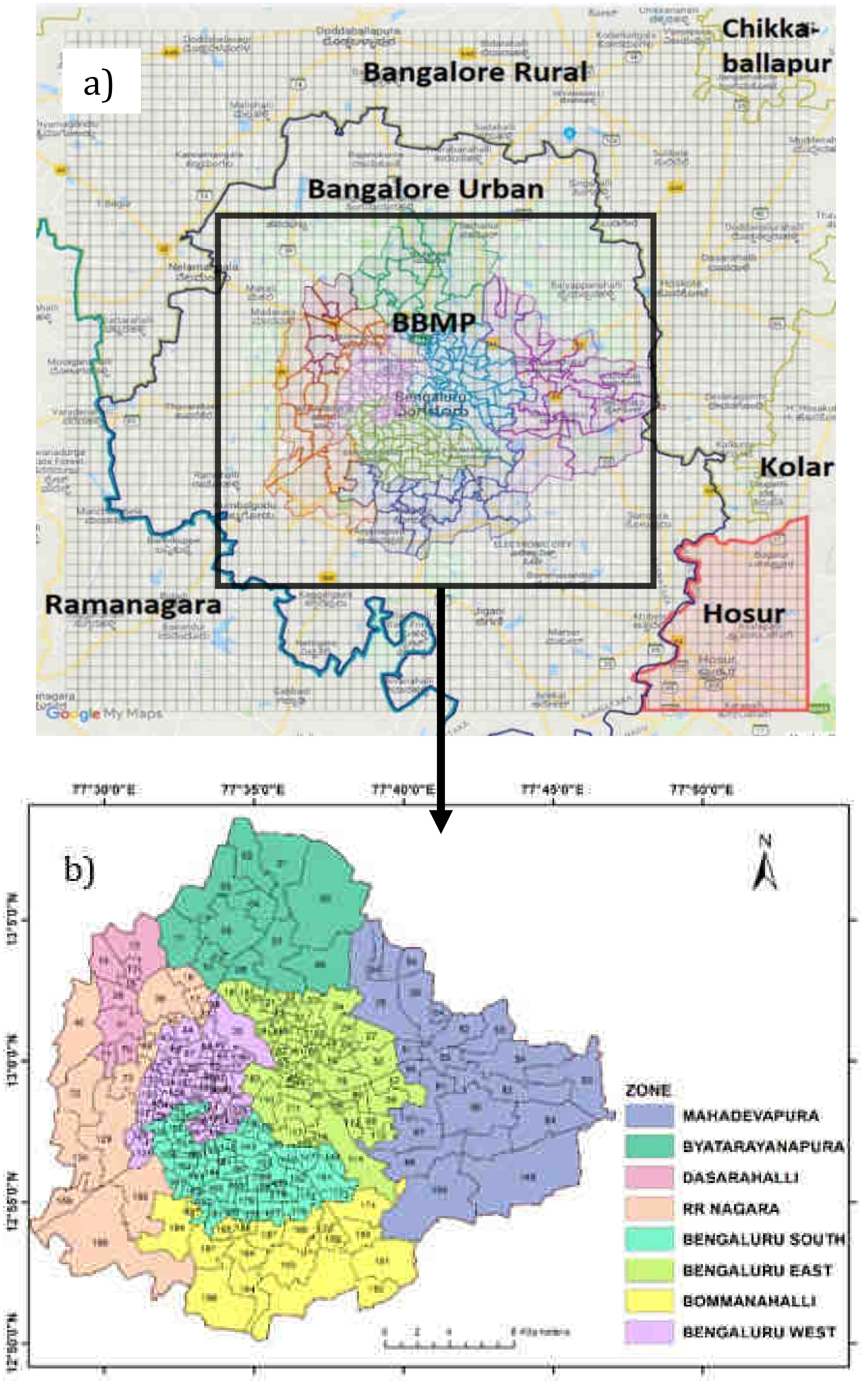


Figure 1-6: (a) Air-shed area for emission inventory study and (b) BBMP area

Study Objectives: The aim of the study is to explore the various polluting sectors in Bengaluru and their share towards the city's total emission load, and identify and suggest prioritised control measures to mitigate emissions. The study objectives are as follows:

- Identification of anthropogenic pollution sources and various corresponding activities source wise in Bengaluru
- Estimation of the sectoral emissions load share for Bengaluru
- Distribution of grid-wise (1 km × 1 km grid) emissions load over Bengaluru
- Estimation of the spatial distribution of pollutant concentration over Bengaluru
- Identification of control measures

For this, we identified key polluting activities in each sector and estimated the corresponding emission load. The estimated emission loads were distributed over the grid on the basis of population density, land use, and land cover for Bengaluru. On the basis of the EI, dispersion modelling was conducted to understand the spread of air pollutants over Bengaluru due to meteorological conditions.

1.3. Study Approach

The study focuses on developing an EI where various activities by every polluting source are identified and the respective emission load is estimated. Figure 1-7 depicts the overall study approach.

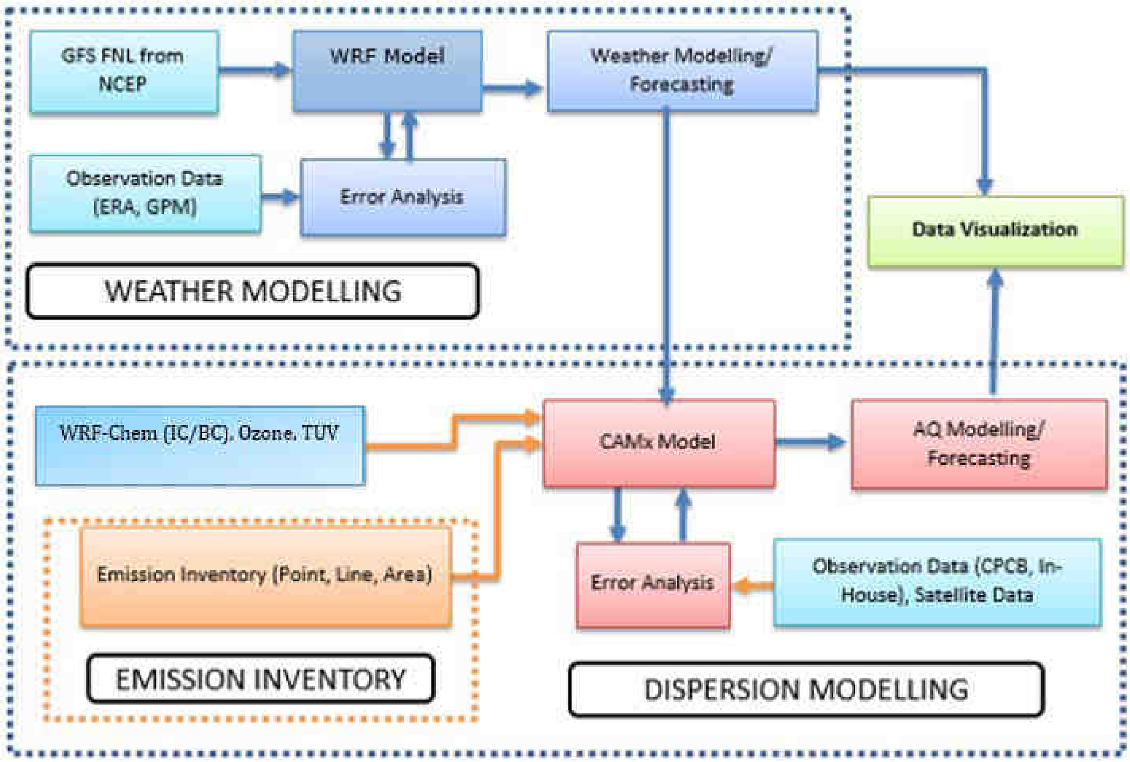
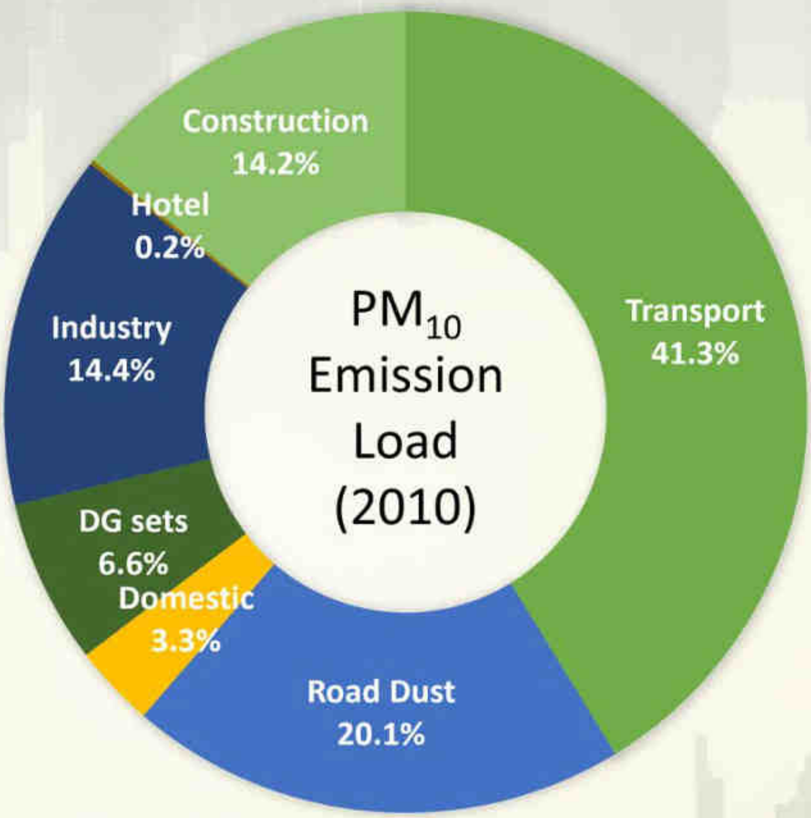


Figure 1-7: Approach for the study

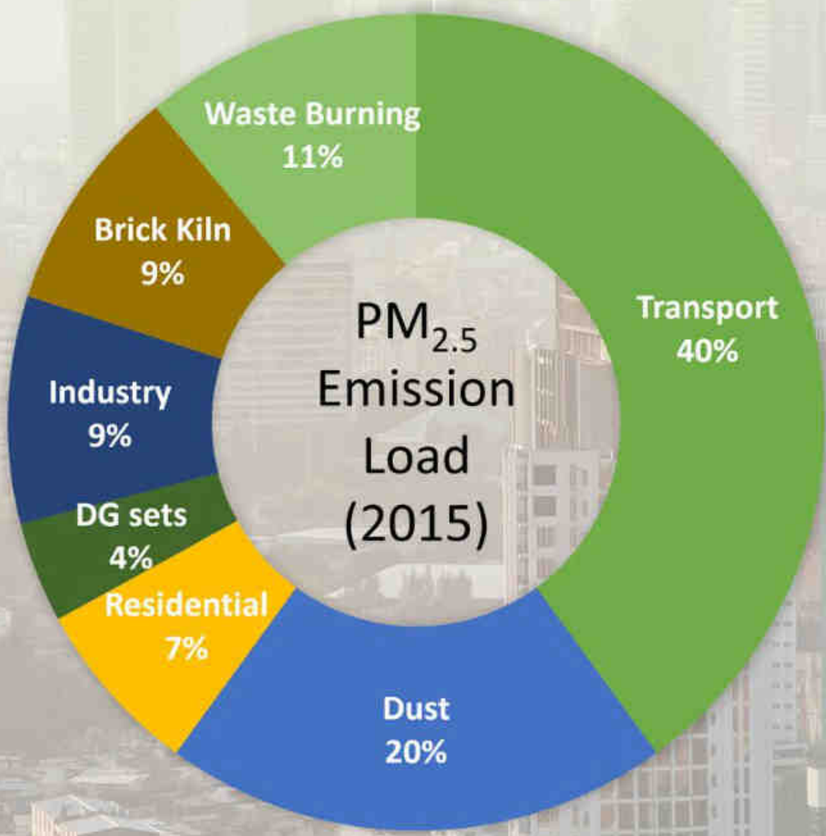
To estimate the spread of pollutants and their concentration level, we used a weather model and a dispersion model for the study air-shed area. Furthermore, for developing a strategy for improving air quality, we first identified sector-wise measures, then assessed emission reduction potential and investment need. This formed the basis for prioritized action steps and Clean Air Plan.

1.4. Structure of the Report

Following Introduction (Section 1), Section 2 of this report describes the various dispersion modelling and EI studies conducted in Bengaluru and provides the emission load estimated in these studies. The section also describes the key polluting sources in Bengaluru. Section 3 presents the methodology used to estimate the total emission load for various polluting sectors in Bengaluru. This section also provides the estimated emission load. An EI does not include meteorology or the remote effects of pollutants on pollutant concentration. Therefore, dispersion modelling was conducted to address this gap. The methodology and the results of dispersion modelling are presented in Section 0. We also estimated the effects of control measures suggested by KSPCB on air pollution levels in Bengaluru. Section 0 discusses the measures considered and the corresponding estimated emission reduction potential for different scenarios. Finally, Section 6 discusses the way forward.



PM$_{10}$ Emission Load (2010)
Transport 41.3%
Road Dust 20.1%
Domestic 3.3%
DG sets 6.6%
Industry 14.4%
Hotel 0.2%
Construction 14.2%



PM$_{2.5}$ Emission Load (2015)
Transport 40%
Dust 20%
Residential 7%
DG sets 4%
Industry 9%
Brick Kiln 9%
Waste Burning 11%

2. Literature Review

2.1 Emission Inventories and Associated Parameters

In preparing EIs for various cities, researchers have considered different polluting sources and study boundaries. Particulate matter (PM_{10} and $PM_{2.5}$), considered to have the most impact on the human body, has been estimated as the primary pollutant. Other pollutants estimated in most of the EIs are sulphur dioxide (SO_2), nitrogen oxides (NOx), ammonia (NH_3), carbon monoxide (CO), and volatile organic compounds (VOCs).

Though PM is primarily emitted from both natural and anthropogenic activities, a significant portion of it comes from human activities such as agricultural operations, industrial and commercial processes (combustion of wood and fossil fuels), construction and demolition activities, and re-suspension of road dust (ARAI, 2010; CPCB, 2010; Guttikunda et al., 2015; IITM, 2010; NEERI, 2010b; Sarkar et al., 2010).

As both natural and anthropogenic activities contribute to a city's emission load, the corresponding polluting sources need to be identified for developing mitigation policies. The sources contributing to the emission load may vary across various cities depending on geographical conditions, economic activities, and livelihood patterns. This makes every city unique, and thus, city-specific strategies are required to mitigate pollution. However, a few of the pollution sources such as transportation, domestic and commercial fuel consumption, and dust from road and construction-demolition activities remain the same for almost all cities.

Emission factors (EFs) are crucial for estimating the emission loads, for developing an EI. EFs for various sectors have been estimated by the United States Environmental Protection Agency (USEPA) (AP 42) (US EPA). India's Central Pollution Control Board (CPCB) has adopted the EF of PM_{10} from the AP 42 list. EFs for the transportation sector have been developed by ARAI (ARAI, 2010; TERI & ARAI, 2018a). Moreover, other global lists such as EDGAR (Janssens-Maenhout et al., 2015) provide EFs for various pollutants. Various factors influence the EF value, such as geographical condition variations, technology changes, fuel changes, and others (Janssens-Maenhout et al., 2015; Li et al., 2017; NEERI, 2010b).

EIs prepared at the city level help in understanding the major polluting activities/sectors in the city, and dispersion modelling help in understanding the spread of the various pollutants. However, modelling requires an understanding of regional- and country-level emissions too, so that the boundary conditions are known.

In the absence of regional- and country-level EIs for India, open-source EIs can be used, such as Emission Database for Global Atmospheric Research (EDGAR), Greenhouse Gas – Air Pollution Interactions and Synergies (GAINS), and MIX inventory. Such open-source EIs help in understanding local polluting sources and modelling trans-boundary pollutants affecting the region. Table 2.1 lists some of the open-source EIs for India, along with their resolutions and categories.

Table 2.1: Existing open-source emission inventories for India

Inventory	Area	Years	Category	Spatial resolution	Temporal resolution
UNFCCC	Global	Mainly 1990 ~	Anthropogenic	Country	Annual
RAINS • GAINS	Global	1990 ~ 2030	Anthropogenic	Country (China, India, Russia)	Annual
EDGAR	Global	Depends on the compound	Anthropogenic/ natural	Country, Region, 1° × 1°	Annual
GEIA	Global	Depends on the compound	Anthropogenic/ natural	1° × 1°	Annual
ACESS	South Asia, Southeast Asia, East Asia	2000	Anthropogenic/ natural	Country, Region (China, Japan, Korea) 1° × 1°	Annual
REAS	South Asia, Southeast Asia, East Asia	1980~2020	Anthropogenic/ natural	0.5° × 0.5°	Annual
MIX	South Asia, Southeast Asia, East Asia	2008 and 2010	Anthropogenic	0.25° × 0.25°	Monthly

2.1.1 Emission Inventory Studies in Indian Cities and Bengaluru

In the last decade and a half, many studies have been conducted to estimate and quantify air pollution in India. However, 2010 was a milestone year for India's EI studies as city-specific EIs were developed for six cities—Delhi, Mumbai, Chennai, Bengaluru, Kanpur, and Pune. Although country-specific (Baidya & Borken-Kleefeld, 2009; T. V. Ramachandra & Shwetmala, 2009; Reddy & Venkataraman, 2002) EIs have been developed earlier, city-specific inventories helped to understand the pollution landscape at the city level.

In these EI studies, researchers had considered most of the pollutants to understand the impact of various sources on the cities' emission load. The EIs developed for the six cities followed a CPCB-approved methodology. Moreover, the EIs focused on the city area and not on the air-shed area. The developed EIs had a spatial resolution of 2 km × 2 km and helped to understand sectoral emission loads and their share in the cities' total emission load. All the studies confirmed that the transportation sector (tailpipe emission and re-suspension of dust) contributed the most to PM_{10} emission load, whereas the domestic sector contributed the least.

After 2010, many studies were conducted to develop EIs for different cities (Mishra & Goyal, 2015; Pandey & Venkataraman, 2014; Sadavarte & Venkataraman, 2014; Sahu, Ohara, et al., 2015; Sahu, Schultz, et al., 2015; M. Sharma & Dikshit, 2016; Sindhwani et al., 2015; TERI & ARAI, 2018a). A detailed list of city-/region-specific EIs developed for PM is provided in Appendix I.

Delhi: As Delhi is the capital of India and one of the most polluted cities in the world, many studies have been conducted to estimate the emission load share of different polluting sectors (Guttikunda & Calori, 2013; Mishra & Goyal, 2015; M. Sharma & Dikshit, 2016; Sindhwani et al., 2015; TERI & ARAI, 2018a). All these studies had different objectives, and hence, the total emission load (PM_{10}) for Delhi as estimated by these studies ranged from 38,230 tonnes per year to 114,000 tonnes per year. The variation in the estimated PM_{10} emission load was due to the variation in the selected study area (780 km^2 to 6400 km^2) and the polluting sectors considered.

Mumbai: For Mumbai, the only EI was developed in 2010 by the National Environmental Engineering Research Institute (NEERI). The study was conducted for an area of 1056 km^2. The total PM_{10} emission was estimated to be 26810.8 tonnes/year. Re-suspension of dust (from paved and unpaved roads) was identified as the biggest polluting source of PM_{10}, and industrial emission was identified as the biggest polluting source of SO_2.

Chennai: For Chennai, the only inventory was prepared by IIT Madras (IITM, 2010), for an area of 812 km^2. Re-suspension of dust was identified as the biggest polluting source of PM_{10}.

Kanpur: Multiple studies (Gaur et al., 2014; A. Goel et al., 2017; M. Sharma, 2010) have been conducted to estimate the pollution sources in the city. The major contributors of SO_2 were found to be vehicular emission, garbage burning, and coal combustion. Wood combustion was found to be limited to the city's outskirts.

Pune: For Pune, the only inventory was prepared by the Automotive Research Association of India (ARAI) (ARAI, 2010), for an area of 440 km^2. Total PM_{10} from all the sources was estimated to be 11789 tonnes/year. The study identified re-suspension of dust (PM_{10}) and tailpipe emissions (NOx) as the biggest pollution sources.

Bengaluru: For Bengaluru, the only EI was developed in 2010 by The Energy and Resources Institute (TERI). This exercise was part of a source apportionment study, which covered an area of 624 km^2 and estimated a PM_{10} emission load of around 19,856 tonnes/year. Since then, the existing EI has not been revised. However, an EI was developed on the basis of secondary data by Guttikunda et al., 2019, which estimated a PM_{10} emission load of 67,100 tonnes/year for an air-shed area of 3600 km^2. For reducing air pollution, TERI, 2010 prescribed limiting heavy vehicles to peripheral ring roads. The institute also suggested using compressed natural gas (CNG) in public buses and installing diesel oxidation catalysts (DOCs) and diesel particulate filters (DPFs) in all pre-2010 vehicles. Wall-to-wall paving was recommended for reducing road dust. Prohibition of diesel generator (DG) sets and implementation of better construction practices were also recommended.

2.1.2 Sources of Air Pollution in Bengaluru

From 2001 to 2011, the population of Bengaluru has increased at a rate of 47%. In order to provide infrastructure for this sudden and great influx of population (Figure 1-1), the city started filling up its breathing spaces with concrete infrastructure (Ramachandra & Kumar, 2010). Figure 2-1 depicts changes in the built-up area in Bengaluru over the years. Clearly, the built-up area has increased considerably. As per our analysis, over the last 20 years, the built-up area within the BBMP-administered region increased from 29% in 2001 (Verma et al., 2017) to 55% in 2019.

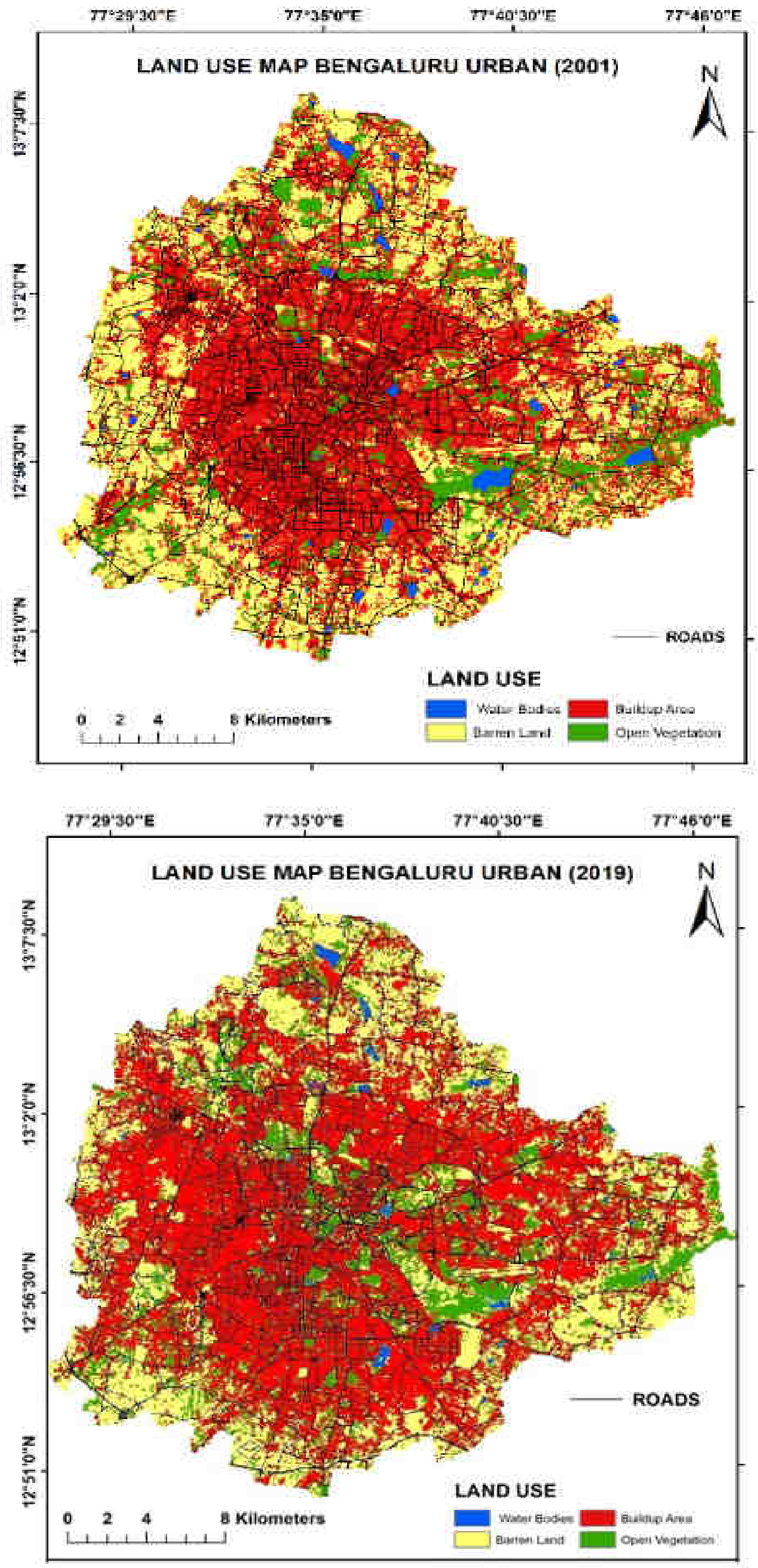


Figure 2-1: Built-up area change in Bengaluru over the years: (a) 2001 and (b) 2019

This population influx has resulted in infrastructural growth, resulting in an increase in emissions from various polluting sources. Activities such as construction and demolition, cooking and heating due to use of wood and kerosene, coal use in various restaurants, garbage burning, and use of DG sets in high-rise buildings (residential and commercial) and IT parks have contributed to the pollution load in the city (Guttikunda, Nishadh, Gota, et al., 2019). Further, unchecked vehicular growth (Figure 1-2) has resulted in vehicular pollution (tailpipe emission and re-suspension of dust) and traffic congestion (Guttikunda, Nishadh, Gota, et al., 2019; Harish, 2012).

A previous study (TERI, 2010) identified the major polluting sources in Bengaluru in 2007 as transport, road and construction dust, domestic and commercial fuels, industries, and DG sets. At the city level, the major sources of PM_{10} emission were identified as transport (42%), road dust (20%), construction dust (14%), industry (14%), DG sets (7%), and domestic fuel (3%). In another study (Guttikunda, Nishadh, Gota, et al., 2019), the major sources of PM_{10} emission in 2015 were identified as transport (19.7%), dust from road and construction (61.4%), industries (8.3%), waste burning (5.5%), domestic fuel (3%), and DG sets (2%). It was observed that the PM_{10} emission share from industries in 2015 had decreased by almost 5% in comparison with that in 2007. However, the share of road and construction dust almost doubled from 2007 to 2015. This increase in dust emission can be attributed to ongoing infrastructure development (increase in the built-up area) such as residential, commercial buildings, roads, flyovers, and metros.

Moreover, the share of industries decreased by 5% between 2007 and 2015, mostly because the major industries were shifted outside the city limits, though a few auxiliary units have remained inside the BBMP limits and have become emission hotspots over time. On the other hand, no change in the PM_{10} emission share from the domestic sector is observed. As the number of slum clusters and households have increased in the city, where wood and kerosene in addition to LPG are still used, it would be interesting to understand whether the share of domestic fuel consumption from cooking, heating, and lighting has changed or remained the same.

2.1.3 Dispersion Modelling Studies over India and Bengaluru

EI, air quality monitoring, and air quality modelling are the three vital components needed to understand the air quality issues in any city. Air quality modelling helps to estimate the effects of point, line, volume, and area sources in any region of interest. Gaussian-based air pollutant dispersion models (e.g. ISCST3, AERMOD, etc.) have been used mainly in environmental impact assessment (EIA) studies.

Several types of dispersion models have been developed over the years. In India, Gaussian-based dispersion models are commonly used, some of which are AERMOD, ISCST3 (Industrial Source Complex Short Term 3), CALPUFF, ADMS-Urban (Atmospheric Dispersion Modelling System—Urban), and CALINE 4 (California Line Source Dispersion Model). The underlying concepts of these models are identical, but they vary primarily in their formulation, complexity, and input requirements. For instance, CALINE 4 works with a limited number of input parameters, while models such as AERMOD, ADMS-Urban, and CALPUFF use detailed terrain information, meteorology, and EI. The performance of these models varies according to their complexity. A comparative study showed that the performance of ISCST3, AERMOD, and ADMS-Urban over an urban intersection of Delhi is satisfactory, while that of CALINE 4 is not (Khare et al., 2012).

Of the various models used for the dispersion assessment of different pollutants, AERMOD by USEPA is one of the most commonly used for regulatory applications. Many studies (Bhaskar et al., 2008; Gulia et al., 2015; Kesarkar et al., 2007; Lal et al., 2016) have used AERMOD to study air pollutant dispersion over different Indian cities. Kesarker et al., 2007 used AERMOD to simulate the dispersion of respirable particulate matter (RSPM/PM_{10}) over Pune. Mohan et al. (2011) used AERMOD for PM exposure assessment in Delhi. A few studies have used ADMS too to predict the PM concentration over Delhi (e.g., Mohan et al., 2011). Guttikunda and Jawahar, 2012 used a simple interactive model–air (SIM-air) modelling system to predict the PM_{10} concentration over six cities in India. Complex regional chemical transport models (CTMs) have also been used in India to estimate the atmospheric dispersion of various air pollutants; some of the most widely used are Weather Research and Forecasting (WRF) model coupled with Chemistry (WRF-Chem), Comprehensive Air Quality Model with extensions (CAMx), Community Multi-scale Air Quality Model (CMAQ), and Model for Ozone and Related chemical Tracers (MOZART). These models are Eulerian CTMs, and they differ mainly in the methodology used for representing physical (e.g., advection, turbulent mixing, etc.) and chemical (e.g., aerosol treatment) processes.

Among these CTMs, the most frequently used in studies across India are WRF-Chem and MOZART (Garaga et al., 2018). Bran and Srivastava, 2017 used the WRF-Chem model to obtain seasonal variations in PM2.5 over India. To study the effect of long-range air pollutant transport, Gupta and Mohan, 2013 employed a WRF-Chem resolution model to simulate the PM_{10} concentration over Delhi. MOZART has also been used to study the ozone (O_3) concentration (Chatani et al., 2014; Surendran et al., 2015). Sharma et al., 2016 used CAMQ to simulate surface O_3 concentrations in India.

In 2010, using the 2007 EI, TERI identified the prominent sources of PM_{10} in Bengaluru to be transport (42%), re-suspended road dust (20%), construction (14%), and industry (14%). Using WRF-CAMx, Guttikunda et al., 2019 conducted the particulate pollution source apportionment of local and non-local sources over Bengaluru. Their modelling showed that vehicle exhaust (28%), dust (including both re-suspended road dust and construction dust) (23%), and open waste burning (14%) are the major sources of air pollution in Bengaluru.

3. Emission Inventory

3.1 Introduction

An EI is an effective tool to understand polluting sources and estimate their emission shares at the city, state, region, or country level. This information aids in formulating strategies to address air pollution challenges. Understanding sectoral emissions also helps policymakers prioritise control measures.

EI is a catalogue of various activities for each polluting source (area, point, and line) over a specific timeframe, which contribute towards ambient emission. The sectors considered in this study for preparing an EI are transport, dust from road and construction, industry, domestic and commercial fuel use, DG sets, waste burning, and emission from airport.

3.1.1 Source Categorisation (Area, Point, and Line Sources)

Air pollution sources can be divided into two categories—natural and anthropogenic. Sea salt spray from oceans, lightning, dust storms, volcanic eruptions, etc., are classified as natural sources, whereas transport (tailpipe emission and re-suspension of dust), biomass burning, and industrial emission are a few sources of anthropogenic origin. Forest fires can be classified as either natural or anthropogenic on the basis of the activity that caused them.

Further, anthropogenic sources can be divided into stationary and mobile sources, depending on whether the source of emission is mobile or stationary. Stationary sources are further classified into area and point sources (Figure 3-1), and mobile sources are classified into line and non-line sources. In recent years, volume sources or fugitive emission sources (e.g., unintentional leaks from a pressured pipeline, evaporative processes, etc.) are also classified as stationary sources. Fugitive emission sources are very difficult to locate and estimate.

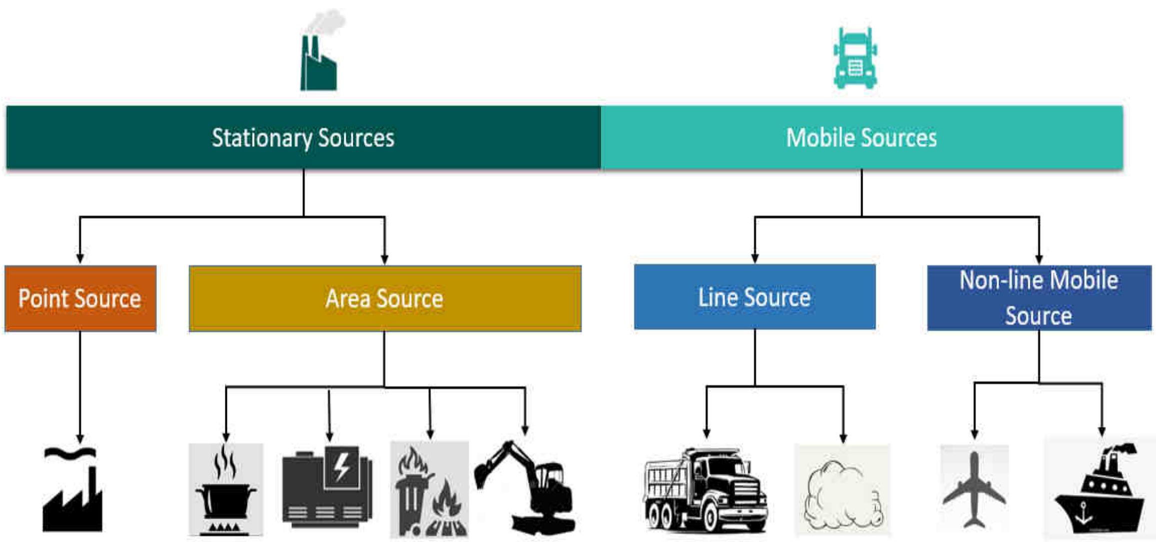


Figure 3-1: Emission source classification

Area sources are defined as a collection of small individual sources of similar activities in a geographical area (San Joaquin Valley Air Pollution Control District, 2013). For example, garbage burning, emissions from eateries, emissions from the domestic sector, and emissions from DG sets are area sources. Often, the physical boundaries of individual area sources are not recognisable. Hence, area sources of similar activities are grouped together and their emissions are estimated using the same methodology.

Point sources are classified as stationary sources that produce a large amount of emissions. Therefore, estimates of emission loads are reported for each point source and they are represented as separate emission sources on air pollution maps. All the stationary sources can be classified as either area or point sources. However, for practical purposes, a threshold emission load is used to distinguish point sources from area sources. CPCB categorises industries with stack emissions of more than 15 kg/day as point sources. Normally, industries with a stack height of 20 m or more are considered point sources (USEPA, 2001).

Mobile sources of pollution, for example, vehicles (motorised), aeroplanes, trains, and water transport (motorised), are further classified into on-road line sources (such as cars, buses, and bikes) and non-road line sources (such as aeroplanes, trains, and water transport) (USEPA, 2001). Not only do vehicular movements create direct emissions, they also disturb the dust on the roads, causing re-suspension of dust. As dust re-suspension depends on the road type and vehicular movement, it is also considered a line source.

3.2 Methodology and Sectoral Emission Estimation

3.2.1 Methodology

Approach: The overall approach for the study is presented in Figure 3-2. The prominent polluting sources were identified on the basis of previous studies and as per the land use and land cover map of Bengaluru. The point, line, and area sources were identified in the air-shed area of Bengaluru (60 km × 60 km). This air-shed area was spread across six districts, as mentioned earlier (Figure 1-6). The EI was developed with a horizontal resolution of 1 km × 1 km. The steps followed are depicted in Figure 3-2.

Figure 3-2: Emission inventory development

The sectoral emission for Bengaluru was estimated using Equation 1 (Pulles and Kuenen, 2016). The equation is consistent with the approach adopted in several studies earlier (Klimont et al., 2002; Sharma et al., 2015; Streets et al., 2003; Wei et al., 2014; Zhang et al., 2009) and in the GAINS modelling framework.

$$E = \sum_{Activities} A \times e\,f \qquad (1)$$

Where E is total emissions, A is activity rate, and ef is emission factor denoting pollutant emissions due to specific activities.

Equation 1 is a basic equation for emission estimation and does not indicate spatial distributions. Equation 2 (Sharma et al., 2015) is a more complex and accurate version of

Equation 1, which denotes the spatial distributions and control technologies of sectoral emission loads.

$$E_k = \sum_l \sum_m \sum_n A_{k,l,m}\, ef_{k,l,m} \left(1 - \eta_{l,m,n}\right) \times X_{k,l,m,n} \qquad (2)$$

Where k, l, m, and n are region, sector, fuel or activity type, and control technology, respectively; E is emissions; A is activity rate; ef is emission factor without any control technology; η is the efficiency of control technology, and X is the application rate of control technology.

Data Collection: Data collection for various polluting activities—a prerequisite for developing a comprehensive EI—was a challenge. A three-pronged data collection approach was adopted—(1) secondary data (from reports, journal papers, and government websites), (2) primary data (Table 3.1) by coordinating with various line departments, (3) and data from ground surveys for domestic, commercial, and industrial fuel consumption; petrol bunk surveys to determine the age of vehicles; traffic flow surveys to understand traffic count for various vehicle types (Figure 3-3).

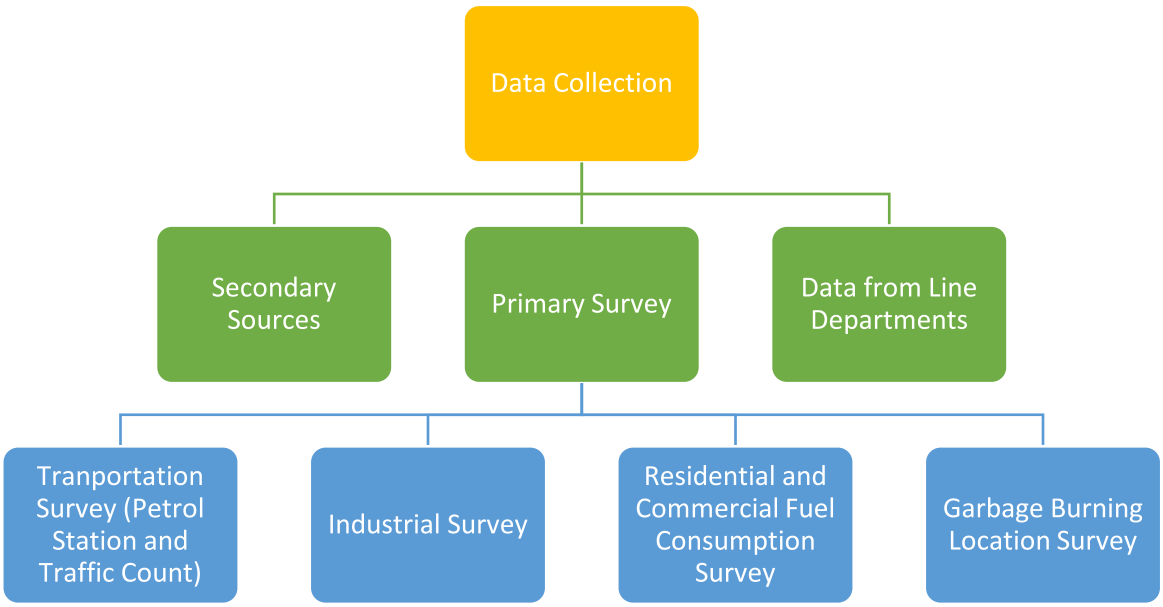


Figure 3-3: Overview of data collection

Table 3.1: Data collection from secondary sources and state departments

Sector	Data from secondary sources and state departments
Fuel consumption, domestic	IOCL: District-wise LPG consumption GAIL: Total PNG consumption in Bengaluru Karnataka Food and Civil Supplies Corporation Ltd: District-wise kerosene consumption
DG sets	Department of Electrical Inspectorate, Government of Karnataka: DG sets capacity and installation locations BESCOM: Average load-shedding hours in a day
Construction	RERA: Total number of constructions and their locations (including area, start date, and end date)
Aviation	BAIL: Number of flight operations (month-wise) and total fuel consumption for ground support vehicles
Fuel consumption, commercial/eateries	IOCL: District-wise commercial LPG consumption GAIL: Total PNG consumption in Bengaluru Zomato open dataset: Number, type, and location of restaurants in Bengaluru
Solid waste burning	BBMP: Solid waste processing capacity and per capita solid waste generation Open City: Location of garbage dumps District administrations: Solid waste generation and processing in areas other than BBMP area
Industry	IOCL: District-wise diesel and fuel oil consumption GAIL: PNG and CNG consumption in Bengaluru KSPCB: Number of industries (based on red and orange categories)
Transportation and resuspended dust	VAHAN database: Yearly vehicle registration NHAI: Number of vehicles entering Bengaluru from various toll plazas IISc: Vehicular movement over Bengaluru roads IOCL: District–wise fuel consumption

EFs for various polluting sources were taken from the CPCB list. However, USEPA (AP 42) EFs were also considered for PM2.5, NOx, and SOx. In addition, articles from the Automotive Research Association of India (ARAI) and other peer-reviewed articles were referred to for cross-validation of the EFs. Table 3.2 and Table 3.3 present the list of EFs considered for non-road and on-road sources, respectively.

Table 3.2: Emission factors for non-road sources

Emission factors for domestic sector and eateries (wherever applicable) (g/kg)				
Fuel type	**PM_{10}**	**$PM_{2.5}$**	**NO_x**	**SO_2**
Natural gas	0.16	0.1	2.16	0.01
LPG	0.51	0.32	3.45	0.0
Wood	15.30	12.24	14.00	0.2
Coal	20.0	12.2	3.99	13.3
Kerosene	0.61	0.59	2.50	4.0
Emission factor for diesel generator sets (kg/kWh)				
Diesel generator	0.00133	0.000974	0.0188	0.00124
Emission factor for waste burning (g/kg)				
Burning waste	8.25	8	3	0.5
Emission factor for construction and demolition (tonnes/acre month)				
Disturbed area	1.2	0.43		
Emission factor for industrial sector				
Fuel Type	**PM_{10} (kg/kl)**	**$PM_{2.5}$ (g/kg)**	**NO_x (kg/kl)**	**SO_2 (kg/kl)**
Diesel	0.24	0.97	2.75	31.05
Fuel oil (FO)		0.65	7.5	77
CNG/NG		0.34	0.0028	0.0000096
Emission factor for aircraft (kg/LTO)				
Flight type	**PM_{10}**	**$PM_{2.5}$**	**NO_x**	**SO_2**
Domestic	0.99	0.9108	10.2	8.1
International	0.99	0.9108	41	50

Source: ARAI, 2010; NEERI, 2010

Table 3.3: Emission factors for on-road sources

Emission factors (g/km)		**2-W**	**3-W**	**Bus**	**Private Cars**		**Commercial Cars**		**HCV**	**LCV**	**MSLV**
					Petrol	Diesel	CNG	Diesel			
5 Yr	CO	0.4	0.69	3.72	0.84	0.06	0.6	0.06	6	3.66	6
	NO_x	0.25	0.19	6.21	0.09	0.28	0.53	0.28	9.3	2.12	9.3
	PM	0.013	0.015	NA	0.002	0.015	0.002	0.015	0.42	0.475	0.42
	VOC	2.03	0.1	0.1	0.24	0.28	0.01	0.28	0.85	0.01	0.85
10 Yr	CO	1.65	0.69	3.72	2.74	0.3	0.85	0.3	12.65	3.66	12.65
	NO_x	0.27	0.19	6.21	0.21	0.49	0.27	0.49	11.57	2.3	11.57
	PM	0.025	0.015	NA	0.006	0.1025	0.0015	0.1025	3.205	0.565	3.205
	VOC	4.31	0.1	0.1	1.88	0.41	0.01	0.41	1.97	0.01	1.97
15 Yr	CO	1.65	0.69	3.72	4.83	0.3	0.85	0.3	12.65	3.66	12.65
	NO_x	0.27	0.19	6.21	0.65	0.49	0.27	0.49	11.57	2.3	11.57
	PM	0.025	0.015	NA	0.006	0.1025	0.0015	0.1025	3.205	0.565	3.205
	VOC	4.31	0.1	0.1	1.88	0.41	0.01	0.41	1.97	0.01	1.97
	BC	0.02	0.19	0.49	0.05	0.05	NA	0.05	0.34	0.19	1.24

Source: SAFAR, 2018

Method: A method based on a simple model suggested in various studies (Pulles and Kuenen, 2016; Klimont et al., 2002; S. Sharma et al., 2015; Streets et al., 2003; Wei et al., 2014; Zhang et al., 2009) and in the GAINS modelling framework was employed for calculating the sectoral emissions. The methodology is depicted in Figure 3-4.

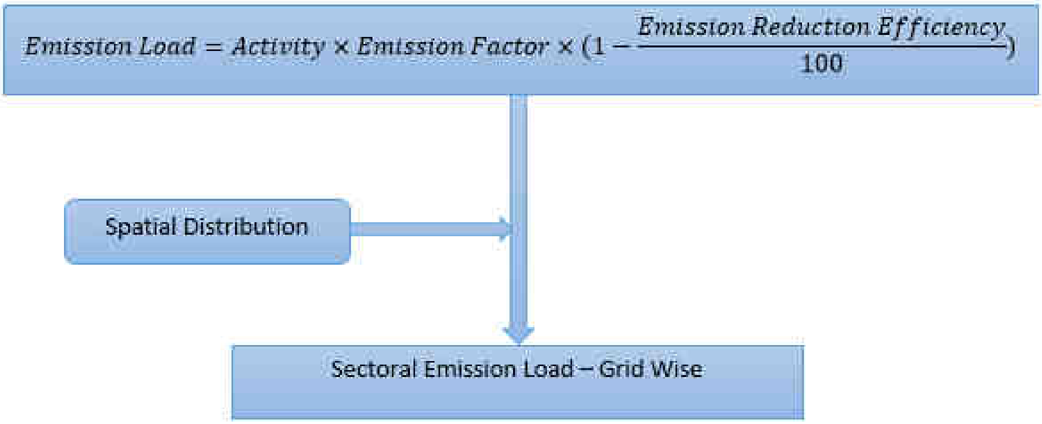


Figure 3-4: Emission estimation methodology

The equations used to estimate various sectoral emissions are provided in Table 3.4.

Table 3.4: Equations for estimating sectoral emissions

<table>
<tr><th>Sector</th><th>Method</th><th>Variables</th></tr>
<tr><td>Transportation</td><td>$VKT_{i,j} = RL_j \times n_i$
$E_j = \sum_{i=1}^{m} VKT_{i,j} \times EF_i$</td><td rowspan="9">$\boldsymbol{A}$: area of construction (acres)
$\boldsymbol{c}$: per capita fuel consumption (tonnes/day)
$\boldsymbol{C}$: total installed capacity (KVA)
$\boldsymbol{d}$: duration of activity (months/year)
$\boldsymbol{E}$: total emission load
$\boldsymbol{EF}$: activity-specific emission factors
$\boldsymbol{F}$: fuel consumption (tonnes/day)
$\boldsymbol{H}$: percentage of households using fuel (LPG, kerosene, wood)
$\boldsymbol{h}$: working hours (hours)
$\boldsymbol{i}$: vehicle type identifier
$\boldsymbol{j}$: grid identifier
k: particle size multiplier
$\boldsymbol{n}$: unit number for various categories
$\boldsymbol{P}$: population
$\boldsymbol{Q}$: quantity of waste burned (tonnes/day)
$\boldsymbol{RL}$: road length (km) in each grid
sL: silt load (g/m²)
$\boldsymbol{VKT}$: vehicular kilometres travelled per day (km/day)
W: average weight of vehicles</td></tr>
<tr><td>Re-suspended dust</td><td>$E = VKT \times EF$
$EF_{Road\ dust} = (k \times (sL)^{0.91} \times (W)^{1.02})$</td></tr>
<tr><td>Solid waste burning</td><td>$E = Q \times EF$</td></tr>
<tr><td>Fuel consumption, domestic</td><td>$F = P \times H \times \mathrm{c}$
$E = F \times EF$</td></tr>
<tr><td>Fuel consumption, eateries</td><td>$E = n \times F \times EF$</td></tr>
<tr><td>Industry</td><td>$E = F \times EF$</td></tr>
<tr><td>DG sets</td><td>$E = C \times \mathrm{h} \times EF$</td></tr>
<tr><td>Construction</td><td>$E = A \times d \times EF$</td></tr>
<tr><td>Aviation</td><td>$E = n \times EF$</td></tr>
</table>

The methods followed for spatial distribution of sectoral emission loads over the study area are provided in Table 3.5.

Table 3.5: Methods for spatial distribution of sectoral emission loads

No	Sector	Methodology
1	Transportation	Based on vehicle kilometre travelled (VKT) of individual vehicle type in a grid.
2	Re-suspended Dust	Based on VKT of individual vehicle type in a grid, road type (paved or unpaved), silt load of the road, and average rainfall in a year.
3	Solid Waste Burning	Distributed based on garbage dumping locations and based on socio-economic households (waste generation and collection)
4	Fuel Consumption – Domestic	Based on the population density of the grid
5	Fuel Consumption – Commercial/ Eateries	Total estimated emission load was distributed based on restaurant data in Zomato dataset
6	Industry	Based on land cover. The industrial area in a grid was considered while distributing the emission load.
7	DG Sets	The installation locations were geo-located in the grids. Then emission from each grid was estimated based on the total capacity of the installations.
8	Construction	RERA data was geo-located on the grids along with construction area and duration. Emission from each grid was estimated based on the total disturbed area and duration of the construction.
9	Aviation	Allocated on the grids (in line with runway). The grids were considered based on the horizontal distance required for an aircraft to achieve 1 km vertical distance.

As the study was conducted to quantify emissions from anthropogenic sources, it was important to obtain the spatial distribution of population data for better estimation. The spatial distribution of the emission load was based on various parameters such as population data for domestic fuel consumption; vehicle kilometres travelled (VKT) of individual vehicle types for transport; VKT, type of road, and silt load of the road for road dust re-suspension; industrial clusters, commercial areas, and new construction locations on the grid.

Gridded population data (for 2015) for the air-shed area (except BBMP area) was obtained from the European Commission's Global Human Settlement (GHS) project (Schiavina, Marcello; Freire, Sergio; MacManus, 2019). The projected ward-wise population was distributed on 3600 grids across the study area as presented in Figure 3-5.

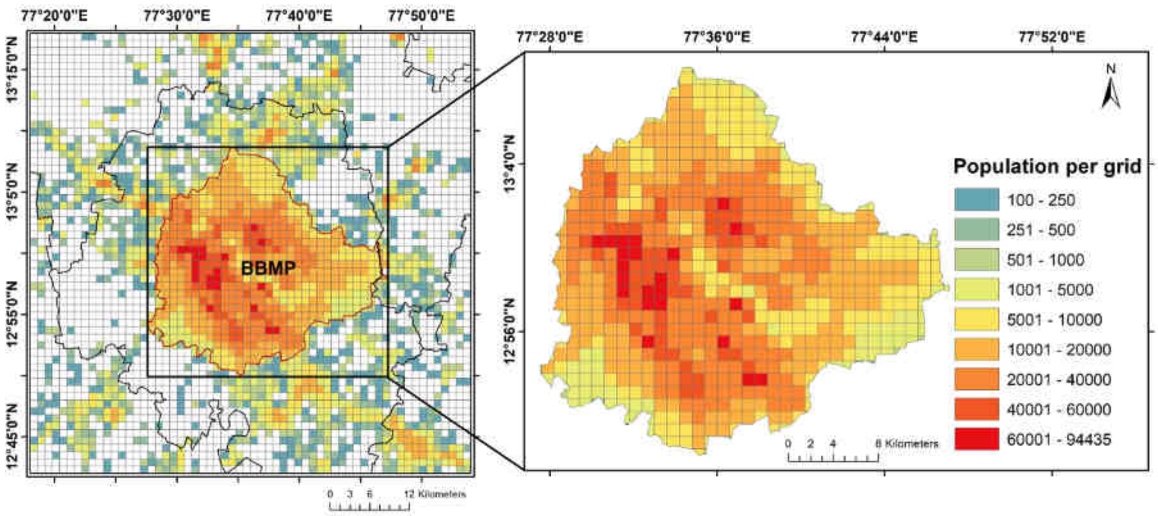


Figure 3-5: Population distribution over the study area

This gridded data was projected for the study year (2019). For the BBMP area, ward-wise population (*Census of India: Primary Census Abstract*) and the population growth rate were obtained from BBMP. The ward-wise population was projected for the study year (2019). The population was then distributed over the grids on the basis of the fraction of ward area(s) intersecting with a particular grid.

Population density in Bengaluru East, Bengaluru West, and Bengaluru South sub-districts is high, probably because of earlier settlements (Figure 2-1). In contrast, the peripheral sub-districts of the BBMP area are comparatively less populated. Apart from the BBMP area, other regions in the air-shed area too are sparsely populated. However, grids along interstate highways have a population density of 1,000–10,000 per km^2.

On the basis of predominant anthropogenic activities, we estimated sectoral emissions from the following sectors—domestic fuel consumption, commercial fuel consumption, emission from DG sets, municipal solid waste (MSW) burning, construction and demolition sector, emission from the airport, industrial fuel consumption, and emission from transportation (tailpipe emission and re-suspension of dust). An overview of the city-level sectoral emission estimation is presented in Section 3.2.2.

Surveys: Surveys were conducted to validate the data obtained from the state departments and to understand the pollution scenario in the city. Following surveys were conducted at various locations in the city.

1. Domestic fuel use
    a. Identification of notified slums
    b. Survey to understand and estimate fuel type and quantity in slums
2. Commercial fuel use
    a. Identification of commercial areas
    b. Segregation of eateries on the basis of footfall (small, medium, and large)
    c. Survey to understand and estimate fuel type and quantity
3. Industrial
    a. Identification of industrial clusters

    b. Survey to understand and estimate fuel type and quantity
4. Transportation
    a. Identification of traffic junctions from video recordings (32 locations)
    b. Identification of fuel stations in the city
    c. Survey at petrol stations to understand vehicle type and fuel use

For data validation of fuel use in the domestic sector, a door-to-door survey was conducted to ascertain and quantify wood consumption by the lower economic strata around the city. Slum areas were identified on the basis of Karnataka State Slum Development Board and BBMP data. A total of 1059 households (95% confidence with 3% error margin) were surveyed. As per the method adopted, the survey was conducted in 14 clusters of lower economic strata.

For commercial fuel use, a survey was conducted in six commercial areas. In total, 126 small, 119 medium, and 15 large restaurants were surveyed to understand the type and quantity of fuel used and the sources.

For industrial emission, eight clusters were identified for surveys—Peenya industrial area, Jigani, Bommasandra, Kadugodi, Attibele, Mahadevpura, Neelamangala, and Bidadi industrial area. However, not much information could be garnered from these surveys as the industrial units did not cooperate in the data collection process.

For transport emission details, video recordings from various traffic junctions were analysed and surveys were conducted at petrol stations. Thirty-two traffic junctions were selected on the basis of traffic flow. The petrol stations were selected at various locations in the city to capture variations in vehicle type, fuel type, and vintage of vehicles.

3.2.2 Sectoral Emission Estimation

3.2.2.1 Domestic Fuel Consumption

In Bengaluru, emission from the residential sector was found to be mainly due to cooking, heating, and lighting activities. Our survey revealed that, like in other Indian cities, people from economically weaker sections in Bengaluru still use wood/dung cake/biomass for their energy requirement (Ekholm et al., 2010; Guttikunda, Nishadh, Gota, et al., 2019). During the winter months particularly, the usage of solid fuel increases as households need to heat water. Moreover, kerosene is still used for lighting in many households.

For estimating the emission from residential fuel consumption, we considered various fuels (LPG, PNG, kerosene, and wood) and followed a mixed approach (both top-down and bottom-up). LPG and PNG consumption data were obtained for the whole district, which was spatially distributed on the basis of population density. Wood consumption data were obtained from our door-to-door survey, which was spatially allocated (based on the number of slum households in each grid) to slum and rural households.

LPG, PNG, and kerosene usage details were obtained from fuel companies (IOCL, BPCL, and HPCL). We obtained the district-level LPG and PNG (for Bengaluru) consumption data for the year 2018–19 from the fuel companies, whereas kerosene consumption data was obtained from the Karnataka Food and Civil Supplies Department.

The fuel consumption and household income data obtained from the survey were analysed for estimating the emissions and understanding the fuel usage on the basis of household income. Figure 3-6 highlights the findings of the domestic fuel survey conducted in the various city wards.

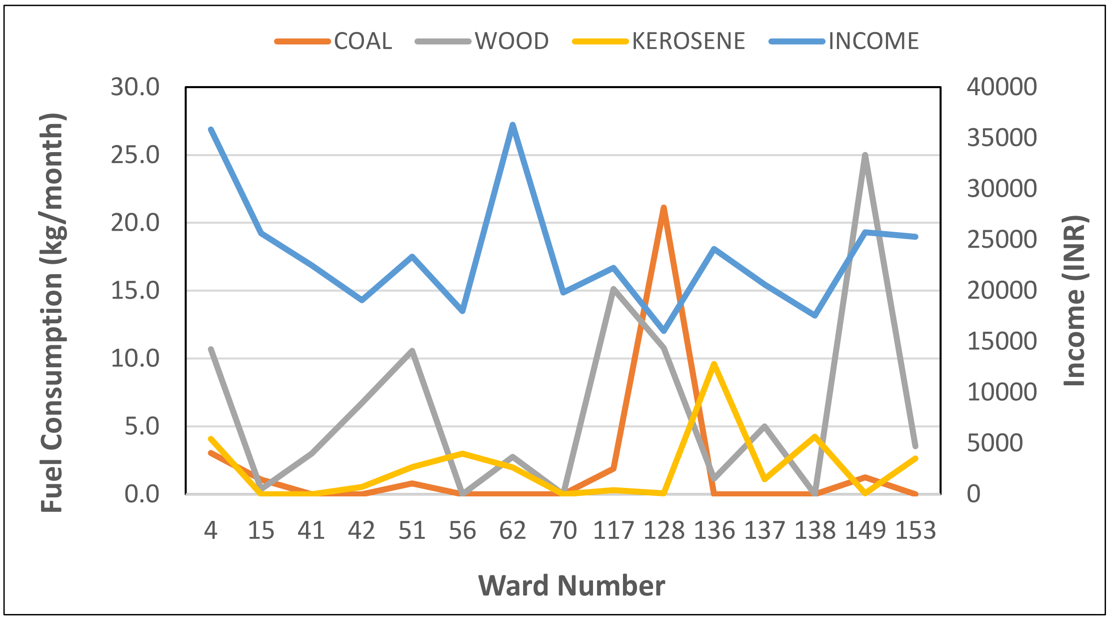


Figure 3-6: Fuel consumption in BBMP wards

The survey helped us identify the various fuel types used by slum dwellers. We found that wood, kerosene, and coal, along with LPG, were used for cooking. Consumption of wood was found to be high in the wards with lower income levels. High wood consumption in ward number 51 (Vijinapura), 117 (Shanthi Nagar), and 149 (Varthuru) corroborate the presence of a higher number of low-socioeconomic households. High coal consumption in ward number 128 (Nagarabhavi) is attributed to the commercial use of coal in the clothes ironing business. In the survey, we found that a few households were using kerosene even though kerosene is not sold by the public distribution system (PDS) within BBMP limits. Through the household survey, we also found that on an average, slum households consume around 0.4 kg of wood per day. Even though Karnataka has achieved 100% LPG penetration (PPAC, 2020), many households were found using wood alongside LPG for cooking.

For the BBMP area, emissions from the domestic sector were estimated to be 584 tonnes/year of PM_{10}, 326 tonnes/year of $PM_{2.5}$, 1033.7 tonnes/year of NO_x, and 5.73 tonnes/year of SO_2. The total emission (from the air-shed area) was spatially distributed over the air-shed area on the basis of population density. Emission from biomass burning was spatially allocated to wards with a higher presence of economically lower strata. Figure 3-7 to Figure 3-10 depict the spatial distribution of pollutant emissions over the air-shed and BBMP areas. It is evident that emission from the domestic sector is more concentrated over Bengaluru East, Bengaluru West, and Bengaluru South zones. The main reason for the higher emission is the high population density coupled with a high number of notified slum areas (with prevalent biomass use).

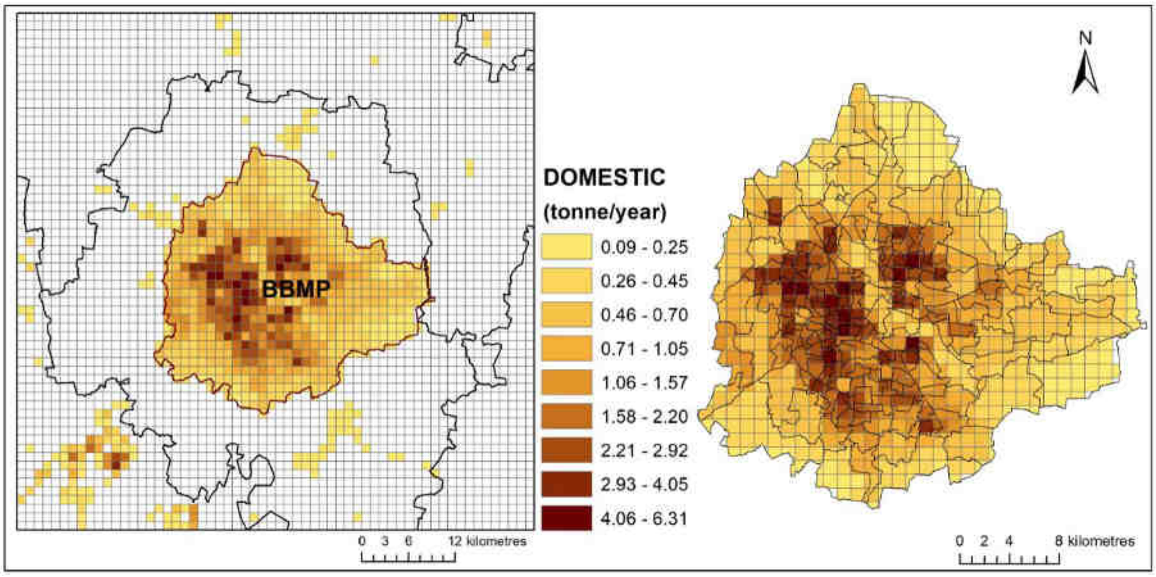


Figure 3-7: PM_{10} emission from domestic fuel consumption

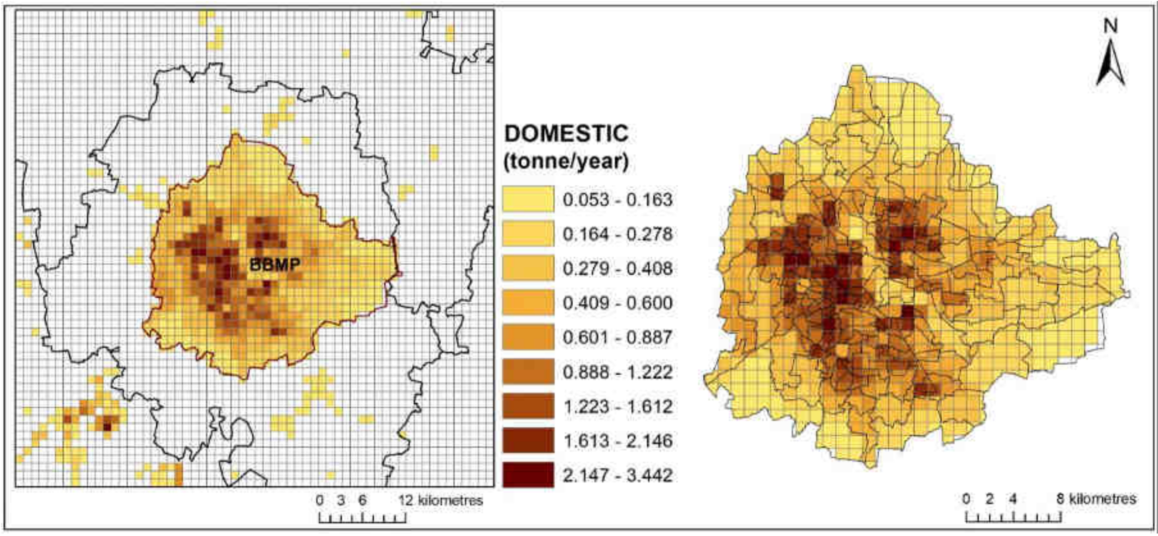


Figure 3-8: $PM_{2.5}$ emission from domestic fuel consumption

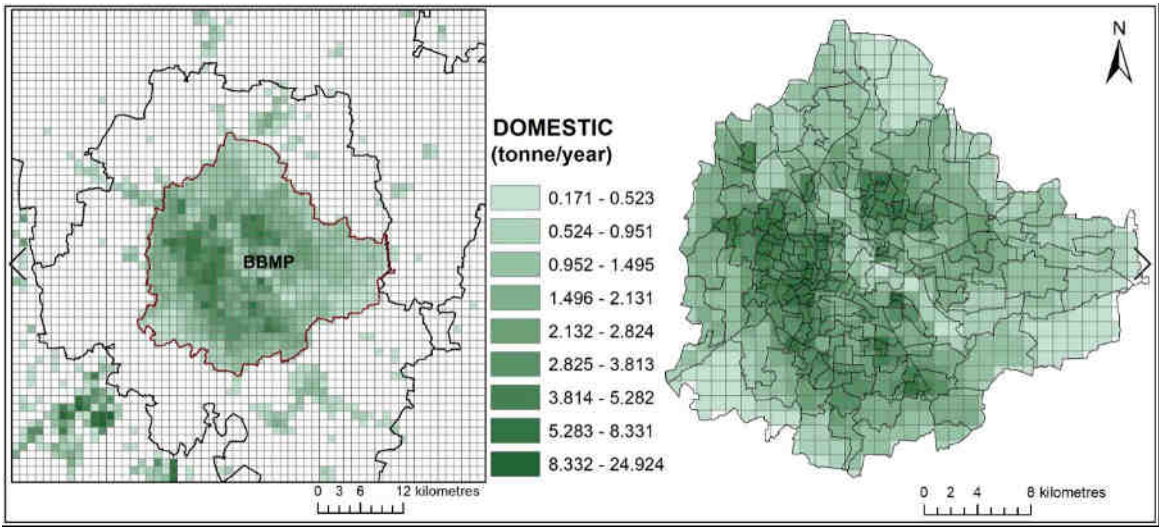


Figure 3-9: NO_x emission from domestic fuel consumption

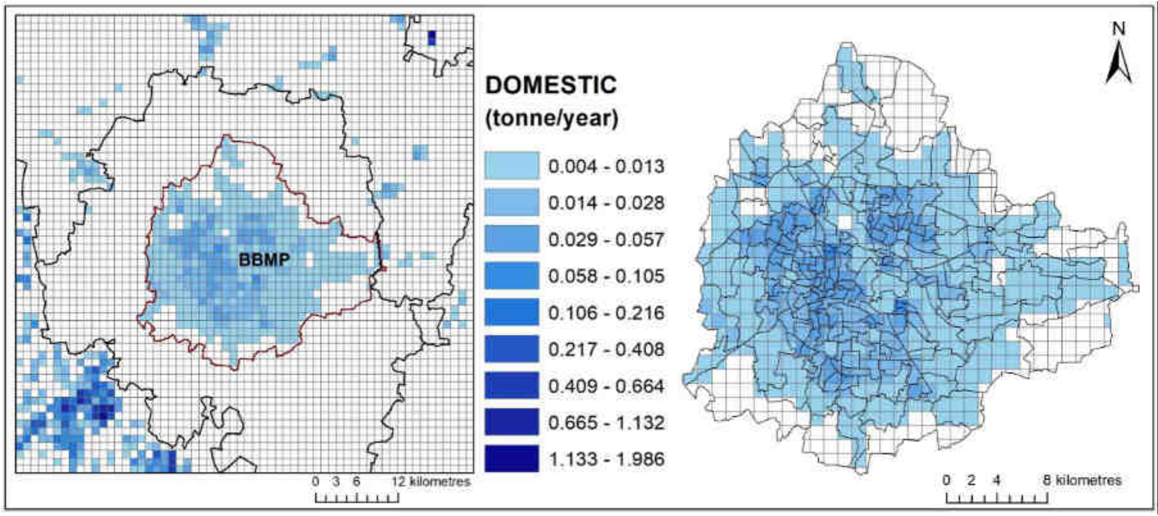


Figure 3-10: SO_2 emission from domestic fuel consumption

From the spatial distribution, it is evident that the majority of emissions are from the BBMP area, which has a much greater population density (more than 40 times) than that of the surrounding areas. Although the majority of the BBMP households use comparatively cleaner fuels (LPG and PNG) than those used in the surrounding areas (mixed use of LPG, biomass, and kerosene), the cumulative emission from the BBMP area is much higher than that from the surrounding areas owing to the higher population density. Likewise, owing to the lower population density of the surrounding areas, emission from the domestic sector was relatively low.

Emission within BBMP wards was largely dependent on the number of socioeconomically weaker households in the wards. Higher emission from wards with a high number of socioeconomically weaker households was due to the use of biomass and kerosene for cooking. Figure 3-11 depicts the relation between emission from wards and the number of socioeconomically weaker households in the wards.

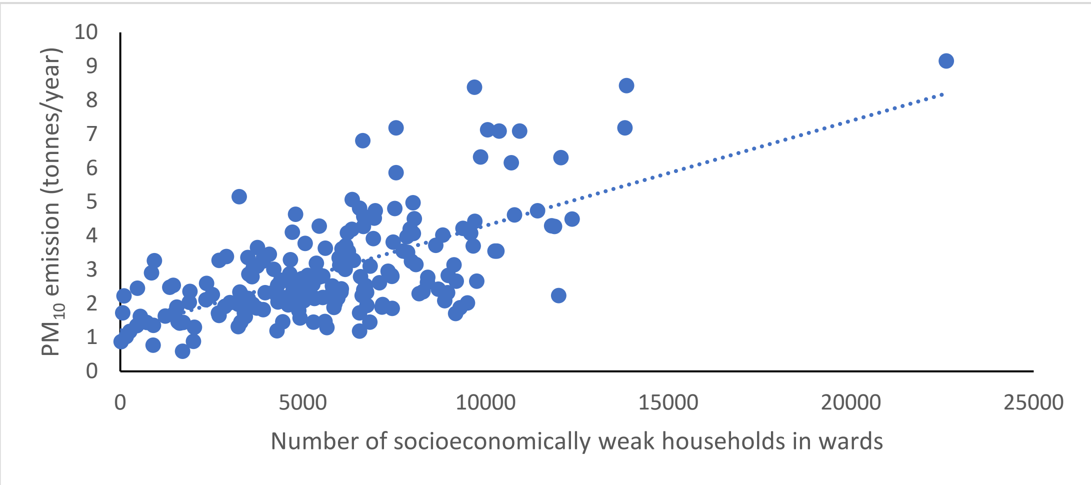


Figure 3-11: Ward-wise PM_{10} emission from domestic fuel consumption

In addition to government-notified slums, there is a large migrant population in Bengaluru specifically employed in the construction sector. This migrant population usually stays in makeshift tents and uses solid fuel for cooking. The emission from these makeshift tents was not estimated because of the unavailability of migrant population data.

Using solid fuel for cooking results in direct exposure to pollutants (specifically $PM_{2.5}$). This aggravates health problems (asthma, chronic obstructive pulmonary disorder, heart disorders, bronchial problems, etc.) in vulnerable sections of society. Access to LPG will help reduce the use of solid fuel for cooking and harmful exposure from it.

For many people, economic condition is a major hurdle in the continuous use of LPG cylinders. Although government schemes such as Pradhan Mantri Ujjwala Yojana have helped poor families get LPG connections, many households do not refill cylinders after the subsidy gets over. BBMP, along with the Gas Authority of India Limited (GAIL), should prioritise city-wide PNG connections, which will further reduce the emission from the domestic sector. Bengaluru can be a pioneer in India if BBMP and BESCOM can encourage people to adopt electricity-based cooking. If a significant percentage of the total number of households adopts electricity-based cooking, domestic emissions can be reduced significantly.

3.2.2.2 Commercial Fuel Consumption

Most Indian cities have mixed development zones—that is, residential and commercial areas are not separated. The commercial places range from provisional stores to high-end hotels. Fuel consumption in these commercial joints depends on the type of establishment. Among these establishments, eateries use the largest amount of fuel (for cooking). Along with LPG, coal is used in eateries for specialised food items (e.g., tandoori food items).

A developing county such as India has a stark difference in the fuel use by eateries in urban and rural areas. We followed a mixed approach (both top-down and bottom-up) for estimating emissions from fuel consumption in eateries. LPG and PNG consumption data were obtained for the whole district and then spatially distributed on the basis of the number of eateries in a grid. Coal consumption data were obtained from a door-to-door survey and then spatially allocated to eateries. The spatial distribution of emission from eateries was based on the number and type of eateries in each grid. Data for the number of restaurants and their locations were obtained from the Zomato open dataset. This data was then geo-located on the grids. Data on the consumption of commercial LPG and PNG were obtained from the information provided by the fuel company (IOCL).

Although commercial LPG and PNG consumption data were readily available for Bengaluru, we conducted a survey to quantify coal/charcoal use by eateries. The survey was conducted at 260 restaurants located in different parts of the city. We found that coal use in restaurants varies by size and daily customer footfall. We divided the surveyed restaurants into three categories (small, medium, and large restaurants) (Figure 3-12) and estimated the percentage of restaurants using coal and its average consumption (Table 3.6). In the survey, we found that speciality restaurants (barbeque places) consume huge quantities of coal/charcoal daily, but these restaurants employ filters to reduce the emission. As information on the emission reduction efficiency of these filters was not available, a flat 75% reduction in emission was assumed. We also found that barbeque places and restaurants famous for tandoori food items were using as much as 15,000 kg of coal/charcoal per month.

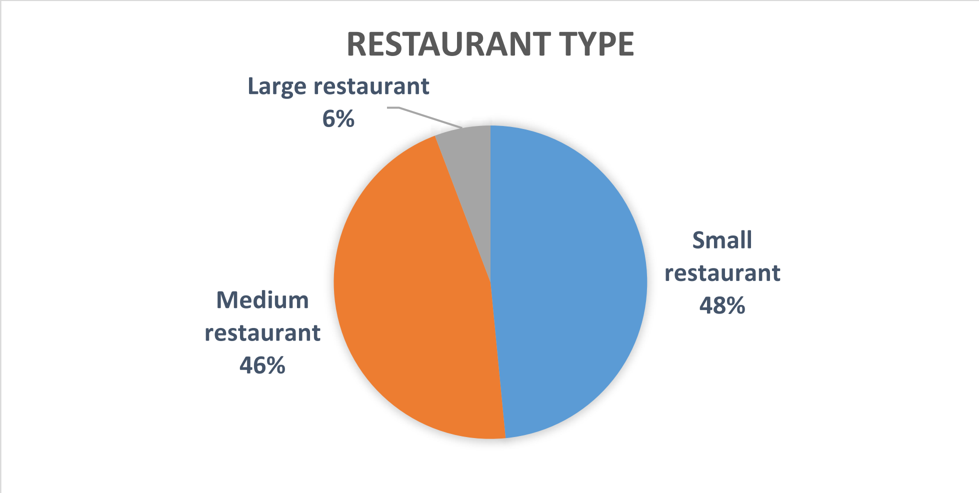


Figure 3-12: Share of restaurant types in Bengaluru

Table 3.6: Coal consumption in restaurants

Restaurant type	Restaurants using coal (%)	Average coal use (kg/day)
Small (daily footfall less than 100)	**22.22**	**13.5**
Medium (daily footfall more than 100 and less than 500)	**32.77**	**27.99**
Large (daily footfall more than 500)	**46.67**	**281**

Charcoal/coal was found to be used for tandoori food items by around 50% of the approximately 12,000 casual dining places in Bengaluru. Considering the coal use along with LPG/PNG used for normal cooking, the emission from eateries was estimated to be 1026 tonnes/year of PM_{10}, 549 tonnes/year of $PM_{2.5}$, 316.3 tonnes/year of NO_x, and 872.5 tonnes/year of SO_2. Figure 3-13–Figure 3-16 depict the spatial distribution of PM_{10} emission over the study area and the BBMP area.

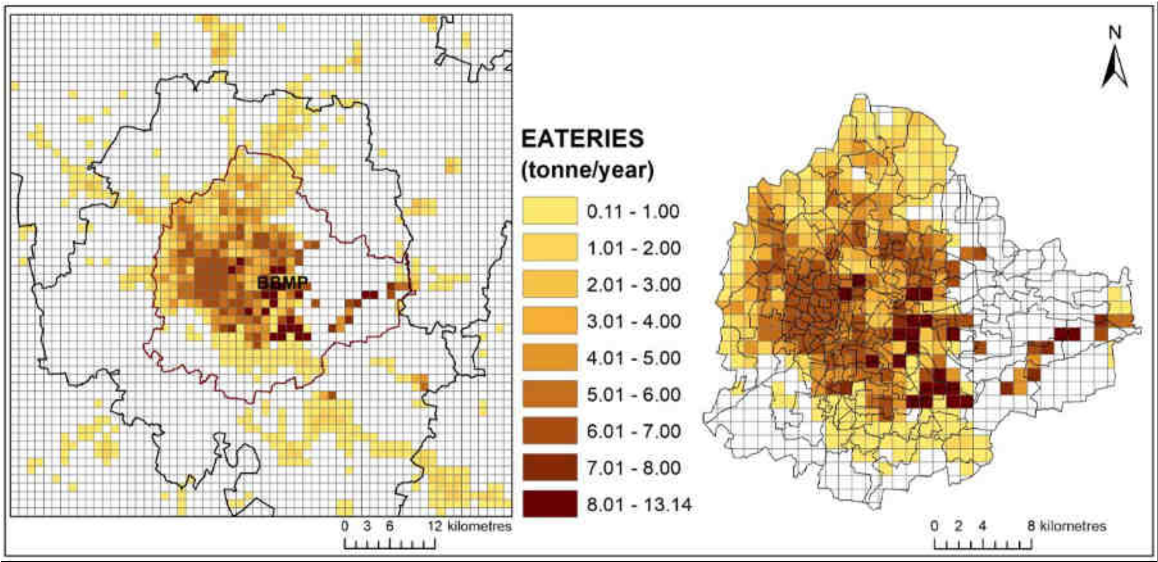


Figure 3-13: PM_{10} emission from commercial fuel consumption

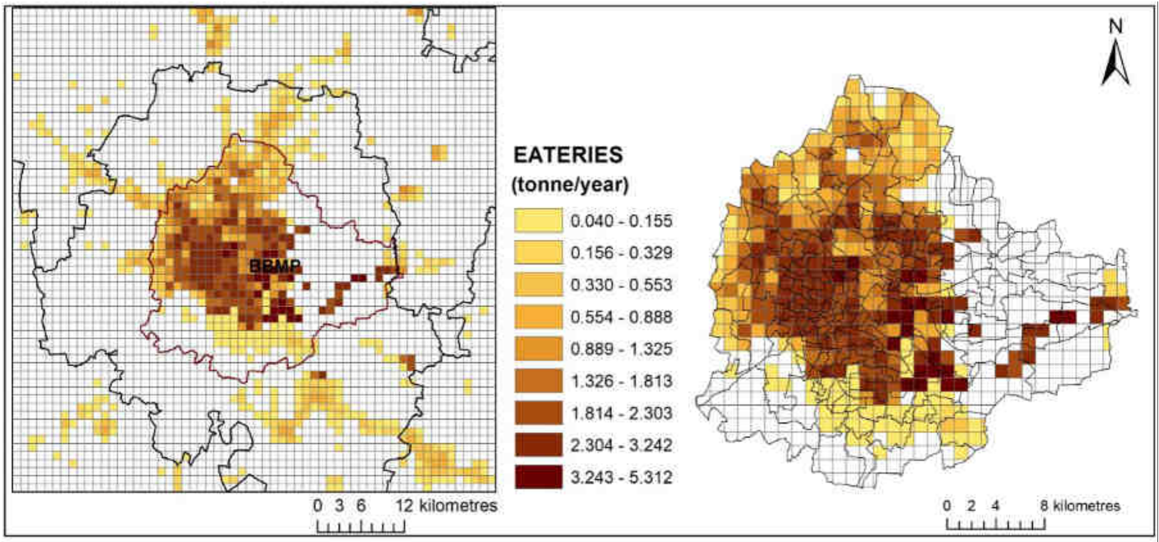


Figure 3-14: $PM_{2.5}$ emission from commercial fuel consumption

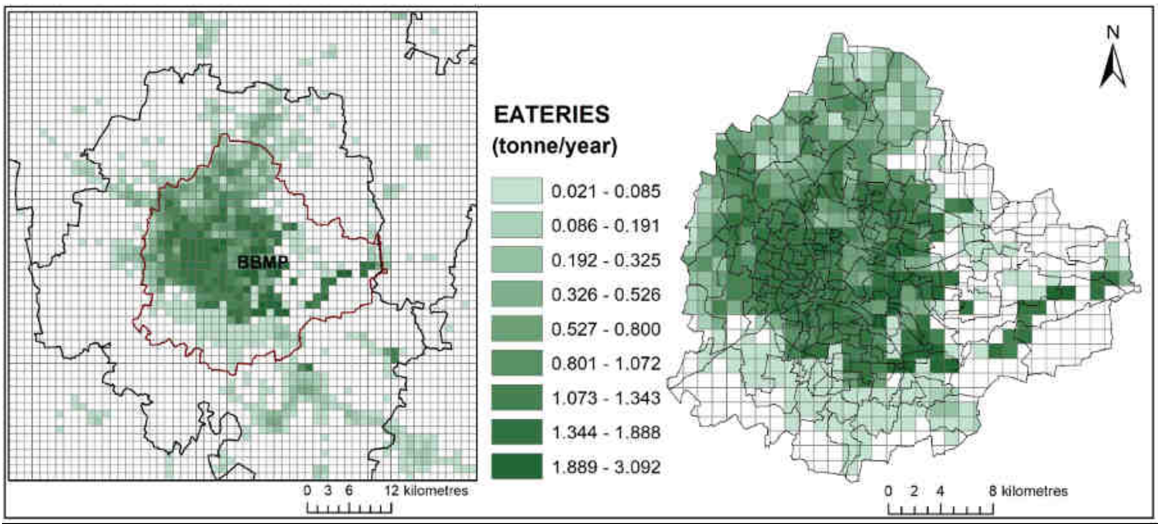


Figure 3-15: NO_x emission from commercial fuel consumption

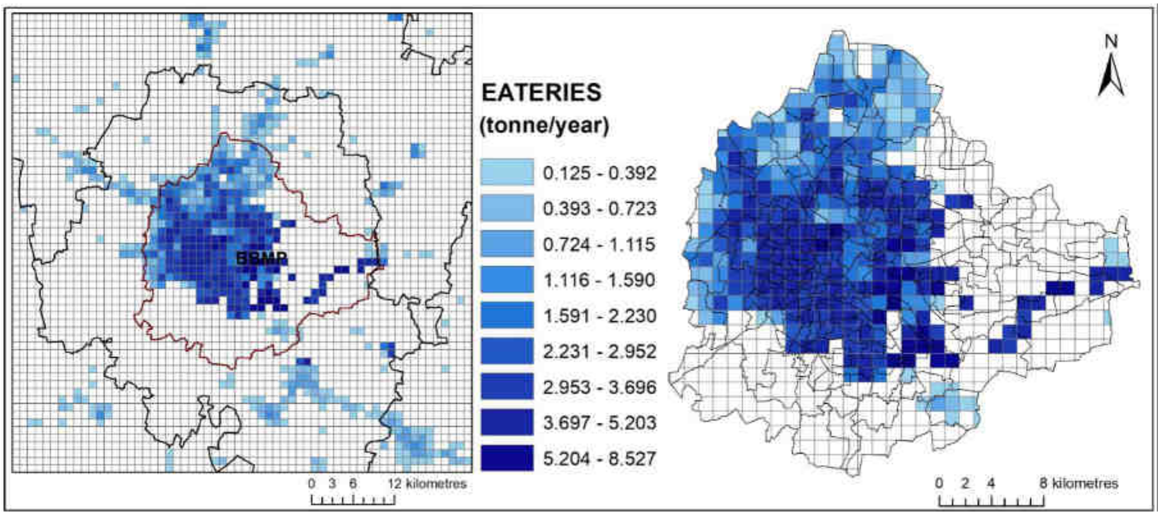


Figure 3-16: SO_2 emission from commercial fuel consumption

Emission from eateries was greater near the areas with more commercial activities, such as Sarjapura, Bellanduru, Marathahalli, Kalyan Nagar, Yeshwanthpura, and MG Road.

Although the consumption of coal in eateries is less than 0.5% of total fuel consumption, coal contributes to more than 96% of total PM_{10} emissions (Figure 3-17). Even with air pollution control devices installed in the premises, large speciality restaurants individually emit more than double PM_{10} than an average medium-size restaurant. However, owing to the smaller number of speciality restaurants, the overall emission contribution from large restaurants is less than that from the other category of restaurants.

Considering the adverse health effects (asthma, chronic obstructive pulmonary disorder, heart problems, bronchial problems, etc.) of $PM_{2.5}$, exposure should be curtailed. However, cooks and regular patrons of speciality restaurants are constantly exposed to $PM_{2.5}$. Based on our ground survey we found that 5-10% of restaurants use filters. However, the operational efficiency of these filters is unknown.

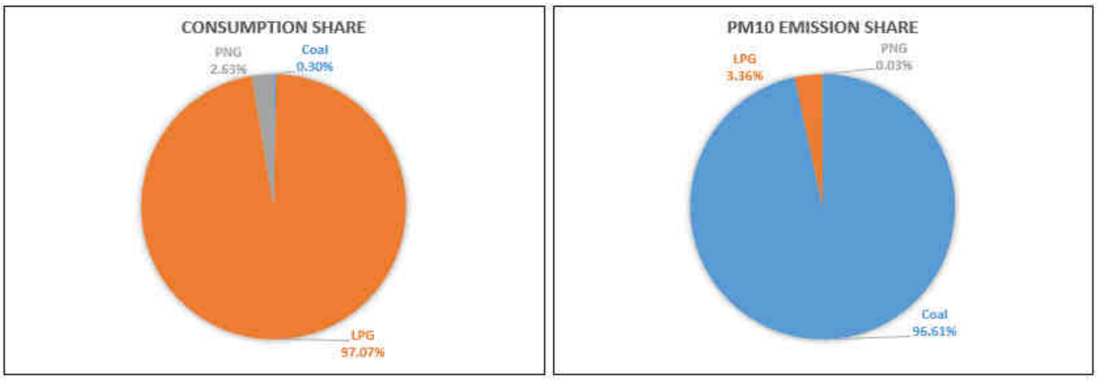


Figure 3-17: Consumption and PM emission share of fuels in eateries

Considering that the emission from coal/charcoal is responsible for more than 95% of the overall emission from eateries, the government should think of restricting the sale of coal/charcoal in the city. Further, restaurants should be encouraged to adopt alternative methods of cooking (for special dishes), and the installation of air pollution control devices should be made mandatory for all restaurant types.

3.2.2.3 Diesel Generator Sets

India had a power deficit of 0.8% during peak hours and an overall energy deficit of 0.6% in 2018–19. The power deficit along with intermittent power cuts due to scheduled maintenance work resulted in high usage of DG sets in high-rise buildings, commercial establishments, and industries.

Emission from DG sets is directly proportional to the number of power-cut hours. We adopted a bottom-up approach to estimate emission from DG sets. We obtained the installation location and installed capacity (kVA) of DG sets from the Department of Electrical Inspectorate, Government of Karnataka. The data were geo-located over the study grid. Around 10,000 DG installation locations were digitised over the study area (8,700 installed within the BBMP area) (Figure 3-18).

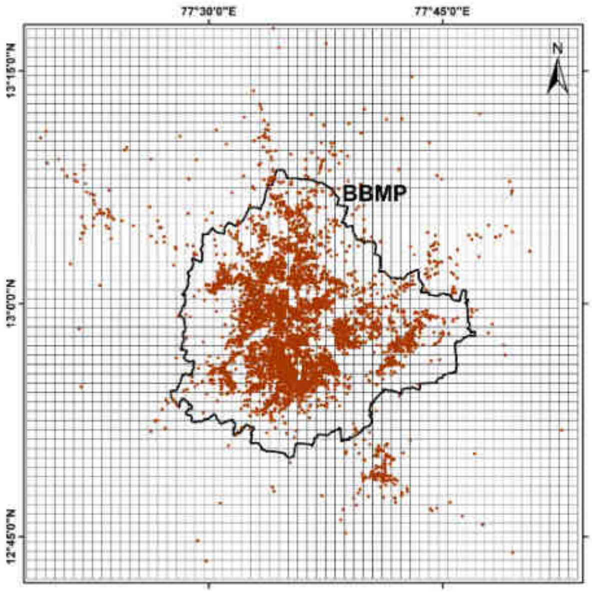


Figure 3-18: DG sets installation location

We obtained the details of average power cuts from BESCOM. We estimated the emission from DG sets on the basis of average power-cut hours and installed capacity of DG sets. The emission from DG sets was spatially distributed on the basis of installation locations. The total emission from DG sets was estimated to be 2,187 tonnes/year of PM_{10}, 1,601 tonnes/year of $PM_{2.5}$, 30,919 tonnes/year of NO_x, and 2,039 tonnes/year of SO_2. Figure 3-19–Figure 3-22 depict the spatial distribution of emission over the study and BBMP areas. As evident from the figures, the emission from DG sets was concentrated over the central and eastern parts of Bengaluru. Mahadevpura contributes the most in terms of emission from DG sets. Further, the emission is higher in Kadugodi, Marathahalli, Doddanakundi, and Bellanduru (under Mahadevpura constituency) mainly because of the high number of installed DG sets in high-rise buildings, IT parks, and commercial establishments in these areas.

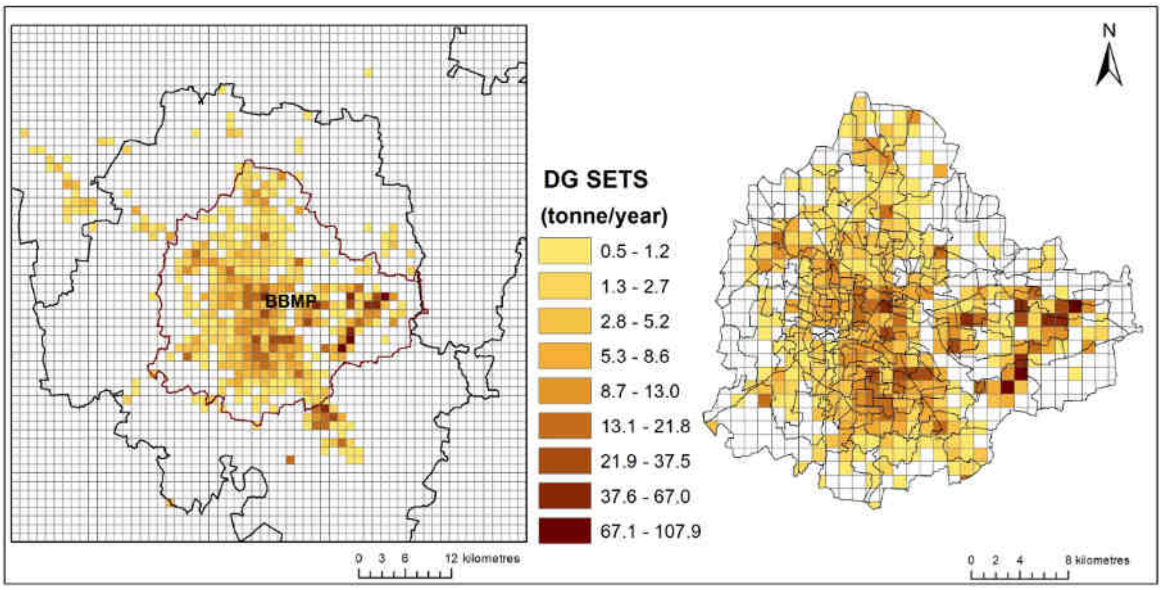


Figure 3-19: PM_{10} emission from DG sets

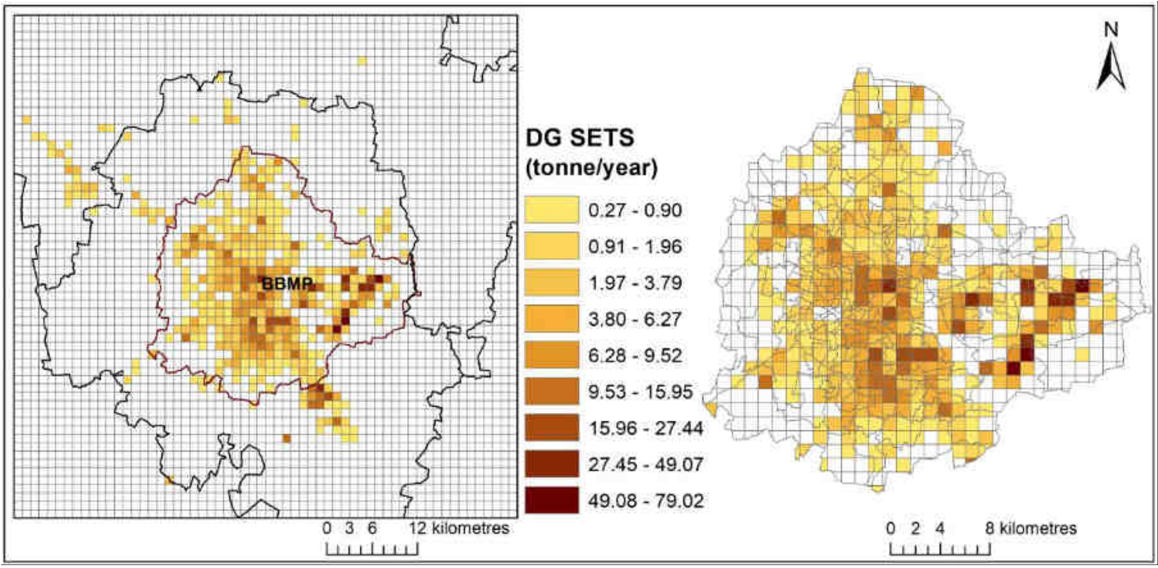


Figure 3-20: $PM_{2.5}$ emission from DG sets

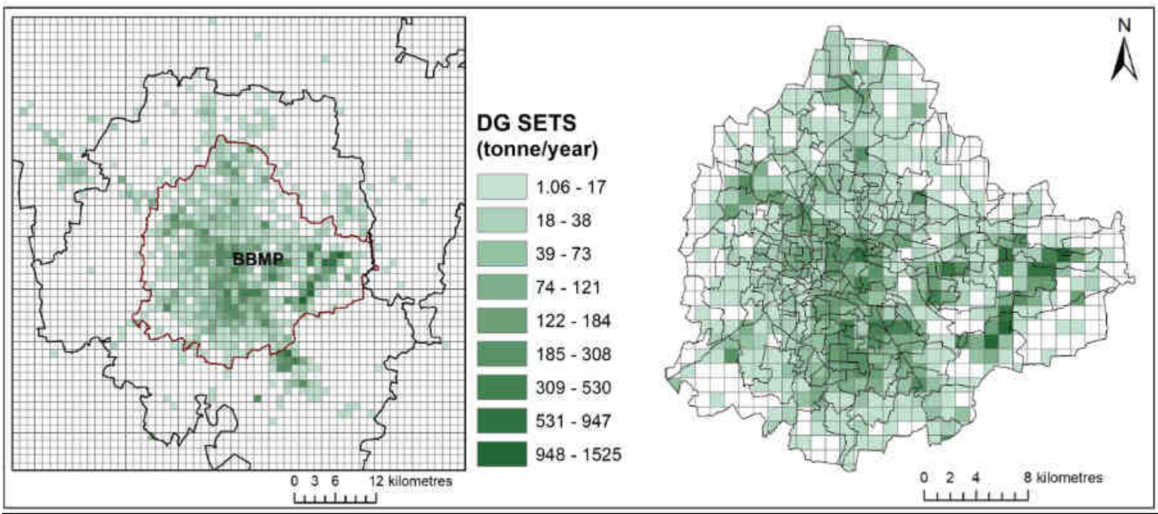


Figure 3-21: NO_x emission from DG sets

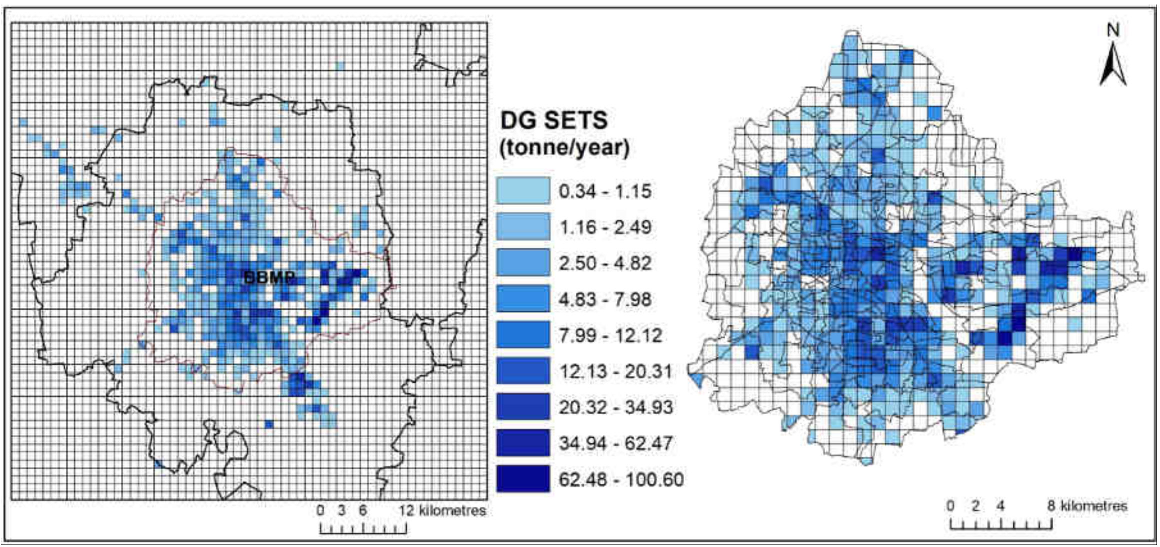


Figure 3-22: SO_2 emission from DG sets

From the results, it is clear that most of the emission from DG sets is from the wards with more commercial spaces, high-rise buildings, and IT parks (Figure 3-23). For example, ward number 150 (Bellanduru) alone contributed to 11% of overall DG set emission (PM_{10}) in the study area.

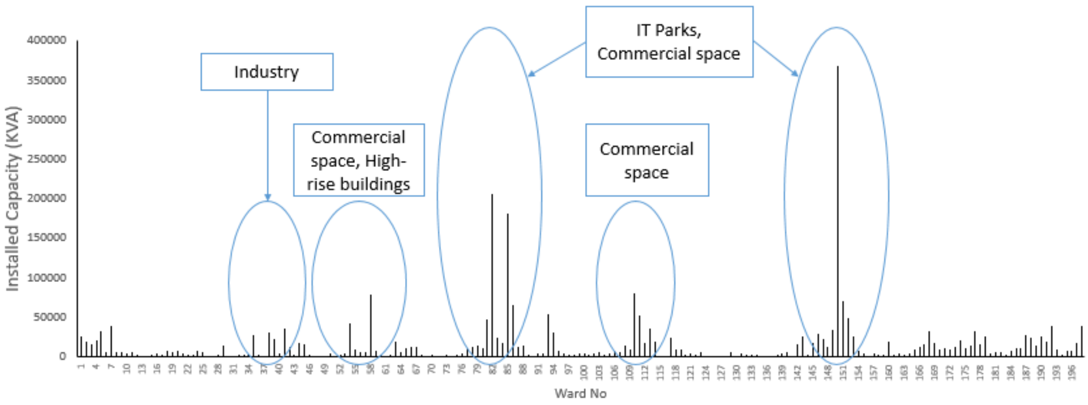


Figure 3-23: Ward-wise installed capacity (kVA)

DG set emission leads to significant pollution in Bengaluru's ambient atmosphere. Other than PM, DG sets also emit a significant amount of gaseous pollutants (NO_x and SO_2), which are precursors to secondary PM (secondary PM is defined as PM created in the atmosphere from various chemical reactions). Curbing emission from DG sets is, therefore, of utmost importance. A more efficient distribution infrastructure (to reduce the number of load-shedding hours) and uptake of rooftop solar photovoltaic (RTPV) cells in Bengaluru will go a long way in reducing emissions from DG sets.

3.2.2.4 Municipal Solid Waste (MSW) Burning

Although per capita waste generated in urban areas in India (~500 g) is less than that in the United States (2 kg) (CSE, 2016; USEPA, 2019), the amount of waste that ends up in landfills is huge in India, owing to inadequate solid waste management. Landfill fire is quite common in India because of unscientific landfilling and decomposition. Though combustion can lead to fires, fire is also used frequently as a tool to clear landfill areas to accommodate new garbage. Although MSW burning is illegal (NGT, 2016), burning of MSW by the roadside or in empty lands is common across India, including Bengaluru.

The estimation of emissions from waste burning is quite uncertain owing to the unavailability of data. It is very difficult to gather data on the quantity of garbage burned in Indian cities. In India, around 5–12% of the collected waste is estimated to be burned (Lal et al., 2016; Nagpure et al., 2015; Rana et al., 2018). We adopted a top-down approach to estimate the emissions from waste burning. The quantity of generated and collected waste, and socioeconomics of neighbourhoods, along with solid waste processing capacity, were considered for estimating the quantity of waste burned.

Data on the generation and processing of solid waste were obtained from district administrations and BBMP. Garbage dumping locations were obtained from opencity.in. Emission from waste burning was distributed on the basis of crowdsourced data for garbage dumping locations (opencity.in). We geo-located the garbage-burning locations through a survey. From the data collected, the total emission from MSW burning was calculated to be

1,455.6 tonnes/year of PM_{10}, 1,411.5 tonnes/year of $PM_{2.5}$, 529.3 tonnes/year of NO_x, and 88.2 tonnes/year of SO_2. Figure 3-24 depicts the spatial distribution of emissions over the BBMP area.

Garbage burning is more in the western parts of the city, specifically RR Nagara and Bengaluru West. Other than these areas, the city market area also experiences a lot of garbage burning. Despite government efforts, garbage burning in Bengaluru is rampant. Sightings of garbage burning around the Outer Ring Road and beside railway tracks are very common. It is evident that waste burning is more prevalent in peripheral wards. The availability of ample land for garbage dumping, underdeveloped infrastructure for collecting waste, etc. may be a few of the factors responsible for garbage burning by people. Regular door-to-door collection of waste and proper auditing of the waste collection mechanism will reduce garbage burning to a large extent.

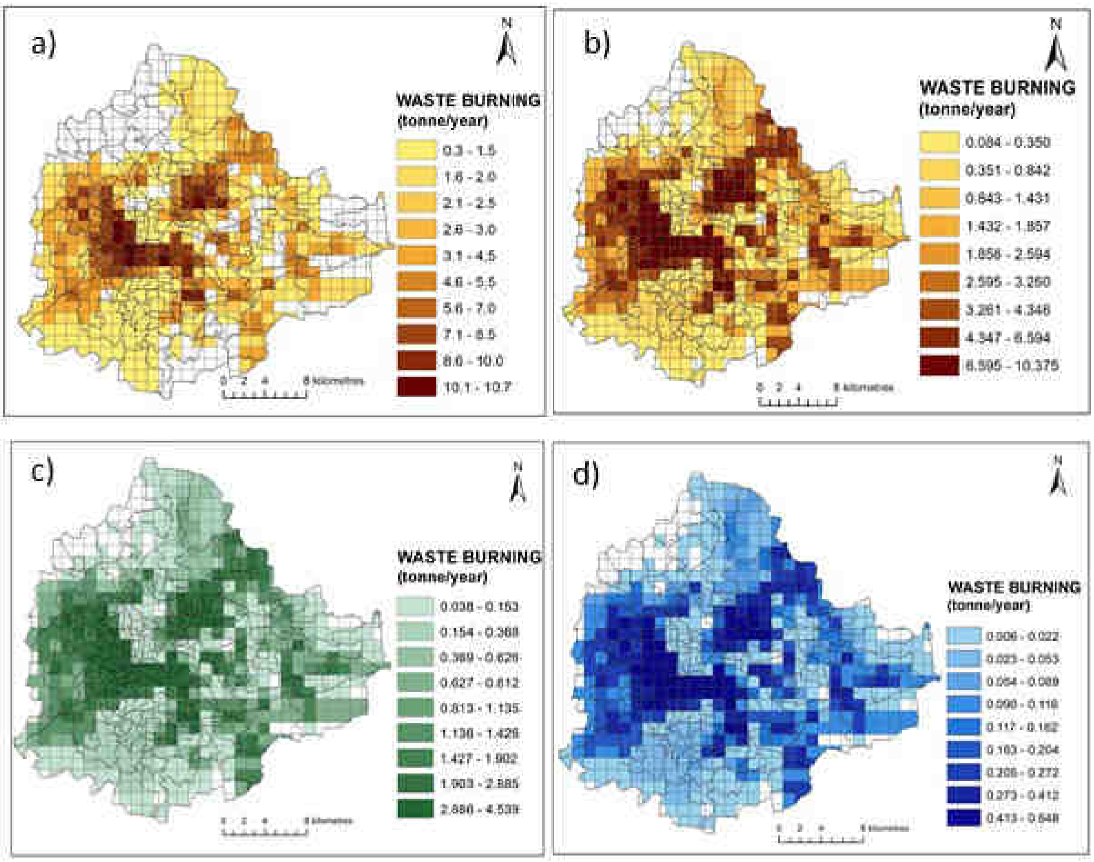


Figure 3-24: (a) PM_{10}, (b) $PM_{2.5}$, (c) NO_x, and (d) SO_2 emission from MSW burning

3.2.2.5 Construction and Demolition

With city expansion and infrastructure development, construction and demolition have become a part of everyday life. Particulate emission predominantly arises from site preparation work, which may include scrapping, grading, loading, digging, compacting, heavy-duty construction equipment movement, and other operations. For estimating emissions from these activities, we assumed that fugitive dust emissions are related to the acreage affected by construction.

We adopted a bottom-up approach to estimate the emission from the construction sector. Data were compiled for the number of construction activities, areas, and duration. The information was geo-tagged over the study area. Emission from construction activities was allocated to the geo-tagged grids.

Data on new construction activities (in 2019) were obtained from the Real Estate Regulatory Authority (RERA). A total of 235 new projects were listed under RERA; the start and tentative completion times of the projects were also obtained. The projects were geo-located in the study area.

The emission from the construction sites was estimated to be 2,702 tonnes/year of PM_{10} and 450 tonnes/year of $PM_{2.5}$. The emission was concentrated in the peripheral areas of Bengaluru. Figure 3-25 and Figure 3-26 depict the emission from the construction sector over the study and BBMP areas. Even though the emission from construction is distributed across fewer grids than is the case with other sectors (except airport), the emission from only two grids in Varthuru was more than the cumulative emission from domestic and commercial fuel consumption in the BBMP area.

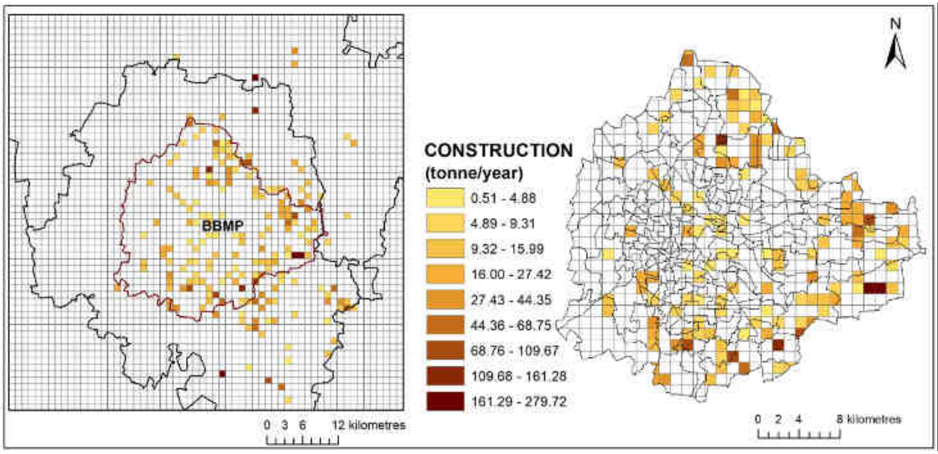


Figure 3-25: PM_{10} emission from construction sector

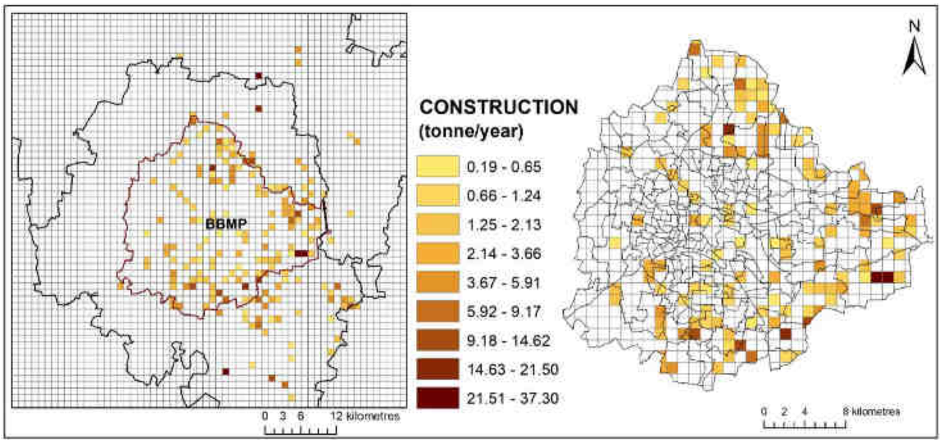


Figure 3-26: $PM_{2.5}$ emission from construction sector

The emissions from the construction sector can be reduced by adopting the control measures prescribed by CPCB. Measures such as the erection of a green screen around the construction site and the use of cover while transporting construction material should be enforced strictly.

Further, BBMP should think of creating a task force to curb violations by construction companies.

There were no data available for the number of demolitions and the areas affected in 2019. In addition, owing to data unavailability, the emission from road/bridge/flyover construction was not accounted for.

3.2.2.6 Airport

Airports are one of the major emitters on account of both ground movement of vehicles and flight operations. Though aeroplanes emit throughout their flight path, most of the flight path is around 30,000 feet above the sea level and dispersion occurs more quickly at higher altitudes. Nevertheless, the effective emission from flight operations is considered only during the landing and take-off (LTO) cycle. Figure 3-27 shows the LTO cycle of an aeroplane.

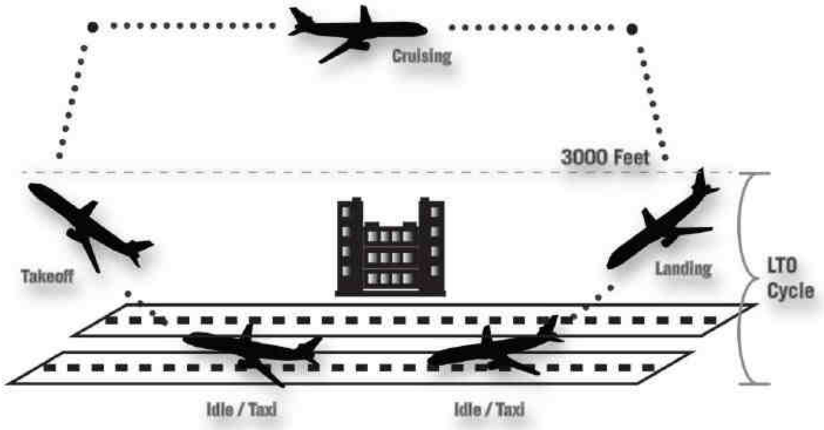


Figure 3-27: Landing and take-off (LTO) cycle at an airport

(Source: Norton, 2014)

Owing to the difference in the amount of fuel burned by narrow- and wide-bodied planes, the LTO cycles of domestic and international flights were estimated separately.

We obtained the data on the number of LTO cycles and fuel consumption in ground operations from Bangalore International Airport Limited (BIAL). Other than the Kempegowda International Airport, there are three more airports (including private and military) in Bengaluru. Activity data for these three airports were unavailable.

Emission from aviation was estimated to be 248 tonnes/year of PM_{10}, 214 tonnes/year of $PM_{2.5}$, 3,575 tonnes/year of NO_x, and 234 tonnes/year of SO_2. The spatial distribution of emission from aeroplanes is based on the flight path and the average horizontal distance to achieve a height of 3000 feet. Emission from the ground movement of vehicles was assigned to grids where the airports are situated (Figure 3-28).

Although emission from airports was restricted to their surrounding areas, the emission per grid was much higher than the emission from domestic and commercial fuel consumption, or MSW burning. Considering the growth of passenger movement through BIAL and the construction of a second runway, the emission from the Kempegowda International Airport will only increase in the near future. However, owing to the large distance between the BBMP area and the airport, the emission from the airport will not affect the inhabitants of the BBMP area in the near future.

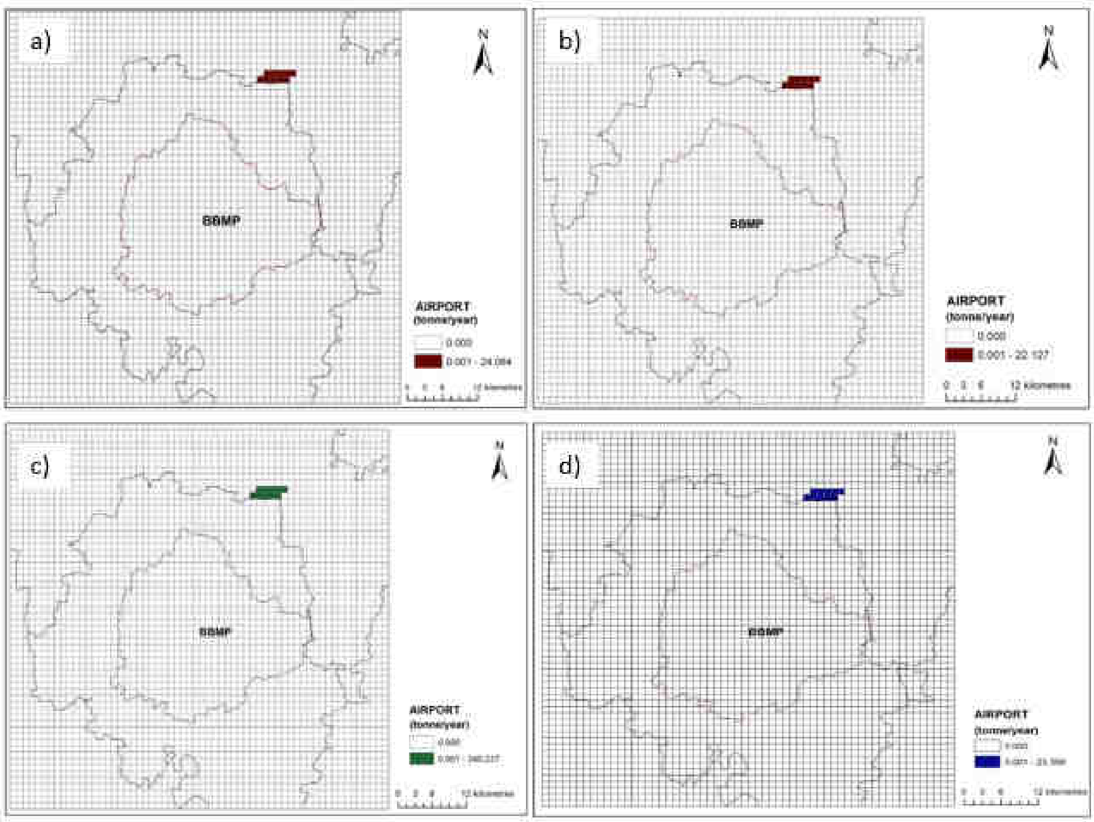


Figure 3-28: (a) PM_{10}, (b) $PM_{2.5}$, (c) NO_x, and (d) SO_2 emission from airport

3.2.2.7 Industrial Fuel Consumption

Depending upon the stack height, industrial emission can be treated as either an area source or a point source. The emission was estimated by either (1) multiplying the flow rate in the stack with operating hours and pollutant concentrations in the stack, or (2) multiplying the average fuel consumption with the fuel EF.

We obtained the names and types of industries (red and orange categories) from the Karnataka State Pollution Control Board (KSPCB) and Karnataka Industrial Area Development Board (KIADB). There are around 10 industrial areas in and around Bengaluru, namely – Bommanahalli, Bengaluru East, Hoskote, Peenya, Dasarahalli, Nelamangala, Bengaluru West, Mahadevpura, Bengaluru South, and Yelahanka. Peenya and Dasarahalli cumulatively have 348 red category industries and 594 orange category industries. District-wise industrial consumption of diesel, natural gas, and fuel oil was obtained from fuel companies. Apart from the data from fuel companies, field surveys were also carried out to obtain the data and understand the activities on the ground.

The industrial emission (from fuel sales) was estimated to be 22.4 tonnes/year for PM_{10}, 20 tonnes/year for $PM_{2.5}$, 136.4 tonnes/year for NO_x, and 1,020 tonnes/year for SO_2. Emissions from industries treated as area sources were spatially distributed on the basis of LULC data. However, point source emissions were marked as emanating from a singular source only in the grids occupied by them. The spatial distribution of industrial emission is depicted in Figure 3-29–Figure 3-32.

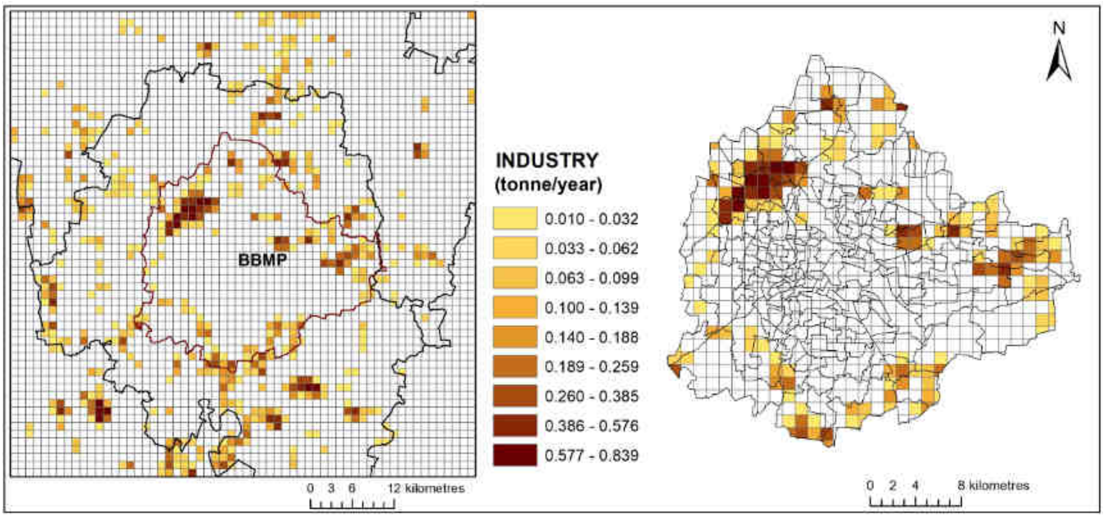


Figure 3-29: PM_{10} emission from industrial fuel consumption

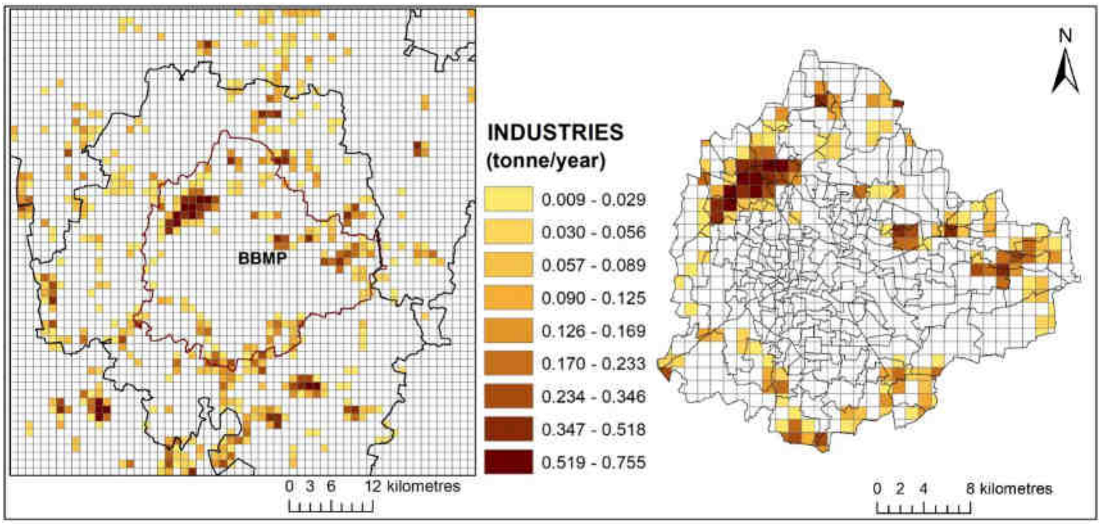


Figure 3-30: PM2.5 emission from industrial fuel consumption

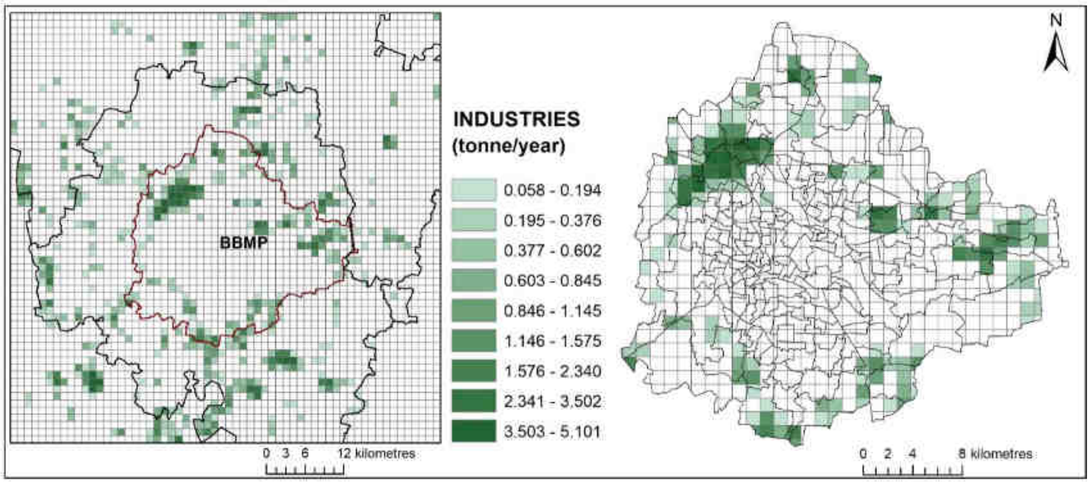


Figure 3-31: NO_X emission from industrial fuel consumption

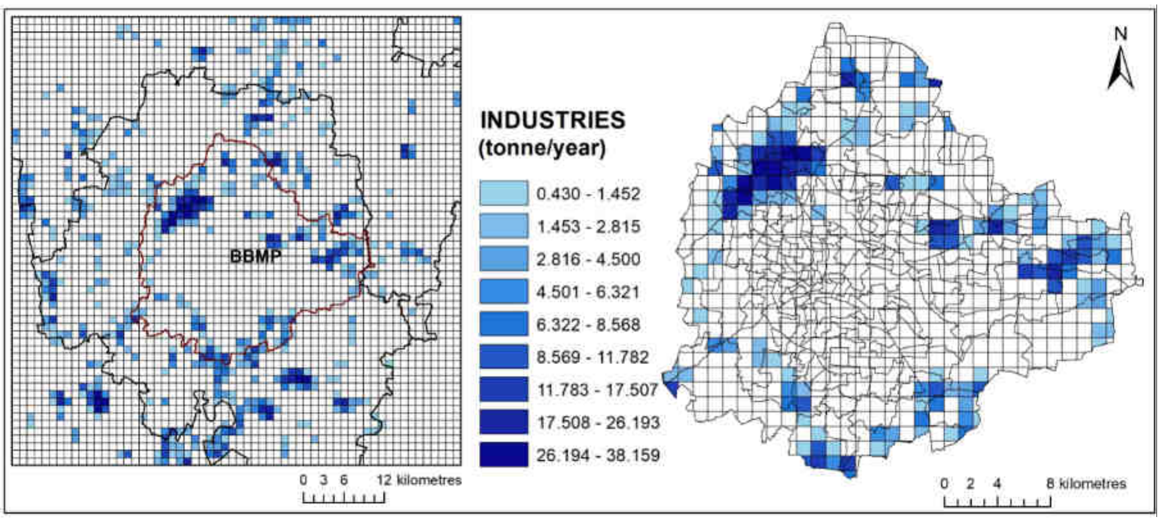


Figure 3-32: SO_2 emission from industrial fuel consumption

In Bengaluru, inhabitants of Peenya, Dasarahalli, Whitefield, and Mahadevpura are exposed to industrial emissions more than the inhabitants in other areas because of the high number of industries (manufacturing and fabrication industries). Although emission from industries is restricted to the peripheral areas of Bengaluru, Peenya and Dasarahalli are responsible for the majority of industrial emissions. These two areas have 942 red and orange category industries, from pharmaceutical, electrical component manufacturing, and fabrication sectors. Other than the BBMP area, nearby areas such as Hoskote, Jigani, and Bidadi have numerous industries that contribute significantly to industrial emissions. Paint manufacturing units in these areas emit a large amount of volatile organic compounds.

We could only obtain data for diesel, fuel oil, and CNG. Our conversations with industry experts point towards the use of wood chips, coal, and refuse-derived fuel (RDF) in industries around the BBMP area. However, we do not have any estimates for these fuel types and therefore did not consider them in our calculations.

3.2.2.8 Transportation

Tailpipe Emission: In most Indian cities, transportation is one of the biggest contributors to air pollution. Emission estimation for the transportation sector requires survey data. VKT was calculated for each vehicle type (two-wheelers, autorickshaws, cars, buses, and trucks) on the basis of the road length in a grid and the number of vehicles of each type. Emission was calculated for each grid individually. This was done by multiplying the VKT and EF for each vehicle type and then adding the emissions from all vehicle types.

Vehicle statistics were obtained from the Department of Transportation (DoT). However, DoT provided the total number of vehicles registered in Bengaluru. Therefore, the number of vehicles registered 15 years ago was deducted from the current number to get a realistic number of vehicles plying on city roads (based on the survival function). The resulting vehicle count was distributed on the road network on the basis of survey data. For estimating vehicle emission, the Bharat Stage (BS) share (i.e., the distribution of engine technology) was considered. As the emission was estimated on the basis of vehicle movement in each grid, no further spatial distribution was required.

We obtained the vehicle registration data from the VAHAN database and Department of Transport, Government of Karnataka (Figure 3-33). Apart from vehicle registration data, the data for vehicles entering Bengaluru were obtained from the National Highways Authority of India (NHAI).

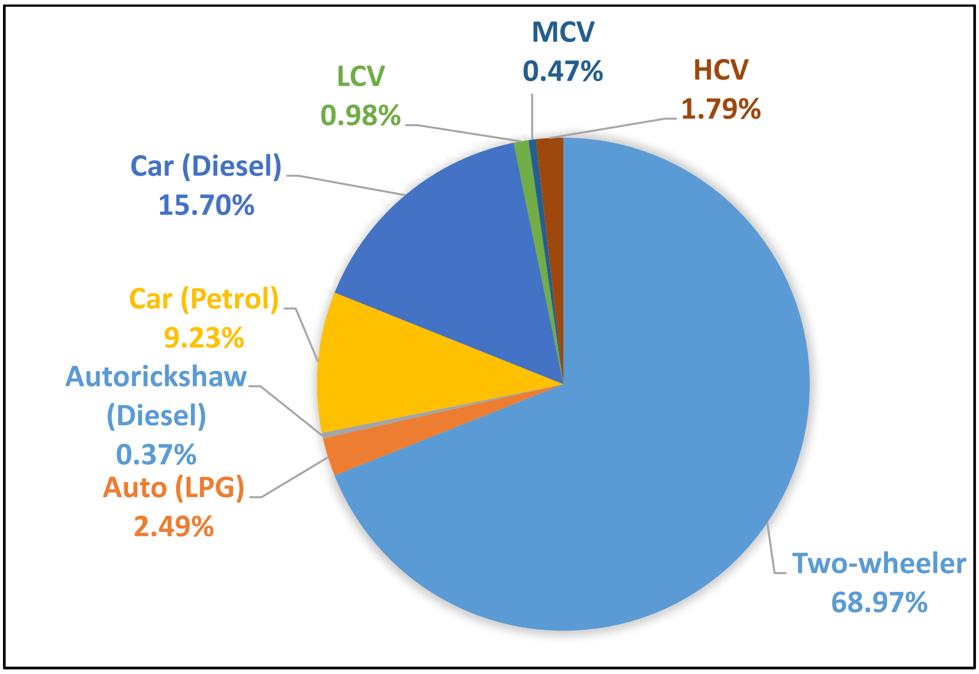


Figure 3-33: Vehicle type share

Two types of surveys were conducted for transportation—a petrol bunk survey to determine the vintage of vehicles and a traffic count survey at 22 locations in Bengaluru to understand the spatial distribution of transportation emission. A total of 1,487 vehicles were surveyed at 12 petrol bunks as part of the survey. From this survey, we determined the age of vehicles plying in Bengaluru and the share of four-wheelers on the basis of fuel (petrol or diesel). The results are presented in Figure 3-34.

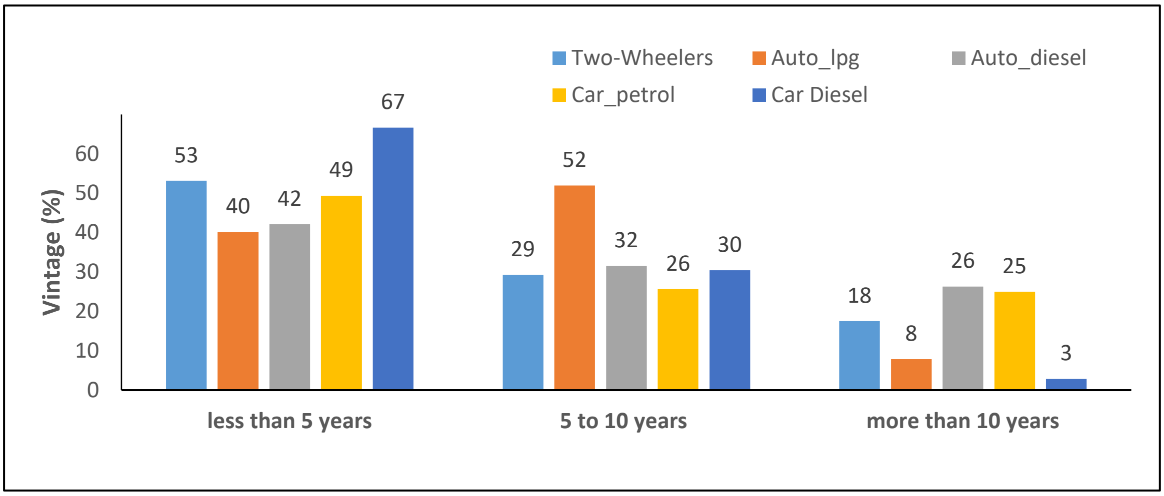


Figure 3-34: Vintage of vehicles

During emission estimation, VKT was obtained from a Delhi study (SAFAR, 2018) and transportation survey in Bengaluru. The effect of vehicle vintage on VKT was also considered

(Goel & Guttikunda, 2015). To account for heavy emitting vehicles, estimates of tail-pipe emissions were increased by 25% (TERI & ARAI, 2018). Tailpipe emission was estimated to be 12,445 tonnes/year of PM_{10}, 9,334 tonnes/year of $PM_{2.5}$, and 49,592 tonnes/year of NO_x. Figure 3-35 shows the tailpipe emission for individual vehicle types. Commercial vehicles (HCVs, MCVs, and LCVs) contributed around 56.5%, 8.5%, and 18.8% of the PM emission load, respectively, whereas diesel cars contributed around 9.11% of the emission load. Two-wheelers contributed around 6.6% of the PM emission load.

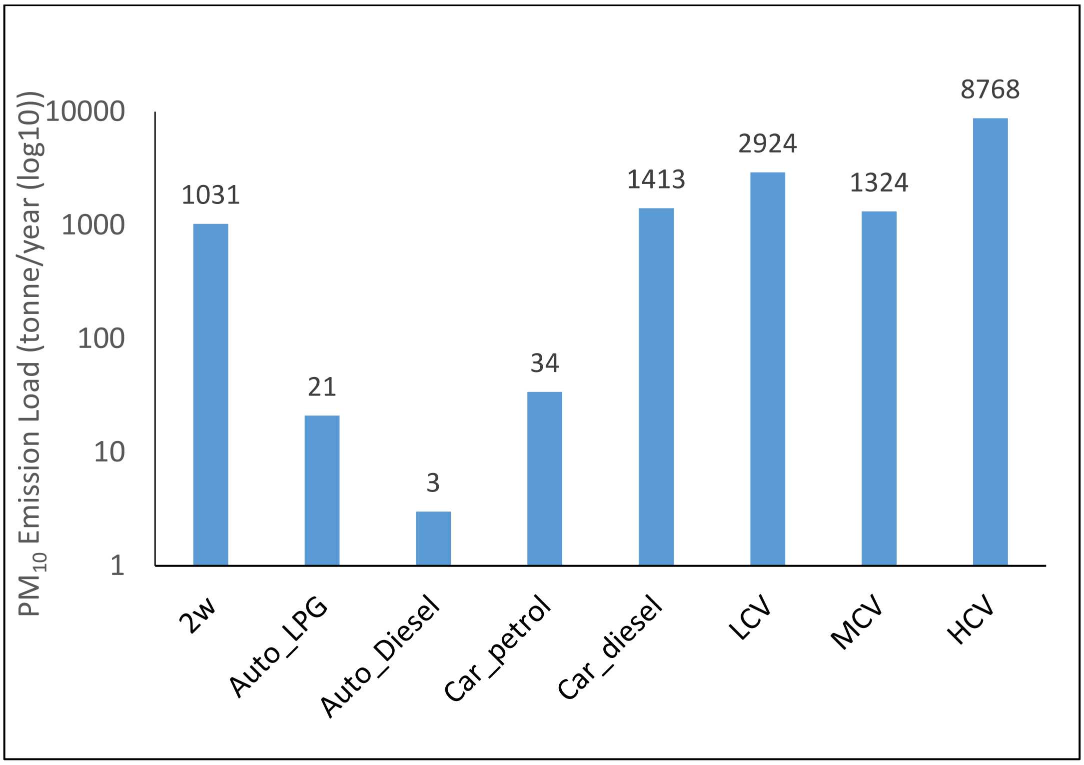


Figure 3-35: PM_{10} emission load from tailpipe emission

A 16-hour videography-based traffic count survey was undertaken to determine the spatial distribution of vehicles plying in Bengaluru along with the peak and off-peak traffic count. The traffic count survey was conducted twice a week (on a weekday and over the weekend) to maintain consistency in the results. We found that on average, cars constituted 30–50% of the traffic in Bengaluru, whereas two-wheelers constituted 20–65% of the traffic (depending on location and timing). The spatial distribution of tailpipe emission is depicted in Figure 3-36–Figure 3-38.

There are many vehicles registered in other states plying in Bengaluru. As most of these vehicles do not cross toll plazas frequently, it is impossible to obtain their numbers, and thus, the emission from these vehicles could not be estimated.

Vehicular emission was found to be high on main and arterial roads because of the traffic volume and movement of HCVs (restricted to these roads only). Emission on the approach roads (state and national highways) was due to interstate and inter-district traffic (mainly HCVs). HCVs (including buses) constitute only 1.8% of total vehicles plying in Bengaluru but contribute 57% of PM_{10} load from transportation. In the BBMP area, the Outer Ring Road and central business district experience more emissions. However, the nature of emission is different in these areas. The emission on the Outer Ring Road was from mixed traffic (including HCVs), whereas that in the central business district was mainly from two- and four-wheelers.

Although newer engine types (BS-VI) will reduce the tailpipe emission from new vehicles, older vehicles will continue to produce high emissions. BBMP should consider implementing low emission zones (similar to London) to reduce vehicular emissions. A better public transport infrastructure with end-to-end connectivity will reduce emissions to a large extent.

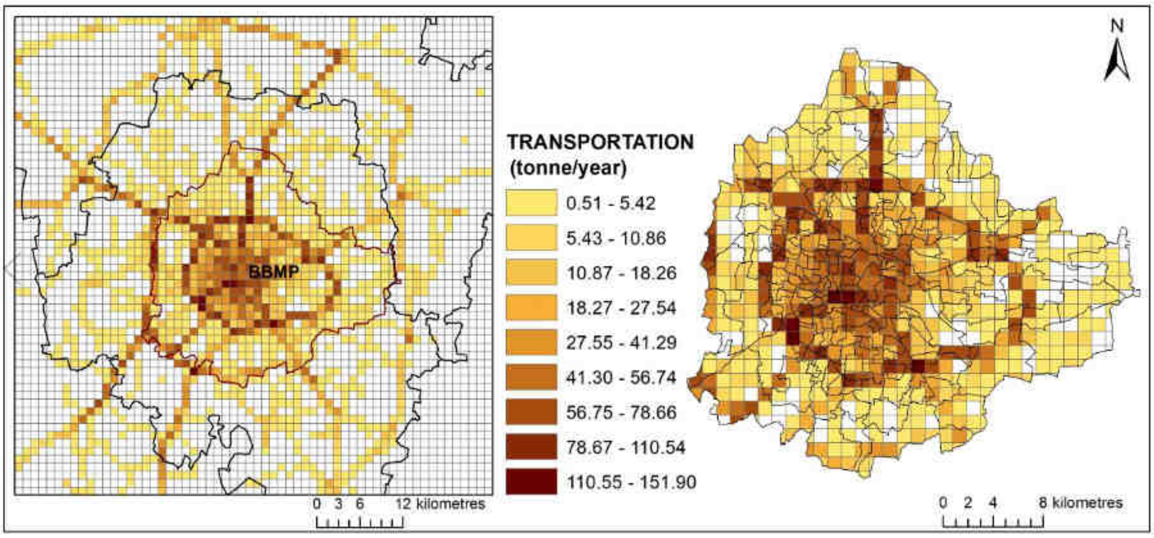


Figure 3-36: PM_{10} emission from tailpipe emission

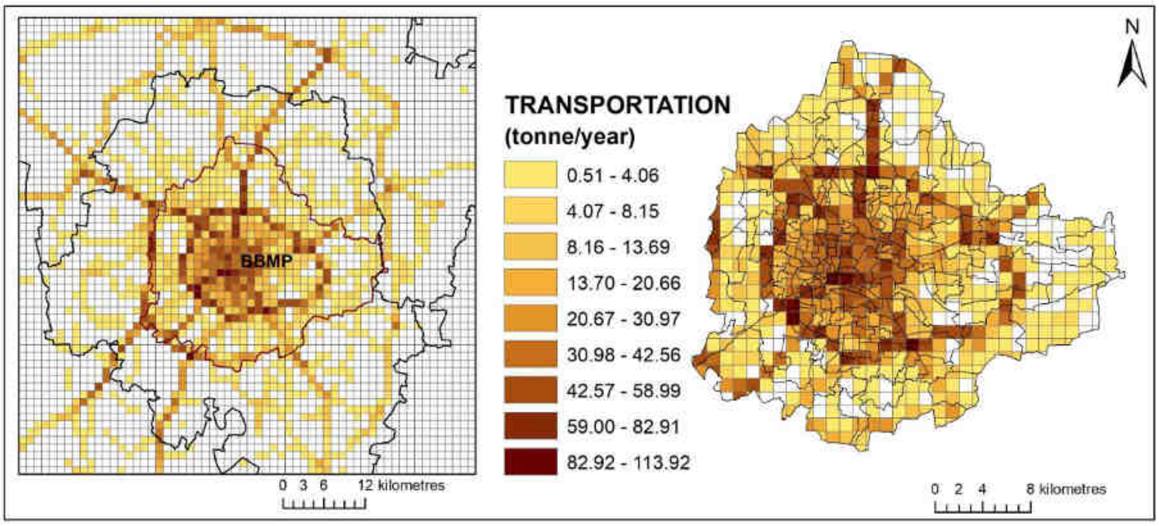


Figure 3-37: $PM_{2.5}$ emission from tailpipe emission

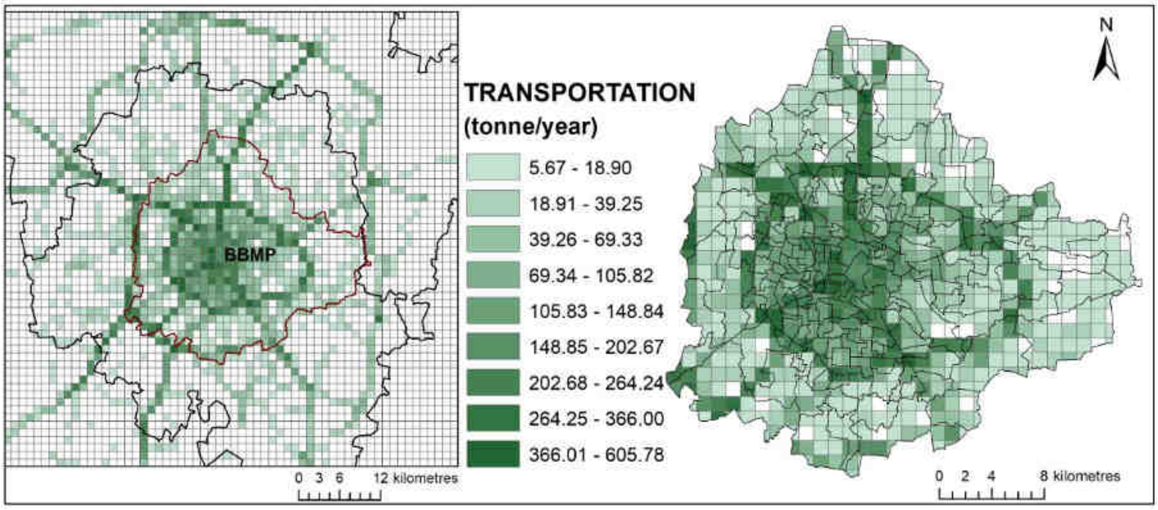


Figure 3-38: NO_x emission from tailpipe emission

Re-suspension of Dust: In addition to tailpipe emission, vehicular movement and bad road infrastructure are responsible for the re-suspension of dust. For the estimation of road dust, road type data were also considered in addition to road network data. The EF for road dust varies with the road type (paved or unpaved), vehicle share, and climatic conditions. Owing to the variation in EFs, emission should be calculated separately for each grid.

The emission from re-suspension of dust was estimated to be 4,154 tonnes/year of PM_{10} and 1,005 tonnes/year of $PM_{2.5}$. Figure 3-39 and Figure 3-40 depict the spatial distribution of emission from re-suspension of dust.

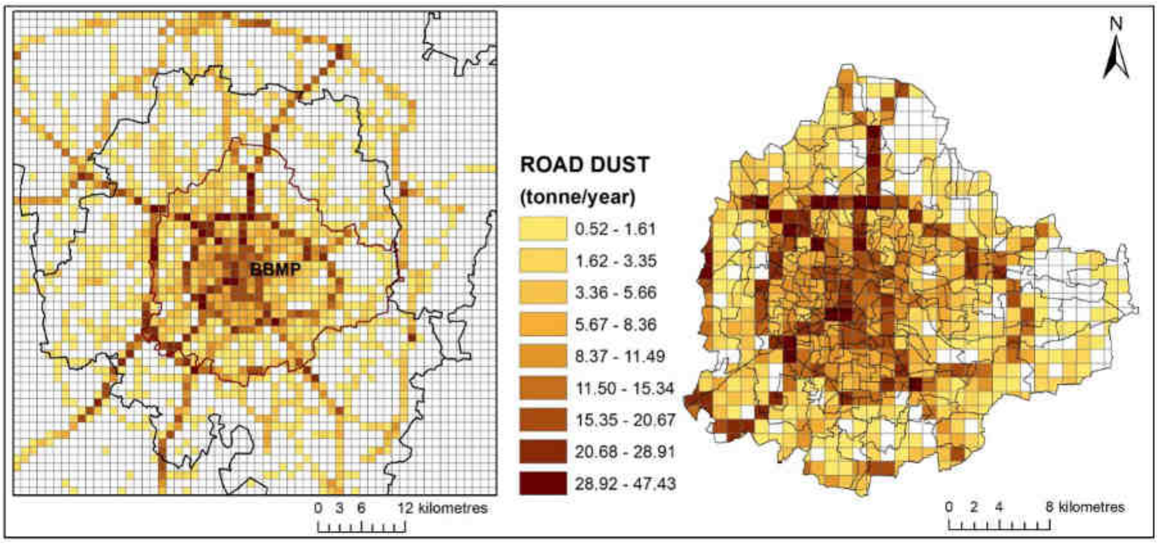


Figure 3-39: PM_{10} emission from re-suspension of dust

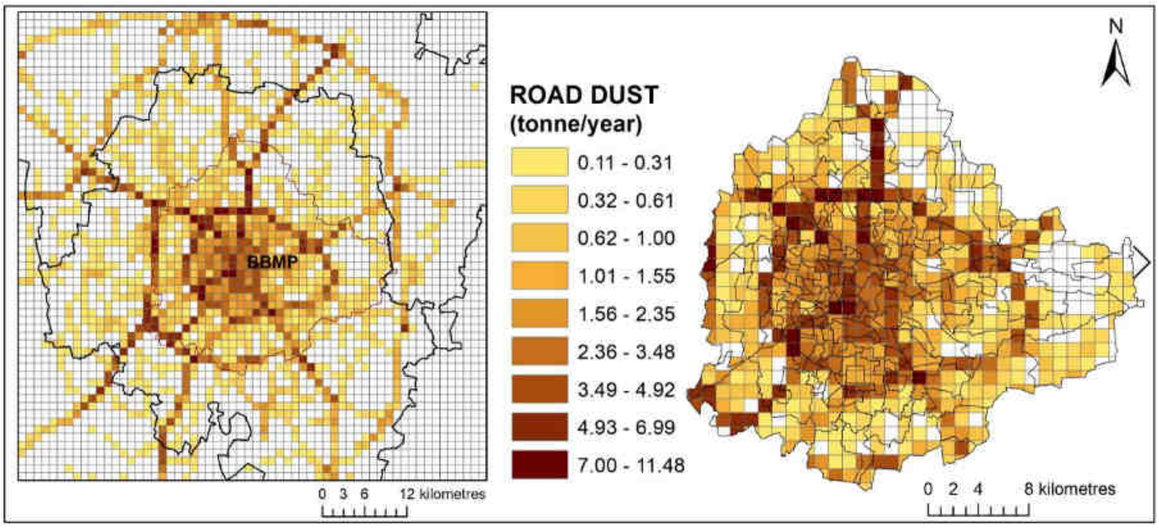


Figure 3-40: $PM_{2.5}$ emission from re-suspension of dust

The re-suspension of dust is directly dependent on vehicular movement. Hence, the spatial distribution of emission is similar to that of transportation emission. One of the major reasons for road dust is silt load. The dust from road sweeping occasionally accumulates by the roadside, which again adds to dust re-suspension. End-to-end paving and removal of silt from the road surface will reduce road dust emission to a large extent.

3.3 Emission Inventory Summary

3.3.1 Sectoral Emission Contribution

Figure 3-41–Figure 3-44 depict the sectoral share of emissions for the air-shed and BBMP areas. Within the air-shed, the majority of the PM emission (around 83%) is attributed to transportation, re-suspension of dust, and construction activities.

Re-suspension of road dust is directly linked to vehicle movement. We can infer that the transportation sector (tailpipe emission and re-suspension of dust) contributes the maximum (71%) of the PM_{10} emission and 75% of the $PM_{2.5}$ emission. Tailpipe emission also contributes 66.8% of the NO_x emission in the air-shed region. The lack of last-mile connectivity along with economic prosperity has contributed to increased personal vehicle ownership. Further, the movement of heavy vehicles on inter-city and inter-state highways in and around Bengaluru contributes significantly to total PM emissions. Although the share of HCV, MCV, and LCV in total vehicles plying in Bengaluru is only 3.3%, they contribute around 84% of the PM load from transportation. Around 900,000 diesel cars ply in Bengaluru, contributing to around 9% of total PM emission from the transportation sector.

New constructions just outside the BBMP area account for around 44% of the PM emission load from the construction sector. Most of the new construction activities in the air-shed area are not in compliance with CPCB norms for reducing emissions from the construction sector.

Of the various fuels used in eateries in the city, coal constitutes only around 0.3% but contributes the largest share (97%) of emissions.

DG sets contribute to 28.6% of NO_x and 36% of SO_2 emissions in the air-shed area. Bellanduru ward alone contributes around 11% of the total PM load. Although industrial fuel consumption contributes less than 1% of PM emission, it is responsible for almost 45% of SO_2 emission in the air-shed area.

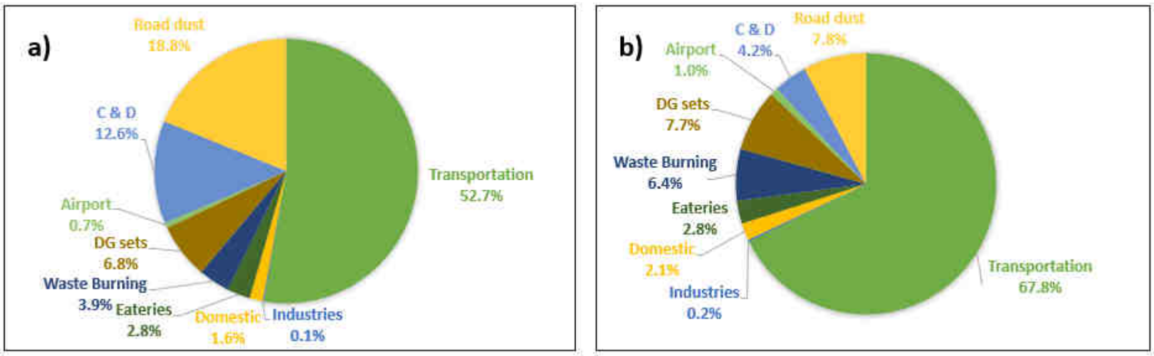


Figure 3-41: Sectoral contribution a) PM_{10} and b) $PM_{2.5}$ emissions over the air-shed area

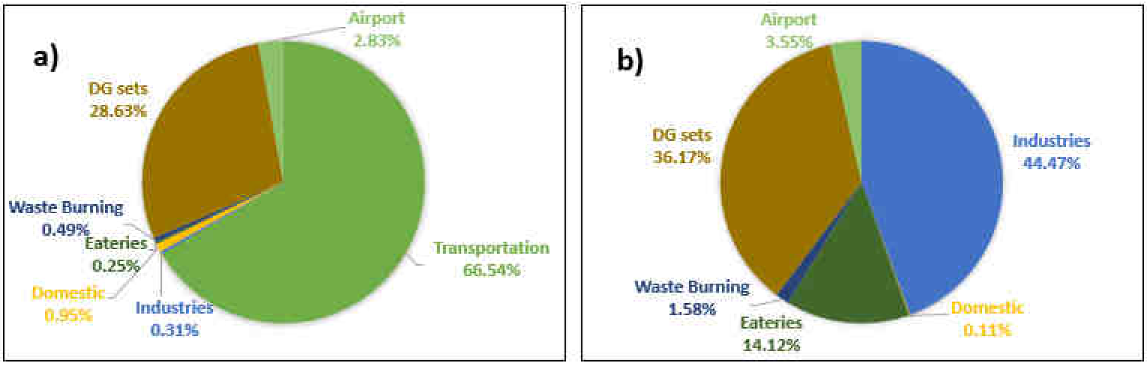


Figure 3-42: Sectoral contribution of a) NO_x and b) SO_2 emissions over the air-shed area

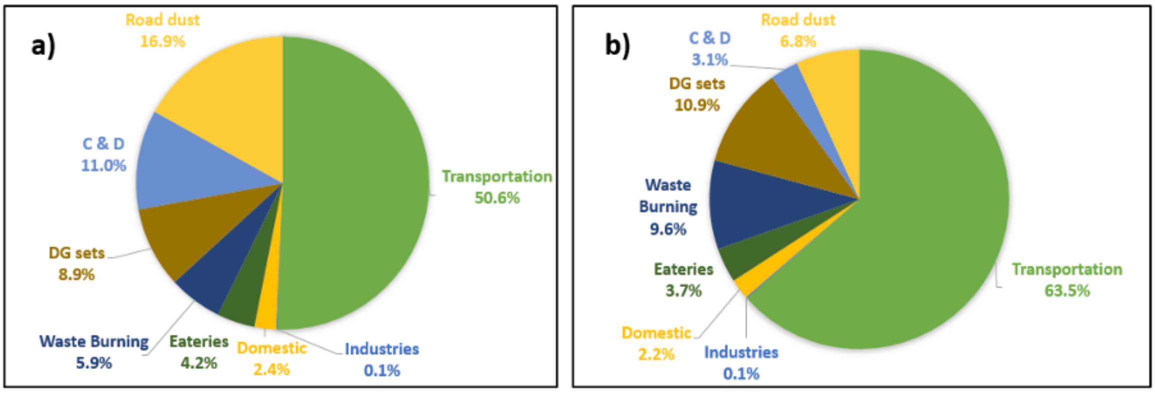


Figure 3-43: Sectoral contribution of a) PM_{10} and b) $PM_{2.5}$ over BBMP area

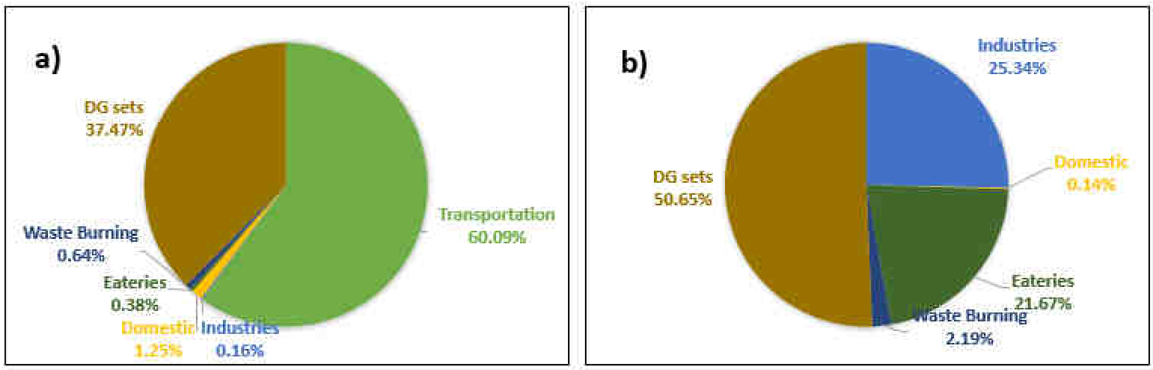


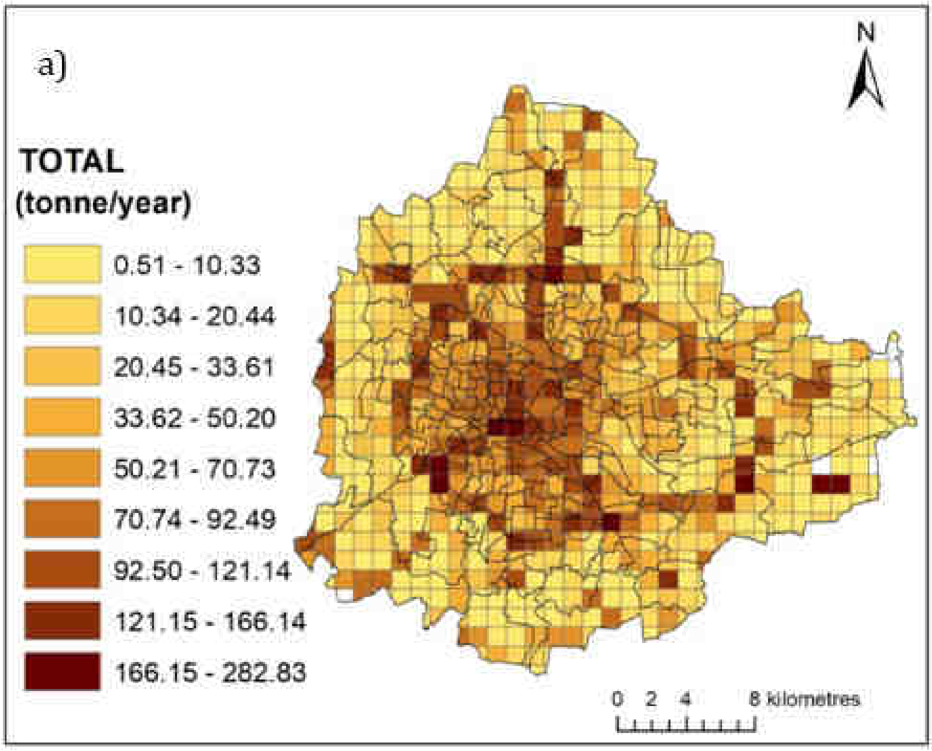
Figure 3-44: Sectoral contribution of a) NO_x and b) SO_2 over BBMP area

The PM_{10} emission share of the transportation sector in the BBMP area is lower than that in the air-shed area. The low emission values are due to the restriction on the movement of heavy-duty vehicles in the outskirts of the BBMP area. As road dust is directly related to vehicle movement, the reduction in PM emission share of road dust in the BBMP area corresponds to a lesser number of heavy vehicle movements. Emission from DG sets is high in the BBMP area because of the high number of installations. As a large number of industries are located in the peripheral areas of the BBMP area, their emission share decreased in the BBMP area. PM_{10} emission from eateries is high in the BBMP area because of the presence of a large number of specialty restaurants (use more coal/charcoal for cooking).

3.4 Summary and Recommendations

The study estimated emission loads from predominant polluting sectors – transportation (tail-pipe and re-suspended dust), domestic, commercial, and industrial fuel consumption, construction and demolition, DG sets, and waste burning in Bengaluru. The study incorporated activity level data from secondary sources, data from line departments, and survey data for estimating sectoral emission loads. The estimated sectoral loads were distributed spatially with help of LULC and population distribution.

The study estimates that in the year 2019, around 24,600 tonnes of PM_{10} and 14,700 tonnes of $PM_{2.5}$ were emitted from the BBMP area. The cumulative PM_{10} and $PM_{2.5}$ emission from all sectors is shown in Figure 33-45.



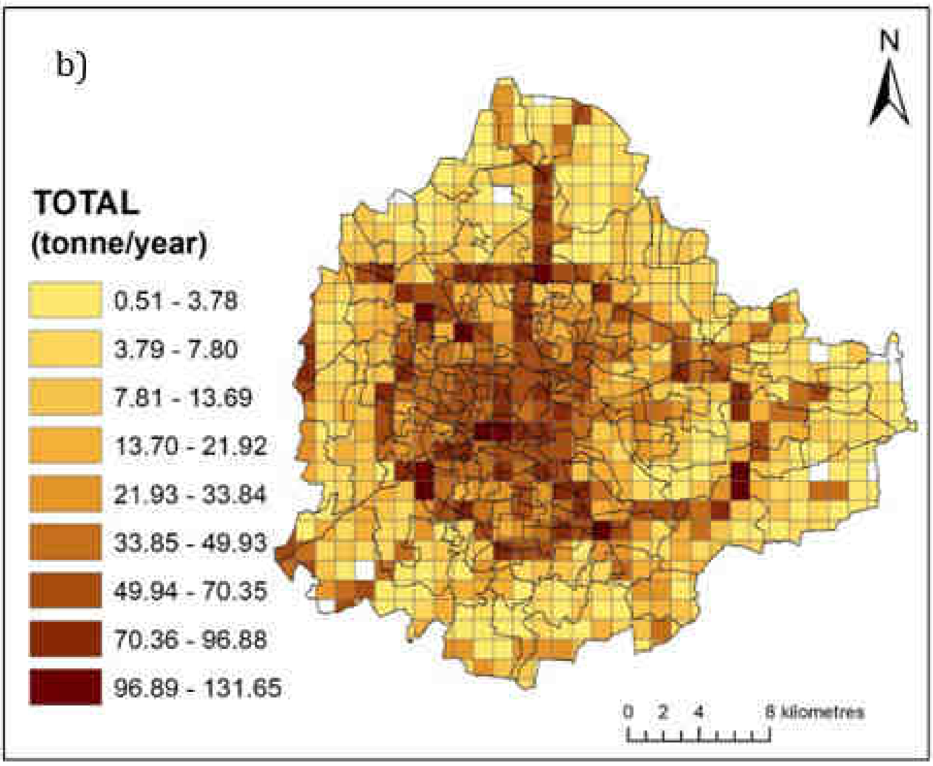


Figure 33-45: a) PM_{10} and b) $PM_{2.5}$ emission in BBMP area

Very high emission is observed in the grids along the Outer Ring Road and the grids with large construction projects (in Varthuru). As around 70% of the emission load (PM_{10} and $PM_{2.5}$) is contributed by the transportation sector (tail-pipe emission and re-suspended road dust), the spatial distribution of PM_{10} and $PM_{2.5}$ follows the spatial distribution of the transportation sector.

In both the air-shed and BBMP areas, transportation and dust have the maximum share of PM_{10} emission load (71% in the air-shed area). Emission from transportation (both tailpipe and re-suspension of dust) is greater along the Outer Ring Road and in the central business district. High emission along the Outer Ring Road is due to mixed traffic that includes heavy carriage vehicles, but that in the central business district is predominantly due to two-wheelers and cars. To reduce pollution, emission needs to be reduced at the source—reducing tailpipe emission by reducing the number of on-road vehicles (through better/efficient public transport) and restricting the usage of vehicles older than 15 years. A significant increase in public transport and end-to-end connectivity is required to reduce the number of on-road vehicles. To strengthen the public transport system, an extensive metro-rail network and feeder buses for end-to-end connectivity are required. In addition, an efficient suburban railway system needs to be realised. As HCVs contribute the maximum to pollution from transportation, their entry within the city limits should be restricted. Government incentives for CNG and electric vehicles in public and pseudo-public transport will help reduce around 25% PM emission.

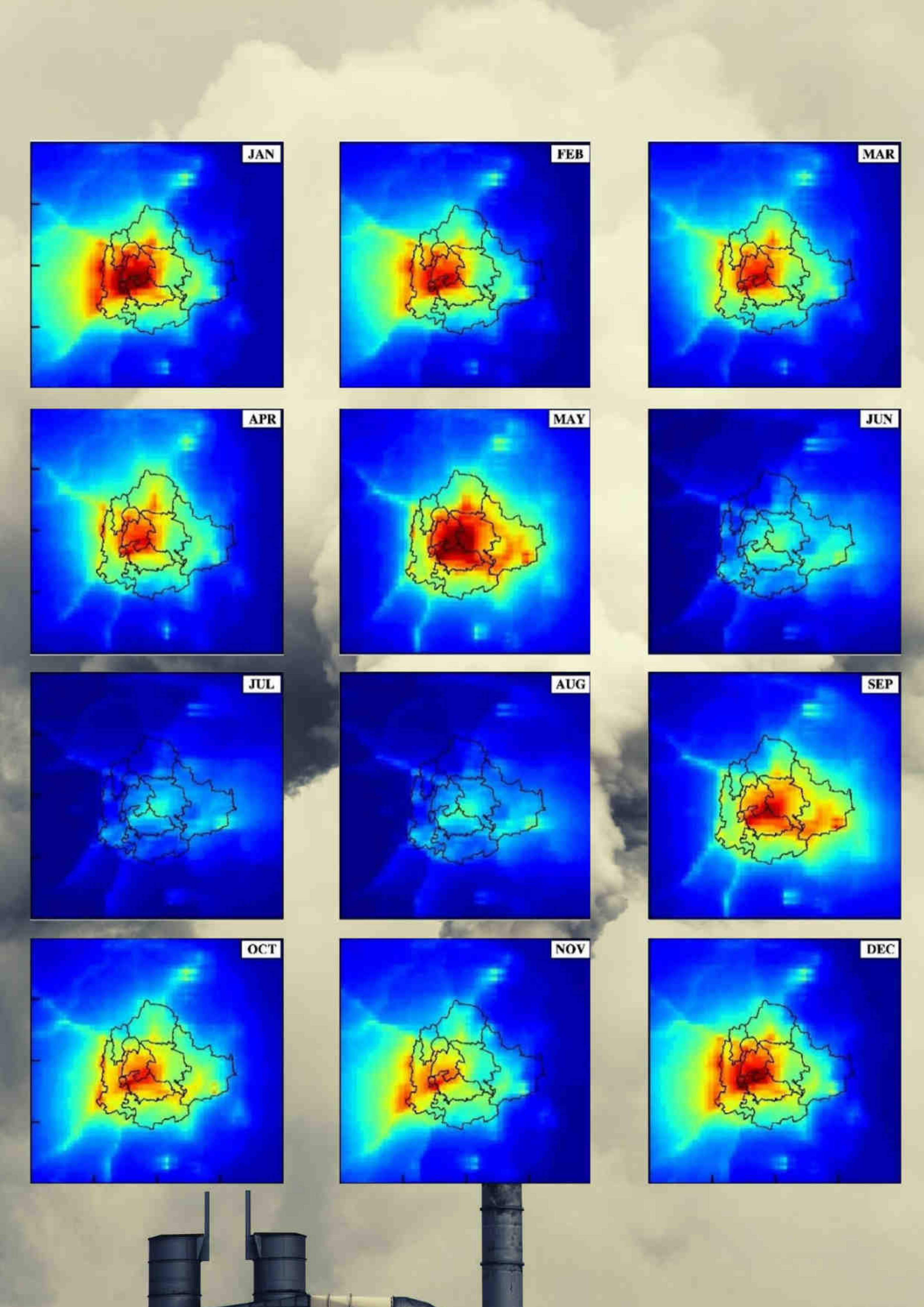
Measures such as concretisation of roads (arterial and sub-arterial), end-to-end road paving, and use of geo-synthetics for covering green belts around the roads will reduce re-suspension of dust to a great extent. Road infrastructure (e.g., footpaths, walking, and cycling zones) needs to be developed and maintained (filling potholes) as a priority. In addition, inter-agency coordination is required to reduce damage to road infrastructure.

Although the new construction activities are mostly happening in the peripheral wards of BBMP, emission from these activities is significant (11% of PM_{10} emission). Construction is mostly restricted to only a few grids in the BBMP area. Construction emissions can be reduced by following CPCB guidelines. An auditing/inspection team can be given authority to enforce these guidelines. Negative encouragement (e.g., hefty penalty) can help enforce the guidelines. It is recommended to either scrap vehicles older than 15 years which are used for transporting construction material or retrofit them with DPFs to reduce emission. Illegal and new construction activities and violations of norms (construction materials lying on the road) within the BBMP area need to be identified and penalised.

The usage of wood is prevalent among economically weaker households. Usage of solid fuel in cooking increases direct exposure to PM2.5 among vulnerable groups. Government should continue providing heavily subsidised clean cooking fuel for the underprivileged to prevent the usage of solid fuels in cooking.

Although the share of PM emissions from industries is very low, they contribute the highest SO_2 emission (45%). DG sets contribute heavily to NO_x (28%) and SO_2 (36%) emission. These gaseous compounds are precursors to secondary PM, and the reduction of these pollutants will greatly reduce the PM concentration over Bengaluru. The use of diesel in generator sets should be restricted with renewable energy being used instead.

A better auditing system, along with efficient door-to-door collection, is needed to reduce the burning of garbage. Industries should be shifted outside the BBMP area to reduce industrial emissions. In addition, regular auditing by KSPCB is needed to enforce compliance with industrial emission norms.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4. Dispersion Modelling

4.1 Introduction

An understanding of the city's ambient air pollutant concentrations is essential to monitor the ground activities causing pollution. Low reference-grade monitoring makes it difficult to monitor pollutant concentrations. Dispersion modelling helps in generating high-resolution spatial distributions of air pollutant concentrations at different temporal scales. Because of air movement and other meteorological conditions at various geographic locations, air pollutants emitted from different sources are dispersed in the atmosphere. Ambient air consists of both primary and secondary pollutants. Primary pollutants are directly emitted from the source (e.g., PM, CO, SO_2, VOCs, NH_3), whereas secondary pollutants are formed when primary pollutants react with atmospheric molecules (e.g., O_3, HNO_3, H_2O_2).

Atmospheric dispersion models are widely used to estimate air pollutant concentrations as functions of location and time (Bruce Turner, 1994). Various types of dispersion models are used to study air pollution in cities (Namdeo et al., 2011; Beig et al., 2013; Gulia et. al., 2015; Guttikunda et. al., 2018). The pollutant concentrations estimated using these dispersion models include the secondary pollutants formed by atmospheric chemistry.

Dispersion models vary according to the complexity and computational requirements. Atmospheric chemical transport models such as WRF-Chem and CAMx are used to forecast the air quality in Indian cities. They provide 1–3 day air quality forecasts for $PM_{2.5}$ concentration, along with source contributions. In this study, we adopted the CAMx chemical transport model to simulate high-resolution air pollutant concentrations over Bengaluru.

4.2 Models, Data, and Methodology

4.2.1 Models (WRF and CAMx) and Configurations

4.2.1.1 Weather Research and Forecast (WRF) Model

Meteorological parameters (wind speed, wind direction, precipitation, temperature, humidity, boundary layer height, etc.) are required as inputs for the dispersion model to estimate the ambient concentrations of various air pollutants. Thus, we used a high-resolution (5 km resolution) weather research forecast–advanced research WRF (WRF-ARW) model to simulate the various meteorological parameters. The WRF model has various parameterisation options to represent the different atmospheric processes such as boundary layer processes, radiation, and convection. On the basis of a sensitivity analysis and available literature, we selected parameterisation schemes that provide the most accurate simulation for the study region and configured the WRF model over southern peninsular India. WRF is a regional model, and it requires initial (i.e., meteorological conditions at time = 0) and time-varying lateral boundary meteorological conditions from a global model. The initial and time-varying lateral boundary conditions for surface variables and three-dimensional atmospheric variables were taken from the European Centre for Medium-Range Weather Forecasts (ECMWF), 2009 reanalysis data sets (ERA interim). The WRF model generates 5-km resolution outputs over peninsular India, which is interpolated to a 1-km resolution over the Bengaluru air-shed region. The temporal resolution of the WRF model output is 1 hour.

4.2.1.2 *Comprehensive Air Quality Model with Extensions (CAMx)*

We used the CAMx model, developed by Ramboll Environ (ENVIRON, 2020), for dispersion modelling. CAMx is an open-source Eulerian photochemical dispersion model, capable of simulating various physical and chemical processes involved in the formation, transport, and degradation of PM and other air pollutants. Similar to WRF, CAMx is a regional chemical transport model. Figure 4-1 represents the approach of the air quality dispersion model implemented at CSTEP. To solve the chemical mass balance equations for a specific region, the model requires initial (i.e., values at time = 0) and time-varying boundary conditions data from a global chemistry model. We used initial and boundary conditions from the community atmosphere model with chemistry (CAM-chem) model. In addition, CAMx requires surface and three-dimensional meteorology from WRF and ozone column data (e.g., TOMS-OMI) for estimating photolysis rates. EI for various pollutants is one of the inputs required for the CAMx model. We used the earlier mentioned 1-km EI (in Section 3) for an air-shed area of 60 km × 60 km over Bengaluru. The CAMx model is configured at a 1-km resolution over the air-shed area of Bengaluru, which will generate pollutant concentrations at a 1-hour temporal resolution.

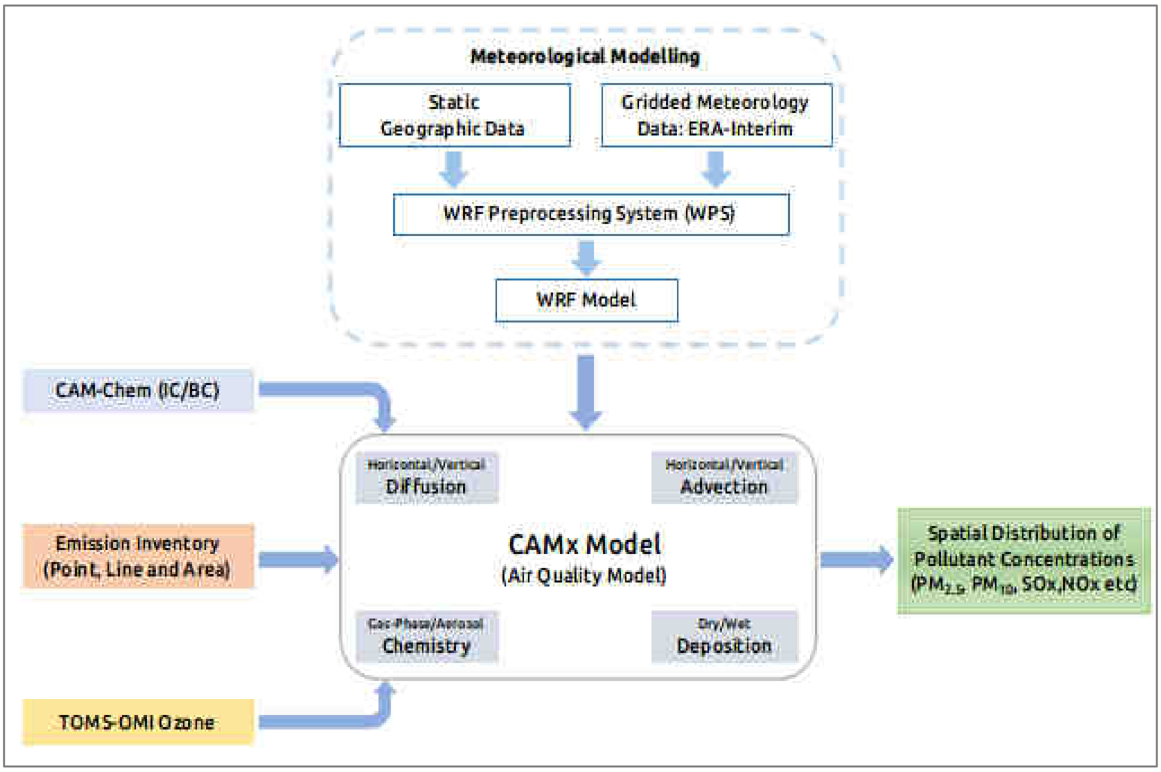


Figure 4-1: Air quality model approach

4.2.2 Data Sets Used for Validation of Weather Model and Dispersion Model

WRF model outputs such as horizontal wind speed, surface air temperature (T), surface relative humidity (RH), and boundary layer height (PBLH) were validated against the fifth generation of the Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalyses (ERA5) data sets. The model-simulated rainfall was validated against the high-resolution (0.25° × 0.25°) observed rainfall data provided by the Indian Meteorological Department (IMD). The monitored ambient pollutant ($PM_{2.5}$, PM_{10}, SO_2, and NO_2)

concentration data (point location) from KSPCB monitoring stations for Bengaluru were used to validate the model. The model simulated monthly and annual pollutant concentrations.

4.2.3 Analysis Methodology

The following equations were used for the analysis.

The mean error percentage (E) is the mean difference between the observed values and model-simulated values (Equation 3).

$$E = \frac{\left\{\sum_{i=1}^{n}(M_i - O_i)\right\} * 100}{\sum_{i=1}^{n} O_i} \tag{3}$$

where E is the mean error percentage, i is a monitoring station located in Bengaluru, n is the total number of stations, M_i is the modelled concentration for the i^{th} station, and O_i is the observed concentration for the i^{th} station.

$$R_{MO} = \frac{n\sum_{i=1}^{n} M_i O_i - \sum_{i=1}^{n} M_i \sum_{i=1}^{n} O_i}{\sqrt{n\sum_{i=1}^{n} M_i^2 - (\sum_{i=1}^{n} O_i)^2}\sqrt{n\sum_{i=1}^{n} M_i^2 - (\sum_{i=1}^{n} O_i)^2}} \tag{4}$$

where R_{MO} is the correlation coefficient between model-simulated value and observed value, i is a monitoring station located in Bengaluru, n is the total number of stations, M_i is the modelled concentration for the i^{th} station, O_i is the observed concentration for the i^{th} station and R_{MO}^2 is the coefficient of determination.

A high value of R_{MO} or R_{MO}^2 suggests that the model performance is good.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(M_i - O_i)^2}{n}} \tag{5}$$

Where RMSE is the root mean square error between model and observation, i is a monitoring station located in Bengaluru, n is the total number of stations, M_i is the modelled concentration for the i^{th} station, and O_i is the observed concentration for the i^{th} station.

4.3 Results and Discussion

4.3.1 Validation of Meteorology Model Outputs

We analysed the daily averaged WRF-model-simulated meteorology fields such as surface wind speed, temperature (T), relative humidity (RH), planetary boundary layer height (PBLH), and rainfall over Bengaluru (area averaged over the BBMP region) for 2019. The determination coefficient (R^2) and root mean square error (RMSE) obtained from the WRF simulations over the observation/reanalysis datasets are listed in Table 4.1. All variables except rainfall (R^2 value = 0.41) indicate high R^2 (>0.73) over the BBMP region. Even though the R^2 value for rainfall is low, the difference between observed (2.76 mm/day) and modelled (2.38 mm/day) average rainfall (for the rainy months from June to October) is only 0.38 mm/day. RMSE is less for the surface wind speed, temperature, and rainfall and high for RH and PBLH. Therefore, our validation shows a satisfactory performance of WRF over the Bengaluru air-shed area.

Table 4.1: Determination coefficient (R^2) and root mean square error (RMSE) obtained from WRF simulations over observation datasets.

Parameter	R^2	RMSE	Mean
Surface wind speed (m/s)	0.97	0.63	3.27
Surface temperature (°C)	0.89	0.85	22.9
Surface relative humidity (%)	0.84	10.11	59.34
PBL height (m)	0.73	97.55	631.36
Rainfall (mm/day)	0.41	1.52	2.13

Note: Model- simulated rainfall is compared with the Indian Meteorological Department (IMD) rainfall data; and all other variables are compared with ERA5 re-analysis data

Wind direction is an important meteorological parameter that causes air pollutant dispersion. Therefore, we analysed the seasonal mean wind speed and wind direction over the BBMP area by using the wind rose diagram shown in Figure 4-2. In winter (January to February), usually the wind direction is from the east (E) and east-north-east (ENE) directions. During the pre-monsoon season (March to May), the wind blows mainly from east-south-east (ESE) and east (E) directions. During the monsoon season (June to September), the prevailing wind is westerly (W), whereas in the post-monsoon season (October to December), the prevailing wind is easterly (E) and east-north-easterly (ENE).

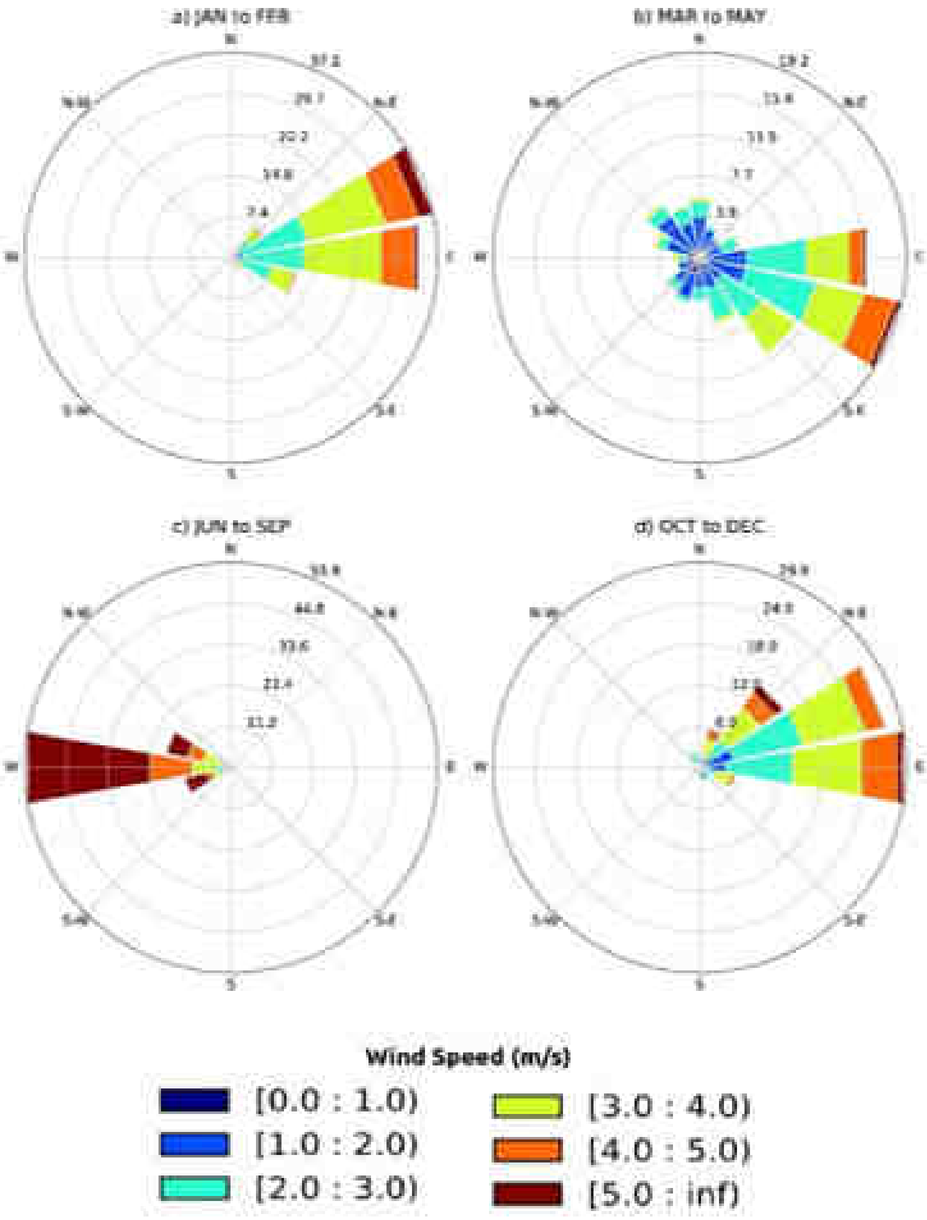


Figure 4-2: Wind rose diagram for different seasons for 2019

Source: ECMWF Reanalysis 5th generation (ERA5) dataset

Further, using the WRF model, monthly mean and standard deviation for meteorological variables such as surface wind speed, T, RH, PBLH, and rainfall for 2019 over the BBMP area was simulated, and the results are shown in Table 4.2. March, April, July, and August showed higher PBLH values (>698.05 m) than the other months. High wind speed (>4.76 m/s) values were observed during the summer monsoon of June, July, and August. Further, high surface temperature (26.48 °C) was observed during April, whereas low temperature (19.65 °C) was observed during January. RH was found to be greater than 75% during June and July. The BBMP region received a reasonable amount of rainfall from May to November.

Table 4.2: WRF-model-simulated monthly mean and standard deviation of meteorological parameters during 2019 over BBMP area

Month	**PBLH (m)**	**Surface wind speed (m/s)**	**Surface temperature (°C)**	**Relative Humidity (%)**	**Rainfall (mm/day)**
January	569.61 ± 81.63	2.88 ± 0.74	19.65 ± 1.50	50.34 ± 12.25	0.47 ± 2.32
February	623.44 ± 101.75	3.28 ± 0.96	21.48 ± 1.27	46.64 ± 14.82	0.17 ± 0.56
March	739.69 ± 112.95	2.58 ± 1.16	24.75 ± 1.33	43.99 ± 14.09	1.29 ± 3.24
April	753.55 ± 137.86	2.01 ± 0.78	26.48 ± 0.96	46.96 ± 10.08	0.96 ± 2.90
May	608.05 ± 119.76	1.75 ± 0.68	26.06 ± 0.63	57.99 ± 12.72	2.84 ± 4.22
June	678.50 ± 137.28	4.76 ± 1.62	23.97 ± 0.76	68.68 ± 8.28	2.74 ± 4.11
July	720.15 ± 106.08	5.69 ± 1.03	23.12 ± 0.50	75.37 ± 7.26	2.61 ± 4.05
August	698.05 ± 96.88	5.28 ± 1.07	22.50 ± 0.60	76.70 ± 7.01	4.21 ± 5.40
September	578.21 ± 76.07	2.57 ± 1.17	23.12 ± 0.73	59.48 ± 12.17	2.15 ± 4.14
October	516.12 ± 104.59	2.34 ± 1.17	22.29 ± 1.26	65.17 ± 15.57	5.64 ± 9.01
November	549.71 ± 75.32	3.18 ± 0.94	21.25 ± 1.29	64.85 ± 14.49	2.48 ± 5.83
December	541.20 ± 61.94	2.89 ± 0.96	20.17 ± 1.02	55.86 ± 12.23	0.05 ± 0.06

4.3.2 Validation of Dispersion Model Outputs

The monthly mean values of WRF-CAMx-simulated $PM_{2.5}$ and PM_{10} concentrations are validated with data from the KSPCB-installed manual monitoring station and CAAQMS in Bengaluru for 2019 (Figure 4-3). The simulated monthly averages of both $PM_{2.5}$ and PM_{10} concentrations, except for May to August, are comparable with the observed values. Except in May, the Pearson's correlation coefficient between measured and monitored concentration levels is observed to be 0.71 and 0.72 for $PM_{2.5}$ and PM_{10}, respectively. The measured and model-simulated annual averages for $PM_{2.5}$ are 36.34 and 40.82 μg/m^3, respectively. For PM_{10}, the corresponding values are 88.86 and 86.01 μg/m^3, respectively. The low bias between observed and model-simulated values shows that the simulated WRF-CAMx model's accuracy is high.

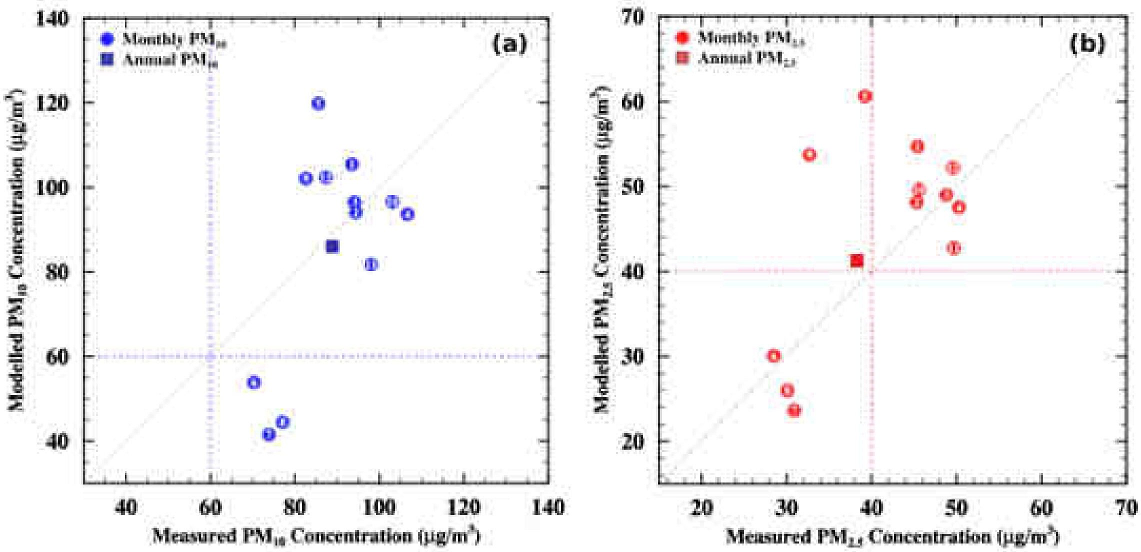


Figure 4-3: Comparison of modelled & CPCB monthly mean concentration (μg/m³) of a) $PM_{2.5}$ and b) PM_{10}

4.3.3 Dispersion Model Outputs—Monthly, Seasonal, and Annual Concentration

Dispersion modelling was conducted for Bengaluru's air-shed area of 60 × 60 km, which includes Bengaluru Urban, Bengaluru Rural, and parts of a few other districts of Karnataka. We validated the model-simulated PM_{10} and $PM_{2.5}$ concentrations on the basis of the observational records of KSPCB. Pearson's correlation coefficients of the monthly concentrations of modelled and observed values over Bengaluru were estimated as 0.608 for PM_{10} and 0.61 for $PM_{2.5}$. Pearson's correlation coefficients between the annual modelled and observed (KSPCB) concentrations for point locations (stations) over Bengaluru were 0.78 for PM_{10} and 0.82 for $PM_{2.5}$. The determination coefficient (R^2) was found to be 0.6 and 0.67 for PM_{10} and $PM_{2.5}$, respectively. The average error percentage (E) between the modelled and observed values, with respect to observed values, according to station locations was found to be 8.03% for PM_{10} and 9.97% for $PM_{2.5}$. These correlation coefficient values indicate that the dispersion model—WRF-CAMx—performance was satisfactory. Table 4.3 shows the annual average values of the observed and modelled concentrations for different pollutants. These average values are based on point locations (where KSPCB monitoring stations are located) over Bengaluru.

Table 4.3: Observed and model-simulated annual mean concentrations for 2019 over stations in BBMP area

	$PM_{2.5}$ (μg/m³)	PM_{10} (μg/m³)	SO_2 (μg/m³)	NO_2 (μg/m³)
Observation	36.34	88.85	4.9	31.7
Model output	40.82	86.01	9.0	51.2

The spatial distribution of annual average values of PM_{10} and $PM_{2.5}$ for the Bengaluru air-shed area during 2019 are presented in Figure 4-4. Highly polluted areas are located in Bengaluru West zone, Bengaluru South zone, and Rajarajeswari Nagara. The average annual PM_{10} and $PM_{2.5}$ concentrations over the BBMP area are estimated to be 70.03 and 34.61 μg/m³, respectively. Thus, it is evident that high concentration values are well captured by the model. The maximum observed values of PM_{10} and $PM_{2.5}$ concentrations are 129.14 and 62.95 μg/m³, respectively. The locations experiencing high concentration values are mostly near the city centre (inside the BBMP area). Sources responsible for these high concentration levels are road transportation activities and dust re-suspension (Figure 4-4). In addition to the BBMP area, high PM_{10} concentration values due to air transportation are observed at the Bengaluru International Airport (north-east side of the city).

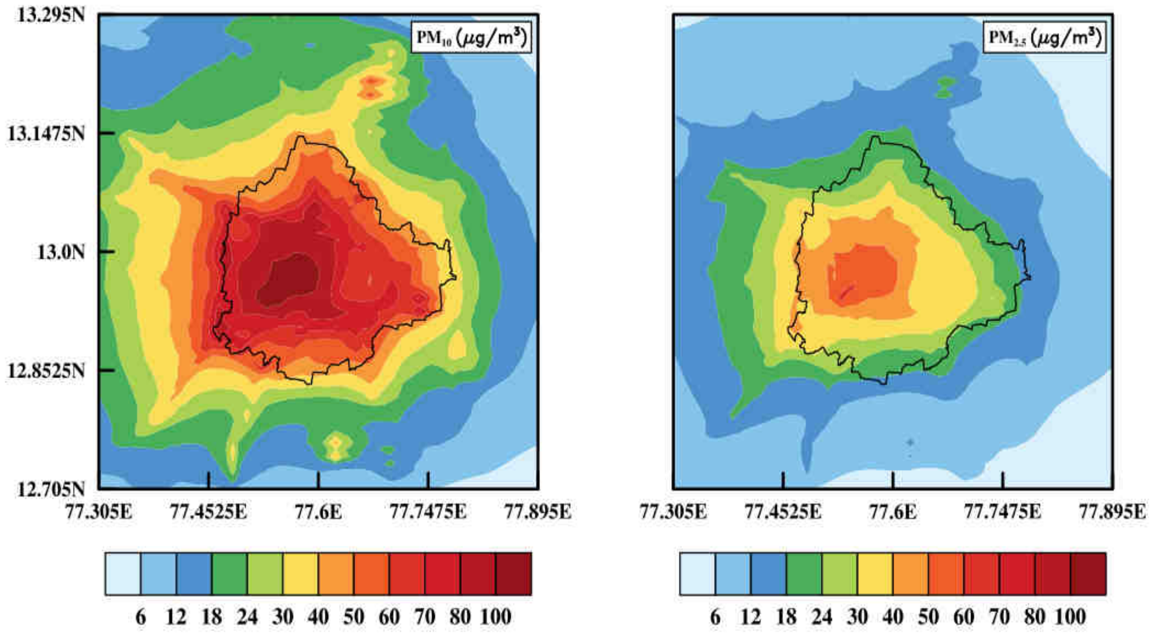


Figure 4-4: Mean annual average concentration of PM_{10} & $PM_{2.5}$ (µg/m³) WRF-CAMx-modelled - 2019

The spatial distribution of annual average values of PM_{10} and $PM_{2.5}$ for the BBMP area during 2019 is presented in Figure 4-5. We identified pollution hotspots in the city on the basis of dispersed concentration levels from the model. Hotspots due to high PM_{10} and $PM_{2.5}$ concentrations are represented in Figure 4-5, some of which are Nayanda Halli, Bapuji Nagar, Rayapuram, and Majestic. These areas are located in and around Mysore Road (connecting the city centre to the NICE Ring Road), which usually experiences heavy traffic congestion during peak hours. Tailpipe emission is found to be very high and the primary emission source in these hotspots, followed by re-suspension of road dust as the second-highest emission source.

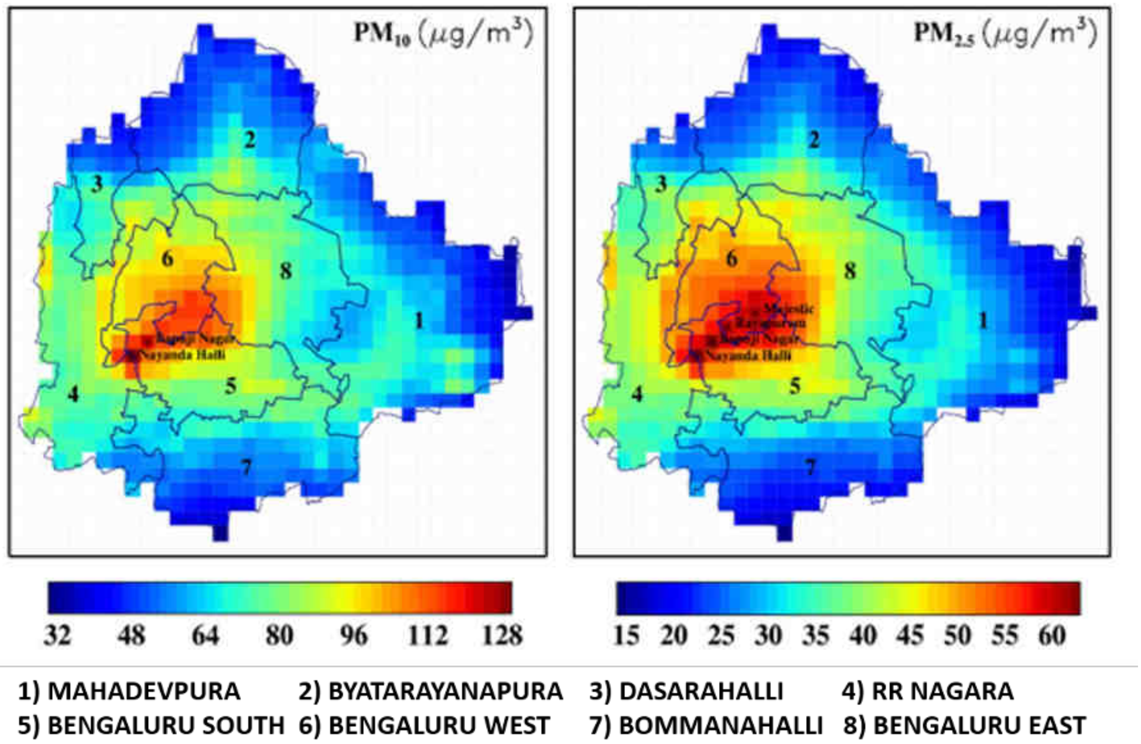


Figure 4-5: Mean annual average concentration values of simulated PM_{10} and $PM_{2.5}$ (µg/m³) - 2019

Note: The concentration hotspots are marked inside the panels.

Figure 4-6 and Figure 4-7 present the spatial distribution of monthly PM_{10} and $PM_{2.5}$ concentration levels, respectively, for the air-shed and BBMP areas. It is observed that during the monsoon season (June to August), both PM_{10} and $PM_{2.5}$ concentrations are considerably low throughout the city—all grid points show concentrations lower than NAAQS standards (i.e., 40 µg/m³ for $PM_{2.5}$ and 60 µg/m³ for PM_{10}). During the monsoon season, high-speed winds blowing from the west to east transport the pollutants towards the east. Further, more rainfall events help settle the PM particles, resulting in low PM concentrations in the region. From the monthly distribution maps, it is visible that the model captures the qualitative variations in the monthly concentration values over the air-shed area quite well.

High PM_{10} concentration values are observed during the winter season (December to February). These high concentrations can be attributed to solid fuel burning. Moreover, owing to a lower mixing height, the dispersion of the pollutants is low, contributing to high PM_{10} values. During the winter months, the wind blows from the east to the west, which disperses the pollutants towards the west. As a result, the pollutant concentration is found to be high over the western region of the BBMP area (i.e., over Bengaluru West and Bengaluru South zones). However, the concentration levels remain high even during March, April, and May. Wind speed is low during these months (Table 4.2); this reduces the dispersion of pollutants and concentration levels inside the BBMP area become high. In May, the main polluting sources are the same as those in other months. However, the lowest wind speed (1.75 ± 0.68 m/s) is observed during May, and pollutant concentrations do not show significant dispersion. Therefore, high concentrations of pollutants are observed in the BBMP area during May. We found that the modelled monthly average PM_{10} concentrations over

Bengaluru exceed the NAAQS annual level of 60 μg/m^3 in all months except June, July, and August.

Furthermore, the $PM_{2.5}$ concentration level observed (Figure 4-5) over the air-shed area is low compared to the observed PM_{10} levels. Major PM contributing sectors in Bengaluru are transportation and total dust (sum of re-suspended dust and construction dust). The transportation sector contributes heavily to $PM_{2.5}$ pollution, whereas dust contributes mainly towards PM_{10}. High $PM_{2.5}$ concentration values are observed during winter (December to February), which can be attributed to high tailpipe emission and re-suspension of road dust in the city. Also, because of a low mixing height, the dispersion of the pollutants is low, contributing to high $PM_{2.5}$ values. However, the $PM_{2.5}$ concentration levels remain high during March, April, and May. Wind speed is low during these months (Table 4.2); this reduces the dispersion of the pollutants and concentration levels become high. The lowest wind speed (1.75 ± 0.68 m/s) is observed during May, and pollutant concentrations do not show much dispersion. Therefore, high pollutant concentrations are observed in the BBMP area during May. We found that the modelled monthly average $PM_{2.5}$ concentrations over Bengaluru exceed the NAAQS annual level of 40 μg/m^3 in all months except June, July, and August.

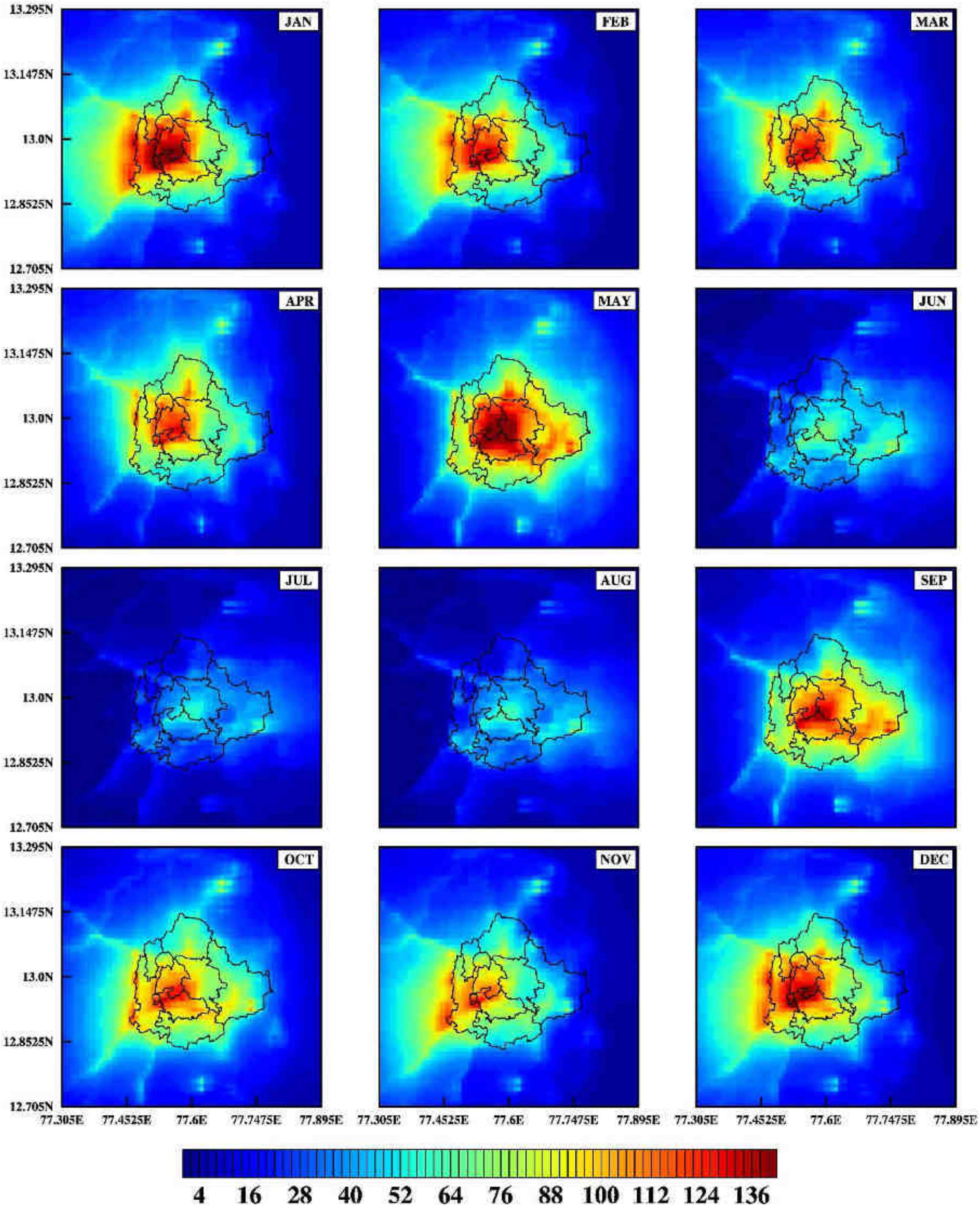


Figure 4-6: Monthly average values of simulated PM_{10} concentration (µg/m^3) - 2019

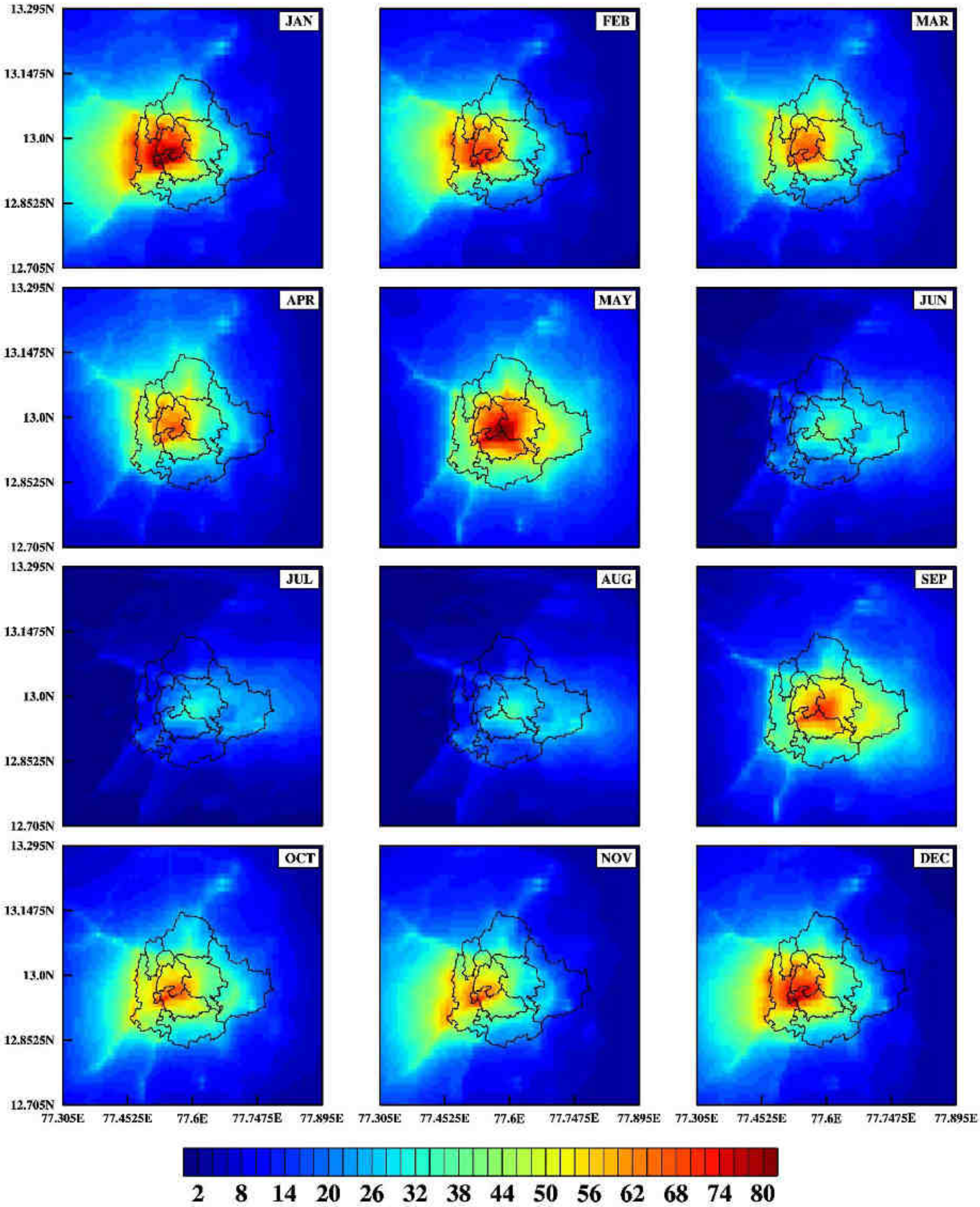


Figure 4-7: Monthly average values of simulated $PM_{2.5}$ concentration (µg/m³) - 2019

SO_2 and NO_2 Concentration Levels: The spatial distribution of the annual average concentrations of SO_2 and NO_2 over the Bengaluru air-shed area for 2019 is presented in Figure 4-8. The average annual SO_2 and NO_2 concentrations over the BBMP area are 8.27 µg/m³ and 51.53 µg/m³, respectively. The SO_2 concentration is high over the Peenya Industrial Area and Mahadevpura Industrial Area. These areas have many manufacturing and fabrication industries. The observed high SO_2 concentration over these areas is closely linked to the emission from industrial fuel consumption (discussed in the previous section). Other than the BBMP area, nearby areas such as Bidadi and Jigani too have numerous industries, which contribute to the high SO_2 concentration. High NO_2 concentration areas are mainly located over the city centre and the Outer Ring Road, which can be attributed to high tailpipe emissions (i.e., 49,592 tonnes/year of NOx). Another NO_2 concentration hotspot is Bengaluru International Airport, which is located in the northeast part of the Bengaluru air–shed area. This location is a hotspot because of NO_2 formation by high NO_x emissions from airport operations, especially the LTO cycle of aircraft and the ground movement of airport vehicles. The emission load from airport operations was found to be 3,575 tonnes/year of NO_x.

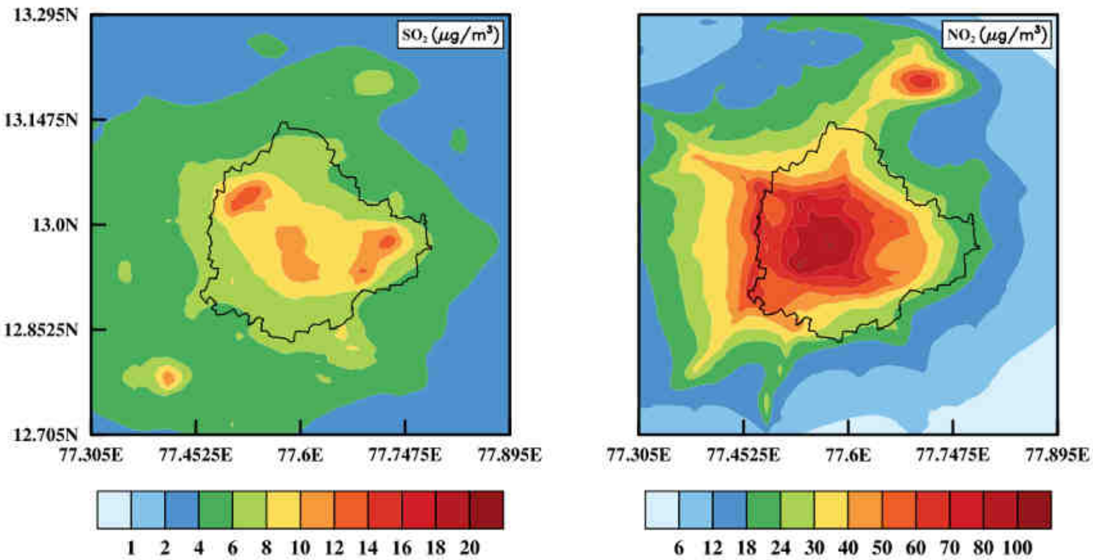


Figure 4-8: Annual average concentration of simulated SO_2 and NO_2 (μg/m³) - 2019

4.3.4 Sectoral Contributions

The individual source contributions to annual total PM_{10} and $PM_{2.5}$ concentrations were estimated using the WRF-CAMx model. A base simulation was conducted using an EI that included all the sources. In addition, multiple simulations were performed without the individual sector for which the source contribution needed to be estimated. The difference between the concentration from the base simulation (i.e., with all the sources) and that from the simulation without the individual sector provided the concentration for that particular sector. This method has also been used by Guttikunda et al. (2019) to estimate source contributions to the $PM_{2.5}$ concentration.

The sectoral contribution of PM_{10} and $PM_{2.5}$ in the BBMP area is shown in Figure 4-9. The estimated percentage share for individual sectors shows that in 2019, the transportation sector accounts for 37.26% and 51.36% of the total annual PM_{10} and $PM_{2.5}$ concentrations, respectively. Road dust together with re-suspended road dust (total dust) accounts for 47.53% and 30.92% of the total annual PM_{10} and $PM_{2.5}$ concentrations, respectively. The percentage share of DG sets is estimated to be 6.6% and 8.8% for PM_{10} and $PM_{2.5}$, respectively. Waste burning inside the BBMP area accounts for 3.86% and 5.67% for PM_{10} and $PM_{2.5}$, respectively.

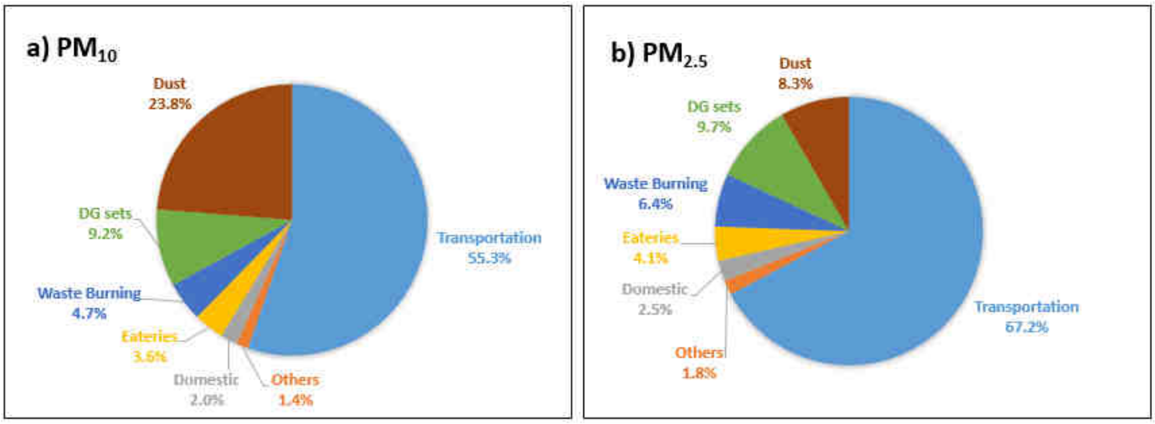


Figure 4-9: Sectoral contribution (%) of a) PM_{10} and b) $PM_{2.5}$ concentration in BBMP area

The modelled PM_{10} concentrations for different sources such as dust (re-suspended road dust and construction dust), transportation, DG sets, and eateries are shown in Figure 4-10. It is found that the high PM_{10} concentration over the Bengaluru South and Bengaluru West zones is mainly due to re-suspended road dust (Figure 4-10a), which is directly linked to the large number of vehicles plying in those areas. Construction activities are the key contributor in the southeast region of the Mahadevpura zone (Figure 4-10a). In the transportation sector, high PM_{10} emissions arise from the Outer Ring Road and city centre, but the concentration is shifted towards the western part of the BBMP area because of wind speed and wind direction (Figure 4-10b). A PM_{10} concentration of about 2–5 μg/m^3 is due to the use of DG sets (Figure 4-10c), which is clearly visible over the Bengaluru South, Bengaluru East, and Mahadevpura zones. A PM_{10} concentration of about 3–3.5 μg/m^3 over the Bengaluru South, Bengaluru West, and Rajarajeswari Nagar zones is attributed to eateries (Figure 4-10d).

The modelled $PM_{2.5}$ concentrations for the four different sectors are shown in Figure 4-11. It is found that dust (Figure 4-11a) and transport (Figure 4-11b) contribute to high $PM_{2.5}$ over Bengaluru South, Bengaluru East, and Rajarajeswari Nagar zones. However, DG sets (Figure 4-11c) are the key contributor over the Mahadevpura zone. The $PM_{2.5}$ concentration due to total dust emission exhibits that emission from the re-suspension of road dust is the major contributor. A $PM_{2.5}$ concentration of about 1–1.5 μg/m^3 over Bengaluru South, Bengaluru West, and Rajarajeswari Nagar zones is attributed to eateries (Figure 4-11d).

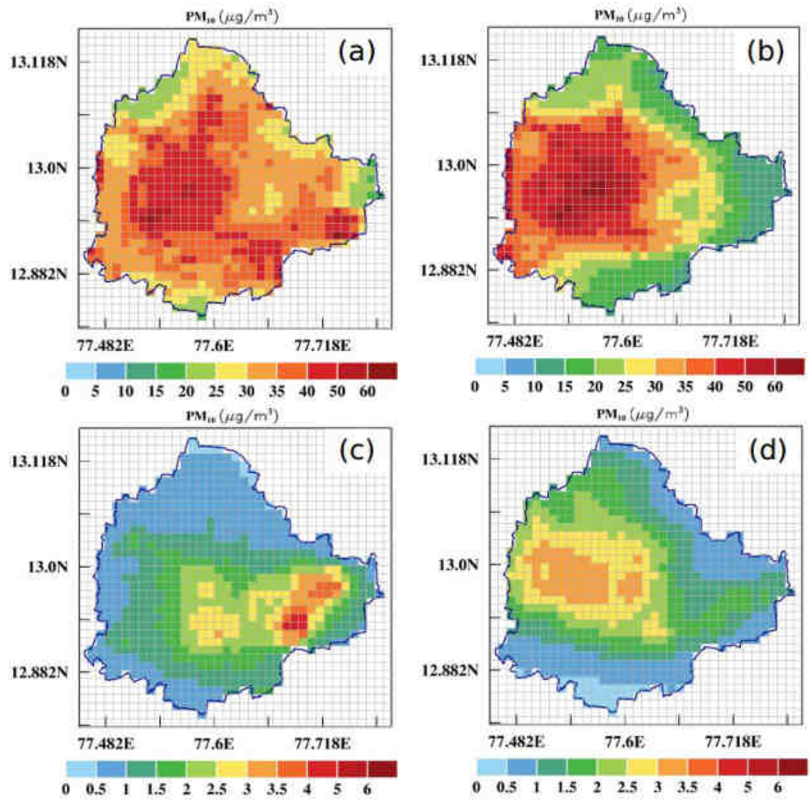


Figure 4-10: PM_{10} concentration (µg/m^3) for a) dust, b) transportation, c) DG sets, & d) eateries

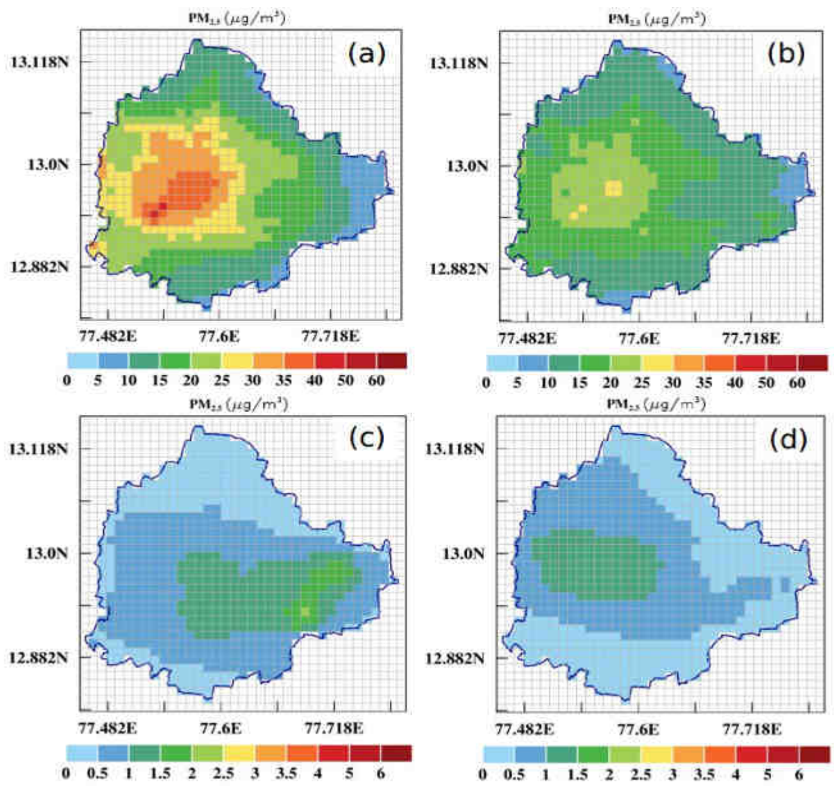


Figure 4-11: $PM_{2.5}$ concentration (µg/m^3) for a) dust, b) transportation, c) DG sets, & d) eateries

5. Emission Control Options and City Strategy: Policy Recommendations

A scenario analysis was conducted to understand the future emission load from various sectors. The approach we adopted is described in Figure 5-1 below.

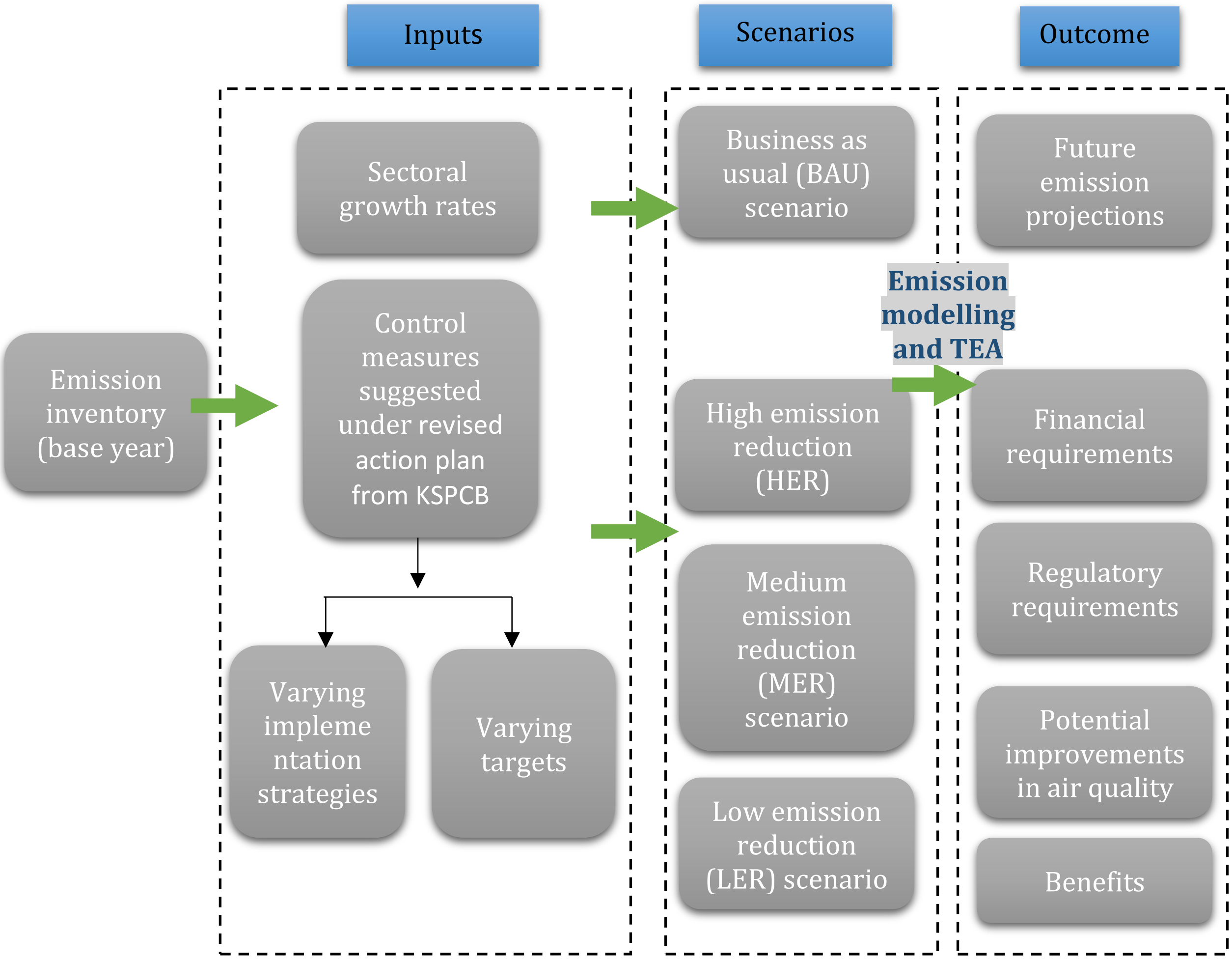


Figure 5-1: Overall approach: scenario analysis

The following steps are involved to assess the impact of control measures:

1. **Scenario Creation:** Scenarios were created by considering sectoral growth rates and the measures suggested under the clean air action plan prepared by KSPCB.
2. **Modelling:** Emission modelling (EI and dispersion modelling) was performed to identify the potential changes in air quality levels for all the scenarios.
3. **Assessment and Evaluation:** A techno-economic assessment was conducted to analyse the effectiveness of each considered technology in terms of cost and benefits. Cost assessment included the financial requirements to adopt a technology, institutional requirements, and other necessary changes in the policy environment. The benefits were estimated from mortality reduction due to reduced concentration levels using the method (Equation 6) proposed by Pope et al. (2014).

$$Mortality\ avoided\ annually = \Delta PM_{2.5} * E_p * \Delta Excess\ Risk * B_d \quad (6)$$

Where E_p: exposed population (population of Bengaluru)
ER (excess risk) =0.4× {1−exp [−0.03 $(PM_{2.5})^{0.9}$]}
B_d: Baseline death rate (Karnataka mortality rate), as per SRS Statistical Report (2018)
$\Delta PM_{2.5}$: Change in $PM_{2.5}$ concentration levels

The control measures considered, implementation strategies adopted, targets, sectoral growth rates, assumptions used, etc., are described in detail in the following sections.

5.1 City-level Scenario Analysis

The analysis was conducted for (a) business as usual (BAU) scenario—no significant changes made in the policy landscape to control emission and (b) emission reduction measures—to assess the potential emission reduction the city could achieve by adopting policies to mitigate emission (high, medium, and low emission reduction targets).

BAU Scenario: We projected the total emission load for $PM_{2.5}$, PM_{10}, NO_x, and SO_2 in the city till 2024 on the basis of sectoral growth rates and existing policies such as state-level EV policies, solid waste management plans, etc. Growth rates considered for the projections are mentioned in Table 5.1.

Table 5.1: Growth rates considered for projection

Sector	Growth rate considered
Transport	Based on growth in vehicle registration for the past six years
Domestic	Based on population growth rate (*Census of India: Primary Census Abstract*)
Construction	Based on population growth rate
Road dust	Based on vehicle registration and changes in VKT
Solid waste burning	Based on population growth rate
Eateries	Based on population growth rate
Industries	No change was assumed, as most of the polluting industries are either closing down or shifting outside the BBMP area
DG sets	Based on population growth rate and industries growth rate

Figure 5-2 presents the projected sectoral $PM_{2.5}$ emission load from 2019 to 2024 under the BAU scenario. It is estimated that the total $PM_{2.5}$ emission load would be around 16,900 tonnes/year in 2024, a 16.5% increase from the 2019 levels (14,500 tonnes/year).

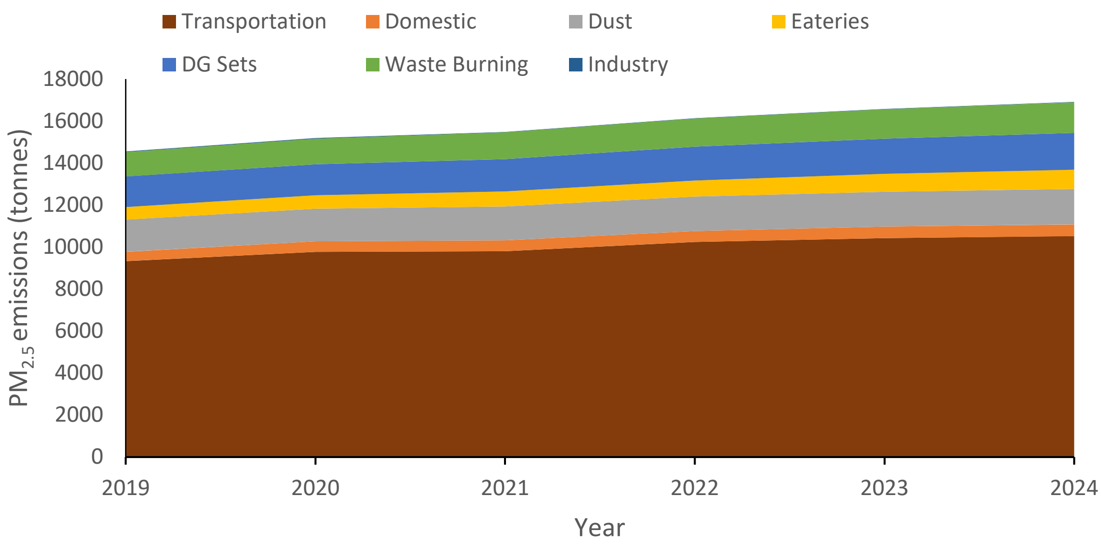


Figure 5-2: $PM_{2.5}$ emissions (BAU) in BBMP area

Transportation (with an increase in the number of vehicles on the roads due to population growth) and dust contribute significantly to the total $PM_{2.5}$ emission load share. Figure 5-3 presents the sectoral share of $PM_{2.5}$ emission load under the BAU scenario in 2024. Transportation and dust contribute around 72% of the total $PM_{2.5}$ emission load followed by DG sets (10.3%), and waste burning (8.6%); sectors such as domestic, eateries, and industries contribute less than 10% to the total emission load.

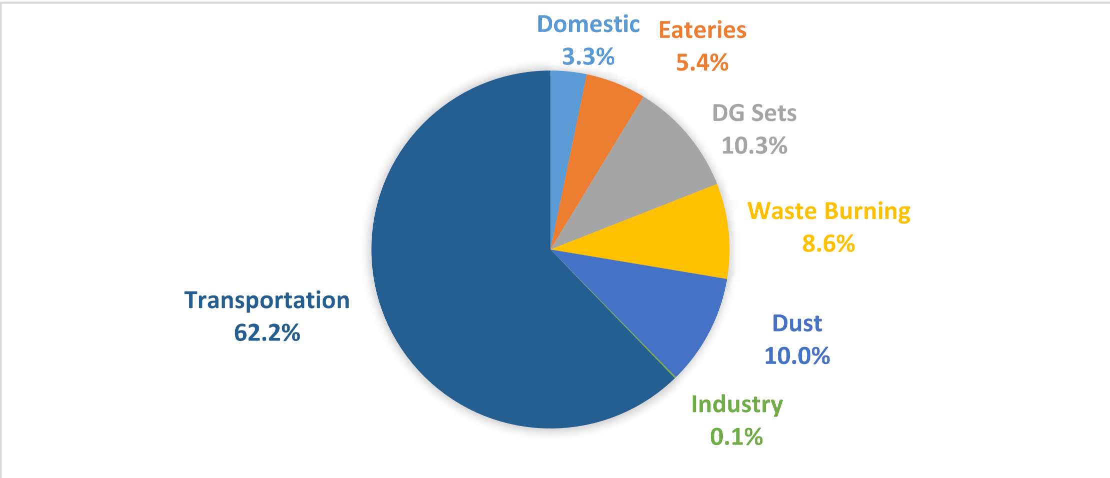


Figure 5-3: $PM_{2.5}$ sectoral emission share (%) (BAU 2024) (BBMP area)

Figure 5-4 presents the sectoral increase in the emission load from 2019 to 2024 under the BAU scenario. The number of eateries over the years has been increasing exponentially, and the trend is expected to continue till 2024. This would result in an increase of 52.9% in the emission from the eateries sector. Sectors such as DG sets (20.2%), waste burning (24.9%), and domestic fuel consumption (24.4%) are directly affected by the change in population, and the emission load is expected to increase by up to 30%. Even though the vehicular demand is expected to increase, policies such as the introduction of BSVI and improvements in public infrastructure would help keep the emissions from transportation under check. Transportation and dust sector emissions are expected to increase by only 11.7% and 8%, respectively.

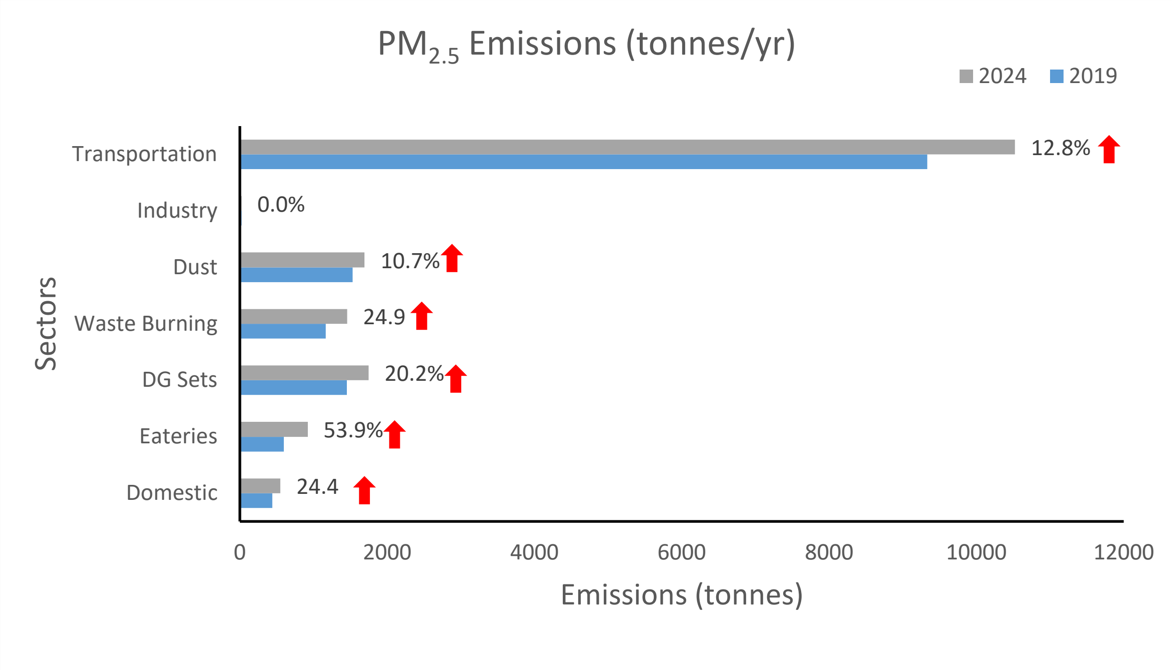


Figure 5-4: Sectoral increase in $PM_{2.5}$ emission load: Year 2019 vs. 2024

The projected emissions for PM_{10}, NO_x, and SO_2 for 2019 and 2024 are presented in Table 5.2. As expected, in 2024 dust (47%) followed by transportation (33%) will be the biggest contributors to the total PM_{10} emission load. Transportation (59%) and DG sets (38%) will remain the greatest contributing sectors for NO_x. DG sets (50%), eateries (28%), and industry (19%) will be the biggest contributing sectors to the SO_2 emission load.

Table 5.2: Pollutant emission levels (BAU) (BBMP area)

	PM_{10} (tonnes/year)		NO_x (tonnes/year)		SO_2 (tonnes/year)	
Year	**2019**	**2024**	**2019**	**2024**	**2019**	**2024**
Transportation	12,445	14,031	49,592	61,906	-	-
Industry	23.8	23.8	136	136	1,020	1,020
Dust	6,855	7,596	-	-	-	-
Waste burning	1,253	1,625	529	706	88	115
DG sets	2,186	2,733	30,919	40,195	2,039	2,651
Eateries	1,026	1,721	316	529	873	1,458
Domestic	584	732	1,034	1,542	5.7	6.5

To understand the influence of meteorological parameters and the effect of atmospheric chemistry on the spread of PM concentration levels, WRF-CAMx modelling was employed. The modelling exercise was also used to simulate various scenarios under BAU and control options to understand the emission reduction potential. Dispersion modelling used the projected EI under BAU from 2020 to 2024; 2019 meteorological conditions were used to project the concentration values. The projections were made on the basis of population growth rate, sectoral growth rates, and existing policies such as state-level EV policies, solid waste management plans, etc.

Projected PM_{10} Monthly Concentration Level for 2020 and 2024: Figure 5-5 and Figure 5-6 show the spatial distribution of projected monthly PM_{10} for 2020 and 2024 under the BAU scenario over the BBMP area. Figure 5-7 and Figure 5-8 show the spatial distribution of projected monthly $PM_{2.5}$ for 2020 and 2024 under the BAU scenario over the BBMP area. It was observed that the concentration levels increase through the years. This spread and dispersion of the concentration levels across the air-shed area over the years have given a fair understanding of the effects of various activities in different sectors (transportation, re-suspended dust and construction dust, etc.) in increasing the concentration levels. For the projected concentration levels for 2024, for both PM_{10} and $PM_{2.5}$, transportation and dust are found to be the major contributing sectors. The concentration levels exceeded NAAQS limits in all months except the monsoon months (June–August) in most of the regions in Dasarahalli, Rajarajeswari Nagara, Bengaluru East, Bengaluru West, and Bengaluru South zones. In May 2024, under the BAU scenario, the concentration levels are very high over the three zones situated at the city centre—Bengaluru East, Bengaluru West, and Bengaluru South. This is because of the low-speed winds in May, which do not result in significant dispersion.

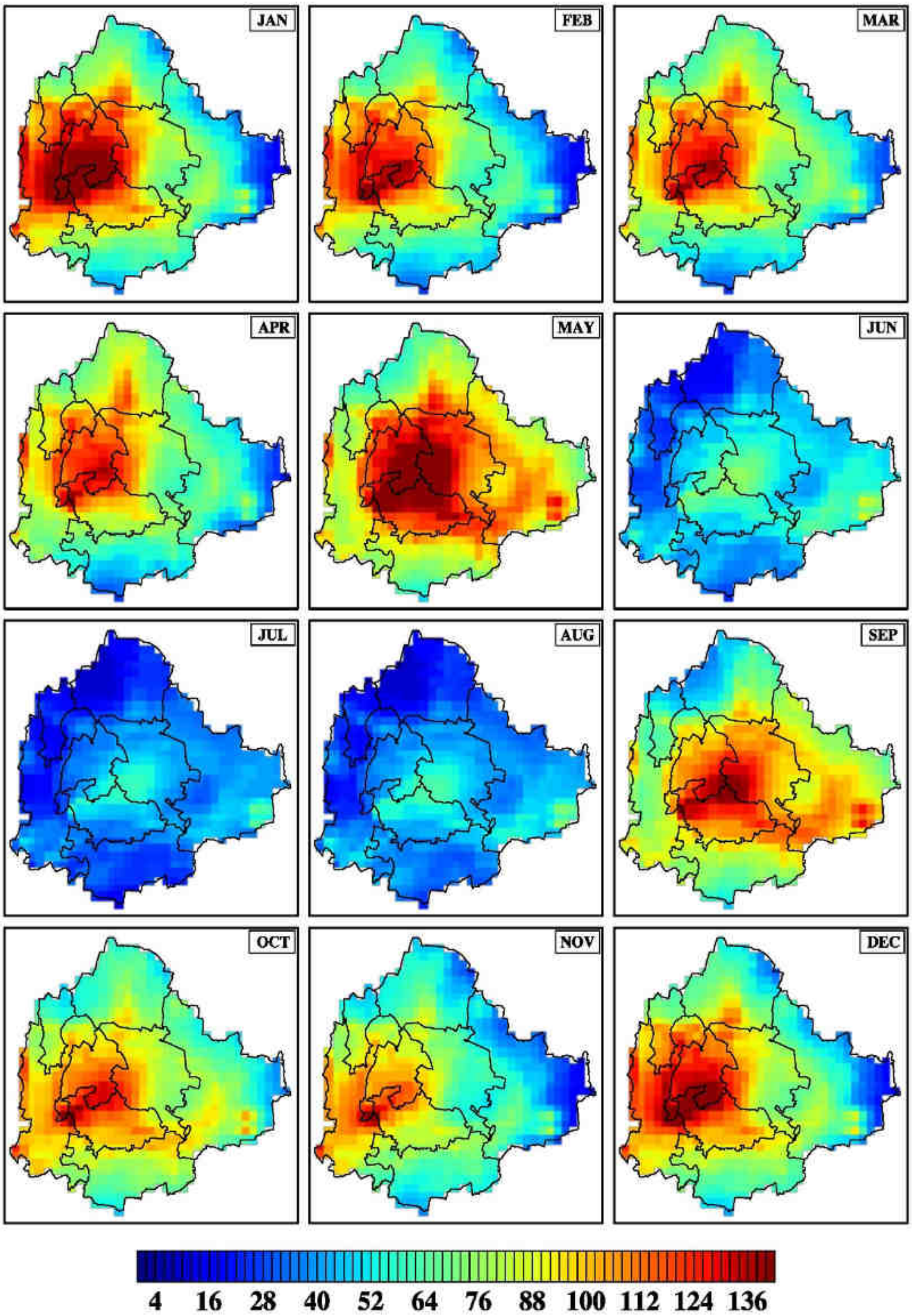


Figure 5-5: Monthly average values concentration of simulated PM_{10} (µg/m^3) during 2020 under BAU scenario

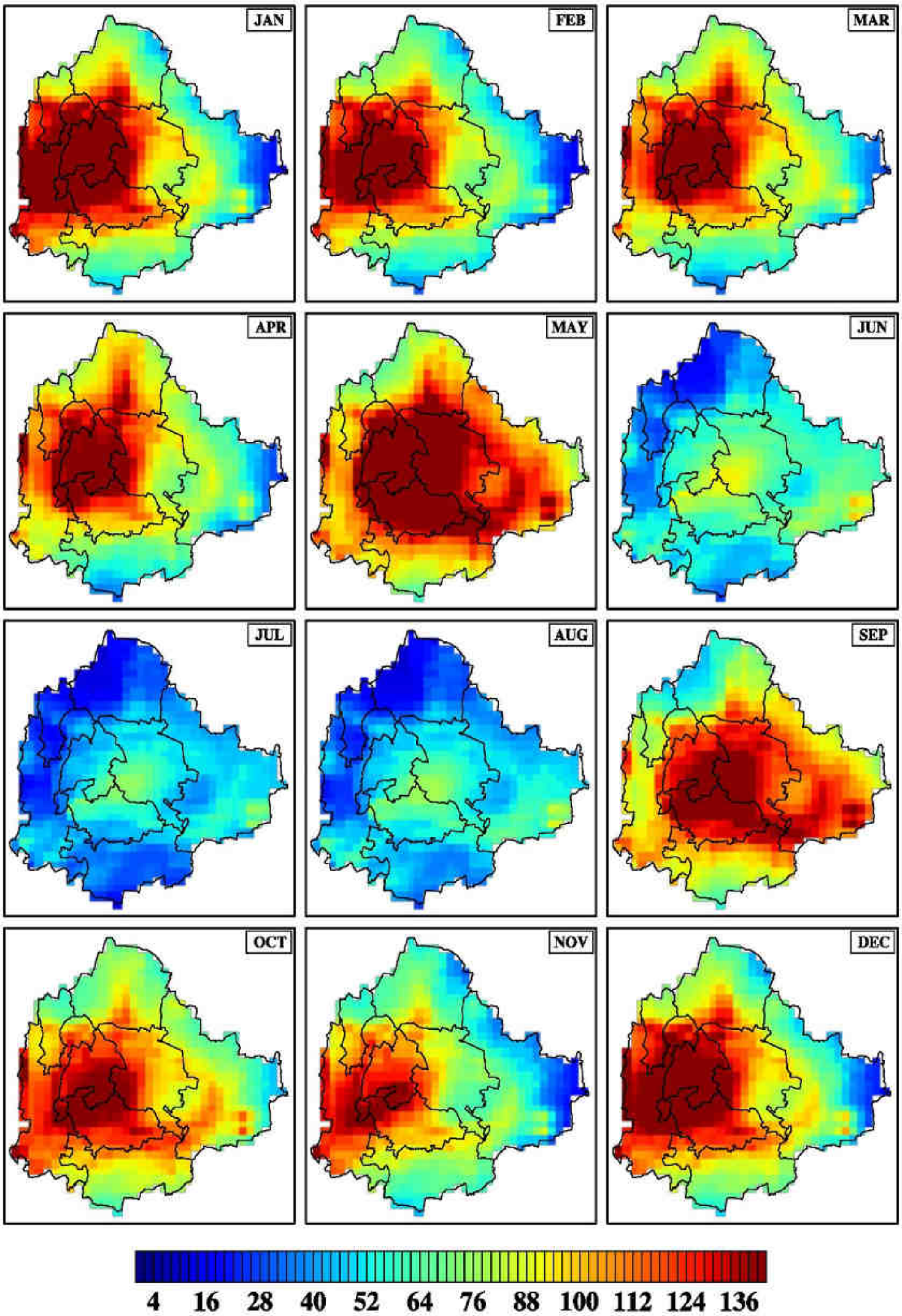


Figure 5-6: Monthly average concentration values of simulated PM_{10} ($\mu g/m^3$) during 2024 under BAU scenario

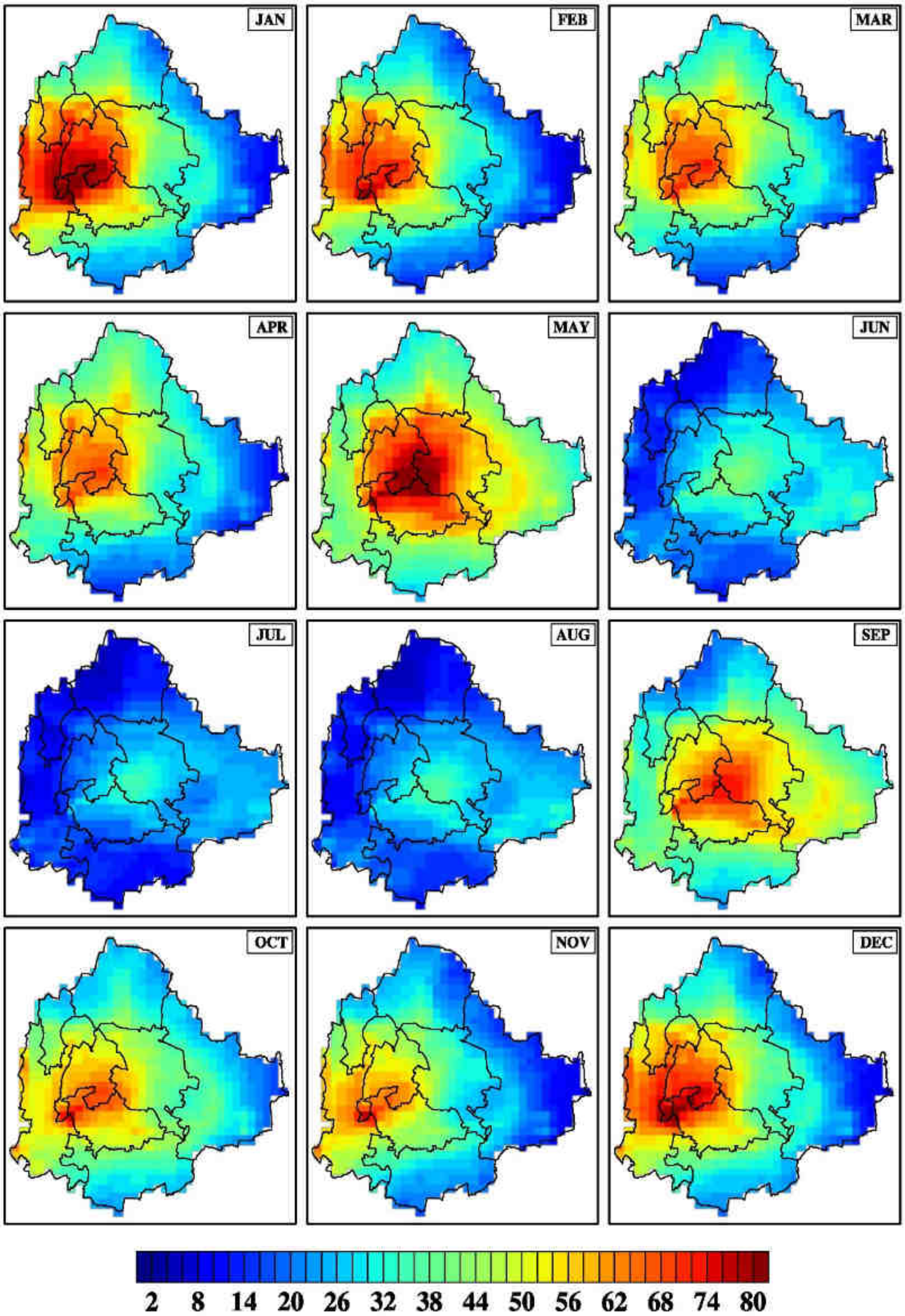


Figure 5-7: Monthly average concentration values of simulated $PM_{2.5}$ concentration (µg/m^3) during 2020 under BAU scenario

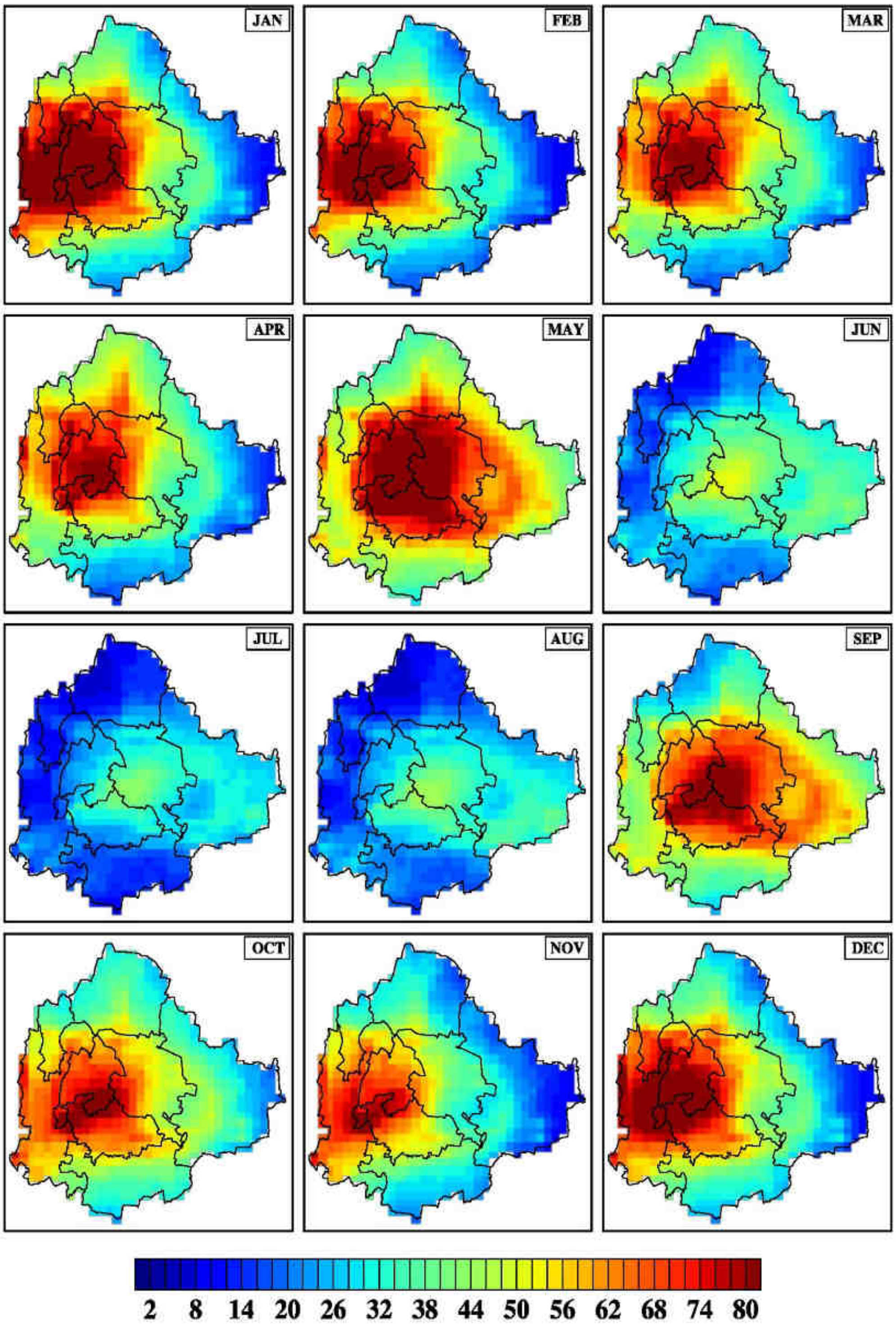


Figure 5-8: Mean monthly average concentration values of simulated $PM_{2.5}$ concentration (μg/m³) during 2024 under BAU scenario

Figure 5-9 and Figure 5-10 presents the increase in the annual concentration levels for $PM_{2.5}$ and PM_{10} under the BAU scenario. The PM_{10} concentration is projected to reach 108.01 μg/m³ in 2024, which is a 25.5% increase with respect to the base year (2019) level (86.01 μg/m³). The $PM_{2.5}$ concentration level will increase by 26.26% (56.59 μg/m³) in 2024 in comparison with the 2019 level (44.82 μg/m³). It was also observed that both the $PM_{2.5}$ and PM_{10} levels were higher than the NAAQS limits ($PM_{2.5}$: 40 μg/m³; PM_{10}: 60 μg/m³).

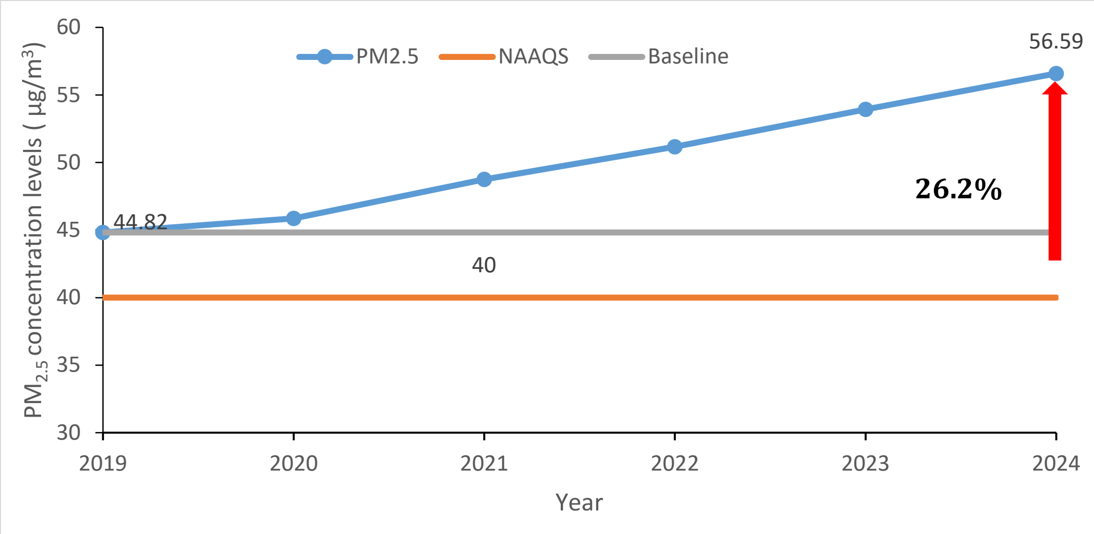


Figure 5-9: Projected annual $PM_{2.5}$ concentration from 2019 to 2024: BAU scenario

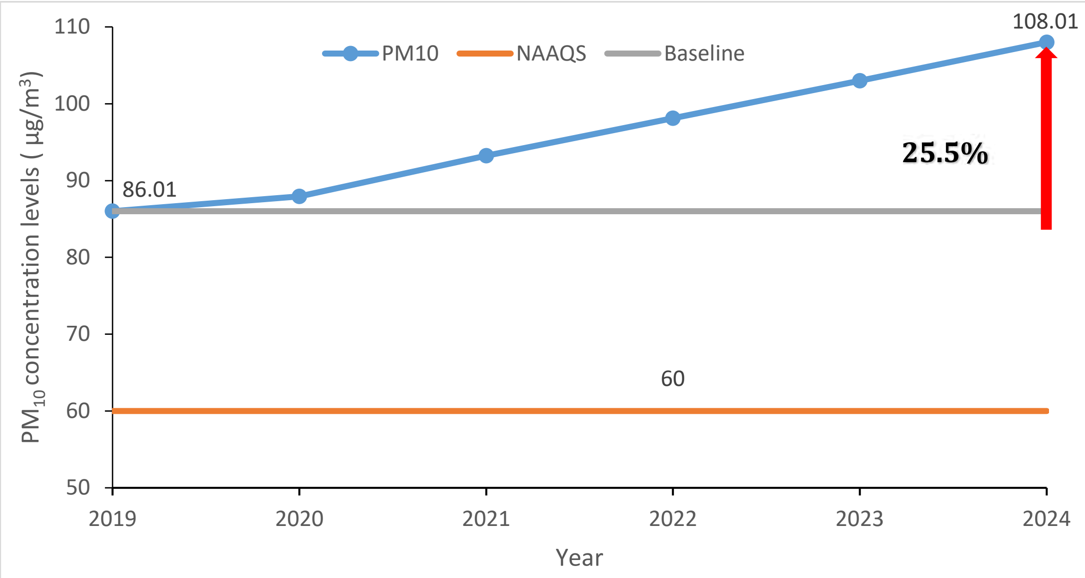


Figure 5-10: Projected annual PM_{10} concentration from 2019 to 2024: BAU scenario

5.1.1 Scenarios

To estimate the potential emission reduction, we conducted a scenario analysis by clubbing major control measures suggested under the clean air action plan by KSPCB. Measures considered under each sector are discussed below.

Transportation

Bengaluru has seen tremendous growth in the past decade. Several initiatives/new infrastructure such as metros, ring roads, bus-only lanes, additional bus routes, etc. have been introduced to accommodate the growing demand for transportation needs. Despite such initiatives, the average commute speed is lowest amongst the Indian metros (MoveInSync, 2019). Increasing the mode share of public transportation, improving the average commute speed through additional infrastructure, and policy changes will be key measures in reducing emission from the transportation sector. A city-level action plan by KSPCB suggests several measures to reduce emissions from the transportation sector, such as promotion of vehicles that emit less, remote sensor-based PUC systems, promotion of public transportation, decongestion of roads, etc. We considered the following key interventions for the scenario analysis:

1. Installation of particulate filters in diesel vehicles, with a major focus on trucks that ply in the city on a daily basis (around 10,000 trucks ply in the city on a regular basis to carry freight (Guttikunda, Nishadh, Gota, et al., 2019)
   Outcome: Installation of DPFs in trucks would reduce emissions by more than 80%.
2. Restriction of two-stroke autorickshaws in a phased manner
   Outcome: Replacing two-stroke autorickshaws with four-stroke ones/e-rickshaws would reduce the emission significantly (two-stroke autorickshaws emit six times more pollutants than four-stroke autorickshaws).
3. Increasing the percentage share of vehicles that run on EV/CNG/BS6 in Bengaluru Metropolitan Transport Corporation (BMTC) (as per BMTC policies and plans)
   i. Introduction of electric buses
   ii. Phasing out of old BS3 vehicles
   Outcome: Increasing the public mode share will reduce the number of private vehicles plying in the city. This should considerably reduce the emission from the transportation sector.

The considered control measures and the associated unit cost for each intervention are presented in Table 5.3.

Table 5.3: Measures considered: transportation sector

Control measure	Remark	Cost/incentive per vehicle (INR)
Installation of particulate filters in diesel vehicles	1. Reduced emission from diesel vehicles 2. Assumed adoption rate 5%-10%	150,000 (approx.)
Restriction of two-stroke autorickshaws	Two-stroke autorickshaws will be replaced with e-rickshaws	30,000 (incentive)
Introduction of electric buses	Electric buses will be introduced instead of diesel variants (up to 2000 buses)	10 million. (approx.)
Phasing out of old BS3 vehicles	Diesel BSVI variants will be introduced, while BSIII variants will be phased out (up to 1000 buses)	Policy enforcement

Domestic

We conducted a survey for estimating the types and quantity of fuel used by the slum population. We found that households are still dependent on wood and other solid fuels for their cooking needs. Easy availability of solid fuels, low-income levels of the households, and difficulty in getting LPG connections are some of the major reasons for slum households relying on dirty fuels for cooking. Shifting to LPG will need support from the government. Ensuring LPG connections and promoting the use of induction stoves/advanced stoves could help reduce the amount of solid fuel being used, ultimately reducing the emission from the sector. A majority of such households are located in slums; the government could either try to increase the subsidies for LPG cylinders, provide new LPG connections to these households, or replace traditional stoves with advanced ones. These measures could reduce the total emission load from the domestic sector considerably. Control measures suggested for the sector are given in Table 5.4 along with the emission reduction potential.

Table 5.4: Measures considered: domestic sector

Control measure	Remark	Incentive
Increasing LPG connections / refilling rate	LPG will reduce biomass use in cooking	INR 1600–2000 per connection / INR 200 – 400 per cylinder
Promotion of advanced *chulahs*	Assumed adoption rate:25%	INR 1500 per stove

Open Solid Waste Burning

According to the data provided by BBMP, Bengaluru generates around 4,279 tonnes of waste per day. BBMP is responsible for collecting municipal solid waste and treating it effectively. The municipal body has built multiple composting plants and dry waste recycling centres in the city. Moreover, there are plans to set up new waste-to-energy plants to treat municipal solid waste. Bulk waste generators will be responsible for treating waste; however, many of these facilities are not operational. Owing to the lack of an efficient disposal mechanism, the generated solid waste gets dumped in vacant lands and is eventually burnt, leading to the emission of toxic pollutants into the atmosphere. In order to restrict open waste burning, KSPCB has suggested several measures such as building capacity to treat waste, routine check-ups in areas where waste burning is predominant, and strict implementation of existing norms. To ensure complete restriction of open waste burning, the government could (a) enforce efficient solid waste management (ensure waste gets shifted to waste treatment plants more effectively) and (b) monitor and deploy additional force where waste burning is predominant.

The control measures suggested herein to reduce solid waste burning are summarised in Table 5.5. The emission reduction potential of the control measure is estimated at 50% for the sector.

Table 5.5: Measures considered: open waste burning

Control measure	Remark	Institutional requirement
Ban open waste burning: Envisaged reduction in open waste burning: 50%	Better door-to-door collection and strict audit for third-party contractors (garbage collectors)	Policy enforcement

Road and Construction Dust

Factors such as growth in population, rise in the number of vehicles, unpaved roads, improper handling of debris and waste at construction sites, and predominant construction activities have resulted in an increase in the emission load from this sector. The paving of roads and strict implementation of existing norms and regulations (some measures that could be adopted are given as remarks in Table 5.6) could help reduce the emission considerably (Table 5.6).

Table 5.6: Measures considered for construction dust and re-suspended dust

Control measure	Remark	Institutional requirement
Implementation of existing norms and regulations	Mechanical sweepers, paving of roads, etc.	Policy enforcement

Others

Industries: There are not many heavy industries in Bengaluru; however, there are several small-scale industries in the city. These industries contribute less than 1% of the total $PM_{2.5}$ emission load. In order to keep the emission from industries in check, the government should ensure that new industries are not allowed to operate within the city area, while constantly monitoring emission levels of the existing industries.

DG Sets: As per the data received from the electoral inspectorate, there are around 8,700 functional DG sets in Bengaluru. Most of these are installed at IT parks and commercial spaces for ensuring an uninterrupted power supply. Installation of pollution control equipment along with roof-top photovoltaic cells could reduce emissions from DG sets.

All these sectoral control measures were clubbed together and categorised –as high-, medium-, and low-emission reduction potential scenarios. All these scenarios had the same suggested control measures with varying levels of emission reduction and implementation/targets. The scenarios for the various sectors are given in Table 5.7.

Table 5.7: Emission reduction scenarios

Sector	**High emission reduction (HER) scenario**	**Medium emission (MER) reduction scenario**	**Low emission reduction (LER) scenario**
Description	Maximum emission reduction potential; achievable targets for every control measure considered	Medium emission reduction potential, with less relaxed targets for each control measure	Minimum emission reduction potential without any major capital requirement.
Key interventions considered and targets to be achieved			
A) Transportation			
Retrofitting heavy commercial vehicles with DPFs entering the city	10,000	7,000	5,000
Complete ban on two-stroke auto rickshaw by 2024 (phasing out)	26,000	26,000	26,000
Increase in the share of vehicles in BMTC fleet			
1) Number of electric buses to be added by 2024	2,000	1,400	1,000
2) Phasing out of BS3 vehicles	1,000	700	500
Emission reduction potential	25–30%	9–12%	6–8%
B) Domestic			
Reduction in solid fuel usage • Percentage of households with new LPG connection	3%	2%	1%
Emission reduction potential	34–37%	20–23%	9–12%
C) Open waste burning			
Open waste burning 1) Build solid waste management capacity 2) Ban open waste burning-reduction in open waste burning	50%	30%	20%

Emission reduction potential	50%	30%	20%
D) Road and construction dust			
Strict enforcement of existing guidelines to control road and construction dust emission	15–20%	13–15%	10–13%
Emission reduction potential	15–20%	13–15%	10–13%
E) DG sets			
Envisaged reduction in DG set usage	30%	20%	10%
Emission reduction potential	30%	20%	10%

PM$_{2.5}$ Emission Load

The estimated PM$_{2.5}$ emission load over the BBMP area under the BAU scenario and three considered scenarios (HER, MER, and LER) are presented in Figure 5-11. It was found that under the HER scenario, the total emission load would be around 12,700 tonnes in 2024, which is 24.8% less than the emission under the BAU scenario (17,000 tonnes) in 2024. The total emission load in the MER and LER scenarios would be around 14,700 and 15,400 tonnes, respectively, which are around 13% and 9% less than the emissions in the BAU scenario.

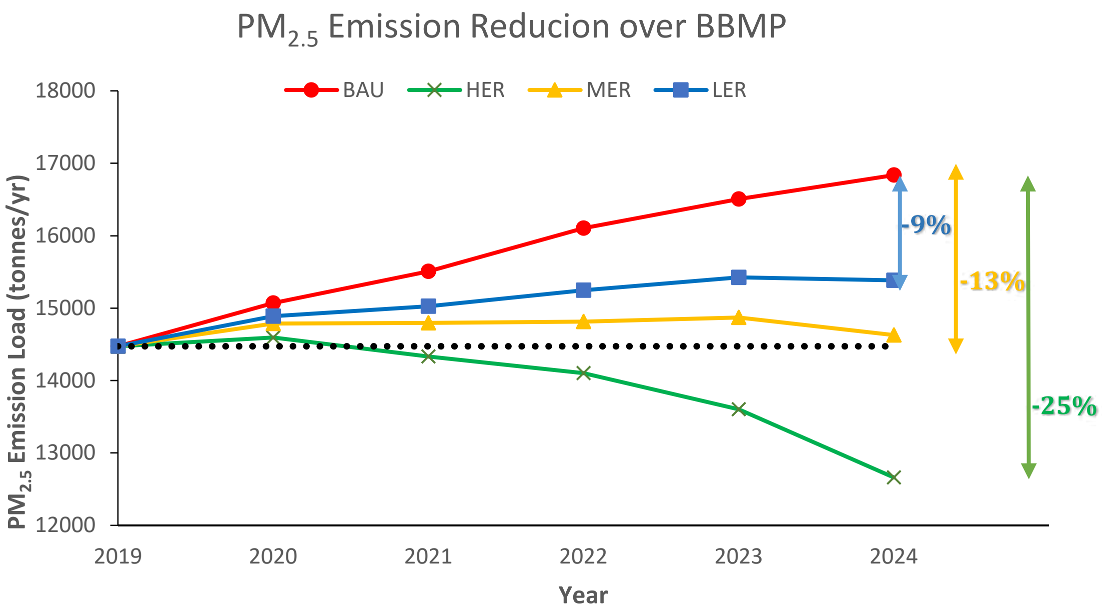


Figure 5-11: Scenarios: emission-reduction potential (PM2.5)

We performed a scenario analysis to estimate the projected future concentration under the three different emission reduction scenarios. We considered 2019 meteorological conditions to project the concentration values. Figure 5-12 and Figure 5-13 show the spatial distribution of PM$_{2.5}$ concentration for the year 2024 under all the scenarios considered and the projected and PM$_{2.5}$ concentration maps under the HER scenario, respectively. The projected values clearly show that the PM$_{2.5}$ concentrations will decrease considerably throughout the city in 2024. Moreover, from the spatial distribution map it can be observed that the number of grids with high PM$_{2.5}$ concentration areas (>50 µg/m^3) will also reduce significantly. PM$_{2.5}$

concentration levels across the BBMP area over the years shows how different control measures in different sectors (transportation, road and construction dust, domestic, DG sets, eateries, etc.) will contribute to reduced concentration levels. The control measures suggested for the transportation sector (installation of DPFs in trucks that enter the city, complete removal of two-stroke auto-rickshaws by 2024, the addition of more electric buses to the BMTC fleet, and phasing out of BS3 vehicles) and road and construction sector (strict enforcement of existing guidelines to control dust emission) can help reduce the PM concentration to a great extent.

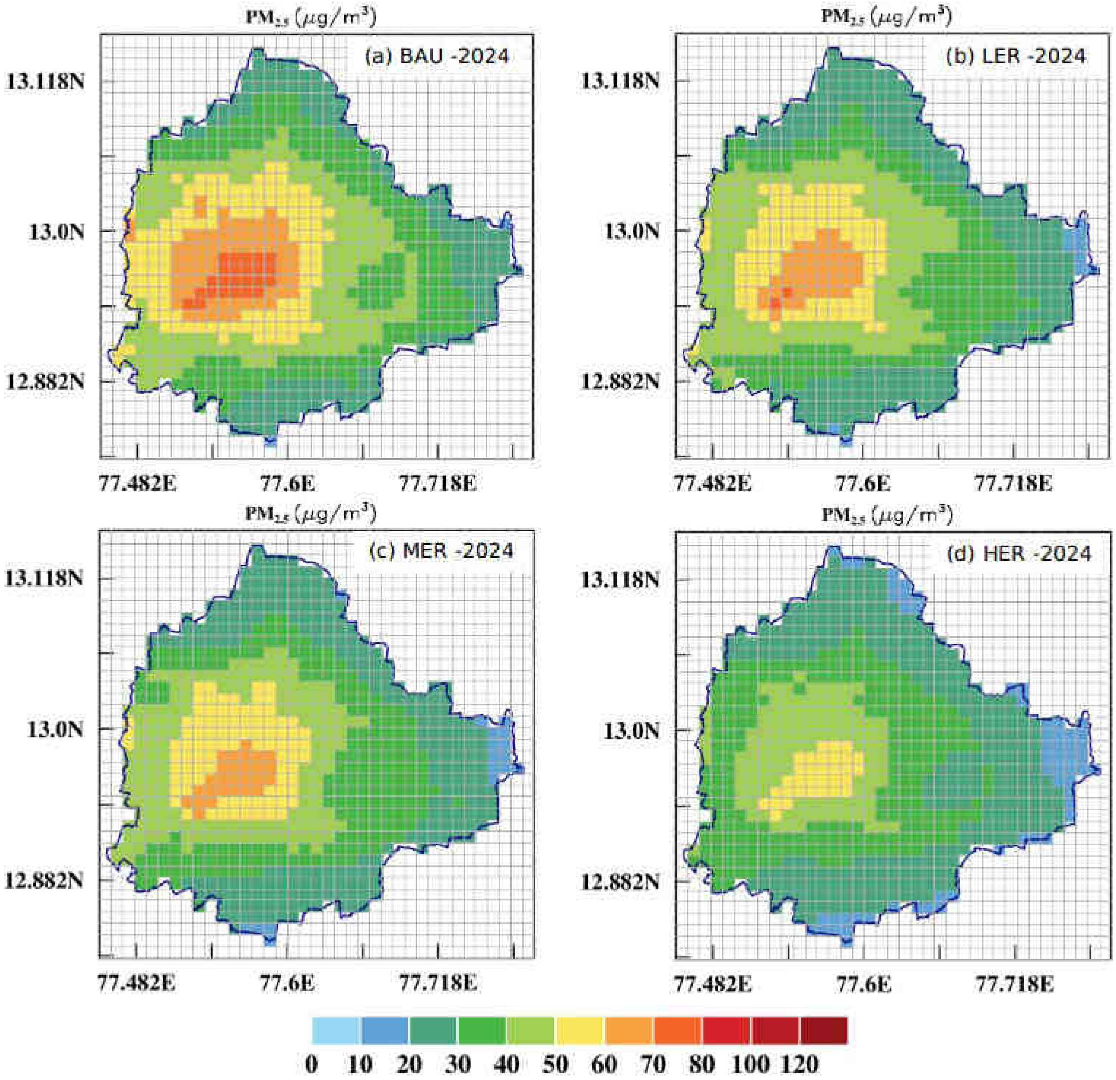


Figure 5-12: Spatial distribution of projected annual $PM_{2.5}$ concentration in 2024: a) BAU, b) LER, c) MER, and d) HER

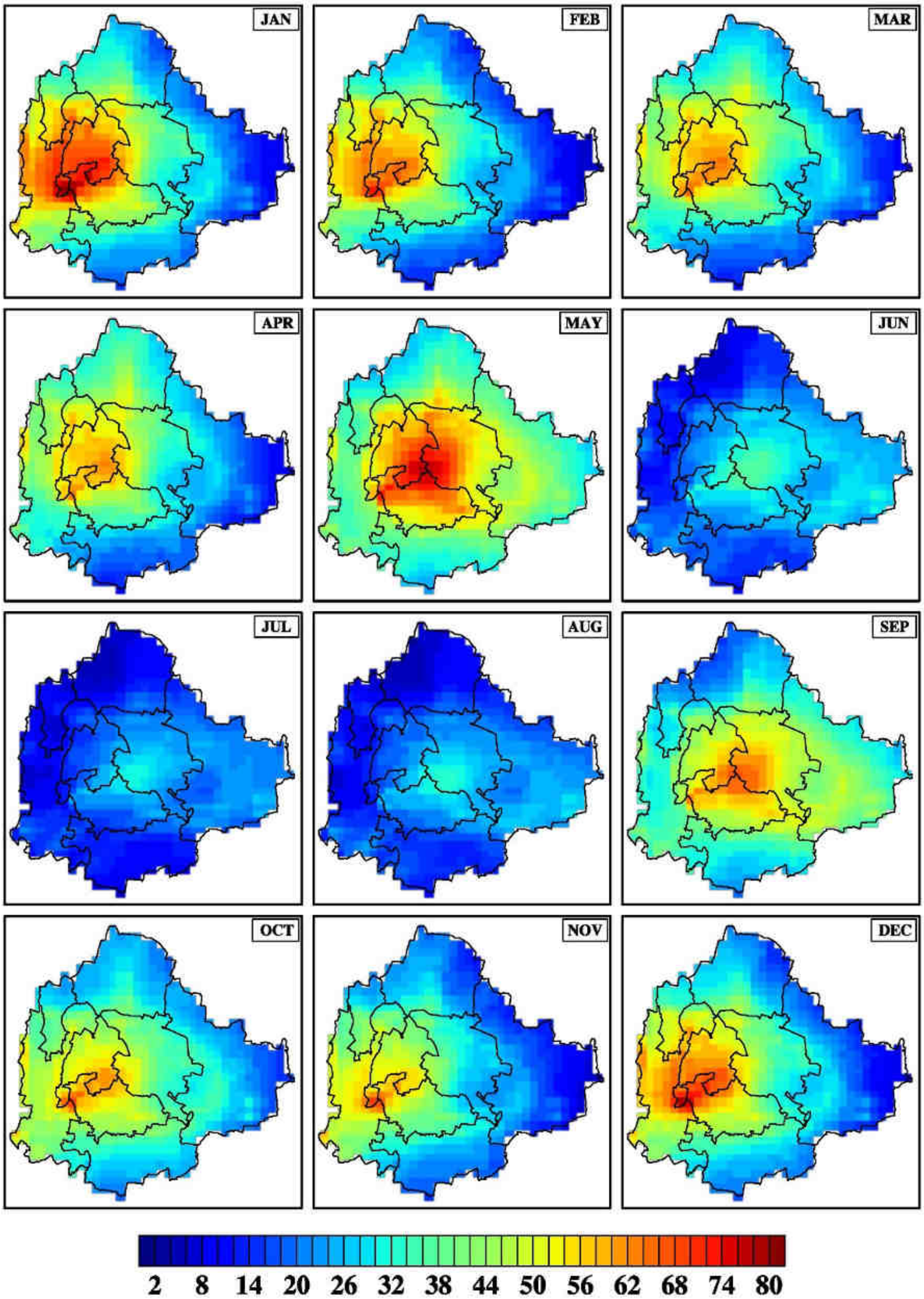


Figure 5-13: Monthly average values of WRF-CAMx-model-simulated $PM_{2.5}$ concentration (µg/m³) during 2024 under high emission reduction scenario over Bengaluru

Figure 5-14 presents the simulated and projected $PM_{2.5}$ concentration levels in Bengaluru under the BAU scenario and the three different scenarios. Under the BAU scenario, the concentration will increase from 44.82 µg/m³ in 2019 to 56.59 µg/m³ in 2024. When compared to the BAU scenario, in 2024, the concentration reduces from 56.59 µg/m³ to 41.55

µg/m³ in the HER scenario. This reduction would save around 4,121 lives/year in 2024. Under MER and LER scenarios, the projected concentration levels in 2024 will be 48.94 µg/m³ and 51.14 µg/m³, respectively, saving around 1,939 and 1,350 lives/year, respectively, when compared to the BAU scenario. Under the HER scenario, the $PM_{2.5}$ levels in the city could reach closer to the NAAQM standards in 2024, and the levels are expected to drop below NAAQM standards post 2024.

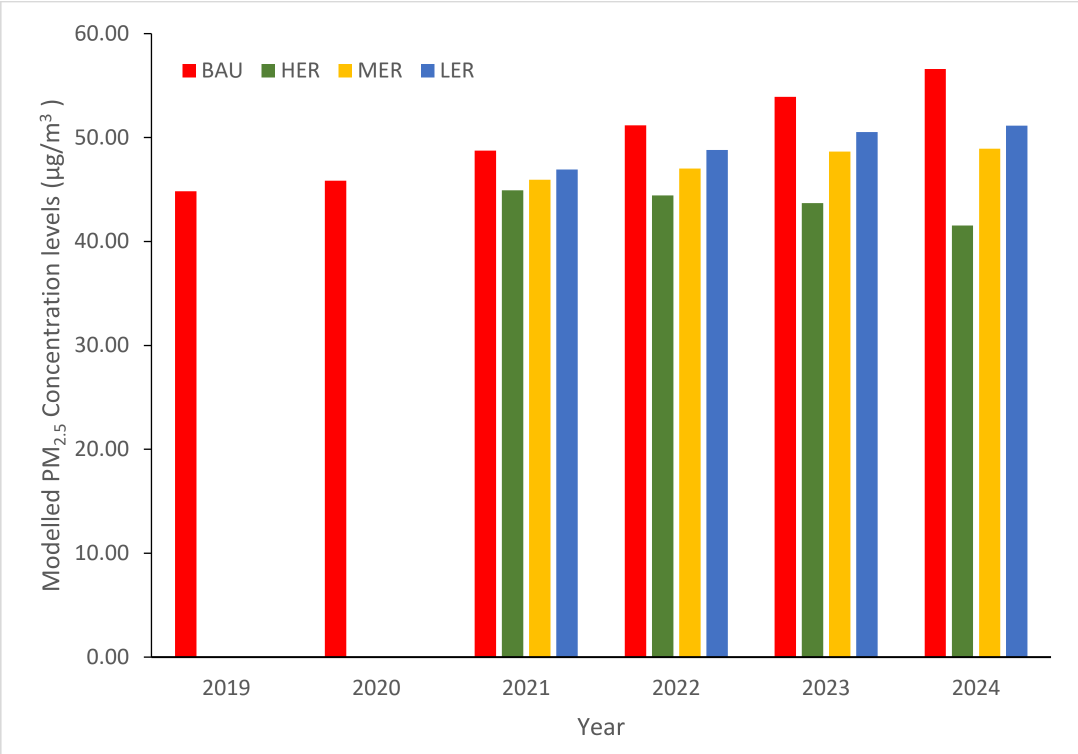


Figure 5-14: Projected annual $PM_{2.5}$ concentration from 2019 to 2024

PM_{10} Emission Load

The estimated PM_{10} emission load under the BAU scenario and the three considered scenarios is presented in Figure 5-15. It was found that under the HER scenario with stringent targets in transportation and road dust sectors, an emission reduction of 21% w.r.t emissions under the BAU scenario would be achieved in 2024. Under the MER and LER scenarios with less stringent targets, a $PM_{2.5}$ reduction of 13% and 9%, respectively, would be achieved. The emissions under the HER scenario would be around 22,500 tonnes, which is significantly less than the 2019 base-line emission.

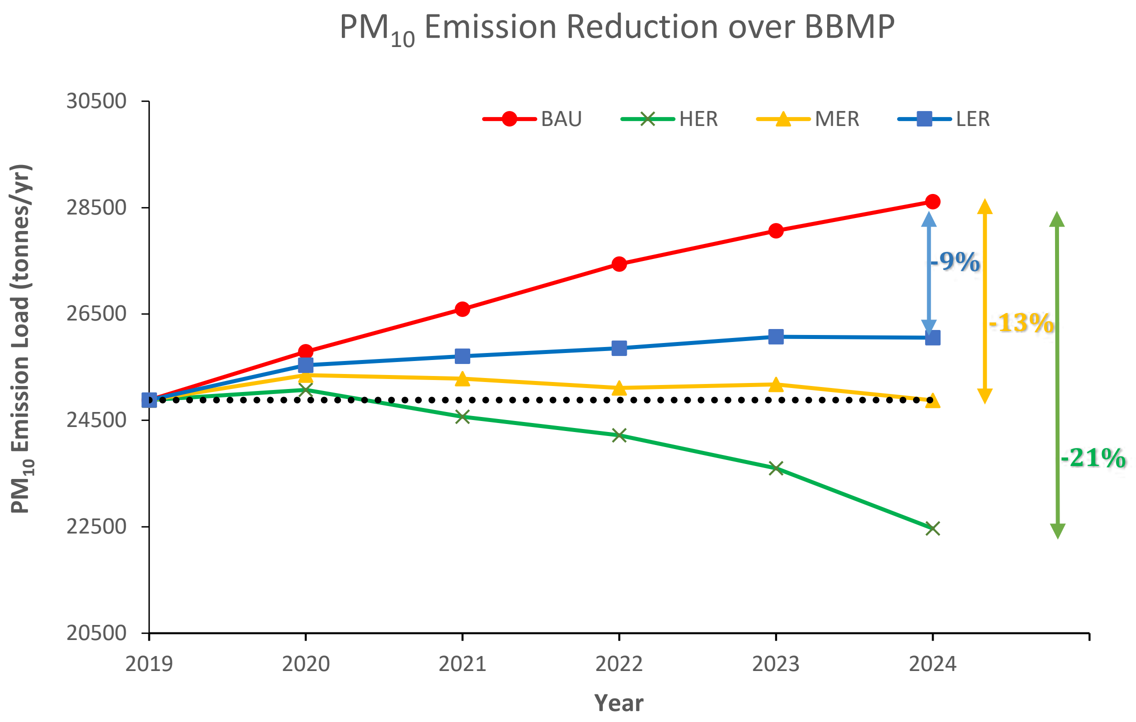


Figure 5-15: Scenarios: emission-reduction potential (PM_{10})

Figure 5-16 presents the simulated and projected PM_{10} concentration levels for the city under the BAU scenario and the three different scenarios. Under the BAU scenario, the concentration will increase from 88.86 µg/m³ in 2019 to 108.01 µg/m³ in 2024. Under the HER scenario in 2024, the concentration drastically reduces from 108.01 µg/m³ in the BAU scenario to 79.74 µg/m³. In the MER and LER scenarios, the 2024 concentrations are projected to reduce to 93.39 µg/m³ and 97.59 µg/m³, respectively. Unlike the $PM_{2.5}$ levels, PM10 levels in the city will be much greater than the NAAQM levels under the HER scenario and the government needs to consider aggressive targets to reach the national standard.

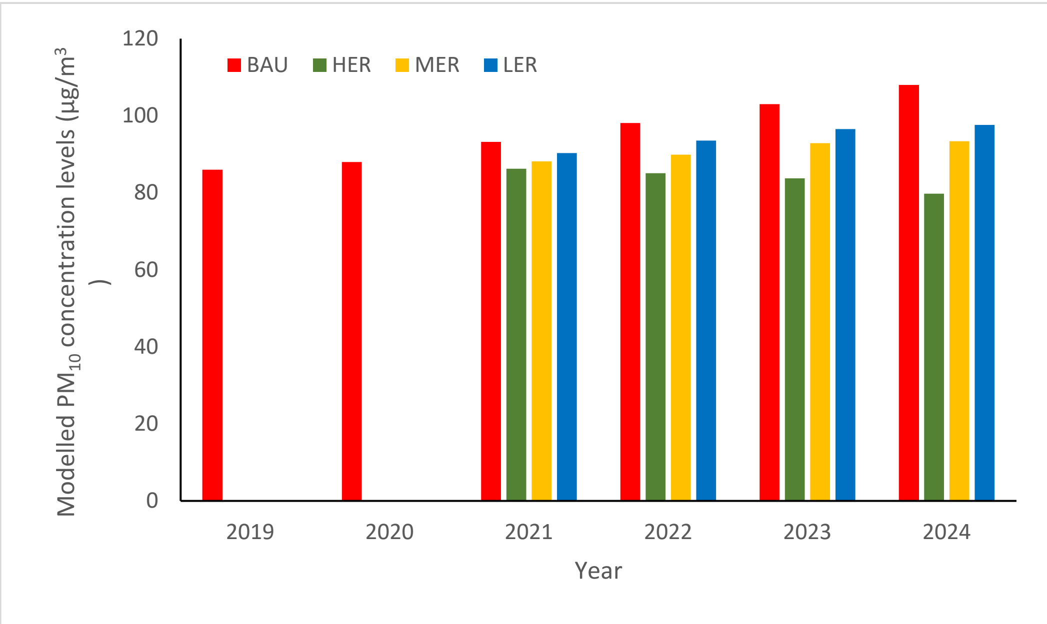


Figure 5-16: Projected annual PM_{10} concentration from 2019 to 2024

The spatial distribution of the PM_{10} concentrations for 2024 under the BAU scenario and the three scenarios and monthly average PM_{10} concentration level is shown in Figure 5-17 and Figure 5-18, respectively. It is clearly evident that the HER scenario shows a drastic reduction in the concentration in comparison with BAU in 2024. Further, in 2024, the high PM_{10} concentration areas (>100 $\mu g/m^3$) are reduced in number under the BAU scenario and confined to the city centre under the HER scenario.

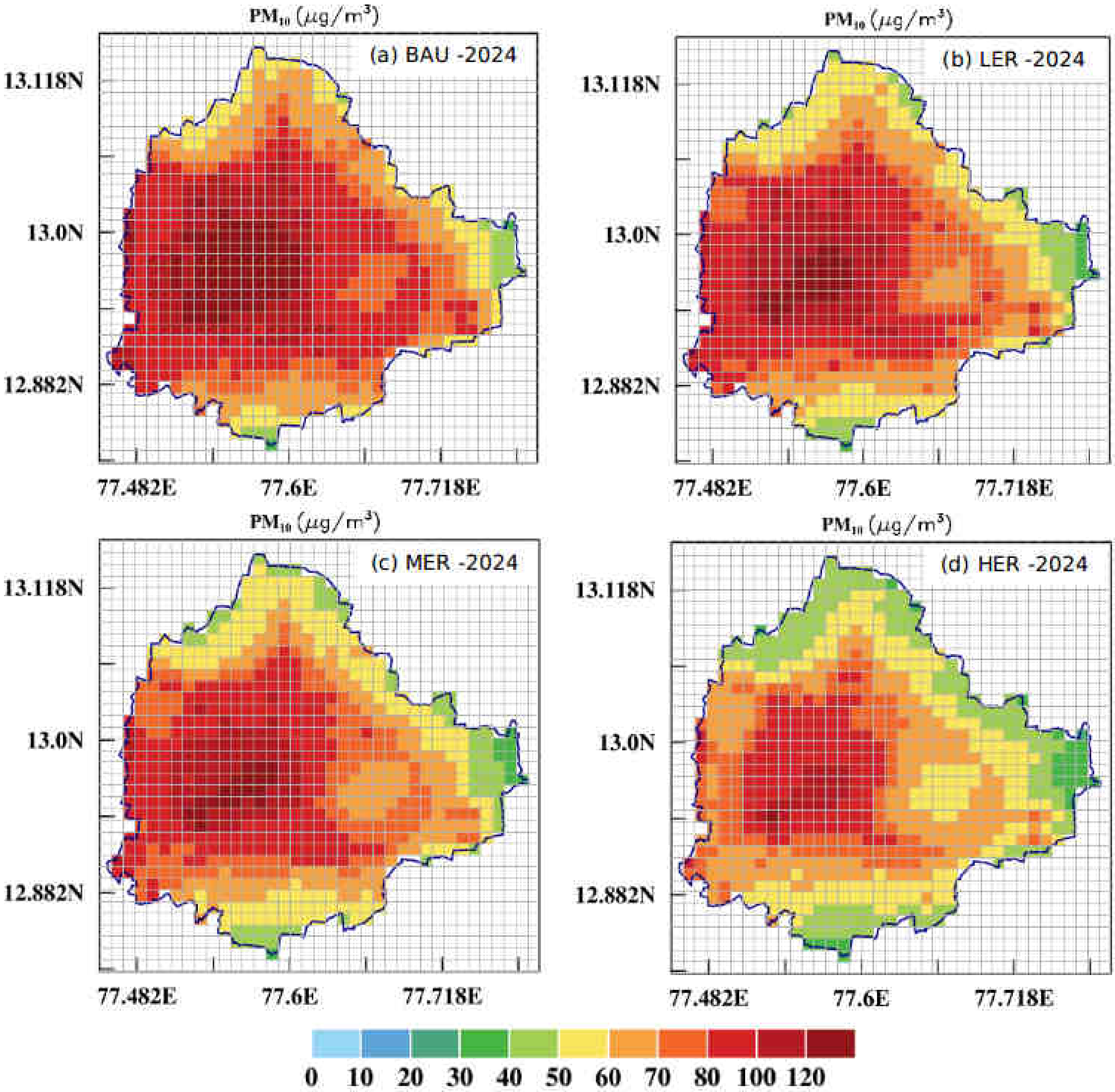


Figure 5-17: Spatial distribution of projected annual PM_{10} concentration in 2024: a) BAU, b) LER, c) MER, and d) HER

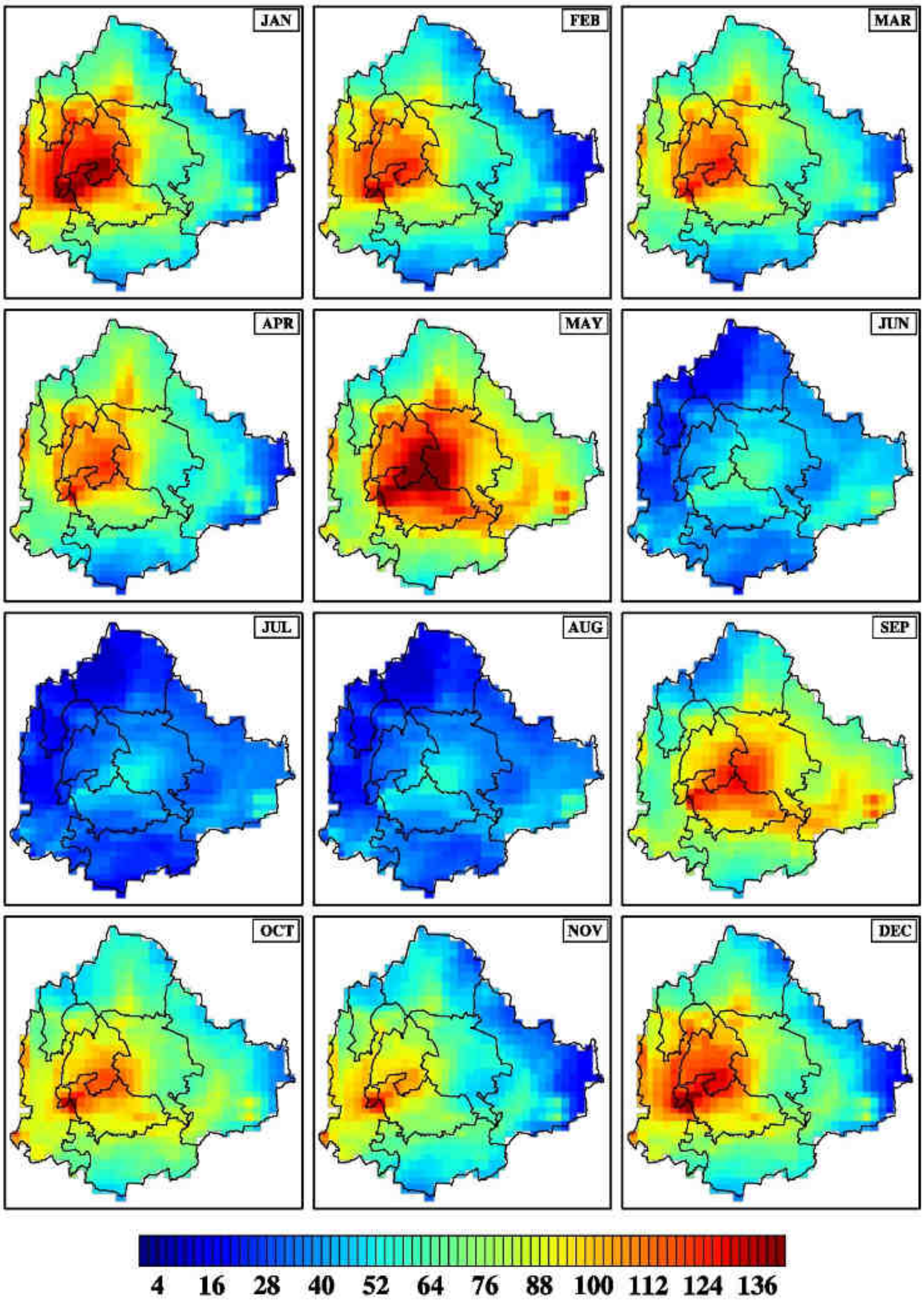


Figure 5-18: Monthly average values of WRF-CAMx-model-simulated PM_{10} concentration (µg/m^3) during 2024 under high emission reduction scenario over Bengaluru

Projected SO_2 and NO_2 Annual Concentration in 2024 under BAU and The Three Emission Reduction Scenarios: The estimated annual SO_2 concentration was 8.269 µg/m^3 in 2019. It is estimated to increase to 9.063 µg/m^3 in 2024 under the BAU scenario. The spatial distribution of the SO_2 concentration for 2024 under the BAU scenario and the three scenarios is shown in Figure 5-19. Under the HER scenario in 2024, the concentration reduces from 9.063 µg/m^3 under the BAU scenario to 7.885 µg/m^3. Under the MER and LER scenarios, the projected 2024 concentrations are reduced to 8.287 µg/m^3 and 8.661 µg/m^3, respectively.

Similarly, the estimated annual NO_2 concentration was 51.535 µg/m3 in 2019 and is estimated to increase to 68.233 µg/m3 in 2024 under the BAU scenario. The spatial distribution of the NO_2 concentration for 2024 under the BAU scenario and the three scenarios is shown in

Figure 5-20. Under the HER scenario in 2024, the concentration reduces from 68.233 μg/m^3 under the BAU scenario to 52.496 μg/m^3. Under the MER and LER scenarios, the projected 2024 concentrations are reduced to 60.628 μg/m^3 and 62.584 μg/m^3, respectively.

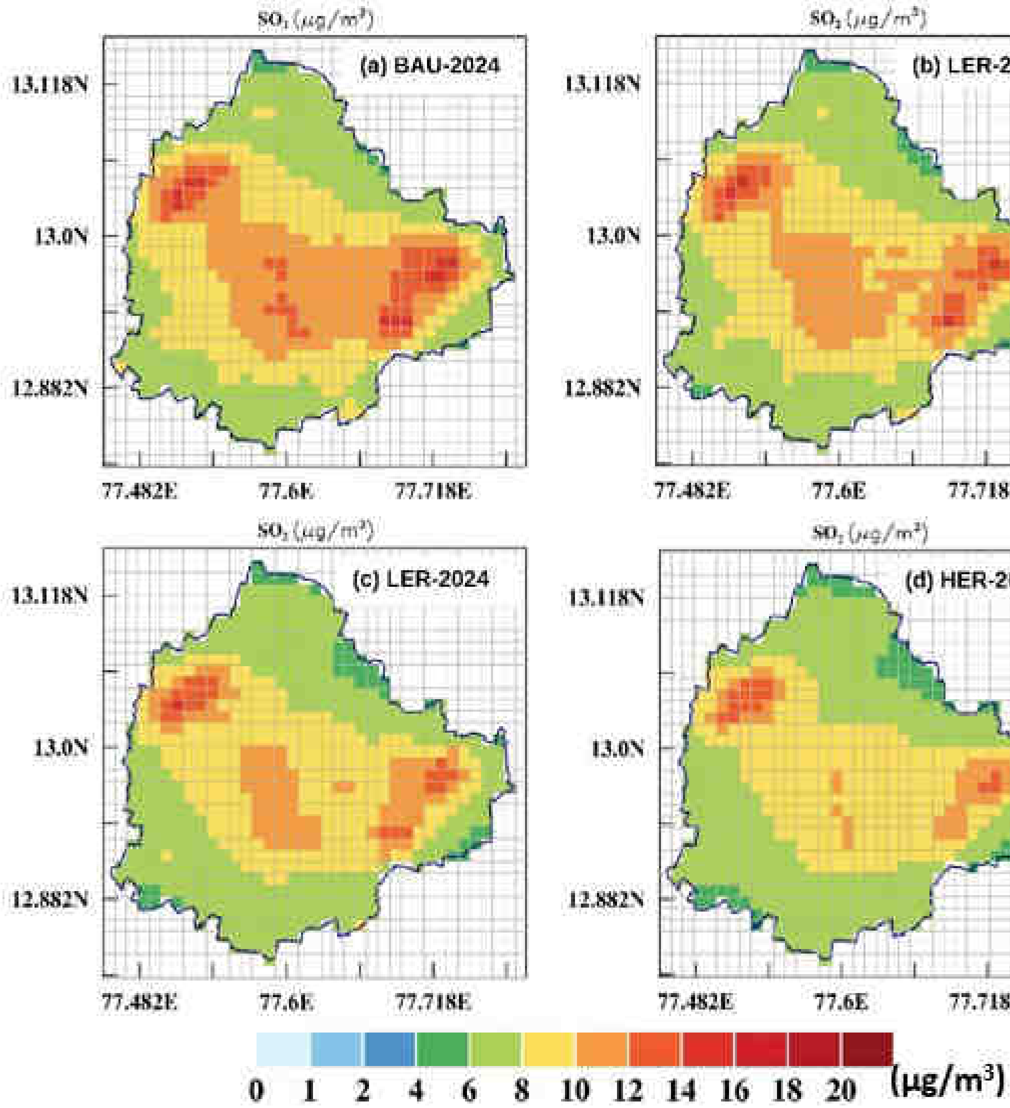


Figure 5-19: Spatial distribution of projected annual SO_2 concentration in 2024: a) BAU, b) LER, c) MER, and d) HER

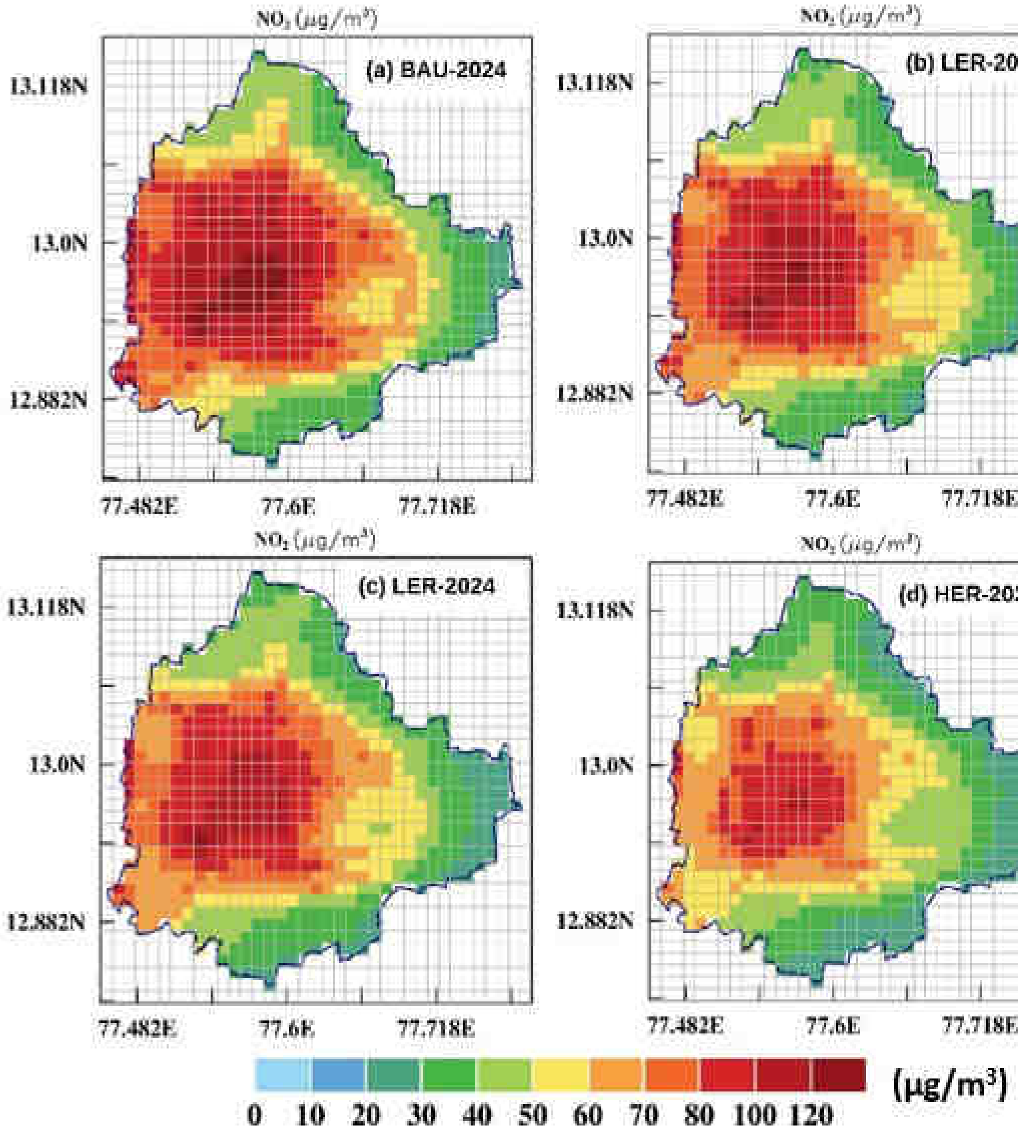


Figure 5-20: Spatial distribution of projected annual NO_2 concentration in 2024: a) BAU, b) LER, c) MER, and d) HER

5.1.2 Implementation Strategy

This section describes the strategies and targets that need to be adopted by the line departments for the desired reduction in air pollution emissions. The strategies concern the high-impact control measures present in the clean air action plan proposed by KSPCB.

Sector: Transportation and Dust

As discussed earlier, transportation is one of the key polluting sectors. The city has already adopted several measures for pollution reduction including the introduction of electric vehicles, increase in the mode share of public transportation, etc. The city could witness a significant emission reduction by adopting the targets mentioned in Table 5.8 below.

Table 5.8: Strategic roadmap – Transportation and Dust

Si. No	Strategy	2021	2022	2023	2024	Implementing Agency
CM 1	**Installation of particulate filters in diesel vehicles**					
1.1	Trucks to be retrofitted with DPFs (No.) (Target: 10,000)	1250	2000	3000	3750	Transport Department
CM 2	**Restriction of two-stroke autorickshaws**					
2.1	Replacing existing two-stroke autos with CNG/EV-based autos (No.)	6500	6500	6500	6500	Transport Department
2.2	Setting up scrapping centres for old autos (No.)	10	-	-	-	
CM 3	**Increasing the share of vehicles that emit less in BMTC**					
3.1	Introduction of electric buses (No.)	500	500	500	500	Transport Department
3.2	Phasing out of old BS3 vehicles (No.)	200	300	300	300	
CM 4	**Implementation of Existing rules to reduce dust emissions**					
4.1	Strict enforcement of norms at construction sites	Immediate (Policy Enforcement)				BBMP/KSPCB
4.2	Regular sweeping of roads (Mechanical)	Immediate (Policy Enforcement)				Transport Department

The government should also carry out regular awareness programmes to increase the adoption rate of electric vehicles and to increase the public mode share.

Sector: Domestic and DG sets

Wood and other solid fuels are widely used in slums for cooking. This leads to significant emissions from the domestic sector. Incentives to encourage clean cooking methods such as liquefied petroleum gas (LPG) should help in controlling emissions from the domestic sector.

Commercial establishments and housing societies often switch to DG sets to meet their power requirement during interruptions in the power supply. Most of these DG sets do not have filters, causing a huge spike in air pollution levels.

Table 5.9 below describes the strategies and targets that the government should adopt in order to achieve desired emission reduction from the domestic sector.

Table 5.9: Strategic roadmap -Domestic and DG sets

Si. No	Strategy	2021	2022	2023	2024	Implementing Agency
CM 1	**Introduction of improved *chulahs***					
1.1	Setting up Incentivising mechanism	Immediate (Policy Enforcement)				Food And Civil Supplies Department
1.2	% of households to switch to improved *chulahs* (%) (Target: 25%)	3%	5%	7%	10%	
1.3	Restriction on freely available solid fuels	Immediate (Policy Enforcement)				
CM 2	**Increasing the LPG connections in low-income strata**					
2.1	% of households* to receive new LPG connection (%)	10%	20%	30%	40%	Food And Civil Supplies Department
CM 3	**Reduction in usage of DG sets**					
3.1	Uninterrupted power supply	-	-	-	100%	BESCOM
3.2	Awareness programmes on installation of pollution control equipment in DG sets					KSPCB

*households with no LPG connection at present

Sector: Open waste burning

Taking into account the city's proposed solid waste treatment plants, Bengaluru will have sufficient capacity to treat the domestic waste by 2024. To ensure a significant reduction in open waste burning, the government could adopt the strategies mentioned in Table 5.10 below.

Table 5.10: Strategic roadmap - Open Waste Burning

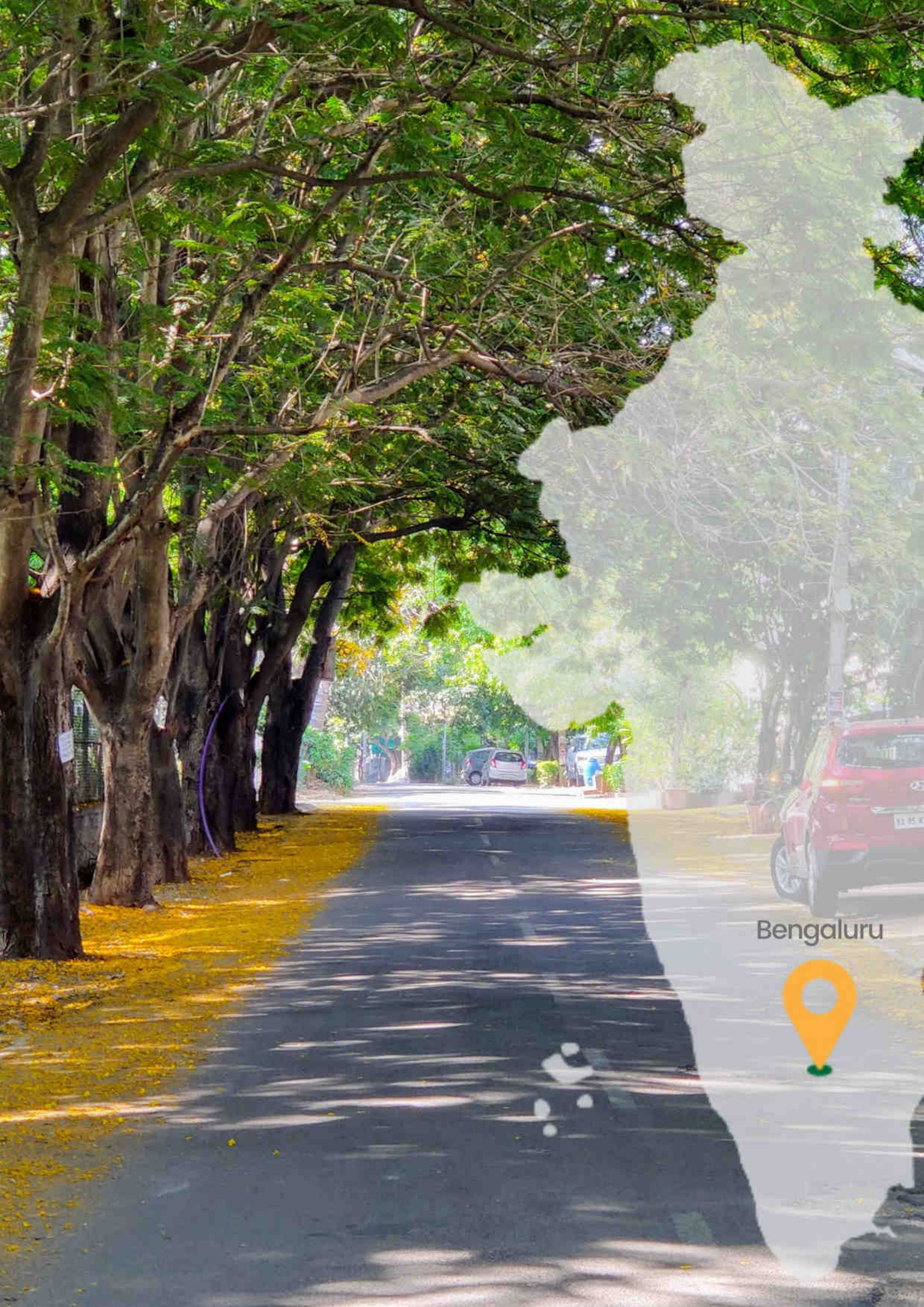
Si. No	Strategy	2022	Implementing Agency
CM 1	**Ensuring effective waste disposal mechanism**		
1.1	Implementing ban on open waste burning	Immediate(Policy Enforcement)	BBMP
1.2	Strict audit on third-party waste management	Immediate(Policy Enforcement)	
1.3	Level of segregation (%)	100%	
1.4	Door-to-door collection (%)	100%	

Table 5.11 below presents the estimated cost for control measures under each scenario. The costs for the transportation sector are the highest. This is attributed to the introduction of electric vehicles. In other sectors, policy implementation may not be capital intensive, with a majority of the costs (installation of filters in DG sets, industries switching to clean fuel) being borne by private players. The table presents only the costs involved in implementing the control measures with high emission reduction potential. It is estimated that under the high emission reduction scenario, the government could incur an expense of INR 3230 crore and save around 4,121 lives from premature death.

Table 5.11: Economic Comparison (HER vs MER vs LER)

Sectors	Departments Responsible	Cost incurred (INR Cr.)		
		HER*	MER*	LER*
Transport	Policy Implementation	<1	<1	<1
	D.O.T	210	165	135
	BMTC (Buses)	3000	2100	1500
Open Waste Burning	BBMP (Policy Implementation)	<1	<1	<1
DG SETS	Policy Implementation	<1	<1	<1
Domestic	FCS (New LPG Connection)	15	10	5
Road & Construction Dust	BBMP (Policy Implementation)	<1	<1	<1
Lives Saved (No.)		4121	1939	1350
Total		3230	2280	1640

* *Cost estimates are only for the shortlisted control measures. The costs will increase if the government decides to implement additional control measures.*


Bengaluru

6. Way Forward

Bengaluru has grown exponentially in the past few decades as a result of urbanisation and large-scale migration from other states in search of better opportunities. From being the Garden City to the Silicon Valley of India, the city has witnessed massive growth in population, infrastructure, and industries. The unplanned growth of the city has come at the cost of deteriorating air quality, polluted water bodies, reduced green covers, and flooding of city areas, among other civic issues.

The city administration has taken several steps to cope with this development. However, issues such as traffic congestion, improper waste management, and preference for private over public transportation still persist. If these issues remain unresolved, our study shows that the PM concentration in the city can increase by 26% by 2024, which will have catastrophic health effects on the residents of Bengaluru. It would also have grave repercussions for the economy.

Though KSPCB and the Government. of Karnataka have already initiated a few mitigation measures such as addressing the solid waste management problem in the city, improving the road infrastructure, and following CPCB norms at construction sites to reduce air pollution in Bengaluru, the ground-level implementation of these strategies remains a challenge. Synergy among various government departments will be the key to addressing this. Also, most of these mitigation measures are restricted to the city, with the air-shed area being completely ignored. As evident from this study, transportation and dust are two key polluting sectors in the city. Therefore, policymakers should focus on the transportation sector to achieve optimum emission reduction. Measures such as increasing the share of public transport modes, promoting the use of pollution-free vehicles, restricting the entry of HCVs inside the city limits, phasing out of old vehicles, and installing pollution control equipment will be instrumental in reducing emissions from the transportation sector.

To curb air pollution in Bengaluru, the city administration should consider the policy measures recommended in this study including the adaptation of green fuels in residential cooking and heating, a strict ban on open waste burning, uninterrupted power supply, and restriction on setting up of new industries inside the city area.

Finally, no policy measure can be successful without public participation. It is important therefore to engage with the public and create awareness on air pollution issues through public campaigns, display of digital boards at traffic junctions and hotspots to give spot pollution levels, and regular public service messages on the ill effects of solid fuels (wood, and coal), kerosene, and furnace oil.

7. References

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8. Appendix

Table I: Emission inventory studies on particulate matter

Study	Location	Sector Considered	Spatial Resolution
ARAI, 2010	Pune, India	Transportation Industry Domestic Agriculture Construction Resuspension of dust Waste burning	2 km × 2 km
Guttikunda & Calori, 2013	Delhi, India	Transport Domestic Diesel Gen sets Brick kilns Industries Construction Waste burning Road dust Power plant	1 km × 1 km
Guttikunda & Jawahar, 2014	India	Thermal power plants	
Guttikunda & Kopakka, 2014	Hyderabad, India	Transport Road dust Domestic Industries Brick kilns Construction Generator sets Waste burning	1 km × 1 km
Guttikunda, Goel, Mohan, Tiwari, & Gadepalli, 2015	Chennai & Vishakhapatnam, India	Transport Domestic Open waste burning Construction Manufacturing industries Power plants Generator sets Road dust Brick kilns (only in Chennai)	1 km × 1 km
Guttikunda, Nishadh, & Jawahar, 2019	Agra, India Amritsar, India Bengaluru, India Bhopal, India Bhubaneswar, India Chandigarh, India Chennai, India Coimbatore, India Dehradun, India Indore, India Jaipur, India Kanpur, India Kochi, India Ludhiana, India Nagpur, India	Transport Road dust Domestic Industries Brick kilns Construction	1 km × 1 km

	Patna, India Pune, India Raipur, India Ranchi, India Varanasi, India		
Guttikunda, Nishadh, Gota, et al., 2019	Bengaluru, India	Transport Dust Domestic Industries Brick kilns Generator sets Waste burning	1 km × 1 km
IITM, 2010	Chennai, India	Transport Industry Domestic Eateries Open burning Crematoria Resuspension of dust	2 km × 2 km
Kurokawa et al., 2013	Asia	Transport Industry Domestic Agriculture Power plants Others – fugitive emissions, solvent use, human, etc.	25 km × 25 km
Li et al., 2017	Asia	Transport Industry Domestic Agriculture Power plants	25 km × 25 km
Majumdar et al., 2020	Kolkata, India	Road transport (exhaust & non-exhaust) Power plant Construction Domestic combustion Agriculture Industrial emission Waste and open burning Non-road machinery Fuel production & distribution Fuel conversion Solvent use	
Mishra & Goyal, 2015	Delhi, India	Transport Industry Power plant Domestic	
NEERI, 2010	Delhi, India	Transport Domestic Eateries Bakeries Crematoria Waste incinerators Diesel generator sets Open burning	2 km × 2 km

		Construction Diesel locomotives Industry Resuspension of dust	
NEERI, 2010	Mumbai, India	Transport Domestic Eateries Bakeries Crematoria Waste incinerators Diesel generator sets Open burning Landfill burning Construction Diesel locomotives Aircraft Marine vessels Industry Power plan Stone crushers Resuspension of dust	2 km × 2 km
Pandey & Venkataraman, 2014	India	Transport	
Rajarathnam et al., 2014		Brick kilns	
S. K. Sahu, Ohara, Beig, Kurokawa, & Nagashima, 2015	India	Sugar industry	25 km × 25 km
S. K. Sahu, Schultz, & Beig, 2015	India	Fossil fuel	
Sadavarte & Venkataraman, 2014	India	Domestic Agriculture Informal industry	
Sharma & Dikshit, 2016	Delhi, India	Transportation Industry Domestic Eateries Solid waste burning Construction DG sets Cremation Medical waste incinerators Waste to energy plants Agricultural soil dust Ready mix concrete - batching	2 km × 2 km
Sharma, 2010	Kanpur, India	Transportation Industry Domestic Garbage burning Agriculture waste burning Eateries DG sets Funeral wood burning Resuspension of dust Construction dust	2 km × 2 km

Sindhwani, Goyal, Kumar, & Kumar, 2015	Delhi-NCR, India	Transport Power plant Industry Construction Domestic DG sets Waste burning Resuspension of dust	2 km × 2 km
Singh, Sharma, & Agrawal, 2017	India	Transport	
TERI & ARAI, 2018	Delhi, India	Transport Industry Power plant Domestic Biomass & garbage burning Construction Crematoria Eateries Waste incinerator Landfill burning Diesel generators	4 km × 4 km
TERI, 2010	Bengaluru, India	Transport Domestic Eateries Open burning Construction Industry Resuspension of dust	2 km × 2 km

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