BEFORE THE NATIONAL GREEN TRIBUNAL
PRINCIPAL BENCH, NEW DELHI

Original Application No. 687/2023

IN THE MATTER OF:

In Re: Air Quality Index in various Cities

INDEX

29.10.2025
New Delhi

Filed By:

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BEFORE THE NATIONAL GREEN TRIBUNAL

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Original Application No. 687/2023

IN THE MATTER OF:

In Re: Air Quality Index in various Cities

Affidavit of Pardeep Kumar, IAS, Member Secretary, Haryana State Pollution Control Board, Haryana on behalf of Additional Chief Secretary, Environment Department, Haryana in compliance to order dated 04th September, 2025.

I, the above name deponent, do hereby solemnly affirm and state as under:-

RESPECTFULLY SHOWETH:-

1. That, one city of the State i.e. Faridabad has been declared as one of the 131 non-attainment cities declared by the Central Pollution Control Board.

2. That, in compliance of directions issued by the Hon'ble Tribunal, the Source Apportionment Study of Faridabad was assigned to M/s The Energy and Resources Institute, Delhi and they have submitted the final Source Apportionment Study report in September, 2025, copy of the same is enclosed as **Annexure-I**.

29 OCT 2025

NOTARY COL. APS CHAHAL (Retd.) PANCHKULA No. 1145 Expires on 22.06.2026 GOVT OF INDIA

3. That, peer review of the source Apportionment Study Report is pending and after the peer review the task of consequential revision of the city action plan in accordance with the Source Apportionment Study will be

undertaken by the stakeholder departments and the same will be submitted to the Central Pollution Control Board. The pending task will be completed by 31st January, 2026.

4. That the deponent may kindly be allowed to place on record the present affidavit in compliance of order dated 04th September, 2025 passed by this Hon'ble Tribunal for kind consideration and appropriate order of Hon'ble Tribunal please.

Place: Panchkula

Dated: 29.10.2025

NOTARY COL. APS CHAHAL (Retd.) PANCHKULA No. 11451 GOVT OF INDIA

(Pardeep Kumar, IAS)

Member Secretary, HSPCB

VERIFICATION:

29 OCT 2025

I, the deponent above named, do hereby verify and state that the contents of the above affidavit are true and correct to the best of my knowledge as derived from the official record. No part of the above affidavit is false and nothing material has been concealed there from.

Place: Panchkula

Dated: 29.10.2025

(Pardeep Kumar, IAS)

Member Secretary, HSPCB

ATTESTED

APS CHAHAL No. 11451

NOTARY PANCHKULA

29 OCT 2025

Annexure-I

Ambient Air Pollution Source Apportionment Study of Faridabad City, Haryana

The Energy and Resources Institute
September 2025

Submitted to
Municipal Corporation of Faridabad

Disclaimer

This report presents the findings of the project "Ambient Air Pollution Source Apportionment and Emission Inventory Study for Faridabad City", conducted under the National Clean Air Program (NCAP) and funded by the Municipal Corporation, Faridabad. The study has been carried out by The Energy and Resources Institute (TERI), New Delhi, India, in alignment with the defined scope of work.

The insights, analyses, and projections in this report are based on data collected through extensive on-ground assessments within the Faridabad Municipal Corporation Area, National Capital Region (NCR) during the study period. Stringent validation measures have been applied to ensure the accuracy and reliability of the findings.

Suggested format for citation

T E R I. 2025
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New Delhi: The Energy and Resources Institute. 154 pp.
[Project Report No.]

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Acknowledgement

TERI extends its sincere gratitude to the Municipal Corporation, Faridabad, for commissioning this study and for their invaluable guidance throughout the project's execution.

The project team expresses deep appreciation to the Director-General, TERI, for their active participation and unwavering support in facilitating the study. Special thanks are also extended to the Haryana State Pollution Control Board and the Municipal Corporation, Faridabad, for their critical role in providing the necessary data essential for this research.

We are immensely grateful to all peer reviewers whose insightful suggestions have significantly enhanced the quality of this report. The dedication and assistance of field staff at various monitoring locations and during activity data collection are also sincerely acknowledged.

Finally, we extend our appreciation to all departments whose contributions have played a crucial role in the successful execution of this project.

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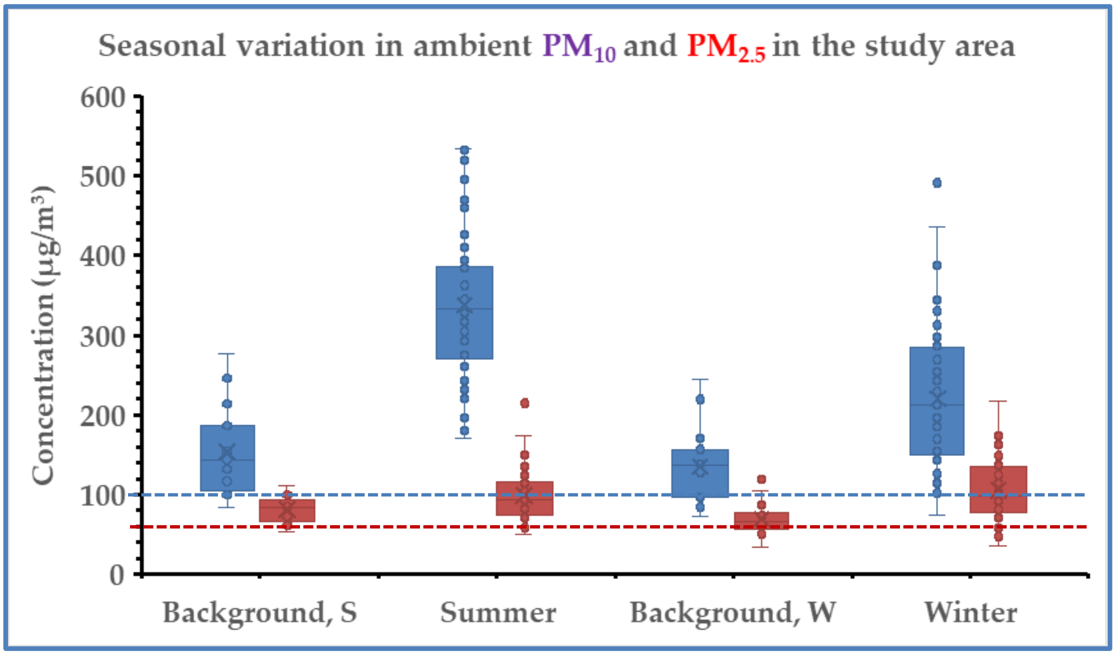
Executive Summary

Air pollution poses significant risks to human health, ecosystems, and economic stability, making it a pressing issue in urban areas, especially in developing nations. While the causes of air pollution vary across cities, understanding its primary sources is critical for devising effective mitigation strategies. Poor air quality directly impacts residents' quality of life and impedes sustainable economic growth. Faridabad, a prominent industrial and residential hub in Haryana, has been classified as a non-attainment city under the National Clean Air Program (NCAP) due to its inability to meet prescribed air quality standards. Addressing the city's air quality challenges requires a comprehensive understanding of pollution sources, their contributions, and the development of targeted interventions to safeguard public health and foster long-term urban sustainability.

The study, conducted by TERI for the Municipal Corporation of Faridabad, aims to address the critical issue of ambient air pollution in Faridabad city. The study focuses on understanding the spatial and temporal variations in particulate matter (PM_{10} and $PM_{2.5}$), identifying their sources, and quantifying their contributions to aid the development of targeted air quality management strategies. Faridabad, a rapidly growing urban and industrial hub in Haryana and part of the National Capital Region (NCR) faces significant air quality challenges due to its diverse sources of pollution, including industries, vehicular traffic, construction activities, and biomass burning. The study domain covers the Faridabad Municipal Corporation area, including residential, industrial, commercial, and green zones and transportation corridors. The city experiences marked seasonal variations in climate, further influencing pollution dynamics.

The primary sources of ambient air pollution in Faridabad city were analyzed through two distinct simulation methods. One approach, the receptor model, used marker pollutants to identify various pollution sources at a specific location. The other approach, the dispersion model, relied on a source emissions inventory, meteorological data, landscape characteristics, and other factors to estimate the ambient concentration of air pollutants at a specific site. To ensure accuracy, the simulated ambient pollutant levels from both methods were validated against actual measurements taken on the ground. Once the ambient concentrations were verified, a source sensitivity analysis was conducted. The source distribution results from both simulation approaches were statistically validated, allowing the dispersion model to project future air quality based on different emissions control strategies. The study then explored various emissions control options under alternate scenarios to estimate future ambient air quality. Based on these projections, policy recommendations were made to help achieve the desired air quality outcomes in Faridabad under various scenarios.

Ambient air quality monitoring was conducted at five strategically selected locations, representing industrial, residential, commercial, kerbside, and background areas, during the summer of 2022 and the winter of 2023. The 15-days continuous monitoring at each location captured PM_{10} and $PM_{2.5}$ concentrations, which were analyzed for chemical composition. Results showed that average PM_{10} concentrations across different locations within the city ranged between 305–364 $\mu g/m^3$ during summer and 176–321 $\mu g/m^3$ during winter, far exceeding the NAAQS standard of 100 $\mu g/m^3$. $PM_{2.5}$ levels ranged from 86–111 $\mu g/m^3$ in summer and 89–126 $\mu g/m^3$ in winter, well above the 60 $\mu g/m^3$ standard. Seasonal trends revealed that PM_{10} levels were higher during summer due to dust-dominated sources, while winter $PM_{2.5}$ levels were elevated due to combustion-related activities and secondary particle formation. The lower $PM_{2.5}$-to-PM_{10} ratio indicated a predominance of coarse particulate sources like road and construction dust.

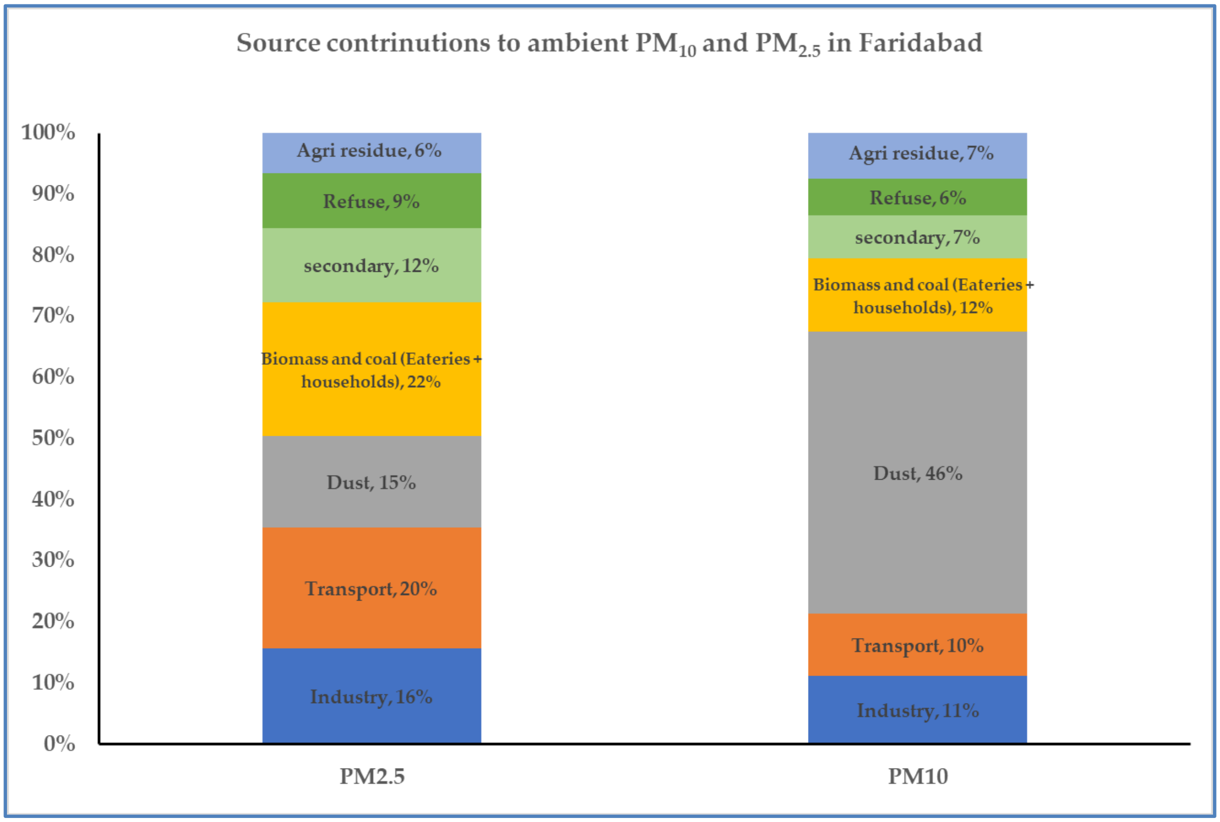


The study involved analyzing ambient particulate matter (PM_{10} and $PM_{2.5}$) deposited on various types of filter media from five different locations within the study area during two separate seasons. The examination focused on identifying the chemical components, including ions, elements, and carbon fractions, in PM_{10} and $PM_{2.5}$ samples collected over 24-hour periods at various locations. Chemical characterization of particulate matter revealed a complex mix of crustal elements, carbon fractions, and ions. Elements such as silicon, aluminum, and iron were dominant in PM_{10}, indicating contributions from soil and construction activities. Sulphur and secondary ions, including sulphates and nitrates, were prevalent in $PM_{2.5}$, highlighting the impact of combustion sources like vehicles and industries. Sulphate was more prevalent in summer and nitrate was more prevalent in winter. Carbon fractions, particularly organic carbon (OC), were significant in both PM_{10} and $PM_{2.5}$, with industrial and vehicular emissions being major contributors.

The mass distribution of various chemical species in atmospheric $PM_{2.5}$ and PM_{10} samples was analyzed using a receptor model to estimate source contributions based on marker species specific to each source. The receptor modeling results from different locations in the study area indicate slight variations in source contributions to ambient PM_{10} and $PM_{2.5}$ concentrations across sites and seasons.

While multiple sectors contribute to ambient PM_{10} and $PM_{2.5}$ levels, dust originating from construction, road dust resuspension, and soil dust are the predominant contributors to PM_{10} concentrations in the Faridabad area. These are followed by biomass and coal combustion, industrial emissions, and transport. Contributions from secondary particulates, agricultural residue burning, and refuse burning to ambient PM_{10} show minimal variation.

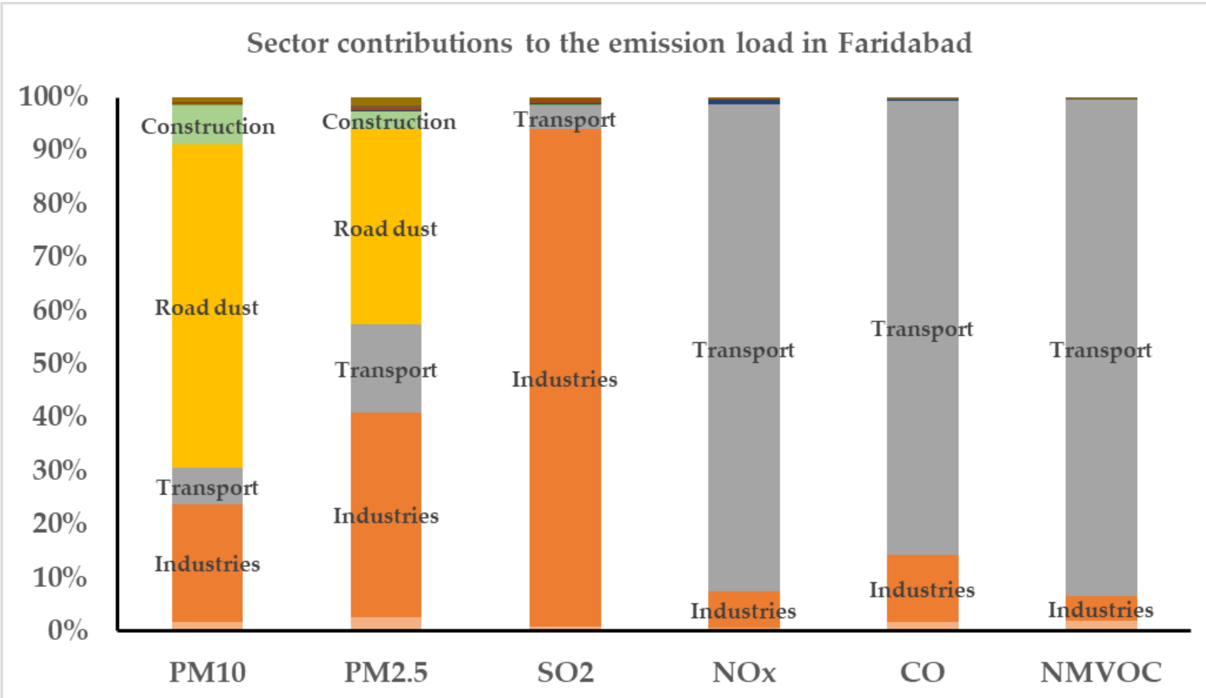
For $PM_{2.5}$, biomass, and coal combustion in residences and hotels/roadside eateries, along with the transport sector, emerge as the primary contributors, with notable contributions from industrial emissions, dust, secondary particulates, and refuse burning. Combustion-related sources dominate $PM_{2.5}$ concentrations, whereas dust-related sources are more significant contributors to PM_{10}. Additionally, transport, secondary particulates, and biomass burning exhibit a higher share in the $PM_{2.5}$ fraction, emphasizing their dominance in finer particle ranges.



The ambient PM concentrations in the Faridabad study area also exhibit seasonal variability. Regardless of particle size fraction, dust contributions are higher during the summer, likely due to transboundary inputs. In contrast, secondary particulates have a greater contribution in winter, driven by enhanced nitrate formation facilitated by lower temperatures and increased humidity levels.

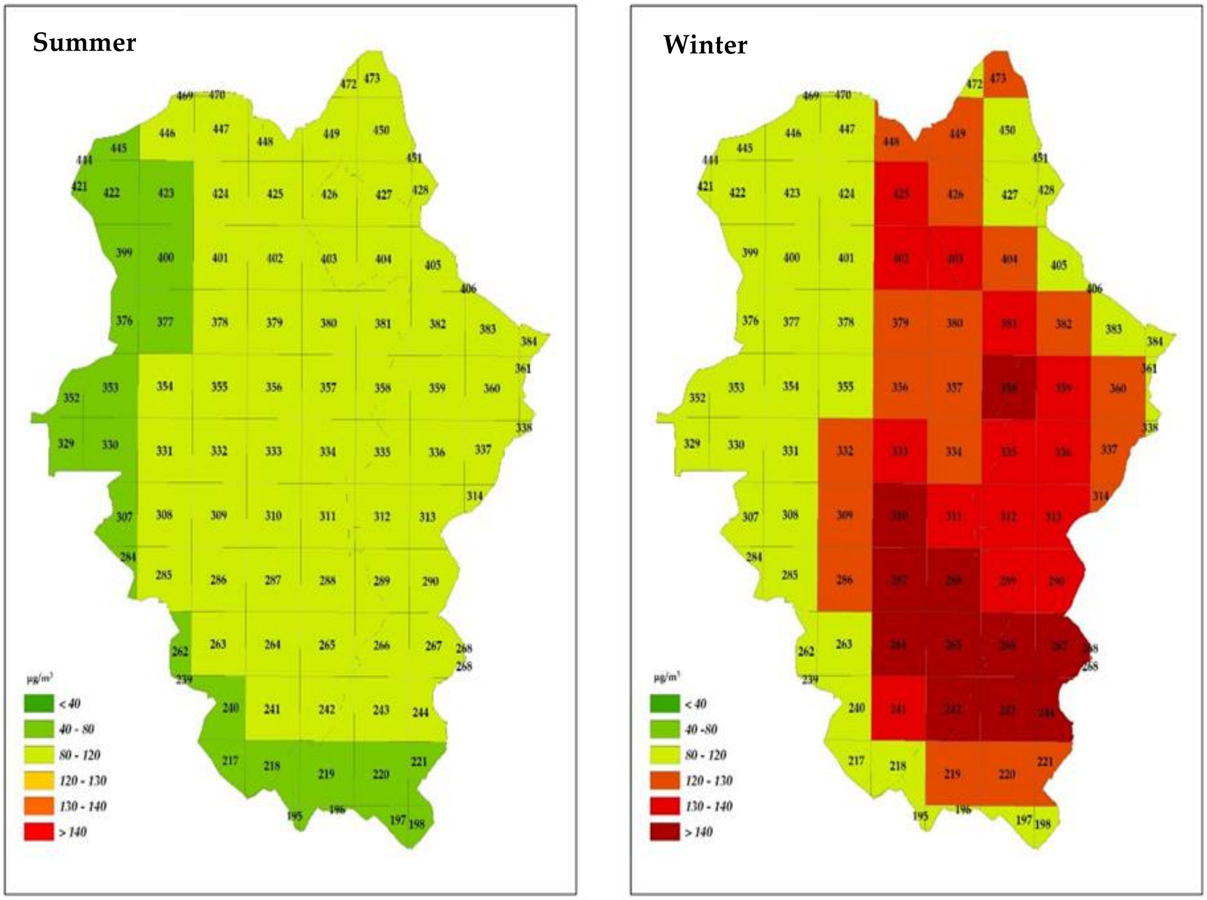
Apart from the measurement of the ambient concentrations of different air pollutants, the development of a comprehensive emission inventory is an important step in the air quality management process. 2 × 2 km^2 grid-wise emission inventory of air pollutants like PM_{10}, $PM_{2.5}$, NO_x, SO_2, CO, and NMVOCs was prepared for different point, line, and area sources for the year 2023 in the study area through ground-level surveys and the acquisition of activity data from various departments. In the study area, different sectors were identified as contributors to atmospheric PM_{10}, $PM_{2.5}$, SO_2, NO_x, CO, and NMVOC emissions, with estimates of approximately 130 t/day, 51 t/day, 43 t/day, 155 t/day, 1099 t/day, and 474 t/day, respectively.

In Faridabad city, more than three-quarters of the total PM_{10} emissions (68% from dust and 22% from industries) and $PM_{2.5}$ emissions (38% from industries and 40% from dust) are attributed to dust (road dust and construction) and industrial activities. Industries account for 93% of SO_2 emissions in the study area, while vehicles contribute 91% of NOx emissions, with industries contributing an additional 7% to total NOx emissions. Furthermore, the transport and industrial sectors are the primary contributors to the total CO and NMVOC emissions in the study area. Overall, the estimated emissions in Faridabad indicate that road dust, industries, and transport are the primary contributors to air pollution in the city.



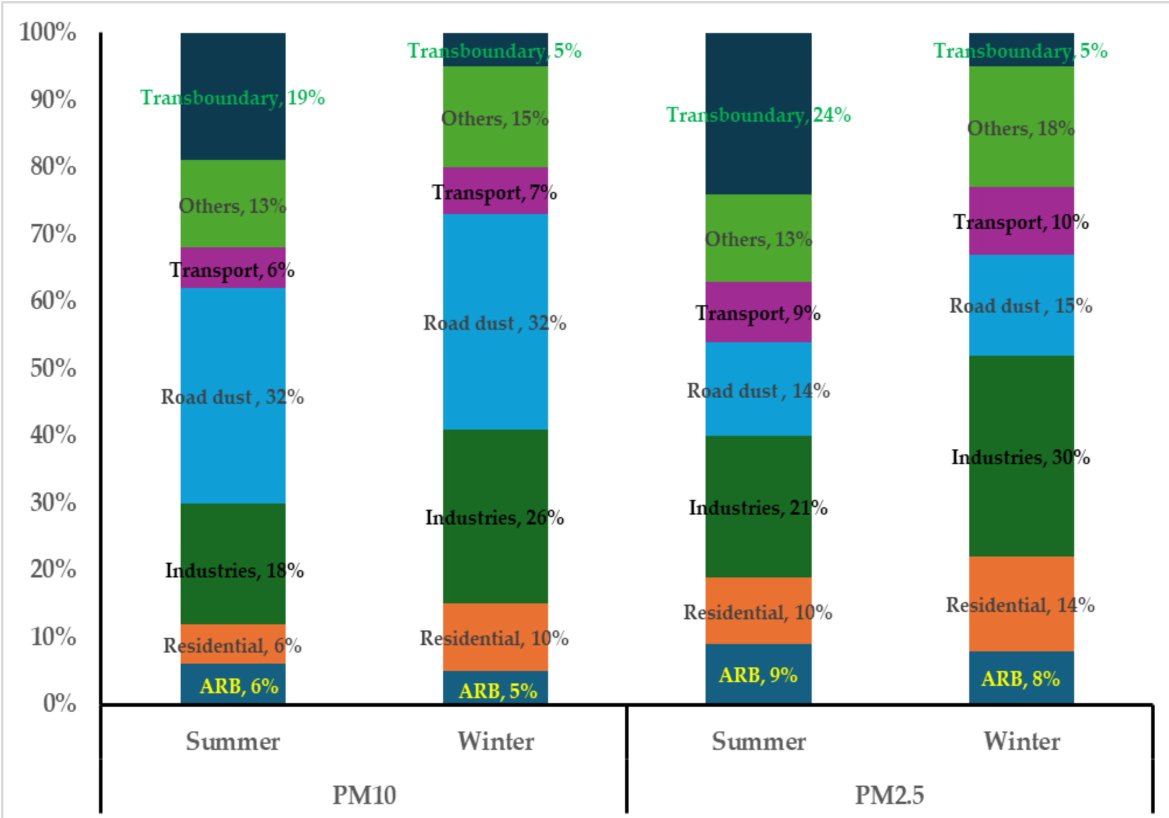
The estimated sector-specific gridded emissions of the Faridabad study area, a 36 Km × 36 Km gridded national level emission inventory, and an international emission database from ECLIPSE together with global air quality product CAM-Chem from the National Centre for Atmospheric Research, USA, were used in WRF-CMAQ to simulate the atmospheric PM_{10} and $PM_{2.5}$ concentrations at 2 Km × 2 Km grid level at Faridabad Municipal Corporation area. Simulated datasets were validated with the measured datasets during the summer and winter at four selected locations within the Faridabad Municipal Corporation area. The average ratio of simulated to observed values averaged for both seasons was quite satisfactory and the annual ratio between simulated and observed $PM_{2.5}$ concentrations was 1.07.

The concentrations on monitored days in January to February 2023 were averaged to estimate winter season concentration, while concentrations in April and May 2022 were averaged for summer seasons to develop spatial $PM_{2.5}$ concentration maps. The simulated atmospheric $PM_{2.5}$ concentrations were significantly higher in winter compared to summer, with widespread exceedances of 120–140 µg/m³ observed across the central, northern, and eastern regions. During summer, $PM_{2.5}$ levels are comparatively lower, and a few localized hotspots in the southern and central grids show moderate elevations. The annual average concentration distribution revealed persistently high $PM_{2.5}$ levels in central, northern, eastern, and southern grids, underscoring the influence of year-round emission sources such as transportation, industrial activities, and biomass burning.



Road dust emerged out to be the major contributor to the ambient PM_{10} concentrations for both summer and winter seasons with an equal share in both seasons (32%), whereas industries (including brick kilns and power plants) were the major contributor to the $PM_{2.5}$ concentrations with its share (21% in summer and 30% in winter) comparatively higher in winter indicating a notable seasonal variation. The other significant contributors of PM were 'others' (including crematoria, hotels/eateries/restaurants, DG sets, and waste burning), residential cooking, transport, agricultural residue burning, and transboundary sources (sources outside the national boundary).

In Faridabad city, local sources account for 54% and 51% of ambient PM_{10} concentrations in summer and winter, respectively. Similarly, local sources contribute about 40% and 39% to ambient $PM_{2.5}$ concentrations in summer and winter, respectively. The remaining contributions are from sources outside the city boundary including those of international origin. This highlights the importance of cross-border pollution control measures to improve air quality.



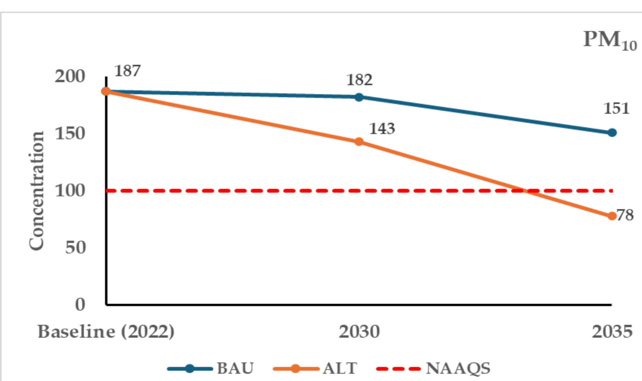
**ARB indicates agricultural residue burning*

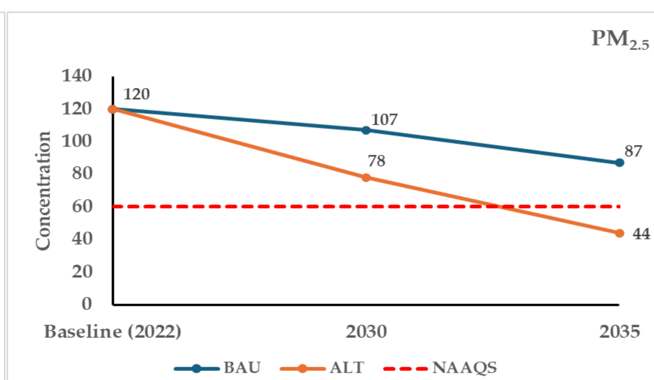
Atmospheric PM_{10} and $PM_{2.5}$ concentrations were simulated with the estimated annual emissions of PM_{10}, $PM_{2.5}$, SO_2, NOx, and CO from different sectors for the years 2030 and 2035 following the implemented policies and growth rate of different sectors in the region. Simulated atmospheric concentrations of PM_{10} and $PM_{2.5}$ suggest an increase (57% and 65% for PM_{10} and $PM_{2.5}$ respectively) over the present concentration in the future following the presently implemented air quality management actions (BAU scenario) at the Faridabad Municipal Corporation area. Future projections indicate that industry, road dust re-suspension, and the transport sector will be the primary sources of atmospheric particulate matter in the coming years.

A scenario analysis has been carried out by considering different interventions and the reduction potential of each of the interventions was estimated. Based on these findings an alternate air quality management plan (ALT scenario) particularly for the major contributing sectors in the study area was developed to meet the NAAQS of PM_{10} and $PM_{2.5}$ at the Faridabad Municipal Corporation area in the future.

Sector	Intervention selected for formulation of ALT scenario
Transport	Fasten the Scrappage Policy and remove older vehicles from the road
	Electrification of Vehicular Fleet in Faridabad
	Congestion management
	Improved inspection and maintenance system
Residential	Cleaner Cooking technology
Industry	Conversion of solid fuel to natural gas.
DG sets	60% reduction in the use of DG sets in 2030 and 90% in 2035.
Construction	Use of Blue sheet and green mesh covering during construction activities.
	Use of Blue sheet and green mesh to cover construction material
	Use of precast construction practices
Restaurants	By the year 2030, the consumption of fuel wood and coal will be eliminated.
Road dust	Reduction in road dust, which includes- • Regular road Sweep through mechanical road sweepers of all the roads throughout the year. • Water Spraying on the road. • Proper Greenbelts beside roads. • Construction of pucca pavement along the roads (Wall-to-wall paving for all types of roads). • Tree plantation along the roads
Waste Burning	100% reduction in open waste burning by 2030.

The analysis of interventions under the ALT scenario suggests that winter season PM_{10} and $PM_{2.5}$ concentrations will decline by 48% and 43%, respectively, compared to the Business-As-Usual (BAU) scenario by 2035. The implementation of these measures is expected to achieve compliance with the National Ambient Air Quality Standards (NAAQS) for daily PM_{10} and $PM_{2.5}$ concentrations by the same year.





Introduction

Background

The composition of the atmosphere is changing due to persistent emissions from human activities, leading to critical environmental challenges such as air pollution. Pollutant concentrations in the atmosphere have significantly exceeded their natural background levels, causing adverse impacts on both human health and the environment over the past few decades. In India, air pollution has emerged as a major concern, with over 70% of cities exceeding the prescribed PM_{10} concentration standards.

The primary sources of air pollution include the consumption of fossil fuels, rising transportation demands, traffic congestion, and the seasonal burning of agricultural crop residues. Additionally, population growth, rapid industrial expansion, and urbanization have significantly exacerbated the issue. As a result, $PM_{2.5}$ and PM_{10} levels in most Indian cities are alarmingly higher than their prescribed standards.

The Ministry of Environment, Forest and Climate Change (MOEF&CC) launched the National Clean Air Program (NCAP) in 2019 to address air pollution across the country, setting an interim target of reducing PM levels by 20-30% by 2024, using 2017 as the base year. Under the NCAP, 132 cities were identified as non-attainment cities, including Faridabad. To better understand atmospheric chemistry, air quality, and their impact on human health, accurate data on spatially and temporally distributed emissions is crucial. Estimating the impacts of pollution sources and identifying their contributions to prevailing pollution levels is essential for developing effective air quality management strategies. An emission inventory serves as a critical tool for identifying pollutant sources and quantifying their pollution loads within a specific area and timeframe. Source apportionment, which involves estimating the contribution of various sources to ambient pollution levels at a given receptor location, is a powerful technique for enhancing air quality management plans. Receptor and dispersion modeling techniques link emissions from sources to their effects on ambient pollutant concentrations, providing valuable insights for devising effective strategies and actionable plans to improve air quality.

The proposed study aims to conduct comprehensive air quality monitoring, identify emission sources, develop an emission inventory, and perform a source apportionment analysis for the city of Faridabad in Haryana.

Study Objectives

- To profile Ground Level Concentration (GLC) of air pollutants in different parts of the city along with air shed of the city including background, residential, commercial/mixed areas and source-specific “hot spots” viz. kerbside/roadside, industrial zones, etc.
- To select “Emission Factors” (EF) for different categories of vehicles with due consideration to variations in fuel quality, technology, size and vintage of sources, control systems, etc.
- To select appropriate emission factors for other non-vehicular sources viz. industries, industrial & domestic fuel combustions, roadside dust, construction activities, generator sets, etc.

- To prepare inventory for different air pollutants, their emission rates & pollution loads from various sources along with spatial and temporal distribution in the city including its air shed covered under this project.
- To profile the source emission characteristics of different possible sources
- To conduct source apportionment studies for PM_{10} and $PM_{2.5}$ and prioritize the source categories for evolving cost-effective air pollution mitigation strategies/plans.

Need for the study

- Particulate Matter (PM) is one of the most critical pollutants affecting air quality in Faridabad.
- Multiple sources contribute to PM emissions, including transportation, construction activities, domestic fuel use, agricultural residue burning, dust, and energy consumption in industries.
- Developing an effective air quality management plan requires identifying the major pollutant sources. Additionally, understanding growth patterns across different sectors is essential to devise control strategies that account for future development and emissions.

Study Approach

The study focuses on air quality monitoring, development of emission inventory, dispersion and receptor modelling and strengthening of the air quality management plan for Faridabad city. The overall approach is shown in Figure 1.

This study conducted a source apportionment analysis of $PM_{2.5}$ and PM_{10} concentrations in the Faridabad study area using two modeling-based approaches. The first approach involved monitoring and chemically characterizing $PM_{2.5}$ and PM_{10} samples. These chemically speciated samples, combined with source profiles, were analyzed using a receptor model to determine source contributions.

The second approach utilized a source-wise emission inventory, meteorological inputs, and boundary conditions, which were integrated into a dispersion model to simulate $PM_{2.5}$ and PM_{10} concentrations. The modeled concentrations were validated against actual observations. The validated model was then employed to assess source sensitivity, derive source contributions, and project future $PM_{2.5}$ and PM_{10} concentrations. Additionally, various intervention scenarios were tested to evaluate their potential to reduce pollutant concentrations in the coming years.

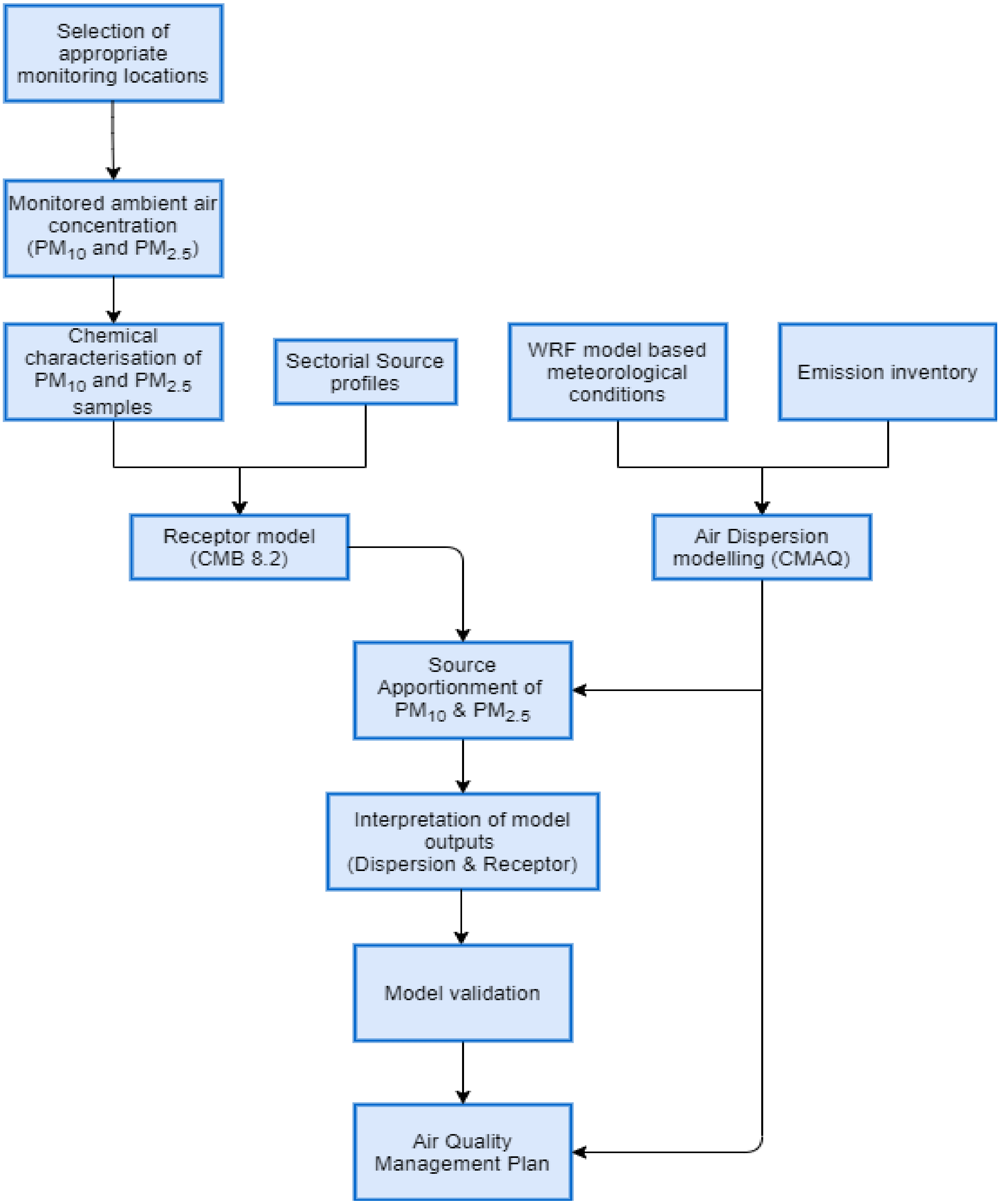


Figure 1: Overall approach of source apportionment study in Faridabad

Methodology

Ambient Air Quality Monitoring

The primary objective of ambient air quality (AAQ) monitoring was to establish baseline data for PM_{10} and $PM_{2.5}$ concentrations and identify the key sources contributing to them. Monitoring was conducted across two critical seasons, summer and winter, to account for seasonal variations. A comprehensive air quality monitoring exercise was undertaken during the summer months of April 2022 and the winter months of February 2023. This effort covered 5 representative locations, selected based on the prevailing wind direction, different land-use patterns, and activity sources, including kerbside, industrial, commercial, and residential sites, following the established monitoring protocol. Additionally, one background/reference location was selected outside the Faridabad city boundary in the upwind direction to assess the background concentration.

Monitoring protocol

The following monitoring protocol was followed:

- No. of sites: A total of 4 AAQ monitoring locations were identified in the Municipal Corporation Limit of Faridabad representing industrial, residential, commercial and kerbside locations.
- A background location was selected outside the city boundary in the upwind direction. Seasons: The AAQ monitoring was carried out in the summer and winter seasons.
- Parameters: A 24-hour manual air-quality sampling was carried out for PM_{10} and $PM_{2.5}$. Samplers: $PM_{10}/PM_{2.5}$ samplers (Envirotech make APM 550M) with an average flow rate of 16.67 litres per minute, were used to collect PM_{10} and $PM_{2.5}$ samples on Teflon and Quartz filter paper
- Filter paper used for sampling
- ✓ Teflon filter paper of 2 µm PTFE 47 mm filter with PP Ring supported (Whatman make) which further analysed for different metals and ions
- ✓ Quartz filter paper: Tissue quartz 2500QAT-UP (Pall Make) which was further analysed for carbon content
- No. of days: Monitoring was carried out for about 15 continuous days at each location in each season for the parameters PM_{10} and $PM_{2.5}$.
- Monitoring exercise was carried out simultaneously at all the selected five locations in each season for two seasons.
- The methods followed are strictly following the guidelines laid down by the Central Pollution Control Board (CPCB) and Bureau of Indian Standards (BIS).
- Summer season ambient air quality monitoring exercise was carried out during the month of April 2022 for all the selected five locations whereas winter season monitoring was carried out during the month of February 2023.

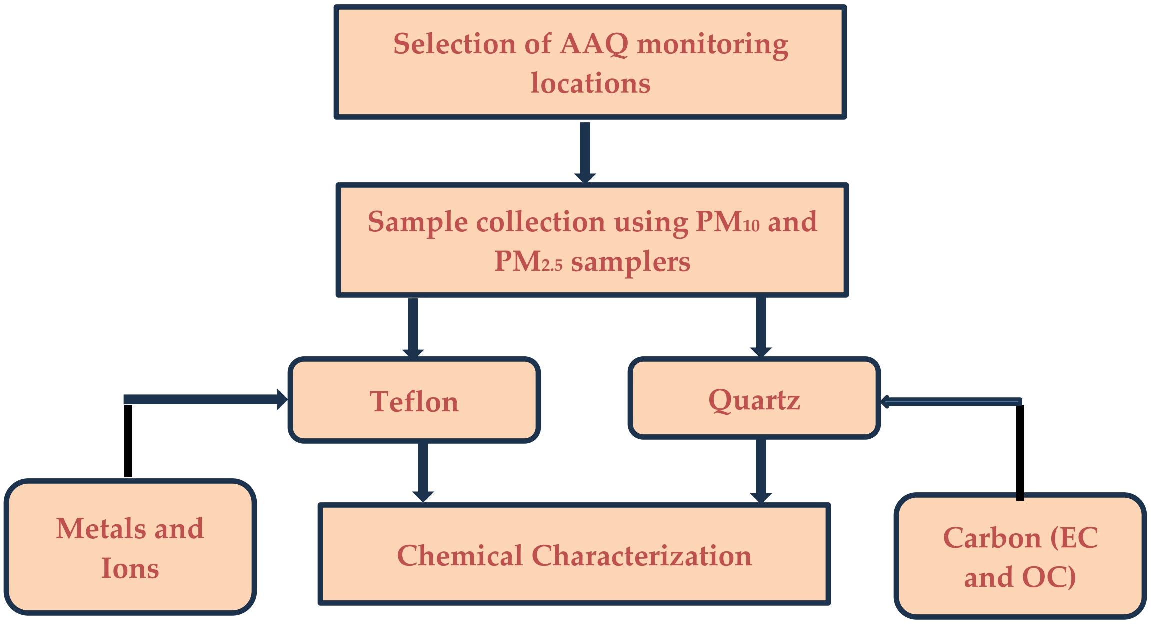


Figure 2: Protocol for ambient PM_{10} and $PM_{2.5}$ sample collection

Chemical Characterization of PM samples

The chemical speciation analysis of PM samples collected on different filter papers were categorized into three main groups: elements, ions, and carbon fractions. This analysis is crucial for identifying pollutant sources in Faridabad. The different metals, ions and carbon analysed are shown in Table 1.

Table 1: Chemical characterisation of PM samples

Component	Required filter matrix	Analytical method
PM_{10}/$PM_{2.5}$	**Teflon**	Sampled using PM samplers and analyzed gravimetrically
Elements (Na, Mg, Al, Si, P, S, Cl, Ca, Br, V, Mn, Fe, Co, Ni, Cu, Zn, As, Ti, Ga, Rb, Y, Zr, Pd, Ag, In, Sn, La Se, Sr, Mo, Cr, Cd, Sb, Ba, Hg, and Pb)	**Teflon filter**	ED-XRF
Ions (F^-, Cl^-, Br^-, NO_2^-, NO_3^-, SO_4^{-2}, K^+, NH_4^+, Na^+, Ca^{++}, Mg^{++})	**Teflon filter**	Ion chromatography with conductivity detector
Carbon Analysis (Organic carbon and elemental carbon)	Quartz filter	TOR method

Sector Specific emission inventory approach

The overall methodology followed for development of sector specific emission inventory of Faridabad study area is depicted in Figure 3.

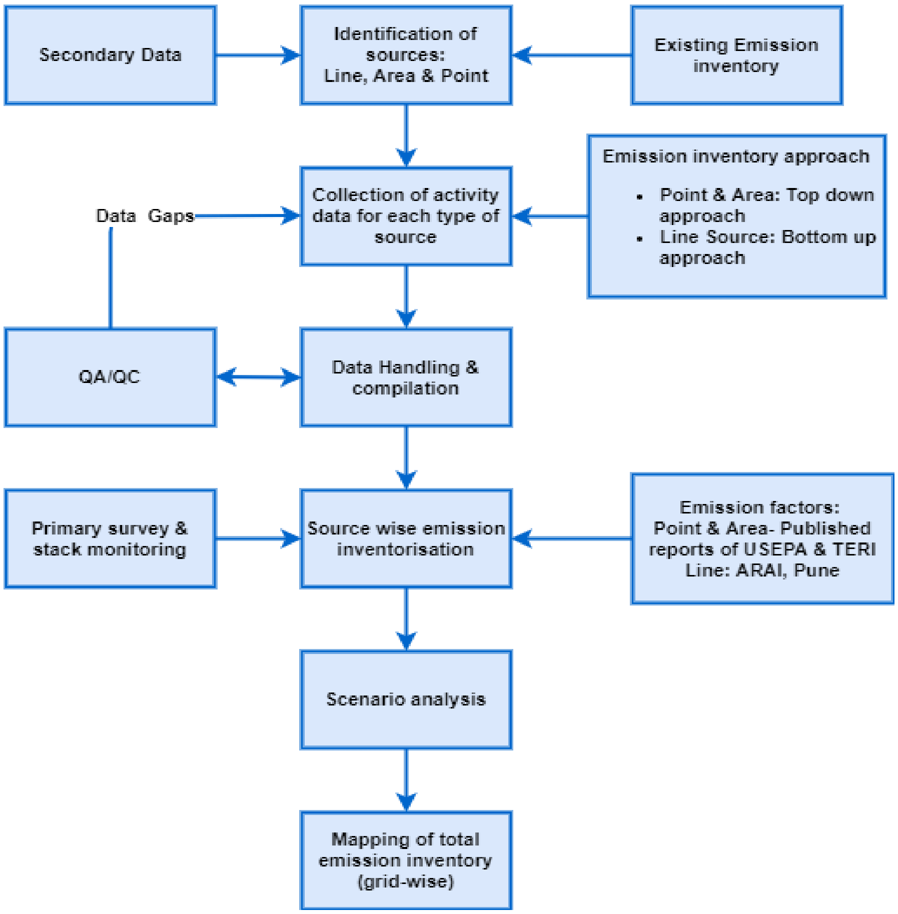


Figure 3: Overall approach for emission Inventorization of Faridabad

A comprehensive list of all significant potential sources of air pollution in Faridabad was compiled based on reconnaissance survey and discussion with officials from HSPCB and MCF, and a high-resolution (2x2 km^2) emission inventory for various pollutants was developed using the emission factors approach. A thorough literature review was conducted to compile a database of emission factors for different sources, with indigenously generated emission factors utilized wherever possible.

In addition to PM, inventories for SO_2, NO_x, carbon monoxide (CO), and non-methane volatile organic compounds (NMVOCs) were also developed to account for the formation of secondary particulates. These emission inventories were prepared for the base year 2023 and spatially allocated over the study area, divided into 2x2 km^2 grids.

The major sectors which have been covered in the analysis were 1) Residential, 2) Transport – tailpipe, 3) Construction, 4) Industries, 5) brick kilns, 6) Road dust, 7) Diesel generators, 8) Refuse burning, 9) Crematoria, 10) Restaurants-hotels, etc.

Activity data for various sectors was collected from multiple government and other reliable sources for the year 2023. Additionally, primary surveys were conducted to gather data on vehicle usage patterns through traffic counts and parking lot observations, as well as information on DG set types and usage, road silt loadings, fuel usage pattern in hotels/restaurants/open eat outs, and other relevant factors. For vehicular sources, a newly developed database of emission factors from the Automotive Research Association of India (ARAI) was used.

Receptor Modelling and Source Apportionment

Receptor models rely on the principle of mass conservation which is used to identify and apportion sources of airborne particulate matter in the atmosphere. The chemical mass balance (CMB) model is one of several receptor models that have been used to identify air pollution sources in a specific region. The model is based on an effective-variance least squares method (EVLS) as it uses the chemical and physical characteristics of gases and particles measured at the source and receptor to both identify and quantity source contributions to pollutants measured at the receptor location.

The overall approach to conducting source apportionment of PM_{10} and $PM_{2.5}$ is presented in Figure 4. During ambient air quality monitoring, the samples collected on the filter paper are analysed for different ions, elements, and carbon content for the characterization of the PM_{10} and $PM_{2.5}$ samples. Characterized sample data and uncertainty estimates are used as inputs to the receptor model CMB. A source profile characteristic (already available and developed in various other studies) is another input to the model. Sample-wise CMB model runs are performed to arrive at the source apportionment of PM_{10} and $PM_{2.5}$ for various area categories in the city.

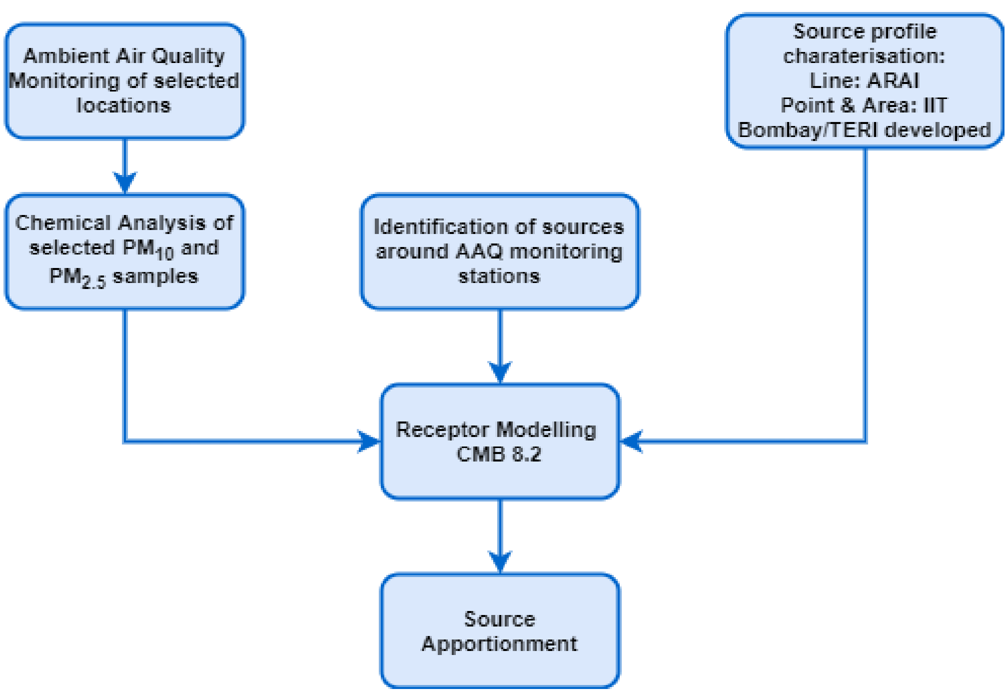


Figure 4: Approach to source apportionment using receptor model

Dispersion modelling and Source Apportionment

Emissions estimated in the previous step were fed into an air quality dispersion model - CMAQ for assessing the air quality concentrations under different scenarios. Meteorological data generated using the WRF model simulations is validated with actual observations.

Based on the emissions inventory developed in the current study and the 3-D meteorological data, ambient concentrations were predicted for the pollutants PM_{10} and $PM_{2.5}$. These simulated concentration values were compared against the measured ambient air quality values to validate the model. Once the model is suitably validated, sensitivities of different sources have been estimated by removing 20% of emissions of each source one by one from the emissions inventory in the CMAQ model. The model was first run at the national level (India scale) using the national-level emission inventory of TERI. The output of India-scale simulations was fed into the CMAQ model to account for the long-range transport of pollution from outside of Faridabad. The overall approach adopted for the dispersion model using WRF-CMAQ is shown in Figure 5.

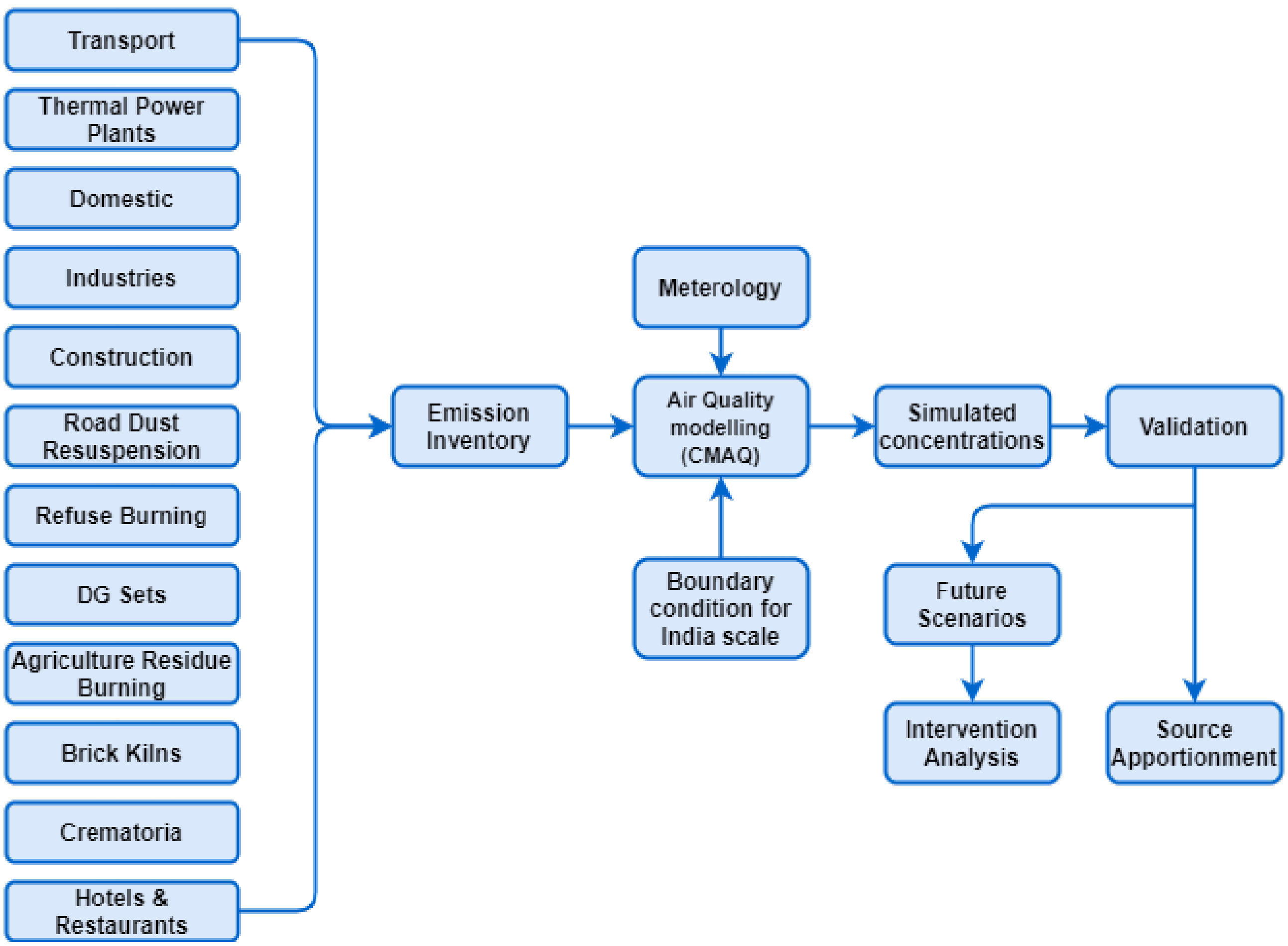


Figure 5: Approach to source apportionment using Dispersion model

Study Domain – Faridabad City

Faridabad is a prominent city in Haryana, India, and is part of the National Capital Region (NCR). It lies adjacent to Delhi, making it a key area for both industrial and residential development. The government of India included it in the second Smart Cities Mission list on 24 May 2016. Faridabad has been described as the eighth fastest-growing city in the world and the third in India by the City Mayors Foundation survey (https://cpcb.nic.in/Actionplan/Faridabad.pdf). Faridabad is a major industrial hub of Haryana. In 2018, Faridabad was considered by the World Health Organization as the world's second most polluted city. In 2020, Faridabad ranked 10th in the Swachh Survekshan Survey's top ten dirtiest cities in India in 2020. Faridabad has been selected as one of the hundred Indian cities to be developed as a smart city under the Government of India's flagship Smart Cities Mission by the Ministry of Urban Development

The Faridabad Municipal Corporation (FMC) area is situated within the geographical coordinates of approximately 28°10'50" to 28°29'04" North latitude and 77°06'49" to 77°33'23" East longitude. This region encompasses the urban expanse of Faridabad city, including various residential, commercial, industrial zones and green spaces. It is known for its thriving industrial sector, with industries like automobiles, textiles, chemicals, and manufacturing contributing significantly to the local economy. The transportation network in Faridabad is heavily influenced by its proximity to Delhi, with a high traffic volume and a growing demand for road infrastructure. The Yamuna River forms the eastern boundary of this area, contributing to its diverse topography and influencing local environmental conditions.

The land-use land-cover pattern of Faridabad is depicted in Figure 6. It demonstrates a diverse range of land uses. The city includes significant areas designated for residential, industrial, and commercial purposes, with substantial zones marked for public utilities, transportation, and open spaces like parks and sports grounds. The eastern boundary is dominated by the Yamuna River and its adjoining natural conservation zones, which include green belts and eco-sensitive areas. The western and southern regions feature a mix of agricultural lands and urban developments, with controlled areas outside the municipal corporation limits planned for future growth. Specific sectors within the city are allocated for recreational spaces, water bodies, and institutional zones, reflecting an integrated approach to urban planning. The inclusion of green belts along major roads and the Eastern Peripheral Expressway highlights efforts to balance development with ecological preservation

Faridabad stands first in its population in the state of Haryana. The Faridabad city had a population of 1,809,733 (as per census 2011) and resides in 35 wards (*Faridabad, municipal office*) later the number of wards has been increased to 40. However, the total number of wards under the Municipal Corporation of Faridabad has gone up from 40 to 46 after the recent ward delimitation process, comprising of total FIDR population of 1,805,660 (as per the data provided by the Municipal Corporation of Faridabad. The total geographical area of Faridabad is 208 square kilometers.

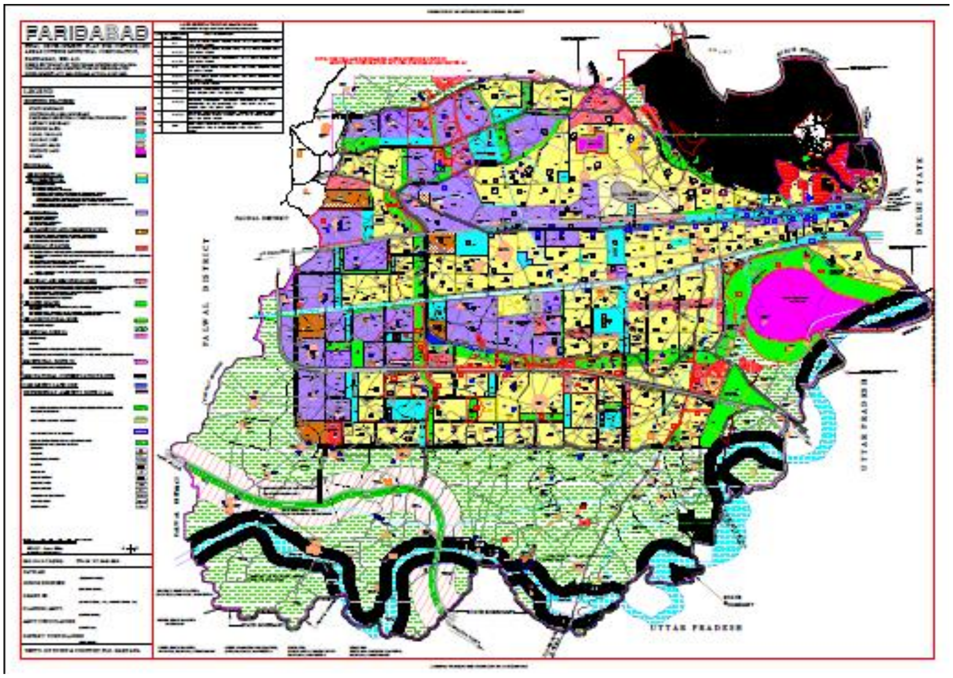
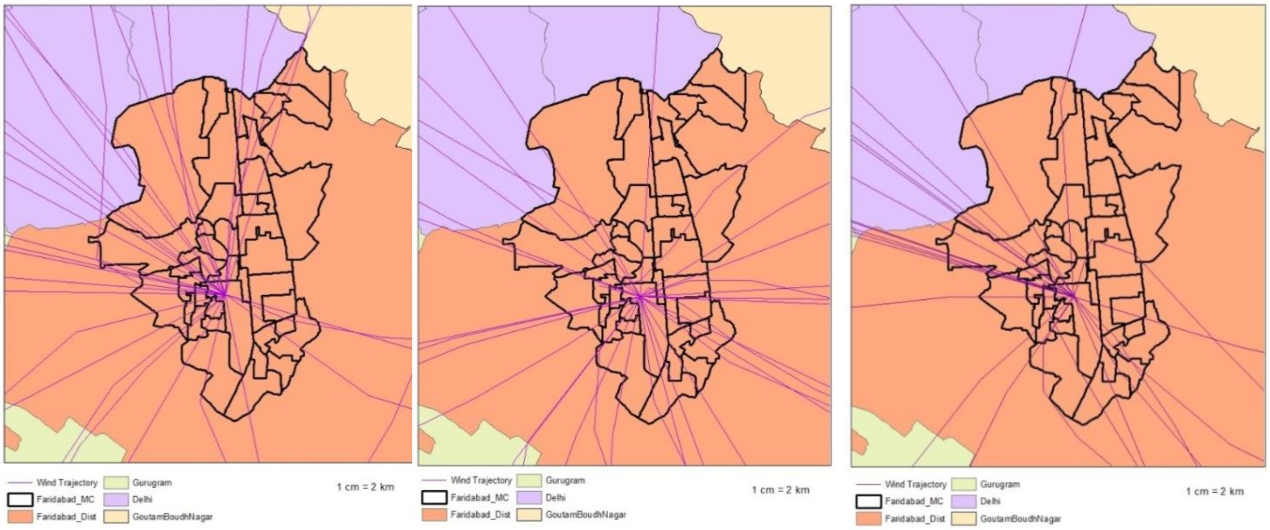


Figure 6: Map of Faridabad depicting the land use land cover pattern

Air Parcel Back Trajectory Analysis of the study area

Faridabad experiences a borderline climate between hot semi-arid and dry-winter humid subtropical. The city has three typical Indian seasons. The "hot" or pre-monsoon season lasts from late March to late June, marked by intense heat and arid conditions that later turn humid. The monsoon season occurs from late June to late September, bringing heavy rainfall and high humidity. The winter season spans from November to February, characterized by mild to cool temperatures and dry weather.

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (www.ready.arl.noaa.gov) was used to calculate 72 hr air mass back trajectories ending at the Faridabad study area during summer and winter seasons. The air mass flow pattern of the summer season (April to June) shows that the majority of air parcel back trajectory originates from the north-west and some from the south-east of the Faridabad district. Similarly, the air mass flow pattern of winter season (December to February) shows that majority of air parcel back trajectories is coming via north-west and some from southeast of Faridabad district.



April **May** **June**

Figure 7: Air Parcel Back Trajectory Analysis at Faridabad during summer

December **January** **February**

Figure 8: Air Parcel Back Trajectory Analysis at Faridabad during winter

Ward wise population

As per census data of 2011, the city has a total population of 1,809,733 and an estimated population of 2,063,096 for the year 2021. The ward-wise distribution of the population of Faridabad based on the data provided by the Municipal Corporation of Faridabad is shown in Figure 9.

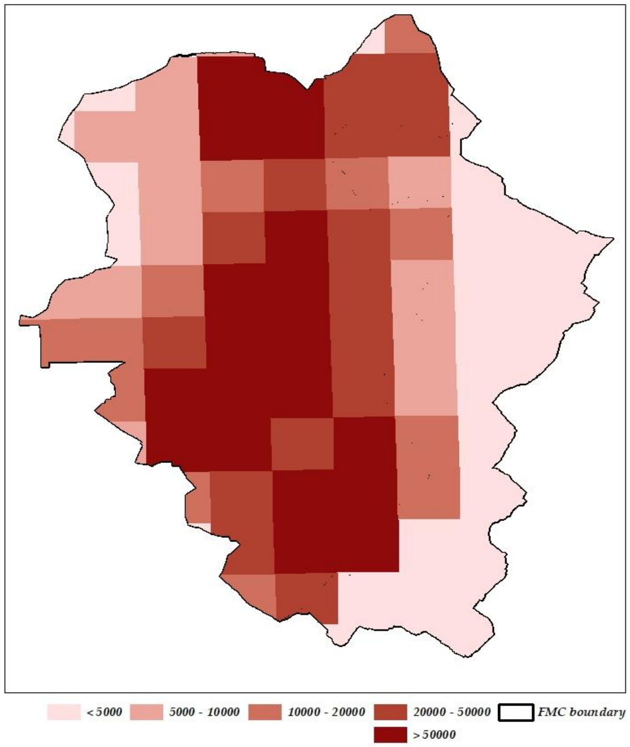


Figure 9: Distribution of the population in the Municipal Corporation Area of Faridabad

The map (Figure 9) illustrates the population density distribution within the Faridabad Municipal Corporation (FMC) boundary. The central and southern regions show the highest density (>50,000), marked in deep red, indicating urban centers. Medium-density areas (10,000–50,000) surround these zones, while the peripheries, shown in lighter shades, have lower densities (<10,000), likely representing rural or less-developed regions. This gradient reflects typical urban patterns with denser populations in core areas, gradually decreasing toward the outskirts.

Ambient Air Quality

Faridabad is one of Hayana's biggest urban agglomerations and is known for its poor air quality. The AAQ monitoring in Faridabad is conducted under the National Air Monitoring Programme (NAMP) and is managed by the Haryana State Pollution Control Board. Under the NAMP, there are currently 2 manual monitoring and 5 continuous air quality monitoring stations in Faridabad. The first CAQMS was installed before 2015 followed by another one in 2019. Due to the poor air quality index in 2020, 3 more CAQMS were installed (https://cpcb.nic.in/Actionplan/Faridabad.pdf). Figure 10 shows the results of air-quality monitoring carried out in Faridabad city under the NAMP for the period from year 2013 to 2015 and from 2021 to 2023. The manual monitoring data is not available for the period from 2016 to 2020. Figure 10 clearly shows that in all observed years, PM_{10} and $PM_{2.5}$ levels consistently exceeded the annual average standards. The annual average levels of PM_{10} were 2 to 5 times higher than the standard, while $PM_{2.5}$ levels were approximately 2 times higher, indicating persistent air quality violations.

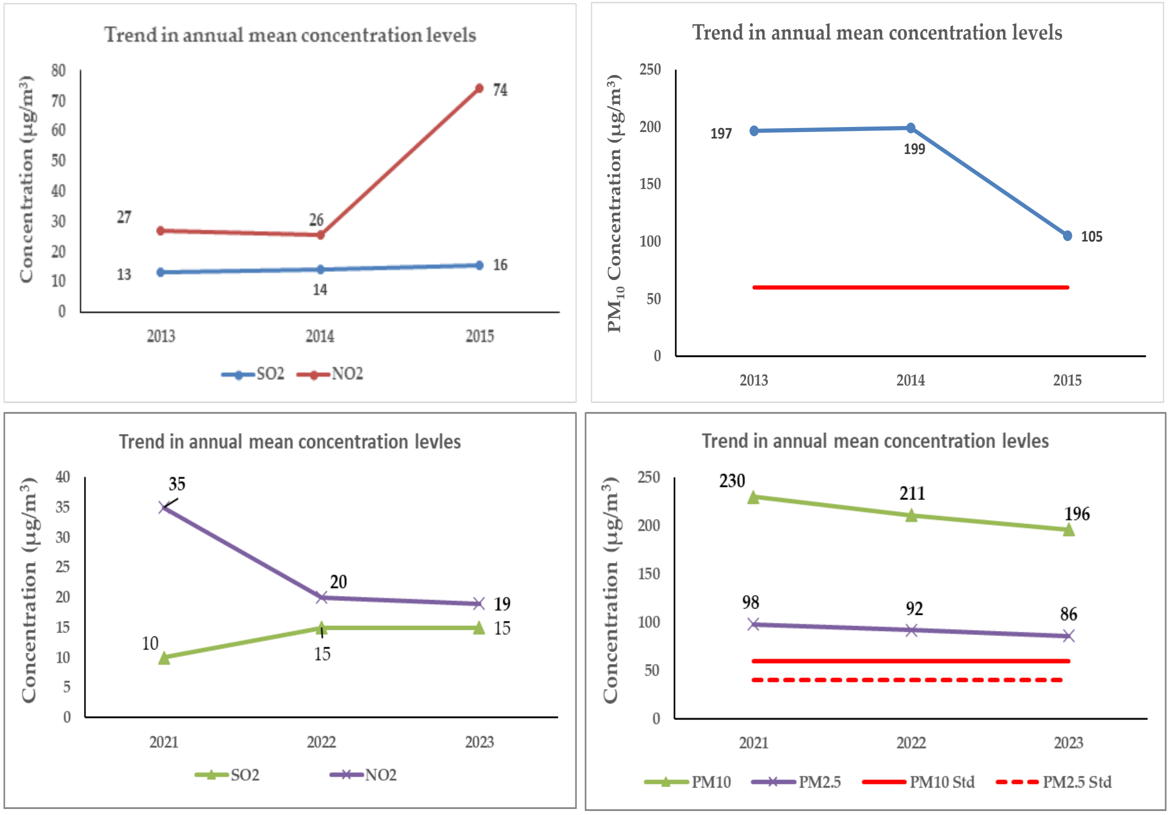


Figure 10: Trend in ambient PM_{10}, $PM_{2.5}$, SO_2 and NO_2 in Faridabad

However, the annual average levels of SO_2 and NO_2 were within the prescribed standards.

The source apportionment study conducted by TERI and ARAI in 2018 identified the major contributors to deteriorating air quality in Faridabad. For PM_{10}, the largest source was re-suspended dust (33%), followed by industries (26%), transport (17%), and biomass (15%). Similarly, for $PM_{2.5}$, the key sources were dust (31%), industry (23%), transport (20%), and biomass (17%). While the study provided valuable insights into source contributions, gaps remained regarding secondary particulates, geographical contributions (local, regional, and international), and sub-sectoral details. Despite several measures taken by central and state governments to mitigate air pollution in Delhi-NCR, including Faridabad, pollutant levels remain alarmingly high. This underscores the need for further investigation into sources and their locations, coupled with proactive planning to draft strategies that account for future sectoral growth.

Report Structure

- This report is structured into seven comprehensive chapters, each addressing a critical aspect of air quality assessment and management in Faridabad.
- The **Introduction** chapter lays the foundation for the study.
- **Chapter 2** presents the air quality status at five monitoring sites across two seasons—summer and winter.
- **Chapter 3** examines the spatio-temporal variations in the chemical composition of PM_{10} and $PM_{2.5}$ across these sites.
- **Chapter 4** focuses on source apportionment of PM_{10} and $PM_{2.5}$ using advanced receptor modeling techniques.
- **Chapter 5** develops a high-resolution emission inventory (2×2 km^2) by integrating primary survey data and secondary sources to quantify emissions from various sectors.
- **Chapter 6** applies dispersion modeling to assess the contribution of different pollution sources under current conditions.
- **Chapter 7** evaluates emission control strategies, analyzing their effectiveness in reducing pollution levels. It also includes city-wide dispersion modeling for select future scenarios, prioritization of management measures, and the formulation of alternative strategies to achieve ambient air quality standards.

Ambient air quality monitoring

Periodic and continuous monitoring of air pollutants is crucial for evaluating the effectiveness of control measures and identifying atmospheric concentration levels, especially given the worsening air quality. Such monitoring helps determine pollutant levels in relation to ambient air quality standards. Ambient air quality monitoring involves measuring pollutant concentrations in a specific region and provides an overview of air quality trends through systematic sampling, monitoring, and analysis. The primary objective of air quality monitoring was to generate baseline data for ambient PM_{10} and $PM_{2.5}$ concentrations, assess air quality levels, capture pollutant loads in the environment, and identify the major contributing sources.

In Faridabad city, air quality monitoring was conducted in accordance with the guidelines provided by the Central Pollution Control Board (CPCB) and the Bureau of Indian Standards (BIS). Five representative locations were selected in consultation with officials from the Faridabad Municipal Corporation. These locations were chosen based on land use, land cover patterns, and prevailing wind directions to ensure comprehensive citywide coverage. The selected sites included one industrial area, one residential area, one commercial area, one kerbside location, and one background site. The selected monitoring locations are shown in Figure 11 and Table 2 represents the details of each of the locations.

Ambient air quality monitoring was carried out over 15 consecutive days at each location during both summer and winter seasons to capture seasonal variations in $PM_{2.5}$ and PM_{10} levels. The gravimetric method was employed to measure PM_{10} and $PM_{2.5}$ concentrations, with both quartz and Teflon filters used for subsequent analysis of metals, ions, and carbon content. Monitoring was conducted using Envirotech APM 550 fine particulate samplers equipped with mass flowrate controllers (MCF) to measure $PM_{2.5}$ and PM_{10} concentrations in the ambient air

Summer season monitoring was carried out during the period from 6th - 20th April 2022 and winter season monitoring was carried out during the period 7th - 21st February 2023.

Table 2: Locations of ambient air quality monitoring station and their details

Location No.	Location type	Location name	Co-ordinates
1	Residential	IP Colony	28⁰4′53.41″ N; 77°03′18.37"E
2	Industrial	Sector-25, Ballabhgarh	28°19'49.41"N 77°18'36.85"E
3	Kerbside	Municipal Corporation of Faridabad office, Ajronda Chowk	28°23'31.07"N 77°18'3.68"E
4	Commercial	Joint Commissioner, Municipal corporation, Old Faridabad	28°25'6.86"N 77°19'1.20"E
5	Background	Parson mandir	28°25'24.79"N 77°16'12.94"E

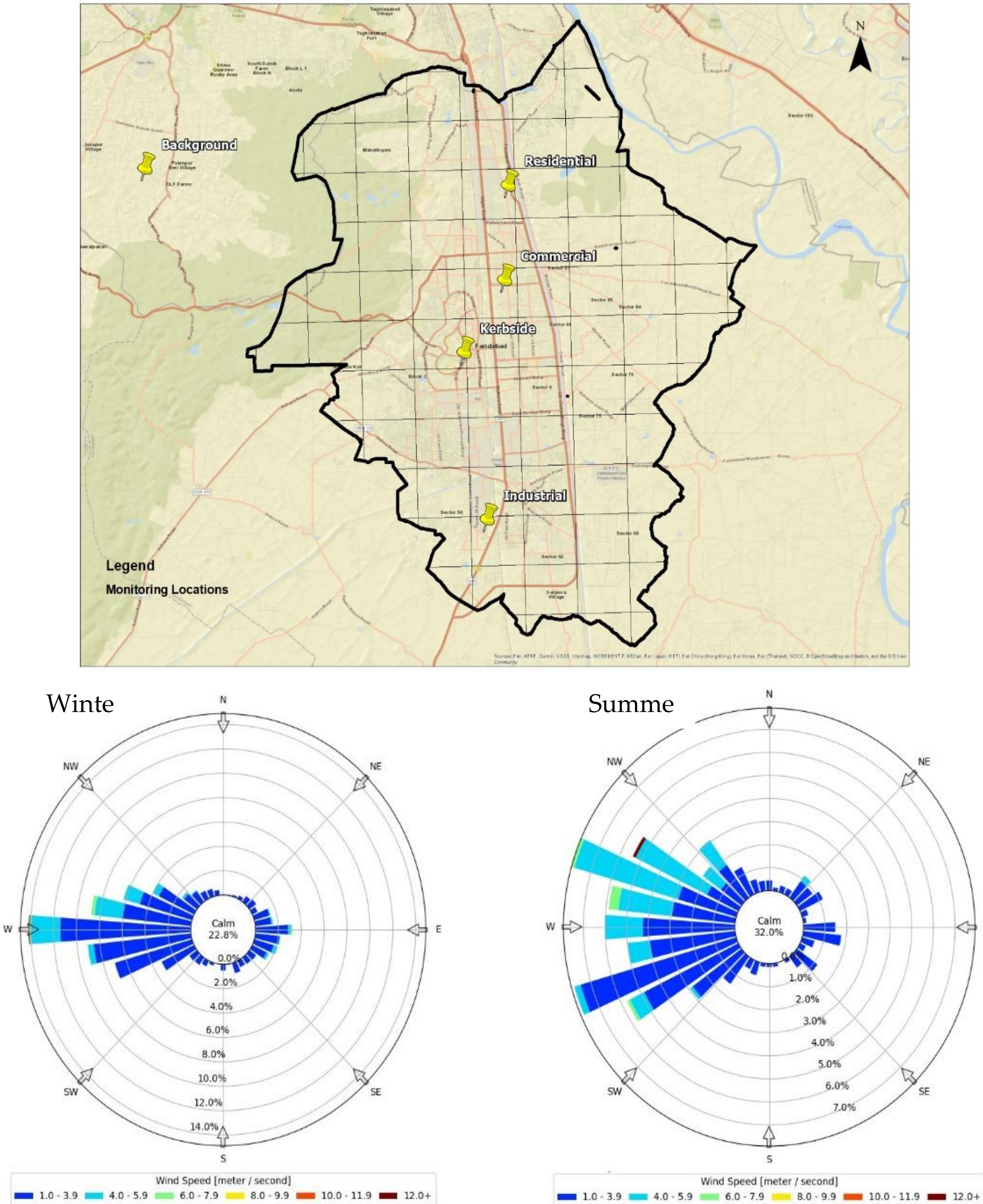


Figure 11: Graphical representation of air quality monitoring station in the study area along with the wind-rose pattern for both summer and winter

Results and discussions

Overview of Ambient Air Quality

- The overall result illustrates that irrespective of all the monitoring locations, the ambient PM_{10} and $PM_{2.5}$ concentrations for both seasons were recorded higher than the 24-hour average NAAQS standard of 100 µg/m³ and 60 µg/m³ for PM_{10} and $PM_{2.5}$ pollutants respectively.
- The average PM_{10} levels across different monitored locations within the Municipal boundary of Faridabad varied between 176 -321 µg/m³ and 305 – 364 µg/m³ respectively for the winter and summer seasons
- The average $PM_{2.5}$ concentrations across different monitoring locations within the city boundary during summer and winter varied between 86 -111 µg/m³ and 89 - 126 µg/m³ respectively.
- Irrespective of the seasons, the background location shows the lowest average PM_{10} and $PM_{2.5}$ concentrations.
- The average PM_{10} levels at different locations within the city during the summer season were higher than in the winter season indicating the prevalence of dusty sources (within and outside the city boundary) in the study area during the summer season
- The average $PM_{2.5}$ concentrations across different locations during the winter season were higher than the corresponding levels during the summer, indicating the prevalence of local combustion sources and elevated secondary particulate matter formation.
- A lower ratio of $PM_{2.5}$ to PM_{10} in the study area for both seasons indicates the predominance of dusty sources in the study area.

The observations from monitoring conducted at five locations in Faridabad for PM_{10} and $PM_{2.5}$, including the daily variations in PM_{10} and $PM_{2.5}$ for both seasons at all five locations, as well as the seasonal variations in PM_{10} and $PM_{2.5}$ across different locations, are presented in the following section.

Industrial location

Probable sources around the location

- Industrial activities
- Heavy traffic
- Movement of heavy vehicles
- Unpaved and poorly managed roads
- Open eat outs, dhabas, etc,
- DG Sets
- Open burning
- Brick kilns

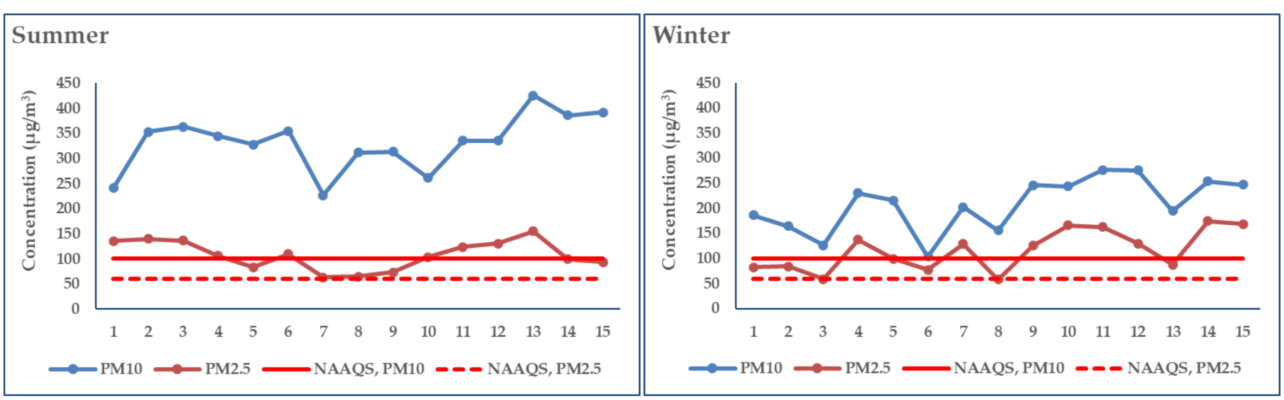


Figure 12: Variation in 24-hourly concentrations of PM_{10} and $PM_{2.5}$ at the Industrial location

Key Observations

- ✓ The daily average concentrations of PM_{10} during the summer season ranged from 227 to 426 µg/m³ (mean: 332±55 µg/m³) and $PM_{2.5}$ levels varied between 64 and 155 µg/m³ (mean: 108±29 µg/m³)
- ✓ PM_{10} concentrations ranged from 104 to 276 µg/m³ (mean: 208±53 µg/m³), and $PM_{2.5}$ levels varied between 58 and 174 µg/m³ (mean: 116±41 µg/m³) during winter
- ✓ Regardless of the season, the daily average concentrations of both PM_{10} and $PM_{2.5}$ consistently exceeded the National Ambient Air Quality Standards (NAAQS) of 100 µg/m³ and 60 µg/m³
- ✓ The average PM_{10} concentrations during the summer and winter seasons were 3.3 and 2.1 times higher than the National Ambient Air Quality Standard (NAAQS), respectively. Similarly, the average $PM_{2.5}$ levels were 1.8 times the standard in summer and 1.9 times in winter

Residential location

Probable sources around the location

- ➢ Construction activities
- ➢ Open eat outs, dhabas, etc,
- ➢ DG Sets
- ➢ Open burning
- ➢ Seasonal agricultural residue burning
- ➢ Light traffic

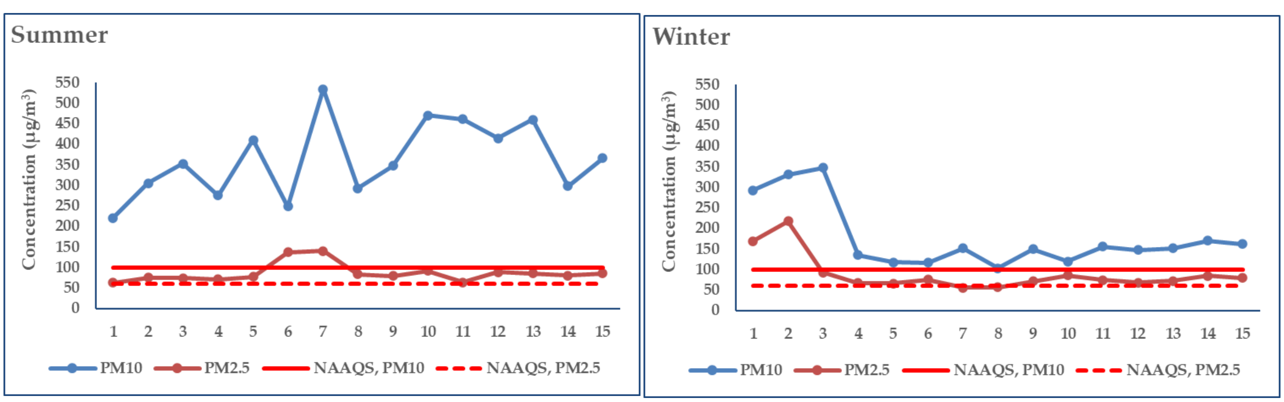


Figure 13: Variation in 24-hourly concentrations of PM_{10} and $PM_{2.5}$ at the Residential location

Key observations

- ✓ The daily average concentrations of PM_{10} during the summer season ranged from 220 to 534 µg/m³ (mean: 364±92 µg/m³) and $PM_{2.5}$ levels varied between 63 and 140 µg/m³ (mean: 86±23 µg/m³)
- ✓ PM_{10} concentrations ranged from 102 to 347 µg/m³ (mean: 176±79 µg/m³), and $PM_{2.5}$ levels varied between 56 and 217 µg/m³ (mean: 89±44 µg/m³) during winter
- ✓ Regardless of the season, the daily average concentrations of both PM_{10} and $PM_{2.5}$ consistently exceeded the National Ambient Air Quality Standards (NAAQS) of 100 µg/m³ and 60 µg/m³
- ✓ The average PM_{10} concentrations during the summer and winter seasons were 3.6 and 1.8 times higher than the National Ambient Air Quality Standard (NAAQS). Similarly, the average $PM_{2.5}$ levels were 1.4 times the standard in summer and 1.5 times in winter
- ✓ The highest mean PM_{10} concentration was observed at this location during the summer season

Commercial location

Probable sources around the location

- Construction activities
- Open eat outs, dhabas, etc,
- Slum area nearby
- Heavy traffic movement
- DG Sets
- Open burning

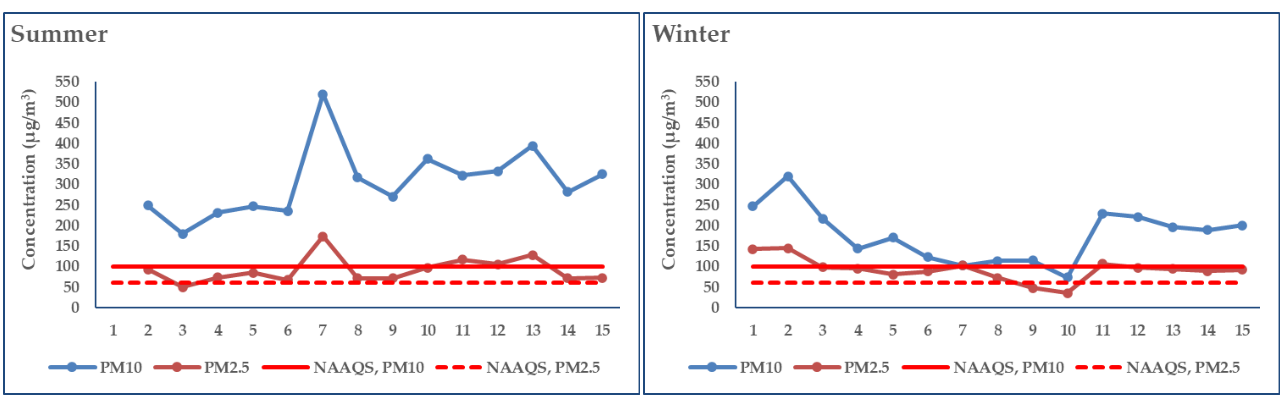


Figure 14: Variation in 24-hourly concentrations of PM_{10} and $PM_{2.5}$ at the Commercial location

Key observations

- ✓ The daily average concentrations of PM_{10} during the summer season ranged from 180 to 520 µg/m³ (mean: 305±85 µg/m³) and $PM_{2.5}$ levels varied between 50 and 174 µg/m³ (mean: 92±32 µg/m³)
- ✓ PM_{10} concentrations ranged from 73 to 321 µg/m³ (mean: 178±66 µg/m³), and $PM_{2.5}$ levels varied between 36 and 145 µg/m³ (mean: 93±29 µg/m³) during winter
- ✓ Regardless of the season, the daily average concentrations of both PM_{10} and $PM_{2.5}$ consistently exceeded (except for a few observations) the National Ambient Air Quality Standards (NAAQS) of 100 µg/m³ and 60 µg/m³
- ✓ The average PM_{10} concentrations during the summer and winter seasons were 3 and 1.8 times higher than the National Ambient Air Quality Standard (NAAQS), respectively. Similarly, the average $PM_{2.5}$ levels were 1.5 times the standard in both summer and winter

Kerbside location

Probable sources around the location

- ➢ Highway, heavy traffic movement
- ➢ Road dust
- ➢ Commercial activities nearby
- ➢ Construction activities
- ➢ Open eat outs, dhabas, etc,
- ➢ Slum area nearby
- ➢ Heavy traffic movement
- ➢ DG Sets
- ➢ Open burning

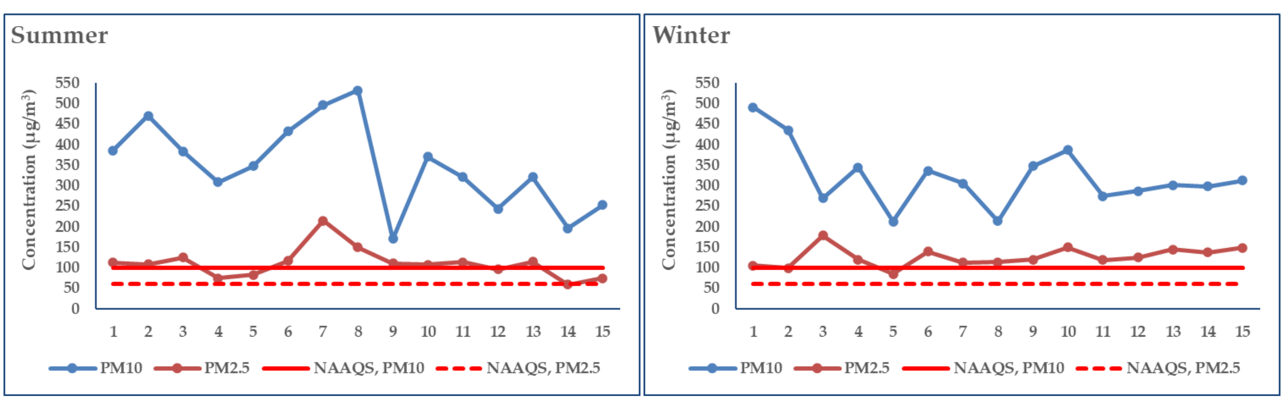


Figure 15: Variation in 24-hourly concentrations of PM_{10} and $PM_{2.5}$ at the kerbside location

Key findings

- ✓ The daily average concentrations of PM_{10} during the summer season ranged from 170 to 532 µg/m³ (mean: 349±106 µg/m³) and $PM_{2.5}$ levels varied between 59 and 215 µg/m³ (mean: 11±37 µg/m³)
- ✓ PM_{10} concentrations ranged from 212 to 491 µg/m³ (mean: 321±75 µg/m³), and $PM_{2.5}$ levels varied between 85 and 179 µg/m³ (mean: 126±23 µg/m³) during winter
- ✓ Regardless of the season, the daily average concentrations of both PM_{10} and $PM_{2.5}$ consistently exceeded the National Ambient Air Quality Standards (NAAQS) of 100 µg/m³ and 60 µg/m³
- ✓ Highest average PM_{10} and $PM_{2.5}$ concentrations were observed at this location during both the summer and winter seasons possibly because of the proximity of this location to heavy traffic road
- ✓ The average PM_{10} concentrations during summer and winter seasons were 3.5 and 3.2 times higher than the National Ambient Air Quality Standard (NAAQS). Similarly, the average $PM_{2.5}$ levels were 1.8 times the standard in summer and 2.1times in winter

Background location

Probable sources around the location

- ➢ Open area
- ➢ Stone crushers and industries in the upwind direction
- ➢ Unpaved roads
- ➢ Light traffic
- ➢ Agricultural activities approximately 2 km from this location
- ➢ DG Sets
- ➢ Temple rituals, including hawan, involve the regular burning of wood and incense
- ➢ Open burning

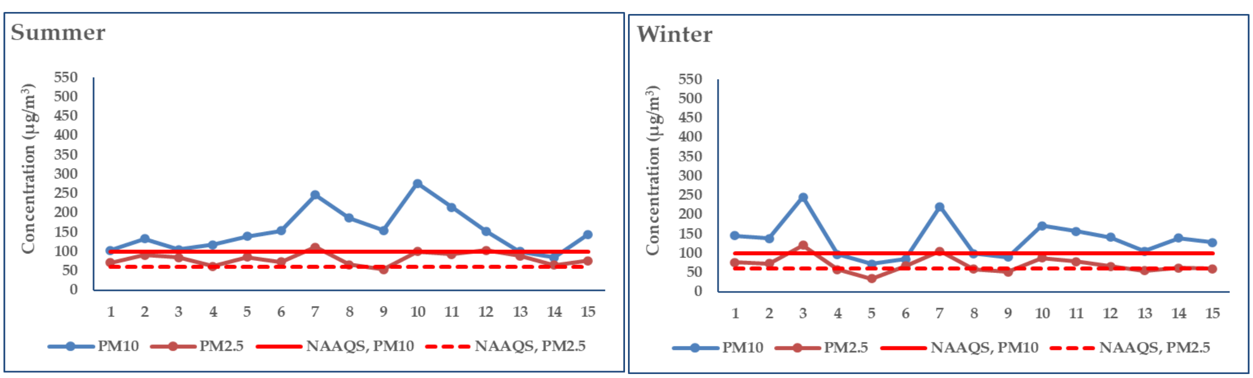


Figure 16: Variation in 24-hourly concentrations of PM_{10} and $PM_{2.5}$ at the background location

Key findings

- ✓ The daily average concentrations of PM_{10} during the summer season ranged from 84 to 276 μg/m³ (mean: 154±55 μg/m³) and $PM_{2.5}$ levels varied between 53 and 111 μg/m³ (mean: 81±17 μg/m³)
- ✓ PM_{10} concentrations ranged from 72 to 245 μg/m³ (mean: 135±49 μg/m³), and $PM_{2.5}$ levels varied between 33 and 120 μg/m³ (mean: 70±22 μg/m³) during winter
- ✓ The daily average concentrations of both PM_{10} and $PM_{2.5}$ consistently exceeded the National Ambient Air Quality Standards (NAAQS) of 100 μg/m³ and 60 μg/m³, respectively, during the summer season, except for one observation each for PM_{10} and $PM_{2.5}$. In contrast, during the winter season, 5 out of 15 observations for PM_{10} and 6 out of 15 observations for $PM_{2.5}$ remained within the permissible limits.
- ✓ Regardless of the season, the fifteen days average PM_{10} and $PM_{2.5}$ levels at this location were the lowest among all five locations
- ✓ The average PM_{10} concentrations during summer and winter seasons were 1.5 and 1.3 times higher than the National Ambient Air Quality Standard (NAAQS). Similarly, the average $PM_{2.5}$ levels were 1.3 times the standard in summer and 1.2 times in winter

Box plots representing the results of ambient air quality monitoring conducted at the five locations for both PM_{10} and $PM_{2.5}$ during the summer and winter seasons are shown in Figures 17 and 18.

$PM_{2.5}$

The measured $PM_{2.5}$ concentration during summer season ranged from 63 to 140 μg/m³ (mean - 86 μg/m³), 64 to 155 μg/m³ (mean - 108 μg/m³), 59 to 215 μg/m³(mean - 111 μg/m³), 50 to 174 μg/m³(mean- 92 μg/m³), 53 to 111 μg/m³(mean - 81μg/m³) at residential, industrial, kerbside, commercial and background locations respectively. Similarly, the measured PM2.5 levels during winter season ranged between 56 and 217 μg/m³ (mean -89 μg/m³), 58 and 177 μg/m³ (mean - 116 μg/m³), 85 and 179 μg/m³(mean - 126 μg/m³), 36 and 145 μg/m³(mean- 93 μg/m³), 33 and 120 μg/m³(mean – 70 μg/m³) at residential, industrial, kerbside, commercial and background locations respectively The highest average $PM_{2.5}$ concentration was recorded at the kerbside location in both the seasons followed by the industrial and commercial locations, whereas, the lowest average $PM_{2.5}$ concentration was observed at the Residential location. The average concentration of $PM_{2.5}$ for all locations has been represented in Figure 17. The average $PM_{2.5}$ concentrations across different monitoring locations within the city boundary during summer and winter seasons varied between 86 -111 μg/m³ and 89 - 126 μg/m³ respectively for summer and winter seasons. It is evident from Figure 17 that in both summer and winter seasons monitoring, the average $PM_{2.5}$ levels exceeded the 24-hour average NAAQS standard of 60μg/m³ for all the locations.

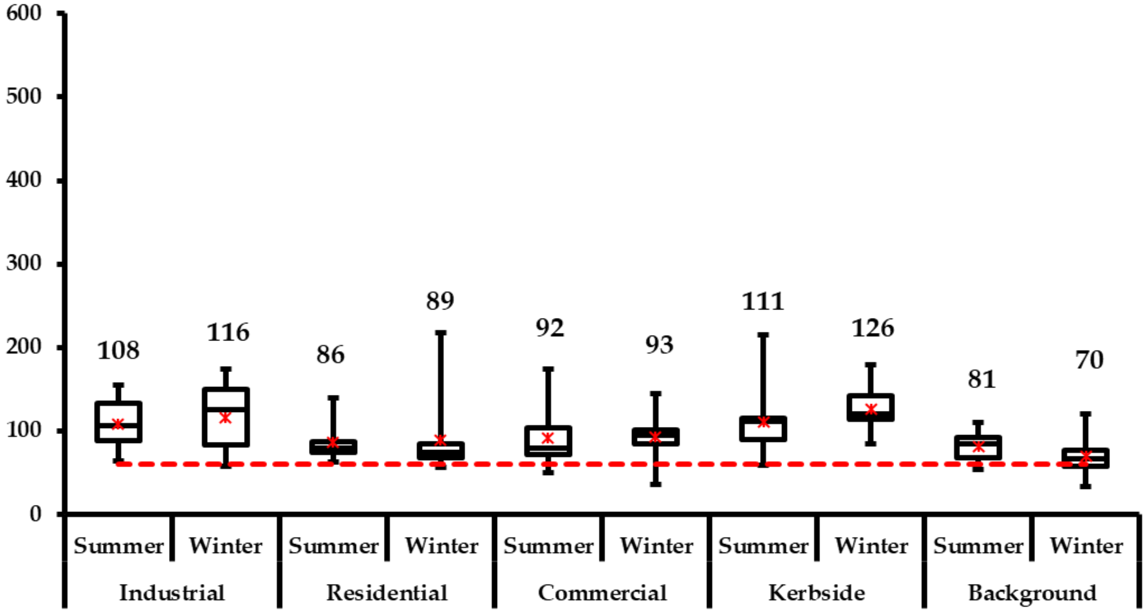


Figure 17: $PM_{2.5}$ concentration at different monitoring locations during the summer and winter seasons

Graphical representation of quantitative dataset using boxplot which splits the data set into quartiles. Box-plot consists of a "box" that goes from the first quartile (Q1) to the third quartile (Q3). The middle line within the box represents the median of the dataset. The first quartile is the median of the lower half of the data set represents 25% of the numbers in the data set lie below Q1 and about 75% lie above Q1 whereas the third quartile, denoted by Q3, is the median of the upper half of the data set represents 75% of the numbers in the data set lie below Q3 and about 25% lie above Q3. The top whisker of the box goes from Q3 to the maximum value in the data set, and the bottom whisker goes from Q1 to the minimum value within the dataset.

Note: Number indicates average monitoring station Concentration value and dashed line indicates NAAQS

PM_{10}

Daily variation in PM_{10} concentrations for different locations for both summer and winter seasons is represented in Figure 18. The measured PM_{10} concentration during summer season varied between 220 to 534 µg/m³ at residential location (Mean - 364 µg/m³), 227 to 426 µg/m³ at industrial location (Mean - 332 µg/m³), 170 to 532 µg/m³ at kerbside location (Mean 349 µg/m³), 180 to 520 µg/m³ (Mean - 305 µg/m³) at commercial location and 84 to 276 µg/m³ (Mean - 154 µg/m³) at background location. Corresponding measured PM_{10} levels at different locations during the winter season ranged between 102 to 347 µg/m³ at residential location (Mean - 176 µg/m³), 104 to 276 µg/m³ at industrial location (Mean - 208 µg/m³), 212 to 491 µg/m³ at kerbside location (Mean 321 µg/m³), 73 to 321 µg/m³ (Mean - 178 µg/m³) at commercial location and 72 to 245 µg/m³ (Mean - 135 µg/m³) at background location. Figure 18 illustrates that the mean PM_{10} levels during both summer and winter seasons exceeded the 24-hour average NAAQS standard of 100 µg/m³ at all monitored locations. The average PM_{10} levels across different monitored locations within the Municipal boundary of Faridabad varied between 176 -321 µg/m³ and 305 – 364 µg/m³ respectively for the summer and winter seasons.

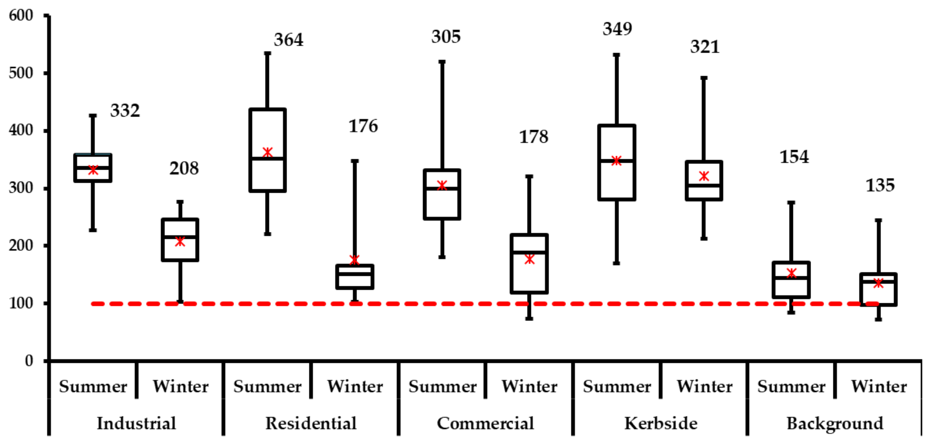


Figure 18: PM_{10} concentration at different monitoring locations during the summer and winter seasons

Graphical representation of quantitative dataset using boxplot which splits the data set into quartiles. Box-plot consists of a "box" that goes from the first quartile (Q1) to the third quartile (Q3). The middle line within the box represents the median of the dataset. The first quartile is the median of the lower half of the data set represents 25% of the numbers in the data set lie below Q1 and about 75% lie above Q1 whereas the third quartile, denoted by Q3, is the median of the upper half of the data set represents 75% of the numbers in the data set lie below Q3 and about 25% lie above Q3. The top whisker of the box goes from Q3 to the maximum value in the data set, and the bottom whisker goes from Q1 to the minimum value within the dataset.

Note: Number indicates average monitoring station Concentration value and dashed line indicates NAAQS

As represented in Figure 18, the highest average concentration during the summer season is observed in residential (364 µg/m³) followed by kerbside location (349 µg/m³). Also, the lowest average concentration is recorded at the background location (154 µg/m³), whereas the highest average PM_{10} levels during the winter season are recorded at the kerbside location (321 µg/m³), followed by the industrial location (208 µg/m³). Just like the summer season, the lowest average PM_{10} level is observed at the background location (135 µg/m³).

Figure 19 represents the seasonal average of all the locations for PM_{10} and $PM_{2.5}$ respectively for both summer and winter.

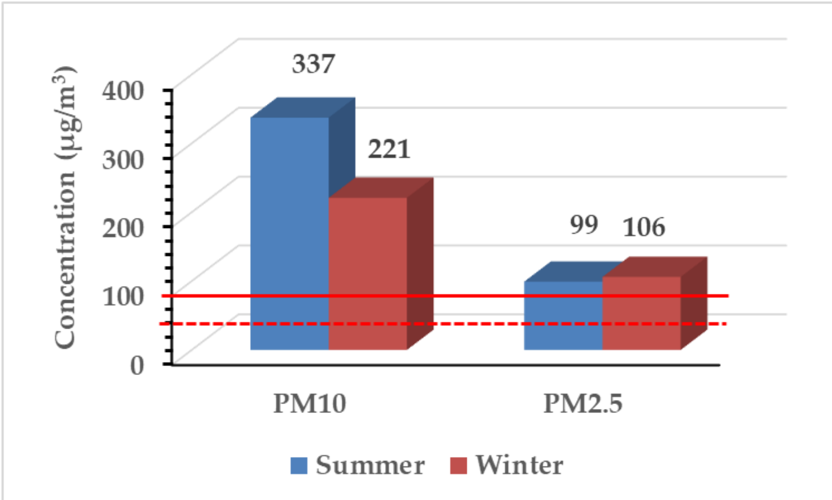


Figure 19: Seasonal variation in PM_{10} and $PM_{2.5}$ within the Faridabad Municipal Corporation area

Note: The Red line indicates the NAAQS for $PM_{10,}$ and the Dotted Red line represents the corresponding value for $PM_{2.5}$.

The seasonal averages of all locations within the Municipal Corporation area of Faridabad indicate that the average levels of both PM_{10} and $PM_{2.5}$ during both summer and winter seasons exceeded their respective standards. For PM_{10}, the seasonal average was higher in summer compared to winter, which is an unusual scenario, whereas for $PM_{2.5}$ as expected, the seasonal average was higher in winter than in summer.

The observed trend of higher PM_{10} levels in summer and higher $PM_{2.5}$ levels in winter can be attributed to meteorological conditions, source contributions, and seasonal activities. Winter conditions, such as temperature inversions and higher humidity, trap pollutants near the surface and promote secondary aerosol formation, leading to elevated $PM_{2.5}$ levels. Additionally, PM_{10} is dominated by coarse particles from road dust and construction which are local in nature and are more prevalent in summer, whereas $PM_{2.5}$ primarily arises from combustion sources, such as vehicular emissions and biomass burning, which intensify in winter due to heating demands

The ratio of $PM_{2.5}/PM_{10}$ varied from 0.24 to 0.53 across all the monitoring sites during the summer season whereas the ratio was in the range of 0.39 to 0.55 during the winter season. The lower $PM_{2.5}/PM_{10}$ ratio during both seasons indicated the presence of coarse particulate fraction from dusty sources such as ongoing construction activities and, nearby road dust, or soil dust. This also indicates that the contribution from combustion sources is less in the study area.

Table 3: Summary of ambient air quality monitoring for summer and winter seasons at Faridabad

Location	Summer			Winter		
	PM_{10}	$PM_{2.5}$	$PM_{2.5}/PM_{10}$	PM_{10}	$PM_{2.5}$	$PM_{2.5}/PM_{10}$
Residential	364 ± 92	86 ± 23	0.24	176 ± 79	89 ± 44	0.5
Industrial	332 ± 55	108 ± 29	0.33	208 ± 53	116 ± 41	0.55
Kerbside	349 ± 106	111 ± 37	0.32	321 ± 75	126 ± 24	0.39
Commercial	305 ± 85	92 ± 32	0.3	178 ± 66	93 ± 29	0.52
Background	154 ± 55	81 ± 17	0.53	135 ± 49	70 ± 22	0.51

Spatiotemporal variations in the chemical profile of atmospheric PM_{10} and $PM_{2.5}$

Key highlights

- Carbon and ions dominate the chemical composition of ambient PM_{10} and $PM_{2.5}$ across the study area.
- The carbon fraction in $PM_{2.5}$ is consistently higher compared to PM_{10}.
- Carbon was the major component of PM_{10} in summer, with the highest proportion at the kerbside location (31%).
- The constituents of Ions in PM_{10} dominated in winter, with the highest proportions at the commercial location (42%).
- Unidentified mass ranged from 11–32% in summer and 5–12% in winter for PM_{10} and the corresponding range for $PM_{2.5}$ is 6–9% in summer and 7–9% in winter
- Carbon fraction in $PM_{2.5}$ dominated in both seasons, with the highest proportion observed at industrial locations (58%).
- Fe, Si, Al, K, and S were identified as dominant elements in both PM_{10} and $PM_{2.5}$.
- The abundance of Fe, Si, and Al in PM_{10} is indicative of crustal sources (e.g., soil and road dust) and construction activities.
- S was more prevalent in $PM_{2.5}$ than PM_{10}, indicating significant contributions from coal/diesel combustion in industries, brick kilns, vehicles, etc.
- Dominant ions in both PM_{10} and $PM_{2.5}$ are NH_4^+ (28–42% in PM_{10}; 27–45% in $PM_{2.5}$), SO_4^{2-}, NO_3^-, and Cl^-.
- SO_4^{2-} was more prevalent in summer, indicating photochemical oxidation of SO_2 and NO_3^- was higher in winter, likely due to increased ozone-driven conversion of NO_x to NO_3^-.
- Primary sources of NH_4^+ included decomposition of organic waste, open drains, and vehicular traffic.
- Elevated NH_4^+ and SO_4^{2-} concentrations indicate significant contributions from local and secondary sources.
- Organic Carbon (OC) accounted for over 50% of total carbon in PM_{10} and $PM_{2.5}$
- Elemental Carbon (EC) contributed 16–30% to the total carbon in $PM_{2.5}$.
- Industrial areas exhibited the highest carbon concentrations, attributed to coal and biomass combustion.

Size fractions influence the chemical profile of ambient particulate matter, the types of fuels used in the vicinity, combustion technologies employed at various sources, and meteorological conditions such as temperature, humidity, rainfall, and wind speed. These chemical characteristics provide valuable insights into the formation processes, reaction mechanisms, duration, and sources of particulate matter.

In the Faridabad study area, ambient particulate matter collected on different types of filter media from various monitoring locations during the two seasons was analyzed for its chemical composition. PM_{10} and $PM_{2.5}$ samples were assessed to determine the composition of ions, elements, and carbon fractions in the ambient air. This analysis is crucial for understanding the sources and mechanisms of particulate matter pollution in the region.

Methodology of chemical profiling of atmospheric PM_{10} and $PM_{2.5}$

The quantitative analysis of elements in PM samples collected on Teflon filters was carried out using Energy Dispersive X-ray Fluorescence Spectrometer (ED-XRF). As XRF analysis is a non-destructive technique this paper was used for subsequent analysis of water-soluble inorganic ions using Ion Chromatograph. PM samples collected on quartz filters were subjected to OC and EC analysis using the Thermal/Optical Carbon Analyzer. Details of the sample analysis are given below:

Energy Dispersive X-ray fluorescence (ED-XRF) spectrometry (EDX 7000, Shimadzu, Japan) was used to determine the concentrations of elements including Al, Si, K, Ca, Ti, V, Fe, Co, Ni, Cu, Zn, As, Se, Zr, Mo, Pd, Cd, Ce, and Pb, on the Teflon filters. Calibration standards, in the form of filter paper, of Micromatter Inc. for various elements were used for calibration of equipment. Measurements were also made on the blank filter and correction in the intensities was made for the loaded filters. Data acquisition and quantitative analysis were carried out by using equipment software.

Concentrations of water-soluble inorganic ionic components in PM collected on Teflon filters were determined using ion chromatography method. Each sample was ultrasonically extracted using 50 mL of deionized water for 90 minutes. The extract was filtered through a 0.22 μm nylon membrane syringe filters to remove insoluble matter and then analysed using an ion chromatography (IC) system (ICS Aquion, ThermoFisher Scientific). Concentration of cations (Na^+, K^+, Mg^+, NH_4^+, Ca^{+2}) were determined using a IonPac CS16, 5mm analytical column and its CDRS600, 4mm guard column, 3.8 mM Methanesulfonic Acid was used as eluent while the concentrations of anions (Cl^-, F^-, Br^-, NO_3^-, SO_4^{-2}) were determined using a separation analytical column IonPac AS23; 4mm and guard column ADRS600, 4mm), and 4.3 mM carbonate and 0.8mM bicarbonate as eluent. The blank filters were also analysed for cations and anions.

0.495 cm^2 punch from a quarter of each quartz filter sample was used for the analysis of organic carbon (OC) and elemental carbon (EC) using a Thermal/Optical Carbon Analyzer (DRI Model 2001A; Desert Research Institute, USA) following IMROVE_A protocol. The four OC fractions i.e. OC1, OC2, OC, and OC4 are produced in a stepwise manner at 140, 280, 480, and 580 0C temperatures, respectively in a pure Helium (100% He) atmosphere. This analysis was further continued for three more temperatures i.e. 580, 740 and 840 0C for determination of three EC fractions i.e. EC1, EC2, and EC3, respectively in 98% helium and 2% oxygen containing atmosphere. The pyrolyzed carbon fraction (OP) is also determined when the reflected laser signal returns to its initial value after oxygen is added to the Helium atmosphere. The IMPROVE protocol defined OC as OC1+OC2+OC3+OC4+OP and EC as EC1+EC2 +EC3-OP. Each filter and blank filters were analyzed to get the representative estimation of OC and EC concentrations.

Chemical profile of atmospheric PM_{10} and $PM_{2.5}$ in the Faridabad Municipal Corporation area

During the measurement period, the most prevalent compounds in the atmospheric PM_{10} and $PM_{2.5}$ in the Faridabad study area were carbon and ions. The proportion of carbon in the ambient PM_{10} at different monitoring locations during the summer season followed the order: Background (32%) > Kerbside (31%) > Residential (30%) > Commercial (29%) > Industrial (26%) (Figure 1). Ions were observed as the most abundant chemical constituents in the ambient PM_{10} during the winter season. The proportion of ions in the ambient PM_{10} at different monitoring locations during the winter season followed this order: Background (47%) > Commercial (42%) > Industrial (41%) > Kerbside (37%) > Residential (35%) (Figure 20).

Again, carbon was identified as the most prevalent chemical constituent in ambient $PM_{2.5}$ across all the monitoring locations during the summer and winter seasons. The proportion of carbon fraction varied between 52% and 58% during summer, 37% and 58% during winter season. The highest proportion of carbon species was observed at Industrial (58%) locations during the summer and winter seasons respectively (Figure 20). The presence of coal and biomass-dependent industries, regular movement of heavy-duty trucks, and coal-dependent brick kiln units are some of the observed characteristics of industrial location. Higher carbon fraction in the ambient $PM_{2.5}$ samples at this location could be attributed to the combustion of coal and solid biomass fuel in the industries, burning of diesel fuel due to the movement of trucks, and coal combustion in the brick kiln units. Moreover, in the total ambient PM_{10} mass about 11% to 32% in summer and 5% to 12% in winter remained chemically unidentified as ion, element, or carbon (Figure 20). Similarly, in the total ambient $PM_{2.5}$ mass about 6% to 9% in summer and 7% to 9% in winter season remained chemically unidentified. The unidentified portion includes organic matter associated with organic carbon, oxygen associated with the oxides of metals, and other unidentified species that were not analyzed. This discrepancy could also be attributed to the probable loss of organic compounds due to volatilization before analyzing the particulate matter.

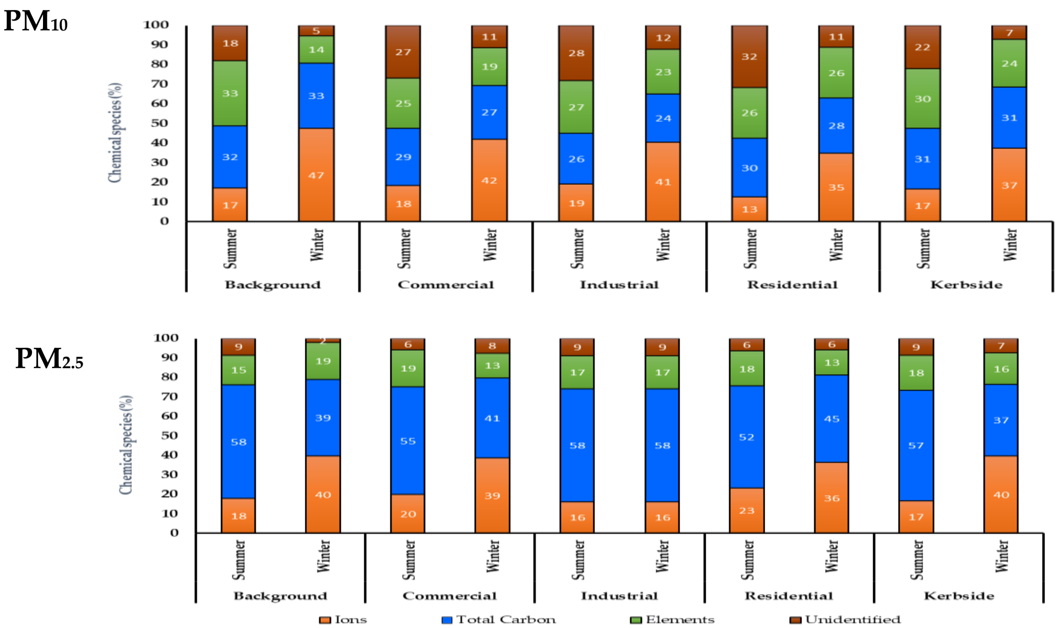


Figure 20: Average seasonal chemical compositions of ambient PM_{10} and $PM_{2.5}$ at different air quality measurement locations in the Faridabad Municipal Corporation area.

Elemental profile of ambient particulate matter

Irrespective of air quality measurement locations, Fe, Si, Al, K, and S were dominant elements in ambient PM_{10}. In contrast, Zn and Pb were observed in low concentrations in the elemental mass of PM_{10}. The proportion of Fe in the elemental concentration of ambient PM_{10} varied between 32% and 40% and 18% and 36% in the summer and winter seasons respectively (Figure 21). The proportion of Si in the elemental concentration of ambient PM_{10} varied between 23% and 37% and 16% and 25% in the summer and winter seasons respectively (Figure 21). The proportion of Al and S in elemental concentration of ambient PM_{10} varied in the range of 7% to 12% and 3% to 18%, respectively across the air quality measurement locations during the study period.

Fe, Si, K, and Al are crustal elements and the presence of Fe, Si, and Al fraction in ambient PM_{10} is indicative of crustal sources namely soil and road dust. Apart from crustal sources, construction activities involving earth mover and concrete, also contribute the atmospheric Si and Al in the ambient PM_{10}. Again, Fe, Zn, and Pb are released due to wear of tyre and brakes during the movement of vehicles (Chenery et al., 2020). Therefore, the occurrence of such elements in the atmospheric PM_{10} is indicative of abraded vehicular part-related road dust. In addition, the transboundary movement of dust due to higher wind speed in summer compared to the other two seasons could contribute to the higher elemental mass of PM_{10} over the study area.

Again, S, Si, Fe, Al, and K were observed as the most dominant elements in the ambient mass of $PM_{2.5}$. The proportion of S and Si within the elemental concentration of ambient $PM_{2.5}$ varied from 10% to 26% and 10% to 33% respectively, across the air quality monitoring locations. The proportion of Fe and Al varied from 8% to 31% and 11% to 20% respectively, across the air quality monitoring locations. The crystalline form of Si and Al in coal can be attributed to atmospheric Si when the coal gets burnt in industries, brick kilns, residential households, or restaurants for energy purposes (Gong et al., 2020). The presence of Si and Al fractions in the ambient $PM_{2.5}$ is mostly attributed to the burning of coal in the near vicinity of air quality measurement locations. The dominance of S in the elemental profile of $PM_{2.5}$ compared to that of PM_{10} (Figure 21) suggests combustion of S containing fuel like coal and diesel in the near vicinity of air quality measurement locations. Coal combustion in the industries or brick kiln units for energy purposes, movement of diesel vehicles, burning of coal in residential households or eateries for cooking activity, and use of diesel in the diesel generator sets could also contribute to S in the elemental mass of $PM_{2.5}$. Further, the proportion of K in the elemental concentration of ambient $PM_{2.5}$ varied from 11% to 22% across the air quality measurement locations. The presence of K in the ambient $PM_{2.5}$ may be attributed to local combustion-based sources namely the use of solid biomass for residential cooking and contribution from the local polluting sources such as refuse burning activity in the surrounding areas of air quality measurement locations (Matawle et al., 2014). Moreover, the proportion of Fe varied from 8% to 28% across the air quality measurement locations. The presence of Fe-bearing $PM_{2.5}$ particles could be attributed to emissions from local industrial activity and the burning of waste incinerators in the near vicinity of air quality measurement locations (Zhou et al., 2015).

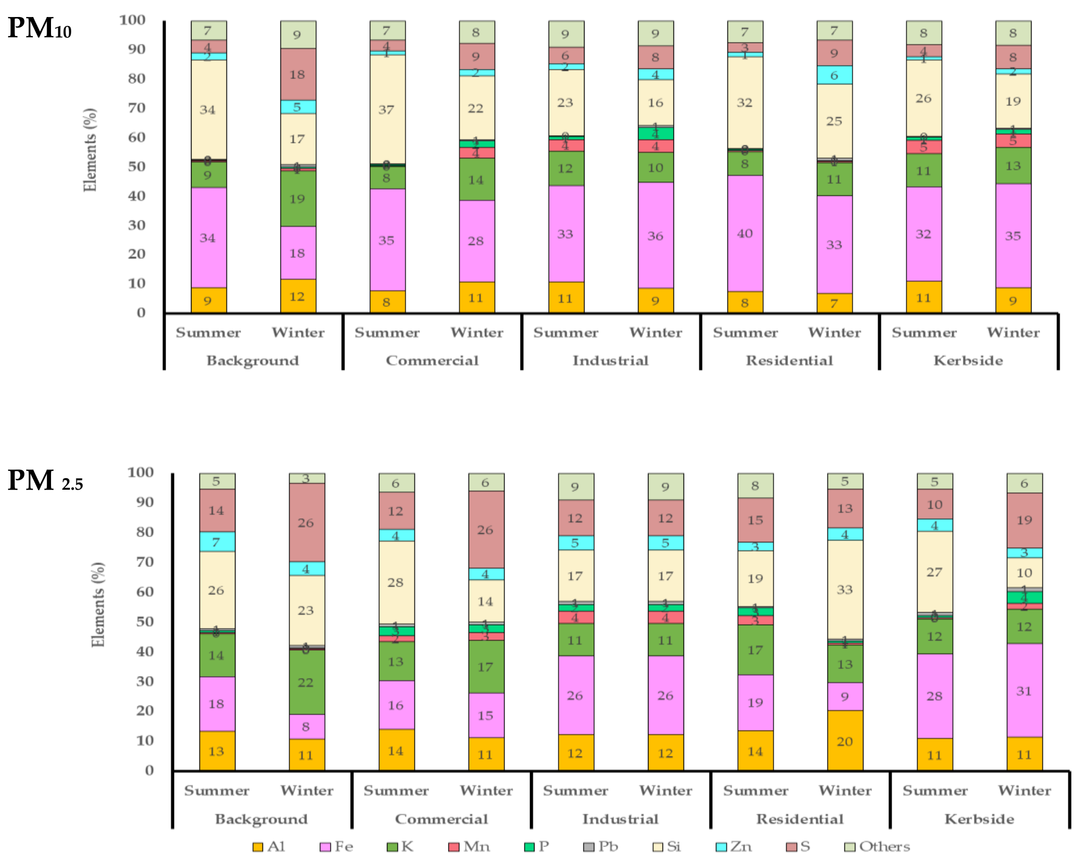


Figure 21: Average seasonal elemental compositions of ambient PM_{10} and $PM_{2.5}$ at different air quality measurement locations in the Faridabad Municipal Corporation area

Ionic profile of ambient particulate matter

NH_4^+, Ca^{2+}, Cl-, SO_4^{2-}, and NO_3^- were the most dominant ionic species in ambient PM_{10} across different air quality measurement locations during the study period. Whereas NH_4^+, Cl-, SO_4^{2-}, and NO_3^- were the most dominant ionic species in ambient $PM_{2.5}$ across different monitoring locations during the study period. Among these ions, SO_4^{2-} and NO_3^- are mostly secondary inorganic aerosols formed in the atmosphere from their precursor molecules (Squizzato et al., 2013).

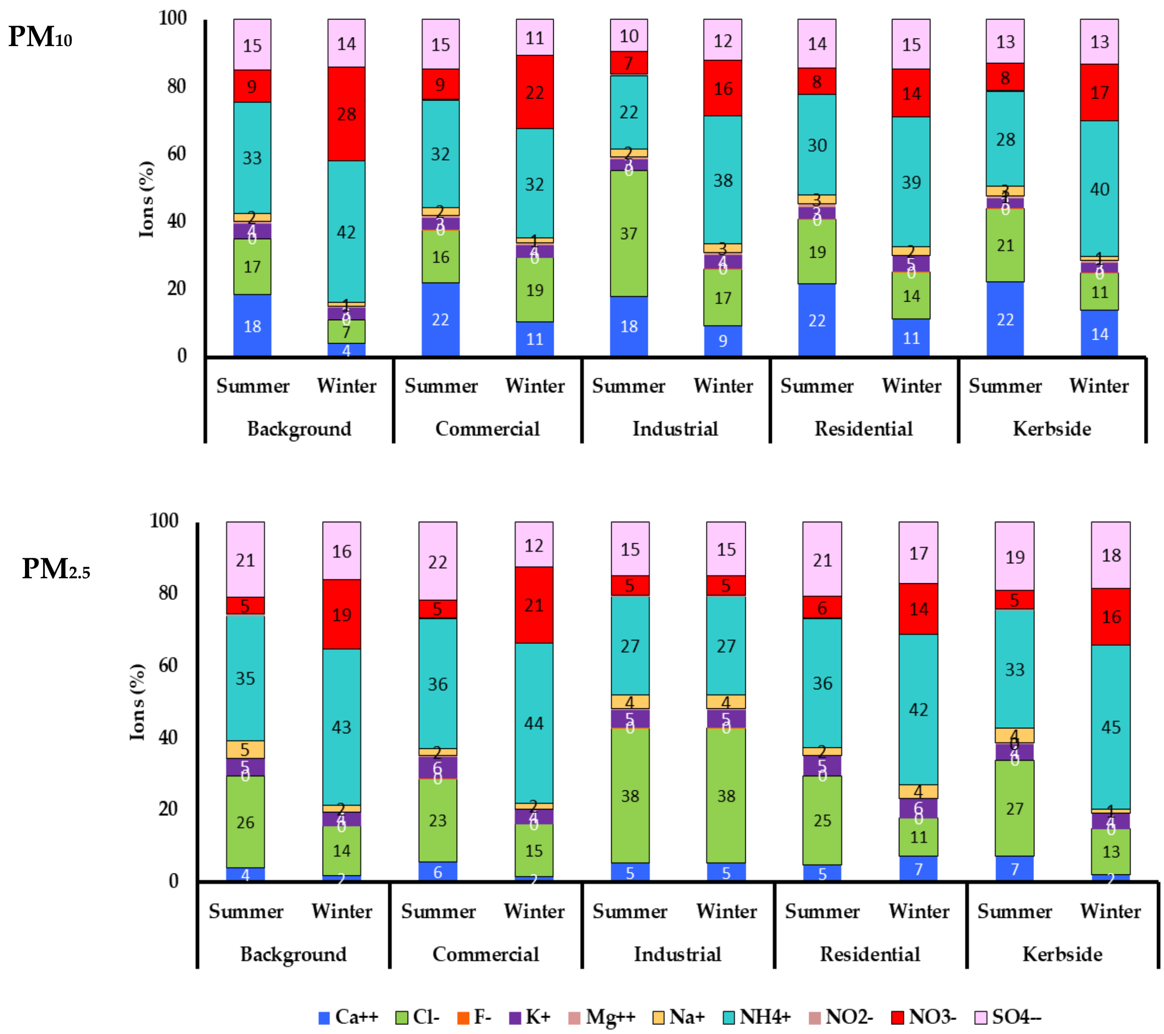


Figure 22: Average seasonal ionic compositions of ambient PM_{10} and $PM_{2.5}$ at different air quality measurement locations in Faridabad Municipal Corporation area

The prevalence of NH_4^+ within the ionic profile of PM_{10} (28% to 42%) and $PM_{2.5}$ (27% to 45%) throughout the study period (Figure 22), suggests that the major source of NH_4^+ across the air quality measurement locations is mostly local. Volatilization from the decomposing of livestock excreta, open drains, garbage containers, sewage treatment plants, and vehicular traffic are some of the common sources of NH_3 in the urban environment (Reche et al., 2015). This might have been attributed to significantly higher concentrations of NH_4^+ in both PM_{10} and $PM_{2.5}$ fractions of the particulate matter throughout the study period.

The proportion of SO_4^{2-} (12% to 22%) within the ionic profile in $PM_{2.5}$ was higher than the ambient PM_{10} (10% to 15%) throughout the study period. The proportion of SO_4^{2-} in the ambient air mainly forms through photochemical oxidation of SO_2 and oxidation with OH^- (Yu et al., 2017). During the summer season, when the atmospheric relative humidity was comparatively lower than in other seasons, the portion of SO_4^{2-} in the ambient particulate matter ($PM_{2.5}$) was higher than in other seasons (Figure 3). This suggests that the formation of SO_4^{2-} through photochemical oxidation might have been prevalent in the study area. Moreover, a significantly large proportion of NH_4^+ in the ambient $PM_{2.5}$ and PM_{10} concentrations suggests that most of the atmospheric SO_4^{2-} in the study area was present in the form of $(NH_4)_2 SO_4$.

On the other side, the NO_3^- proportion in the particulate matter (PM_{10} and $PM_{2.5}$) was higher during the winter seasons compared to the summer season (Figure 22). This might be attributed to higher O_3 concentration in the ambient atmosphere during winter. High O_3 and $OH^.$ formation in winter might have facilitated the fast gas-phase and heterogeneous conversion of NO_X to HNO_3 which subsequently converted to NO_3^- (Fu et al., 2020).

The proportion of Cl^- varied from 7% to 37% and 11% to 38% in the ambient PM_{10} and $PM_{2.5}$ fractions of the particulate matter respectively (Figure 22). Coal combustion and biomass burning is an indicative of presence of atmospheric Cl^-. Burning of solid biomass fuel in the residential households and roadside eateries are also one of the major sources of atmospheric Cl^-.

Among cations, Ca^{2+} concentration (4% to 22%) within the ionic profile of ambient PM_{10} was significantly higher across the air quality measurement locations during the summer season compared to the winter season (Figure 22). The presence of higher Ca^{2+} concentration in the ambient PM_{10} suggests that there is the prominent contribution of Ca^{2+} from crustal materials like erosion of topsoil or dust generated from local construction activities.

Carbon profile of ambient particulate matter

The organic carbon (OC) shares more than 50% of total carbon concentration in ambient PM_{10} and $PM_{2.5}$ at all air quality measurement locations throughout the study period (Figure 23). EC is a primary pollutant formed during combustion processes whereas OC is a complex mixture of many groups of compounds originating from primary sources and secondary organic aerosols (Samara et al., 2014).

The share of elemental carbon (EC) to the total carbon concentration in ambient $PM_{2.5}$ varied between 16% to 30% while, the share of organic carbon (OC) in the total carbon concentration of ambient $PM_{2.5}$ varied between 72% and 81% across the air quality measurement sites during the study period. Biomass or refuse-burning activity, the use of biomass fuels in industries for energy purposes is a major primary source of atmospheric OC. Also, the transboundary movement of OC due to transportation from distant sources could contribute to atmospheric OC. On the other side, EC is formed or generated during the combustion of any carbon material, thus coal burning in industries/brick kiln units, combustion of fuels in diesel generators, movement of vehicles, use of coal in roadside eateries, etc. are important sources of atmospheric EC.

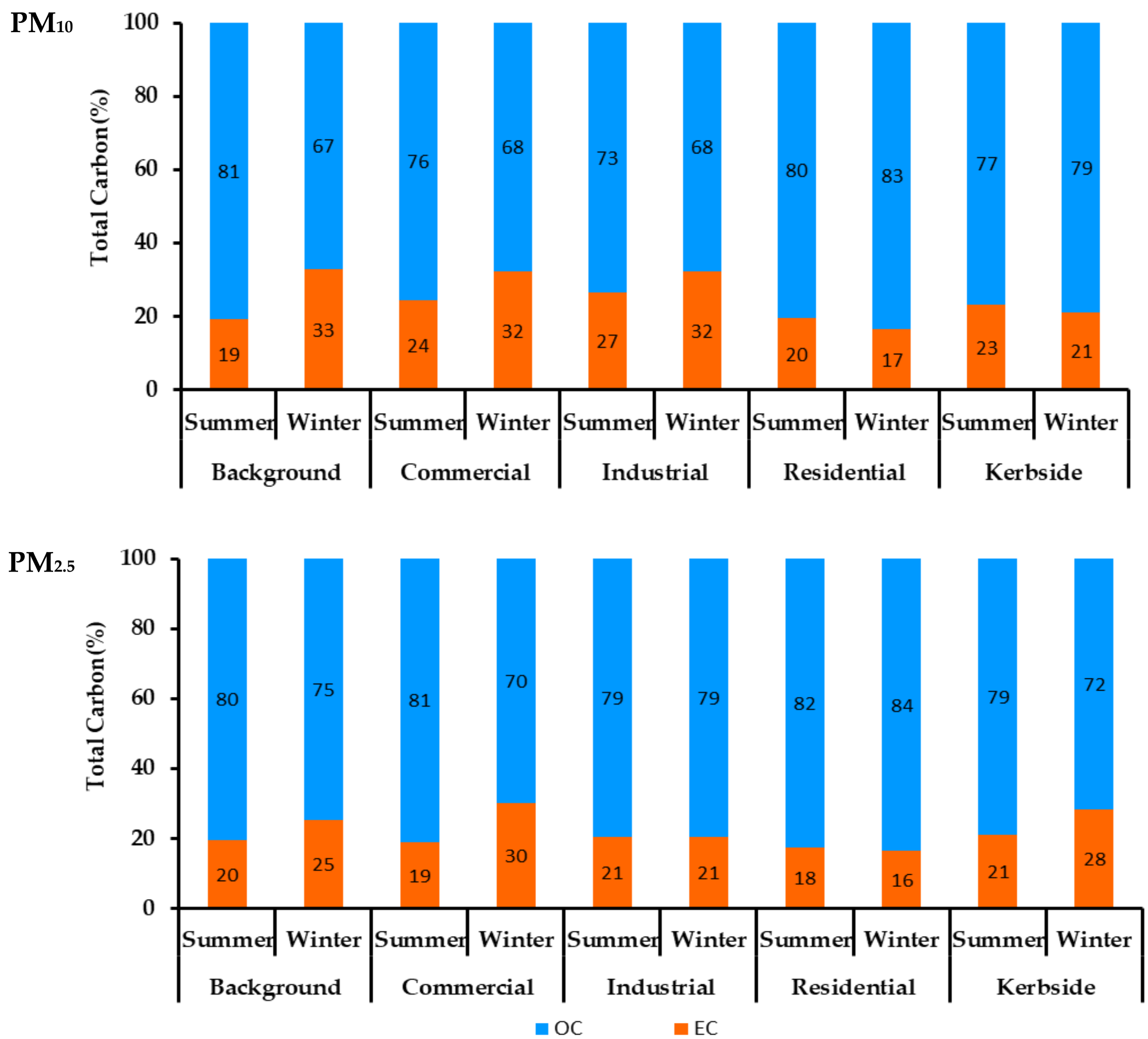


Figure 23: Average seasonal fractions of total carbon in ambient PM_{10} and $PM_{2.5}$ at different air quality measurement locations in the Faridabad Municipal Corporation area

Source apportionment of ambient PM_{10} and $PM_{2.5}$ – Receptor modelling

Overview of CMB modelling

- Dust (road dust, construction, and wind-blown soil) is the major contributor to PM_{10}, with annual contributions of 46% for PM_{10} and 15% for $PM_{2.5}$. Dust contributions are higher during summer due to drier conditions and wind-driven resuspension.
- Biomass and coal burning in households and eateries contribute 12% annually to PM_{10} and 22% to $PM_{2.5}$. These contributions are more pronounced during winter due to lower temperatures and increased local source activity.
- Transport contributes 21% to $PM_{2.5}$ in summer and 19% in winter, showing higher contributions to $PM_{2.5}$ than PM_{10}, as vehicular emissions predominantly release fine particles.
- Industries contribute 11% annually to PM_{10} and around 16% to $PM_{2.5}$, with slightly higher $PM_{2.5}$ contributions in summer due to regional influences and meteorological factors.
- Secondary particulates contribute more significantly to $PM_{2.5}$ (17% in winter and 7% in summer) than PM_{10}. Enhanced nitrate formation during winter accounts for these higher levels.
- Refuse burning contributes up to 15% to $PM_{2.5}$, while agricultural residue burning contributes up to 14%, with higher contributions during winter due to emissions from neighboring states like Haryana and Punjab.
- Dust contributes 6%-29% to $PM_{2.5}$, with higher levels during summer at most locations due to dry conditions and wind-driven transport. Residential locations also record significant dust contributions in winter due to nearby construction.
- Combustion sources (biomass burning, transport, industries) dominate $PM_{2.5}$ contributions, highlighting their prevalence in finer particle fractions compared to PM_{10}.
- Transport sector contributions are higher in summer than winter, potentially due to increased vehicle activity, better atmospheric dispersion, and localized monitoring effects.
- Dust is the dominant contributor to PM_{10} levels, while combustion sources (biomass, transport, industries) dominate $PM_{2.5}$ levels.

Air pollution source apportionment using receptor modeling is a "top-down approach" that employs statistical methods to estimate the contributions of various pollution sources to air quality at specific receptor locations. This method compares the chemical and physical characteristics (source profiles) of atmospheric particles from known sources with those measured at monitoring locations (receptors).

Receptor models operate on the principle of mass conservation and are designed to identify and apportion the sources of airborne particulate matter in the atmosphere. The input dataset for receptor modeling includes a wide range of chemical constituents from particulate matter samples. These models analyze monitored pollutant concentrations and their chemical compositions alongside local source profiles to determine the relative contributions of different sources at a given monitoring site.

Receptor models are retrospective, meaning they evaluate the impacts of source categories based on pollutant concentrations that have already been monitored. This approach involves determining the best-fit linear combination of source chemical composition profiles required to reconstruct the measured chemical composition of ambient samples (Watson et al., 1984). By doing so, receptor modeling provides valuable insights into the sources driving air pollution and helps inform effective control strategies.

The framework for using receptor models consists of;

a) Formulating a conceptual model,
b) Identifying potential sources contributing to ambient particulate matter concentrations,
c) Chemically characterizing source profiles based on literature review or developing study-specific profiles,
d) Chemically characterizing source profiles based on literature review or developing study-specific profiles,
e) Estimating uncertainties associated with sampling and analysis of different constituents of particulate matter,
f) Confirming source types with receptor models,
g) Quantifying source contributions with the chemical mass balance (CMB) model,
h) Various diagnostic checks are performed for each model run to ensure the reliability of the modelled results.

The CMB model (version 8.2) was used in this study to determine different source contributions at each air quality measurement location under the present study.

CMB is a USEPA-approved model that uses source profiles and speciated ambient data to quantify source contributions. Contributions are quantified from chemically distinct source-types rather than from individual emitters. The CMB Receptor model consists of a solution to linear equations that express each receptor chemical concentration as a linear sum of products of source profile abundances and source contributions.

Chemical Mass Balance model

The basic equation (eq. 1) of the CMB receptor model as a statement of species conservation has been given by Watson et al., 1984:

$$Ci = \sum_{j=1}^{m} f_{ij}S_j + e_i \qquad \textbf{Equation 1}$$

Where Ci is the ambient concentration of species i; f is the fraction of species i in source j; Sj is the source contribution of source j; and ei is the standard error of measurement of species i.

Major assumptions accounted for in CMB modelling

- Compositions of source emissions are constant throughout ambient and source sampling.
- Chemical species do not react with each other (*i.e.* they add linearly)
- All sources with the potential for contributing to the receptor have been identified and have had their emissions characterized
- The number of sources or source categories is less than or equal to the number of species
- The source profiles are linearly independent of each other, and
- Measurement uncertainties are random, uncorrelated, and normally distributed.
- The Receptor model simulates the contribution of different sources but does not specify the geographical location of the sources.

Key steps followed to carry out CMB modelling

- Identification of the contributing sources to the monitoring sites. Detail reconnaissance survey of the monitoring locations were undertaken to identify potential sources of air pollution during the air quality measurement periods.
- Chemical species were analyzed in the PM_{10} and PM2.5 samples collected at respective sites in summer, post-monsoon and winter seasons.
- The selection of representative source profiles may affect the air quality of respective site. This was selected based on the sources identified through reconnaissance survey and discussions with residents.

Selected source profiles for CMB analysis

Non-Vehicular Source Profiles:

- Refuse burning and dust (Source: Source Apportionment of $PM_{2.5}$ & PM_{10} of Delhi NCR, 2018: TERI & ARAI).
- Biomass burning, construction, and industry sector. (Source: Stationary Source Profiling report (2009). Developed by IIT-Bombay. Central Pollution Control Board.

Vehicular Source Profiles:

- New composite profiles of different fuel types developed for newer technology vehicles (post-2005) (Source Apportionment of PM2.5 & PM_{10} of Delhi NCR, 2018: TERI & ARAI).
- Earlier profiles of pre-2005 vehicle technology. (CPCB, 2009, Vehicle Source Profiling report).

The approach of CMB modelling – in brief

- A solution to the chemical mass balance equation (*eq. 1*) was obtained through CMB-8.2 receptor model.
- 24-h concentrations of different species at five ambient air quality measurement locations of Faridabad city were used as an input to the receptor model.
- The profile of the potential contributing sources at each air quality measurement identified through the reconnaissance survey was used along with the measured 24-hour dataset of different species.
- The average of the simulated results for each site was used to derive average contributing sources of PM_{10} and $PM_{2.5}$ at Faridabad city during different seasons.

Analysis of simulated output

Source contribution estimates (SCE) are the main output of the CMB receptor model. The sum of these approximates the total mass concentrations. The source contribution was not considered when any SCE was less than its standard error.

Performed various diagnostic checks on each model run to ensure the reliability of the simulated output. These include t-statistics (source contribution divided by the error of source contribution), chi-square test, regression coefficient, and percentage mass explained by the model. The US EPA has set a standard range for each of these diagnostic measures.

The reduced Chi-square ($\chi 2$), coefficient of determination (R^2), and percent mass are goodness of fit measures for the least-squares calculation. $\chi 2$ is the weighted sum of squares of the differences between calculated and measured fitting species concentrations divided by the effective variance and the degrees of freedom. $\chi 2$ value < 1.0 suggests a very good fit between the measured and simulated data. $\chi 2$ values < 4 were considered acceptable. $\chi 2$ value > 4.0 suggests that the source contribution estimates do not explain one or more fitting species concentrations.

R^2 is determined by the linear regression of the measured versus simulated values of the fitting species. R^2 ranges from 0 to 1.0. The closer the value to 1.0, the better the SCEs explain the measured concentrations. When $R^2 < 0.8$, the SCE fails to explain the observations well with the given source profiles. $R^2 \geq 0.8$ was considered acceptable.

The ratio of the sum of simulated SCEs to the measured mass concentration(C/M) and the ratio of residuals to uncertainty (R/U) were evaluated for each species. Values ranging from 0.8 to 1.2 were considered acceptable for C/M. The simulated SCEs of ambient PM_{10} and $PM_{2.5}$ using the CMB-8.2 model at different ambient air quality measurement locations are presented in the following sections,

Estimation of seasonal variations of source contribution to ambient particulate matter

The results of the Chemical Mass Balance (CMB) model applied to Faridabad provide valuable insights into the contributions of various sources to particulate matter (PM_{10} and $PM_{2.5}$) in the city. The analysis highlights the significance of seasonal variations, source-specific dynamics, and receptor site characteristics in determining the levels of particulate pollution. These findings reveal critical trends and help prioritize effective air quality management interventions.

Seasonal variations of sources of ambient PM_{10} at different monitoring locations

The results from the CMB model at Faridabad for both summer and winter seasons across various receptor locations for PM_{10} highlight the dominance of dust (arising from road dust, construction dust, and wind-blown soil) at all locations, regardless of the season. Contributions from other sectors, such as industries (including power plants and brick kilns), biomass and coal burning (in households, hotels, restaurants, and eat-outs), vehicular transport, agricultural residue burning, refuse burning, and secondary particulates, show relatively consistent patterns across different locations and seasons.

The contribution of dust to PM_{10} levels across different locations within the city ranged from 24% to 56%, with peaks observed during the summer months. This seasonal spike is attributed to dry conditions, enhanced resuspension from roads, and ongoing construction activities. Additionally, elevated dust levels during summer can be linked to contributions from distant dusty sources that are transported to the city at high wind speeds. Industrial receptor sites recorded the highest dust contributions (56%) in summer due to their proximity to construction zones and unpaved roads. Furthermore, the dust contribution at this site can also be attributed to the frequent movement of heavy vehicles on poorly maintained roads in the industrial area. At the background site, the dust contribution remains significant year-round, ranging from 41% to 47% for the summer and winter seasons, respectively. Stone crushers and construction activities that are happening upwind of the background location, contributing to the high PM levels at this location and other locations within the city.

Industries contribute between 9% and 16% of PM_{10} across different locations, with industrial locations experiencing the highest contributions. At all locations, there is minimal variation in their contribution to PM_{10} across different seasons. The consistent contribution of industrial emissions across locations can be attributed to localized industrial sources, steady year-round activity, and limited influence from regional transport. Background location also shows contributions from industries, probably because of the presence of industries in the upwind of this location.

Vehicular emissions were another significant source of particulate pollution, contributing between 6% and 15% of PM_{10} across different locations and seasons, with the highest contributions observed at the kerbside location during the summer season. The contribution of tailpipe emissions from vehicle movement across different locations does not vary significantly, likely due to uniform traffic patterns, limited impact of meteorological conditions, the proximity of monitoring sites to roads, and the dominance of local emissions over regional influences.

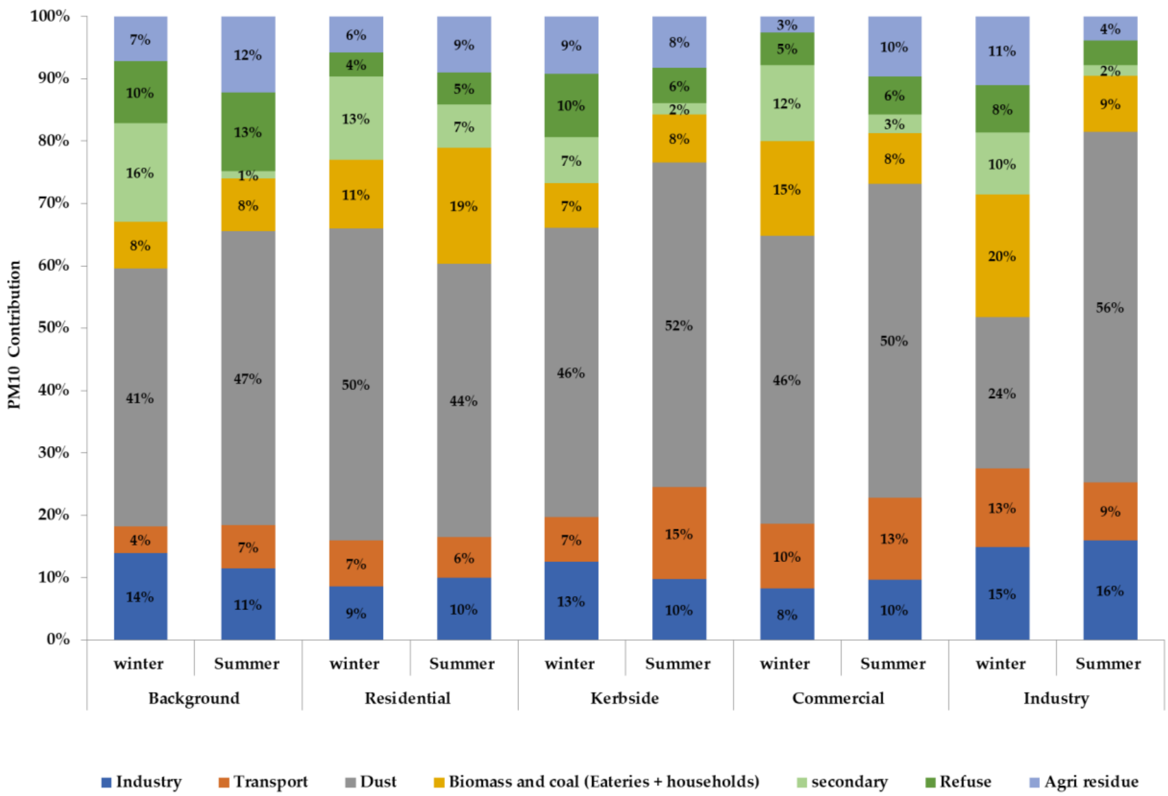


Figure 24: Source contributions to ambient PM_{10} at different monitoring locations during the two seasons

Secondary particulates were found to contribute about 2% to 13% across different locations and seasons within the study area. The highest contributions were estimated at residential locations (13%), commercial locations (12%), and industrial locations (10%). A notable trend observed across all locations was the comparatively higher contribution of secondary particulates to ambient PM_{10} during winter, attributed to enhanced nitrate formation driven by lower temperatures and higher humidity levels.

The contribution of refuse burning to PM_{10} across different locations and seasons varied between 4% and 10% whereas the corresponding contribution of agricultural residue burning fluctuated between 3% and 11%. However, the contribution from both these activities did not vary significantly across different locations within the study area. As expected, comparatively higher contributions from refuse burning were observed during the winter season.

The share of biomass and coal burning in residential households and restaurants/bakeries/open eat-outs to atmospheric PM_{10} across different locations and seasons ranged between 7% to 20% with higher contributions observed at industrial (20%), residential (19%), and commercial (15%) locations. Higher contributions were observed during the winter season (with lower temperatures and a shallow boundary layer, that traps pollutants closer to the ground, making the impact of local sources more pronounced) indicating the influence of local sources such as slums and eateries within the study area.

Seasonal variations of sources of ambient $PM_{2.5}$ at different monitoring locations

Like PM_{10}, seasonal variations are observed in source contributions of existing sources towards prevailing $PM_{2.5}$ concentrations.

The results indicate that combustion-based sources such as transport, biomass burning (in residential and hotels/restaurants/open eat-outs), and industries are the primary contributors to ambient $PM_{2.5}$ in Faridabad. This is because combustion-based sources release a fine fraction of PM, which contributes significantly to $PM_{2.5}$ levels.

The contribution of dust to atmospheric $PM_{2.5}$ levels across different locations varied between 6% and 29%, with peaks during the summer at most of the locations. A higher contribution during summer is expected as drier conditions and higher wind speeds lead to increased dust suspension from sources such as soil, construction sites, and roads, especially from far-off locations. However, higher contribution from dust was observed at the residential location (29%) during the winter season, likely due to heavy construction activities in the vicinity combined with unfavorable weather conditions that trap pollutants and prevent their dispersion. Compared to other locations, the background station recorded a higher contribution from dust, ranging from 15% to 17%.

Industries were identified as the third major contributor to ambient $PM_{2.5}$. Their contribution ranged from 7% to 25% during the summer season and from 9% to 22% during the winter season with higher contribution observed at the industrial locations during both seasons. Notably, their contribution was higher during the summer season, indicating a regional influence.

The tailpipe emissions from vehicles are the second-largest contributor to ambient $PM_{2.5}$ concentrations, with contributions ranging between 18% and 20% during winter and 14% and 29% during summer, with the highest contributions observed at kerbside locations. Unlike other sectors, the transport sector's contribution to $PM_{2.5}$ was comparatively higher across all locations, with the lowest contribution being 14%.

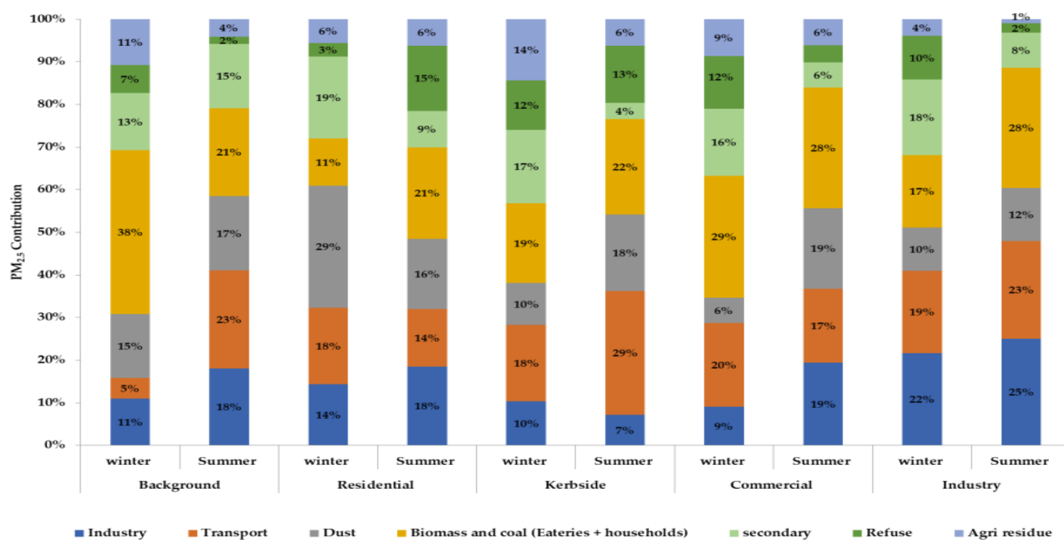


Figure 25: Source contributions to ambient $PM_{2.5}$ at different monitoring locations during the two seasons

The impact of biomass and coal burning on $PM_{2.5}$ levels varies across seasons and locations, but its contribution is significant year-round. During summers, biomass burning accounts for between 21% to 28% of $PM_{2.5}$, while during winters, this figure ranges from 11% to 29%. The prevalence of solid biomass fuel for cooking purposes, both within and outside the study area, plays a crucial role in this contribution. Additionally, regional transport further exacerbates the situation, with higher biomass contributions observed at background location. The commercial location exhibits the highest contributions from biomass burning compared to other monitoring locations for both seasons. They contributed approximately 28% of $PM_{2.5}$ during summers and 29% during winters. Whereas at industrial location biomass burning contributed 28% to $PM_{2.5}$ concentration during summer. While biomass burning contributions affect all locations regionally, the higher contribution observed at commercial location can be attributed to additional burning of biomass in small eateries and dhabas (roadside food stalls) in the nearby vicinity.

The study reveals that the contribution of secondary particulates to ambient $PM_{2.5}$ across different locations ranged from 4% to 9% in summer and 16% to 19% in winter. Comparatively higher contribution of secondary particulates to ambient $PM_{2.5}$ during winter is attributed to enhanced nitrate formation driven by lower temperatures and higher humidity levels.

The contribution of refuse burning across different locations and seasons varied between 2% and 15%, with the highest contribution observed at residential locations. Open burning of refuse is a common practice in urban and peri-urban areas, which impacts the overall air quality of the study area, although its share is not substantial throughout the year. The share of agricultural residue burning ranged from 1% to 14% across different locations and seasons, with the maximum contribution recorded at kerbside locations. The contribution of agricultural residue burning to atmospheric $PM_{2.5}$ was higher in winter than in summer across all locations. Although agricultural residue burning is not prevalent within the city limits, winter sees an increase in such activities in neighboring states like Haryana and Punjab, whose emissions significantly influence Faridabad's air quality

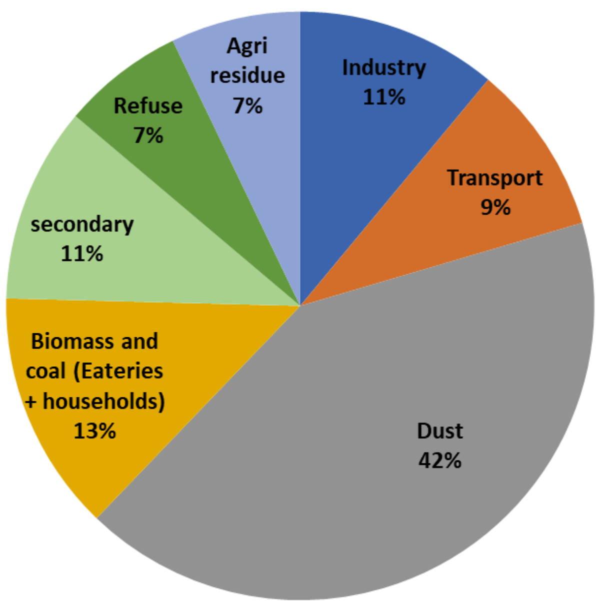
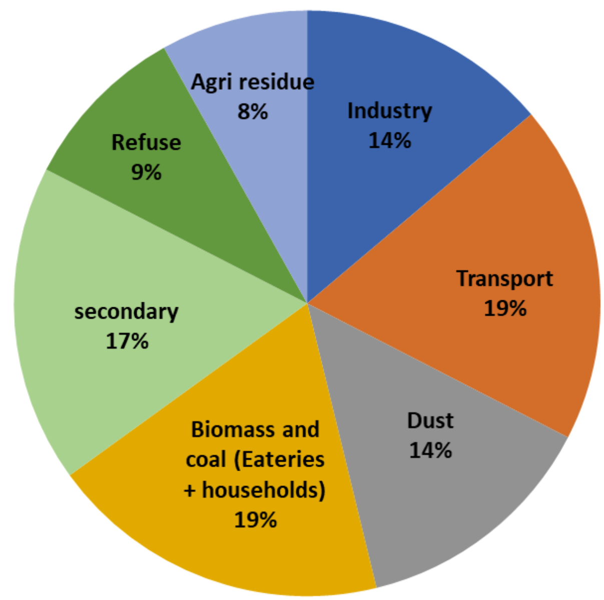
Average source contributions to ambient particulate matter in Faridabad in two seasons

The average source contributions to PM_{10} and $PM_{2.5}$ in the study area (average of 4 locations in the study area) are provided in Figure 26.

Dust (road dust, construction, and wind-blown soil) was identified as the major source of atmospheric pollution, contributing 51% and 42% of PM_{10} during the summer and winter seasons, respectively with an annual contribution of 46% to PM_{10} and 15% to $PM_{2.5}$. In addition to PM_{10}, dust also contributed significantly to ambient $PM_{2.5}$ concentrations, with an estimated contribution of 16% during the summer season and 14% in winter. The contribution of dust to atmospheric pollution was higher in summer compared to winter for both PM_{10} and $PM_{2.5}$. This can be attributed to drier conditions and higher wind speeds during the summer season, leading to the re-suspension of dust particles and atmospheric transport from distant dusty sources.

Biomass and coal burning in residential households and eateries, second major contributors to the ambient PM_{10} and $PM_{2.5}$, have a major share of the overall air quality in Faridabad city, and its impact is more pronounced during winter months than in summer for PM_{10} (13% and 11% for winter and summer respectively with an annual share of 12%). The share of biomass burning to ambient $PM_{2.5}$ for summer and winter is 25% and 19% with an annual contribution of 22%. Also, the higher share of biomass and coal burning in $PM_{2.5}$ fraction indicates the dominance of finer particles in biomass PM emissions.

Industries and transport are the third major contributor to the ambient PM_{10} during the summer season (11% each) followed by agricultural residue burning (8%), refuse burning (5%), and secondary (3%), whereas industries and secondary (11%) sectors are the third major contributors of atmospheric PM_{10} in winter season followed by transport (9%), agricultural residue and refuse burnings (7% each).

<table>
<tr><th></th><th>PM_{10}</th><th>$PM_{2.5}$</th></tr>
<tr><td>Winter</td><td>
</td><td>
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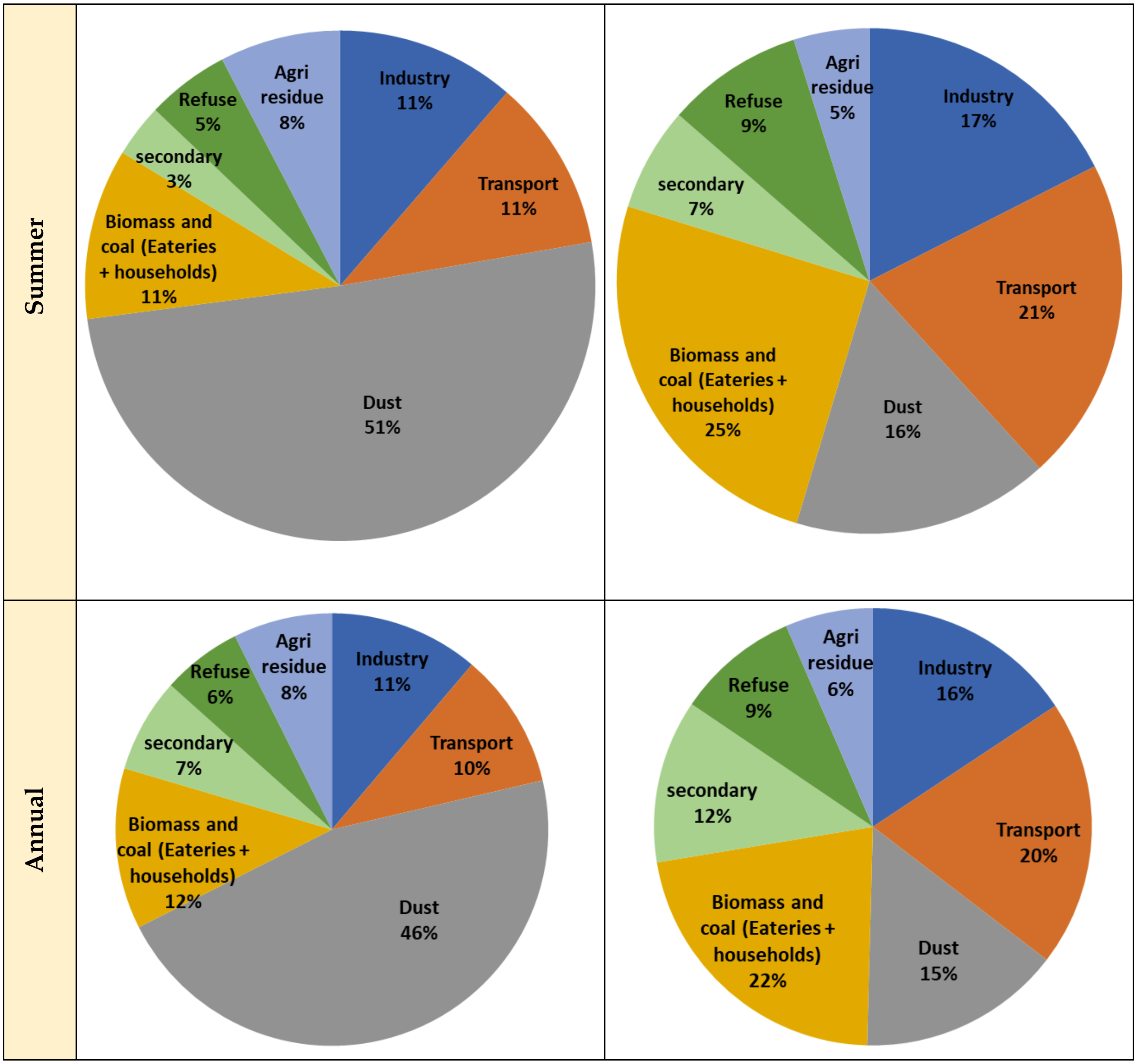


***The comparative analysis has been done for the two-monitoring season (June) for summer and (Dec) for the winter season for both $PM_{2.5}$ and PM_{10}*

Figure 26: Seasonal and annual contributions of different sources to ambient PM_{10} and $PM_{2.5}$ in Faridabad city (average of 4 locations)

The transport sector is the second major contributor to the atmospheric $PM_{2.5}$ levels for both summer and winter seasons, contributing to 21% and 19% in summer and winter respectively.

The third major contributor to the atmospheric $PM_{2.5}$ during the summer season is the industrial sector (17%) followed by Dust (16%), refuse burning (9%), secondary (7%), and agri-residue burning (5%). On the contrary, the third major contributor to ambient $PM_{2.5}$ during the winter season is secondary (17%), followed by industry & dust (14% each), refuse burning (9%), and agri-residue burning (8%).

Secondary particulates, while constituting a smaller share of the overall ambient PM in Faridabad, were found to contribute more to ambient $PM_{2.5}$ levels than to PM_{10} levels during both summer and winter seasons. The higher contributions of secondary particles in the $PM_{2.5}$ fractions indicate their dominance in the finer particle range, which refers to particles with a diameter of less than 2.5 micrometers in diameter (<2.5 μm).

Also, irrespective of size fraction, the contribution of tailpipe emissions from the transport sector is higher in summer compared to winter, which is unusual. This could be attributed to increased vehicle activity during summer, potentially due to higher commercial, or seasonal traffic. Additionally, improved atmospheric dispersion in summer spreads pollutants over larger areas, making their contributions appear higher relative to winter. In contrast, winter sees increased secondary pollutant formation and dominant biomass contribution, which might reduce the relative contribution of transport emissions. Furthermore, localized monitoring effects near major roads and seasonal variations in fuel usage may also influence this trend. Additionally, regardless of the season, tailpipe emissions from vehicles contribute more to the ambient $PM_{2.5}$ fraction than to the PM_{10} fraction. This is because emissions from the tailpipe of vehicles predominantly consist of fine particles that fall within the $PM_{2.5}$ size range.

Industrial contributions to ambient $PM_{2.5}$ levels are slightly higher in summer than in winter, but for PM_{10}, its contribution remains the same for both seasons. This seasonal variation of $PM_{2.5}$ can be attributed to regional influences combined with meteorological factors. Also, the higher contribution of secondary particulates in winter reduces the relative contribution of industries.

It is evident from Figure 26 that dust is the major contributor to ambient PM_{10} concentrations in the Faridabad study area, while combustion sources such as biomass burning, transport, and industries are the primary contributors to atmospheric $PM_{2.5}$ levels. The higher share of the transport sector and secondary particulates in ambient $PM_{2.5}$ compared to PM_{10} highlights their dominance in the finer particle range. Additionally, the annual average concentrations of PM_{10} and $PM_{2.5}$ reveal that the share of all combustion-based sources is significantly higher in $PM_{2.5}$ than in PM_{10}, further emphasizing the prevalence of finer particles in combustion-related emissions.

Emission Inventory

Overview of Emission inventory

- Emission inventory has been prepared for the year 2023 with a resolution of 2 km × 2 km
- Major sectors covered were Industries including brick kilns, residential, refuse, DG sets, hotels/restaurants/open eat outs, construction, crematoria, transport, and road dust
- Emission inventory was prepared for key pollutants PM_{10}, $PM_{2.5}$, SO_2, NOx, CO and NMVOCs
- Activity data was collected using both primary and secondary methods
- Largest contributors of PM_{10}: Road dust (39%), industries (38%), construction activities (13%)
- Largest contributors of $PM_{2.5}$: Industries (56%), road dust (21%), and transport (9%).
- Industries contribute 94% of total SO_2 emissions, emphasizing the need for stringent industrial emission controls
- The transport sector dominates with 78% of NOx emissions, followed by industries (14%) and DG sets (7%)
- The transport sector accounts for 69% of CO emissions and 84% of NMVOC emissions
- Industrial sector contributing significantly to all pollutant emissions
- The transport sector is a major emitter of NO_x, CO, and NMVOCs
- The residential sector contributes notably to PM, CO, and NMVOC emissions
- Road dust and construction sectors contribute significantly to the PM emissions
- Although DG set is a small contributor, this sector is adding to NOx emissions

The development of a comprehensive emission inventory is necessary for understanding the contributions of different sources toward prevailing pollutant levels and is an important step in the air quality management process. Developing an air emission inventory arose from the need to improve air quality across the region and prevent adverse effects on the health of humans and ecosystems. Emission inventory lists the emission contribution of individual pollutant species from different sources within a defined geographic boundary. Apart from formulating action plans, air emission inventories may be developed for a single source or for a very small area for testing the efficacy of pilot experiments or recently deployed control techniques. Emission inventorization is done to assess the change in air quality trends of a region. Emission inventorisation is carried out to understand the spatiotemporal distributions of emissions from different sources existing in a region.

These inventories are generally compiled for various pollutant emissions generated due to energy use in different sectors such as transport, industries, power, residential, hotels/restaurants, etc. In addition, emissions are also contributed by fugitive sources (non-energy use sources), such as road dust, open burning of refuse materials, construction/demolition activities, crematoria, etc. (Figure 27). These sectors were further divided into line, area, and point sources (Figure 28). In this study, we developed and evaluated sectorial emission inventory of particulate matter and other gaseous pollutants in the Municipal Corporation area of Faridabad for the year 2023 of air pollutant loads originating from different sectors viz. transport, road dust, open waste burning, residential, diesel generators sets, Hotels, Restaurants and Bakeries, Crematoria, brick kilns, and construction sector.

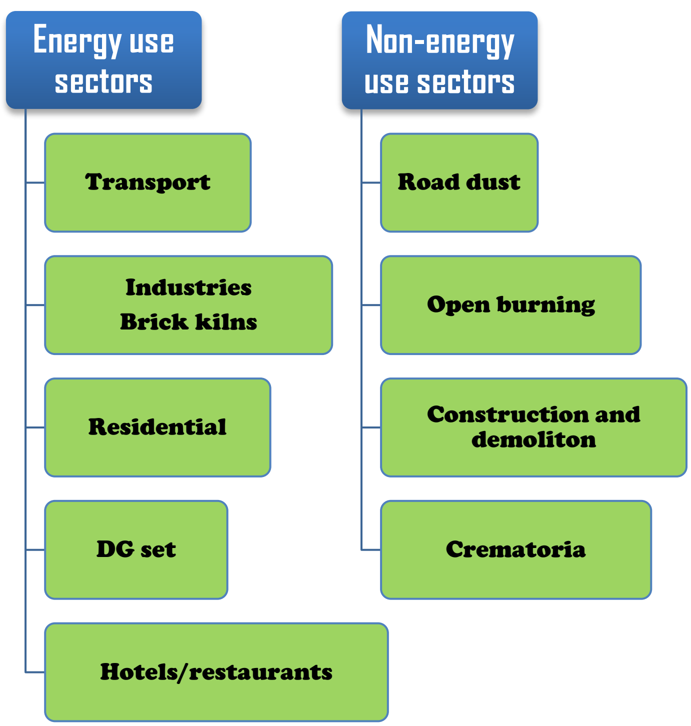


Figure 27: Identified energy use and non-energy use sectors in the study area

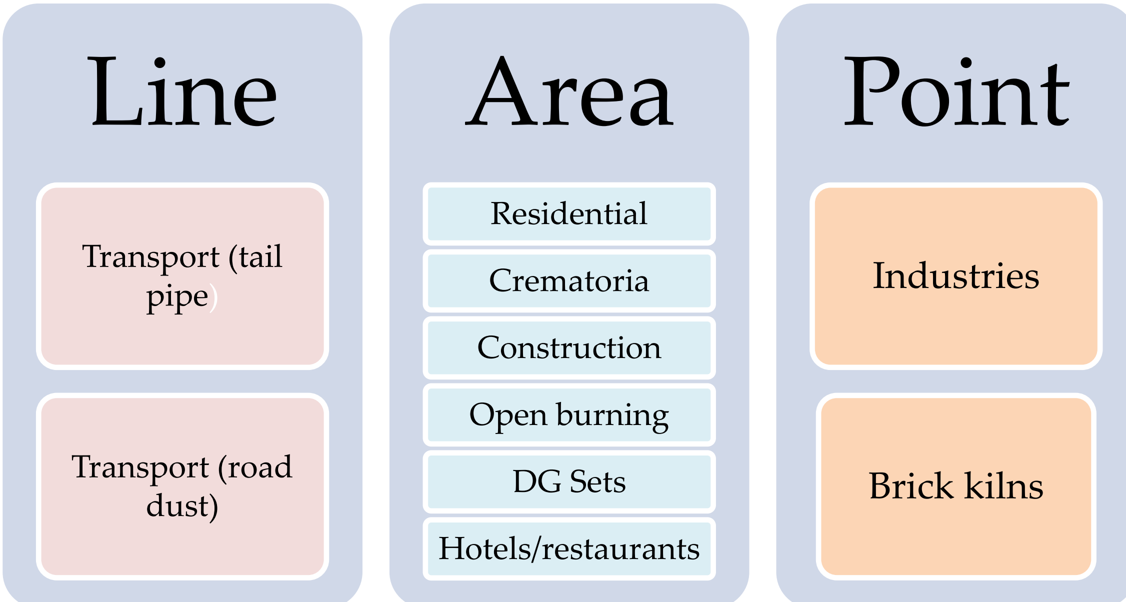


Figure 28: Different pollution sources inventorized in the study area

Methodology

Source-wise wise multi pollutant inventories for PM_{10}, $PM_{2.5}$, SO_2, NOx, CO, and NMVOCs have been prepared for the year 2023 with a resolution of 2 km × 2 km. The main objective of inventories is to improve knowledge of sources, types of pollutants, and their emission rates in the Faridabad region. For controlling air pollution, understanding source emission rates and characteristics is essential, as pollutant emissions, along with prevailing meteorological conditions and topographical factors, determine the ambient concentrations of pollutants to which the residing community will be exposed. The major sectors covered for estimation of emissions in Faridabad are shown in Figure 28. The step-wise methodology adopted in this study for estimation of emissions from different sectors is presented in Figure 29.

Emissions inventory is the quantitative compilation of pollutants emitted from different source categories in a region. While there are several ways of developing an emission inventory, most commonly air pollutants are inventoried using the emission factor approach based on activity data and emission factors as per equation (2). Activity data is described as the measure of activities generating emissions of different types of pollutants. Emission factors are the average emission rate of a given pollutant from a given source per unit source activity such as the burning of fuel or vehicle kilometers travelled. In absence of actual measurement of emissions from different sources (which is a resource and time-intensive exercise), the emissions factor approach is extremely useful and reliable (equation 2).

$$(Ep)a = A \times Ef \times (1 - \alpha) \qquad \textbf{Equation 2}$$

Where (Ep)a is the emission of the pollutants p for activity a, A is the activity data (fuel consumption or other related data), Ef is the emission factor and α is the efficiency of the air pollution control device.

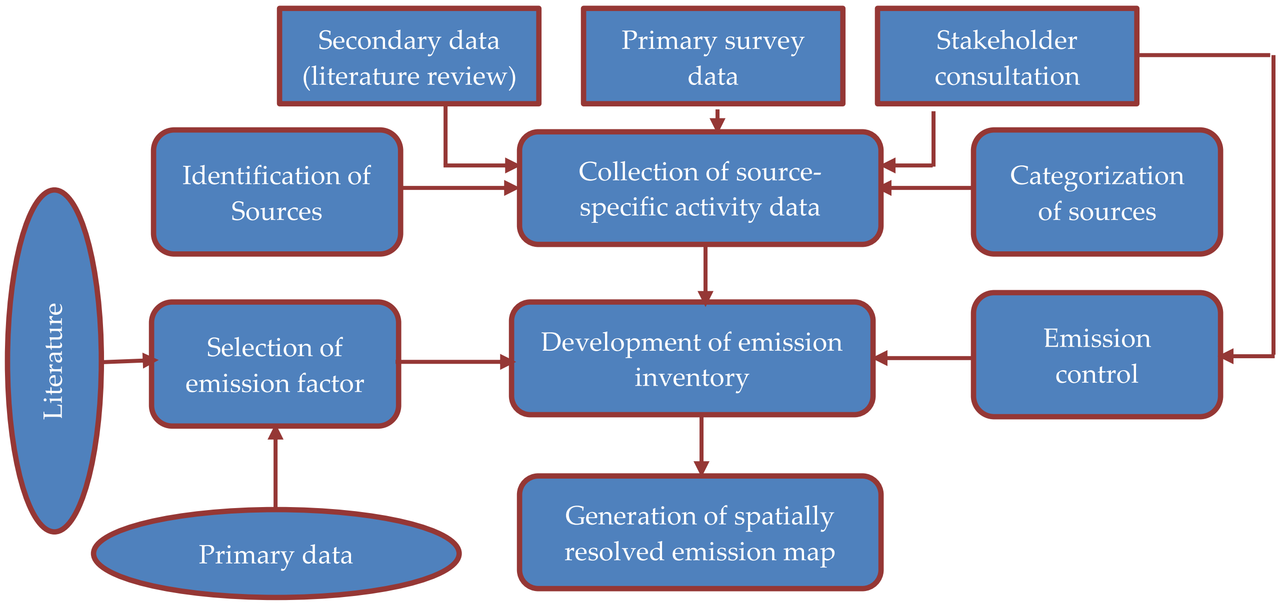


Figure 29: Approach for sector-specific emission inventory preparation

Data Collection

Secondary information/data such as city maps (land use, road network, industrial, etc), demography, vehicular data (registered vehicle types and their growth trends, vehicle kilometer travelled, I & M), traffic patterns, road conditions, festivals, and seasonal activities, industrial emissions data, DG sets, construction patterns were collected from reliable sources. Secondary information was supplemented by primary surveys specific to each sector. Table 4 shows the sector-specific primary surveys carried out to fill the data gaps in the study area. The primary survey locations are shown in Figure 30.

Table 4: Sectors covered for carrying out primary survey in the study area

S.No	Sector	Type of survey
1	Transport	Traffic count surveys / Parking Lot surveys
2	Domestic	Fuel use pattern of different households (type and quantity of fuel usage)
3	DG sets	Commercial /Household fuel consumption (capacity of DG sets, quantity of fuel, operating hours, etc.)
4	Road dust	Road dust monitoring (different categories of roads in the study area)
5	Open burning	Quantity of residue burnt
6	Hotels/restaurants/open eat-outs	Fuel use pattern (type and quantity of fuel used)

To facilitate the collection of emission data, the study area was divided into small grids (2 km x 2 km) as seen in Figure 30 with due consideration to prominent activities in that grid. Appropriate methodologies were adopted for the collection of emission data. The secondary data on the quantity and composition of the sources (transport, domestic & commercial) in different zones of the study area was collected. The data gaps and limitations in data collection were also identified. Focus was kept on the impact zones around the existing air quality monitoring sites of NAMP in the study domains. However, additional sites were selected for primary surveys to fill in data gaps.

Traffic count and parking lot surveys were carried out to estimate emissions from the transport sector. Based on land use patterns in the study domain, locations for traffic count survey were selected for different categories of roads namely arterial, sub-arterial, and local roads. A parking lot survey was carried out for participants owing different categories of vehicles to understand the model of vehicle, vintage, technology, engine capacity, fuel use pattern, vehicle kilometer travelled, etc. Road dust samples were collected from the different categories of roads (where the traffic count was carried out) to estimate emissions from road dust re-suspension due to the movement of vehicles.

Emphasis was given to quality assurance and quality control of data and documentation. Finally, data collected from secondary sources and primary surveys were compiled to convert them into usable forms for the preparation of emission data.

Emission factors were selected as developed by the Indian Institute of Technologies (IITs), the Energy and Resources Institute (TERI), and the Automotive Research Association of India (ARAI) to prepare the database of emissions from the existing sources. National emission factors were used wherever possible, but in the absence of national EF, international EF such as USEPA (for sectors like construction, road dust, DG sets, etc.) were used. Emission data was prepared for the study area as well as grid-wise emissions for 2 km × 2 km grids. For all sectors, emission estimates were carried out for pollutants PM_{10}, $PM_{2.5}$, SO_2, NOx, CO, and NMVOCs

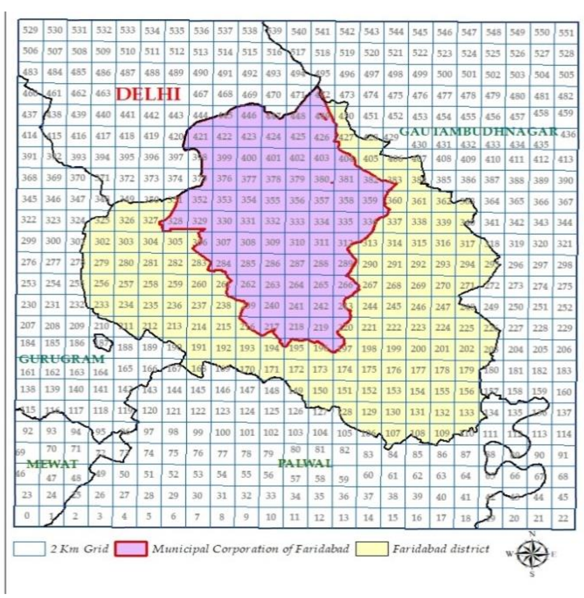


Figure 30: Grid map of Faridabad Municipal Corporation area

The methodology used for estimating the emission inventory, along with the results for each of the identified sectors within the study area, is detailed in the following sections. The sectors are classified into point, area, and line sources.

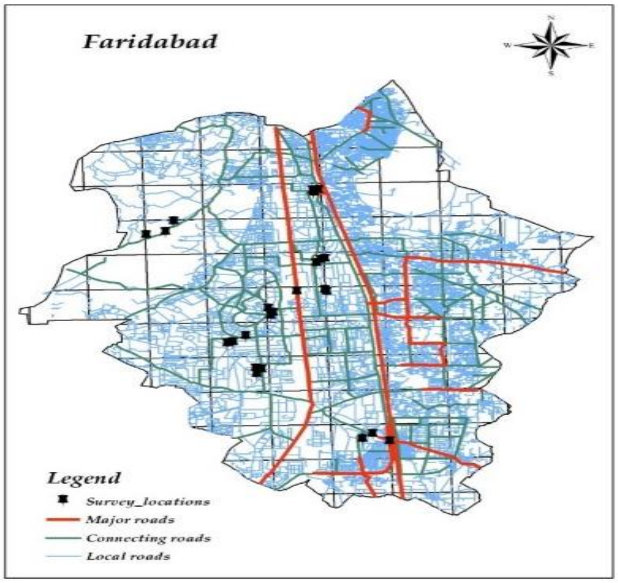


Figure 31: Locations of primary survey in the study area

Point Sources

Brick kilns

In addition to major polluting sectors such as transport, the residential sector, and municipal solid waste burning, brick kilns significantly contribute to the deterioration of ambient air quality. Brick kilns are among the largest coal consumers, with an annual consumption of approximately 35-40 million tonnes in the country (Rajaratnam et al., 2016). In addition to coal, brick kilns also use biomass as a fuel source. The biomass consumption in the brick kiln industry in India varies, but it is estimated to be around 5-15 million tonnes per year. As per the data provided by the Haryana Pollution Control Board, there were 100 kilns in the Ballabhgarh region and 8 kilns in the Faridabad region which were under operation. The production-based approach accounts for the weight of each brick as the activity data. The cumulative weight of the bricks produced annually (from the number of bricks produced annually and the average weight of each fired brick) from all the kilns was used to estimate emissions for the brick kiln industry.

Emissions were estimated using Equation 3

$\boldsymbol{Ep} = \mathbf{Wb} \times \mathbf{Ef}$ **Equation 3**

where Ep is the emission of pollutant p, Wb is the cumulative weight of bricks produced annually and Ef is the production-based emission factors.

There are a variety of technologies that can be used to produce bricks in India. It was understood from HSPCB that the main technology used to produce bricks in Faridabad is Zig-Zag. The total weight of the bricks produced by a particular firing technology is estimated from the total number of bricks produced annually in a region and the weight of the fired brick. After consultation with experts and based on TERI's experience in this sector, we have assumed the weight of the fired brick as 3 kg and the data on the total brick produced was collected from HSPCB. Since bricks are not produced year-round, officials from the HSPCB have indicated that the kilns in these regions operate from March 1st to June 30th each year, thereby totalling 122 days of operation of brick kilns annually. Emission factors for different pollutants are selected from a review of published literature (Greentech Knowledge Solutions and GAINS Asia data set).

Estimated emissions and emission factors used for the estimation of emissions from Brick kilns in the Faridabad study area are summarized in Table 5. Brick kiln emissions are allocated at their respective locations marked on Google Earth (Figure 32).

Table 5: Emission Factors and total emission of different pollutants from Brick Kilns in the Faridabad Study area

Pollutants	EF (g/kg of fired bricks)	Emissions (kg/day) All kilns	Kilns in study area
*PM_{10}	0.26	493	71
*$PM_{2.5}$	0.13	247	36
*SO_2	0.32	607	88
**NOx	0.00004	0.1	0.01
*CO	1.47	2789	402
**VOCs	0.1	190	27

*EF Source: *A roadmap for cleaner brick production in India, 2012, **GAINS Asia*

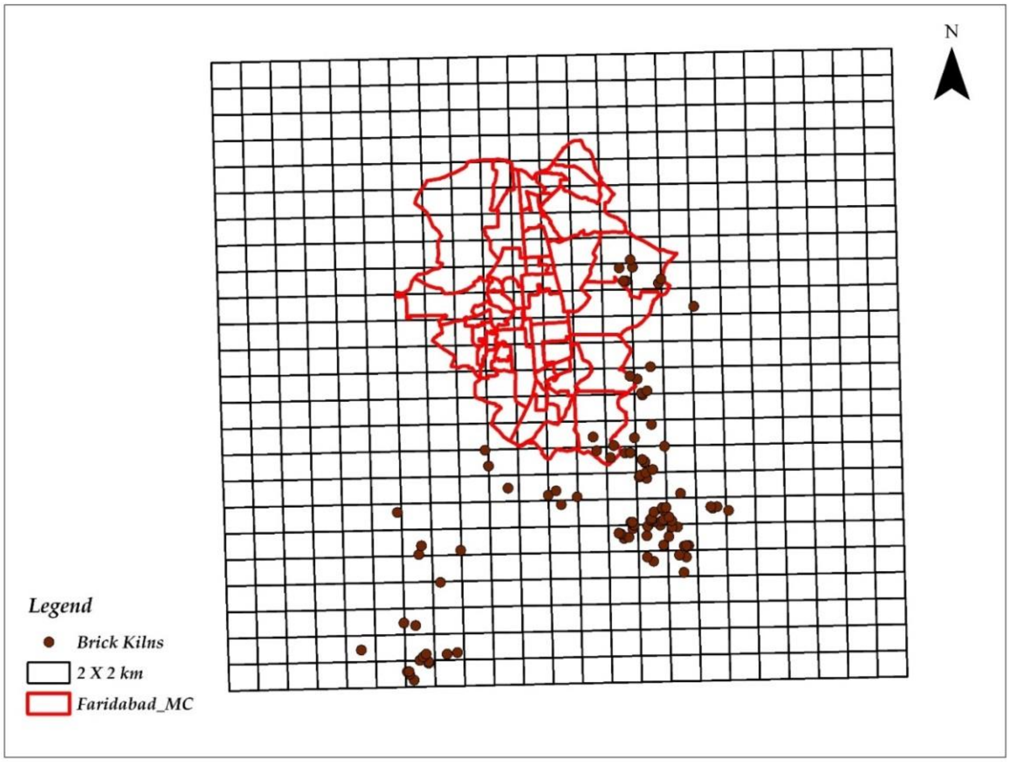


Figure 32: Google image showing brick kilns in Faridabad

Industries

The industrial sector is a major driver of economic growth in India but is also a significant contributor to the declining air quality in many Indian cities. Emissions from industrial activities arise from various manufacturing processes in the study area. A substantial portion of these emissions is due to the combustion of various fossil fuels in boilers, furnaces, and similar equipment. The pollutants produced are released into the surrounding areas through industrial chimneys or stacks, often after passing through air pollution control devices.

To enforce the rules and regulations on polluting industries, the Central Pollution Control Board (CPCB) has classified industries into Red (highly polluting), Orange (moderately polluting), and Green (non-polluting) categories based on the pollution generated by the industry and further sub-categorized into small, medium, and large industries, based on the scale of setup.

According to the data provided by the HSPCB, there are 297 industries in the Ballabhgarh region and 126 industries in the Faridabad region. In Ballabhgarh, out of the 297 industries, 27 are classified under the green category, 179 under the orange category, and 91 under the red category. Similarly, in Faridabad, out of the 126 industries, 8 are categorized as green, 55 as orange, and 63 as red. The number of large, medium, and small-scale industries in the study area is 38, 86, and 299 respectively.

As per the data provided by HSPCB, the major types of fuel used in the industries in Faridabad and Ballabhgarh regions are coal, coke, biomass (wood, agro-waste briquettes), Natural Gas, and Diesel (HSD, LSHS, LDO). Also, the industries are equipped with APCDs with varying controlling efficiencies.

The approach followed for estimating emissions from the industrial sector is based on the activity data of fuel consumption in the manufacturing processes, the type of fuel consumed, and the type of Air Pollution Controlling Devices (APCDs) equipped in the industries.

The emissions from the industrial sector are estimated using the fuel consumption data and emission factor as per equation 4.

$$Ep = Cf \times Ef \times (1 - \eta) \qquad \textbf{Equation 4}$$

Where **Ep** is the emission of pollutant **p**, **Ef** is the emission factor of the fuel consumed, **Cf** is the fuel consumed in the industry, and **η** is the efficiency of the APCD device installed in a particular industry.

Table 6 shows the emission factors of different pollutants used to estimate emissions from the combustion of different fuels in the industries of the Faridabad Study area. Figure 33 shows the Google Earth map of the industries in the study area Figure 34 represents the emissions of different pollutants from the industrial sector in the Faridabad study area.

Table 6: Emission factors used for estimation of emissions from industries in the study area

Fuel/Pollutant	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	NMVOC
***Wood (g/Kg)**	17.3	15.743	0.2	1.3	126.3	114.5
Coal (g/Kg)	**187.6	**65.66	**9.75	*4.5	*0.3	-
Coke (g/Kg)	**80.4	**28.14	**9.75	*4.5	*0.3	-
#HSD (g/L)	0.24	0.216	9.405	1.2	0.6	-
#LSHS (g/L)	2.592	1.737	9.405	6.6	0.6	
***Natural Gas (Kg/10^6m³)**	121.6	121.6	9.6	1600	1344	0.091
#LDO (g/L)	0.24	0.216	0.33858	1.2	0.6	-

*https://cpcb.nic.in/displaypdf.php?id=QmFuZ2Fsb3JlLnBkZg== . ** *based on ash content (30% for coal and 15% for coke) and sulphur content (0.5% for both coke and coal) of coal and coke,* #https://cpcb.nic.in/displaypdf.php?id=RGVsaGkucGRm

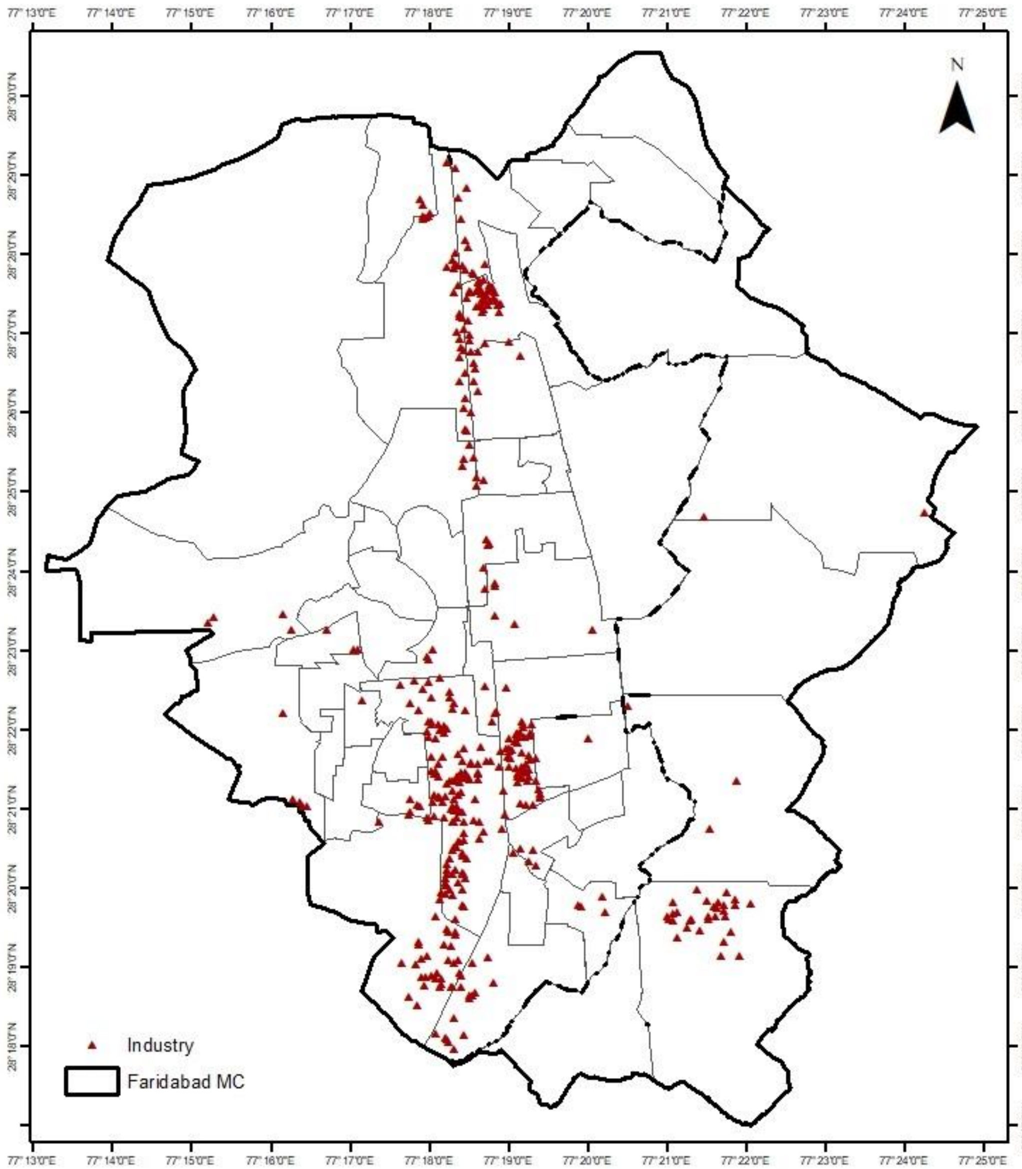


Figure 33: Google image showing the location of industries in the study area

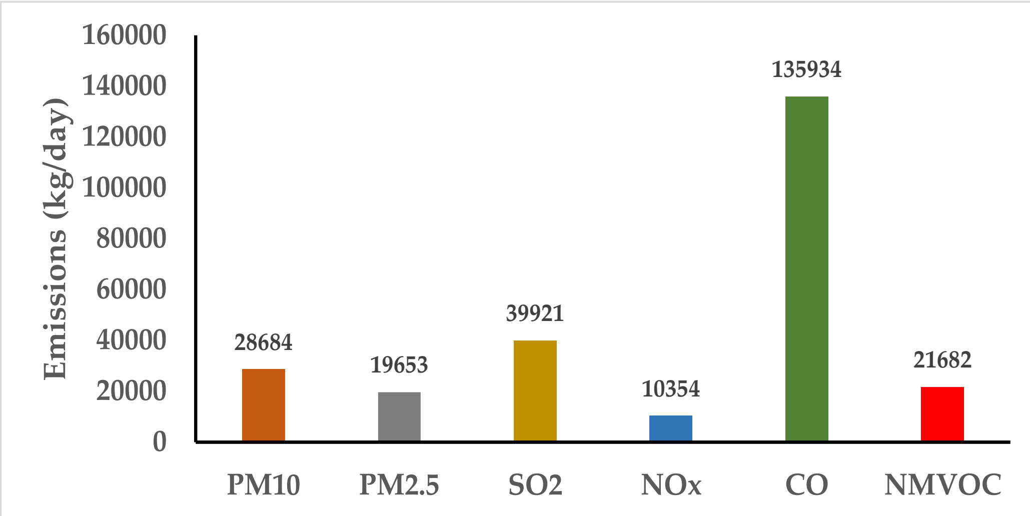


Figure 34: Estimated emissions of different pollutants from industries in the study area

Fuel-wise emissions of different pollutants in the Faridabad study area are depicted in Figure 33.

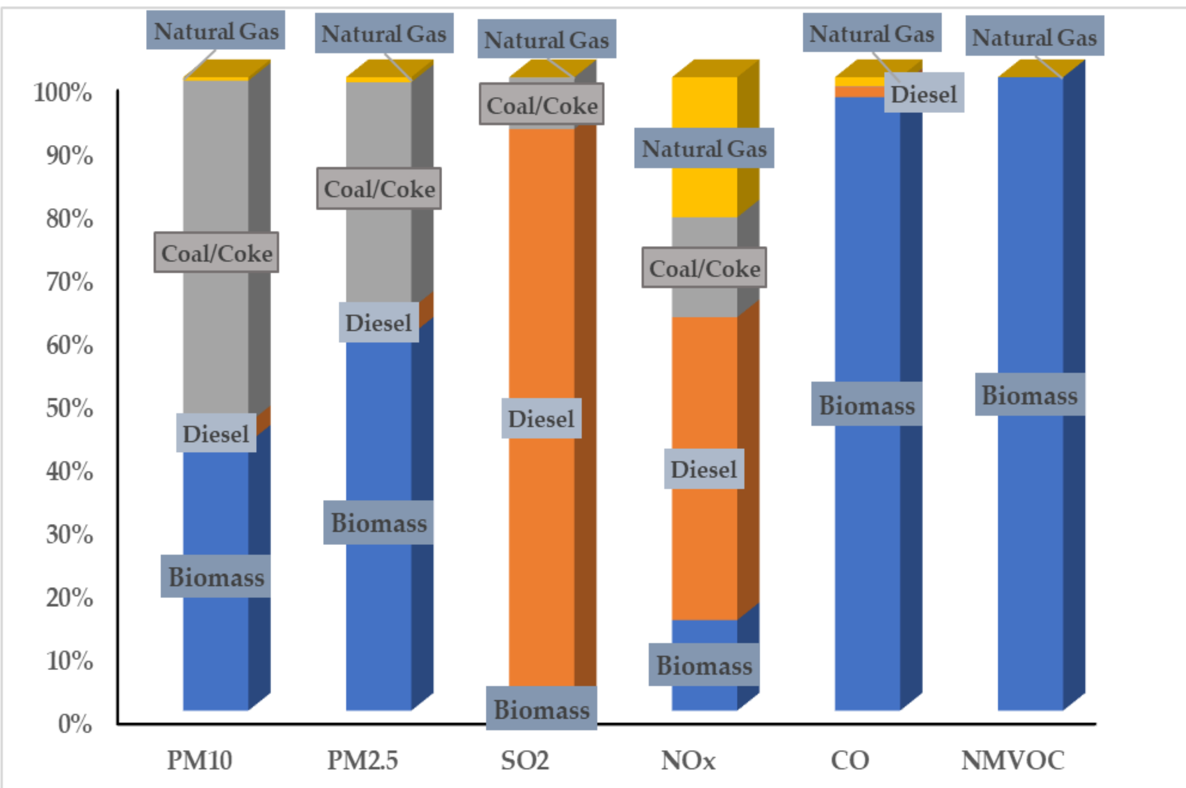


Figure 35: Fuel-wise emissions of different pollutants in the Faridabad study area

The emissions of various pollutants from the industrial sector within the Faridabad Municipal Corporation boundary indicate that biomass fuel combustion results in the highest levels of PM_{10} and $PM_{2.5}$ emissions, followed by coal and coke combustion. Diesel combustion is the primary source of SO_2 and NOx emissions in the study area. Other significant contributors to NOx emissions include natural gas, biomass, and coal/coke combustion. Biomass combustion, which encompasses wood, agro-residue, briquettes, etc., is the main source of CO and NMVOC emissions.

Area Sources

DG sets

There is no thermal power plant in the study domain. Diesel Generator (DG) sets play a crucial role in India's power generation and provide a reliable backup and standby power solution. DG sets find extensive usage in various sectors, including commercial establishments, industries, hospitals, data centres, telecommunications, and residential complexes to ensure uninterrupted operations during power cuts and load shedding. Despite the increasing emphasis on renewable energy and decreasing power deficits, DG sets continue to be a crucial component of India's power infrastructure, ensuring reliability and resilience in the face of electricity supply challenges.

Emissions from the DG set operations depend on the capacity of the DG set, the type and quantity of fuel used, and the operational hours of the DG set and the emissions from DG set usage in the study area were estimated using Equation 5.

$$Ep = ENdg \times Efp \qquad \textbf{Equation 5}$$

Where Ep is the emissions of pollutant p, ENdg is the energy used in DG sets and Ef is the emission factor of the pollutant p. Edg, the energy used by DG sets in the study area was estimated using Equation 6.

$$ENdg = Cdg \times t \times 3600000 \qquad \textbf{Equation 6}$$

Where ENdg is the energy used in Joules, Cdg is the capacity of the DG sets in kW, t is the duration of operation of DG sets in hours and 3600000 is the conversion factor from kW-hr to Joules

A questionnaire-based primary survey was conducted at the selected eight grids in the MCF area to develop the primary data on the capacity of DG sets and duration of operation. The survey was conducted in office complexes, malls, residential societies, commercial buildings, hospitals, mobile towers, etc. This was extrapolated in other grids in the study area to get the emissions from DG sets in the entire study area. In addition, information related to the operations of industrial DG sets was collected from the HSPCB. As per the data provided by HSPCB, all industries in the study area use DG sets with varying capacities ranging from 5 kVA to 7250 kVA. Based on the primary survey carried out in the study area, the average operating hours of DG set was 2.5 hours per day.

Emission factors (EF) for the development of emission inventory of DG set operation in the study area were taken from AP-42, USEPA (Table 7)

Table 7: Emission factors of different pollutants for estimation of emission from the diesel generator set operation

Pollutant	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	NMVOC
ng/J	133.3	113.3	124.7	1896.3	408.5	154.8

Source: https://www3.epa.gov/ttn/chief/ap42/ch03/final/c03s03.pdf

The estimated emissions of different pollutants from DG set operations in the study area are depicted in Figure 36.

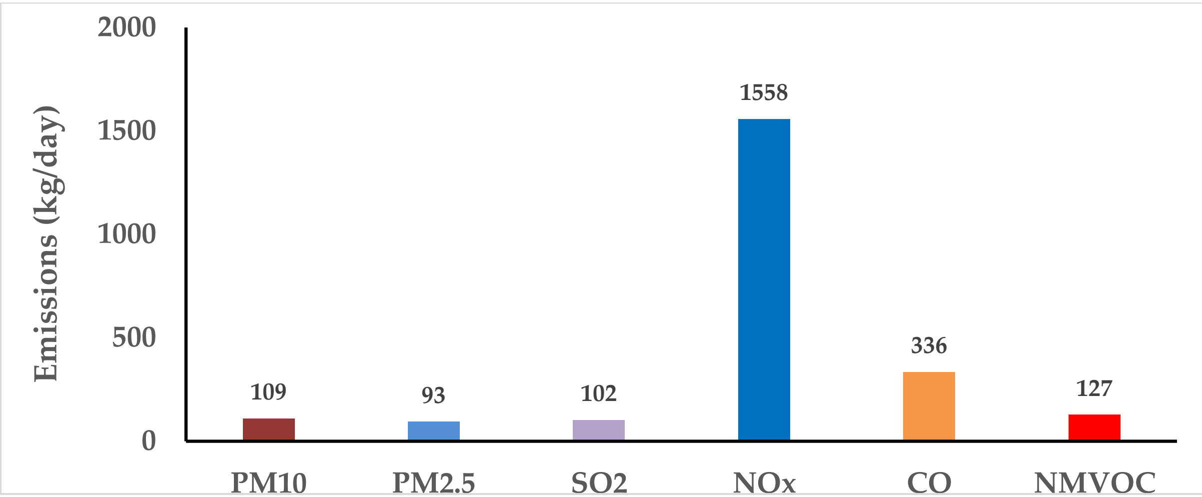


Figure 36: Estimated emissions of pollutants from DG set operations in the study area

Hotels and restaurants

The use of coal, liquefied petroleum gas (LPG), and wood in restaurants, eateries, and hotels plays a significant role in contributing to air pollution. While these establishments rely on these fuels primarily for cooking and heating, the specific use of wood and coal in tandoors and barbeques is particularly concerning. The burning of these solid fuels releases a variety of harmful pollutants into the atmosphere, particularly, the use of coal in this sector is a major source of sulphur dioxide (SO_2). While LPG is considered a cleaner fuel compared to coal and wood, its combustion still produces nitrogen oxides (NOx) and other pollutants that can contribute to the formation of ground-level ozone and smog, particularly in urban settings.

To inventorize emissions from this sector, a primary questionnaire-based survey was carried out in the eight selected grids to understand the fuel usage pattern in hotels/restaurants/bakeries in the study area. The collected fuel consumption data from the restaurants/eateries/hotels/bakeries is used to quantify the emissions. This was extrapolated in other grids in the study area to get the emissions from this sector in the entire study area The emission factors are adopted from published literature. We have assumed that no control devices are installed in the restaurants to control the emissions.

Emissions of different pollutants from restaurants/eateries were calculated using Equation 7.

$$Ep = Cf \times Efp \qquad \textbf{Equation 7}$$

*Where E_p is the **emissions** of a particular pollutant p, C_f = fuel consumption by hotels/restaurants/eateries, E_{fp} is the Emission factor of a pollutant p generated using fuel f (Table 8).*

As per data collected through the primary survey in the study area, there are three major fuels, i.e., LPG, wood, and Coal, are being consumed by restaurants, hotels, and eateries in the study area. Most of the coal consumption is being used in tandoors only.

Table 8: Emission factors for different pollutants from different fuels used in restaurants and eateries.

Pollutant	Coal (g/Kg)	LPG (g/Kg)	Wood (g/kg)
PM_{10}	8.3	0.35*	6.77
$PM_{2.5}$	4.0	0.35*	4.6
SO_2	13.3#	0.4*	0.8
NOx	3.99#	2.9*	1.7
CO	24.92#	2*	66.5
NMVOC	10.5	3.7**	15.89

** Pandey et al. (2014); ** Reddy and Venkataraman (2002) others were adopted from Datta and Sharma (2014), #* https://cpcb.nic.in/displaypdf.php?id=UHVuZS5wZGY=

The estimated emissions of different pollutants in hotels/restaurants/eateries in the study area are shown in Figure 37.

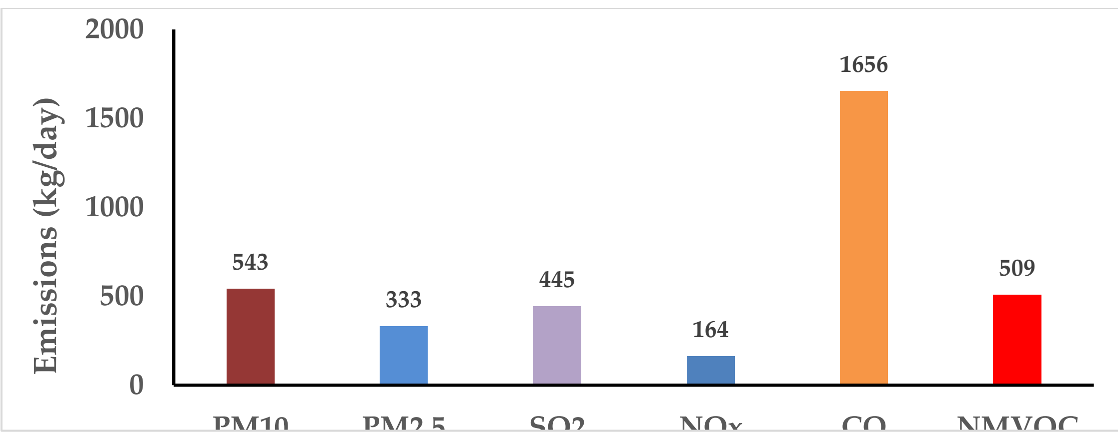


Figure 37: Estimated emissions of pollutants from hotels/restaurants/eateries operations in the study area

Crematoria

Cremation is done in India as a part of the last rituals performed on the deceased person. This ceremony is performed by certain religious groups in society i.e., Hindus, Jains, and Sikhs. A significant quantity of wood is burned during cremation.

The estimation of emissions from cremation is done based on the total wood burnt during the ceremony. Equation 8 is used for the estimation of emissions from the cremation process in the study area.

$$\boldsymbol{Ep = P \times F \times DR \times Qf \times Efp} \qquad \textbf{Equation 8}$$

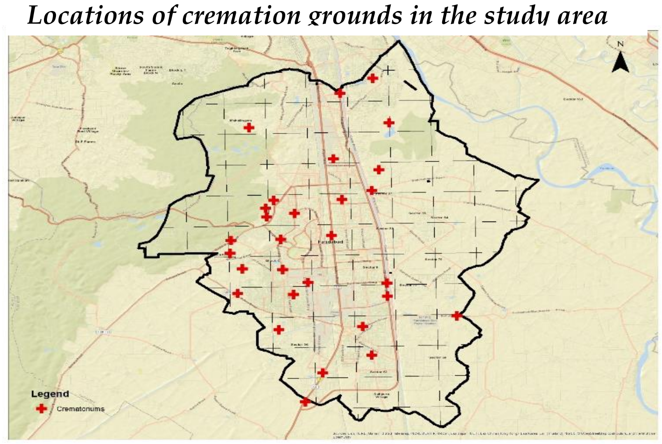
Where Ep is the emission of pollutant p, P is the total population of the study area, F is the fraction of Hindus, Jains, and Sikhs in the study area, DR is the crude death rate of the population, Qf is the quantity of wood required for each cremation, Efp is the emission factor of pollutant p.

As per the census 2011, there are about 87.77% Hindus, 1.91% Sikhs and 0.27% Jains were residing in the district of Faridabad, and we assumed the same percentage for our study area. The projected population of Faridabad for the year 2023 was estimated based on the 2011 census population and population growth rate in Faridabad. On average, 350 kg of wood is consumed in each cremation, as per the interaction with people from different crematoria in the study area and this was also supported by earlier surveys (NEERI, 2010). Thus, the total wood burnt every year in the study area was estimated based on the population (grid-wise) and Crude Death Rate (the total number of deaths per year per 1,000 people), which is found to be 5.5 per 1000 people for Haryana as per the SRS Bulletin 2022. The emissions factor (Table 9) is taken from the review of published literature (Akagi et al. 2011 and Sharma et al. 2016). The total estimated emissions of different pollutants from the cremation of bodies in the study area are depicted in Figure 38. The data provided by MCF indicated that there were about 29 cremation grounds in the study area. The total estimated emissions from the cremation of bodies in the study area were spatially allocated based on the actual location of the cremation ground.

Table 9: Emission factor used for estimation of emissions from cremation of bodies in the study area

Pollutant	Emission Factor (g/Kg)
PM_{10}	18.5
$PM_{2.5}$	9.1
SO_2	0.4
NOx	2.55
CO	93
NMVOC	51.9

Locations of cremation grounds in the study area



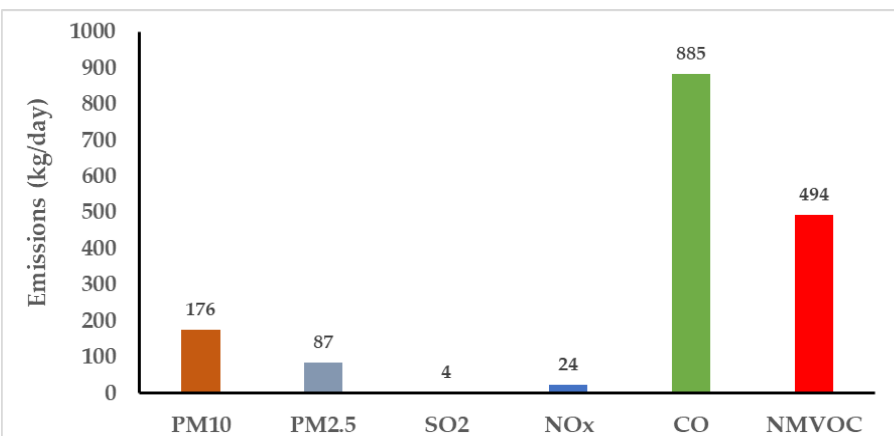


Figure 38: Estimated emissions of pollutants from cremation of bodies in the study area

Construction

The construction sector plays a significant role in India's economic growth, providing employment and infrastructure development. In urban areas, construction or demolition activities contribute significantly to the deterioration of the air quality within all the stages of the building life cycle. Different sources are responsible for the particulate matter emission at construction and demolition sites, which includes site clearance, excavation, and compaction of the construction site, loading and unloading activities, transportation of bulk materials, and movement of construction equipment and heavy machinery such as cranes, dumpers, excavators, and bulldozers. It is also affecting the health of workers and residents living near the construction site. The emissions from the construction of residential and commercial buildings in India have been steadily increasing due to the surge in rapid urbanization. Dust and particulate matter (Total PM, PM_{10}, and $PM_{2.5}$) are common emissions originating from activities such as demolition, foundation work, site preparation, and material transportation.

To estimate emissions from the construction sector, digitization of the identified sites with the help of a polygon covering the Faridabad study area was carried out manually with the help of Google Earth's inbuilt tool. High-resolution images using the GIS tool were also used to identify different construction sites (Figure 39). After the completion of mapping for all the construction activities in Google Earth, ArcGIS software was used to further process the data for the estimation of the construction or demolition area.

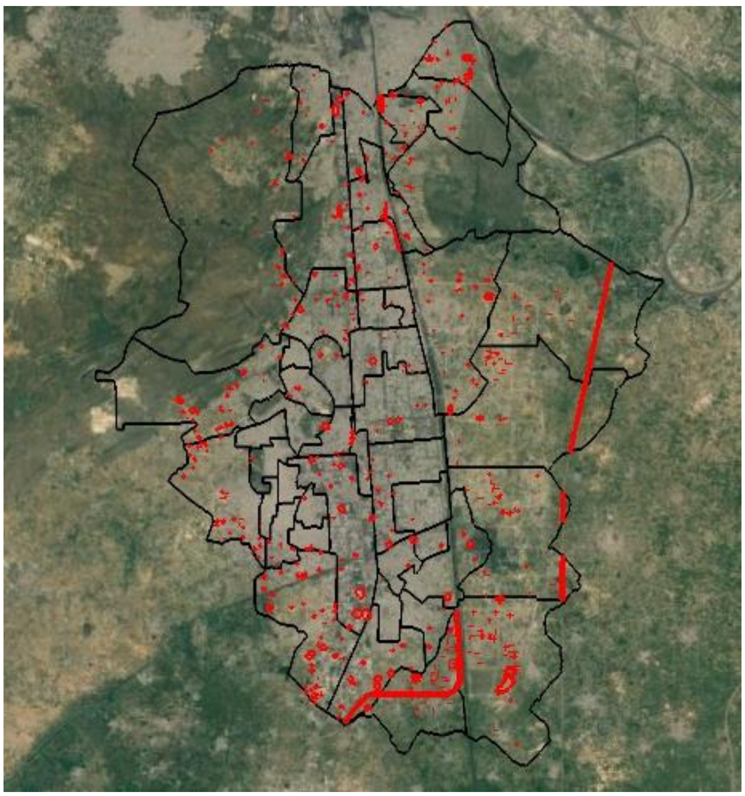


Figure 39: Google Earth image showing construction areas marked in the study area

Particulate matter emission due to construction and demolition activities in the study area was estimated using Equation 9.

$$\boldsymbol{Epm = Ac \times EFpm \times Tc \times (1 - \frac{Dp}{4 \times 365})} \qquad \textbf{Equation 9}$$

where Epm is the emission of particulate matter from construction and demolition activities in the study area (tons); A_c is the area identified construction activity (acre); EFpm is the emission factor of suspended particulate matter (SPM: 1.2 ton/acre/month of activity, Source: https://www3.epa.gov/ttn/chief/ap42/ch13/final/c13s02-3.pdf); T_c is the duration of construction activity (day), D_p is the number of wet days (rainfall > 5mm) in 2023 outside monsoon season, which was found to be 60 days. According to USBR (2002), PM_{10} emission from overburden removal and bulldozing activities during construction activity is 35% of total particulate matter emission. Again, Muleski et al. (2005) have reported the ratio of $PM_{2.5}$ to PM_{10} varied between 0.2 and 0.46 at the construction sites. Based on these, it was assumed that 35% of the particulate matter (Epm) was PM_{10} and 6% was $PM_{2.5}$ (Ahuja et al. 1989; Houck et al., 1989, 1990). As per the data extracted from Google Earth, approximately 819.5 acres of land were under construction in the study area for the year 2023.

The estimated particulate matter emissions to the ambient air during the study from the construction and demolition activities in the study area are given in Figure 11**.**

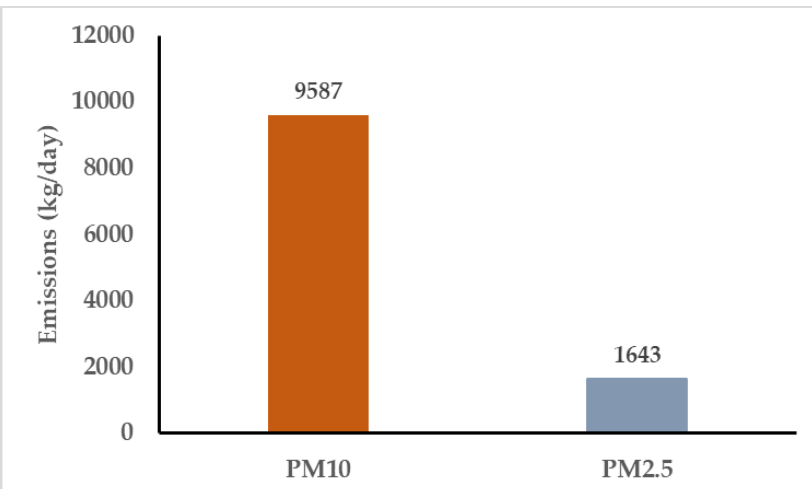


Figure 40: Estimated emissions from construction/demolition activities in the study area

Residential

The emission inventory of the residential sector comprises emissions due to fuel consumed in residential households for cooking, heating, and lighting activities. The emission inventory of the residential sector for the Faridabad study domain was prepared based on the information collected through primary survey and secondary information available with the India Census (2001, 2011) and NSSO (2014).

Equation 10 presents the basic equation employed for emission estimation from the residential sector.

$$E_p = \sum_{a=1}^{n}\sum_{f=1}^{4} Pop_{(a,f)} \times C_{(a,f)} \times EF_{(f,p)} \qquad \textbf{Equation 10}$$

where, $[E_p]_R$ is the emission of a particular pollutant (p) from the residential sector, $Pop_{(a,f)}$ is the population of a particular ward of Faridabad study domain using a particular type of fuel (f), $C_{(a,f)}$ per capita consumption of particular fuel for cooking purpose, $EF_{(f,p)}$ = Emission factor of particular pollutant (p) for particular fuel type (f). Four major fuels that are used in residential households for cooking purposes is included in this emission inventory estimation – a) Fuel wood, b) dung cake, c) crop residue, d) coal, e) kerosene, and f) LPG. Fuel-specific emission factors of different pollutants ($EF_{(f,p)}$) were taken from Datta and Sharma (2014) and Pandey et al. (2014) (Table 10)

Table 10: Emission factors (g/kg) of different pollutants from different fuel types used in the residential sector

Fuel type	$PM_{2.5}$	PM_{10}	SO_2	NOx	CO	NMVOC
Fuel wood	4.6	6.8	0.8	1.7	66.5	15.9
Crop residue	5.7	8.6	0.7	1.8	64.0	8.5
Dung cake	4.4	10.5	0.6	1.0	78.6	24.1
Coal	4.0	8.3	15.3	2.2	59.5	10.5
Kerosene (for cooking)	3.0	3.6	0.4	1.3	43.0	13.3
Kerosene (for lighting)	91.3*	91.3*	NA	NA	29.3*	NA
LPG	0.4*	0.4*	0.4*	2.9*	2.0*	3.7**

** Pandey et al. (2014); ** Reddy and Venkataraman (2002) others were adopted from Datta and Sharma (2014); NA: Not available*

Population and household data of the Faridabad study domain was collected from the India census (2001, 2011) for the years 2001 and 2011. These data were used to derive the annual population growth rate and growth rate of the number of people living in a particular household. These growth rates were then used to project the population and number of households during 2023 based on the population data of 2011. Also, the primary survey was conducted at selected slums of the Faridabad municipal area (Figure 41) to understand the cooking pattern and monthly consumption of different fuels used for cooking activities. Slum areas were selected based on the socio-economic profile and population density of the Faridabad study domain. During the survey, a pre-designed questionnaire was used to gather cooking-related information. Questions that were asked of interviewed households included family size, type of fuel used for cooking, monthly consumption of cooking fuel, etc. The information collected through interviewed households was extrapolated to estimate the fuel consumption in the remaining slums considering similar cooking pattern.

Figure 41: Household survey in the slum area of Faridabad study area

Again, the number of households in other areas of the study domain using a particular fuel for cooking activity during 2023 was calculated using the household amenity dataset of the Census of India (2011). This was used to calculate the number of people using a particular fuel in respective wards/areas by considering the average household population in each ward. However, there is a significant annual growth in household LPG usage after 2011, this affects the biomass and coal use pattern in the households. The biomass and coal consumption use in the households during 2023 was re-estimated by incorporating the growth rate of LPG. State-level annual growth of LPG consumers from 2020 to 2022 (MoPNG, 2020-2022) was used to estimate LPG usage in the Faridabad study domain in 2023. It is assumed, that one LPG consumer is equal to one household-level LPG connection. The increase in the number of households using LPG is then uniformly distributed to adjust the number of fuelwood, dung cake, and coal-using households during 2023. Moreover, data related to per capita consumption of different cooking fuels ($C_{f,a}$) used in the households of the study region was collected from the NSSO report (NSSO, 2014).

Annual consumption of different cooking fuels in the residential households of the Faridabad study area followed the order: Fuelwood (88.91 kt) > LPG (80.12 kt) > Dung Cake (16.29 kt) > Coal (0.52 kt) (Figure 42).

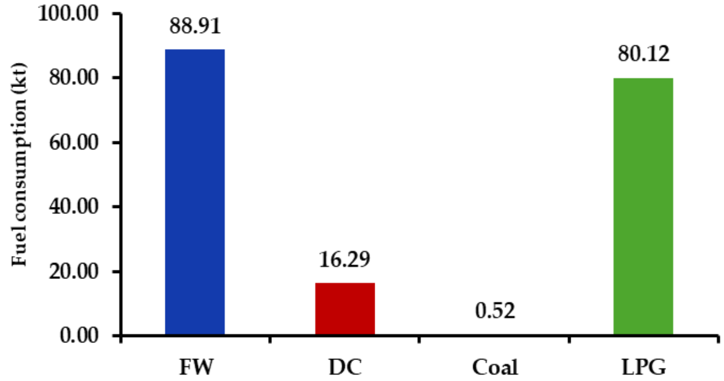


Figure 42: Annual consumption (kt) of different types of fuel for cooking activity in the Faridabad study area during 2023

FW: Fuel wood; DC: Dung Cake; LPG: Liquid Petroleum Gas

The estimated fuel-specific emission (kt) of different pollutants for cooking activity in the residential sector of the Faridabad study area is illustrated in Figure 43 and the estimated total emissions of different pollutants from the residential sector is depicted in Figure 44.

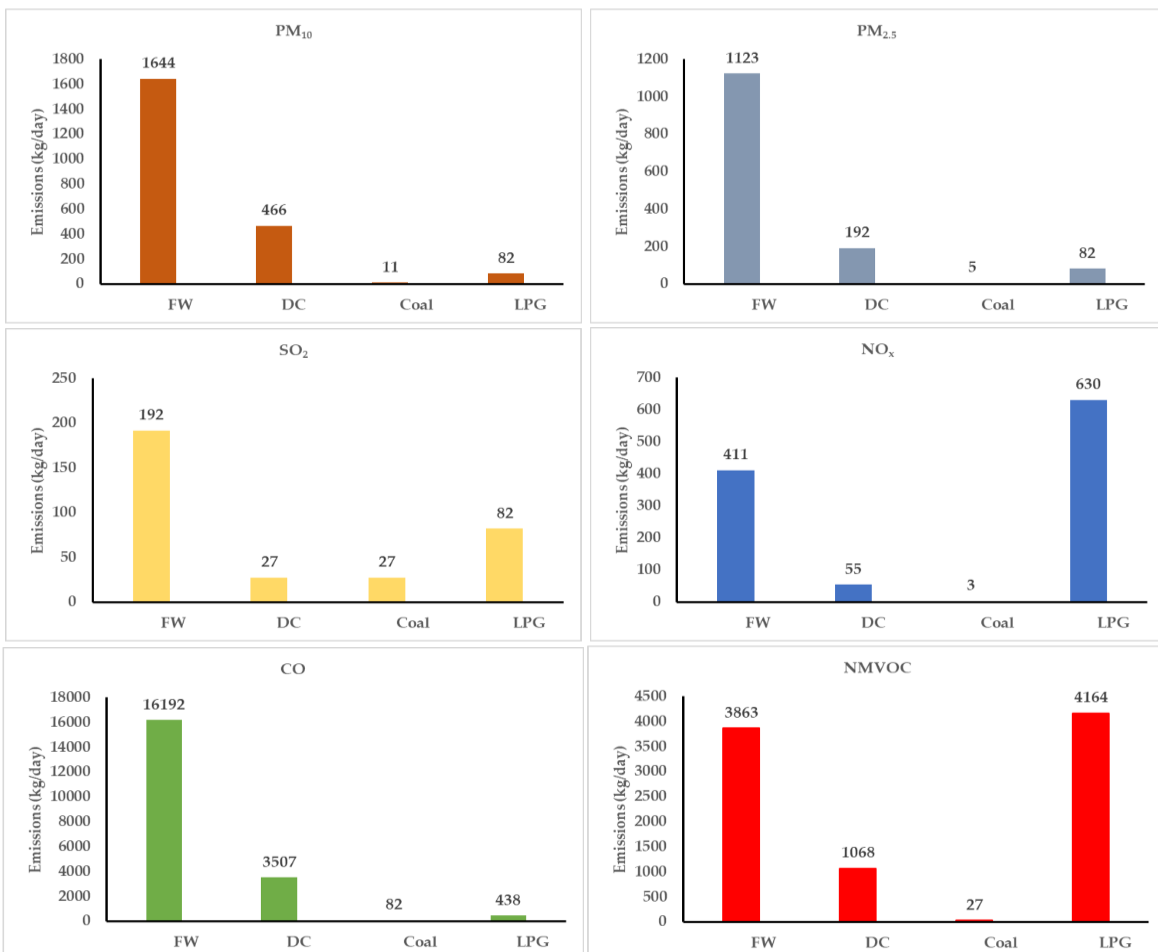


Figure 43: Estimated fuel-wise emission (kg/day) of different pollutants in residential households of the Faridabad study area during 2023.

FW: Fuel wood; DC: Dung Cake; LPG: Liquid Petroleum Gas

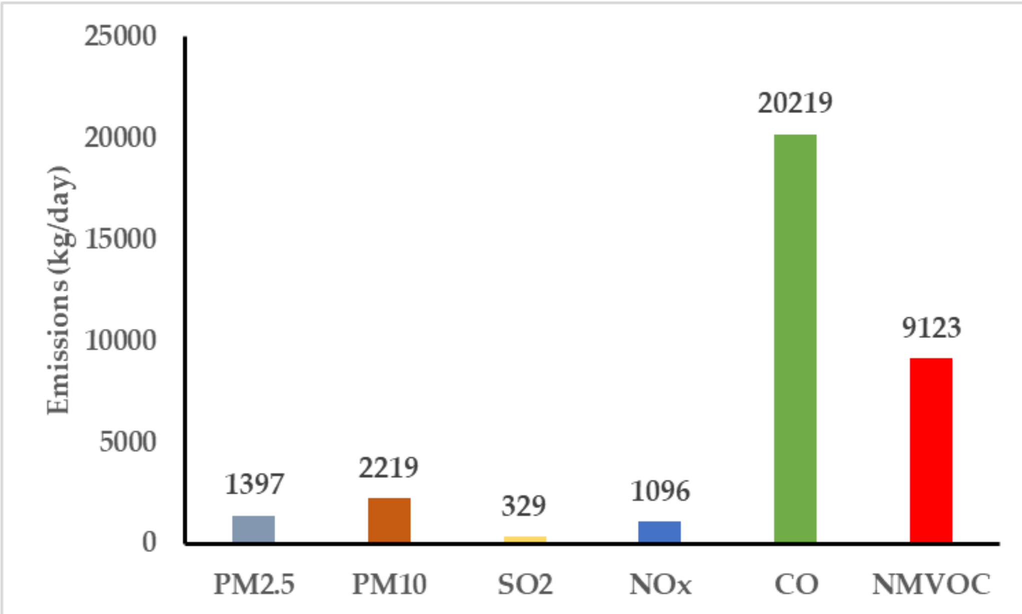


Figure 44: Estimated total emissions of different pollutants from the residential sector in the Faridabad study area

Refuse burning

The emission inventory of refuse refuse-burning sector comprises emissions due to the open burning of waste materials such as waste biomass, paper, plastic, rubber, etc generated from residential households and commercial places. The emission inventory of the refuse-burning sector for the Faridabad study area was developed based on the primary survey and reported data from scientific research journals.

Equation 11 represents the basic equation employed for emission estimation from the refuse-burning sector

$$\boldsymbol{E_p = \sum_{a=1}^{n} Wb_a \times EF_p} \quad \textbf{Equation 11}$$

Where E_p is the emission of a particular pollutant (p) from the burning of refuse materials, Wb_a is the quantity of refuse material burned in the Faridabad study area; and EF is the emission factor of a particular pollutant from burning of the refuse material. The emission factor of various pollutants due to the burning of refuse materials considered in the present study is summarized in Table 11.

It is required to estimate the total quantity of refuse generated in a particular area to calculate the quantity of refuse material burned. The amount of waste generated depends on the socio-economic profile and livelihood of the population in a particular area. In general, there are several ways for disposing of the refuse material but due to lack of proper waste management practices and to reduce the volume of waste, open burning of refuse material becomes a common practice. The fraction of waste that remains uncollected becomes the subject of burning. Therefore, Wb_a is calculated using 12.

$$Wb_a = Pop_{(a)} \times C_{w(a)} \times (1 - \emptyset) \times B_f$$ **Equation 12**

Where, $Pop_{(a)}$ is the population of the Faridabad study area, $C_{w(a)}$ is per capita solid waste generated from a particular area, ϕ is the collection efficiency of solid waste generated, and B_f is the fraction of refuse material burned in a particular area.

Table 11: Emission factor of different pollutants from burning of refuse materials

$PM_{2.5}$	PM_{10}	NO_x	SO_2	CO	VOC
9.8	11.9	3.74	0.5	38	15.5

Source: Pappu et. al (2007)

Population and household data of the Faridabad study area was collected from the India census (2001, 2011) for the years 2001 and 2011. This data was used to derive the annual population growth rate and growth rate of the number of people living in one household. These growth rates were then used to project the population and number of households during 2023 based on the population data of 2011. Again, a primary survey was conducted in slum and non-slum areas of the Faridabad study area to understand the quantity of refuse material generated and collected at the household level. During the survey, a pre-designed questionnaire was used to collect the required information. Questions such as the quantity of waste generated from households per day, type of waste collection facility, type of waste disposal mechanism (door-to-door collection, community bins, or on the roadside), collection frequency of generated waste (once a week, twice a week, thrice a week, every day), etc. were asked to interviewed households. Even, information related to the occurrence of waste-burning incidents and frequency of waste-burning activity taking place near the vicinity of the interviewed households was asked during the survey.

Based on the survey findings, the daily average per capita waste generated in the Faridabad study domain was considered as 0.4 kg/day and the collection efficiency of generated refuse material was estimated as 76%. Moreover, the burning fraction of refuse material depends on the quantity of waste that remains uncollected and the combustible fraction of uncollected waste (comprising of biodegradable, paper, and plastic material). Accordingly, the burning fraction of refuse material is considered as 62% for the Faridabad study area.

The estimated emissions (kg/day) of PM_{10}, $PM_{2.5}$, SO_2, NO_x, CO, and NMVOC from burning refuse materials in the Faridabad study domain are estimated as 1014, 849, 55, 329, 3233, and 1315 respectively (Figure 45).

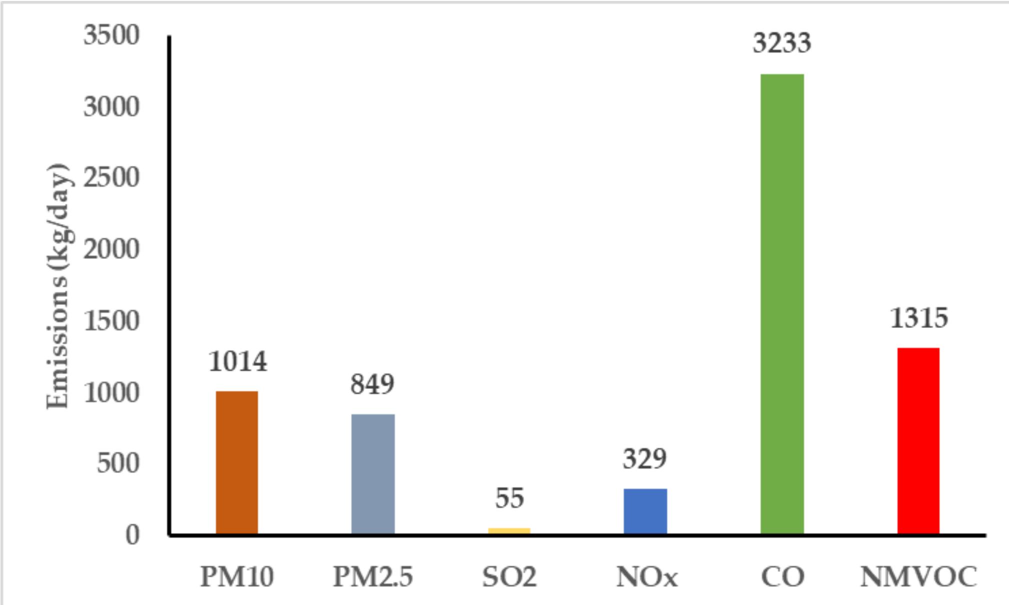


Figure 45: Estimated total emissions of different pollutants from the refuse-burning sector in the Faridabad study area

Line Sources

Transport – tail pipe

Vehicular pollution is a significant contributor to the air quality challenges faced by Indian cities. The rapid expansion of the road transport sector, driven by rising population, economic growth, and advances in technology and financial accessibility, has exacerbated the issue. Diesel vehicles are major sources of particulate matter (PM) and nitrogen oxides (NOx), while gasoline vehicles release gaseous pollutants like carbon monoxide (CO) and volatile organic compounds (VOCs). NOx and VOCs from the transport sector act as precursors for secondary pollutants, such as ground-level ozone (O3) and secondary particulates, which are linked to various respiratory diseases. The transport sector emissions in Faridabad city have been estimated using the on-road vehicle kilometers travelled approach (i.e. VKT) based on traffic count surveys and parking lot surveys at different locations in Faridabad. The basic equation used to quantify tailpipe emission for the transport sector is,

$$E_p = \sum_{c=1}^{n} \sum_{s=1}^{4} VKT_{c,s} \times EF_{c,s,p} \times \varepsilon_{c,s} \times n_c \qquad \textbf{Equation 13}$$

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

Traffic count survey and parking lot survey

The traffic count survey has been conducted in Faridabad to analyze the behaviour of the vehicular population plying on the roads. This was done by counting the number of vehicles and their variation on different roads (Arterial, Sub-Arterial, and Local) of the study domain. For conducting traffic count, a total of 24 roads were selected in the entire region, comprising 8 major (arterial) roads, 8 sub-arterial (connecting) roads, and 8 minor (local) roads that interconnect Faridabad city. These roads were chosen in different grids of the study domain representing different land use patterns - residential colonies (high, medium, and low density), commercial areas, industrial hubs or mixed settlements, etc. To analyse the diversity in different types of vehicles on roads, a manual method of traffic counting was used. A representative sample of traffic count in a period is collected from major, minor, and connecting roads in the different land use regions in Faridabad city. Figure 46 shows the road network density and traffic count locations in Faridabad city.

Figure 46: Map showing selected locations for traffic count and road dust sampling and pictures of traffic count and parking lot surveys

Based on the traffic count results, it is derived that the traffic count on major roads is higher than that of connecting and minor roads. Parking lot surveys were also conducted to understand the type of existing fleet of vehicles and their distributions in the region by collecting information such as model, vintage, technology, fuel mix, average daily distance travelled, occupancy, and mileage. This information is required for the application of appropriate emission factors to each vehicle category. In all, a sample size of about 5000 different categories of vehicles is taken to carry out the questionnaire-based parking lot surveys in Faridabad city. The surveys are random for each category of vehicle without any bias to fuel, age, model, or any other factor. Results of parking lot surveys in terms of vintage distribution are shown in Figure 48.

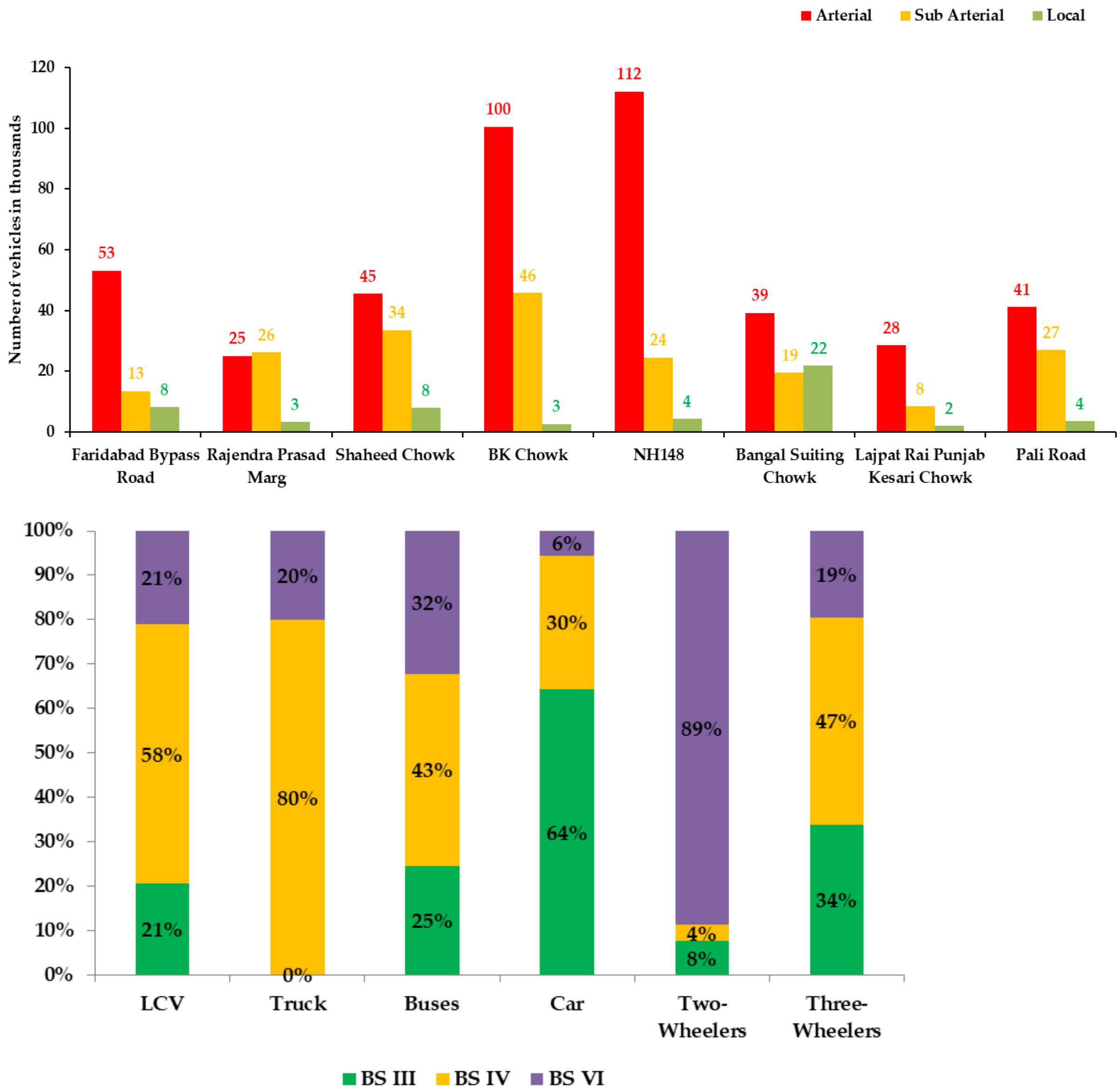


Figure 48: Vintage distribution for different categories of vehicles based on parking lot survey in Faridabad city

In all categories, most vehicles follow BSIV & BSVI norms. However, most vehicle categories especially two-wheelers are found to be majorly following the BS-VI norms in Faridabad city. Technological distributions of different vehicle categories are shown in Figure 49. Petrol cars greater than 1400 cc accounted for 36%, 1000-1400 cc accounted for 58%, and smaller than 1000 cc accounted for 6% of the total petrol cars surveyed. On the other hand, diesel cars less than 1600 cc accounted for 68% 1600- 2400 cc accounted for 20%, and >2400cc accounts for 12% of all diesel cars surveyed in Faridabad city. In the case of two-wheelers, 17% are 2-stroke and 83% are 4–4-stroke in the city. 2W greater than 100 cc accounted for 27%, greater than 200 cc accounted for 4% and 100-200 cc accounted for 69% of the total 2W surveyed.

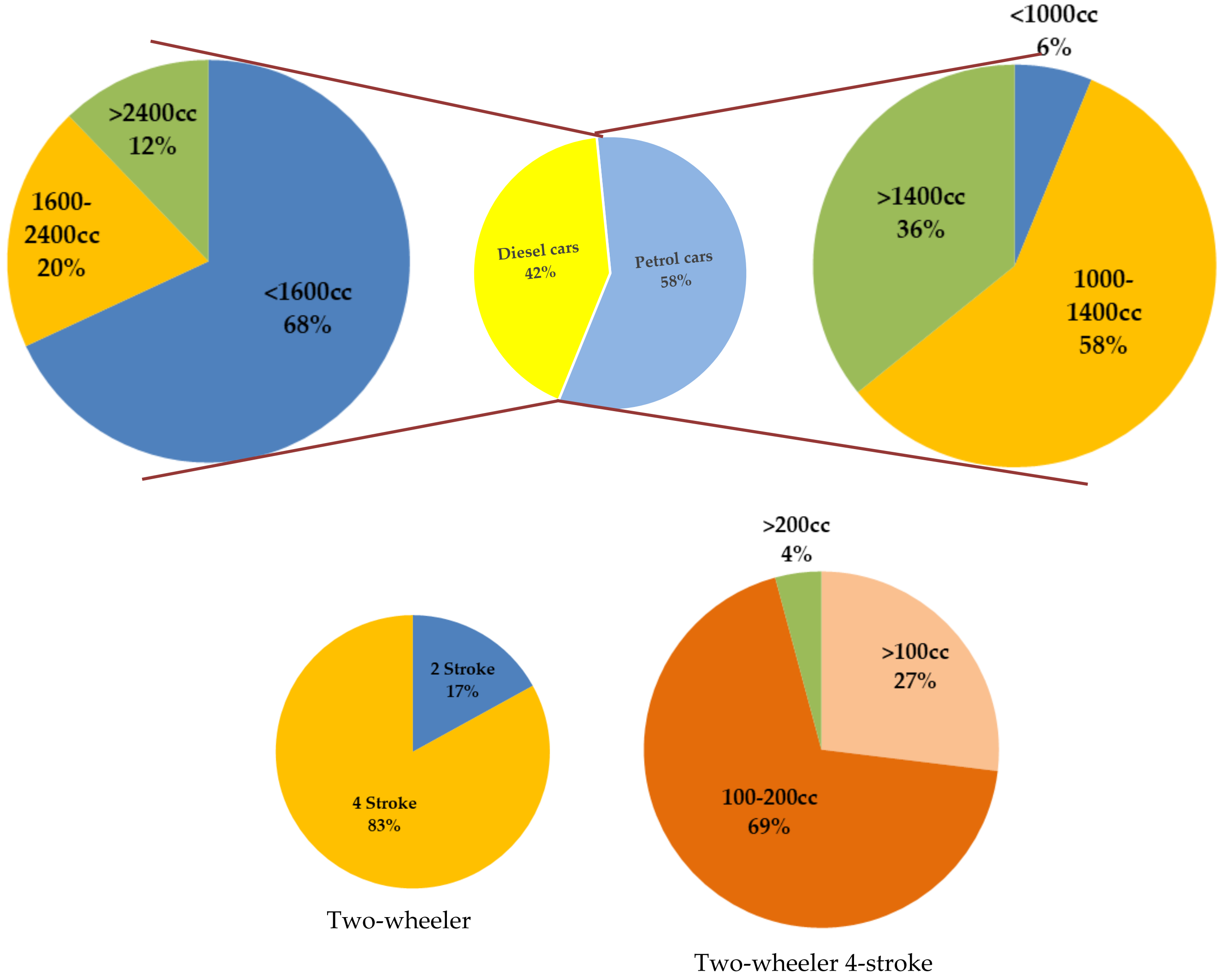


Figure 49: Technology-wise distribution of cars and two-wheelers in Faridabad city

Tailpipe emission for road transport for various pollutants was estimated using Equation 13.

VKT was estimated by using Equation 14.

$$VKT = TC \times RL \qquad \textbf{Equation 14}$$

Where VKT is the Vehicle Kilometer Travelled for a given grid, TC is the traffic count on road for a given location and RL is the total road length of the given grid.

Road length in each of the grids was estimated using GIS. Emission factors play a vital role in computing the emissions from a typical vehicle category. In the current study, indigenous emission factors developed by ARAI, 2016 are used. Emissions from the transport sector are estimated following the methodology briefly illustrated in Table 12 and Figure 50.

Table 12: Methodology for emission estimation

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

The traffic count information of the 24 road locations is used to extrapolate emissions for the whole study domain. By estimating traffic intensities in the surveyed grids, traffic intensities were allocated to other grid-based on resemblance to the land use categories. Finally, VKTs in the remaining grids were estimated using allocated traffic intensities, and their respective road lengths. VKTs were finally multiplied with emission factors to estimate emissions for all the grids in the area.

Estimated emissions of different pollutants from the transport sector in Faridabad city are shown in Table 13 and Figure 51. As seen in Figure 21, trucks and 2W's are responsible for the majority of the PM_{10} emissions and contributed to 36% and 26% of the total PM_{10} emission respectively, followed by Three- Wheelers (12%), LCVs (7%), Buses (6%) and Cars (6%). Two-wheelers (46%) are the major contributor to NOx emissions in Faridabad city, followed by Trucks (18%), LCVs (16%), and Cars (8%). Also, 97% of PM_{10} emissions from vehicles are $PM_{2.5}$, which accounts for 1.17 kt/year of $PM_{2.5}$ emissions from the vehicular sector in the Faridabad city. In total, 1.20 kt/year of PM_{10} and 21.64 kt/year of NOx are released from the transport sector in Faridabad city.

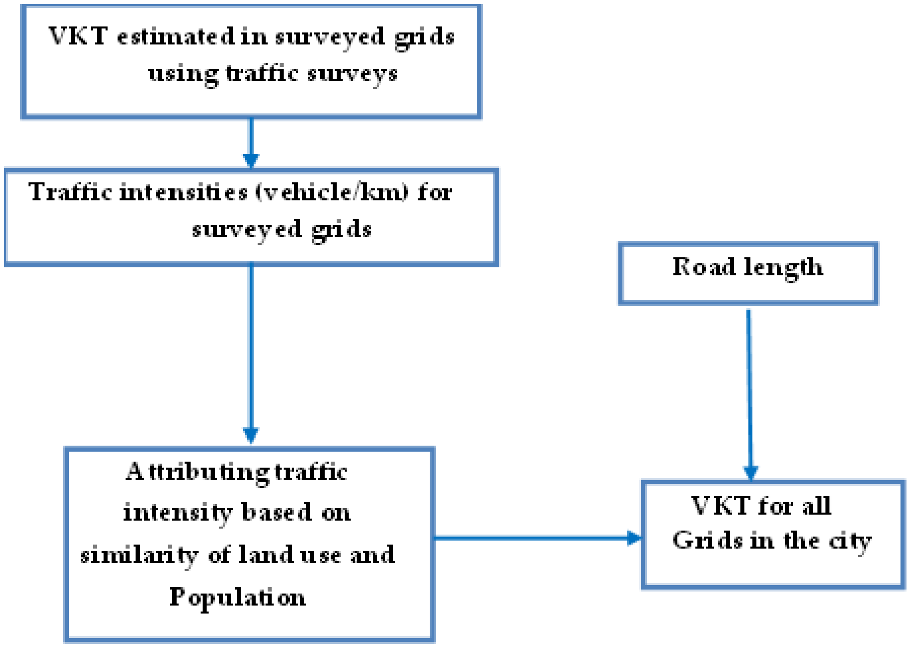


Figure 49: Method used for emission assessment of the transport sector in the study area

Table 13: Estimated vehicle category-wise emissions of different pollutants in the Faridabad study area in kg/day

Pollutants	Truck	Tractor/ Trailer	Bus	Cars	2W	3W	LCVs	Totals
PM_{10}	3188	580	507	507	2246	1087	652	**8767**
$PM_{2.5}$	3049	581	508	508	2178	1089	581	**8493**
SO_2	237	0	59	474	770	178	178	**1896**
NO_x	24813	4661	4529	11816	65773	8205	22121	**141918**
CO	91471	4781	10124	58215	685578	52099	34170	**936438**
HC	89467	2875	4137	13813	236780	87504	6521	**441096**

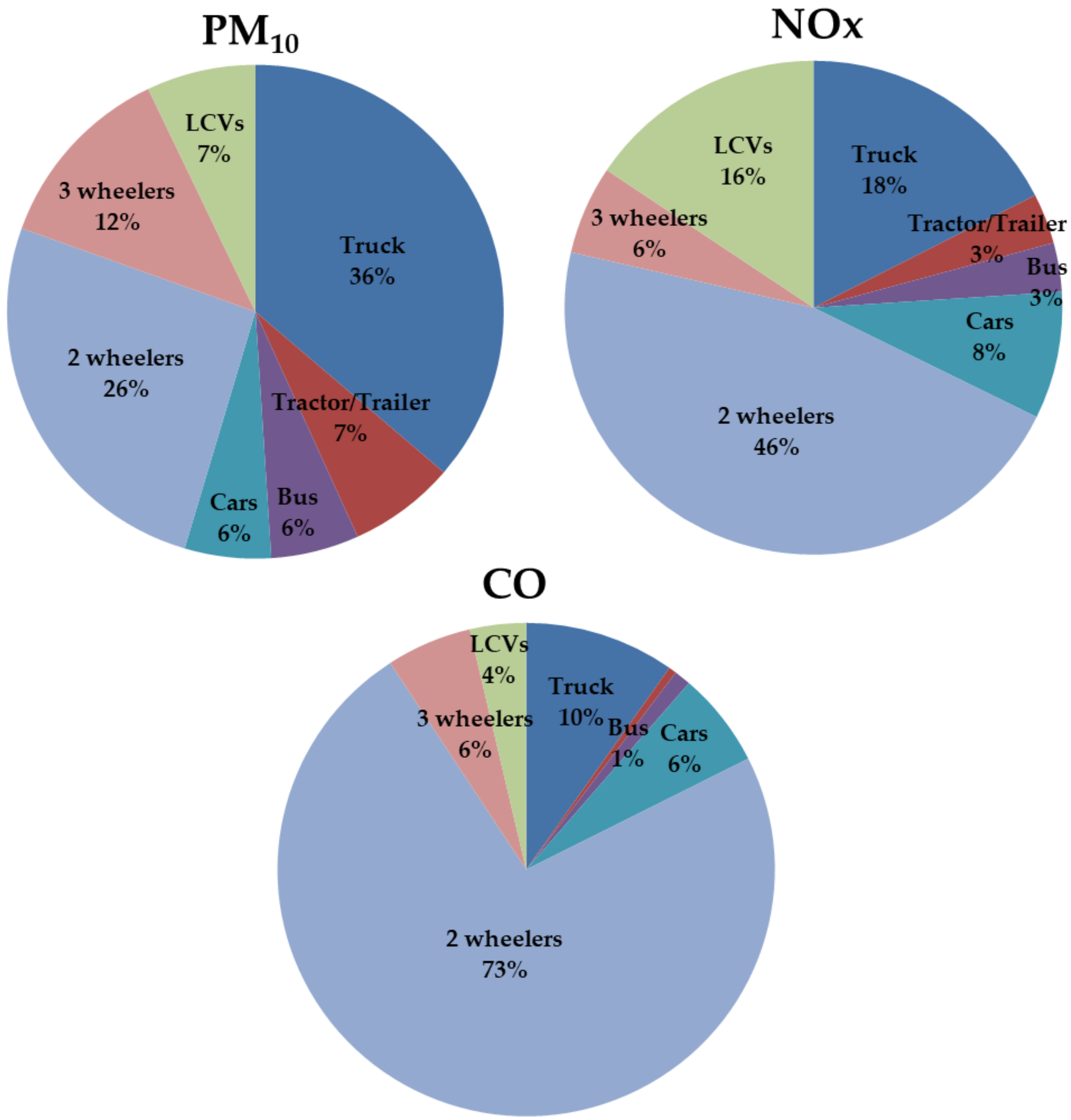


Figure 50: Vehicle category wise distribution of PM_{10}, NOx and CO emissions in Faridabad city

Transport – road dust resuspension

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

Dust samples are collected from the selected roads (Figure 52) in the study area as per the USEPA AP42 method and are tested for their silt content and then converted into silt loading (g/m^2), which is used for the estimation of emissions from the sector. A portable vacuum cleaner was used for the collection of samples from a designated area in the middle of the road. The filter bag of the vacuum cleaner was emptied and weighed before the sampling. Sampling material is collected only from the portion of the road over which the wheels and carriages travel routinely. Collected samples were weighed and stored in a clean and labelled container. After collecting the sample, sieve analysis was performed for 10 minutes by stacking the sieves of mesh no. 20, 28, 60, 100, and 200. The material collected underneath the mesh no. 200 is then collected and weighed as it represents the silt content of the sample.

Figure 51: Collection of road dust samples from Faridabad study area

Road dust samples were collected from the roads (covering arterial, sub-arterial, and minor roads) identified for carrying out the traffic count survey. Therefore, a total of 24 road dust samples were collected from the study region and its silt contents are estimated. Particulate matter emissions from the re-suspension of road dust due to the movement of vehicles on paved roads are calculated using Equation 15 as provided in AP-42.

$$[E_p]_t = \sum VKT_r \times k \times w^{1.02} \times Mo^{0.91} \qquad \textbf{Equation 15}$$

where [Ep]t is the fugitive emission of pollutant (p) from the transport sector; r is the type of road (arterial, sub-arterial, and local); VKT is Vehicle Kilometer Travelled, k is a function of particle size (0.62 for PM_{10} and 0.15 for $PM_{2.5}$); w is the average weight of vehicle travelling on the road and Mo is road surface silt (≤ 75 μm in physical diameter) loading in the unit area. The [Ep]t is directly proportional to the silt loading on the road surface and average weight of the vehicles plying on the road. Based on the k factor, 15% of the [Ep]t is considered as $PM_{2.5}$, while 62% is considered as PM_{10}.

For Faridabad city, the average value of silt loading is found to be 0.72, 2.62, and 4.27 g m^{-2} on arterial, sub-arterial, and local roads, respectively. The VKT for Faridabad city is estimated by using the method explained in the transport sector emission estimation. After estimating [Ep]t using the above equation, the effect of rainy days was considered to finalize the fugitive emission (f[Ep]t) from road dust re-suspension using Equation 16,

$$f\left([E_p]_t = [E_p]_t \times \left(1 - \frac{Dp}{4 \times 365}\right)\right.$$ **Equation 16**

Where Dp is the number of wet days in a year. A total of 49 days is considered wet days in a year based on the meteorological conditions in Faridabad city. The estimated PM_{10} and $PM_{2.5}$ emissions from road dust re-suspension in Faridabad city are 78630 and 18904 kg/day respectively (Figure 53).

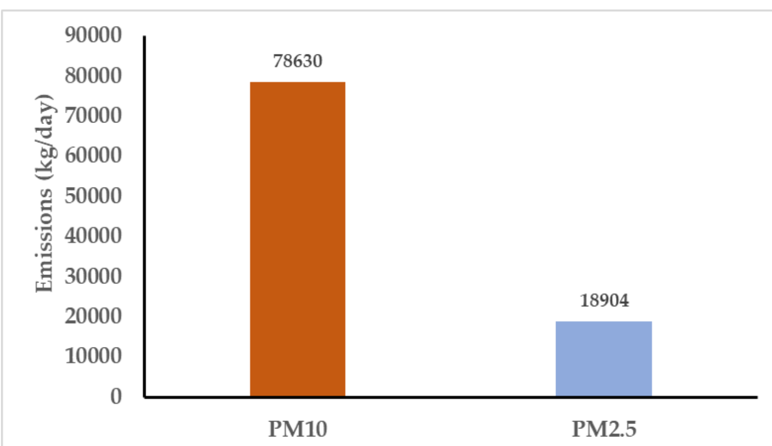


Figure 52: Estimated emissions from road dust resuspension in the study area

Total estimated emissions from all the sectors of the Faridabad study area

The estimated PM_{10} and $PM_{2.5}$ emission load in the Faridabad study area is 130 t/day and 51 t/day respectively. The largest sources of PM_{10} are road dust (61%), industries (22%), transport (7%), and construction activities (7%) whereas $PM_{2.5}$ emissions are predominantly from industries (38%), followed by road dust (37%) and transport sources (16%). This indicates that industrial activities, transport, and dust (including road dust and construction dust) are the primary contributors to particulate matter emissions in the study area.

The total estimated SO_2 emissions in the study area are 43 t/day. Industries are by far the largest source, contributing approximately 93% of the total emissions, which is significantly higher than other sectors. SO_2 is primarily emitted from the combustion of sulfur-containing fuels, such as coal and coke, used by industries. However, the elevated emissions in this study area are specifically attributed to the use of diesel by these industries. This underscores the need for stringent controls on industrial emissions to effectively manage SO_2 levels in the region

155 tonnes of NOx emissions are estimated per day in the Faridabad study area, of which 91% of contributions are from the transport sector. The other major contributors to NOx emissions are industries (7%).

In the Faridabad study area, CO and NMVOC emissions are estimated at 1099 t/day and 474 t/day, respectively. The transport sector accounts for 85% of total CO emissions and 93% of NMVOC emissions. Other significant contributors to CO and NMVOC emissions include the industrial (13% and 5% for CO and NMVOC emissions respectively) and residential (2% each for CO and NMVOC emissions) sectors.

Figure 54 shows the sector-wise contributions to total emissions for various pollutants, while Figures 55–60 illustrate the spatial distribution of total emissions for different pollutants.

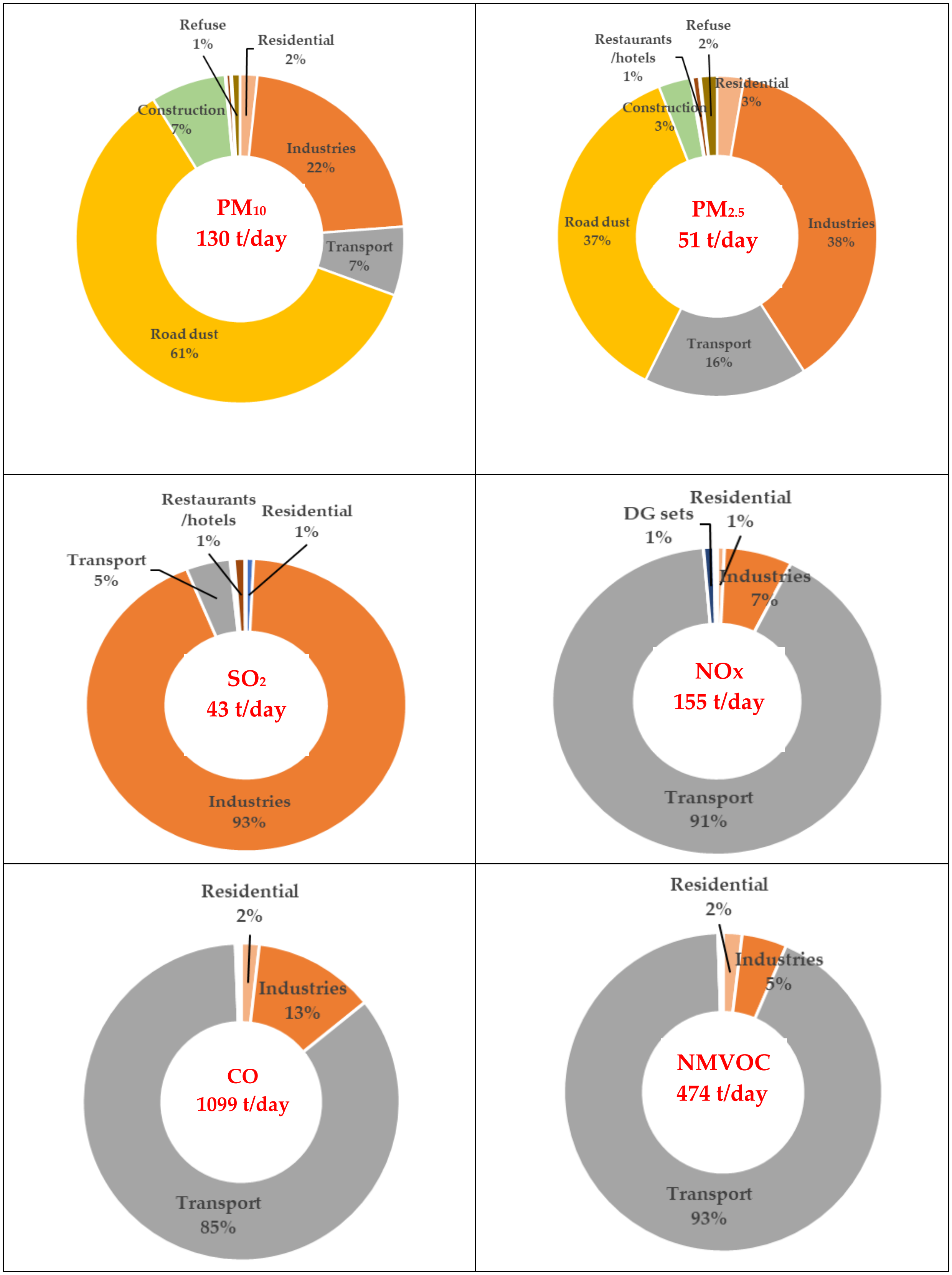


Figure 53: Sector-wise contribution of different pollutants to the total estimated emissions in the Faridabad study area

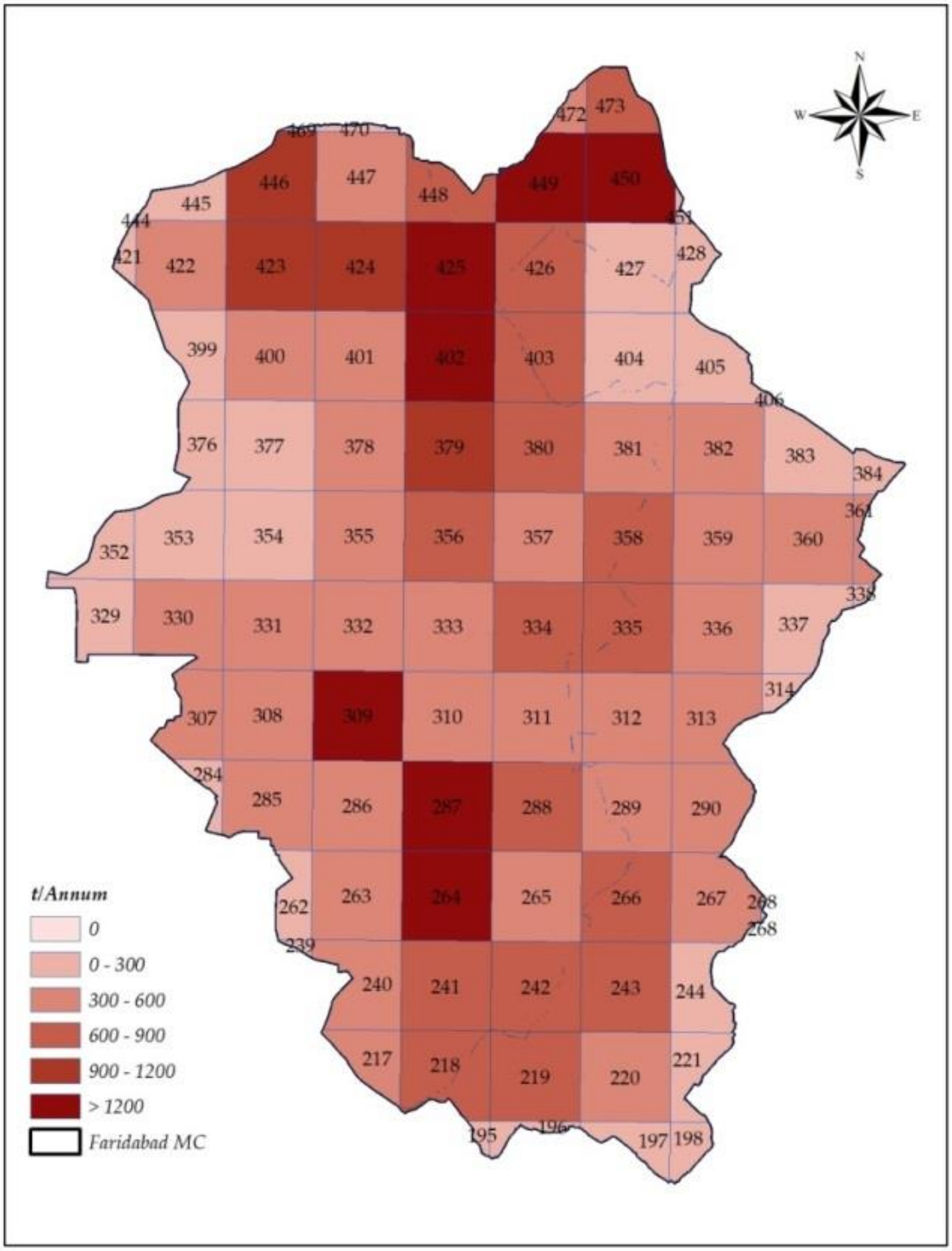


Figure 54: Spatial distribution of total estimated PM_{10} emissions from all sectors within the study area

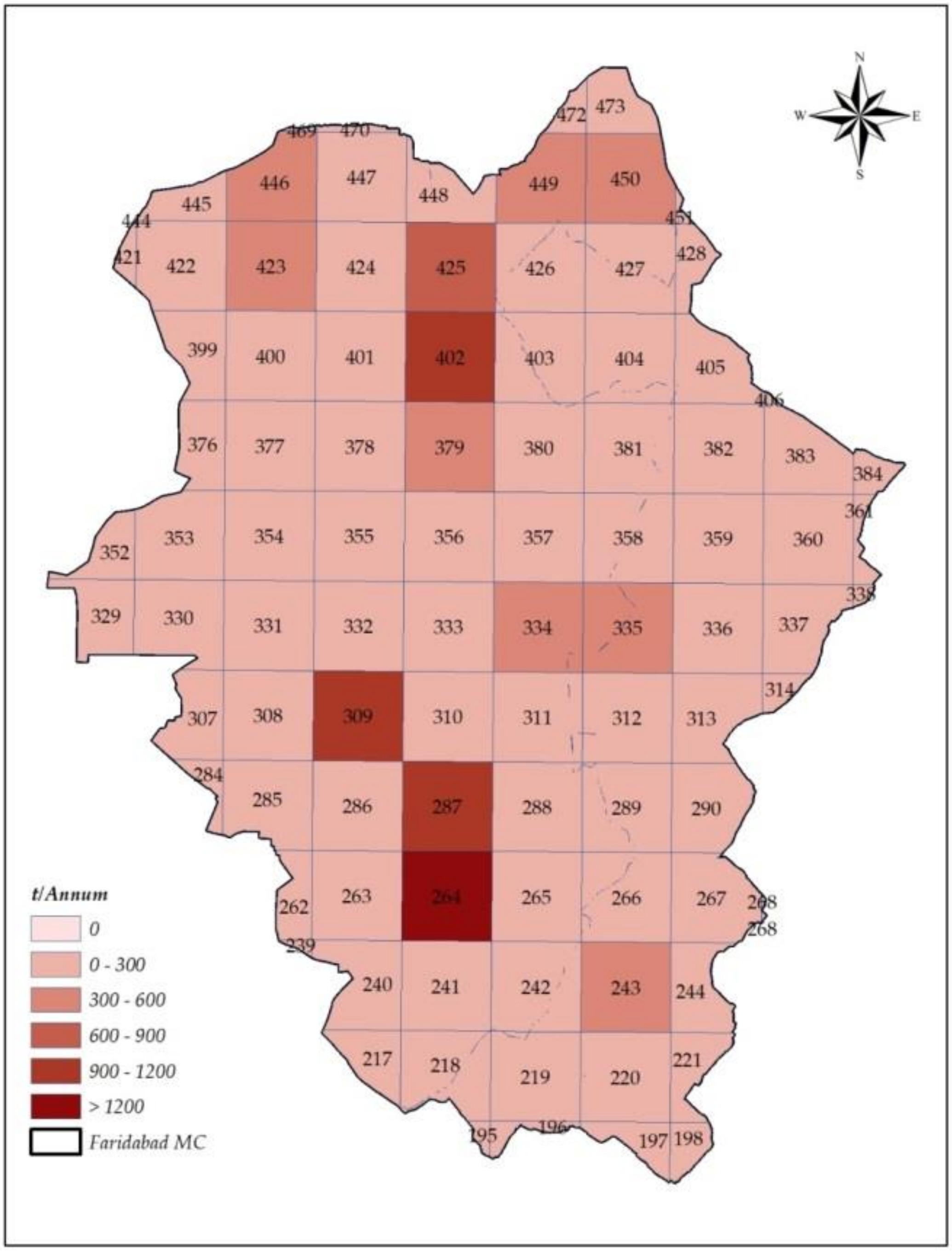


Figure 55: Spatial distribution of total estimated $PM_{2.5}$ emissions from all sectors within the study area

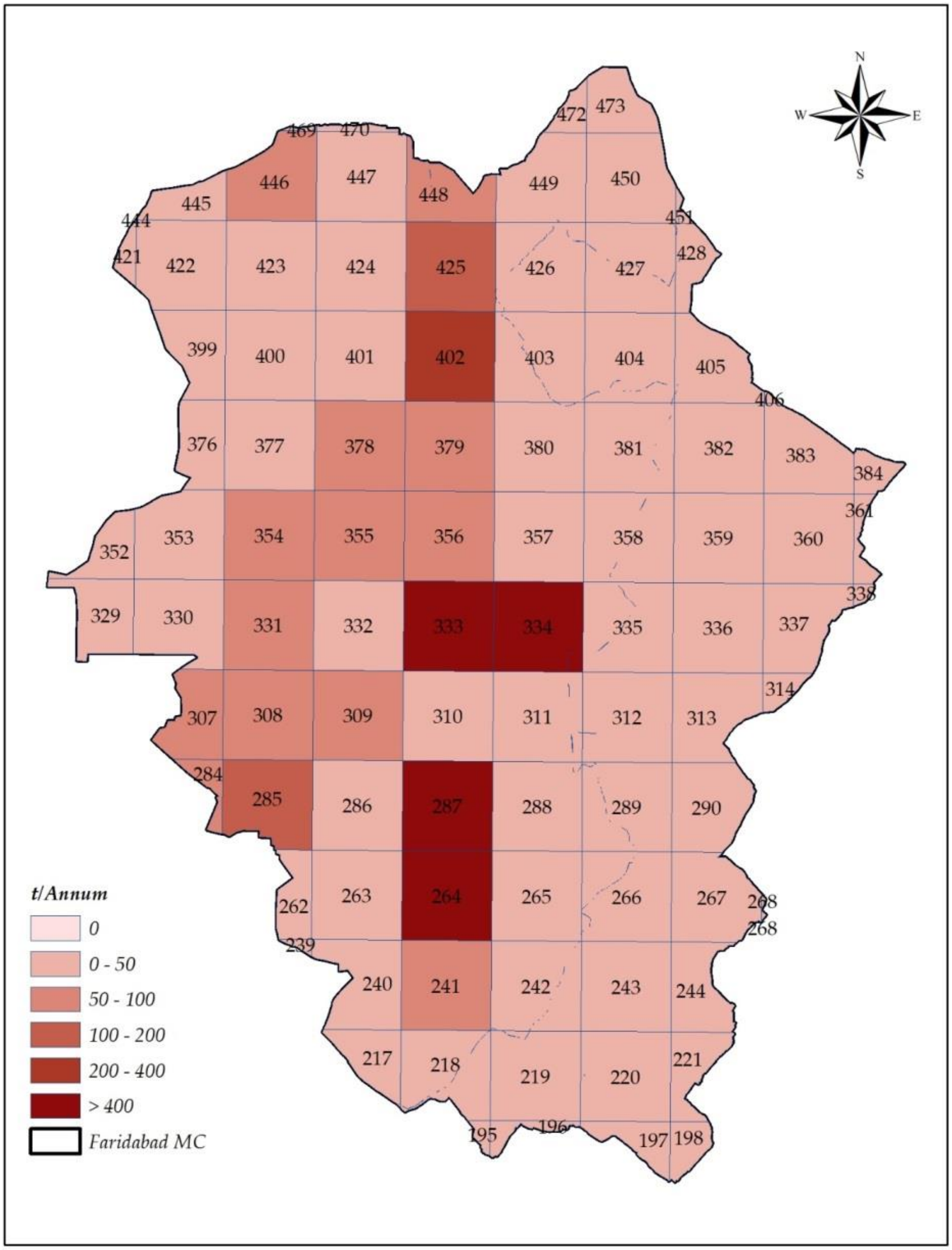


Figure 56: Spatial distribution of total estimated SO_2 emissions from all sectors within the study area

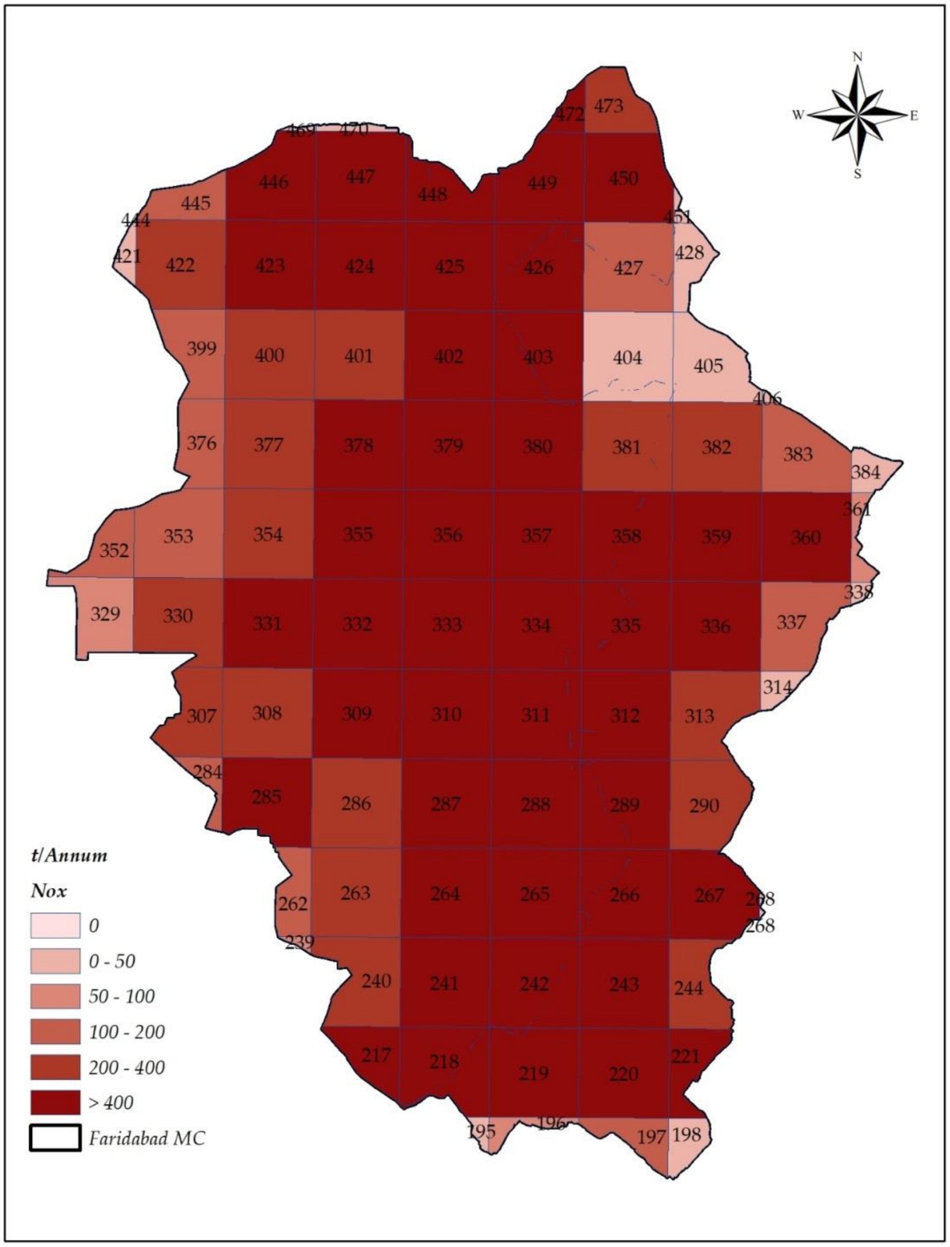


Figure 57: Spatial distribution of total estimated NOx emissions from all sectors within the study area

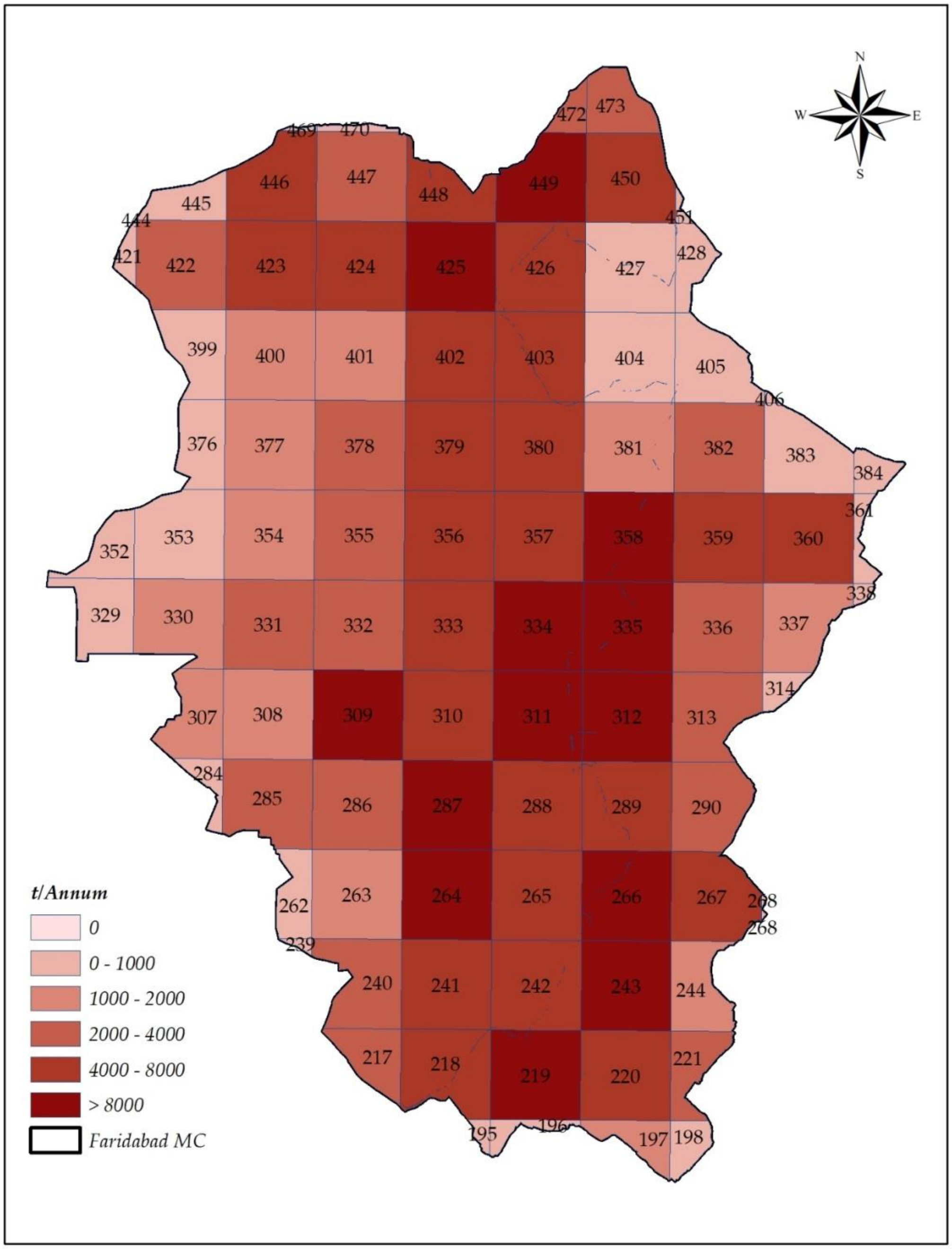


Figure 58: Spatial distribution of total estimated CO emissions from all sectors within the study area

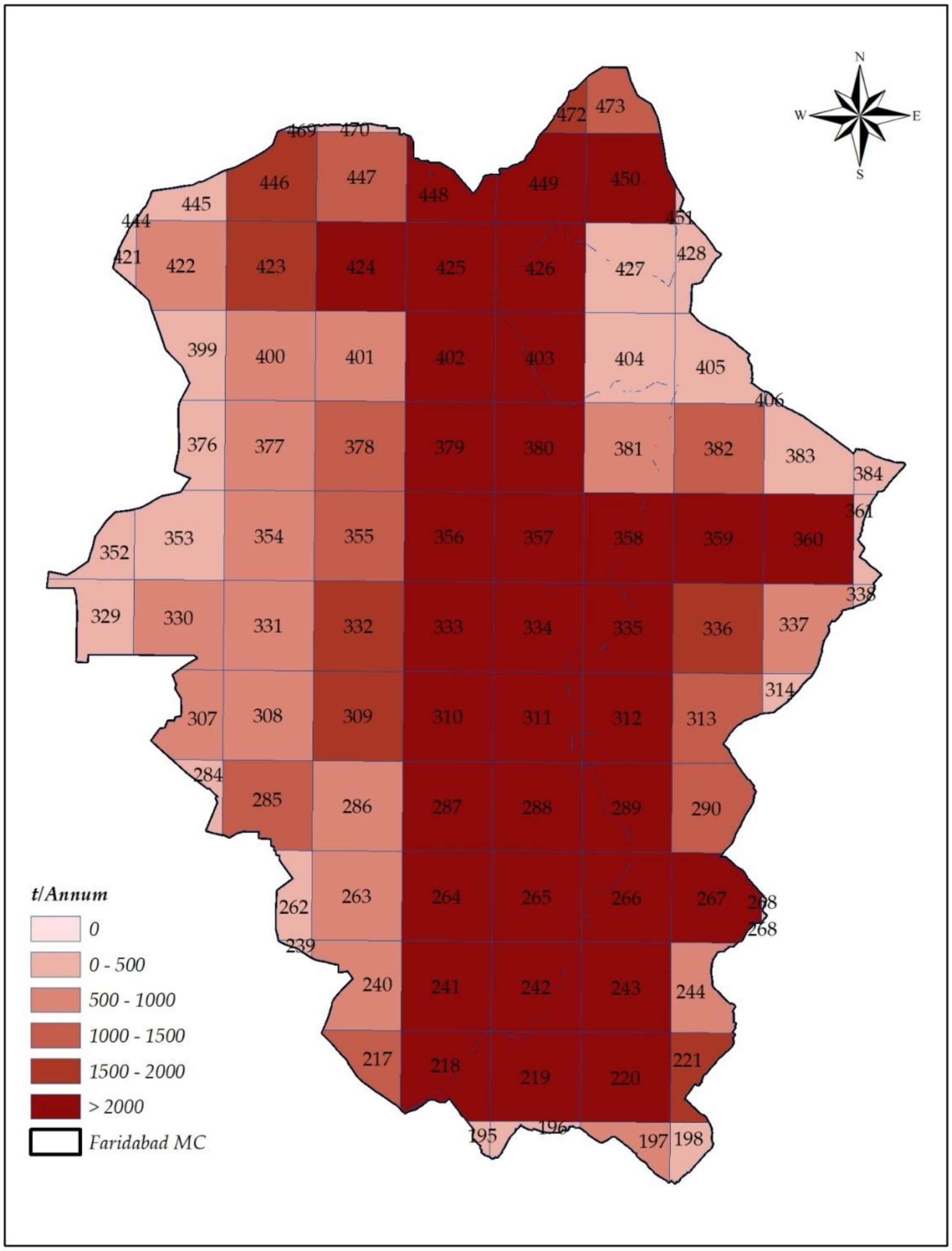


Figure 59: Spatial distribution of total estimated NMVOC emissions from all sectors within the study area

Air Pollution Source Apportionment – Dispersion Modelling approach

Key findings

- The CMAQv5.3.1 model, integrated with the WRF framework, was used to simulate $PM_{2.5}$ and PM_{10} concentrations over Faridabad
- The model accounts for meteorological impacts on pollutant dispersion and chemical reactions, enhancing predictive accuracy
- Simulated $PM_{2.5}$ concentrations were compared with observed data, showing seasonal variation (ratio of 0.86 in summer and 1.28 in winter) and suggesting satisfactory model performance.
- $PM_{2.5}$ and PM_{10} concentrations were significantly higher in winter due to lower temperatures, stable atmospheric layers, and reduced vertical mixing
- High PM concentrations were observed along major traffic corridors, industrial hubs and densely populated areas, with stronger impacts in northern, central, and Eastern grids
- Road dust was the largest contributor to PM_{10} (32%) and $PM_{2.5}$ (14-15%). Industrial emissions also contributed significantly, with higher winter impacts
- The transport sector contributed 6-7% to PM_{10} and 9-10% to $PM_{2.5}$ with higher contributions in winter due to weaker dispersion
- Biomass and coal combustion from household cooking contributed up to 10-14% of $PM_{2.5}$ pollution, particularly in peri-urban areas
- Industrial sources contributed 14-20% of PM_{10} and 16-23% of $PM_{2.5}$ with higher impacts in winter due to lower dispersion
- Agricultural residue burning contributed 5-6% of PM_{10} and 8-9% of $PM_{2.5}$ with peak impacts in winter due to stagnant atmospheric conditions
- Waste burning, a minor yet persistent source, with a 2-3% contribution to PM_{10} and $PM_{2.5}$ increasing slightly in winter
- Transboundary Dust **c**ontributed 19% of PM_{10} and 24% of $PM_{2.5}$ in summer but dropped to 5% in winter due to lower wind speeds and boundary layer changes
- Local emissions dominated (51-54% for PM_{10} and 39-40% for $PM_{2.5}$), but regional sources within India contributed significantly more in winter

Atmospheric dispersion modeling is an advanced computational technique used to simulate the transport, dispersion, and chemical transformation of pollutants under varying meteorological conditions. This approach enables a deeper understanding of pollutant behavior and aids in developing effective air quality management strategies. In this study, the CMAQv5.3.1 model was used within the WRF-CMAQ modeling framework to simulate ambient $PM_{2.5}$ and PM_{10} concentrations over Faridabad city. The model captures primary as well as the formation of secondary aerosol species through complex photochemical and heterogeneous reactions, contributing to the ambient particulate matter concentrations. Additionally, it accounts for meteorological influences on pollutant dispersion and chemical interactions, enhancing the predictive capability of air quality assessments. The insights derived from this study contribute to data-driven policy decisions for mitigating air pollution and improving urban air quality.

The WRF-CMAQ modeling framework has been widely recognized for its robust applications in both academic research and policy-driven air quality assessments, and has been extensively applied across various geographical regions, including the Mediterranean Basin (Paza et al., 2013), London (Sokhi et al., 2006), Beijing (Chen et al., 2007), Japan (Khiem et al., 2010), and the USA (Lee et al., 2011). Within India, TERI has employed this integrated modeling system for air pollution source apportionment studies across multiple urban centers, including Delhi NCR, Ludhiana, Surat, Lucknow, Kanpur, Kashipur, Rishikesh, Varanasi, Sangareddy, Vadodara, Gurugram, Kolkata, Howrah, and others.

The Weather Research and Forecasting (WRF) model (version 3.9.1) was used to generate detailed meteorological data for the Faridabad study area. Meteorological input for WRF was taken from ECMWF's 6-hourly ERA5 datasets to generate high-resolution, three-dimensional meteorological fields at 2 x 2 km^2 resolution over the Faridabad study domain. These meteorological outputs provided essential atmospheric parameters for subsequent chemical transport modeling.

To account for pollution transport from outside Faridabad, a national-scale simulation was conducted using a 36 × 36 km^2 emission inventory developed by The Energy and Resources Institute (TERI). Emissions from neighboring countries within the national study domain were incorporated using data from the ECLIPSE database (IIASA, 2014). Additionally, to capture long-range pollutant transport from international regions beyond India, boundary conditions were derived from the CAM-Chem (Community Atmosphere Model with Chemistry) dataset, developed by the National Center for Atmospheric Research (NCAR, USA). The pollutant concentrations generated from these simulations served as boundary conditions for the Faridabad runs, ensuring that external pollution influences were accurately taken into account.

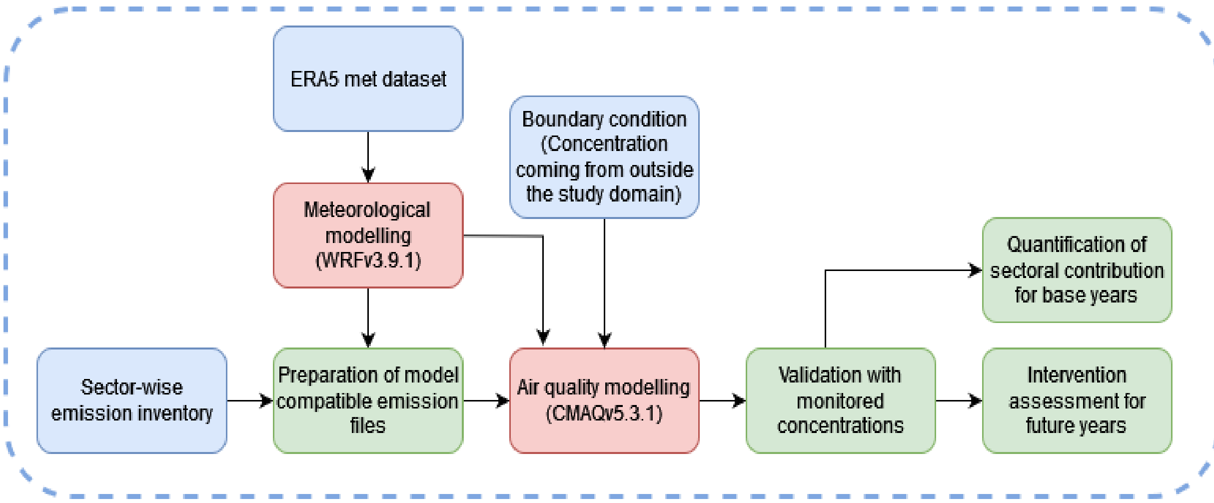


Figure 59: The WRF-CMAQ modelling framework used for source apportionment of PM in Faridabad

The hourly meteorological fields generated by the WRF model, the emission inventory of Faridabad city developed under the study and allocated at 2 × 2 km^2 spatial resolution, and boundary conditions derived from national-scale simulations, were utilized as key inputs for the CMAQ chemical transport model. This WRF-CMAQ modeling framework post-validation was applied to quantify the seasonal sectoral contributions to PM_{10} and $PM_{2.5}$ concentrations within the study domain for the year 2022–2023, providing critical insights into the source dynamics influencing regional air quality.

Validation of the WRF-CMAQ modelling framework

The WRF-CMAQ modeling framework was evaluated by comparing simulated $PM_{2.5}$ concentrations with measured data from air quality monitoring stations deployed within the Faridabad study domain. The model exhibited seasonal variability in performance, with simulated-to-observed $PM_{2.5}$ ratios of 0.86 in summer and 1.28 in winter. On an annual basis, the mean ratio was 1.07, suggesting overall reasonable model performance in reproducing observed $PM_{2.5}$ concentrations.

The validation of the WRF-CMAQ framework highlights its capability to simulate key atmospheric processes governing pollutant dispersion and transformation. The agreement between simulated and observed values supports the model's robustness in representing spatiotemporal variations in $PM_{2.5}$ concentrations. Additionally, the validated framework is a reliable tool for conducting source identification and sensitivity analyses, enabling a quantitative assessment of sectoral contributions to particulate matter pollution in Faridabad city. These findings substantiate the applicability of the WRF-CMAQ framework for designing data-driven emission control strategies and policy interventions aimed at reducing atmospheric pollutant levels in the study region.

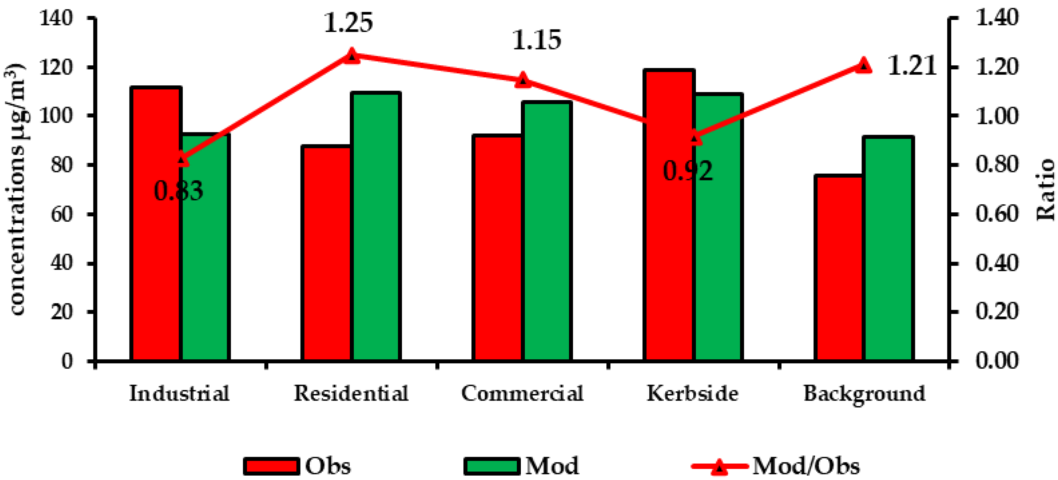


Figure 60: Location-wise validation of measured and WRF-CMAQ simulated atmospheric $PM_{2.5}$ concentrations in Faridabad city

Simulated spatiotemporal variations in atmospheric concentrations of $PM_{2.5}$

The simulated seasonal concentrations of atmospheric $PM_{2.5}$ are shown in Figure 63. The summer season is represented by the average source contribution during April and May 2022, the winter season is the average source contribution during January and February 2023, while the annual represents the average contribution for both the summer and winter seasons.

$PM_{2.5}$ concentrations are significantly higher in winter than in summer, with widespread exceedances of 120–140 µg/m³ observed across the central, northern, and eastern regions. The highest modeled concentrations are aligned with major traffic corridors, industrial hubs, and densely populated areas, indicating strong local emission contributions. In contrast, $PM_{2.5}$ levels are comparatively lower during summer, with most areas exhibiting concentrations in the 40–80 µg/m³ range. Only a few localized hotspots in the southern and central grids show moderate elevations, but the extreme pollution levels observed in winter are largely absent. The annual average concentration distribution reveals persistently high $PM_{2.5}$ levels in central, northern, eastern, and southern grids, underscoring the influence of year-round emission sources such as transportation, industrial activities, and biomass burning.

The seasonal variations in $PM_{2.5}$ concentrations can be largely attributed to meteorological factors. During summer, increased solar radiation enhances atmospheric turbulence, leading to stronger convective mixing and a significant expansion of the planetary boundary layer. This promotes vertical and horizontal pollutant dispersion, reducing near-surface concentrations. Additionally, stronger horizontal advection accelerates air movement, decreasing the residence time of pollutants and limiting their accumulation. In contrast, winter conditions are characterized by a shallow planetary boundary layer, frequent temperature inversions, and stable atmospheric layers that trap pollutants near the surface. These conditions severely restrict vertical mixing and enhance pollutant stagnation, leading to significantly elevated $PM_{2.5}$ levels.

Reduced horizontal transport further exacerbates localized pollution buildup, particularly in areas with high emissions.

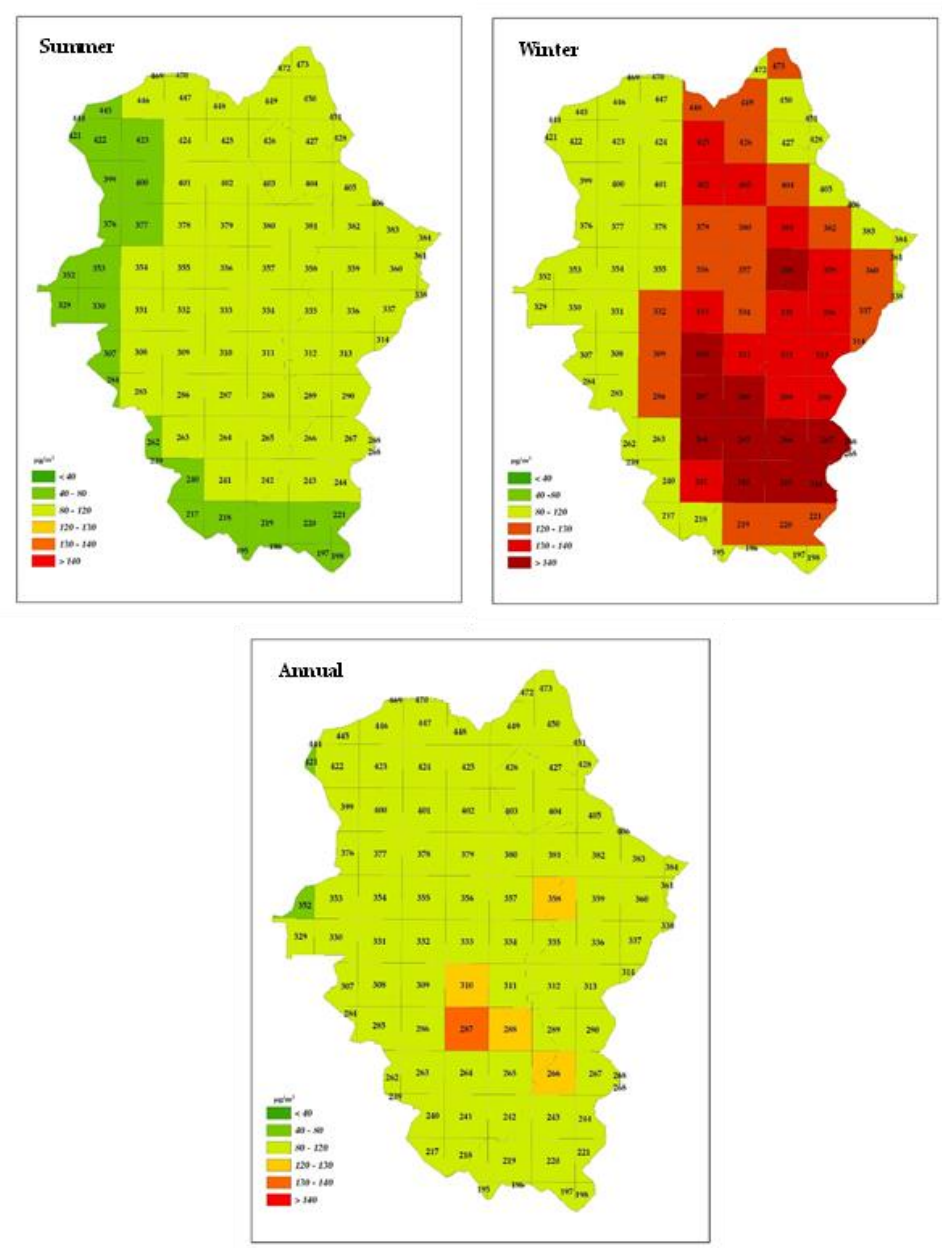


Figure 61: Spatial distribution of simulated $PM_{2.5}$ concentrations in Faridabad city during summer, winter, and annually of 2022-23

Overall, these findings emphasize the strong seasonality of $PM_{2.5}$ pollution in the region, with winter conditions leading to severe air quality deterioration. Given the persistent high concentrations in key urban and industrial regions throughout the year, targeted mitigation efforts—particularly during winter—are essential to managing pollution episodes and improving air quality.

Simulated proportionate contribution of different sources to atmospheric PM_{10} and $PM_{2.5}$

The validated WRF-CMAQ modelling system was employed for sectoral sensitivity analysis to assess contributions to atmospheric PM_{10} and $PM_{2.5}$ levels under distinct seasonal atmospheric conditions in the Faridabad city.

Road dust has been identified as a significant source of atmospheric particulate matter concertation with its influence persisting throughout the year. The estimated contribution of road dust to PM_{10} levels is 32% for both seasons, whereas $PM_{2.5}$, constitutes 14% in summer and 15% in winter, signifying its predominant role in the coarse particulate fraction. This persistent impact is driven by large-scale infrastructure expansion, high vehicular flux, and substantial dust accumulation on both paved and unpaved roads, further intensified in some locations by inadequate road maintenance.

The seasonal variability for road dust emissions is predominantly governed by meteorological conditions and planetary boundary layer dynamics. During summer, elevated ambient temperature, reduced relative humidity, and minimal precipitation enhance particulate resuspension, as the lack of surface moisture weakens interparticle cohesion, facilitating greater lofting of dust due to mechanical disturbances. Additionally, intense solar radiation and convective turbulence amplify vertical mixing, exacerbating the suspension of both coarse and fine particulate fractions. In contrast, winter meteorology fosters pollutant entrapment and prolonged atmospheric retention of road dust particles. Lower mixing heights diminished convective activity, and the occurrence of temperature inversions significantly reduced vertical dispersion, resulting in the accumulation of particulate matter near the surface. Reduced wind speeds and stagnant conditions further inhibit the dispersion of resuspended dust, thereby maintaining elevated particulate matter concentration for extended durations.

Simulated industrial emissions exhibit a substantial source of atmospheric PM_{10} and $PM_{2.5}$, with their contributions exhibiting notable seasonal variation. In summer, industrial atmospheric concentrations contribute 14% to PM_{10} and 16% to $PM_{2.5}$, whereas in winter, PM_{10} concentrations surge to 20% and $PM_{2.5}$ to 23%, respectively. Although the relative share of industrial $PM_{2.5}$ emissions increases significantly in winter, its absolute impact is even greater due to higher ambient $PM_{2.5}$ concentrations. This seasonal surge is primarily driven by reduced planetary boundary layer heights, suppressed vertical dispersion, and pollutant entrapment due to temperature inversions. Additionally, industrial clusters located in upwind regions, including those around Faridabad, contribute to increased wintertime PM levels through regional transport facilitated by prevailing wind patterns. Emissions from neighboring industrial hubs may also influence and further amplify particulate matter levels during winter.

Table 14: Estimated seasonal variations in sectoral shares to atmospheric PM_{10} and $PM_{2.5}$ concentrations in the Faridabad city

Sources	PM_{10}		$PM_{2.5}$	
	Summer	Winter	Summer	Winter
Transport	6%	7%	9%	10%
Road dust resuspension	32%	32%	14%	15%
Residential Cooking	6%	10%	10%	14%
Industries	14%	20%	16%	23%
Power	2%	3%	2%	3%
Brick Kiln	2%	3%	3%	4%
DG sets	1%	0%	2%	1%
Waste Burning	2%	3%	3%	4%
Agriculture Residue Burning	6%	5%	9%	8%
Others*	10%	13%	8%	13%
Transboundary dust**	19%	5%	24%	5%

**Others include crematoria, eateries, hotels and restaurants*

*** Trans-boundary dust refers to the dust particles coming outside the city boundary*

Residential combustion for cooking substantially elevates particulate matter concentrations, specifically in low-income and peri-urban areas where the use of biomass and coal combustion are prevalent. Simulated results indicate that domestic concentrations contribute 6% to PM_{10} and 10% to $PM_{2.5}$ in summer, rising to 10% and 14% in winter, respectively. A significant fraction of this concentration originates from rural and slum settlements located in the upwind regions, where the use of biomass and coal in traditional stoves leads to incomplete combustion, releasing substantial amounts of fine particulate matter. During winter, atmospheric stagnation conditions amplify the local concentration, leading to higher exposure levels and shaping seasonal air pollution dynamics in the region.

The proportion of atmospheric particulate matter from the transport sector was estimated to increase during the winter season, with 7% to PM_{10} and 10% to $PM_{2.5}$, primarily due to reduced planetary boundary layer height, weak convective turbulence, which inhibit vertical dispersion and temperature inversions create a stable atmospheric layer that traps vehicular emissions, increasing near-surface particulate matter concentrations. Further, to decrease in long-range sources of emissions in the winter season due to lower wind speed results in an increase in contributions from localized sources like transport and road dust. The seasonal increase of the planetary boundary layer, coupled with intensified atmospheric mixing and higher wind-driven dispersion, reduces PM_{10} to 6% and $PM_{2.5}$ to 9% during summer. Further, to increase in the influx of particulate concentrations from sources outside the city results in a decrease in overall contribution from the transport sector.

Brick kilns and waste burning are relatively minor contributors to atmospheric PM_{10} and $PM_{2.5}$ but exhibit distinct seasonal variations. The impact of waste burning on PM_{10} and $PM_{2.5}$ concentrations increases from 2% and 3% in summer to 3% and 4% in winter, primarily due to the greater influence of local sources during winter. Similarly, emissions from restaurants, crematoria, and construction contribute 10% (PM_{10}) and 8% ($PM_{2.5}$) in summer, rising to 13% for both pollutants in winter as pollutant influx from external sources decreases. The brick kiln sector, which accounts for 2% of PM_{10} and 3% of $PM_{2.5}$ concentrations in summer, sees its contribution increase to 3%-4% in winter.

The open burning of agricultural residue contributes 6% and 5% to ambient PM_{10} concentrations in summer and winter, respectively, and 9% and 8% to ambient $PM_{2.5}$ concentrations. The dominant wind direction in Faridabad is from the west and northwest, bringing pollutants from upwind regions of Haryana and Punjab, where farmers continue to burn crop residues for field clearing. While this practice has declined due to policy interventions, it remains a significant contributor to air pollution in the city. Although the percentage contribution appears similar in both seasons, the absolute pollution levels are higher in winter, meaning that in terms of actual concentrations, the impact of crop residue burning is more pronounced during the winter months.

Transboundary sources, driven by large-scale atmospheric transport mechanisms, vary significantly across seasons due to changes in meteorological conditions, boundary layer dynamics, and pollutant dispersion pathways. In summer, elevated solar radiation increases atmospheric instability, leading to an elevated planetary boundary layer and stronger convective mixing. These conditions, facilitate the long-range transport of particulate matter, resulting in atmospheric contribution to 19% for PM_{10} and 24% for $PM_{2.5}$. Pollutants can remain suspended in the atmosphere for extended periods and travel across regions due to higher wind speeds and less atmospheric resistance. Conversely, winter is dominated by stable atmospheric conditions, characterized by lower temperatures, reduced wind velocities, and frequent temperature inversions. These inversions occur when a layer of warm air traps colder air below, preventing vertical mixing and causing pollutants to accumulate near the surface. Additionally, a shallower planetary boundary layer reduces the volume available for pollutant dispersion, further concentrating emissions at ground level. This suppression of vertical and horizontal transport limits the influence of distant pollution sources, leading to a sharp decline in concentration to 5% for atmospheric PM_{10} and $PM_{2.5}$. The interplay of seasonal meteorological variables plays a defining role in shaping transboundary pollution trajectories, modulating pollutant dispersion, deposition rates, and regional air quality fluctuations.

Simulated geographic contribution to atmospheric PM_{10} and $PM_{2.5}$ concentrations

The validated WRF-CMAQ modelling framework was applied to quantify the geographic contributions to atmospheric PM_{10} and $PM_{2.5}$ concentrations in Faridabad city. The seasonal variations in percentage contributions from Faridabad city, India, and international dust sources for both summer and winter are illustrated in Figure 64.

At the city level, source contributions exhibit minimal seasonal variability, with local emissions from vehicular traffic, industrial operations, and residential fuel combustion constituting 54% of PM_{10} and 40% of $PM_{2.5}$ during summer, slightly declining to 51% and 39% in winter. However, wintertime meteorological conditions, characterized by reduced planetary boundary layer heights, suppressed turbulent mixing and enhanced atmospheric stability, limited pollutant dispersion, and promoted near-surface accumulation, thereby intensifying the influence of regional and long-range transport on ambient air quality.

The contribution of sources within India increases significantly from summer to winter, with PM_{10} rising from 27 to 44% and $PM_{2.5}$ from 35 to 56% respectively.

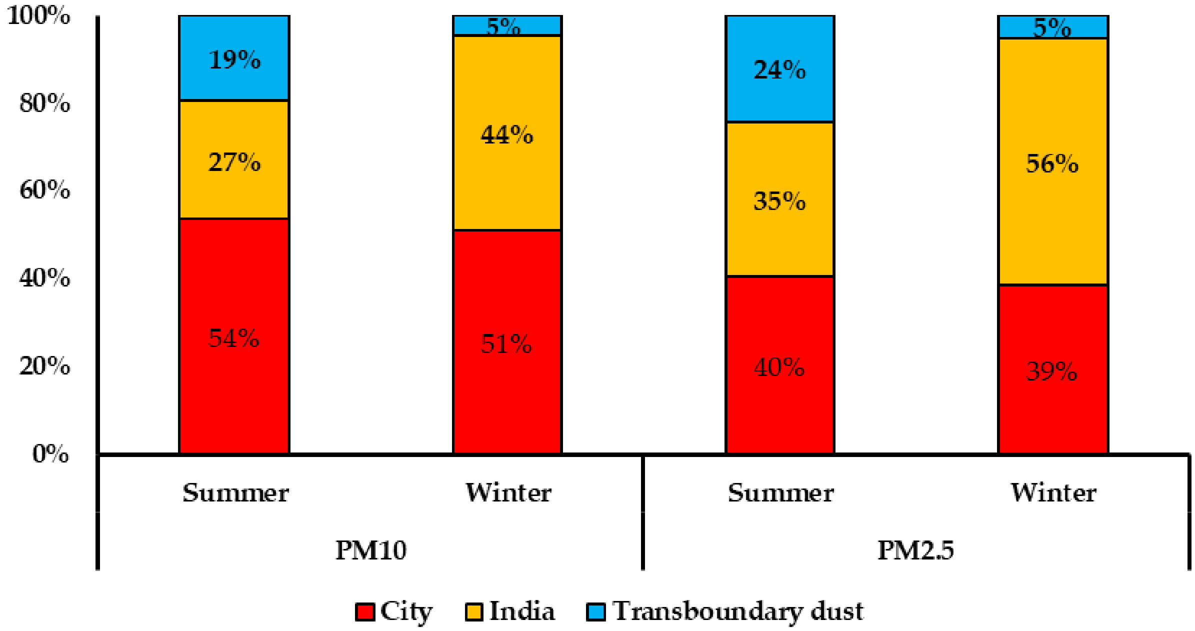


Figure 62: Simulated seasonal variations of geographical contribution to atmospheric PM_{10} and $PM_{2.5}$ concentrations in the Faridabad city

International dust exhibits significant seasonal variation, with contributions rising in summer at 19% for PM_{10} and 24% for $PM_{2.5}$ before decreasing sharply to 5% for both atmospheric PM_{10} and $PM_{2.5}$ in winter. This variation is primarily driven by atmospheric dynamics, where summer conditions, including an elevated planetary boundary layer and enhanced convective mixing, facilitate the long-range transport of mineral dust. In contrast, winter is dominated by stable atmospheric conditions, lower boundary layer heights, and frequent temperature inversions, which restrict pollutant dispersion and significantly reduce transboundary inflow. As a result, the contribution of distant sources diminishes, while local and regional emissions become the dominant drivers of ambient particulate matter levels.

Estimated Future Scenario & Management of Air Pollution in the Faridabad City

Key findings

Business as Usual Scenario

- PM_{10} emissions are projected to increase by 57% and $PM_{2.5}$ by 65% from 2022 to 2035. Industry, road dust re-suspension, and transport are the primary contributors.
- Industry, road dust, residential activities, transport, and construction will contribute 87% of PM_{10} levels by 2035
- For $PM_{2.5}$ levels, road dust, transport, residential sector, industry, and external sources will contribute over 81% by 2035
- Due to the adoption of BS-VI emission norms and widespread LPG transition, transport's contribution to PM_{10} is expected to decline by 50%, and the residential sector's contribution by 82% from 2022 to 2035
- Despite the reductions in some sectors, air quality in Faridabad will still exceed National Ambient Air Quality Standards (NAAQS), necessitating additional interventions

Intervention strategies for key sectors

- **Transport**: Accelerated vehicles scrappage policy, 100% electrification of public buses, 70% electrification of new vehicles, congestion management, and stricter pollution checks
- **Residential**: Increased LPG adoption, transition to improved cookstoves and solar cooking by 2035
- **Industry**: Complete transition from solid fuels to natural gas by 2035

Projected Emission Reductions Through Interventions by 2035

- Transport: PM_{10} and $PM_{2.5}$ emissions could reduce by 66% and 68%, respectively
- Residential: PM_{10} and $PM_{2.5}$ emissions could reduce by 48% each
- Industry: PM_{10} and $PM_{2.5}$ emissions could decrease by 68% and 66%, respectively
- Road dust: Reduction of PM_{10} by 53% and $PM_{2.5}$ by 50%

Projected Air Quality Improvements (Alternative Scenario)

- By implementing all interventions, PM_{10} and $PM_{2.5}$ winter season concentrations could reduce by 48% and 43%, respectively, by 2035
- This will bring PM_{10} levels between 143-78 $\mu g/m^3$ and $PM_{2.5}$ between 86-44 $\mu g/m^3$, ensuring compliance with NAAQS by 2035

The exploration of future scenarios is a pivotal method for comprehending the intricate and unpredictable long-term impacts on various aspects. Scenarios are invaluable tools for advocating policies and guiding actions toward sustainable practices to enhance Faridabad City's air quality. This chapter focuses on assessing the potential for improving air quality through existing policies or planning, with implications for the region's future air quality. The overarching goal is to formulate necessary policies across different sectors, aligning with the National Ambient Air Quality Standards (NAAQS) for prescribed PM_{10} and $PM_{2.5}$ concentrations within a specific timeframe.

We have developed potential future growth scenarios for different sectors under the outlined circumstances to achieve the NAAQ standard in the city. These scenarios are projected for the years 2030 (medium-term), and 2035 (long-term). The ensuing analysis thoroughly investigates the potential impact of these scenarios on atmospheric $PM_{2.5}$ concentrations, providing crucial insights to facilitate well-informed policy decisions.

Business as Usual (BAU) Scenario

In analyzing atmospheric pollution in the City of Faridabad, the study examined pre-existing policies across various sectors within the Business as Usual (BAU) scenario to assess their impact on changing concentrations of PM_{10} and $PM_{2.5}$ over the years. The BAU scenario encompasses the ongoing changes, growth, and controls within sectors like transport, domestic activities, open burning, crematoria, restaurants, and more, extending until 2035. The growth rates attributed to different sectors were derived from a comprehensive review of published government documents and peer-reviewed articles, ensuring a robust foundation for analyzing air quality dynamics in Faridabad. This study aims to provide a comprehensive understanding of the impact of existing policies on atmospheric particulate matter concentrations in the city. The growth rates adopted for projections of various sectors under the BAU scenario are summarized in Table 15.

Table 15: Growth rate adopted for various sectors under BAU scenario

Sector	Growth rate	Reasoning	Controls assumed
Transport/ **Road dust- re-suspension**	7% growth rate up to 2035	Based on the past trends of different types of vehicle registrations in Faridabad (MoRTH, 2022, VAHAAN Database)	BS VI norms from 2020 No further control for road dust
Restaurant and Eateries	Assumed to follow the projected population growth rate of Haryana, i.e. 2.61 CAGR till 2022, 2.38	Commercial activities depend on the population residing in the	As per the action plan, the use of coal and wood in bakeries, Eateries, and

	CAGR from 2022 to 2030, and 2.15 CAGR from 2030 to 2035. **(Sources: Census, Projected Population Report, 2020)**	study area. (City-level and rural area data are lacking)	restaurants is assumed to reduce by 50%, and 100% in 2030, and 2035, respectively.
Industry	A 7% growth rate has been taken for the Industrial sector in 2030 and 2035	Same as the growth rate of gross domestic product (GDP) of the secondary sector in the NCR region (NCRPD, 2015a)	Assumed to be the same as the base year
DG sets	Assumed to follow the projected population growth rate of Haryana, i.e. 2.61 CAGR till 2022, 2.38 CAGR from 2022 to 2030, and 2.15 CAGR from 2030 to 2035. **(Sources: Census, Projected Population Report, 2020)**	There is a lack of data on installed DG sets in small commercial buildings, residential societies, roadside juice stands, and other private entities.	The same scenario is assumed as accounted for in the base year. **(*Assumption)** No further Control
Crematoria	The crude death rate is assumed to remain at 5.5 for the years 2030, and 2035, as it was used in the baseline inventory in 2022 for Haryana urban areas. Similarly, the percentage ratios of Sikhs, Jains, and Hindus are assumed to remain constant across all BAU years, as they were in the 2022	Future prediction of the crude death rate and the ratio of Sikhs, Jains, and Hindus in the total projected population is not possible	The same scenario is assumed as accounted for in the base year. **(*Assumption)** No further Control

	inventory.		
Construction	CAGR of 6.89% for all the years i.e. 2030 and 2035.	Based on the gross domestic product of construction activities in Haryana from 2011-2022. **Source: RBI Handbook, 2023**	No control assumed
Residential	Annual population growth of 3.03% Annual LPG consumption growth of 4%	MoPNG reports LPG consumption information at the state level. Annual LPG consumption during 2019-20, 2020-21 and 2021-22 for the state of Haryana has been considered to project the LPG-using households in Faridabad during 2030 and 2035 respectively	No control assumed
Refuse-Open burning	Population growth of 3.03% annually has been used to estimate per capita waste generation during different years in Faridabad.		No control assumed

Estimated emissions of air pollution from different sectors under the BAU scenario

The BAU scenario has been developed based on the growth rates in various sectors, and emission loads for PM_{10} and $PM_{2.5}$ have been estimated. Table 16 gives the estimates for the years 2030, and 2035.

Table 16: Detailed sector-wise estimated emissions (kT/year) of Faridabad City for 2022, 2030 and 2035

Sector	2022		2030		2035	
	PM_{10}	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**	**PM_{10}**	**$PM_{2.5}$**
Industry	10.70	7.22	18.38	12.40	25.78	17.39
Construction	3.44	0.59	4.34	0.74	5.02	0.86
Residential	0.80	0.51	0.77	0.50	0.73	0.48
Refuse Burning	0.37	0.31	0.47	0.38	0.54	0.44
Restaurants	0.20	0.12	0.12	0.07	0.00	0.00
DG sets	0.04	0.03	0.05	0.04	0.05	0.05
Crematoria	0.08	0.04	0.09	0.05	0.10	0.05
Transport	3.21	3.11	2.76	2.68	2.12	2.05
Road dust Re-suspension	28.70	6.94	34.72	8.40	40.46	9.79
Total	47.53	18.86	61.70	25.27	74.81	31.11

In business-as-usual (BAU) projections, it is estimated that from 2022 to 2035, Faridabad City will see a significant rise in PM_{10} and $PM_{2.5}$ emissions, with increases of 57% and 65% respectively. This growth of PM_{10} and $PM_{2.5}$ is attributed to the expansion of sectors emitting coarse particles. Industry, Road dust re-suspension, and the Transport sector are expected to be the main contributors to particulate matter in the coming years.

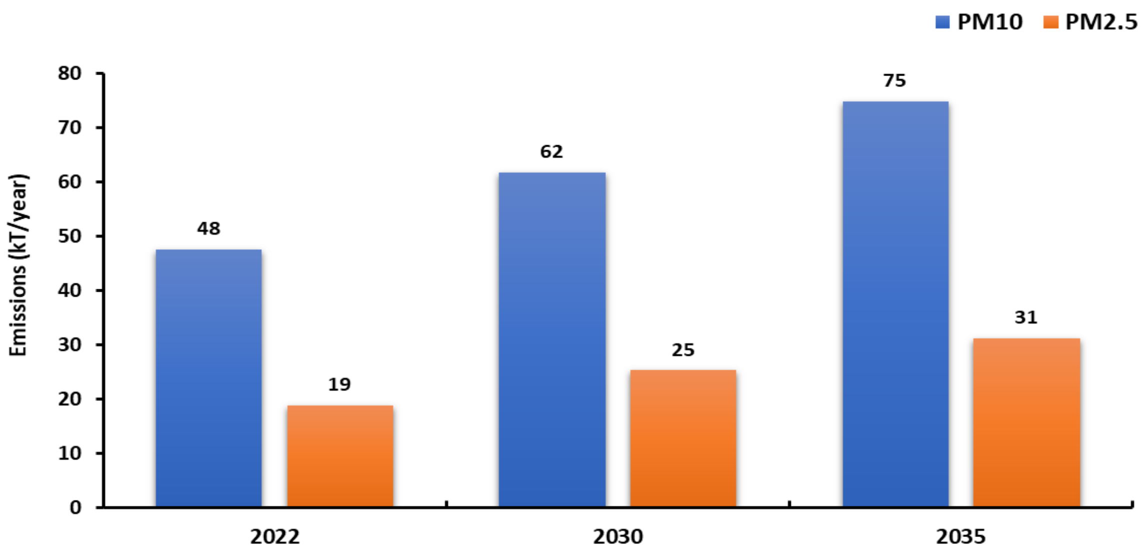


Figure 63: Emissions of PM_{10} and $PM_{2.5}$ during 2022, 2030, and 2035 for Faridabad city under the BAU scenario

The emissions projected for 2030 and 2035 under the BAU scenario have been incorporated into the C-MAQ model. Using the source sensitivity approach, similar to the baseline 2022 assessment, sectoral contributions to PM_{10} and $PM_{2.5}$ concentrations for 2030 and 2035 have been estimated. The results for PM_{10} and $PM_{2.5}$ during winter—when pollutant levels are typically higher—are presented in Figure 66. Since winter concentrations are more likely to exceed the National Ambient Air Quality Standards (NAAQS), ensuring compliance during this season would imply that summer concentrations also remain within the NAAQS limits.

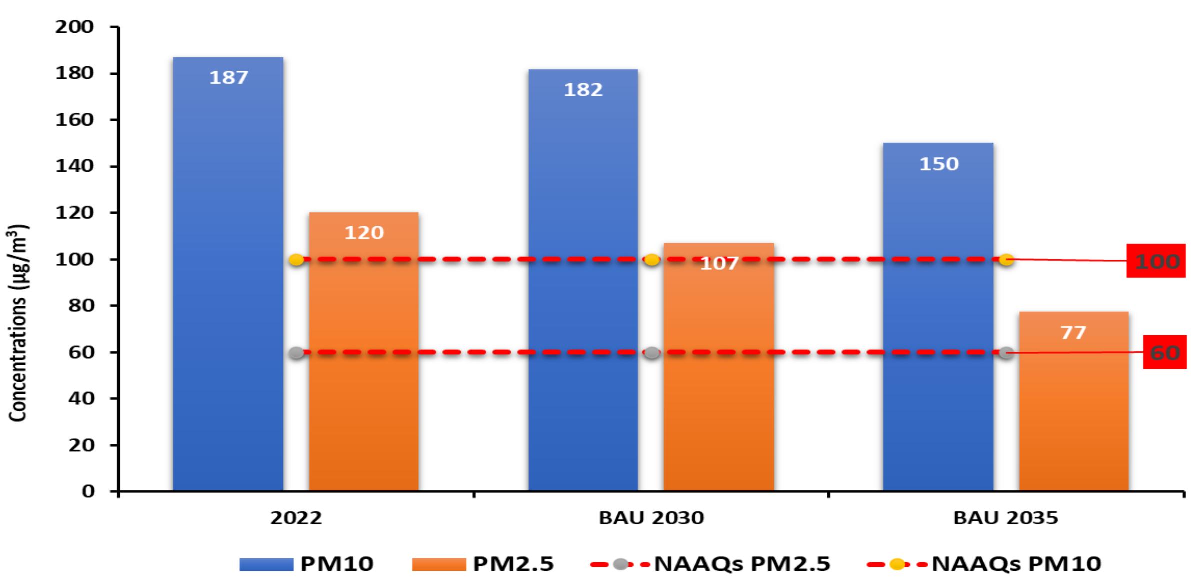


Figure 64: Simulated PM_{10} and $PM_{2.5}$ winter season concentrations in Faridabad during the years 2022, 2030, and 2035

As seen from Figure 66, the concentrations of PM_{10} and $PM_{2.5}$ are to remain above the daily NAAQ standards during the winter season. Sectoral contributions in PM_{10} and $PM_{2.5}$

concentrations in the BAU scenario for the year 2035 are shown in Figure 67 and Figure 68 respectively. During the winter of 2035, the major contributors to PM_{10} concentrations in Faridabad are projected to be industrial emissions, road dust re-suspension, residential activities, the transport sector, construction activities, and particulate matter from beyond the national boundary, collectively accounting for 87% of total PM_{10} levels.

Similarly, key sources of $PM_{2.5}$ concentrations will include road dust re-suspension, transport emissions, residential activities, industrial sources, and transboundary particulate matter, contributing over 81% of total $PM_{2.5}$ levels. Notably, the influence of the transportation and residential sectors on particulate matter concentrations is expected to decline significantly between 2022 and the Business-as-Usual (BAU) scenario of 2035, with reductions of 50% and 82%, respectively. These reductions are attributed to the adoption of BS-VI-compliant vehicles and the widespread transition to LPG for cooking.

Despite these projected changes, compliance with the National Ambient Air Quality Standards (NAAQS) will remain unattainable in the coming years. Therefore, an alternative strategy is imperative to achieve NAAQS compliance by 2035. An intervention analysis has been conducted to evaluate the potential impact of various sector-specific interventions on particulate matter concentrations in Faridabad. Further details on this analysis are provided in the subsequent sections.

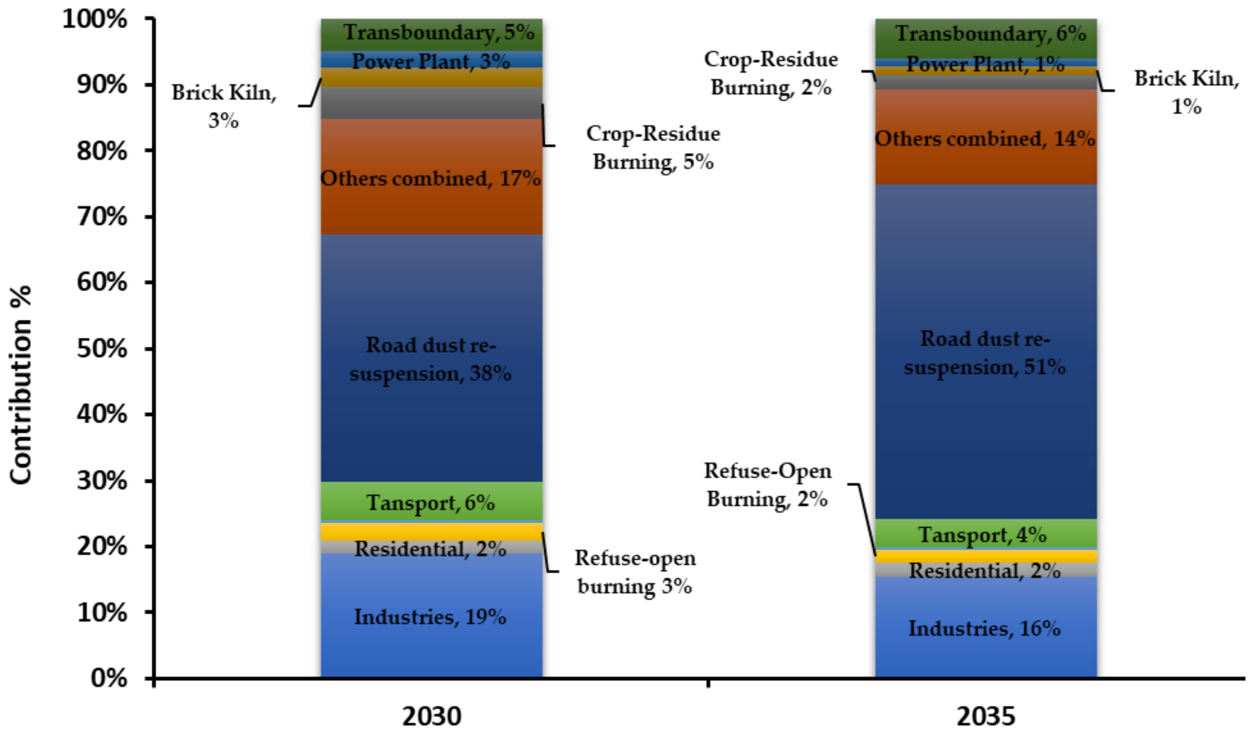


Figure 65: Sectoral contribution in PM_{10} concentration of Faridabad city in winter season during the years 2030 and 2035

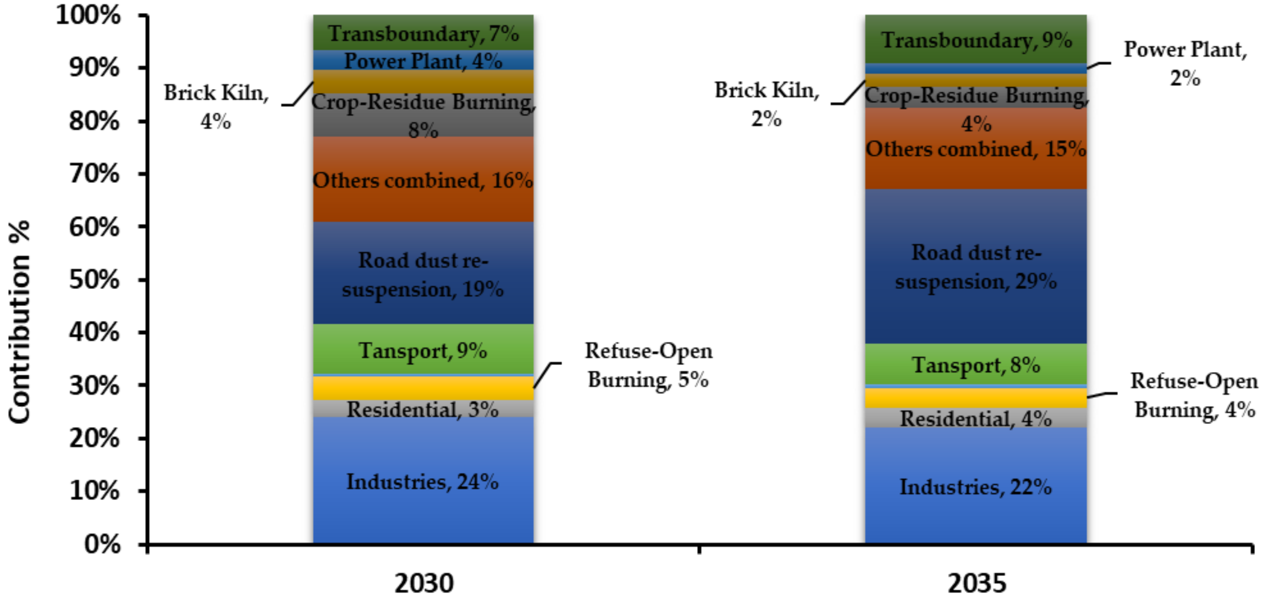


Figure 66: Sectoral contribution in $PM_{2.5}$ concentration of Faridabad city in winter season during the years 2030 and 2035

Intervention Analysis

To formulate the alternative scenario, an intervention analysis has been conducted to assess the potential emissions reduction and concentration mitigation achievable through various control strategies implemented across transport, industries, biomass, and other sectors. A comprehensive overview of the tested control strategies, along with their respective efficacy in reducing emissions, is outlined in Table 17.

Table 17: Details of further interventions considered in various sectors

S.No.	Strategies	Description
Transport Sector		
1.	Fasten the Scrappage Policy and remove older vehicles from the road	100% phasing out of 15-year-old private and 10-year-old commercial diesel-driven vehicles in 2030 and 2035.
2.	Electrification of Vehicular Fleet in Faridabad	This comprehensive strategy targets the 100% conversion of the public bus fleet to electric vehicles (EVs) by 2030 and an additional 70% electrification of newly registered two-wheelers, three-wheelers, and cars by 2035.
3.	Congestion management- Measures to reduce congestion in the city (By removing encroachment, illegal parking, illegal C&D waste lying on the Road etc.) Tendering On	Reduce real-world emissions to 50% in 2030 and 2035

	Road Parking with High Price compared to designated parking (For Behavioral Change)	
4.	Improved inspection and maintenance system which includes- ▪ Regular checking of vehicles and Establishment of an adequate number of Pollution Checking Centre's to issue PUC (Pollution Under Control Certificate) ▪ Increase in Penalty of Rs 1000 to Rs 5000 in case of violation of PUC. ▪ Integration of all Pollution Checking Centre's with Single web-based software for ensuring control & monitoring of polluting vehicles. Strengthening facility for enforcement regarding the vehicles involved in pollution emission. ▪ Monitoring of vehicle fitness of Commercial Vehicles Periodic calibration test of vehicular emission monitoring instrument	High emitter emissions go down to 50% in 2030 and 2035
Residential Sector		
5.	Cleaner Cooking technology	Annual LPG consumption growth of 4% In 2030, 50% of biomass and coal-dependent households will shift from traditional to improved solid-fuel cookstoves while 25% of biomass-using households will shift to solar-based cooking. However, the remaining 25% will continue to use the traditional cookstove In 2035, existing improved solid fuel cookstoves using households will continue to depend on ICS-based cooking. However, the estimated newly/increased households (from 2030 to 2035) will use solar power technology for cooking
Industry Sector		

6.	Conversion of solid fuel to natural gas.	50% and 100% of solid fuels-using industries will switch to natural gas in 2030, and 2035, respectively.
Road Dust		
7.	Reduction in road dust, which includes- ▪ Regular road Sweep through mechanical road sweepers of all the roads throughout the year. ▪ Water Spraying on the road. ▪ Proper Greenbelts beside roads. ▪ Construction of pucca pavement along the roads (Wall-to-wall paving for all types of roads). ▪ Tree plantation along the roads	30% and 60% reduction in silt content of arterial, sub-arterial and local roads in 2030 and 2035.
Other Sectors		
8.	Hotels & restaurant sector	100% transition of wood and coal consumption in restaurants to clean energy by 2030
9.	Construction sector	Use of Blue sheet and green mesh covering during construction activities.
		Use of Blue sheet and green mesh to cover construction material
		Use of precast construction practices
10.	Waste burning sector	100% reduction in open waste burning by 2030.
11.	Crematoria	20% shift to electric cremation in 2030, and 30% in 2035.
12.	DG Sets	60% reduction in the use of DG sets in 2030, and 90% in 2035.

Transport Sector

In the BAU scenario of winter seasons of 2022 (base year), 2030 and 2035 the transport sector's contribution to overall PM_{10} concentration in Faridabad stood at 10%, 9% and 8%, respectively, and its contribution to $PM_{2.5}$ concentration during these years stood at 7%, 6%, and 4% respectively. However, by BAU 2035, the Particulate Matter concentration tends to reduce by 50% w.r.t base year, this is primarily attributed to the implementation of BSVI emissions standards. Various strategies have been explored beyond the Business-As-Usual (BAU) scenario to reduce its share further. These strategies include:

- Fast-tracking the scrappage policy to phase out private diesel vehicles older than 15 years and commercial diesel vehicles older than 10 years by 2030 and 2035.
- Achieving 100% electrification of public bus fleets by 2030 and an additional of 70% electrification of newly registered two-, three-wheelers, and cars by 2035.
- Establishing an improved inspection and maintenance system with higher PUC penalties, centralized monitoring, and strengthened enforcement for vehicle fitness.
- Reducing traffic congestion through removal of encroachments, illegal parking, and introduction of high-priced on-road parking.
- Reducing road dust through daily cleaning, water spraying, pucca pavements, and tree plantation along roads and in green belts.

Detailed insights into these strategies are outlined in Table 17, while the emission reduction potential is depicted in Figure 69.

The transport sector primarily contributes to the emission of finer particulate matter, resulting in similar reduction potentials for $PM_{2.5}$ and PM_{10} across various mitigation strategies. Significant reductions in $PM_{2.5}$ emissions were achieved across all proposed strategies, as illustrated in Figure 5. For example, Fastening the scrappage policy, which involves phasing out older vehicles, can reduce both PM_{10} and $PM_{2.5}$ emissions by 24% by 2030, with a further reduction to 25% by 2035 compared to the Business-as-Usual (BAU) scenario. Electrifying the vehicular fleet, including the public bus fleet and 70% of newly registered vehicles, is projected to achieve a 14% reduction in PM_{10} and $PM_{2.5}$ emissions by 2030, with a substantial increase to 35% by 2035. Congestion management strategies, such as reducing encroachments and illegal parking, are expected to reduce emissions by 15% by 2030, improving to 18% by 2035. Strengthening the inspection and maintenance system can lead to a 40% reduction in emissions by 2030, with a further reduction to 44% by 2035.

These emissions were subsequently incorporated into a dispersion model to evaluate the reduction in particulate matter concentrations. The transport sector intervention reduction potential for ambient PM concentrations in Faridabad is summarized in Table 18. By 2035, the implementation of these strategies is projected to achieve a reduction of 66% and 68% in transport sector PM_{10} and $PM_{2.5}$ concentrations, respectively, during the winter season relative to BAU 2035.

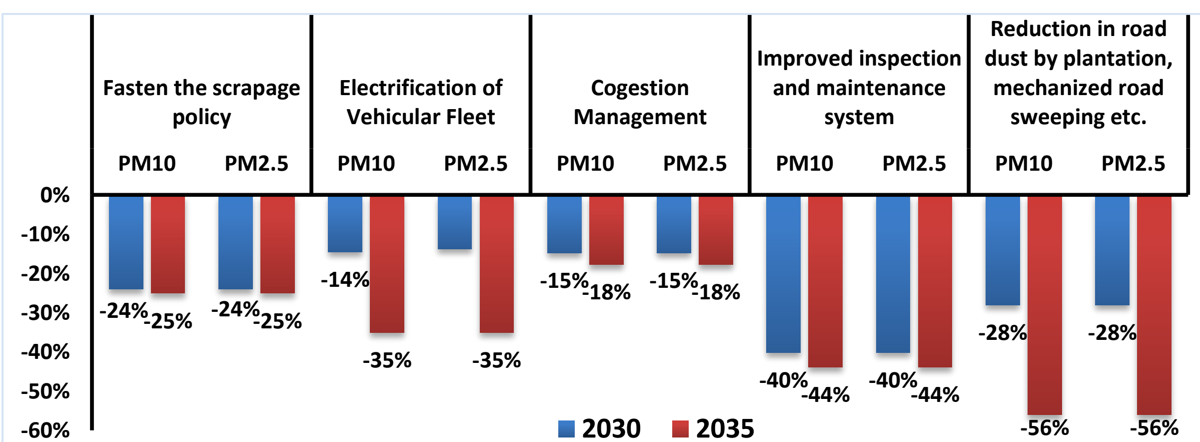


Figure 67: PM_{10} and $PM_{2.5}$ emission reduction potential of various strategies with respect to BAU 2030 and 2035 of transport sector emissions

This variability is primarily attributable to the diminished contribution of the transport sector in future years. Notably, the most substantial reduction potential was observed from the improved inspection and maintenance system, followed by the electrification of the vehicular fleet.

Road dust re-suspension

During the winter season, road dust is estimated to contribute 31%, 38%, and 51% to the PM_{10} concentration and 15%, 19%, and 30% to the $PM_{2.5}$ concentration in Faridabad for the years 2022, 2030, and 2035, respectively. To mitigate emissions from road dust, interventions such as mechanized sweeping, water spraying, and green belt development are projected to reduce PM_{10} and $PM_{2.5}$ emissions by 28% by 2030, with a more substantial reduction of 56% by 2035. These mitigation measures are expected to significantly improve air quality in Faridabad over the coming decades.

Following the estimation of emissions reduction potential, modelling was conducted to estimate the concentration reduction potential of these strategies. Detailed results are provided in Table 18, indicating that reducing the silt content of road dust could lead to a 53% and 50% reduction in PM_{10} and $PM_{2.5}$ concentration, respectively, in Faridabad during the winter season of 2035 compared to BAU 2035 (Table 18).

Residential Sector

Under the BAU scenario, of winter seasons of 2022 (base year), 2030, and 2035 the residential sector's contribution to overall PM_{10} concentration in Faridabad stood at 9%, 2% and 2%, respectively, and its contribution to $PM_{2.5}$ concentration during these years stood at 14%, 3%, and 4% respectively. However, by BAU 2035, the Particulate Matter concentration tends to reduce by 53% w.r.t base year, this is primarily attributed to the widespread transition to LPG for cooking.

In the intervention analysis, efforts were made to reduce emissions from the residential sector by providing clean energy access and better combustion technology to non-LPG-using households in the Faridabad study area for cooking activity. In addition to the growth of LPG consumption, biomass-using households are assumed to gradually shift from traditional cookstoves to improved solid fuel cookstoves and "Surya Nutan", a solar-powered cookstove technology developed by Indian Oil and Ministry of Petroleum & Natural Gas. There is no reported air pollution from solar-powered cookstoves, and the implementation of Surya Nutan will emit no smoke thereby achieving significant air quality benefits. For the present estimation the following assumptions were considered under the intervention scenario:

- Biomass-using households will gradually shift from traditional to improved solid fuel cookstoves in 2030 and 2035 having thermal efficiency of 28.1%
- In 2030, 50% of biomass and coal-dependent households will shift from traditional to improved solid-fuel cookstoves while 25% of biomass-using households will shift to solar-based cooking. However, the remaining 25% will continue to rely on the traditional cookstove
- In 2035, existing improved solid fuel cookstoves using households will continue to depend on ICS-based cooking. However, the estimated newly /increased households (from 2030 to 2035) will use Surya Nutan along with existing solar-based cooking households. There will be no traditional cookstove-using households during 2035.

The emissions are expected to decrease during 2030 and 2035 due to increased access to clean modes of cooking i.e. improved solid-fuel cookstoves and solar cookstoves. PM_{10} emissions are projected to reduce by 60% to 139% and $PM_{2.5}$ tends to reduce by 57% to 130% during 2030 and 2035 respectively concerning BAU emissions (Figure 70).

The estimated emissions were incorporated into a dispersion model to assess the potential reductions in ambient particulate matter concentrations. The sector-specific reduction potentials for PM concentrations in Faridabad are summarized in Table 18. By 2035, the implementation of these mitigation strategies is projected to result in a 48% reduction in ambient particulate matter (PM_{10} and $PM_{2.5}$) concentrations during the winter season compared to the BAU scenario for 2035.

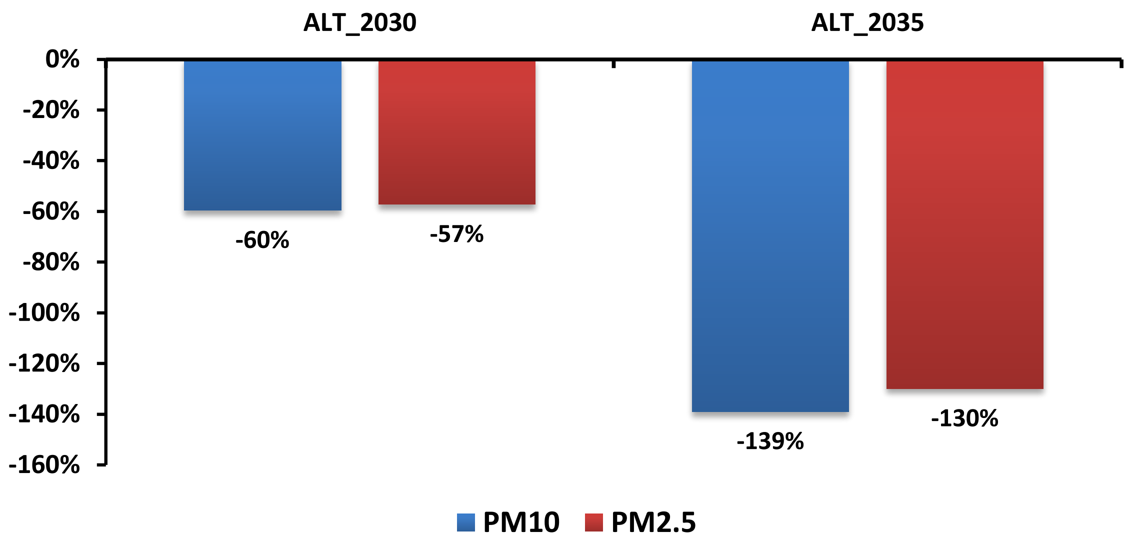


Figure 69: Emission reduction potential from residential sector w.r.t BAU 2030 and 2035

Industry Sector

In the Business-As-Usual (BAU) scenario, the industrial sector stands as a notable contributor to particulate matter concentrations in Faridabad. During the winter seasons of 2022, 2030, and 2035, industries are projected to account for approximately 20%, 19%, and 16% of PM_{10} concentrations, respectively. Similarly, the sector is expected to contribute 23%, 24%, and 22% to $PM_{2.5}$ concentrations during these same periods. Estimates suggest a projected increase in the sector's share, reflecting anticipated growth without additional pollution controls. An alternative strategy has been proposed for the industrial sector to mitigate pollution (refer to Table 17). Transitioning industries from solid fuels to natural gas holds promise, offering potential reductions of 96% and 95.9% in PM_{10}, and $PM_{2.5}$ emissions, respectively, from the industrial sector in 2035 compared to the BAU scenario in Faridabad.

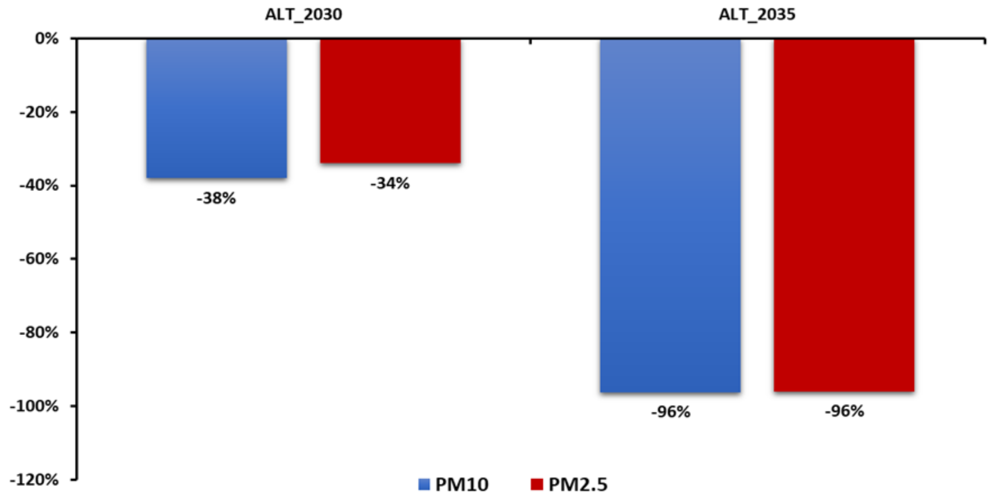


Figure 70: Emission reduction potential from the Industrial sector w.r.t BAU 2030 and 2035

Detailed emission reduction strategies are outlined in Table 18, while the potential reductions associated with this strategy are presented in Figure 71.

The emission reduction potential was further evaluated through air quality simulations to quantify the corresponding concentration reduction. The results, summarized in Table 18, indicate that controlling emissions from the "Industry" sector could reduce the contribution to the ambient PM_{10} and $PM_{2.5}$ concentrations by 68% and 66%, respectively, in Faridabad by 2035 relative to BAU 2035.

Others

During the winter season, the "Others" sector contributed 16%, 17%, and 14% to PM_{10} and $PM_{2.5}$ concentrations in Faridabad for 2022, 2030, and 2035 under the Business-As-Usual (BAU) scenario. This sector encompasses emissions from construction activities, hotels and restaurants, crematoria, and waste burning.

A mitigation strategy has been proposed to address emissions from the "Others" sector. It assumes a complete transition to clean energy for 100% wood and coal consumption in hotels and restaurants by 2035, alongside a total ban on open waste burning within the Faridabad area by the same year. To control particulate matter emissions from construction sites, strict adherence to construction guidelines is expected to achieve reductions of 65% in PM_{10} and $PM_{2.5}$ emissions by 2035. Overall, these measures are projected to result in a 66% reduction in PM_{10} emissions and a 69% reduction in $PM_{2.5}$ emissions from the "Others" sector by 2035.

The emission reduction potential was further evaluated through air quality simulations to quantify the corresponding concentration reduction. The results, summarized in Table 18, indicate that controlling emissions from the "Others" sector could reduce the contribution to the ambient PM_{10} and $PM_{2.5}$ concentrations by 45% and 46%, respectively, in Faridabad by 2035 relative to BAU 2035.

After estimating the emission reduction potential for each intervention within each sector, air quality simulations were used to quantify the corresponding reduction in pollutant concentrations. Table 18 presents the cumulative concentration reduction potential for different sectors, considering all interventions within each sector.

Table 18: Concentration reduction potential of various sectors in Faridabad city during the winter season

Sectors	2030		2035	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
Transport	-46%	-48%	-66%	-68%
Domestic	-27%	-27%	-48%	-48%
Road Dust Re-suspension	-26%	-24%	-53%	-50%
Industry	-17%	-15%	-68%	-66%
Other sectors (Construction, Waste Burning, Hotel and Restaurant, Crematoria)	-26%	-27%	-45%	-46%

Alternative (ALT) Scenario

Despite multiple interventions, the Business-As-Usual (BAU) scenario projects a substantial decline of 35% in $PM_{2.5}$ concentrations and a 19% reduction in PM_{10} concentrations between 2022 and 2035 during the winter season in Faridabad City. However, despite this decline, particulate matter concentrations remain well above the daily National Ambient Air Quality Standards (NAAQS) (refer to Figure 66). This highlights the urgent need to enhance the efficacy of pollution control measures to achieve compliance with NAAQS, particularly during the winter months when air quality deteriorates most severely.

An in-depth analysis of interventions has identified specific measures with significant potential for air quality improvement. While the implementation of these measures within Faridabad can lead to notable reductions in pollutant levels, scaling up these interventions is expected to yield even greater benefits. Strengthening and expanding these efforts can further reduce PM_{10} and $PM_{2.5}$ concentrations, bringing them closer to regulatory thresholds.

The key interventions identified through this analysis have been utilized to develop alternative air quality scenarios for Faridabad, as detailed in Table 19.

Figures 72 and 73 depict the potential reductions in winter season PM_{10} and $PM_{2.5}$ concentrations in Faridabad City achievable through implementing all proposed interventions within the study area. Under the Alternative (ALT) scenario, winter season PM_{10} and $PM_{2.5}$ concentrations are projected to decline by 48% and 43%, respectively, compared to the Business-As-Usual (BAU) scenario by 2035.

Table 19: List of interventions selected for the formulation of the ALT scenario for Faridabad

Sector	Intervention
Transport	Fasten the Scrappage Policy and remove older vehicles from the road
	Electrification of Vehicular Fleet in Faridabad
	Congestion management
	Improved inspection and maintenance system
Residential	Cleaner Cooking technology
Industry	Conversion of solid fuel to natural gas.
DG sets	60% reduction in the use of DG sets in 2030 and 90% in 2035.
Construction	Use of Blue sheet and green mesh covering during construction activities.
	Use of Blue sheet and green mesh to cover construction material
	Use of precast construction practices
Restaurants	By the year 2030, the consumption of fuel wood, and coal will be eliminated.
Road dust	Reduction in road dust, which includes- ▪ Regular road Sweep through mechanical road sweepers of all the roads throughout the year. ▪ Water Spraying on the road. ▪ Proper Greenbelts beside roads. ▪ Construction of pucca pavement along the roads (Wall-to-wall paving for all types of roads). ▪ Tree plantation along the roads
Waste Burning	100% reduction in open waste burning by 2030.

During the winter period from 2030 to 2035, PM_{10} concentrations under the Alternative (ALT) scenario are projected to range between 143 and 78 µg/m³, while $PM_{2.5}$ concentrations are expected to vary from 86 to 44 µg/m³. By 2035, road dust is anticipated to be the dominant source of particulate matter, contributing approximately 46% to PM_{10} and 26% to $PM_{2.5}$ concentrations. The significant contributors followed by the road dust resuspension are the 'other' sector (comprising construction activities, hotels and restaurants, and crematoria), which are estimated to account for 15% of both PM_{10} and $PM_{2.5}$ concentrations. The industrial sector is projected to contribute 10% to PM_{10} and 13% to $PM_{2.5}$ concentrations. The implementation of these interventions is expected to ensure compliance with the National Ambient Air Quality Standards (NAAQS) for daily PM_{10} (100 µg/m³) and $PM_{2.5}$ (60 µg/m³) concentrations by 2035.

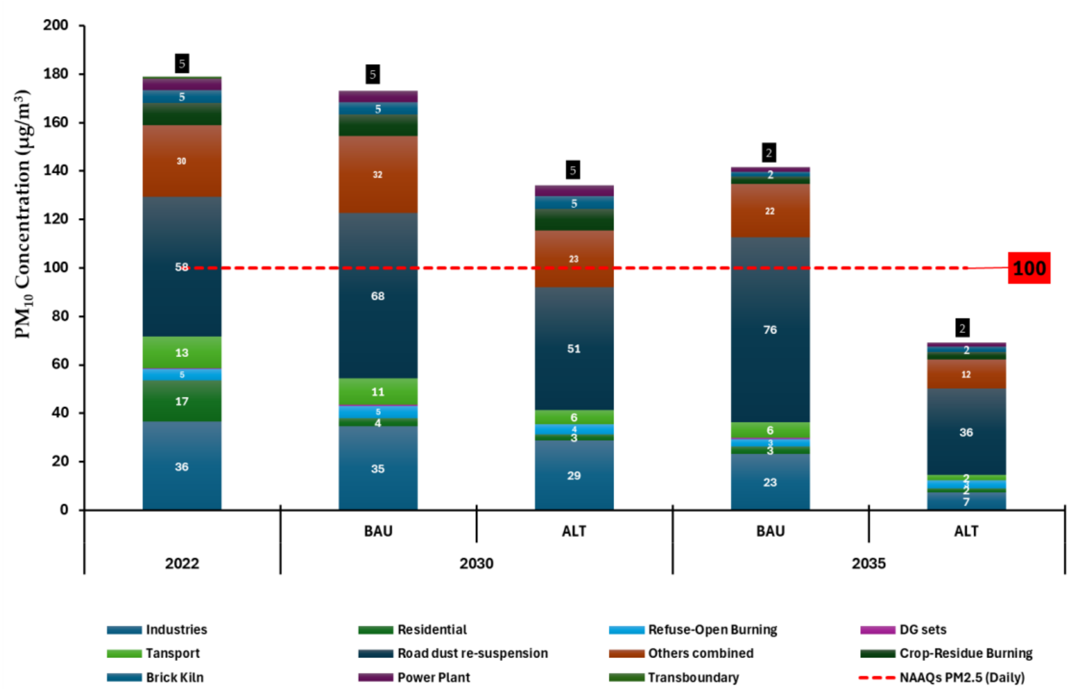


Figure 68: Winter season PM10 concentration under different scenarios in Faridabad

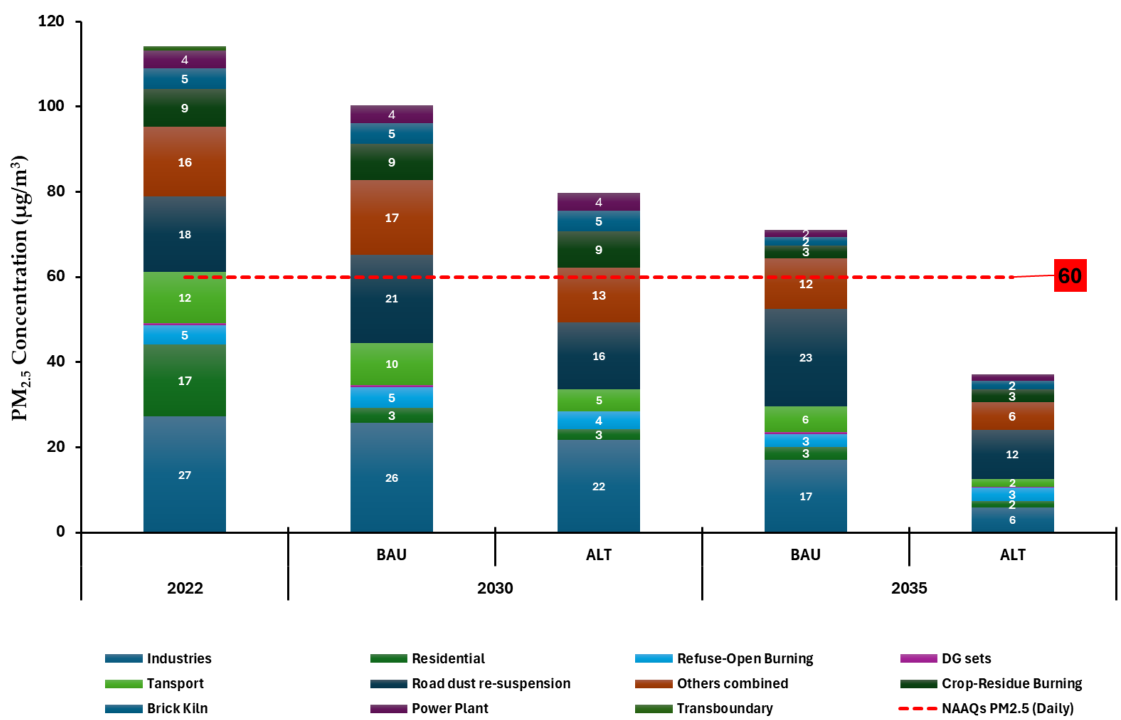


Figure 69: Winter season PM2.5 concentration under different scenarios in Faridabad

Identification of hotspots, traffic congestion spots and dust generating areas in the Faridabad study area.

To understand the spatial variability of air pollution in Faridabad, ten hotspot locations were identified based on the distribution of annual average concentrations of PM_{10} and $PM_{2.5}$. These sites represent areas with consistently elevated pollutant levels and were further examined to determine the key contributing sources. In addition, major traffic congestion points and dust-generating locations were mapped to capture their role in local air quality deterioration.

Identified hotspots in the study area

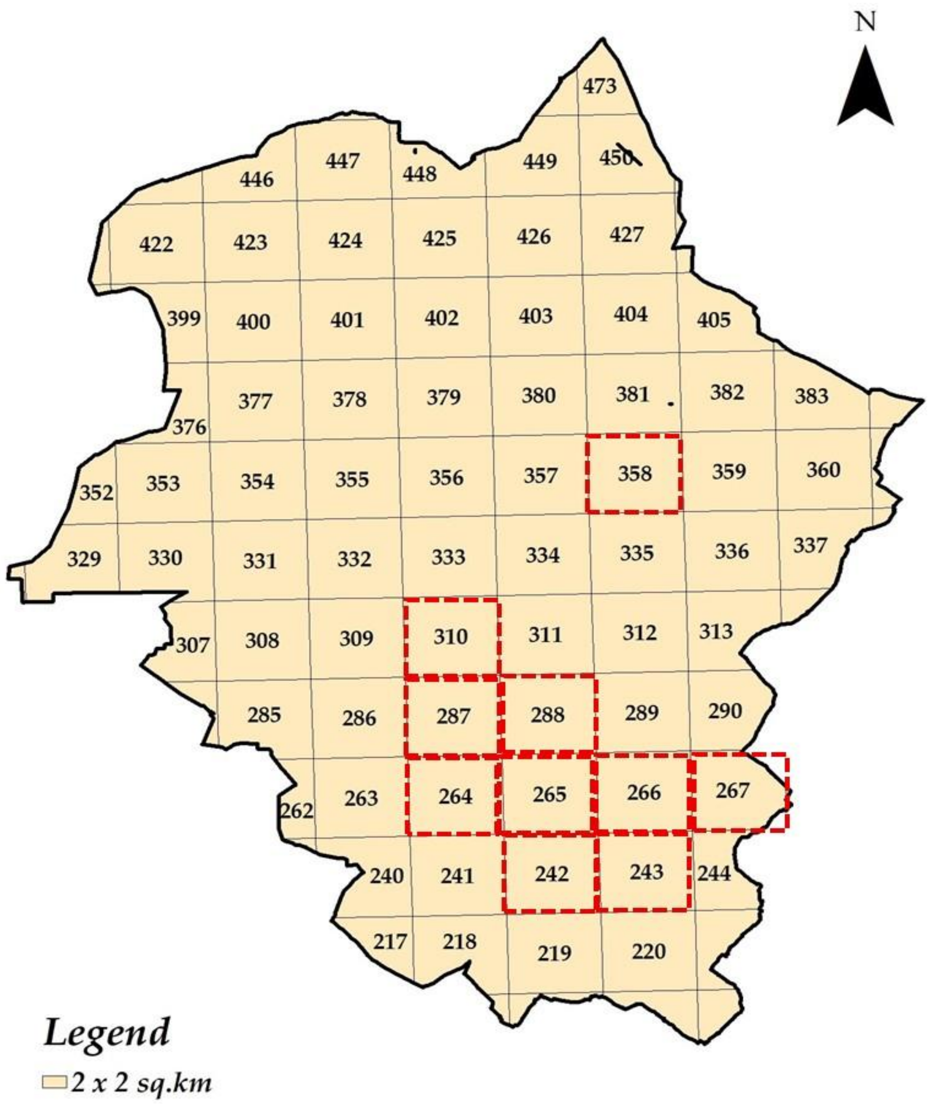


Figure 70: Identified ten hotpsot grids in the study area based on the spatial distribution of $PM_{2.5}$ concentrations

Figure 74 shows the ten identified hotspot grids in the study area based on the spatial distribution of $PM_{2.5}$ concentrations, while Figure 75 illustrates the sources contributing to these hotspots. Similarly, Figures 76 and 77 present the hotspot grids identified from the spatial distribution of PM_{10} concentrations and the corresponding contributing sources, respectively. The major landmark locations within each identified hotspot grid have been provided in the Annexure IX to facilitate better understanding of the grids and to support the implementation of pollution control measures.

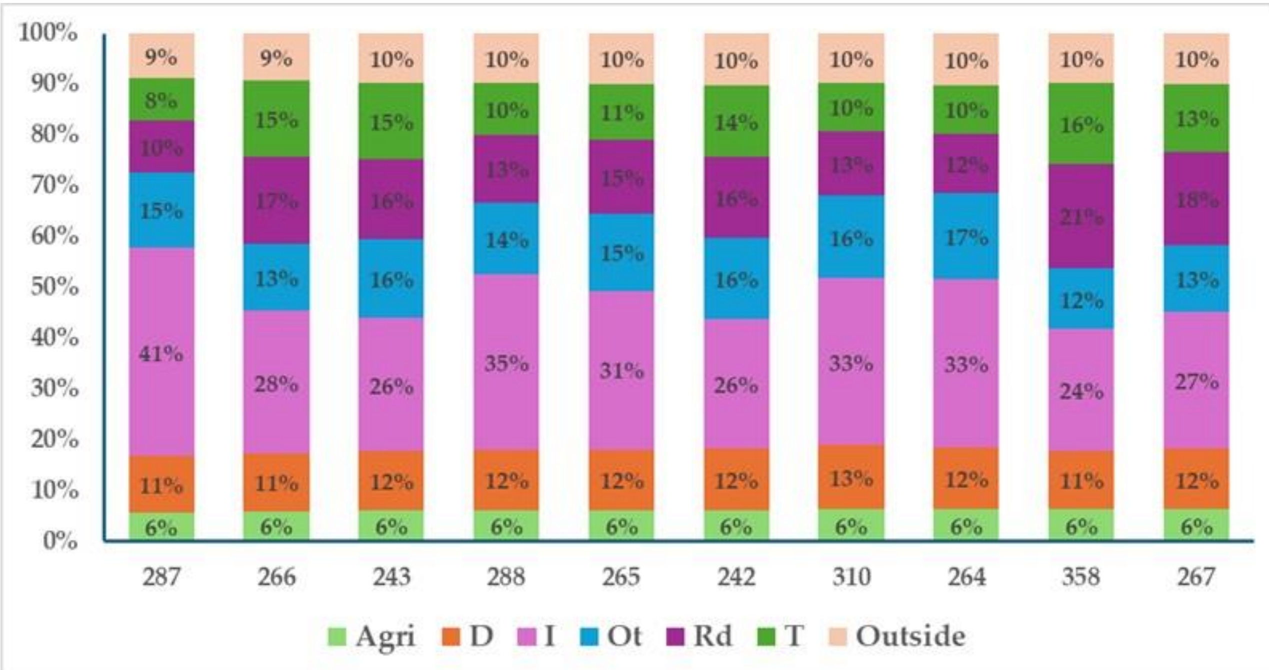


Figure 71: Major Contributing Sources of $PM_{2.5}$ in Hotspot Locations of Faridabad Municipal Corporation Area

Agri – agricultural residue burning, D – Domestic cooking, I – Industries (includes brick kilns and power plants), Ot – others (which includes crematoria, hotels/restaurants/roadside eateries), Rd – Road dust, T – Transport and outside – contribution from outside the Municipal Corporation area of Faridabad.

Across all these ten locations, industrial emissions are the predominant contributor, accounting for 24% to 41% of $PM_{2.5}$ levels. This is followed by road dust (10%–18%) and transport emissions (8%–16%). The residential sector also contributes notably, with a consistent share ranging from 11% to 13%, while emissions from agricultural residue burning contribute approximately 6% across all identified hotspots.

The hot spots identified based on the spatial distribution of PM_{10} show a similar pattern of sectoral contributions. Road dust emerged as the leading contributor, accounting for 24% to 44% of PM_{10} levels across various hotspots. This is followed by industrial emissions, contributing between 19% and 39%, and transport-related sources, which contribute 6% to 11%. The domestic sector and agricultural residue burning also make consistent contributions to PM_{10} concentrations across the identified hotspots.

At the city level, targeted interventions can be implemented at the identified hotspots, with a primary focus on the major contributing sectors, such as industries, road dust, and transport.

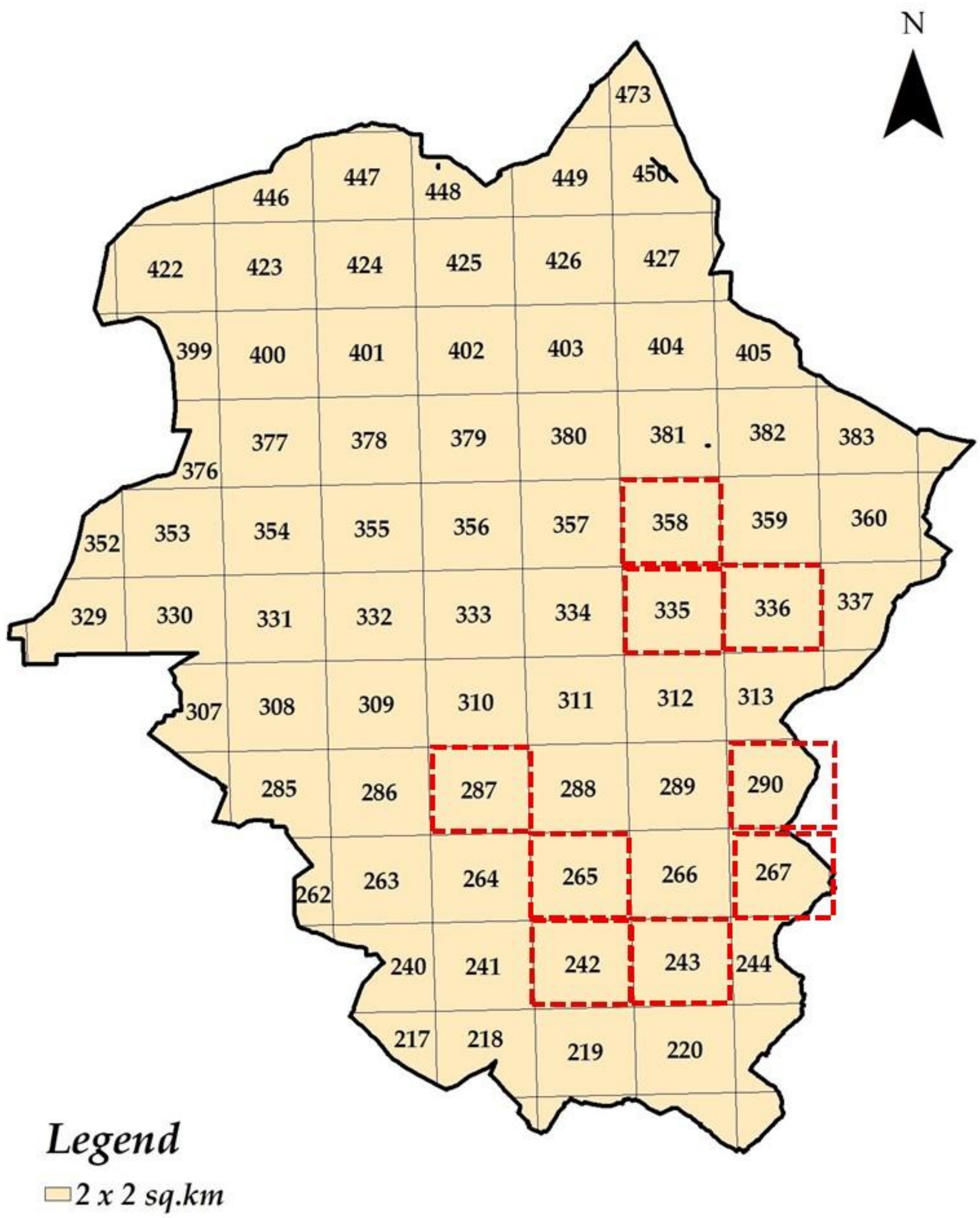


Figure 72: Identified ten hotpsot grids in the study area based on the spatial distribution of PM_{10} concentrations

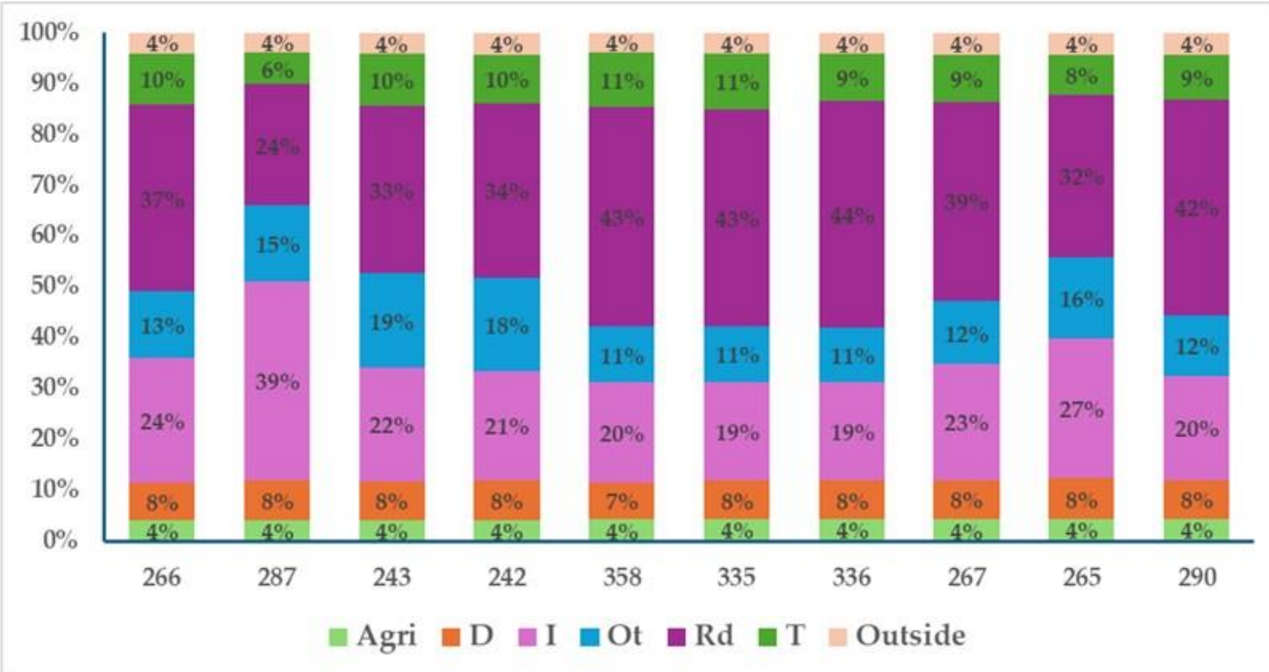


Figure 73: Major Contributing Sources of PM_{10} in Hotspot Locations of Faridabad Municipal Corporation Area

Agri – agricultural residue burning, D – Domestic cooking, I – Industries (includes brick kilns and power plants), Ot – others (which includes crematoria, hotels/restaurants/roadside eateries), Rd – Road dust, T – Transport and outside – contribution from outside the Municipal Corporation area of Faridabad.

Some of the measures that can be implemented at these identified hotspots to reduce emissions from these key sectors are:

Industrial Emissions Control:

- Conduct regular audits and enforce strict compliance with stack emission norms.
- Promote cleaner production technologies and fuel switching (e.g., from coal to PNG or electricity).
- Relocate highly polluting units away from dense residential zones and hotspots.
- Develop and monitor a digital emissions inventory using continuous emission monitoring systems (CEMS).

Dust and Road Dust Management:

- Increase mechanized sweeping and regular washing of roads, especially near industrial clusters and construction sites.
- Enforce dust suppression measures at construction and demolition (C&D) sites, including barriers and water sprinkling.

- Encourage greening of open areas and medians to reduce dust resuspension.

Transport Emissions Mitigation:

- Promote the use of electric vehicles (EVs) through targeted incentives and expanded EV charging infrastructure.
- Improve last-mile public transport connectivity and introduce cleaner fuel buses (e.g., CNG/electric).
- Strengthen vehicle emission testing and retire old, polluting vehicles

Targeted Monitoring and Regulation:

- Install additional air quality sensors in hotspot zones to capture real-time variations and inform micro-level interventions.
- Conduct regular hotspot-wise source apportionment studies to track progress and fine-tune strategies.

Policy and Community Engagement:

- Integrate pollution control measures into the city development and industrial zoning plans.
- Promote public awareness campaigns in collaboration with industries and RWAs (Resident Welfare Associations).
- Encourage industries and transport operators to participate in voluntary clean air initiatives.

Traffic congestion spots

While the precise identification of traffic congestion hotspots ideally requires congestion index modeling, which considers dynamic parameters such as road width, vehicular volume, and traffic flow patterns, the current scope of our study does not include primary data collection or modeling of traffic metrics at such a granular level.
However, in alignment with the objectives of the study, we have adopted a proxy-based approach that leverages the following:

- Traffic Emission Pattern Analysis: Using available data on traffic-related emissions (notably $PM_{2.5}$), we have identified locations with elevated emission intensities likely attributed to transport activities.
- Hotspot Analysis: We conducted a spatial analysis of $PM_{2.5}$ concentrations, where elevated levels in certain locations were found to correlate with high vehicular density and urban traffic activity. These areas, therefore, serve as proxies for potential traffic congestion zones.

- Ground-Level Insights: We have also incorporated local knowledge from previous studies, stakeholder consultations, and field reconnaissance to validate these locations as frequent congestion points.

Based on this multi-pronged approach, the grids (Figure 78) have emerged as probable congestion hotspots and contributors to transport-related $PM_{2.5}$ emissions. The major landmark locations in each of these identified grids are provided in Annexure X.
While these identifications are not the result of congestion index modeling, they represent evidence-based estimates within the scope of the current study and can serve as a reliable basis for targeted interventions or prioritization of further detailed traffic assessments.

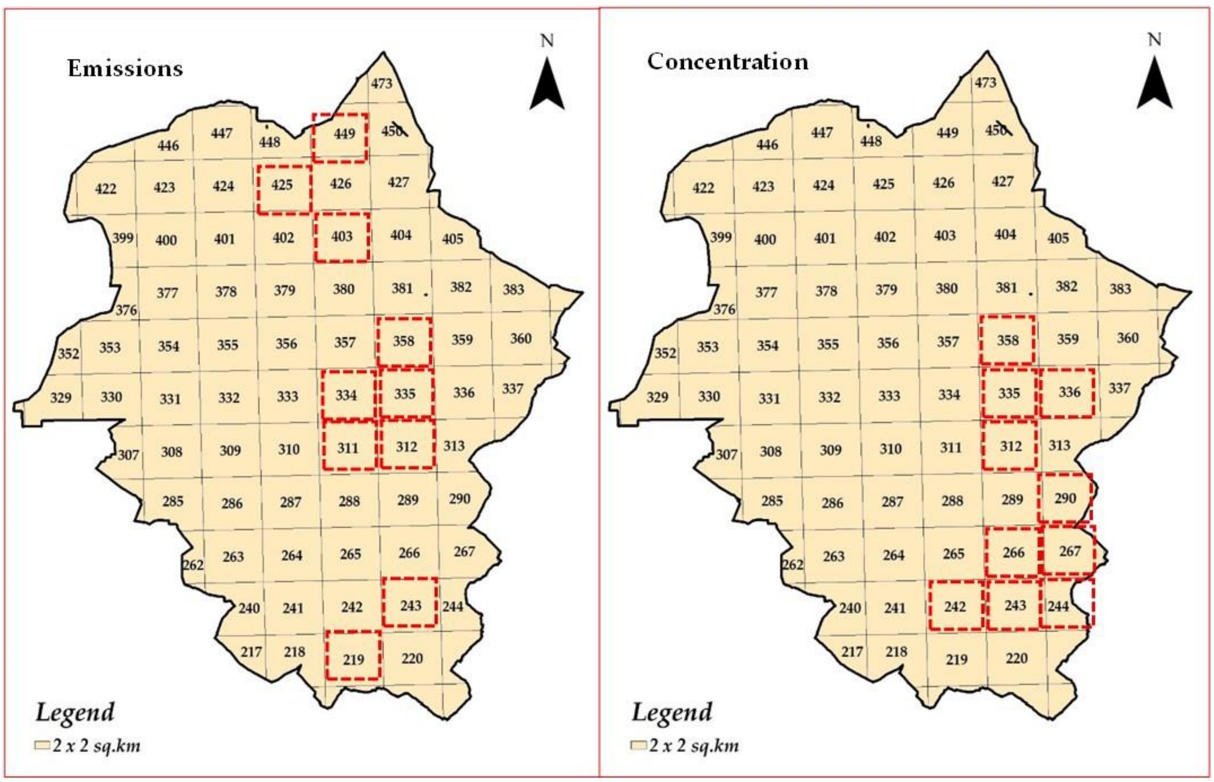


Figure 74: Selected hotspots based on the spatial distribution of $PM_{2.5}$ emissions and concentration from the transport sector

High-dust generation roads

Identifying road segments with high dust generation typically requires detailed field assessments, including measurements of traffic volume, road surface conditions, and silt load. Although a full survey of all roads was beyond the study's scope, a primary survey was carried out to estimate traffic volume in five representative grids and silt load on 15 roads (three roads in each grid, representing arterial, sub-arterial, and minor roads). This provided ground-truthing and calibration data for broader emission estimations.
To address the client’s requirement for supporting short- and long-term mitigation strategies, we have adopted a practical, spatially informed approach, which is appropriate and adequate within the constraints of the study.

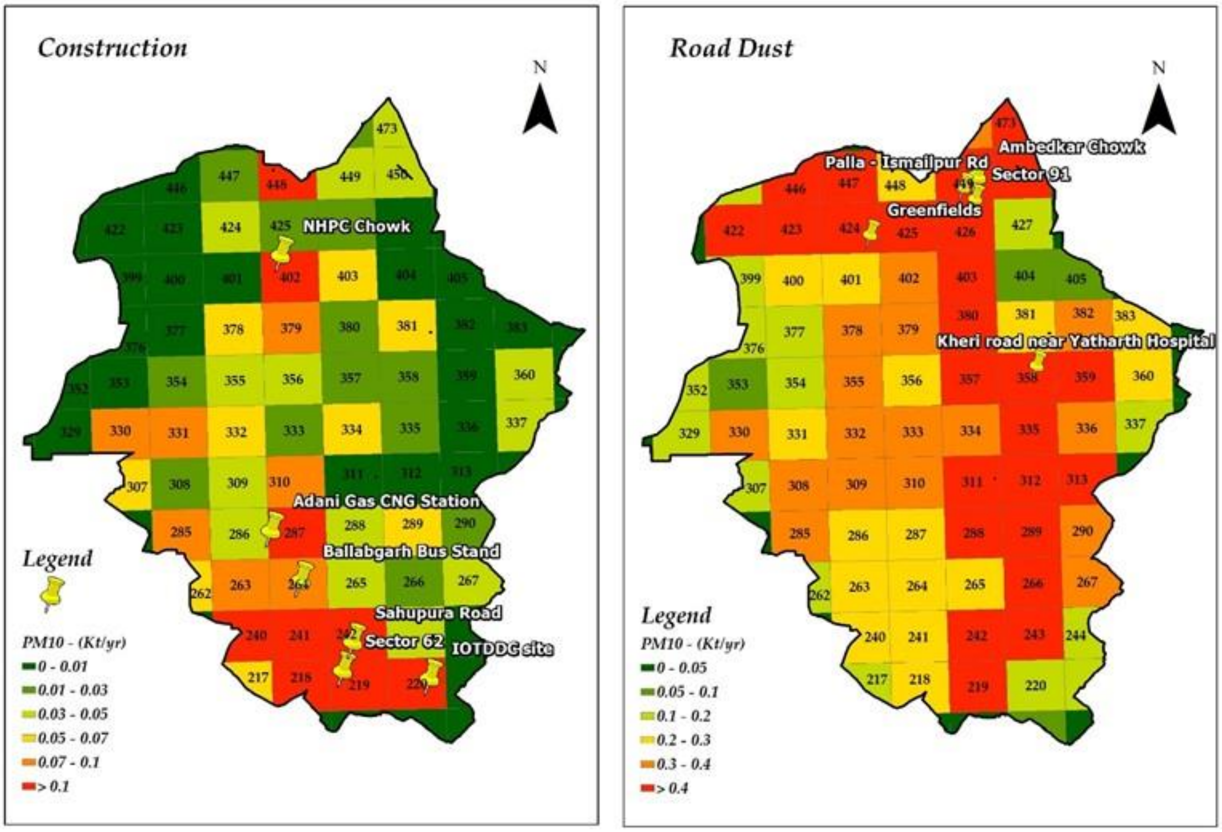


Figure 75: Identified high dust generation grids based on the spatial distribution of PM_{10} emissions from construction and road dust sectors

Our methodology includes:

- Grid-Based Emission Analysis**:** We have analyzed spatial emission data to identify grids (typically 2 km × 2 km or similar resolution) with relatively higher levels of road dust and construction dust emissions**.**
- Proximal Road Length Estimation**:** Within each high-emission grid, we are compiling the total length of road segments. This serves as a reasonable proxy for estimating the extent of surface area contributing to dust generation**.**
- Indicative Prioritization for Mitigation: The identified high-emission grids, along with associated road lengths, allow for evidence-based prioritization of areas that would benefit from dust control interventions such as:
    - Mechanical street sweeping
    - Water sprinkling
    - Road paving or repair
    - Enforcing construction site dust norms

- **Strategic Planning Relevance:** This approach is sufficient to inform short-term strategies (e.g., targeted dust suppression and enforcement) and supports long-term strategies (e.g., infrastructure upgrades and urban planning improvements) by identifying priority zones**.**

While direct identification of individual "high dust-generating roads" may be constrained, the use of emission hotspot grids coupled with road length data within those zones provides a robust and actionable framework for dust mitigation planning. This level of analysis is both appropriate and adequate to support both short-term and long-term strategies within the current study's scope.
The key hotspots in the city, identified based on PM_{10} emission levels from road dust, along with their corresponding grid locations and the total length of various categories of roads within these grids, are presented in the table 20.

Table 20: Dust-Generation Grids and Length of Different Road Categories in Each Grid

Grid No	Major in km	Connecting in km	Local in km
449	1.16	4.35	151.31
450	0.00	5.41	122.40
358	2.97	8.04	65.89
426	0.28	4.48	82.78
424	0.00	5.38	87.40

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ANNEXURES

ANNEXURE I

Traffic Count Survey Form

Time	Scooter	Motor-cycle	Moped	Car	3-wheeler (Passenger)	3-wheeler (Goods)	Truck	LCV	Minibus	Bus	Tractor
0800 hrs. to 0815 hrs.											
0900 hrs. to 0915 hrs.											
1000 hrs. to 1015 hrs.											
1100 hrs. to 1115 hrs.											
1200 hrs. to 1215 hrs.											
1300 hrs. to 1315 hrs.											
1400 hrs. to 1415 hrs.											

1500 hrs. to 1515 hrs.											
1600 hrs. to 1615 hrs.											
1700 hrs. to 1715 hrs.											
1800 hrs. to 1815 hrs.											
1900 hrs. to 1915 hrs.											
2000 hrs. to 2015 hrs.											
2100 hrs. to 2115 hrs.											
2200 hrs. to 2215 hrs.											
2300 hrs. to 2315 hrs.											

2400 hrs. to 2415 hrs.											
0100 hrs. to 0115 hrs.											
0200 hrs. to 0215 hrs.											
0300 hrs. to 0315 hrs.											
0400 hrs. to 0415 hrs.											
0500 hrs. to 0515 hrs.											
0600 hrs. to 0615 hrs.											
0700 hrs. to 0715 hrs.											

Place: **Date:**

ANNEXURE II

Parking Lot Survey Form

Place:
Date:

Codes	Questions	Response
A1	Vehicle Type	☐ Private ☐ Commercial
A2	Vehicle Type	Eg. Car, Jeep, Truck, Scooter, Motorcycle, Bus etc
A3	Year of Registration	
A4	Two wheeler/ Three wheeler engine:	☐ 2-Stroke ☐ 4-Stroke
A5	Vehicle Manufacturer	
A6	Model Name	
A7	Engine Capacity (CC)	
A8	Fuel Type	☐ Petrol ☐ Diesel ☐ CNG ☐ LPG
A9	In case CNG / LPG was installed later: Year of CNG / LPG kit fixation	
A10	How much mileage does your vehicle give on an average (in Kms/litre or km/kg)?	

A11	How many people normally travel in your vehicle?		
A12	• Fuel Consumption : • Fuel bill per month:		
A13	After how many kms do you get your vehicle serviced?		
A14	After how many months do you get your vehicle serviced?		
A15	On a weekday how many kms you travel within the Faridabad city limits (per day)		
A16	On a weekend how many kms you travel within the Faridabad city limits (per day)		
A17	What is the origin of your current trip?	☐ Faridabad	☐ Outside Faridabad
A18	What is the destination of your current trip?	☐ Faridabad	☐ Outside Faridabad

ANNEXURE III

DG Set Survey Form

Location

Survey Date: ______/_______/________

Ward No.:___________________

Name of the respondent: ______________________________

Commercial/house/hotel/restaurant/Hospital/Mall/Construction site/any other (please specify)? ……………………………………………

1. Do you use any power back-up at your home/shops/hotel/restaurant/Hospital/Mall/Construction site etc.?

   A. Yes B. No

2. If yes to Q1, what are you using?
   A. Generator B. Inverter C. Common generator D. Any other (please specify)________
3. How many hours per day do you generally require power back-up?

   Summer Hours [ ]

   Winter hours [ ]

   Monsoon hours [ ]

4. If answer to Q2 is 'A', Name and make of the generator:
   ……………………………………………..
5. What is the capacity of the generator that you are using?
   ……………………………..
6. What is the type of fuel used for your generator?

A. Diesel B. Kerosene C. Any other ________________________

7. What is the average monthly consumption of fuel for your generator?

   Summer [ ] Litres

   Winter [ ] Litres

ANNEXURE IV

Restaurant Survey Form

Survey Date: ______/_______/________

Location: **Ward Number:**

Sr. No.	Description	Details
1	Name and Address of Restaurant	
2	Fuel Used	☐ Wood ☐ Coal ☐ Charcoal ☐ Agro-residue ☐ LPG
4	Quantity of fuel used/month (kg/month)	☐ Summer ☐ Winter

ANNEXURE V

Residential Survey Form

Survey Date: ______/_______/________

Location: **Ward Number:**

Sr. No.	Description	Details
1	Responding Person Name	
2	Total Family Members	
3	Fuel Used	☐ Wood ☐ Coal ☐ Charcoal ☐ Agro-residue ☐ LPG
5.	Quantity of fuel used/month (kg/month)	☐ Summer ☐ Winter

ANNEXURE VI

Selected locations for traffic count and road dust sampling

Survey location for Faridabad			
Road	**Major (Arterial)**	**Minor (Sub-Arterial)**	**Local**
Faridabad Bypass Road	28°19'18.92"N, 77°20'39.21"E	28°19'32.75"N, 77°20'17.52"E	28°19'22.91"N, 77°20'4.77"E
Dr. Rajendra Prasad Marg- Near Hotel Howdy	28°21'35.57"N, 77°17'58.65"E	28°21'37.61"N, 77°17'51.26"E	28°21'26.74"N, 77°17'52.47"E
Shaheed Chowk Near Baba Deep Singh Ji Shaheed Marg	28°22'38.61"N, 77°17'38.73"E	28°22'27.47"N, 77°17'22.61"E	28°22'24.91"N, 77°17'15.75"E
BK Chowk	28°23'31.20"N, 77°18'7.20"E	28°23'18.05"N, 77°18'10.09"E	28°23'23.72"N, 77°18'13.09"E
NH148	28°24'4.32"N, 77°18'42.67"E	28°24'7.26"N, 77°19'17.59"E	28°24'3.41"N, 77°19'20.55"E
Bangal Suiting Chowk	28°27'17.14"N, 77°19'9.95"E	28°27'16.68"N, 77°19'2.91"E	28°27'12.28"N, 77°19'3.63"E
Lajpat Rai Punjab Kesari Chowk	28°24'57.80"N, 77°19'7.16"E	28°25'3.92"N, 77°19'12.27"E	28°25'6.34"N, 77°19'17.65"E
Pali Road Background Location	28°25'57.34"N, 77°15'57.93"E	28°26'17.35"N, 77°16'8.13"E	28°25'51.05"N, 77°15'33.61"E

ANNEXURE VII

Results of ambient air quality monitoring Summer

Date	Industrial		Residential		Commercial		Kerbside		Background	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
06-04-2022	241	136	220	63			386	112	103	71
07-04-2022	354	140	305	75	249	94	471	108	132	90
08-04-2022	363	136	352	74	180	50	384	125	105	85
09-04-2022	345	106	275	70	231	74	309	74	117	62
10-04-2022	328	84	410	78	247	85	348	83	139	85
11-04-2022	355	110	249	137	236	67	432	117	153	73
12-04-2022	227	64	534	140	520	174	496	215	246	111
13-04-2022	312	65	293	83	317	72	532	149	187	66
14-04-2022	314	74	347	80	271	72	170	111	155	53
15-04-2022	261	104	470	92	363	97	370	108	276	100
16-04-2022	336	124	461	64	322	117	321	113	214	93
17-04-2022	336	131	414	88	333	106	243	96	153	103
18-04-2022	426	155	460	85	395	129	320	114	100	88
19-04-2022	386	99	297	80	282	72	196	59	84	64
20-04-2022	392	93	366	86	326	72	252	74	144	76
Std Dev	±55	±29	±92	±23	±85	±32	±107	±37	±55	±17

ANNEXURE VIII

Results of ambient air quality monitoring Winter

Date	Industrial		Residential		Commercial		Kerbside		Background	
	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_{10}	$PM_{2.5}$
07-02-2023	186	82	293	169	247	143	491	105	145	76
08-02-2023	164	84	331	217	321	145	436	99	137	73
09-02-2023	126	59	347	92	218	99	270	179	245	120
10-02-2023	230	137	135	67	144	96	345	120	97	57
11-02-2023	216	99	117	65	171	81	212	85	72	33
12-02-2023	104	77	117	75	124	88	336	139	85	66
13/2/2023	202	129	151	56	103	103	305	113	220	105
14/2/2023	156	58	102	56	114	72	213	114	98	58
15/2/2023	246	125	150	71	115	48	348	120	89	51
16/2/2023	243	166	120	86	73	36	387	150	171	87
17/2/2023	276	162	155	74	230	106	274	118	157	78
18/2/2023	275	130	147	68	221	98	287	125	141	66
19/2/2023	195	88	151	72	197	95	301	144	105	54
20-02-2023	254	174	170	84	189	89	298	137	139	62
21-02-2023	247	168	162	79	201	92	313	149	128	59
Std Dev	±53	±41	±79	±44	±66	±29	±75	±24	±49	±22

ANNEXURE IX

Indicative landmark locations of the identified hot spot locations in the study area

Grid No	Ward No	Locations in ward with coordinates
266	44	Ansal Royal Heritage society, Lat- 28°20'15.79"N, Long- 77°21'9.21"E
287	3,14,37	ward 3- JBM group (Lat- 28°21'19.21"N, Long- 77°18'30.70"E), ward 14- Aaradhya packaging Pvt Ltd (lat- 28°22'1.04"N, long- 77°18'48.61"E), ward 37- BSNL office (lat- 28°21'22.23"N, long- 77°19'10.85"E)
288	37,39,40,41	ward-37- Sarvodaya hospital (Lat- 28°22'3.81"N, Long- 77°20'10.83"E), ward-39- St Thomas School (lat- 28°21'45.54"N, Long- 77°20'16.79"E), ward- 40- Bypass road (Lat- 28°21'4.63"N, long- 77°20'25.04"E), ward-41 Tagore schol road (Lat- 28°20'59.71"N Long- 77°20'1.94"E)
243	44	Chandawali Cahtri, Lat- 28°19'20.74"N, Long- 77°21'11.92"E
242	42,43,46,45,44	ward-42 - Nav Divya Apartment (Lat- 28°19'37.91"N. Long- 77°20'11.97"E), ward-43- Adore ananda apartment (Lat- 28°19'35.67"N, Long- 77°20'29.67"E), ward- 45- primary school (Lat- 28°18'50.96"N, long- 77°20'15.65"E), ward-46- Manavta hospital (Lat- 28°19'42.25"N, Long- 77°19'52.49"E), ward-44- sector 64-65 Dividing road (Lat- 28°19'2.02"N, Long- 77°20'36.62"E)
358	33,34,35,30	ward-34 RPS Savana (Lat- 28°24'55.41"N, Long- 77°21'22.51"E), ward-33 SRS peral Heights (lat- 28°24'44.20"N, Long- 77°20'48.03"E), ward- 35 BPTP princess park (Lat- 28°24'19.14"N, Long- 77°20'34.40"E), ward- 30 Canara bank (Lat- 28°25'14.08"N, Long- 77°20'40.41"E)
335	34,35,38	ward-34 Aravali Internationl School (Lat- 28°23'58.23"N, long- 77°21'29.69"E), ward-35 BPTP Park 81 (Lat- 28°23'48.51"N, Long- 77°20'46.64"E), Ward-38- Near Omaxe new hieght road (Lat- 28°23'19.47"N, Long- 77°21'41.68"E)
336	34,38	ward 38- Agriculte land (Lat- 28°23'17.16"N, Long- 77°22'50.12"E), ward- 34- Shiv mandir (lat- 28°24'3.77"N, long- 77°22'31.45"E)
310	13,3,14,37,36	ward-13-Gurudwara (Lat- 28°23'1.01"N, long- 77°18'8.62"E), ward-3-Baba hirdey ram mandir (lat- 28°22'6.73"N, long- 77°18'11.67"E), ward-14- Hanuman mandir (Lat- 28°22'46.88"N, Long- 77°18'48.16"E), ward-37- Parshuram road (Lat- 28°22'15.10"N, Long- 77°19'11.75"E), ward-36- Near bata chowk metro (Lat- 28°23'6.87"N, long- 77°18'52.65"E)
267	44	Govt senior secondary school, Lat- 28°20'30.02"N, Long- 77°22'18.64"E
264	3,41,37,42,46,1,2	ward-3-SAIL (Lat- 28°20'43.09"N, Long- 77°18'46.07"E), ward-41- raja nahar singh metro (Lat- 28°20'23.34"N, long- 77°18'58.82"E), ward-37- near to coordinates (lat- 28°20'57.12"N, long- 77°19'21.42"E), ward-42- near to coordinates (Lat- 28°20'27.92"N, long- 77°19'23.03"E), ward-46- Garg colony (Lat- 28°19'55.95"N, Long- 77°19'17.25"E), ward-1- maxwell industries (Lat- 28°19'52.38"N, long- 77°18'22.03"E), ward-2-Hanuman mandir- (lat- 28°20'44.74"N, long- 28°20'44.74"N)
265	40,41,37,42,43,46	ward 40- Raghunath mandir (Lat- 28°20'57.92"N, long- 77°20'15.84"E), ward-41 - Laurel paradise school (lat- 28°20'57.59"N, Long- 77°19'25.33"E), ward-37- small area (lat- 28°20'57.89"N, Long- 77°19'23.23"E), ward-42- near sihi gate road (Lat- 28°20'11.65"N, Long- 77°19'31.27"E), ward- 43- community centre sec-2 (lat- 28°20'11.42"N, long- 77°20'21.92"E), ward-46- Janki Bal Vidya Niketan (Lat- 28°19'53.05"N, Long- 77°19'25.35"E)
290	44	Neemka post office, Lat- 28°21'30.44"N, Long- 77°22'15.10"E

ANNEXURE X

Indicative landmark locations of the identified traffic congestion locations in the study area

Grid No	Ward No	Locations in ward with coordinates
449	26,27	ward 26-M.R. Garden (Lat- 28°29'48.60"N, Long- 77°20'16.10"E), ward 27-CSC center (Lat- 28°30'1.87"N, Long-77°20'16.92"E)
425	21,22,24,29	ward 21-Krishna marg (Lat- 28°27'32.65"N, Long- 77°17'59.64"E), ward 22-Bharat Gears (Lat- 28°28'30.42"N, Long- 77°18'0.65"E), ward 24-Espire Towers (Lat- 28°28'27.64"N, Long- 77°18'50.29"E), ward 29-Unknown road (Lat- 28°27'32.04"N, Long- 77°19'3.02"E)
426	24,25,26,28,29	ward 24-Shree Radha krishna Ashram (Lat- 28°27'42.35"N, Long- 77°19'14.92"E), ward 25-Anshu Hospital (Lat- 28°28'23.09"N, Long- 77°19'17.29"E), ward 26-Dwarika housing complex (28°28'37.46"N, Long- 77°20'18.43"E), ward 28-Radha ballabh temple (Lat- 28°27'40.56"N, Long- 77°19'45.87"E), ward 29-Gail gas Plant Road (Lat- 28°27'33.28"N, Long- 77°19'18.68"E)
403	28,29	ward 28-panchmukhi mandir (Lat- 28°26'41.38"N, Long- 77°19'52.42"E), ward 29-Shiv Vidya Mandir School (Lat- 28°26'31.10"N, Long- 77°19'39.49"E)
358	33,34,35,30	ward-34 RPS Savana (Lat- 28°24'55.41"N, Long- 77°21'22.51"E), ward-33 SRS peral Heights (lat- 28°24'44.20"N, Long- 77°20'48.03"E), ward- 35 BPTP princess park (Lat- 28°24'19.14"N, Long- 77°20'34.40"E), ward- 30 Canara bank (Lat- 28°25'14.08"N, Long- 77°20'40.41"E)
334	35,36	ward 35-Manav Rachna International School-2 (Lat- 28°24'0.15"N, Long- 77°19'55.65"E), ward 36-Geeta Mandir (Lat- 28°23'36.83"N, Long- 77°19'29.80"E)
335	34,35,38	ward-34 Aravali Internationl School (Lat- 28°23'58.23"N, long- 77°21'29.69"E), ward-35 BPTP Park 81 (Lat- 28°23'48.51"N, Long- 77°20'46.64"E), Ward-38- Near Omaxe new hieght road (Lat- 28°23'19.47"N, Long- 77°21'41.68"E)
311	35,36,37,38	ward-35 Ansal Crown Heights (Lat- 28°23'7.07"N, long- 77°20'29.94"E), ward 36- Excise & Taxation Department (Lat- 28°23'7.33"N, Long- 77°19'33.58"E), ward 37- B R Hospital (lat- 28°22'22.43"N, Long- 77°19'43.96"E), ward 38-Old Badoli Chowk (Lat- 28°22'35.52"N, Long- 77°20'31.67"E)
312	35,38,44	ward 35- Unknown place (Lat- 28°23'10.41"N, Long- 77°20'36.72"E), ward 38-Baag wala mandir (Lat- 28°22'41.39"N, Long- 77°20'41.20"E),ward 44- Unkown place (lat- 28°22'9.00"N, Long- 77°21'48.77"E)
243	44	Chandawali Cahtri, Lat- 28°19'20.74"N, Long- 77°21'11.92"E
219	44,45	ward 44- Sri Balaji Dham Temple Sahupura (Lat- 28°17'57.89"N, Long- 77°20'16.02"E), ward 45- Sat Guru Apartment (Lat- 28°18'42.44"N, Long- 77°20'35.09"E)
336	34,38	ward 38- Agriculte land (Lat- 28°23'17.16"N, Long- 77°22'50.12"E), ward- 34- Shiv mandir (lat- 28°24'3.77"N, long- 77°22'31.45"E)
290	44	Neemka post office, Lat- 28°21'30.44"N, Long- 77°22'15.10"E
266	44	Ansal Royal Heritage society, Lat- 28°20'15.79"N, Long- 77°21'9.21"E
267	44	Govt senior secondary school, Lat- 28°20'30.02"N, Long- 77°22'18.64"E
242	42,43,46,45,44	ward-42 - Nav Divya Apartment (Lat- 28°19'37.91"N. Long- 77°20'11.97"E), ward-43- Adore ananda apartment (Lat- 28°19'35.67"N, Long- 77°20'29.67"E), ward- 45- primary school (Lat- 28°18'50.96"N, long- 77°20'15.65"E), ward-46- Manavta hospital (Lat- 28°19'42.25"N, Long- 77°19'52.49"E), ward-44- sector 64-65 Dividing road (Lat- 28°19'2.02"N, Long- 77°20'36.62"E)
243	44	Chandawali Cahtri, Lat- 28°19'20.74"N, Long- 77°21'11.92"E
244	44	CKR Road (Lat- 28°18'53.28"N, Long- 77°22'9.40"E)

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