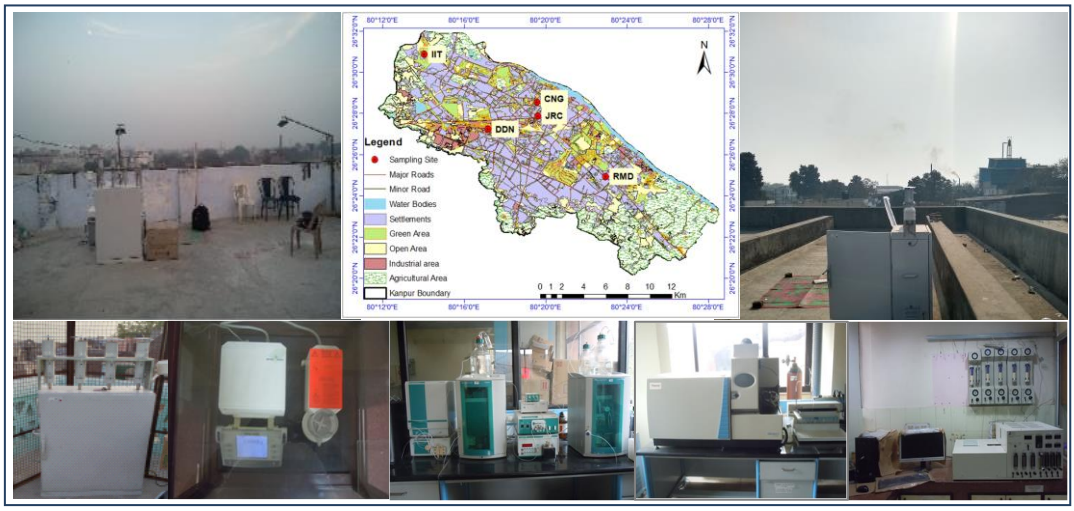
Air Quality Assessment, Trend Analysis, Emission Inventory and Source Apportionment Study in the City of Kanpur

(Final Report)

Submitted to

Uttar Pradesh Pollution Control Board, Lucknow



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Executive Summary

Since the enactment of the Air Act 1981, air pollution control programs have focused on point and area sources of emission. However, most cities in the country still face continuing particulate non-attainment problems from particles of unknown origin (or those not considered for pollution control) despite the high level of control applied to many sources.

To address the air pollution issues of the City of Kanpur, the Uttar Pradesh Pollution Control Board (UPPCB), Lucknow has sponsored the study "Air Quality Assessment, Trend Analysis, Emission Inventory and Source Apportionment Study in Kanpur City" to the Indian Institute of Technology Kanpur (IITK). The main objectives of the study were the preparation of emission inventory, air quality monitoring in two seasons, chemical composition of PM_{10} and $PM_{2.5}$, apportionment of sources to ambient air quality, trend analysis in historical air quality data and development of pollution control plan for the city. The project has the following specific objectives:

- Identify and inventorize emission sources (industry, traffic, power plants, local power generation, small-scale industries, household cooking, etc.);
- Chemical speciation of particulate matter (PM) and measurement of other air pollutants;
- Perform receptor modeling to establish the source-receptor linkages for PM in ambient air;
- Identification of various control options and assessment of their efficacies for air quality improvements and development of control scenarios consisting of combinations of several control options; and
- Selection of best control options from the developed control scenarios and recommend implementing control options in a time-bound manner.

This study had five major components (i) air quality measurements, (ii) emission inventory, (iii) air quality modeling, (iv) control options, and (v) action plan. The highlights of these components are presented below.

Air Quality: Measurements

A total of five air quality sampling sites were selected and categorized based on the predominant land-use pattern (Table 1) to cover varying land-uses prevailing in the city. PM_{10} (particulate matter of size less than or equal to 10 μm diameter), $PM_{2.5}$ (particulate matter of

size less than or equal to 2.5 µm diameter), SO_2, NO_2, VOCs (volatile organic compounds), OC (organic carbon), EC (elemental carbon), ions, elements, and PAHs (polyaromatic hydrocarbons) were considered for sampling and analysis. The air quality sampling was conducted for two seasons: winter (2018-19) and summer (2019).

Table 1: Description of Sampling Sites of Kanpur

S. No.	Sampling Location	Site Code	Description of the site	Type of sources
1.	RAMADEVI	RMD	Residential and commercial	Domestic cooking, vehicles, road dust, garbage/MSW burning, restaurants
2.	CHUNNIGANJ	CNG	Commercial	vehicles, road dust, garbage/MSW burning
3.	DADANAGAR	DDN	Industrial	Industries, DG sets, vehicles, road dust, garbage/industrial waste burning
4.	JARIB CHOWKI	JRC	Commercial	vehicles, road dust, garbage/MSW burning
5.	IIT KANPUR	IIT	Institutional cum Residential	Domestic cooking, Vehicles, road dust, restaurants

Based on the air quality measurements in summer and winter and critical analyses of air quality data (Chapter 2), the following inferences and insights are drawn for understanding the current status of air quality. The season-wise, site-specific average air concentrations of PM_{10}, $PM_{2.5}$ and their compositions have been referred to bring the important inferences to the fore.

- Particulate pollution is the main concern in the city where PM_{10} levels are 2.2 – 6.0 times higher than the national air quality standards in the winter season and 1.3 – 3.0 times in the summer season. $PM_{2.5}$ levels are 2.4 – 6.5 times higher than the national standard in the winter season. In the summer, $PM_{2.5}$ levels were 1.1 – 1.9 times higher than the national standards except at JRC where the $PM_{2.5}$ standard is met.

- The chemical composition of PM_{10} and $PM_{2.5}$ carries the signature of sources and their harmful contents. The chemical composition is variable depending on the size fraction of

particles and the season. The PM levels and chemical composition are discussed separately for two seasons.

PM_{10} (winter and summer)

The overall average concentration of PM_{10} was 367±164 µg/m^3 in winter and 205±64 µg/m^3 in summer against the acceptable level of 100 µg/m^3. The highest levels were observed at DDN (598±227 µg/m^3) and lowest at CNG (220±121 µg/m^3) in winter. In summer, the highest levels were at DDN (297±68 µg/m^3) and the lowest at JRC (133±53 µg/m^3).

In winter, crustal component (Si + Al + Fe + Ca) accounts for about 13% of total mass (much less compared to 26% in summer). This suggests soil and road dust have reduced significantly in PM_{10} in winter. The coefficient of variation (CV) is about 0.34 (of the fraction of crustal component), which suggests the crustal source contributes consistently even in winter, though much less than in summer.

In summer, the crustal component (Si + Al + Fe + Ca) accounts for about 26% of total PM_{10}. This suggests airborne soil and road dust are the major sources of PM_{10} pollution in summer. The coefficient of variation (CV) is about 0.11 (of the fraction of crustal component), which suggests the sources are consistent and uniform all around the city, forming a layer that envelops the city. RMD has the highest crustal fraction (around 31% of total PM_{10}). It is difficult to pinpoint the crustal sources as these are widespread and present all around in Kanpur and are more prominent in summer when soil and dust are dry and high-speed winds make the particles airborne. It was observed that in summer, the atmosphere looks light grayish, which can be attributed to the presence of large amounts of soil dust particles in the atmosphere.

In winter, the other important component is the combustion-related total carbon (TC = EC + OC), which account for about 31% of total PM_{10} and secondary inorganic particles (NO_3^- + SO_4^{-2} + NH_4^+) account for about 21%; both fractions of secondary particles and combustion-related carbons have increased and account for 52% of PM_{10}.

In summer, the combustion-related total carbon (EC+OC) accounts for 15% of total PM_{10} and secondary particles (NO_3^- + SO_4^{-2} + NH_4^+) account for about 13%.

The Cl^- content in PM_{10} in winter is consistent and varies between 3 – 5%, an indicator of the burning of municipal and plastic solid waste (MSW); poly vinyl chloride (PVC) is a significant part of MSW. The highest Cl^- content is observed at DDN at 30 µg/m^3 compared to the overall city level of 13.5 µg/m^3. The Cl^- content in PM_{10} in summer is consistent at 1.3 – 2.5%. The high level at DDN signifies some local burning of waste either in industrial processes or as means of disposal of solid waste.

The lead (Pb) levels are highly variable, with a city average of 6.29 µg/m^3 (because of one station DDN) in winter and 1.93 µg/m^3 in summer; these levels are very high and not acceptable (see action plan to reduce Pb emissions). The maximum levels were at DDN in winter (29.2 µg/m^3) and summer (8.7 µg/m^3). The high levels of Pb signify the industrial emissions from lead smelting units in the city. DDN is an industrial site having several secondary lead smelting units.

$PM_{2.5}$

The overall average concentration of $PM_{2.5}$ is 238±96 µg/m^3 in winter and 78±23 µg/m^3 in summer and against the acceptable level of 60 µg/m^3. The highest levels are observed at DDN (388±190 µg/m^3) and lowest at CNG (146±102 µg/m^3) in winter. In summer, the highest levels were at DDN and the lowest at JRC.

The crustal component (Si + Al + Fe + Ca) accounts for about 7% in winter and 11% in summer in total $PM_{2.5}$. The CV is about 0.15 in summer, which suggests the source is consistent all around the city though relatively small in winter.

In winter, the important components are the combustion-related total carbon (TC=EC+OC), which account for 36% of total $PM_{2.5}$ and secondary inorganic particles ($NO_3^- + SO_4^{-2} + NH_4^+$) account for 25%; both secondary particles and combustion-related carbon are consistent contributors to $PM_{2.5}$ at about 61%. The highest TC level was observed at major traffic site RMD (103 µg/m^3) and secondary particles at IIT (about 83 µg/m^3).

In summer, the combustion-related total carbon (EC+OC) accounts for 29% and secondary particles account for 25%; both secondary particles and combustion-related carbon are consistent contributors to $PM_{2.5}$ at about 54%. The highest TC was at DDN and secondary particles at CNG.

The Cl^- content in $PM_{2.5}$ was consistent in the winter and summer seasons and varied between 3 – 6%, which is an indicator of the burning of MSW. This is relatively lower in summer than in winter.

The maximum Pb levels were at DDN in winter (20.5 µg/m^3) and summer (3.39 µg/m^3). The high levels of Pb signify the industrial emissions from lead smelting units in the city.

Potassium levels

In general, potassium levels are high and variable for PM_{10} (3.7 to 9.7 µg/m^3) in winter and drop in summer to 2.3 to 5.1 µg/m^3. In $PM_{2.5}$, potassium levels in winter vary between 1.8 to 6.2 µg/m^3. In general, the potassium levels are more than 2.0 µg/m^3 in urban areas. Potassium is an indicator of biomass burning and high levels and variability (CV ~ 0.60) show a day-to-day variation in winter as biomass burning is not a uniform activity.

NO_2 levels

NO_2 levels in winter are higher than those in summer at all sites and the levels meet the national air quality standard of 80 µg/m^3, except some days at RMD and DDN. The highest NO_2 levels were at DDN in winter, an industrial site and at RMD in summer, a traffic site. In addition, high levels of NO_2 are expected to undergo chemical transformation to form fine secondary particles in the form of nitrates, sulfates and organics, adding to high levels of existing PM_{10} and $PM_{2.5}$.

SO_2 levels (generally less than 6.0 µg/m^3 except for DDN) in the city were well within the air quality standard.

General inferences

In winter, $PM_{2.5}$, OC and EC levels are significantly higher at all sites than summer levels. PM_{10} levels were also higher at all sites except at CNG. In general, air pollution levels in ambient air (barring traffic intersections) are uniform across the city, suggesting the entire city is stressed under high pollution; in a relative sense, DDN is most polluted, followed by RMD. JRC and IIT are the least polluted areas, but PM standards exceed at all sites.

It is to be noted that OC3/TC ratio (OC3 refers to carbon content of higher molecular weight organic compounds) is above 0.20 and the highest among the ratio of the fraction of OC to TC. It suggests a significant component of secondary organic aerosol is formed

in the atmosphere due to condensation, oxidation and nucleation of volatile to semi-volatile organic compounds, which suggests emissions of VOCs within and outside of Kanpur.

Total PAH levels (17 compounds; particulate phase) in winter is high (relatively to levels generally seen in urban areas) at 105 ng/m^3 and B(a)P at 3.71 ng/m^3 (annual standard is 1.0 ng/m^3); the comparison with the annual standard is not advisable due to different averaging times. PAH levels in summer drop significantly to about 65 ng/m^3. The highest PAH levels were observed at RMD (winter 250 ng/m^3 and in summer 192 ng/m^3).

The total BTX levels are slightly higher in summer (15.1±16.7 µg/m^3) than in winter (12.4±8.6 µg/m^3). The emission rate is expected to be high in summer due to higher temperature, but not much difference in the concentration is due to better dispersion and large ventilation coefficient in summer. The benzene generally meets the annual national standard (5 µg/m^3) in winter and summer.

In a broad sense, the air quality is worse in winter than in summer as air contains a much larger contribution of combustion products in winter than in summer.

Emission Inventory

Emission inventory (EI) is a necessity for planning air pollution control activities. The overall baseline EI for Kanpur City is developed for the base year 2020. The pollutant-wise contribution is shown in Figures 1 to 5. The spatial distribution of pollutant emissions from all sources is presented in Figure 6.

The total PM_{10} emission load in the city is estimated to be 106 t/d. The top four contributors to PM_{10} emissions are road dust (82%), vehicles (6%), industries (4%) and construction (2%); these are based on annual emissions. Seasonal and daily emissions could be highly variable. The estimated emission suggests that there are many important sources and a composite emission abatement including most of the sources will be required to obtain the desired air quality.

$PM_{2.5}$ emission load in the city is estimated to be 34 t/d. The top four contributors to $PM_{2.5}$ emissions are road dust (58 %), vehicles (18 %), industries (12%), and domestic fuel burning (6 %); these are based on annual emissions. Seasonal and daily emissions could be highly variable.

NO_x emissions load in the city is estimated to be 82 t/d. Nearly 78 % of emissions are attributed to vehicular emissions followed by industries (13%) and DG (diesel generator) set (6%). Vehicular emissions that occur at ground level, probably make it the most important emission. NOx apart from being a pollutant itself is an important component in the formation of secondary particles (nitrates) and ozone. NOx from vehicles and industry are potential sources for controlling NOx emissions.

SO_2 emission load in the city is estimated to be 12 t/d. Industry accounts for 76 percent of the total emission. Vehicles contribute 11% followed by Hotels and Restaurants (4%).

The estimated CO emission is about 147 t/d. Nearly 81 % emission of CO is from vehicles, followed by industries (3%), domestic (7%), and about 7 % MSW burning. Vehicles could be the main target for controlling CO for improving air quality with respect to CO.

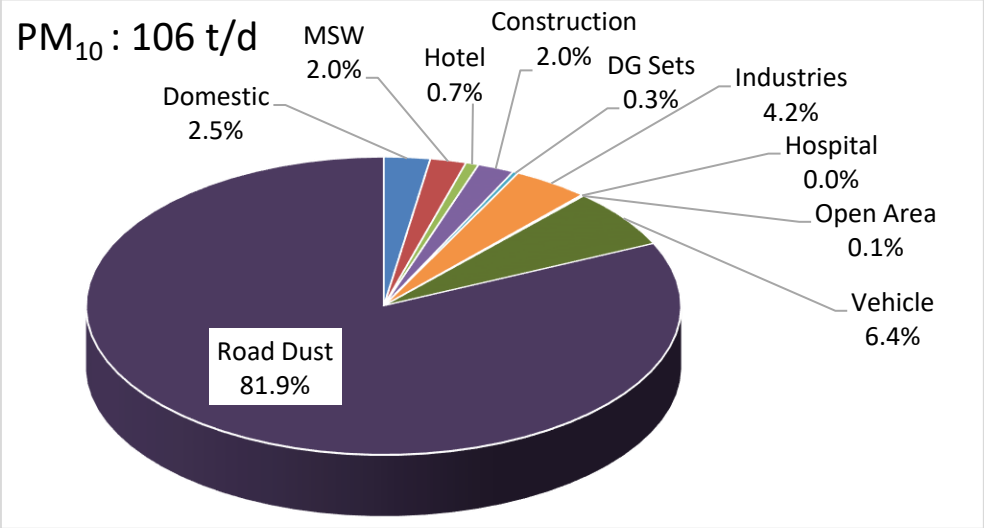

Figure 1: PM_{10} Emission Load of Different Sources in Kanpur

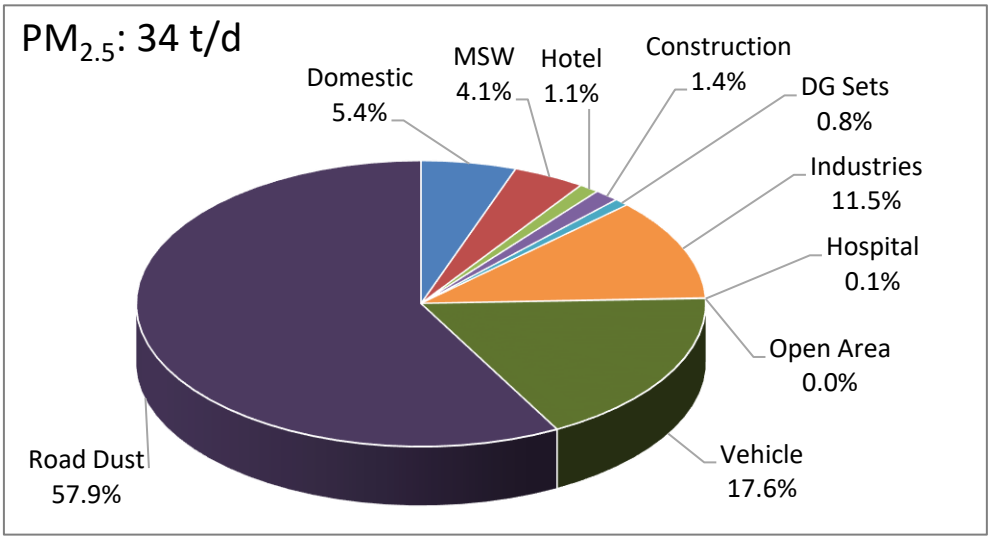

Figure 2: $PM_{2.5}$ Emission Load of Different Sources in Kanpur

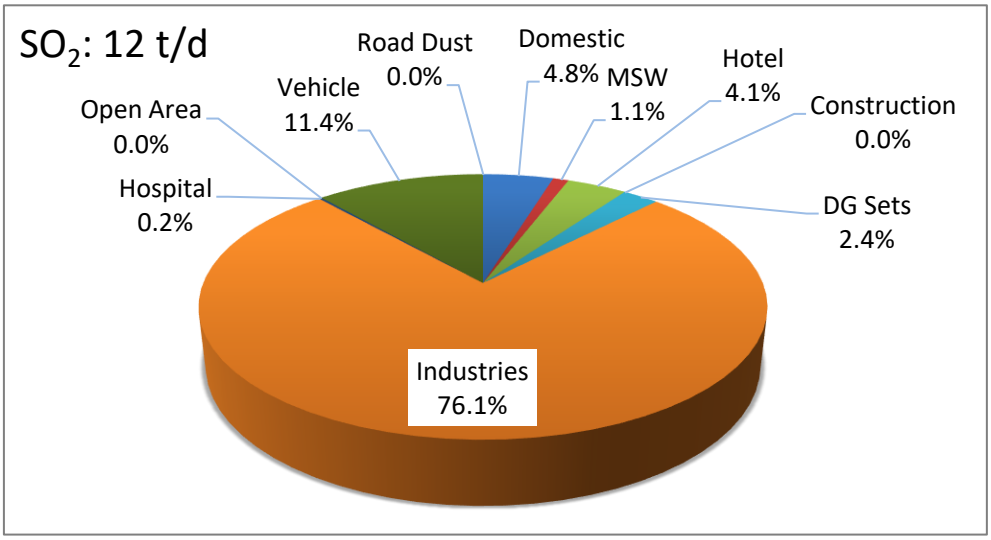

Figure 3: SO_2 Emission Load of Different Sources in Kanpur

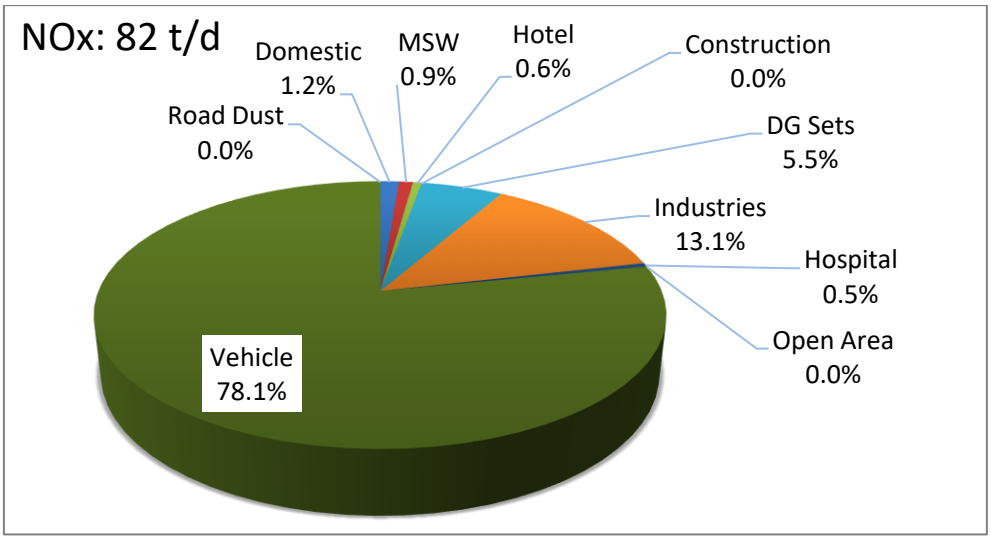

Figure 4: NOx Emission Load of Different Sources in Kanpur

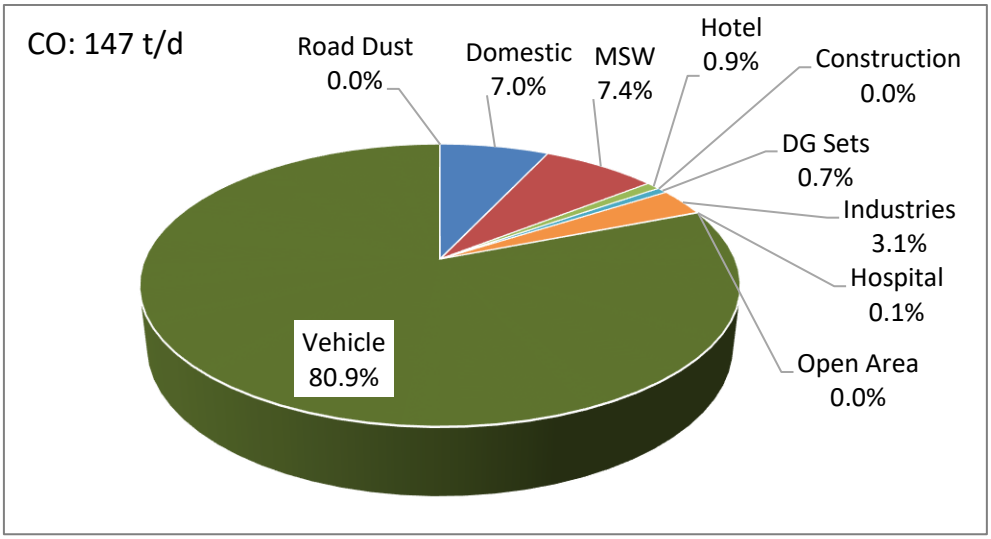

Figure 5: CO Emission Load Contribution of Different Sources in Kanpur

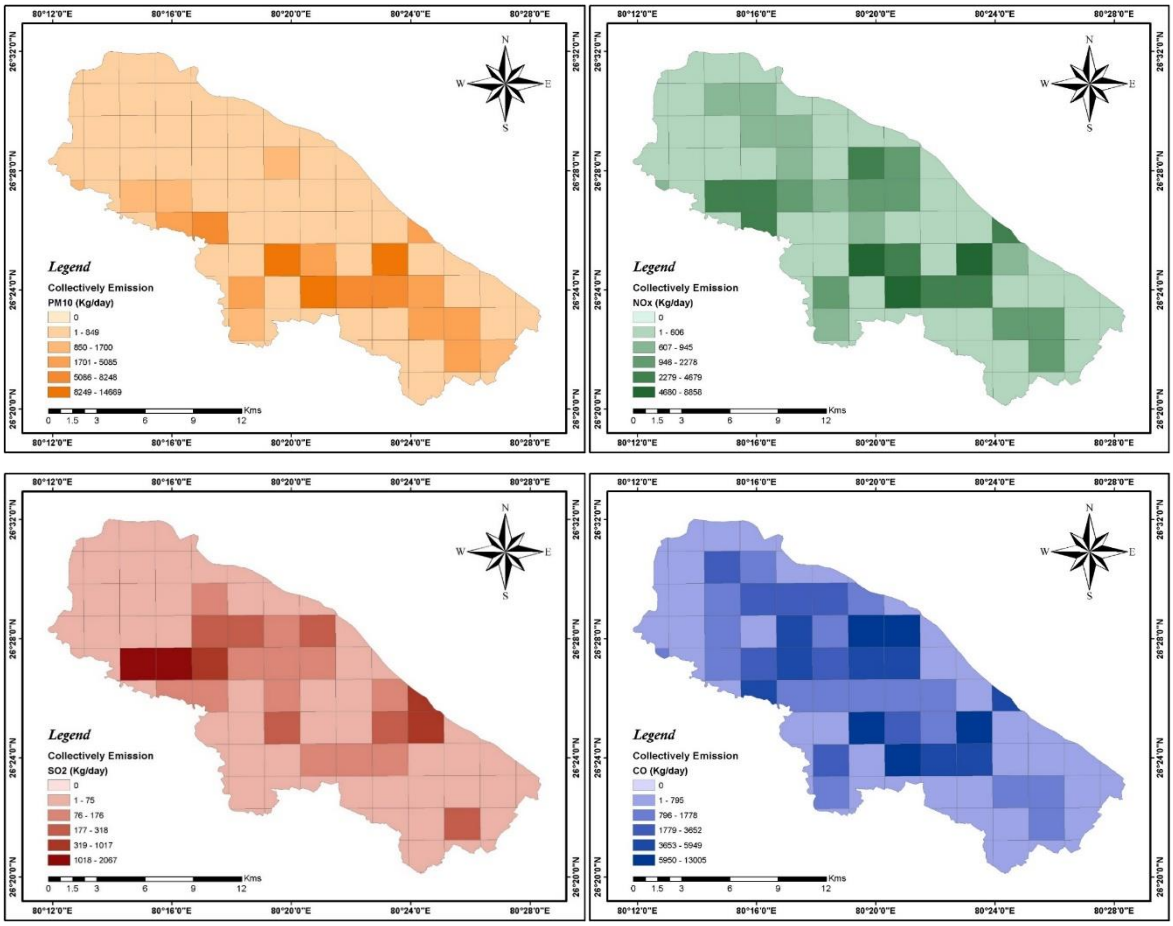

Figure 6: Spatial Distribution of PM_{10}, NO_x, SO_2 and CO Emissions in Kanpur City

Air Quality Modeling for Source Apportionment: Receptor Modeling

Based on the PMF5.0 (positive matrix factorization model; USEPA 5.0 version) modeling results (Figure 7) and their critical analyses, the following inferences and insights are drawn to establish quantified source-receptor impacts and to pave the path for the preparation of action plan. The important inferences are:

- The sources of PM_{10} and $PM_{2.5}$ contributing to ambient air quality are different in summer and winter.
    - In winter, % contribution of PM_{10} – $PM_{2.5}$ sources (given in parenthesis) to the ambient air level are: vehicles and DGs (24.5 – 29.9%), secondary organic aerosol (SOA; 16.8 – 17.9%), secondary inorganic aerosol (SIA; 16.0 – 18.7%), soil and road dust (13.7 – 11.7%), coal and fly ash (15 – 16%; includes ash from burning of residual oil), biomass burning (9.2 – 2.9%), MSW burning (7.5 – 8.8%), industrial

(5.2 – 5.5%) and construction material (2.8 – 1.1%). It is noteworthy, in winter, major sources for PM_{10} and $PM_{2.5}$ are generally the same.

- In summer, % contribution of PM_{10} - $PM_{2.5}$ sources (given in parenthesis) to the ambient air level are: soil and road dust (47.2 – 21.9%), biomass burning (10.5 – 14.8%), construction (8.5 – 11.9%), SOA (secondary organic aerosol) (8.7 – 15.5%), SIA (7.6 – 9.7%), MSW burning (4.7 – 10.3%), vehicles and DGs (4.5 – 7.1%), industrial (3.9 – 5.3%), and coal and fly ash (4.6 – 3.5%; includes burning of residual oil). It is noteworthy, in summer also, the major sources for PM_{10} and $PM_{2.5}$ are generally the same as $PM_{2.5}$ is a subset of PM_{10}.

- The most consistent sources for PM_{10} and $PM_{2.5}$ in both seasons are SOA, and vehicles and DGs. The other sources on average may contribute more (or less), but their contributions have day-to-day variations.
- The high presence of soil and dust, construction, MSW burning, biomass burning and vehicles (in PM_{10}) at most sites envelop the entire region.
- In summer, soil and road dust, coal and fly ash and construction activities contribute 60% to PM_{10} and 37% to $PM_{2.5}$. It is observed that in summer, the atmosphere looks grayish to the brownish indicating presence of large amounts of dust. In winter, the contributions of coal and fly ash, soil and road dust and construction material reduce significantly both in PM_{10} and $PM_{2.5}$ (by 21 and 16%) when winds are low and prevalent atmospheric conditions are calm.
- Vehicles and DGs (including domestic) is the highest contributing source that indicates the slow-moving traffic with high congestions on the major roads.
- SIA and SOA are the most significant contributors to PM_{10} and $PM_{2.5}$. High and consistent contributions of secondary aerosols suggest the high emissions of precursors gases from different sectors, i.e., combustion sources, industries, brick kilns, biomass, MSW burning, domestic at far distances at regional levels from the receptor sites.
- The contribution of MSW burning is higher in the summer than in the winter. In winter, the contribution of MSW burning is very high at RMD in PM_{10} – $PM_{2.5}$ (9.5 – 14.8%) followed by DDN (9.2 – 10.7%). In summer, contribution of MSW burning varied 3 - 7% in PM_{10} and 8 - 15% in $PM_{2.5}$.

- The Industrial contribution is high in winter months (5.2 – 5.5%) in PM_{10} − $PM_{2.5}$. The maximum contribution was in winter at DDN, (an industrial site); $PM_{2.5}$ (16.2%) and PM_{10} (13.8%). It is also highest at DDN in summer.

Options for PM control (see Chapter 6 for details)

- Soil and road dust

  In summer, this source contributes about 47% to PM_{10}. The silt load on most of the roads is very high and silt can become airborne with the movement of vehicles. The estimated PM_{10} emission from road dust is about 87 tons per day. Similarly, soil from the open fields gets airborne in summer. The potential control options can be the maintenance of roads, sweeping and watering of roads, better construction and maintenance, growing plants, grass at the shoulder sites and at the dividers etc., to prevent re-suspension of dust.

- Vehicular and DG sets pollution

  This source is the largest source in winter and the most consistently contributing source to PM_{10} and $PM_{2.5}$ in winter and summer. Various control options include the implementation of BS-VI, introduction of electric and hybrid vehicles, traffic planning and restriction of movement of vehicles, retro-fitment in diesel exhaust, improvement in public transport, parking etc. These options are further discussed in Chapter 6.

- Coal and fly ash

  Coal and fly ash contribute about 4% to PM_{10} and unless sources contributing to fly ash are controlled, one cannot expect improvement in air quality. It appears these sources are more fugitive than regular point sources. Fly ash emissions from hotels, restaurants, tandoors and brick kilns within a 50 km radius also cause large emissions and require better housekeeping, fly ash disposal and improved zigzag technologies in brick kilns. The city has a flyash pond of Panki power plant and emissions from the pond could also be an important source.

- Biomass burning

  Biomass burning including dung should be minimized if not completely stopped at household cooking and heating. Possibly, all residents should switch to cleaner fuel,

local bakeries and hotels, industries and other local thermal energy-consuming industries. All biomass burning in Kanpur should be banned and enforced.

- MSW burning

  One of the reasons for the burning of MSW/plastic waste is the lack of infrastructure for timely collection of MSW and people conveniently burn or it may smolder slowly for a long time. In this regard, infrastructure for collection and disposal of MSW has to improve and the burning of MSW should be completely stopped and penalty imposed as enforced by other cities.

- Industrial sources

  The industrial units in the DDN must comply with the norms notified by the UPPCB. There might be some unauthorized industries in the surroundings of DDN and RMD that must be closed. At DDN, a significant contribution is from lead smelting industries having high uncontrolled emissions. These industries must comply with the norms and shift to other industrial clusters outside the city in a phased manner.

  The other industries should shift to bag filters (or equivalent control devices) and in the next two years coal must be phased out from all industries.

- Secondary particles

  The secondary particles are expected to source from precursor gases (organic gases, SO_2 and NO_x) which are chemically transformed into particles in the atmosphere. Mostly the precursor gases are emitted both locally and from large far distances sources. For sulfates, the major contribution can be attributed to large power plants, refineries and brick kilns. However, the contribution of NO_x is mostly from local sources, especially vehicles and the city's power plants. VOCs are the major emissions from coal combustion, biomass burning, MSW burning, solvent uses, fueling stations, vehicles, DGs are the major contributors to form organic aerosols. Behera and Sharma (2010) for Kanpur have concluded that secondary aerosol (SIA and SOA) accounted for a significant mass of $PM_{2.5}$ (about 47% - 50% with SIA 32 – 33%). Any particulate control strategy should also include control of primary precursor gases.

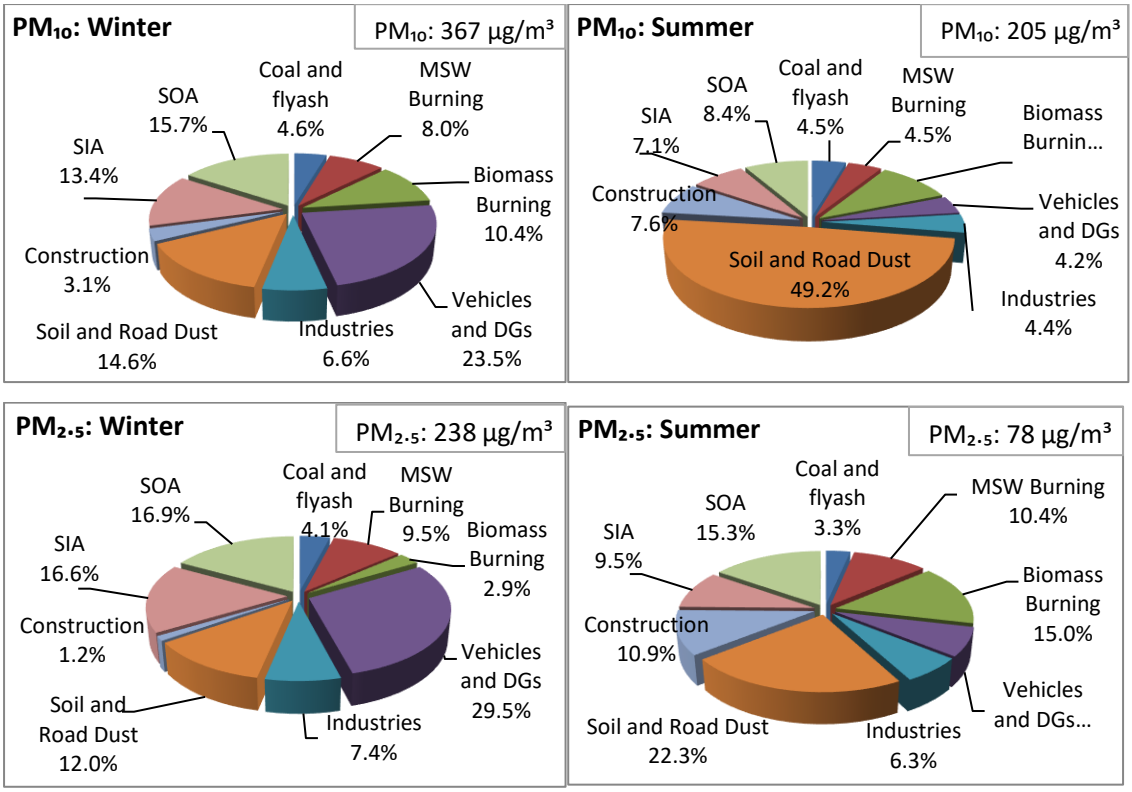

Figure 7: City level source contribution to ambient air PM_{10} and $PM_{2.5}$ levels

Dispersion Air Quality Modeling

The WRF (Weather Research and Forecasting) model for meteorology parameters was validated against the measured data from UPPCB continuous air quality monitoring station, Nehru Nagar, Kanpur. The model performed satisfactorily with a statistically significant correlation coefficient (r = 0.44; n = 365) for predicting wind speeds in the year 2018. In general, the wind speeds were overestimated by a factor of 1.5 times.

Furthermore, the time-series plot of observed 24 hourly ambient temperature levels with modeled levels showed a good agreement (r = 0.37; n = 365) for all months of 2018. In general, the temperature was underestimated by a factor of 1.15 times. It was concluded that the WRF model provided realistic meteorology and the WRF outputs were used in air quality modeling.

The $PM_{2.5}$ modeled and observed levels over one year showed a linear association (r = 0.28 n= 358). It is noteworthy that the model under-predicts the concentration by a factor of 1.5 at Nehru Nagar receptor. The probable reasons for underestimation by the model are (i) over prediction of wind speed by the WRF model in some months, (ii) inventory may be incomplete and some sources may be missing, and (iii) there is a substantial contribution of sources present

outside the Kanpur City. Since the linear association in the model-computed and observed levels is very good, the model could be used for decision-making and useful insights.

The deficit in the model and measured (referred to as unidentified) $PM_{2.5}$ levels at Nehru Nagar were highest during the January and December months. Also, it is noteworthy that there was a sudden spike in these unidentified concentrations of $PM_{2.5}$ during the last week of October, first and last week of November. This episodic spike in the unidentified $PM_{2.5}$ concentrations with an average value was almost 137 $\mu g/m^3$ in the city, which can be attributed to the influx from the surrounding regions outside the city.

For better insight, Kanpur City was divided into five regions (Figure 5.11). The modelled concentration in region 3 had the average $PM_{2.5}$ concentration of 692.25 ± 185.03 $\mu g/m^3$ derived from the peak 24-hour concentrations (in the region) followed by region 4 with 516.43 ± 173.01 $\mu g/m^3$ and region 5 with 454.87 ± 146.11 $\mu g/m^3$ and least in Region 1 at 263.86 ± 63.51 $\mu g/m^3$.

Regions 3 and 4 are densely populated and regions 1 and 2 have a large number of industries. The highest 24-hour average $PM_{2.5}$ concentrations were observed during the winter months (November and December) while the lowest was during the summer (June and July).

From the annual average plots, it is seen that $PM_{2.5}$ envelops a large area that gets elongated along the prevailing wind direction (N-W) within Kanpur City. The annual standard for $PM_{2.5}$ concentration (40 $\mu g/m^3$) is exceeded in the area surrounding industries, main roads and the National Highway.

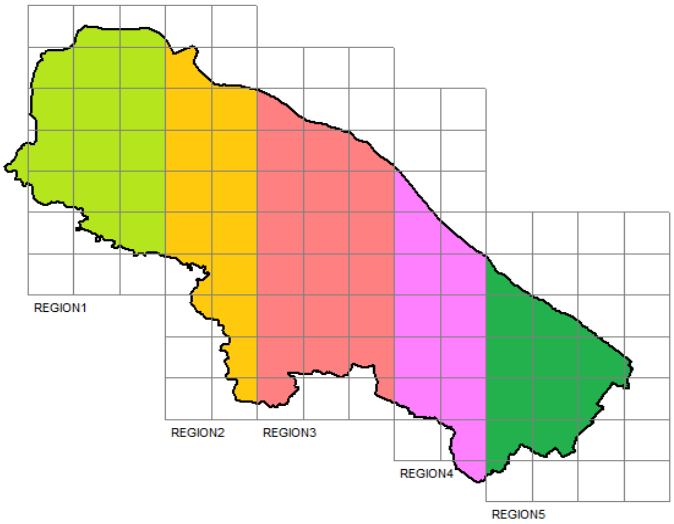

Figure 8: Demarcation of Five Regions for Impact Assessment

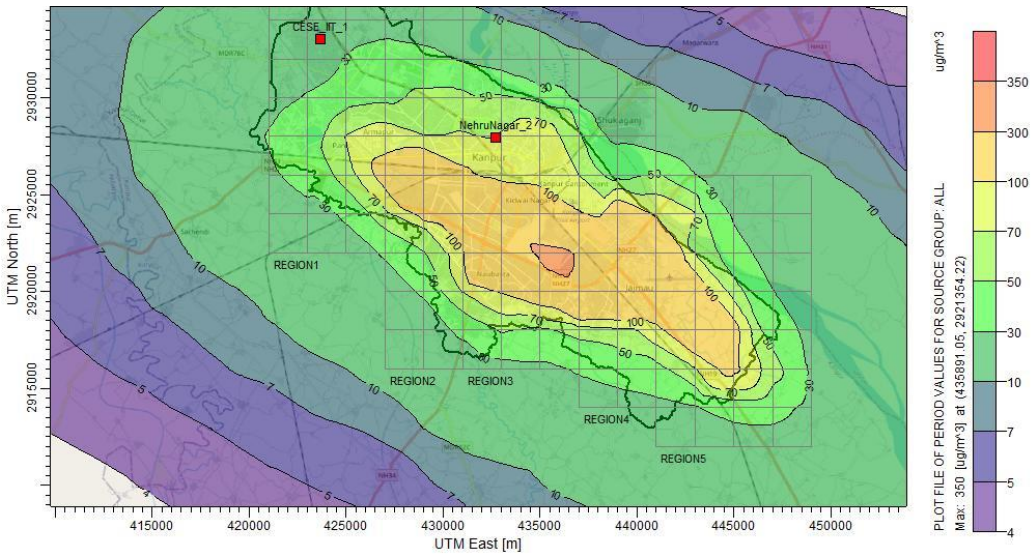

Figure 9: Annual Average $PM_{2.5}$ Levels from All Sources in the City

Control Options and Actions

A detailed analysis of control options for PM is given in Chapter 6. The proposed control options are summarized below in Table 2.

Table 2: Control Options and Action Plan for City of Kanpur

Source	Control Action	Responsible authorities	Time Frame (within specified time)
Hotels/ Restaurants/ Banquet Halls	All Restaurants small or large should not use coal and shift to gas-based or electric (for sitting capacity of more than 10 persons) appliances.	Kanpur Municipal Corporation	1 year
	Link Commercial license to clean fuel	Kanpur Municipal Corporation, Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	1 year
	Ash/residue from the tandoor and other activities should not be disposed of near the roadside. Requires ward-level surveillance.	Kanpur Municipal Corporations	1 year
Domestic Sector	LPG to all. Slums and about 15% of populations are still using wood, biomass, and dung as cooking fuel.	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	1 year
	No new building complex or society be allowed without PNG supply distribution network	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	1 year

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	By 2030, the city may plan to shift to electric cooking (common in western countries) or to PNG at the minimum	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	10 years
Municipal Solid Waste (MSW) Burning	Any type of garbage burning should be strictly stopped. Current waste collection and surveillance are poor.	Kanpur Municipal Corporation	Immediate
	Surveillance is required that hazardous waste goes to TSDF.	Kanpur Municipal Corporation, UPPCB	
	Desilting and cleaning of municipal drains	Kanpur Municipal Corporation	
	Waste burning in Industrial areas should be stopped.	UPSIDC, UPPCB	
	Daily, Monthly mass balance of MSW generation and disposal	Kanpur Municipal Corporation	
	Sensitize people and media through workshops and literature distribution as not to burn the waste.	Kanpur Municipal Corporation, UPPCB, and NGO	
Construction and Demolition	Wet suppression	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	Immediate

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Wind speed reduction (for large construction sites)	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	Enforcement of C&D Waste Management Rules. The waste should be sent to construction and demolition processing facility	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	Immediate
	Proper handling and storage of raw material: covered the storage and provide the windbreakers.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	Vehicle cleaning and specific fixed wheel washing on leaving the site and damping down of haul routes.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	The actual construction area should be covered by a fine screen.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	No storage (no matter how small) of construction material near roadside (up to 10 m from the edge of the road)	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	Builders should leave 25% area for green belt in residential colonies to be made mandatory.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	Sensitize construction workers and contract agencies through workshops.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD, UPPCB, and NGO	
Road Dust	The silt load in Kanpur varies from 8.2 to 62.7 g/m^2. The silt load on each road should be reduced under 3 gm/m^2. Regular vacuum sweeping should be done on the road having a silt load above 3 $gm/m^{2.}$	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, PWD, UPPCB (for silt load compliance)	Immediate
	Convert unpaved roads to paved roads. Maintain pothole-free roads.	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, PWD, UPPCB to carry out surveillance	

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Implementation of truck loading guidelines; use appropriate enclosures for haul trucks and gravel paving for all haul routes.	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, PWD	
	Increase green cover and plantation. Undertake to the green of open areas, community places, schools, and housing societies.	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, State Forest Department, PWD	
	vacuum-assisted sweeping is carried out four times a month on major roads with road washing.	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, PWD	
Vehicles	Diesel vehicles entering the city should be equipped with DPF which will bring a reduction of 40% in emissions (This option can be implemented with vehicles of BS-IV category as well)	State Transportation Department	3 years
	Industries must be encouraged to use BS-VI or BS-IV (with DPF) vehicles for transportation of raw and finished products	Industrial Associations and State transport Department	Immediate

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Restriction on plying and phasing out of 10 years old commercial diesel-driven vehicles.	Transport Department	2 years
	Introduction of cleaner fuels (CNG/ LPG) for all vehicles (other than 2-W).	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	2 years
	Check overloading: Expedited installation of weigh-in-motion bridges and machines at all entry points to Kanpur.	Transport Department, Traffic Police, Kanpur, NHAI, Toll agencies	Six-months
	Electric/Hybrid Vehicles should be encouraged; New residential and commercial buildings to have charging facilities. All new city buses should be electric.	Transport Department, Kanpur City Transport Services Ltd	1 year
	Bus stop and their parking should be rationalized to ensure more efficient utilization. The depots should include well-equipped maintenance workshops. Adequate charging stations.	Transport Department, Kanpur City Transport Services Ltd	1year

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Enforcement of bus lanes and keeping them free from obstruction and encroachment.	Kanpur Municipal Corporation, Kanpur City Transport Services Ltd	1 year
	Ensure integration of the upcoming metro system with bus services.	Kanpur Metro Rail Corporation, Kanpur Development Authority, Kanpur Municipal Corporation, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	1 year
	Route rationalization: Improvement of availability by rationalizing routes and fleet enhancement with requisite modification.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	1 year
	IT systems in buses, bus stops, and control centers, and passenger information systems for the reliability of bus services and monitoring.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	1 year
	Movement of materials (raw and product) within city should be allowed between 10 PM to 5 AM.	Transport Department, Kanpur, Kanpur Development Authority, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	1 year
Industries and DG Sets	Ensuring emission standards in industries. Shifting of polluting industries.	UPPCB, Industries Department	1 year

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Strict action to stop unscientific disposal of hazardous waste in the surrounding area	Municipal council and UPPCB	
	There should be separate Treatment, Storage, and Disposal Facilities (TSDFs) for hazardous waste.	Industrial Associations, UPSIDC, Industries Department, UPPCB	2 years
	Industrial waste burning should be stopped immediately	Industrial Associations, UPSIDC, UPPCB	Immediate
	Following best practices to minimize fugitive emission within the industry premises, all leakages within the industry should be controlled	Industrial Associations, UPSIDC, UPPCB	Immediate
	Area and road in front of the industry should be the responsibility of the industry	Industrial Associations, UPSIDC, UPPCB	
	Category A Industries (using coal and other dirty fuels)		
	About 707 boilers and furnaces in Kanpur are running over coal, wood, and other dirty solid fuels which should be shifted to natural gas and electricity	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.), Industrial Associations, UPPCB	2 years

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Almost all rotary furnaces having significant emissions are running on coal that needs to be shifted to natural gas and electricity	Industrial Associations, UPPCB	2 years
	Multi-cyclones should be replaced by baghouses. Ensure installation and operation of air pollution control devices in industries.	Industrial Associations, UPPCB	2 years
	Category B Industries (Induction Furnace)		
	Recommended Fume gas capturing hood followed by Baghouse should be used to control air pollution	Industrial Associations, UPPCB	2 years
	Diesel Generator Sets		
	Strengthening of grid power supply, uninterrupted power supply to the industries	State Energy Department, JVVNL	2 years
	Renewable energy should be used to cater to the need of office requirements in the absence of power failure to stop the use of DG Set	Industrial Associations	2 years
	Dada Nagar area had very high lead levels. There are more than 35 secondary lead smelting units in the	UPPCB	1 year

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	area. Given that these lead units are in highly populated mixed land-use area, it is suggested that these industries shift to other areas with low population density and with highly efficient capture devices and suitable disposal of collected lead particles.		
Decongestion of Roads at high traffic areas	Strict action on roadside encroachment. Disciplined movement of tempos to stop only at designate spots. Action on driving on wrong lane	Kanpur Development Authority, Kanpur Municipal Corporations, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	6 months
	Disciplined Public transport (designate one lane stop).	Kanpur City Transport Services Ltd., Traffic Police, Kanpur	
	Removal of the free parking zone. No parking withing 50 m of any major crossing and or chaurahs, rotaries. Strictly follow Indian Road Congress guidelines	Kanpur Development Authority, Kanpur Municipal Corporation, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Examine the existing framework for removing broken vehicles from roads and create a system for speedy removal and ensure minimal disruption to traffic.	Kanpur Development Authority, Kanpur City Transport Services Ltd, NHAI, Traffic Police, Kanpur	
	Synchronize traffic movements or introduce intelligent traffic systems for lane-driving.	Kanpur Development Authority, Kanpur City Transport Services Ltd, NHAI, Traffic Police, Kanpur	
	Mechanized multi-story parking at bus stands, railway stations, and big commercial areas. Remove at least 50 percent of on-street parking in the city	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, NHAI, Traffic Police, Kanpur	
	Identify traffic bottleneck intersections and develop a smooth traffic plan. For example, Ramadevi, Tatmill, Afimkothi, Jarib chowki, and Rawatpur crossing are the main bottlenecks for traffic.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, Traffic Police, Kanpur	

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Parking policy in congestion area (high parking cost, at city centers, only parking is limited for physically challenged people, etc).	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, NHAI, Traffic Police, Kanpur	
	Jhakarkati Bus Stand causes extreme congestion and increased emissions and should be decongested at priority. It is recommended that the city should relocate these bus stations to the outskirts of the city.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, Traffic Police, Kanpur	
	The important point of congestions is Naubasta Chaburah. For example, vehicles coming from Jhansi and going towards Hamirpur or vice versa can be avoided by constructing flyovers at Naubasta Chaburah and similarly a connecting flyover for vehicles coming/going from Hamirpur. As a result of connecting flyovers, other major connecting routes within city will also decongest.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, Traffic Police, Kanpur, NHAI	2 years

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	The high frequency of railway traffic through several railway crossings results in long queues of the vehicle on both sides of the boom barrier traffic spilling over the main road. The commuters tend to barge into the wrong/opposite lane further aggravating the congestion. Since it is no possible to have the flyovers at all crossings a system of smooth U-turns and approach to railway crossing is proposed (Figure 6.23). This system can be employed at several locations on the GT road.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, Traffic Police, Kanpur, NHAI, Kanpur metro	1 year
*The above steps should not only be implemented in Kanpur municipal limits rather these should be extended to up to at least 25 km beyond the boundary. This will need support from the central government.			

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Acknowledgments

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1 Introduction

1.1 Background

Air pollution has emerged as a major challenge, particularly in urban areas. The problem becomes more complex due to the multiplicity and complexity of air polluting source mix (e.g., industries, automobiles, generator sets, domestic fuel burning, roadside dust, construction activities, etc.). The Kanpur city is known for its colonial architecture, gardens, parks and fine quality leather products and textile industries. Being a major centre of commerce, industry and education, Kanpur has experienced significant growth in recent years. The burgeoning population coupled with rapid growth in terms of vehicles, construction, and energy consumption has resulted in serious environmental concerns in Kanpur.

Until recently, traditional approaches to the problem of apportioning source impacts have been limited to dispersion, or source, models which use emission inventory data (gathered at emission source) with meteorological data to estimate impacts at the receptor. Unlike source models, receptor models (especially for particulate matter) derive source impacts based on ambient particulate morphology, chemistry and variability information collected at the receptor. The increased interest in receptor models has resulted from the inability of dispersion models to assess short-term source impacts or identify sources, which collectively account for all of the measured mass (USEPA, 1991). These shortcomings are largely the result of the difficulty in developing accurate 24-hour particulate emission inventories and meteorological databases. Although traditional techniques using dispersion modelling for source impact apportionment will remain an important tool in air-shed management, recent advances in receptor-oriented techniques offer an additional useful tool.

Since the enactment of the Air Act 1981, air pollution control programs have focused on point and area source emissions, and many areas have benefited from these control programs. Nonetheless, most cities in the country still face continuing particulate non-attainment problems from particles of unknown origin (or those not considered for pollution control) despite the high level of control applied to many point sources. It is in the latter case that an improved understanding of source-receptor linkages is especially needed if cost-effective emission reductions are to be achieved. Determining the sources of airborne particulate matter is a difficult problem because of the complexity of the urban source mix. The problem is often compounded by the predominance of non-ducted and widely distributed area (fugitive) sources

and the lack of understanding of the sources of secondary aerosol, their formation and transport. The advent of receptor modeling and recent developments in the areas of trace element analysis now permit a much more detailed analysis of ambient aerosol samples. By providing detailed information on the sources of the total, fine and inhalable particles, receptor models can play a major role in developing strategies for controlling airborne particulate matter.

It is evident from the above discussions that receptor modeling is a promising tool for source identification and apportionment in complex urban conditions. This is particularly true when many unorganized activities are releasing particulate into the atmosphere, which is typically true for our urban cities. In order to apply receptor modeling, it is essential to identify sources (small or large), generate emission profiles in terms of fingerprints and elemental composition. The next vital step is determining the chemical characterization of collected particulate matter on filter paper. In fact, it is easily conceivable that receptor and dispersion modeling can complement each other for better interpretations and decision making and can be applied in tandem.

To address the air pollution issues of the City of Kanpur, the Uttar Pradesh Pollution Control Board (UPPCB), Lucknow has sponsored the study "Air Quality Assessment, Trend Analysis, Emission Inventory and Source Apportionment Study in Kanpur City" to the Indian Institute of Technology Kanpur (IITK). The main objectives of the study are preparation of emission inventory, air quality monitoring in two seasons, chemical composition of PM_{10} and $PM_{2.5}$, apportionment sources to ambient air quality, trend analysis in historical air quality data.

1.2 General Description of City

1.2.1 Geography and Demography

Kanpur is the largest metropolitan city in the State of Uttar Pradesh situated between the latitude 25.433º - 26.967º N and longitude 79.517º - 80.567º E on the southern bank of the river Ganga and sprawling over an area of 260 sq km. Kanpur is the most populous city in Uttar Pradesh and placed 12th in India. In Kanpur, the key business activities are trade, commerce, industries and education. The industry sectors in Kanpur are categorized as leather and footwear, textiles, fertilizer, chemicals, sugar mills, flour mills, power plant, soaps, pan-masala, hosiery and engineering industries.

The population of Kanpur city is 2,765,348; of which male and female are 1,489,062 and 1,276,286 respectively (as per the 2011 census) and has shown a consistent increase in the past 50 years (Census-India, 2012). The city is governed by Municipal Corporation, which has 110 wards.

1.2.2 Climate

The climate of Kanpur features a tropical nature and the temperature varies from 2°C in winter to 48 °C in peak summer. The city features mild winters, hot and dry summers and a monsoon season. In summers, the city witnesses a sudden surge in temperature and at times, mercury goes up to 48 °C. The total rainfall in the district varies from 450 mm to 750 mm on an average of 40 rainy days (mostly in monsoon). The relative humidity in the city varies between 15% to 85%.

1.2.3 Emission Source Activities

The source activities for air pollution in the city of Kanpur can be broadly classified as: transport sector (motor vehicles and railways), commercial activities, industrial activities, domestic activities, institutional and office activities and fugitive non-point sources. For transport of men, mostly public transport, tempos and taxies fulfill the transport requirement for the city. The combustion of fuels like coal, liquefied petroleum gas (LPG) and wood come under the source of domestic activities. As far as industrial activities are concerned, mostly small and medium scale industries are responsible for industrial air pollution. In most institutions and offices, diesel generators are used at the time of power failure.

1.3 Need for the Study

1.3.1 Air Pollution Levels: Earlier Studies

$PM_{2.5}$ and PM_{10} concentrations varied seasonally with atmospheric processes and the anthropogenic activities in Kanpur. A few studies on source apportionment of PM levels have been reported in Kanpur (Behera et al., 2011; Behera and Sharma, 2010; CPCB, 2011; Rajput et al., 2016; Shukla and Sharma, 2008). These studies have employed trace element markers and principal component analysis at a few locations. Nagar et al. (Nagar et al., 2019) have reported that the bi-monthly pattern for PM_{10} is in Kanpur at four sites. Their study (Nagar et al., 2019) concluded that the PM_{10} levels exceed the Indian air quality standard of 100 $\mu g/m^3$ at

all sites by a factor of 2 – 4. A sudden rise in PM_{10} level is reported from the second half of October to the first half of November, after that, levels drop slowly in the winter.

Ram et al. (2012) have reported the levels of TSP (total suspended particulate size 100 μm or less; 442 – 493 μg/m^3), PM_{10} (particulate matter of size 10 μm or less; 208 – 211 μg/m^3) and $PM_{2.5}$ (60 – 150 μg/m^3).

Behera and Sharma (2010) have characterized the $PM_{2.5}$ for chemical composition for ionic species, 18 metals and carbon contents (EC and OC) and reconstructed the primary and secondary components in the urban area. It was reported that $PM_{2.5}$ (136 – 232 μg/m^3 in summer and 172 – 304 μg/m^3 in winter) constituted the primary component (crustal matter, EC and OC mass; 24% in winter and 27% in summer) and secondary component, SIA and SOA (50% in winter and 45% in summer) and other unidentified mass (26% in winter and 27% in summer).

Although Kanpur city faces air pollution problems due to the number of sources, no detailed study of the chemical composition of PM_{10} and $PM_{2.5}$ in recent years has been undertaken to identify the sources and their contributions to air pollution.

1.4 Objectives and Scope of Work

Objectively the project aims to achieve the following:

- Development of GIS-based gridded (2 km × 2 km resolution) emission inventory for air pollutants (particulate matter equal and less than 10μm diameter (PM_{10}), particulate matter equal and less than 2.5μm diameter ($PM_{2.5}$), sulphur dioxide (SO_2), carbon monoxide (CO), and oxides of nitrogen (NOx) for the base year, 2020.
- Compilation of emission factors for all sources, parking lot surveys through questionnaires for vehicle technology, model, engine capacity and measurement of driving patterns of various classes of vehicles operating on roads.
- Compilation and interpretation of ambient air quality data for PM_{10}, $PM_{2.5}$, SO_2, NO_2 and other pollutants being monitored. The time-series analyses will identify trends such as: (i) significant downward, (ii) significant upward, (iii) firstly decreasing and then increasing, (iv) firstly increasing then decreasing (iv) no trend.
- Monitoring of air pollutants PM_{10}, $PM_{2.5}$, SO_2, NO_2, Benzene, Toluene, and Xylene. Analyze collected PM_{10} and $PM_{2.5}$ mass for elemental composition, ions, elemental carbon, organic carbon, PAHs (Di methyl Phthalate (DmP), Acenaphthylene (AcP), Di

ethyl Phthalate (DEP), Fluorene (Flu), Phenanthrene (Phe), Anthracene (Ant), Pyrene (Pyr), Butyl benzyl phthalate (BbP), Bis(2-ethylhexyl) adipate (BeA), Benzo(a)anthracene (B(a)A), Chrysene (Chr), Benzo(b)fluoranthene (B(b)F), Benzo(k)fluoranthene (B(k)F), Benzo(a)pyrene (B(a)P), Indeno(1,2,3-cd)pyrene (InP), Dibenzo(a,h)anthracene (D(a,h)A) and Benzo(ghi)perylene (B(ghi)P)).

- Reconstruction of chemical species of PM and assessment for primary and secondary sources of air pollutants.
- Application of receptor model to establish source receptor linkages of PM_{10}, and $PM_{2.5}$ using state-of-the-art modeling to arrive at source apportionments at various sampling sites.
- Identification of various control options (e.g., adoption of EURO IV/V, diesel filter, etc.) and assessment of their efficacies for air quality improvements and development of control scenarios (in a techno-economical perspective) consisting of combinations of several control options.
- Selection of most effective control options for implementation and development of time-bound action plan.

1.5 Approach to the Study

The approach to the study is based on the attainment of its objectives within the scope of work, as explained in section 1.4. The summary of the approach to the study and major tasks are presented in Figure 1.1. The overall approach to the study is broadly described below.

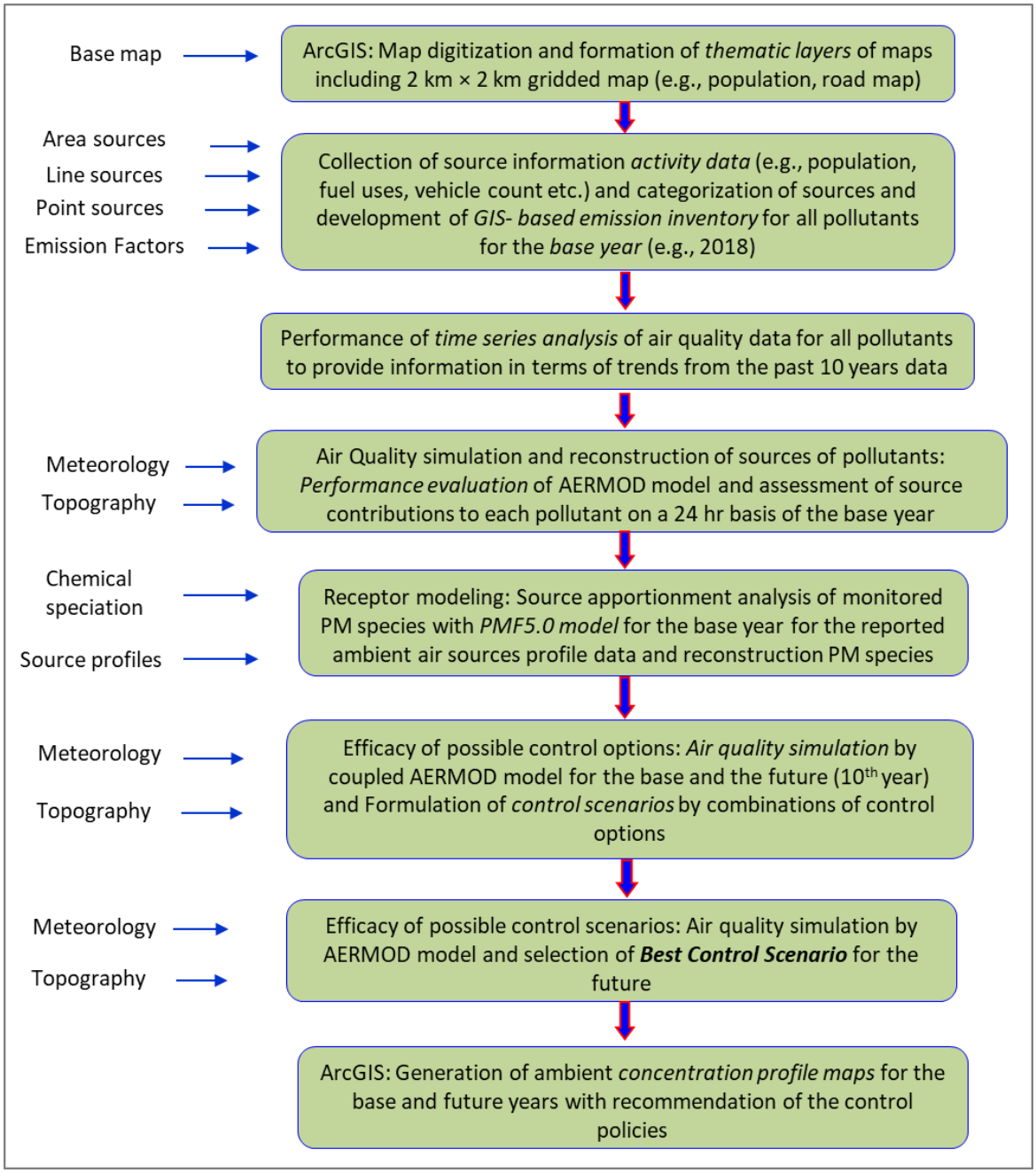


Figure 1.1: Approach to the Study and Major Tasks

1.5.1 Selection of sampling sites: Representation of Urban Land-use

It was considered appropriate that five sites in a city like Kanpur can represent typical land-use patterns. It needs to be ensured that at all sites, there is a free flow of air without any obstruction (e.g., buildings, trees, etc.). In view of the safety of the stations, most public buildings could be better choices as sampling sites. Sites were finalized in consultation with the officials of UPPCB, Kanpur.

1.5.2 Identification and Grouping of Sources for Emission Inventory

An on-the-field exercise was taken up to physically identify all small and large sources around the sampling sites. This exercise included the presence of emission sources like refuses and biomass burning, road dust, and coal/coke burnt by street vendors/small restaurants to large units like power generation units and various vehicle types. It was necessary to group some of the similar sources to keep the inventory exercise manageable. It needs to be recognized that particulate emission sources change from one season to another. Finally, the collected data were developed into emission inventory for the following pollutants: SO_2, NOx, CO, PM_{10} and $PM_{2.5}$ on a GIS platform.

1.5.3 Emission Source Profiles

PMF model does not require emission source profiles. Instead, it generates the local profiles based on the matrix database. First, however, a database is developed to find source-specific fingerprint chemical species for assigning the source to the factor generated from the PMF model.

Since for $PM_{2.5}$, Indian or Kanpur specific source profiles are not available except for vehicular sources (ARAI, 2009), the source profiles for this study were taken from 'SPECIATE version 3.2' of USEPA (2006) and updated version 5.1 of SPECIATE (USEPA, 2020). For vehicular sources, profiles were taken from ARAI (2009). 'SPECIATE' is a repository of Total Organic Compound (TOC) and PM speciated profiles for a variety of sources for use in source apportionment studies (USEPA, 2006, 2020); care has been exercised in adopting the profiles for their applicability in the local environment of Kanpur city. For the sake of uniformity, source profiles for non-vehicular sources for PM_{10} and $PM_{2.5}$ were adopted from USEPA (2006). These profiles (SPECIATE version 5.1 and ARAI) were used to verify profiles derived from ambient PM levels and its chemical compositions by positive matrix factorization (PMF) model.

1.5.4 Application of Receptor modeling

There are several methods and available commercial software that can be used for apportioning the sources if the emission profiles and measurements are available in the ambient air particulate in terms of elemental composition. The most common software is USEPA PMF 5.0 (USEPA, 2014). This model should be able to provide the contribution of each source in the

particulate in ambient air. The modeling results should help identify major sources for pollution control. It was important to note that along with source contribution, the model could also provide the associated uncertainties in estimated source contributions.

1.5.5 Application of Dispersion Modeling

In addition to receptor modeling, dispersion modeling in the study area was undertaken. The hourly meteorological data were generated through WRF "Version 3.6" model (NCAR, 2012). The emission quantities coupled with predominant meteorological data of the city were used in the dispersion model in estimating the concentration of various pollutants and examining the contribution of each of the sources. AERMOD View "Version 9.0." model (USEPA, 2015) was used for dispersion modeling.

1.6 Report Structure

The report is divided into six chapters. The brief descriptions of the chapters are given below.

Chapter 1

This chapter presents the background of the study, general description of the city, including geography and demography, climate and sources of air pollution. The current status of the city in terms of air pollution is described by reviewing the previous studies. The objectives, scope and approach to this study are also briefly described in this chapter.

Chapter 2

This chapter presents the air quality status of the city based on the monitoring and chemical characterization results of various air pollutants of all sampling sites for two seasons, i.e., winter and summer. In addition to the above information, this chapter also describes methodologies adopted for monitoring, laboratory analyses, quality assurance and quality control (QA/QC). Finally, this chapter also compares the results of all sites both diurnally and seasonally.

Chapter 3

This chapter describes the methodology of developing an emission inventory of pollutants at different grids of the city. The chapter also presents and compares the grid-wise results of emission inventory outputs for various pollutants. The contributions of various sources towards

air pollution loads (pollutant-wise) are presented. The QA/QC approaches for emission inventory are also explained in this chapter.

Chapter 4

This chapter presents the methodology used for PMF5.0 modeling for source apportionment study for PM_{10} and $PM_{2.5}$ in the summer and winter. The contribution of various sources at receptor sites and the overall scenario of sources that influences the air quality in the city is presented.

Chapter 5

This chapter presents the methodology used for dispersion modeling for source apportionment study for $PM_{2.5}$ in the summer and winter seasons. The pattern of $PM_{2.5}$ is described temporally and spatially at different receptor sites and the overall scenario of sources that influence the city's air quality is presented.

Chapter 6

This chapter describes, explores and analyzes emission control options and analysis for various sources based on the modeling results from Chapters 3, 4 and 5.

This chapter discusses alternatives for controlling the prominent sources in the city from the management, administrative and technology points of view.

2 Air Quality: Measurements, Data Analyses and Inferences

2.1 Introduction

Air pollution continues to remain a public health concern despite various actions taken to control air pollution. There is a need to take stock of benefits that have accrued and ponder on 'Way Forward'. Further analysis of actions and future needs become even more important in view of the revised air quality standards that have been notified (http://www.cpcb.nic.in/National_Ambient_Air_Quality_ Standards.php (CPCB, 2009). The first step to accomplish future action is to assess the current air pollution status.

This chapter presents and discusses the current status of the air quality of Kanpur from the sampling and chemical analysis results for two seasons carried out under the present study.

2.2 Methodology

2.2.1 Site selection and details

Total of five air quality sites have been selected to cover various land-use patterns prevailing in the city. It is ensured that at all sites, there was a free flow of air without any obstruction (e.g., buildings, trees etc.). In view of the safety of the stations, public buildings (institutions, office buildings, etc.) were selected. The sites were selected in consultation with UPPCB, Lucknow. Table 2.1 describes the sampling sites with prevailing land use and other features. Figure 2.1 shows the physical features (photographs) of the sampling sites. Figure 2.2 shows the locations of the sampling sites on the map and the overall land-use pattern of the city.

Table 2.1: Description of Sampling Sites of Kanpur

S. No.	Sampling Location	Site Code	Description of the site	Type of sources
1.	RAMADEVI	RMD	Residential and commercial	Domestic cooking, vehicles, road dust, garbage/MSW burning, restaurants
2.	CHUNNIGANJ	CNG	Commercial	vehicles, road dust, garbage/MSW burning
3.	DADA NAGAR	DDN	Industrial	Industries, DG sets, vehicles, road dust, garbage/industrial waste burning
4.	JARIB CHOWKI	JRC	Commercial	vehicles, road dust, garbage/MSW burning
5.	IIT KANPUR	IIT	Institutional cum Residential	Domestic cooking, Vehicles, road dust, restaurants

Figure 2.1: Photographs of Sampling Sites showing the physical features

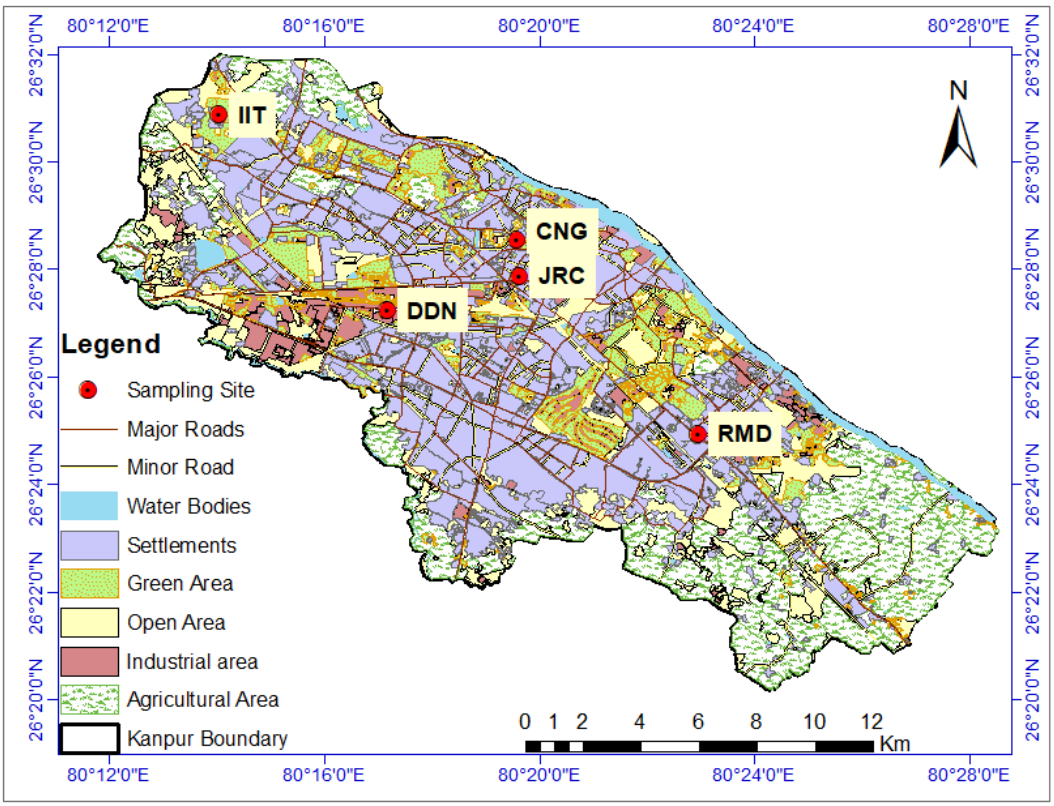


Figure 2.2: Land-use Pattern and Locations of Sampling Sites

The parameters for sampling and their monitoring methodologies, including the type of filter papers/chemicals and calibration protocols, are adopted from CPCB, Delhi (www.cpcb.nic.in). The entire monitoring programme is divided into two groups, i.e., (i) gaseous sampling and (ii) particulate matter (PM) sampling (PM_{10} and $PM_{2.5}$). Nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and volatile organic compounds (VOCs) are among the gaseous species. The monitoring parameters for this study along with sampling and analytical methods are presented in Table 2.2 and the chemical components (of PM) in Table 2.3.

Table 2.2: Details of Samplers/Analyzers and Methods

Sr. No.	Parameter	Sampler/Analyzing Instrument	Method
1.	PM_{10}	4-Channel Speciation Sampler (4-CSS)	Gravimetric
2.	$PM_{2.5}$	4-Channel Speciation Sampler (4-CSS)	Gravimetric
3.	SO_2	Bubbler/Spectrophotometer	West and Gaek
4.	NO_2	Bubbler/Spectrophotometer	Jacob &Hochheiser modified
5.	OC/EC	OC/EC Analyzer	Thermal Optical Reflectance
6.	Ions	Ion-Chromatograph	Ion-Chromatography
7.	Elements	ICP-MS	USEPA

8.	PAHs	GC-MS	Mass spectrophotometry
9.	VOCs	GC-MS with ATD	Mass spectrophotometry

Table 2.3: Target Chemical components for Characterization of PM

Components	Required filter matrix	Analytical methods
$PM_{10}/PM_{2.5}$	Teflon filter paper.	Gravimetric
Elements (Be, B, Na, Mg, Al, Si, P, K, Ca, Cr, V, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba and Pb)	Teflon filter paper	ICP-MS
Ions (F^-, Cl^-, NO_3^-, SO_4^{2-}, K^+, NH_4^+, Na^+, Mg^{2+}, and Ca^{2+})	Teflon filter paper	Ion-chromatography
Carbon Analysis (OC, EC and Total Carbon)	Quartz filter (Prebaked at 600ºC)	TOR/TOT method

2.2.2 Instruments and Accessories

The 4-channel speciation samplers (Umwelttechnik MCZ GmbH, Germany) (with mass flow controller) are used in this study for monitoring particulate matter (Figure 2.3(a)). A flow rate is 16.7 LPM for PM_{10} and $PM_{2.5}$ is used in the sampler. Three channels of the sampler are utilized: First channel for PM_{10}, second channel for $PM_{2.5}$ (Teflon filters -Whatman grade PTFE filters of 47 mm diameter) and third for collection of $PM_{2.5}$ on quartz fiber filter (Whatman grade QM-A quartz filters of 47 mm Diameter). PTFE filters are used for the analysis of ions and elements and quartz filters are used for OC-EC and PAHs.

Ecotech AAS 118 (Ecotech, India; flow rate of 1.0 LPM) sampler was used for gaseous pollutants (SO_2 and NO_2) and a low flow pump (Pocket pump 210 series; SKC Inc, USA) was used for sampling of VOCs (flow rate – 50 ml/min).

PM_{10} and $PM_{2.5}$ concentrations are determined gravimetrically by weighing the PTFE filters before and after the sampling using a digital microbalance (Metler-Toledo MX-5, USA; sensitivity of 1µg; Figure 2.3(b)) in USEPA standard weighing and filter conditioning laboratory.

Water-soluble ions are extracted from the Teflon filters in ultra-pure Milli-Q water following the reference method (USEPA, 1999a). Ions analysis of extracted sampled is carried out using Ion Chromatography (Merohm 882 compact IC, Switzerland; Figure 2.3(e)). Ion recovery

efficiencies were determined by spiking the known quantity of ion mass and reproducibility tests were performed by replicate analysis. Recovery was found between 90% and 106%, which was within ±10% for all species analyzed.

In addition to conventional pollutants and parameters, this study has analyzed the fraction of organic carbon (OC) and elemental carbon (EC) by thermal optical transmittance (DRI Model 2001A Thermal/Optical Carbon Analyzer; Figure 2.3(c)). The explanation of fractions of EC and OC is given in below:

- OC1: Carbon evolved from the filter punch in a He-only (>99.999%) atmosphere from ambient (~25 °C) to 140 °C.
- OC2: Carbon evolved from the filter punch in a He-only (>99.999%) atmosphere from 140 to 280 °C.
- OC3: Carbon evolved from the filter punch in a He-only (>99.999%) atmosphere from 280 to 480 °C.
- OC4: Carbon evolved from the filter punch in a He-only (>99.999%) atmosphere from 480 to 580 °C.
- EC1: Carbon evolved from the filter punch in a 98% He/2% O_2 atmosphere at 580 °C.
- EC2: Carbon evolved from the filter punch in a 98% He/2% O_2 atmosphere from 580 to 740 °C.
- EC3: Carbon evolved from the filter punch in a 98% He/2% O_2 atmosphere from 740 to 840 °C.
- OP: The carbon evolved from the time that the carrier gas flow is changed from He to 98% He/2% O2 at 580 °C to the time that the laser-measured filter reflectance (OPR) or transmittance (OPT) reaches its initial value. A negative sign is assigned if the laser split occurs before the introduction of O_2.
- OC: OC1 + OC2 + OC3 + OC4 +OP
- EC: EC1 +EC2 + EC3
- Total Carbon (TC): OC1 + OC2 + OC3 + OC4 + EC1 +EC2 + EC3; All carbon evolved from the filter punch between ambient and 840°C under He and 98% He /2% O_2 atmospheres.

For elemental analysis, PTFE filters were digested in hydrochloric/nitric acid solution using the microwave digestion system (Anton-Paar, Austria) as per the USEPA method (USEPA, 1999b). The digested samples were filtered and diluted to 25 mL with deionized (ultra-pure) water. The digested samples for elements were analyzed using ICP-MS (Thermo fisher Scientific Inc, USA; Figure 2.3(f)) (USEPA, 1999c).

PAHs were extracted in hexane and dichloromethane (DCM) solvent (1:1v/v) followed by passing it through silica cartridge (Rajput et al., 2011, USEPA, 1999d). The extracted samples were concentrated using the rotary evaporator (up to 10 mL) and Turbo Vap (Work Station-II, Caliper Life Sciences, Hopkinton, USA) for a final volume of 1 mL. Extracted samples were analyzed for PAHs using the Gas chromatography-Mass spectrophotometer (Model Clarus 600 S, Perkin Elmer, USA; Figure 2.3(d)).

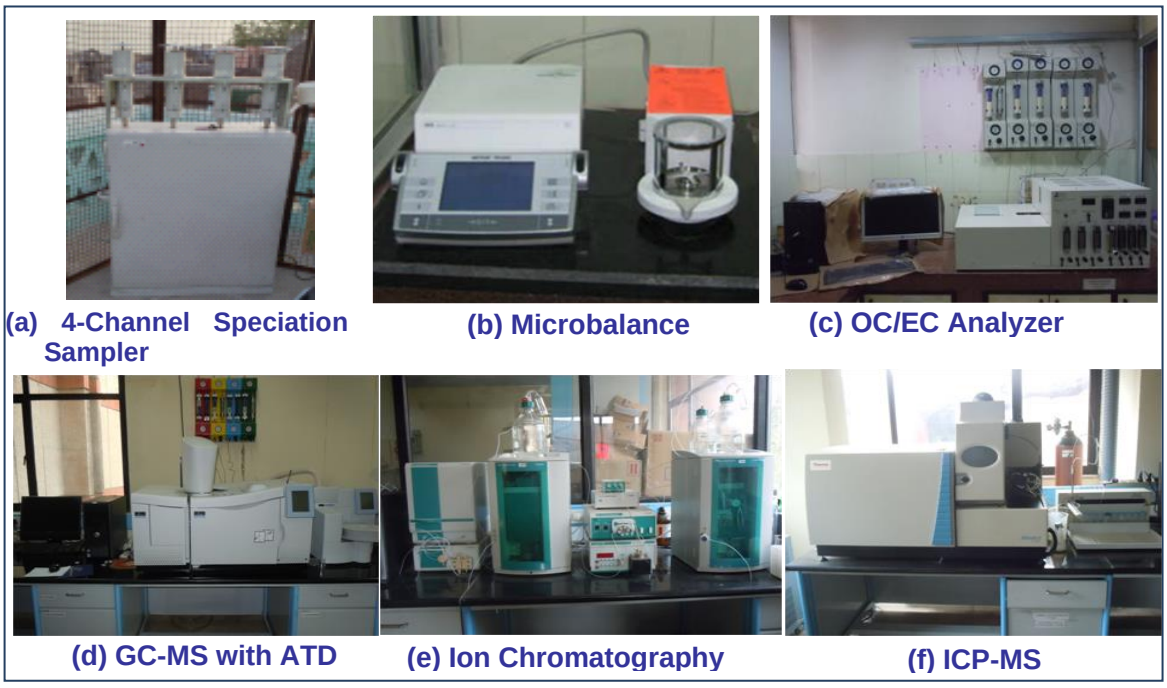


Figure 2.3: Instruments for Sampling and Characterization

2.3 Quality Assurance and Quality Control (QA/QC)

Quality assurance and quality control (QA/QC) in entire project planning and its implementation at all levels were designed and the hands-on training was imparted to the project team before the beginning of any sampling and analysis. During sampling and analysis, a coding system has been adopted to eliminate any confusion. Separate codes for seasons, site locations, parameters, time slots are adopted.

For SO_2, and NO_2, analyses were done regularly just after the sampling following the standard operating procedures (SOPs) in the laboratory at Kanpur. All other measurements and analyses were carried out at the laboratories of IIT Kanpur after completion of sampling. The calibrations for all samplers were done at regular intervals at the time of sampling. The calibrations of overall analyses were established by cross-checking with known concentrations of the pollutants. The major features of QA/QC are briefly described here.

- SOPs for entire project planning and implementation were developed, peer-reviewed by other experts and project personnel have been trained in the field and in the laboratory. Whenever necessary, the SOPs were adjusted to meet the field challenges.
- SOPs include type of equipment (with specifications), sampling and calibration methods with their frequency.
- SOPs for chemical analysis includes a description of methods, standards to be used, laboratory and field blanks, internal and external standards, development of the database, screening of data, record-keeping including backups, traceability of calculations and standards.

There are dedicated computers for instruments and data storage with passwords. It ensures that computers do not get infected. These computers are not hooked to Internet connections.

Sampling periods: The ambient air sampling has been completed for 20 days at each site for winter (December 13, 2018 – March 02, 2019) and summer (March 26, 2019 - June 26, 2019). The analysis of SO_2 and NO_2 are carried out daily on a regular basis, while gravimetric analysis for particulate matters is done after the completion of the sampling at IIT Kanpur. All efforts were made for the 100% achievement of the sampling and analysis. The overall sampling was achieved over 95% of the time. Efforts were made to sample on extra days to cover the missing days of sampling. The details of sampling days for all pollutants at all monitoring sites are presented in Tables 2.4 to 2.13 for the winter and summer seasons, respectively.

Table 2.4: Sampling days of various pollutants in winter (2018-19) at RMD

RMD, Winter	9-Jan-19	10-Jan-19	11-Jan-19	12-Jan-19	13-Jan-19	14-Jan-19	15-Jan-19	16-Jan-19	17-Jan-19	18-Jan-19	19-Jan-19	20-Jan-19	21-Jan-19	22-Jan-19	23-Jan-19	24-Jan-19	25-Jan-19	26-Jan-19	27-Jan-19	28-Jan-19	29-Jan-19	30-Jan-19	31-Jan-19	1-Feb-19
PM10																								
PM2.5																								
OC																								
EC																								
VOC																								
NO2																								
SO2																								

Table 2.5: Sampling days of various pollutants in winter (2018-19) at CNG

CNG, Winter	4-Feb-19	5-Feb-19	6-Feb-19	7-Feb-19	8-Feb-19	9-Feb-19	10-Feb-19	11-Feb-19	12-Feb-19	13-Feb-19	14-Feb-19	15-Feb-19	16-Feb-19	17-Feb-19	18-Feb-19	19-Feb-19	20-Feb-19	21-Feb-19	22-Feb-19	23-Feb-19	24-Feb-19	25-Feb-19	26-Feb-19	27-Feb-19	28-Feb-19	1-Mar-19	2-Mar-19
PM10																										
PM2.5																										
OC																										
EC																										
VOC																										
NO2																										
SO2																										

Table 2.6: Sampling days of various pollutants in winter (2018-19) at DDN

DDN, Winter	22-Dec-18	23-Dec-18	24-Dec-18	25-Dec-18	26-Dec-18	27-Dec-18	28-Dec-18	29-Dec-18	30-Dec-18	31-Dec-18	1-Jan-19	2-Jan-19	3-Jan-19	4-Jan-19	5-Jan-19	6-Jan-19	7-Jan-19	8-Jan-19	9-Jan-19	10-Jan-19	11-Jan-19	12-Jan-19
PM10																						
PM2.5																						
OC																						
EC																						
VOC																						
NO2																						
SO2																						

Table 2.7: Sampling days of various pollutants in winter (2018-19) at JRC

JRC, Winter																							
	20-Jan-19	21-Jan-19	22-Jan-19	23-Jan-19	24-Jan-19	25-Jan-19	26-Jan-19	27-Jan-19	28-Jan-19	29-Jan-19	30-Jan-19	31-Jan-19	1-Feb-19	2-Feb-19	3-Feb-19	4-Feb-19	5-Feb-19	6-Feb-19	7-Feb-19	8-Feb-19	9-Feb-19	10-Feb-19	11-Feb-19
PM10																							
PM2.5																							
OC																							
EC																							
VOC																							
NO2																							
SO2																							

Table 2.8: Sampling days of various pollutants in winter (2018-19) at IIT

IIT, Winter																									
	13-Dec-18	14-Dec-18	15-Dec-18	16-Dec-18	17-Dec-18	18-Dec-18	19-Dec-18	20-Dec-18	21-Dec-18	22-Dec-18	23-Dec-18	24-Dec-18	25-Dec-18	26-Dec-18	27-Dec-18	28-Dec-18	29-Dec-18	30-Dec-18	31-Dec-18	1-Jan-19	2-Jan-19	3-Jan-19	4-Jan-19	5-Jan-19	6-Jan-19
PM10																								
PM2.5																								
OC																								
EC																								
VOC																								
NO2																								
SO2																								

Table 2.9: Sampling days of various pollutants in summer (2019) at RMD

RMD, Summer																	
	19-May-19	20-May-19	21-May-19	22-May-19	23-May-19	24-May-19	25-May-19	26-May-19	27-May-19	28-May-19	29-May-19	30-May-19	31-May-19	1-Jun-19	2-Jun-19	3-Jun-19	4-Jun-19	5-Jun-19
PM10																		
PM2.5																		
OC																		
EC																		
VOC																		
NO2																		
SO2																		

Table 2.10: Sampling days of various pollutants in summer (2019) at CNG

CNG,Summer																									
	1-Apr-19	2-Apr-19	3-Apr-19	4-Apr-19	5-Apr-19	6-Apr-19	7-Apr-19	8-Apr-19	9-Apr-19	10-Apr-19	11-Apr-19	12-Apr-19	13-Apr-19	14-Apr-19	15-Apr-19	16-Apr-19	17-Apr-19	18-Apr-19	19-Apr-19	20-Apr-19	21-Apr-19	22-Apr-19	23-Apr-19	24-Apr-19
PM10																								
PM2.5																								
OC																								
EC																								
VOC																								
NO2																								
SO2																								

Table 2.11: Sampling days of various pollutants in summer (2019) at DDN

DDN,Summer																			
	27-Apr-19	28-Apr-19	29-Apr-19	30-Apr-19	1-May-19	2-May-19	3-May-19	4-May-19	5-May-19	6-May-19	7-May-19	8-May-19	9-May-19	10-May-19	11-May-19	12-May-19	13-May-19	14-May-19	15-May-19	16-May-19
PM10																				
PM2.5																				
OC																				
EC																				
VOC																				
NO2																				
SO2																				

Table 2.12: Sampling days of various pollutants in summer (2019) at JRC

JRC,Summer																			
	7-Jun-19	8-Jun-19	9-Jun-19	10-Jun-19	11-Jun-19	12-Jun-19	13-Jun-19	14-Jun-19	15-Jun-19	16-Jun-19	17-Jun-19	18-Jun-19	19-Jun-19	20-Jun-19	21-Jun-19	22-Jun-19	23-Jun-19	24-Jun-19	25-Jun-19	26-Jun-19
PM10																				
PM2.5																				
OC																				
EC																				
VOC																				
NO2																				
SO2																				

Table 2.13: Sampling days of various pollutants in summer (2019) at IIT

IIT,Summer																					
	26-Mar-19	27-Mar-19	28-Mar-19	29-Mar-19	30-Mar-19	31-Mar-19	1-Apr-19	2-Apr-19	3-Apr-19	4-Apr-19	5-Apr-19	6-Apr-19	7-Apr-19	8-Apr-19	9-Apr-19	10-Apr-19	11-Apr-19	12-Apr-19	13-Apr-19	14-Apr-19	15-Apr-19	16-Apr-19
PM10																					
PM2.5																					
OC																					
EC																					
VOC																					
NO2																					
SO2																					

2.4 Ambient Air Quality - Results

2.4.1 Ramadevi (RMD)

The sampling period was January 09 – February 01, 2019 for winter and May 19 – June 05, 2019 for summer.

2.4.1.1 Particulate Matter (PM_{10}, $PM_{2.5}$)

Time series of 24-hr average concentrations of PM_{10} and $PM_{2.5}$ at RMD are shown for winter (Figure 2.4) and summer (Figure 2.5). Average levels at this site were: $PM_{2.5}$: 273±132 (winter)

and 73±20 µg/m^3 (summer) and PM_{10}: 480±303 (winter) and 239±132 µg/m^3 (summer). In winter, the $PM_{2.5}$ levels were 4.5 times higher than the national air quality standard (NAQS: 60 µg/m^3) and PM_{10} levels were 4.8 times higher than the NAQS (100 µg/m^3). In summer, the $PM_{2.5}$ levels slightly exceed by 1.2 times the standards, while PM_{10} is 2.4 times higher than the NAQS.

A statistical summary (Mean, maximum, minimum, standard deviation (SD) and coefficient of variation (CV)) of PM concentrations is presented in Tables 2.17 – 2.20 for the winter and summer season. In summer, $PM_{2.5}$ levels drop significantly compared to PM_{10} levels that continued to be high in spite of improvement in meteorology and better dispersion. The particle airborne from the soil during dust storms in the dry months of summer can contribute significantly to a coarse fraction (i.e., $PM_{2.5\text{-}10}$).

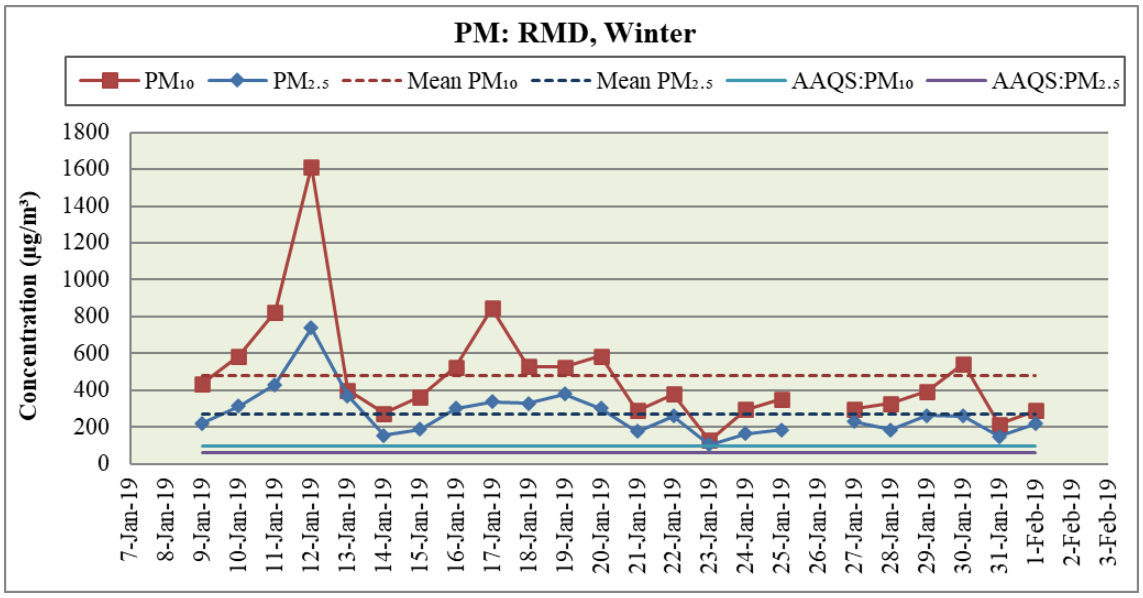


Figure 2.4: PM Concentrations at RMD for Winter Season

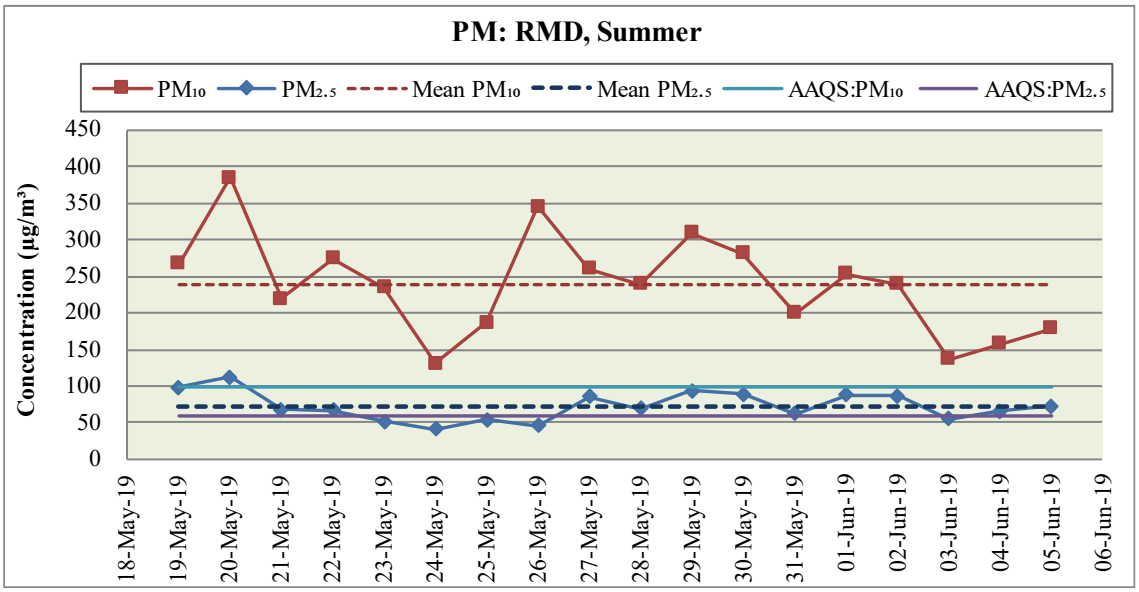


Figure 2.5: PM Concentrations at RMD for Summer Season

2.4.1.2 Gaseous pollutants

Time series of 24-hr average concentrations of SO_2 and NO_2 are shown for winter (Figure 2.6) and summer (Figure 2.7) seasons. It was observed that SO_2 concentrations were low (mostly < 5.0 µg/m^3) and met the air quality standard. NO_2 levels also meet the national standard (80 µg/m^3) with an average of 20 days at 53.6±11.1 µg/m^3 in winter and 55.1±7.4 µg/m^3 in summer season (Table 2.14). The summer concentration of NO_2 dropped dramatically, as does the $PM_{2.5}$ levels. Although NO_2 levels are meeting the standard, it is a matter of concern as NO_2 is largely attributed to vehicular pollution, which is on the rise. Variation in NO_2 is due to variability in meteorology and the presence of occasional local sources like DG sets, traffic jams or local open burning, etc.

The Mean concentrations of benzene, toluene, p-xylene and o-xylene (BTX) are presented in Figure 2.8 and the statistical summary in Table 2.14. The total BTX level is observed 10.9±7.2 µg/m^3 (Benzene: 3.1 and Toluene: 5.3 µg/m^3) in winter and 10.0±1.4 µg/m^3 (Benzene: 3.0 and Toluene: 3.7 µg/m^3) in summer seasons. The BTX levels were higher during winter than in the summer.

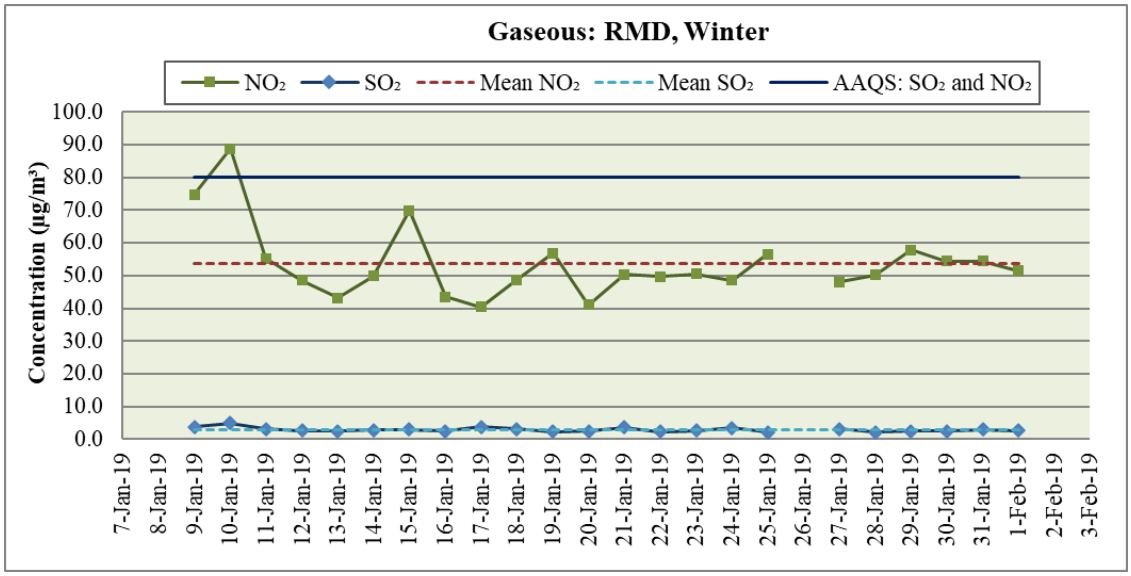


Figure 2.6: SO_2 and NO_2 Concentrations at RMD for Winter Season

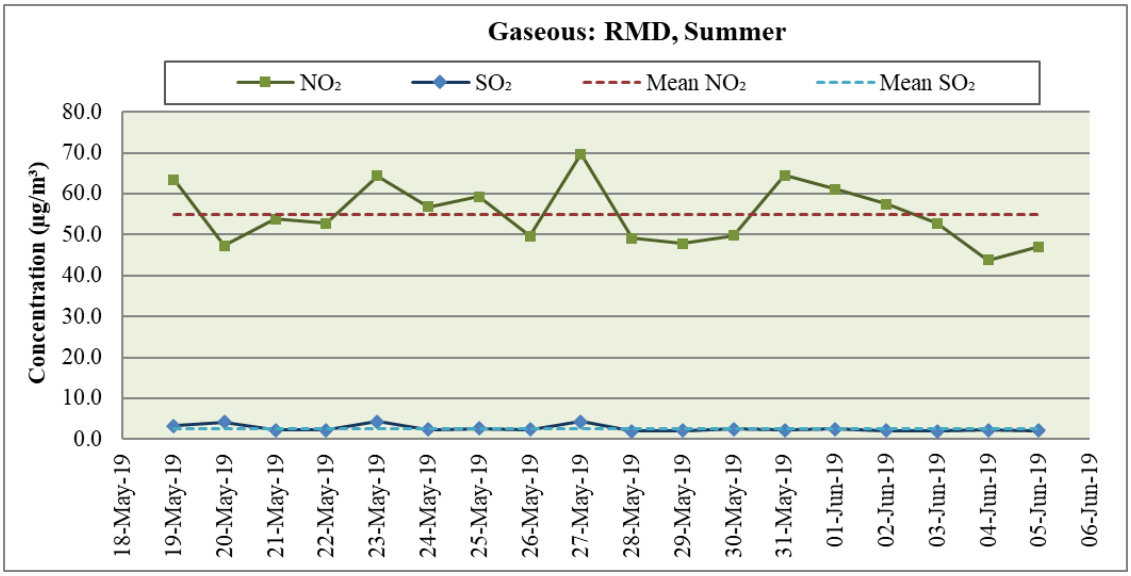


Figure 2.7: SO_2 and NO_2 Concentrations at RMD for Summer Season

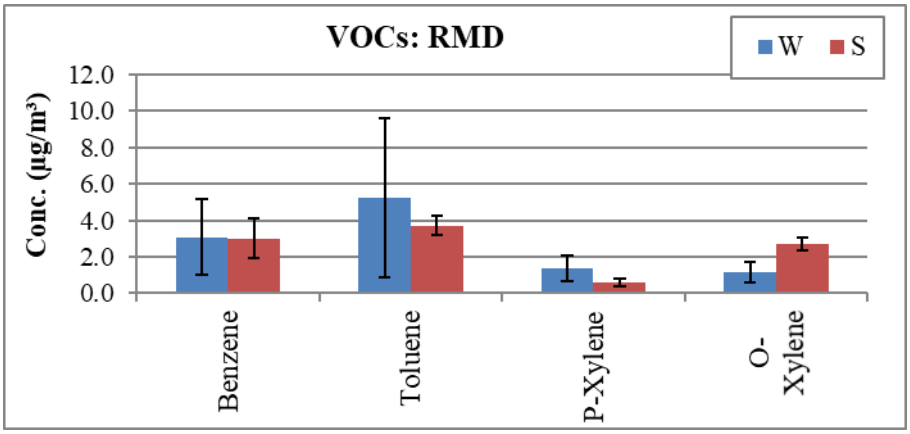


Figure 2.8: VOCs concentration at RMD

2.4.1.3 Carbon Content (EC/OC) in $PM_{2.5}$

Average concentrations of EC, OC (OC1, OC2, OC3 and OC4) and the ratio of OC fraction to TC are shown in Figure 2.9 (a) and (b) for winter and summer seasons. Organic carbon is observed slightly higher (winter: 60.7±32.1 and summer: 11.9±3.4 µg/m^3) than the elemental carbon (winter: 51.5±28.4 and summer: 11.3±4.4 µg/m^3). It is also observed that the OC and EC are higher in the winter than in the summer. A statistical summary of carbon content (TC, EC, OC; OC1, OC2, OC3 and OC4 with fractions OC1/TC, OC2/TC, OC3/TC and OC4/TC) is presented in Table 2.15 for winter and summer. The ratio of OC3/TC is observed higher that indicates the formation of secondary organic carbon in the atmosphere at RMD.

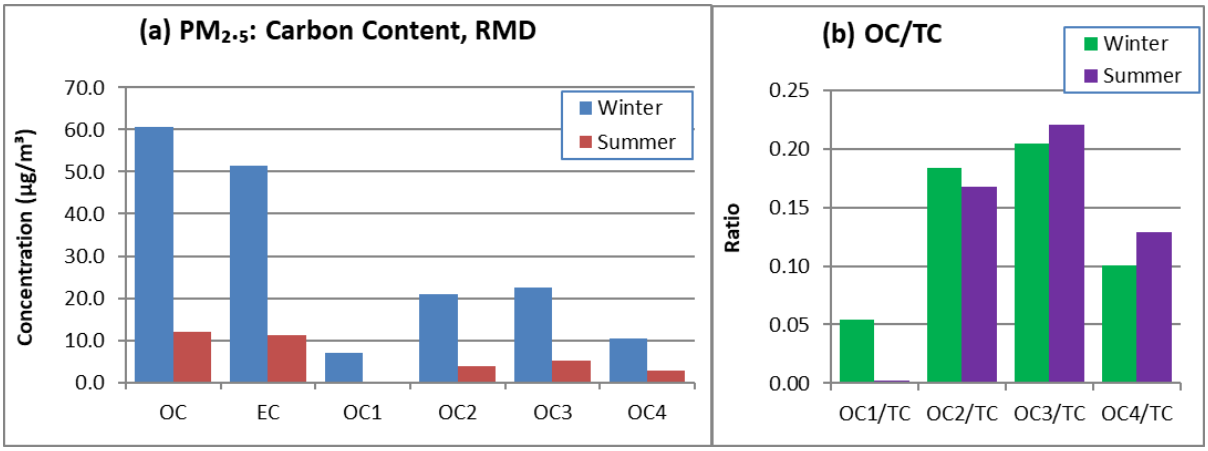


Figure 2.9: EC and OC Content in $PM_{2.5}$ at RMD

TC typically present in an urban environment (i.e., 20–45% of $PM_{2.5}$) (Dinoi et al., 2017), and the results match as TC in $PM_{2.5}$ in winter is about 38% in winter and 31% in summer. It also suggests fresh nearby combustion and burning.

2.4.1.4 PAHs in $PM_{2.5}$

The concentrations of PAHs (from solid phase only) with some specific markers were analyzed. Figure 2.10 shows the average measured concentration of PAHs at RMD for winter and summer seasons. A statistical summary of PAHs is presented in Table 2.16 for winter and summer seasons. The PAHs compounds analyzed were: (i) Di methyl Phthalate (DmP), (ii) Acenaphthylene (AcP), (iii) Di ethyl Phthalate (DEP), (iv) Fluorene (Flu), (v) Phenanthrene (Phe), (vi) Anthracene (Ant), (vii) Pyrene (Pyr), (viii) Butyl benzyl phthalate (BbP), (ix) Bis(2-ethylhexyl) adipate (BeA), (x) Benzo(a)anthracene (B(a)A), (xi) Chrysene (Chr), (xii) Benzo(b)fluoranthene (B(b)F), (xiii) Benzo(k)fluoranthene (B(k)F), (xiv) Benzo(a)pyrene (B(a)P), (xv) Indeno(1,2,3-cd)pyrene (InP), (xvi) Dibenzo(a,h)anthracene (D(a,h)A) and (xvii)

Benzo(ghi)perylene (B(ghi)P). It is observed that Total PAHs concentrations are higher in winter season (250±156 ng/m^3) compared to summer season (192±110 ng/m^3). Major PAHs (mostly higher molecular weight compounds) are InP (61 ng/m^3), B(ghi)P (47 ng/m^3), B(b)F (32 ng/m^3), Chr (26 ng/m^3) and B(k)F (19 ng/m^3) for winter season and InP (50 ng/m^3), B(ghi)P (37 ng/m^3), B(b)F (23 ng/m^3), BeA (21 ng/m^3) and B(a)P (13 ng/m^3) for summer season.

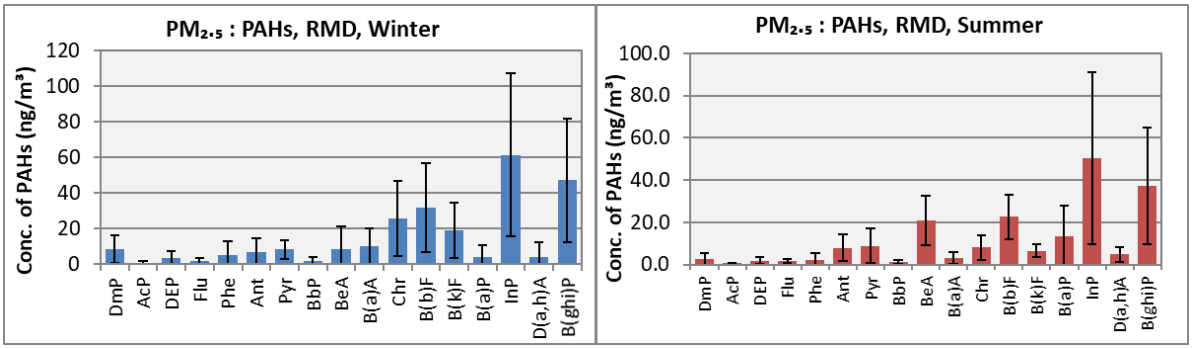


Figure 2.10: PAHs Concentrations in $PM_{2.5}$ at RMD

2.4.1.5 Chemical Composition of PM_{10} and $PM_{2.5}$ and their correlation

Graphical presentations of chemical species are shown for the winter and summer seasons for PM_{10} (Figure 2.11) and $PM_{2.5}$ (Figure 2.12). Statistical summary for particulate matter (PM_{10} and $PM_{2.5}$), its chemical composition [carbon content (EC and OC), ionic species (F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2}) and elements (Be, B, Na, Mg, Al, Si, P, K, Ca, Cr, V, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, Pb)] along with mass percentage (% R) recovered from PM are presented in Tables 2.17 – 2.20 for winter and summer season.

The correlation between different parameters (i.e., PM, TC, OC, EC, F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2} and Metals (elements)) with major species (PM, TC, OC, EC, NO_3^-, SO_4^{-2}, NH_4^+, Metals) for PM_{10} and $PM_{2.5}$ composition is presented in Tables 2.21 – 2.24 for both seasons. It is seen that most of the parameters showed a good correlation (>0.30) with PM_{10} and $PM_{2.5}$. The percentage constituents of the PM are presented in Figure 2.13 (a) and (b) for the winter season and Figure 2.14 (a) and (b) for the summer season.

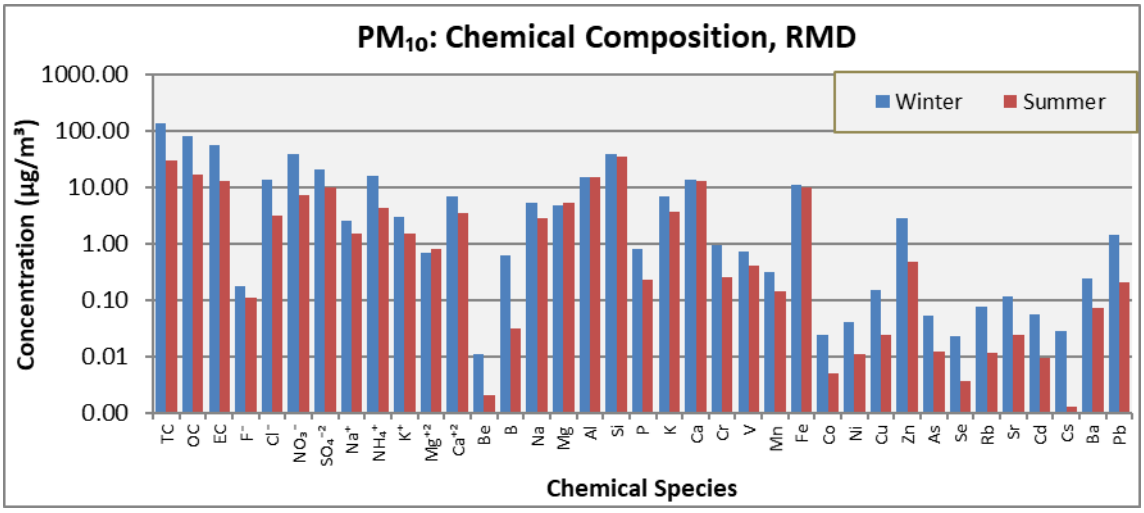


Figure 2.11: Concentrations of species in PM_{10} at RMD

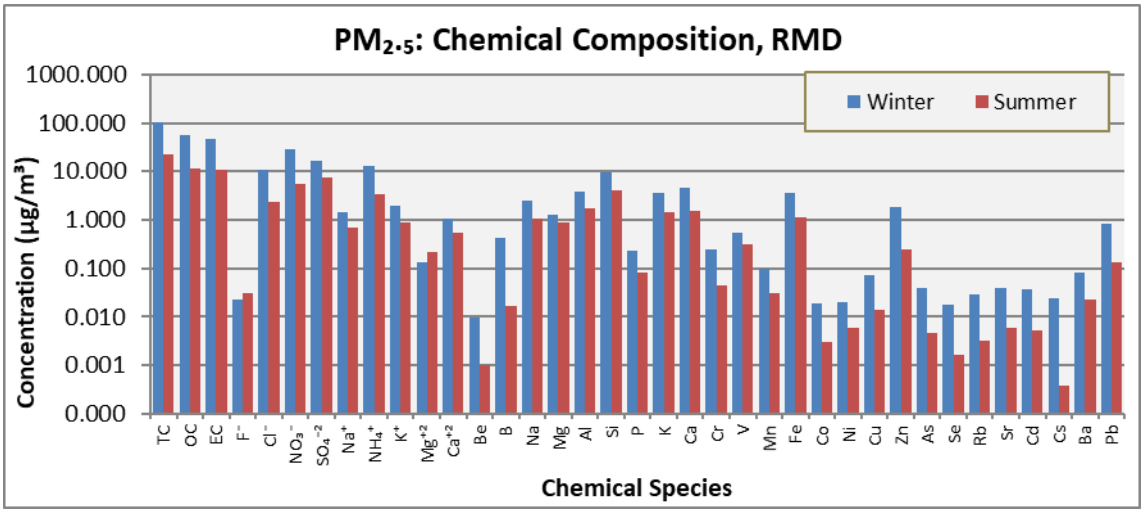
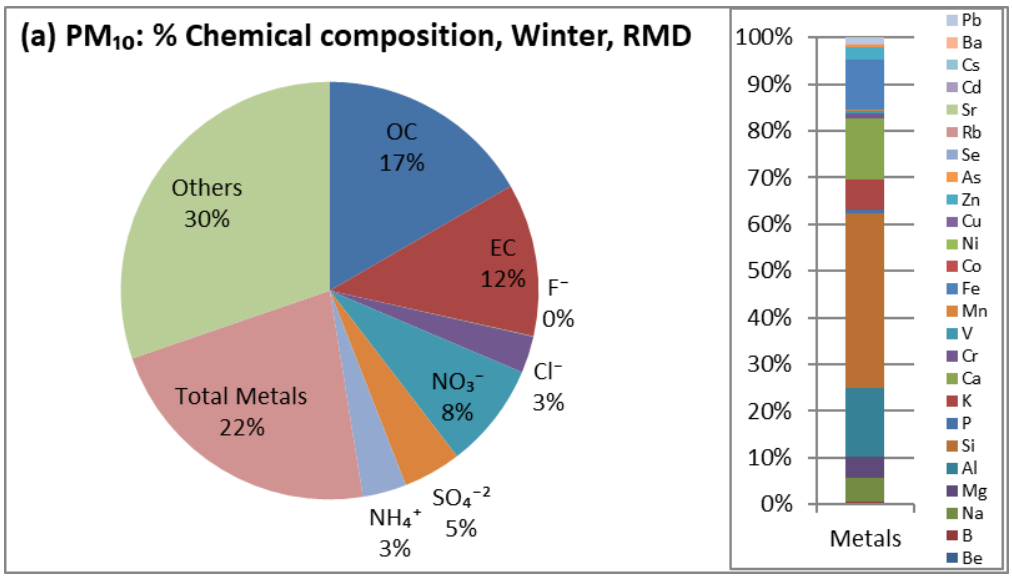


Figure 2.12: Concentrations of species in $PM_{2.5}$ at RMD



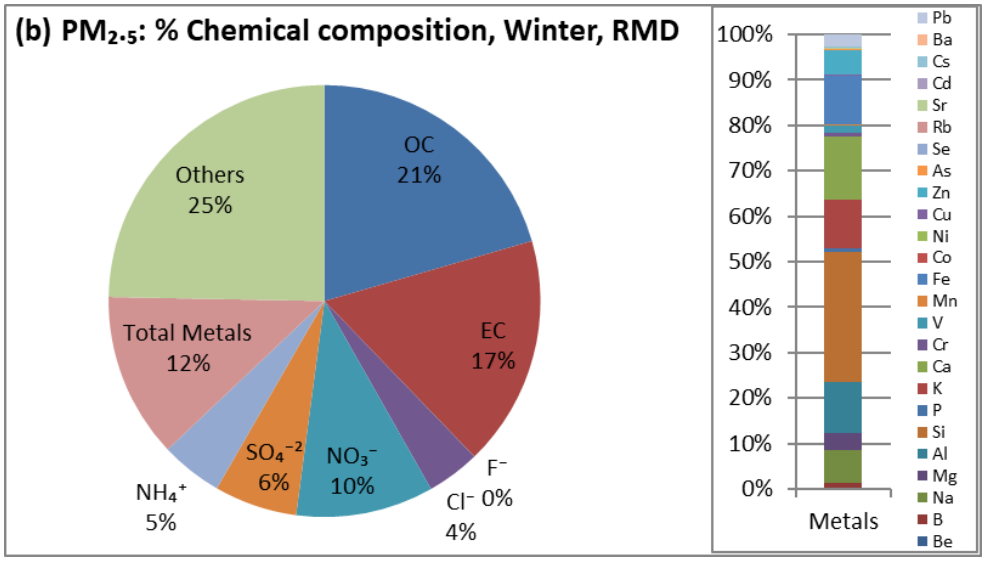


Figure 2.13: Percentage distribution of species in PM at RMD for Winter Season

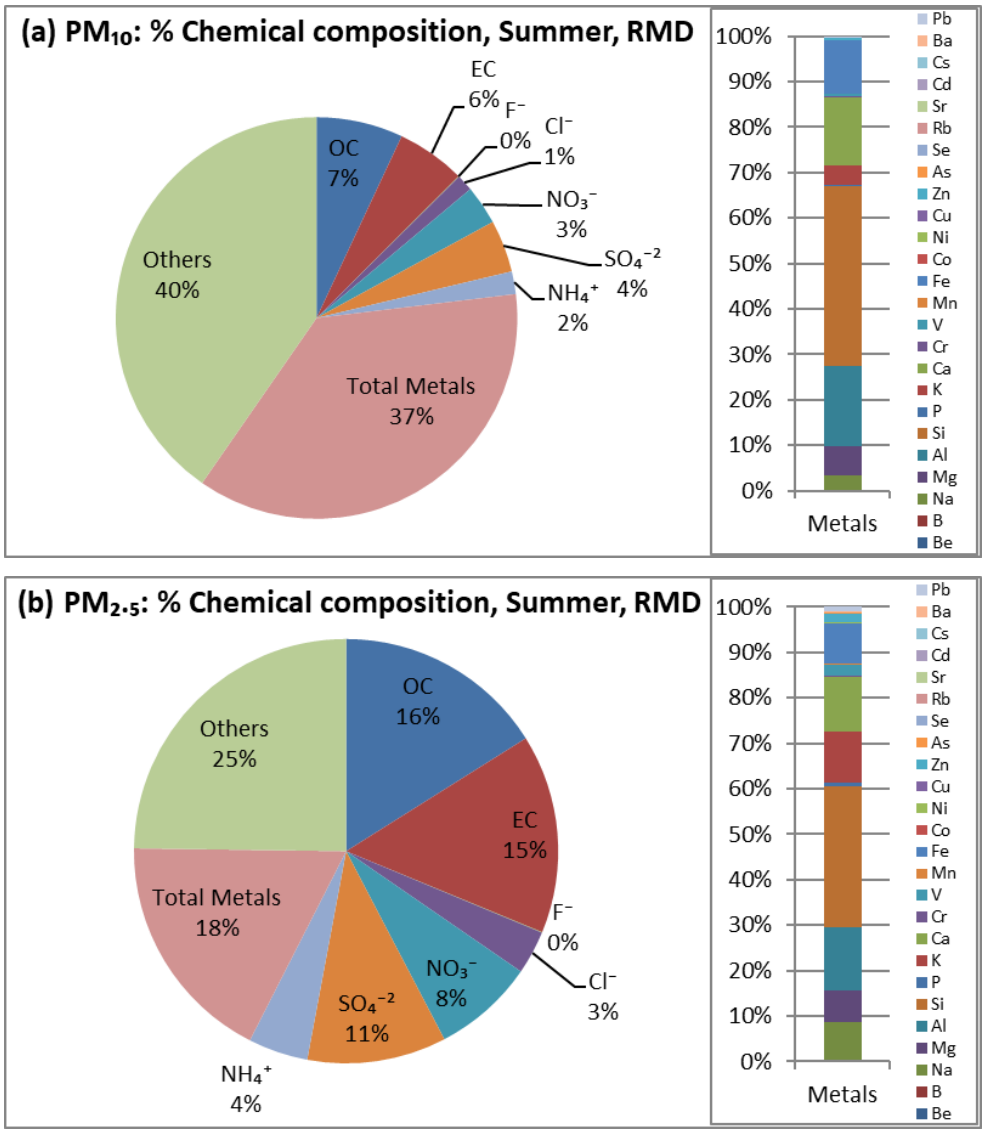


Figure 2.14: Percentage distribution of species in PM at RMD for Summer Season

2.4.1.6 Comparison of PM_{10} and $PM_{2.5}$ Composition

This section presents some important observations from the experimental findings related to fine particles and PM_{10} concentrations. The graphical presentation is a better option for understanding the compositional variation. A compositional comparison of $PM_{2.5}$ vs PM_{10} for all species is shown for winter and summer seasons (Figure 2.15) at RMD.

The chemical species considered for the comparisons are carbon content (TC, OC and EC), ionic species (F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2}) and elements (Be, B, Na, Mg, Al, Si, P, K, Ca, Cr, V, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, Pb). It is concluded that most portion of PM has fine mode during winter (57%) than summer (30%). The major species contributing to fine mode are TC, OC, EC, Cl^-, NO_3^-, SO_4^{-2}, NH_4^+, K^+, B, V, Co, Zn, Cd and Pb; whereas, major species contributing in coarse mode are F^-, Mg^{2+}, Ca^{2+}, Na, Mg, Al, Si, P, Ca, Cr, Mn, Fe, Rb, Sr and Ba.

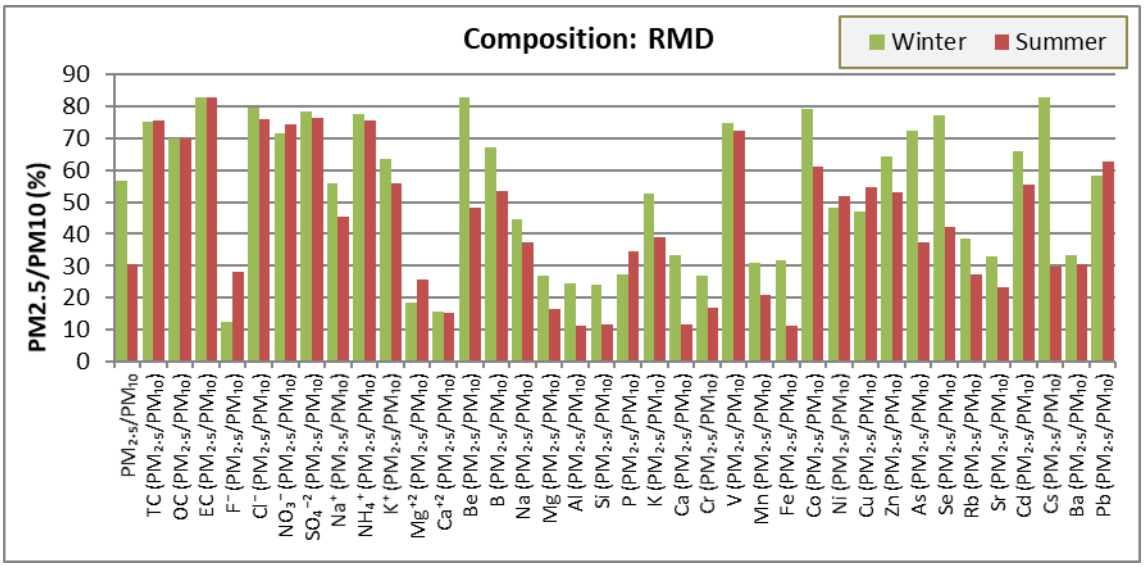


Figure 2.15: Compositional comparison of species in $PM_{2.5}$ Vs PM_{10} at RMD

Table 2.14: Statistical results of gaseous pollutants (µg/m^3) at RMD for winter (W) and summer (S) seasons

RMD (W)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	53.60	2.86	3.08	5.25	1.37	1.17	10.87
SD	11.10	0.65	2.09	4.38	0.69	0.55	7.19
Max	88.86	4.82	9.26	19.63	3.38	3.26	35.53
Min	40.49	2.08	0.66	1.74	0.50	0.51	4.15
CV	0.21	0.23	0.68	0.83	0.50	0.47	0.66
RMD (S)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	55.07	2.62	3.00	3.70	0.58	2.70	9.99
SD	7.42	0.82	1.09	0.52	0.23	0.35	1.42
Max	69.74	4.36	6.95	5.08	1.03	3.70	13.43
Min	43.86	2.00	2.18	2.89	0.31	2.08	7.98
CV	0.13	0.31	0.36	0.14	0.39	0.13	0.14

Table 2.15: Statistical results of carbon contents (µg/m^3) in $PM_{2.5}$ at RMD for Winter (W) and summer (S) seasons

RMD (W)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	272.9	112.28	60.74	51.54	6.90	20.92	22.47	10.45	0.055	0.184	0.204	0.101
SD	131.8	60.28	32.08	28.40	6.23	11.75	11.42	4.57	0.024	0.012	0.017	0.029
Max	738.3	296.12	158.88	137.24	25.52	55.45	58.72	20.78	0.127	0.204	0.241	0.156
Min	104.5	37.78	19.41	18.37	1.13	6.54	8.25	3.48	0.030	0.158	0.167	0.036
CV	0.48	0.54	0.53	0.55	0.90	0.56	0.51	0.44	0.439	0.067	0.083	0.283
RMD (S)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	72.5	23.16	11.88	11.29	0.07	3.94	5.05	2.82	0.002	0.168	0.221	0.129
SD	19.6	7.68	3.44	4.35	0.14	1.62	1.59	0.49	0.005	0.019	0.035	0.024
Max	112.2	39.91	19.01	20.90	0.56	8.34	8.10	3.56	0.019	0.209	0.333	0.162
Min	41.1	11.82	6.75	5.07	0.00	2.05	2.78	1.92	0.000	0.136	0.185	0.080
CV	0.27	0.33	0.29	0.39	2.07	0.41	0.32	0.17	2.070	0.115	0.159	0.190

Table 2.16: **Statistical results of PAHs (ng/m^3) in $PM_{2.5}$ at RMD for winter (W) and summer (S) seasons**

RMD(W)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	8.73	1.07	3.69	1.69	5.45	6.89	8.49	2.02	8.57	9.97	25.64	31.86	18.91	4.00	61.32	4.06	47.21	249.56
SD	7.72	1.08	3.62	1.88	7.68	7.77	5.24	2.20	12.81	10.32	20.87	24.87	15.59	6.69	45.68	8.34	34.53	156.39
Max	20.89	3.03	12.45	6.89	21.08	27.58	16.60	7.17	45.59	34.57	74.89	88.35	47.84	21.14	128.93	28.55	90.94	484.06
Min	0.12	0.10	0.11	0.06	0.00	0.02	0.90	0.21	0.00	0.30	1.82	5.97	4.50	0.05	0.43	0.00	1.13	49.47
CV	0.88	1.01	0.98	1.11	1.41	1.13	0.62	1.09	1.49	1.04	0.81	0.78	0.82	1.67	0.74	2.05	0.73	0.63
RMD(S)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	2.58	0.57	1.78	1.52	1.95	7.92	8.88	1.15	20.76	3.03	8.01	22.49	6.38	13.29	50.11	4.70	37.13	192.26
SD	2.59	0.30	1.52	0.91	3.59	6.47	8.20	1.03	11.58	2.71	5.75	10.70	3.03	14.77	40.68	3.31	27.71	110.89
Max	8.78	1.10	4.70	3.16	8.65	18.22	27.93	3.45	40.73	7.85	19.01	37.05	11.84	41.33	138.64	10.25	99.00	410.93
Min	0.40	0.22	0.54	0.60	0.00	0.18	1.92	0.07	6.77	1.11	3.09	9.10	2.36	1.13	15.24	1.51	12.66	71.20
CV	1.01	0.53	0.86	0.60	1.84	0.82	0.92	0.90	0.56	0.89	0.72	0.48	0.47	1.11	0.81	0.70	0.75	0.58

Table 2.17: Statistical results of chemical characterization (µg/m^3) of PM_{10} at RMD for winter (W) season

RMD (W)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	480	80.0	56.8	0.2	13.7	39.2	21.5	2.6	16.3	3.1	0.7	7.0	1E-2	0.64	5.46	4.85	15.55	40.20	0.84
SD	303	42.8	31.8	0.2	9.7	24.9	12.1	1.0	10.3	1.6	0.5	5.8	6E-3	0.32	6.27	2.64	14.84	36.94	0.47
Max	1612	227.0	165.3	1.0	45.2	127.2	59.9	4.9	52.4	8.5	2.2	25.4	3E-2	1.44	33.40	13.60	66.88	168.07	1.93
Min	130	27.7	17.6	0.0	2.3	8.3	6.9	0.8	6.5	1.1	0.1	0.5	5E-3	0.13	1.62	1.84	2.10	6.99	0.23
CV	0.63	0.54	0.56	1.22	0.70	0.63	0.56	0.38	0.63	0.52	0.71	0.83	0.51	0.50	1.15	0.54	0.95	0.92	0.56
RMD (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	6.89	14.02	0.95	0.74	0.31	11.20	0.02	0.04	0.15	2.90	0.05	0.02	0.08	0.12	0.06	0.03	0.24	1.47	71.3
SD	3.67	13.67	0.56	0.32	0.17	8.02	0.01	0.02	0.10	1.84	0.02	0.01	0.04	0.06	0.04	0.01	0.16	1.09	5.1
Max	19.85	67.43	2.30	1.38	0.73	38.95	0.05	0.11	0.43	7.48	0.10	0.04	0.17	0.25	0.22	0.06	0.77	3.53	82.0
Min	1.34	3.26	0.20	0.07	0.11	1.54	0.01	0.02	0.04	0.72	0.02	0.01	0.03	0.04	0.02	0.02	0.06	0.17	61.9
CV	0.53	0.97	0.59	0.43	0.53	0.72	0.40	0.46	0.62	0.63	0.41	0.33	0.47	0.47	0.72	0.35	0.66	0.74	0.07
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.18: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at RMD for winter (W) season

RMD (W)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	273	56.0	47.1	0.0	10.9	28.1	16.9	1.4	12.6	1.9	0.1	1.1	9E-3	0.43	2.44	1.30	3.78	9.66	0.23
SD	132	30.0	26.4	0.0	7.2	15.3	8.7	0.7	6.9	0.9	0.1	0.7	4E-3	0.27	0.83	0.51	1.73	5.09	0.14
Max	738	158.9	137.2	0.1	30.2	70.1	37.1	2.6	30.8	4.6	0.3	2.5	2E-2	1.29	4.65	2.72	8.96	24.55	0.69
Min	104	19.4	14.6	0.0	1.9	7.0	5.9	0.0	5.0	0.7	0.0	0.1	5E-3	0.08	1.27	0.73	1.87	5.00	0.05
CV	0.48	0.54	0.56	1.20	0.66	0.54	0.52	0.48	0.55	0.46	0.58	0.61	4E-1	0.64	0.34	0.39	0.46	0.53	0.62
RMD (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	3.62	4.69	0.25	0.55	0.10	3.55	0.02	0.02	0.07	1.87	0.039	0.018	0.030	0.039	0.038	0.024	0.081	0.86	75.6
SD	1.44	2.37	0.20	0.23	0.06	2.51	0.01	0.01	0.04	1.43	0.014	0.006	0.009	0.013	0.020	0.006	0.078	0.77	3.2
Max	7.18	9.21	1.00	0.95	0.31	11.50	0.04	0.04	0.18	5.25	0.077	0.034	0.056	0.072	0.099	0.047	0.392	2.73	81.1
Min	0.76	2.15	0.03	0.05	0.04	1.29	0.01	0.01	0.03	0.36	0.021	0.008	0.019	0.025	0.017	0.017	0.032	0.10	70.8
CV	0.40	0.50	0.79	0.42	0.58	0.71	0.28	0.31	0.59	0.77	0.37	0.32	0.31	0.33	0.53	0.26	0.97	0.89	0.04
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.19: Statistical results chemical characterization (µg/m^3) of PM_{10} at RMD for summer (S) season

RMD (S)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	239	16.7	13.2	0.1	3.2	7.5	10.0	1.6	4.4	1.6	0.8	3.5	2E-3	0.03	2.94	5.51	15.44	34.59	0.23
SD	68	5.0	5.3	0.0	1.4	2.7	3.7	0.3	1.8	0.5	0.4	1.1	2E-4	0.02	0.77	2.09	5.38	12.04	0.05
Max	384	27.2	25.2	0.2	6.5	13.8	17.2	2.4	7.4	2.9	1.3	6.5	2E-3	0.08	4.52	10.06	27.34	60.52	0.30
Min	131	9.6	6.1	0.0	1.4	3.7	4.9	1.1	1.8	0.8	0.2	1.8	2E-3	0.01	2.19	2.68	7.89	16.98	0.11
CV	0.28	0.30	0.40	0.40	0.44	0.36	0.37	0.22	0.40	0.32	0.48	0.32	0.07	0.55	0.26	0.38	0.35	0.35	0.21
RMD (S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	3.73	12.99	0.26	0.43	0.15	10.11	5E-3	1E-2	2E-2	0.48	0.01	4E-3	1E-2	3E-2	9E-3	1E-3	0.07	0.21	60.03
SD	1.11	4.58	0.08	0.07	0.08	3.73	2E-3	5E-3	2E-2	0.22	0.01	2E-3	8E-3	2E-2	5E-3	5E-4	0.04	0.18	2.53
Max	6.18	22.30	0.45	0.54	0.36	18.52	1E-2	3E-2	7E-2	0.96	0.03	6E-3	4E-2	7E-2	2E-2	3E-3	0.17	0.63	64.74
Min	1.74	6.14	0.17	0.26	0.05	4.80	3E-3	4E-3	8E-3	0.17	0.01	1E-3	2E-3	9E-3	3E-3	5E-4	0.02	0.02	54.04
CV	0.30	0.35	0.32	0.17	0.53	0.37	0.32	0.43	0.69	0.46	0.50	0.40	0.72	0.60	0.52	0.39	0.57	0.82	0.04
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.20: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at RMD for summer (S) season

RMD (S)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	73	11.7	11.0	0.0	2.4	5.6	7.7	0.7	3.3	0.9	0.2	0.5	1E-3	0.02	1.09	0.91	1.77	4.01	0.08
SD	20	3.5	4.4	0.0	1.1	2.0	3.1	0.3	1.3	0.4	0.1	0.3	2E-4	0.01	0.35	0.28	0.60	1.31	0.03
Max	112	19.0	20.9	0.1	5.1	10.2	14.1	1.5	5.8	1.8	0.3	1.2	2E-3	0.05	1.79	1.38	2.81	6.39	0.13
Min	41	6.7	5.1	0.0	1.1	2.9	3.7	0.3	1.3	0.3	0.1	0.2	8E-4	0.00	0.62	0.44	0.65	1.61	0.05
CV	0.27	0.30	0.40	0.81	0.44	0.36	0.41	0.40	0.40	0.41	0.32	0.55	0.18	0.67	0.32	0.31	0.34	0.33	0.31
RMD (S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	1.46	1.54	0.04	0.31	0.03	1.15	3E-3	6E-3	1E-2	0.25	5E-3	2E-3	3E-3	6E-3	5E-3	4E-4	2E-2	0.14	75.21
SD	0.63	0.53	0.02	0.08	0.02	0.41	4E-4	3E-3	1E-2	0.10	2E-3	8E-4	2E-3	3E-3	3E-3	2E-4	1E-2	0.13	1.98
Max	2.60	2.44	0.09	0.44	0.08	2.07	4E-3	1E-2	3E-2	0.49	1E-2	3E-3	9E-3	1E-2	1E-2	9E-4	6E-2	0.50	79.19
Min	0.36	0.61	0.01	0.15	0.01	0.47	2E-3	3E-3	3E-3	0.12	2E-3	6E-4	1E-3	3E-3	2E-3	2E-4	7E-3	0.01	70.66
CV	0.43	0.35	0.52	0.26	0.56	0.36	0.13	0.43	0.73	0.39	0.40	0.51	0.60	0.50	0.49	0.54	0.61	0.98	0.03
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.21: Correlation matrix for PM_{10} and its composition at RMD for winter season

RMD (W)	PM_{10}	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
PM_{10}	1.00	0.89	0.88	0.88	0.89	0.90	0.86	0.80	0.55	0.83	0.91	0.75	0.92	0.97
TC		1.00	1.00	1.00	0.84	0.84	0.66	0.65	0.42	0.77	0.82	0.61	0.78	0.76
OC			1.00	0.99	0.83	0.83	0.65	0.63	0.42	0.76	0.81	0.62	0.78	0.76
EC				1.00	0.84	0.85	0.68	0.68	0.41	0.78	0.83	0.60	0.78	0.76
NO_3^-					0.77	0.80	1.00	0.87	0.66	0.85	0.84	0.65	0.72	0.85
SO_4^{-2}					0.66	0.75		1.00	0.39	0.88	0.84	0.56	0.71	0.75
NH_4^+					0.72	0.79			0.46	1.00	0.83	0.56	0.71	0.74
Metals					0.86	0.84			0.56		0.87	0.76	0.92	1.00

Table 2.22: Correlation matrix for $PM_{2.5}$ and its composition at RMD for winter season

RMD (W)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.93	0.91	0.93	0.81	0.92	0.81	0.72	0.53	0.83	0.88	-0.12	0.38	0.86
TC		1.00	1.00	1.00	0.75	0.81	0.60	0.48	0.51	0.63	0.81	-0.03	0.44	0.69
OC			1.00	0.99	0.74	0.80	0.57	0.45	0.46	0.60	0.79	0.01	0.43	0.67
EC				1.00	0.75	0.82	0.61	0.51	0.56	0.65	0.83	-0.06	0.45	0.69
NO_3^-					0.68	0.73	1.00	0.87	0.42	0.90	0.81	-0.24	0.32	0.72
SO_4^{-2}					0.55	0.63		1.00	0.37	0.92	0.74	-0.34	0.26	0.62
NH_4^+					0.69	0.76			0.52	1.00	0.86	-0.38	0.28	0.69
Metals					0.64	0.86			0.45		0.69	-0.13	0.23	1.00

Table 2.23: Correlation matrix for PM_{10} and its composition at RMD for summer season

RMD (S)	PM_{10}	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
PM_{10}	1.00	0.69	0.64	0.72	0.76	0.50	0.41	0.13	0.11	0.24	0.33	0.52	0.50	0.97
TC		1.00	0.98	0.99	0.30	0.43	0.49	0.17	0.21	0.33	0.57	0.20	0.42	0.54
OC			1.00	0.94	0.27	0.36	0.42	0.16	0.16	0.29	0.53	0.20	0.34	0.49
EC				1.00	0.32	0.48	0.54	0.17	0.24	0.35	0.60	0.20	0.47	0.57
NO_3^-					0.22	0.67	1.00	0.81	0.41	0.83	0.71	0.09	0.88	0.23
SO_4^{-2}					0.07	0.38		1.00	0.25	0.87	0.43	0.03	0.63	-0.03
NH_4^+					0.06	0.38			0.39	1.00	0.58	0.02	0.67	0.07
Metals					0.81	0.40			0.06		0.18	0.55	0.37	1.00

Table 2.24: Correlation matrix for $PM_{2.5}$ and its composition at RMD for summer season

RMD (S)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.79	0.74	0.82	0.16	0.59	0.87	0.66	0.36	0.78	0.54	-0.03	0.60	0.85
TC		1.00	0.98	0.99	0.33	0.44	0.52	0.17	0.12	0.35	0.38	-0.16	0.26	0.42
OC			1.00	0.94	0.31	0.36	0.44	0.15	0.05	0.32	0.35	-0.20	0.19	0.35
EC				1.00	0.34	0.49	0.56	0.19	0.18	0.37	0.39	-0.13	0.31	0.46
NO_3^-					-0.01	0.69	1.00	0.83	0.22	0.84	0.63	-0.02	0.52	0.76
SO_4^{-2}					-0.21	0.46		1.00	0.12	0.91	0.48	0.09	0.60	0.68
NH_4^+					-0.10	0.43			0.27	1.00	0.51	-0.11	0.59	0.77
Metals					0.01	0.38			0.59		0.44	0.08	0.70	1.00

2.4.2 Chunniganj (CNG)

The sampling period was February 04 – March 02, 2019 for winter and April 01 – 24, 2019 for summer.

2.4.2.1 Particulate Matter (PM_{10}, $PM_{2.5}$)

Time series of 24-hr average concentrations of PM_{10} and $PM_{2.5}$ are shown at CNG for winter (Figure 2.16) and summer (Figure 2.17). Average levels for winter and summer season were 146±102 and 79±24 µg/m^3 (for $PM_{2.5}$) and 220±121 and 177±49 µg/m^3 (for PM_{10}) respectively. The $PM_{2.5}$ levels are 2.4 times higher than the NAQS and PM_{10} is 2.2 times higher than the NAQS in winter. The $PM_{2.5}$ levels are 1.3 times higher and PM_{10} levels are 1.8 times higher than the NAQS in summer. A statistical summary of PM concentrations is presented in Tables 2.28 – 2.31 for the winter and summer seasons. In summer, $PM_{2.5}$ levels drop significantly compared to PM_{10} levels that continued to be high despite improvement in meteorology and better dispersion. The particle airborne from the soil during dust storms in the dry months of summer can contribute significantly to a coarse fraction (i.e., $PM_{2.5\text{-}10}$).

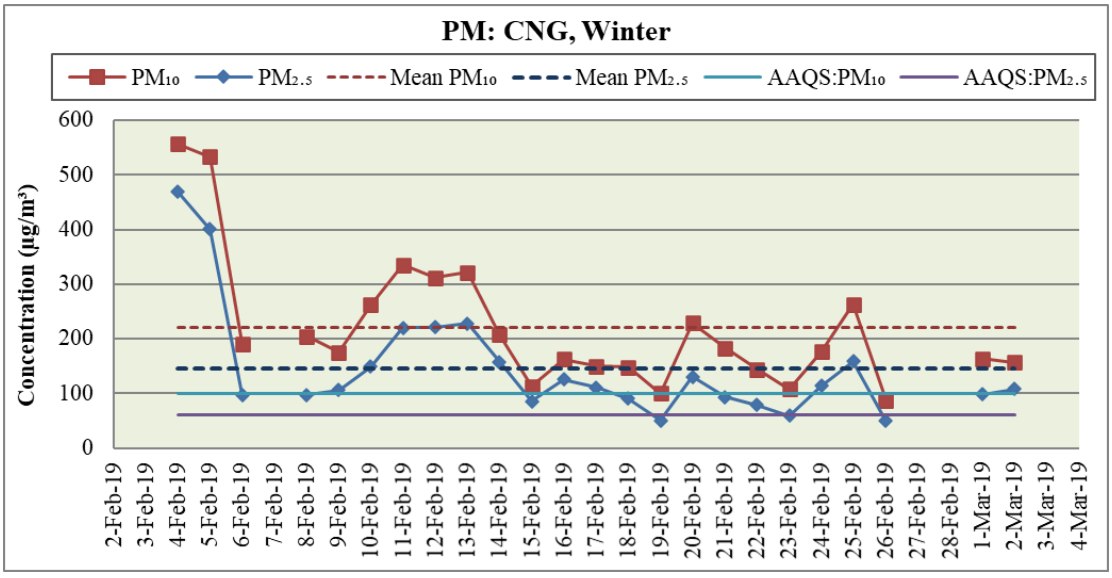


Figure 2.16: PM Concentrations at CNG for Winter Season

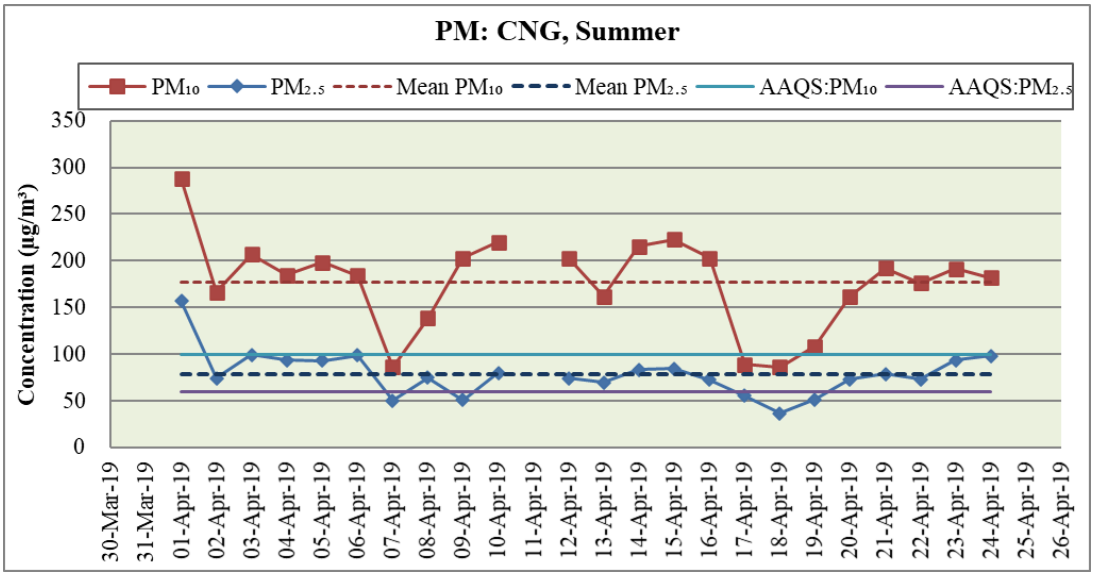


Figure 2.17: PM Concentrations at CNG for Summer Season

2.4.2.2 Gaseous pollutants

Time series of 24-hr average concentrations of SO_2 and NO_2 are shown for winter (Figure 2.18) and summer (Figure 2.19) seasons. It was observed that SO_2 concentrations were low (mostly < 5.0 µg/m^3) and met the air quality standard. NO_2 levels are also under the NAQS with an average of 20 days at 45.9±15.1 µg/m^3 in winter and 33.0±8.1 µg/m^3 in summer season (Table 2.25). The summer concentration of NO_2 dropped dramatically similarly $PM_{2.5}$ levels. Although the NO_2 is certainly a matter of concern in the winter season and these values can largely be attributed to vehicular pollution and DG sets. The Variation in NO_2 is due to variability in meteorology and the presence of occasional local sources like DG sets, traffic jams or local open and coal-burning etc.

The Mean concentrations of BTX were presented in Figure 2.20 and the statistical summary in Table 2.25. The total BTX level is observed 6.8±9.4 µg/m^3 (Benzene: 2.1 and Toluene: 3.4 µg/m^3) in winter and 6.1±4.6 µg/m^3 (Benzene: 2.0 and Toluene: 3.1 µg/m^3) in summer seasons. The BTX levels were slightly high during winter than in the summer.

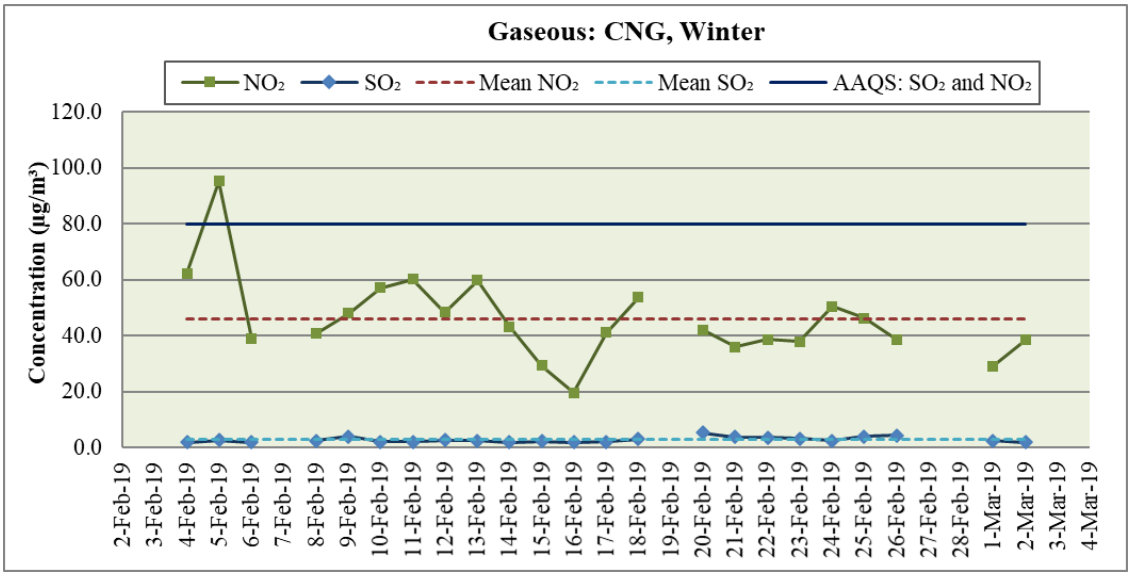


Figure 2.18: SO_2 and NO_2 Concentrations at CNG for Winter Season

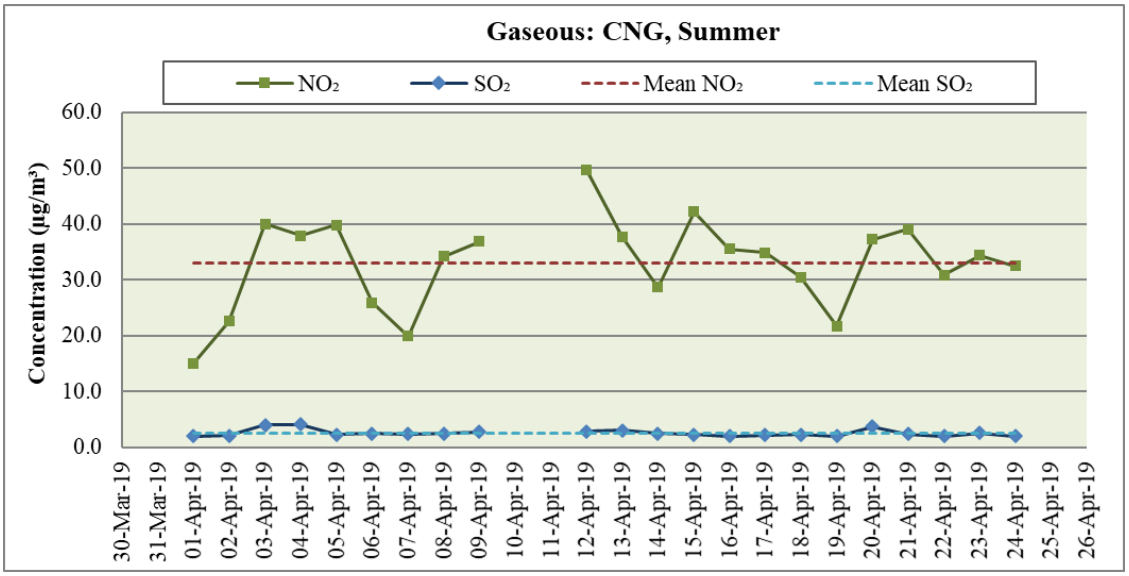


Figure 2.19: SO_2 and NO_2 Concentrations at CNG for Summer Season

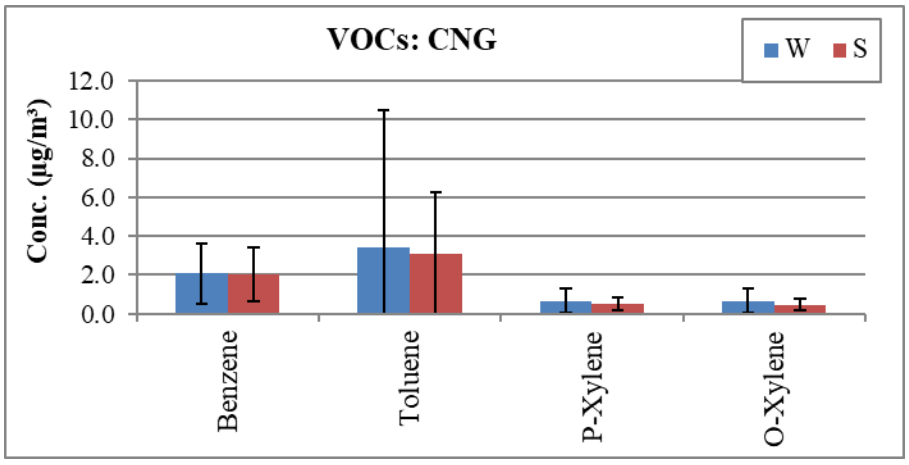


Figure 2.20: VOCs concentration at CNG

2.4.2.3 Carbon Content (EC/OC) in $PM_{2.5}$

Average concentrations of EC, OC (OC1, OC2, OC3 and OC4) and the ratio of OC fraction to TC are shown in Figure 2.21 (a) and (b) for winter and summer seasons. OC is observed higher (winter: 34.7±22.4 and summer: 13.1±5.8 µg/m^3) than the EC (winter: 26.4±17.8 and summer: 10.9±4.5 µg/m^3). It is also observed that the OC and EC are much higher in the winter season than in the summer season. A statistical summary of carbon content (TC, EC, OC; OC1, OC2, OC3 and OC4 with fractions OC1/TC, OC2/TC, OC3/TC and OC4/TC) is presented in Table 2.26 for winter and summer seasons. The ratio of OC3/TC is observed higher that indicating the formation of secondary organic carbon in the atmosphere at CNG.

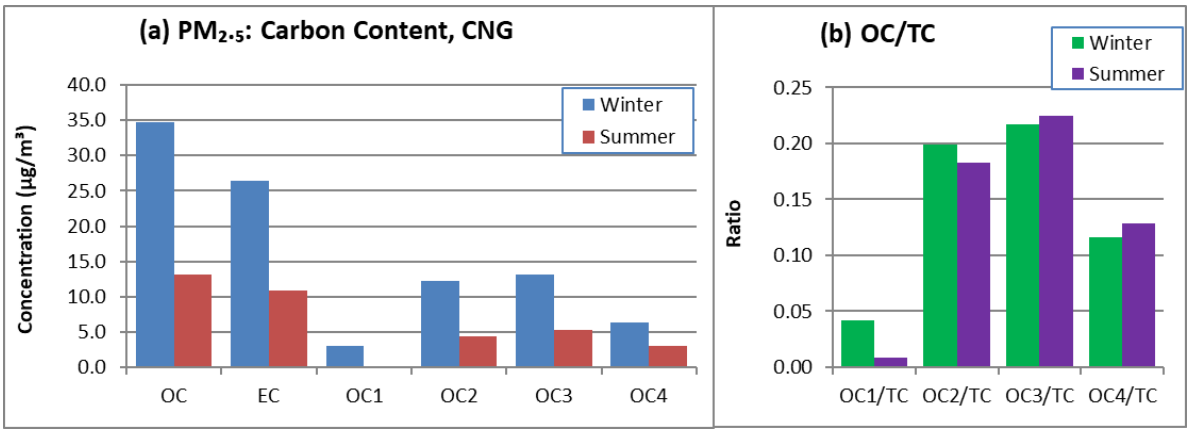


Figure 2.21: EC and OC Content in $PM_{2.5}$ at CNG

2.4.2.4 PAHs in $PM_{2.5}$

Figure 2.22 shows the average measured concentration of PAHs at CNG for winter and summer seasons. A statistical summary of PAHs is presented in Table 2.27 for winter and summer seasons. The PAHs compounds analyzed were: (i) DmP, (ii) AcP, (iii) DEP, (iv) Flu, (v) Phe, (vi) Ant, (vii) Pyr, (viii) BbP, (ix) BeA, (x) B(a)A, (xi) Chr, (xii) B(b)F, (xiii) B(k)F, (xiv) B(a)P, (xv) InP, (xvi) D(a,h)A and (xvii) B(ghi)P. It is observed that Total PAHs concentrations are lower in winter season (30±14 ng/m^3) compared to summer season (38±20 ng/m^3). Major PAHs are B(a)P (4.9 ng/m^3), B(k)F (4.3 ng/m^3), Flu (4.2 ng/m^3), B(b)F (4.0 ng/m^3) and Ant (3.3 ng/m^3) for winter season and DmP (17.9 ng/m^3), Phe (5.6 ng/m^3), DEP (4.5 ng/m^3), B(b)F (1.5 ng/m^3), Ant (1.6 ng/m^3) and Flu (1.3 ng/m^3) for summer season.

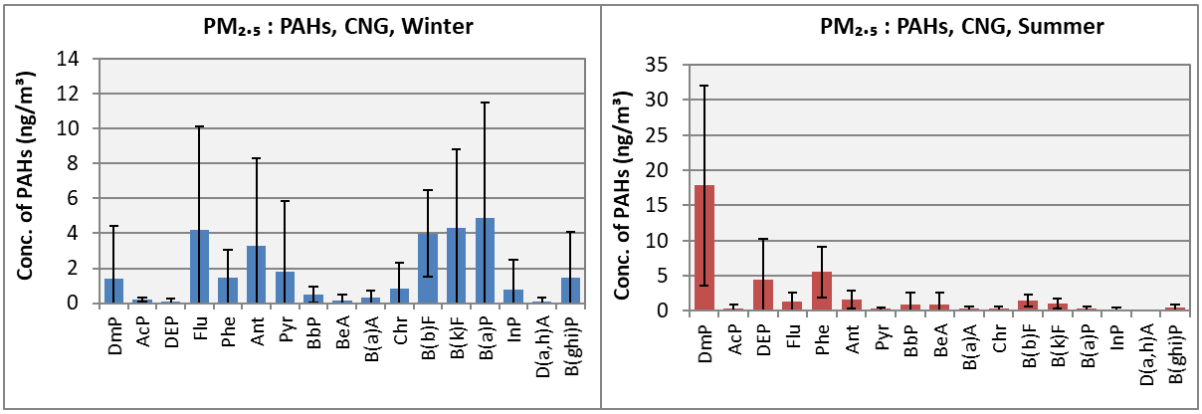


Figure 2.22: PAHs Concentrations in $PM_{2.5}$ at CNG

2.4.2.5 Chemical composition of PM_{10} and $PM_{2.5}$ and their correlation matrix

Graphical presentations of chemical species are shown for the winter and summer seasons for PM_{10} (Figure 2.23) and $PM_{2.5}$ (Figure 2.24). Statistical summary for particulate matter (PM_{10} and $PM_{2.5}$), its chemical composition [carbon content, ionic species and elements] along with mass percentage (% R) recovered from PM are presented in Tables 2.28 – 2.31 for winter and summer season.

The correlation between different parameters (i.e., PM, TC, OC, EC, F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2} and Metals (elements)) with major species (PM, TC, OC, EC, NO_3^-, SO_4^{-2}, NH_4^+, Metals) for PM_{10} and $PM_{2.5}$ composition is presented in Tables 2.32 – 2.35 for both seasons. It is seen that most of the parameters showed a good correlation (>0.30) with PM_{10} and $PM_{2.5}$. The percentage constituents of the PM are presented in Figure 2.25 (a) and (b) for the winter season and Figure 2.26 (a) and (b) for the summer season.

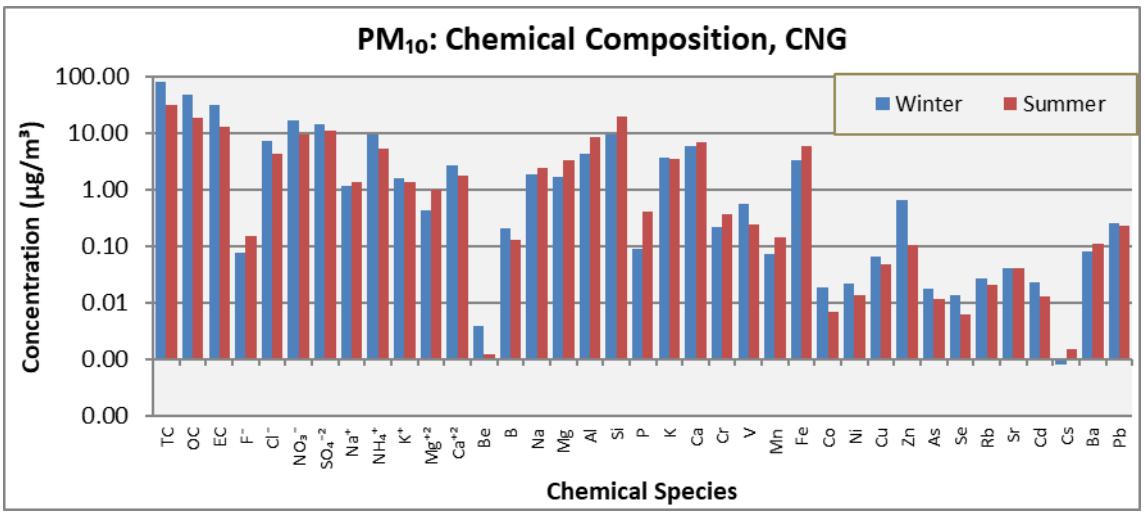


Figure 2.23: Concentrations of species in PM_{10} at CNG

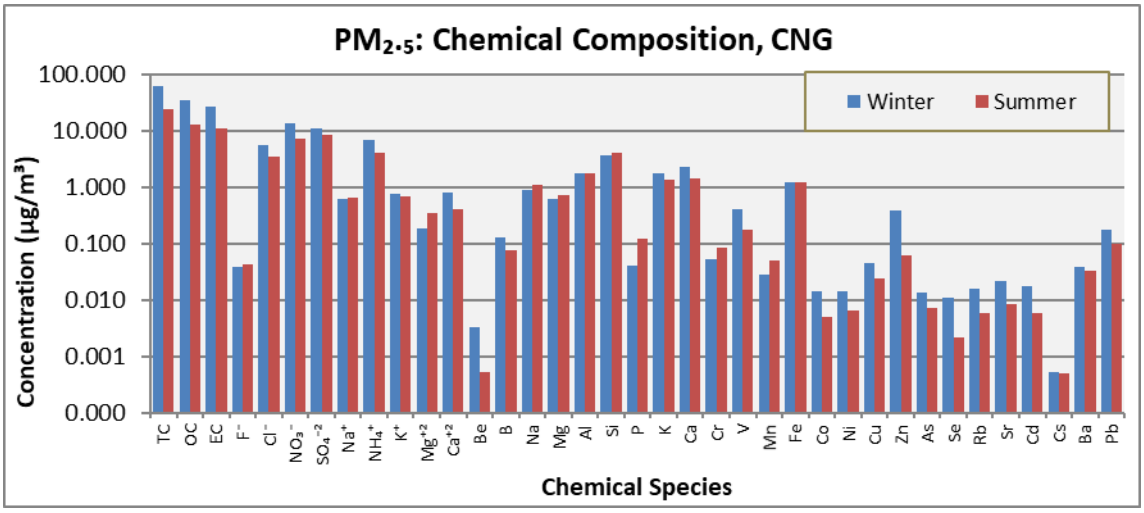


Figure 2.24: Concentrations of species in $PM_{2.5}$ at CNG

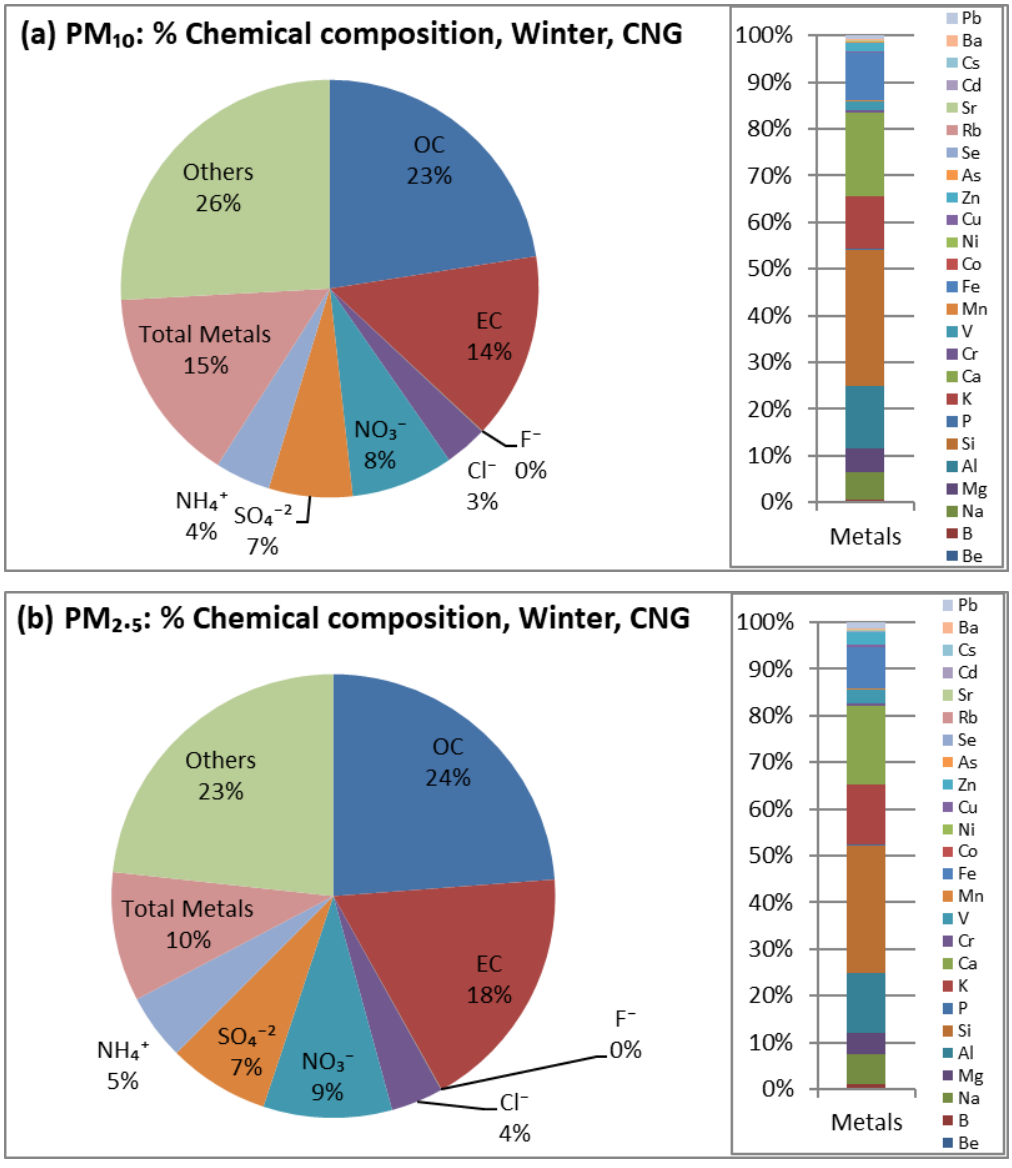


Figure 2.25: Percentage distribution of species in PM at CNG for Winter Season

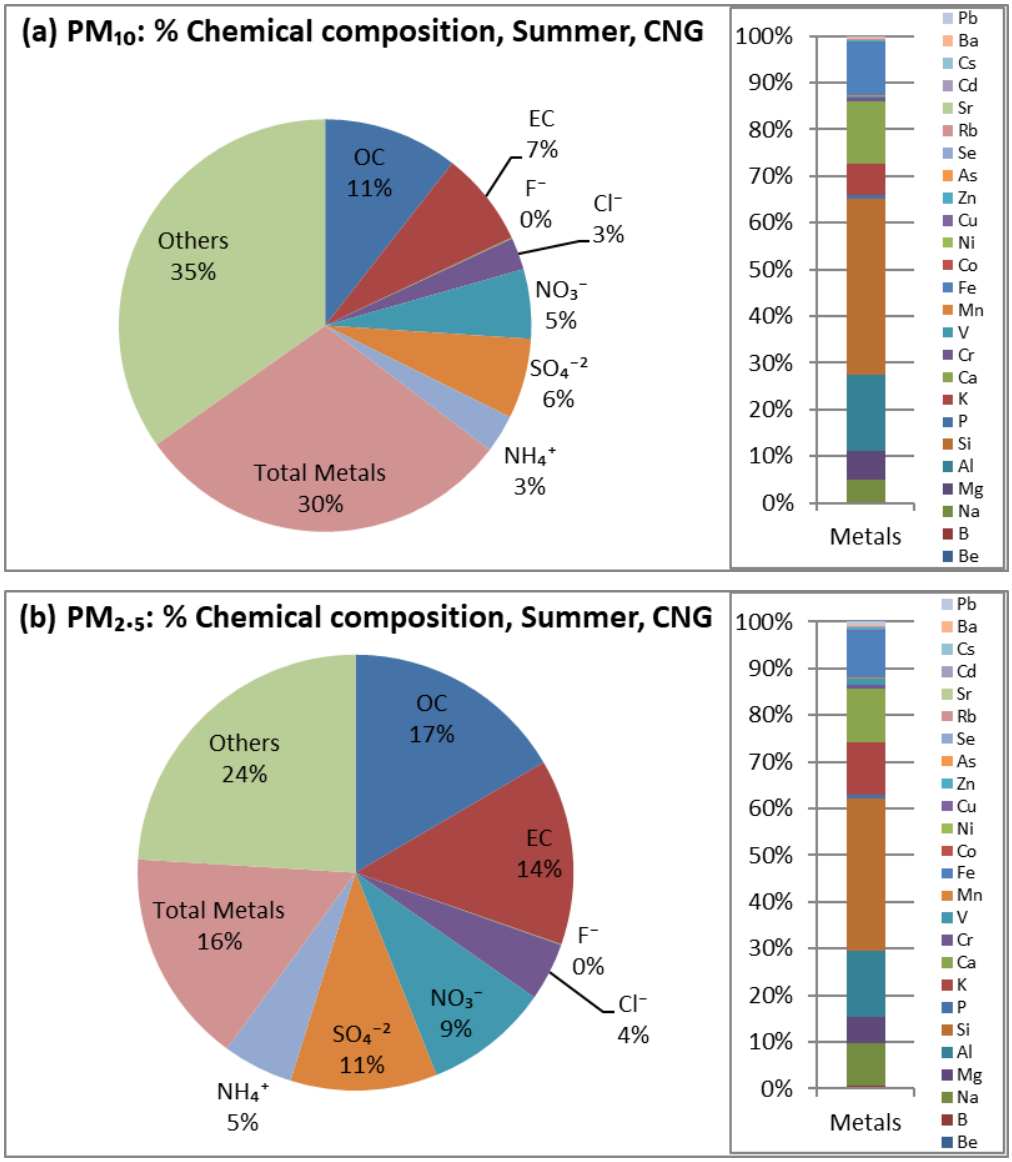


Figure 2.26: Percentage distribution of species in PM at CNG for Summer Season

2.4.2.6 Comparison of PM_{10} and $PM_{2.5}$ Composition

The graphical presentation is the better option for understanding the compositional variation. A compositional comparison of $PM_{2.5}$ vs PM_{10} for all species is shown for winter and summer seasons (Figure 2.27) at CNG. The chemical species considered for the comparisons are carbon content (TC, OC and EC), ionic species (F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2}) and elements (Be, B, Na, Mg, Al, Si, P, K, Ca, Cr, V, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, Pb). It is concluded that most portion of PM has fine mode during winter (66%) than summer (45%). The major species contributing to fine mode are TC, OC, EC, Cl^-, NO_3^-, SO_4^{-2}, NH_4^+, B, V, Co, Zn and As; whereas major species contributing in coarse mode are K^+, Mg^{2+}, Ca^{2+}, Na, Mg, Al, Si, P, K, Ca, Cr, Mn, Fe and Ba.

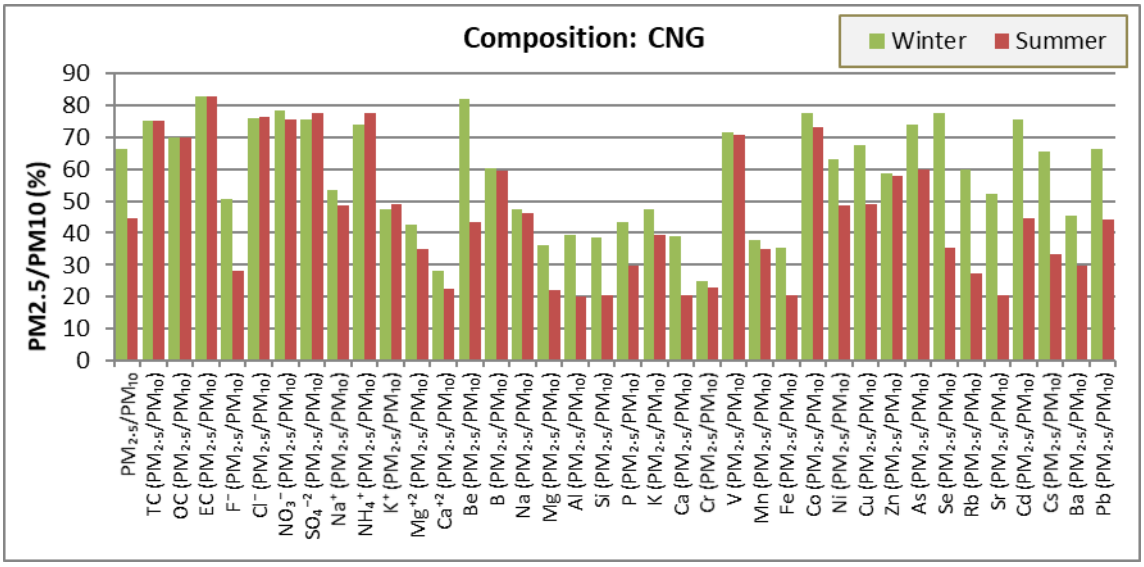


Figure 2.27: Compositional comparison of species in $PM_{2.5}$ Vs PM_{10} at CNG

Table 2.25: Statistical results of gaseous pollutants (µg/m^3) at CNG for winter (W) and summer (S) seasons

CNG (W)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	45.92	2.88	2.07	3.38	0.66	0.66	6.77
SD	15.09	0.96	1.53	7.12	0.63	0.61	9.36
Max	95.28	5.48	6.42	36.28	3.13	2.95	48.79
Min	19.67	2.00	0.28	0.20	0.09	0.06	0.78
CV	0.33	0.33	0.74	2.10	0.95	0.92	1.38
CNG (S)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	33.05	2.58	2.02	3.10	0.48	0.45	6.05
SD	8.14	0.63	1.39	3.13	0.33	0.31	4.56
Max	49.59	4.09	5.71	11.29	1.04	0.97	15.09
Min	15.06	2.00	0.27	0.09	0.00	0.01	0.43
CV	0.25	0.24	0.69	1.01	0.68	0.69	0.75

Table 2.26: Statistical results of carbon contents (µg/m^3) in $PM_{2.5}$ at CNG for winter (W) and summer (S) seasons

CNG (W)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	145.9	61.09	34.73	26.36	3.03	12.24	13.09	6.37	0.042	0.199	0.217	0.116
SD	102.2	39.95	22.40	17.83	3.18	8.26	8.22	3.12	0.016	0.011	0.017	0.027
Max	468.7	162.80	92.61	70.20	11.23	33.26	34.41	14.57	0.080	0.228	0.250	0.158
Min	49.4	17.19	10.06	7.13	0.39	3.49	3.65	2.27	0.022	0.179	0.192	0.065
CV	0.70	0.65	0.64	0.68	1.05	0.67	0.63	0.49	0.377	0.054	0.076	0.237
CNG (S)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	79.1	24.00	13.11	10.90	0.22	4.42	5.37	3.09	0.009	0.182	0.225	0.128
SD	24.2	9.95	5.83	4.54	0.34	1.94	2.37	1.59	0.010	0.018	0.039	0.026
Max	156.6	42.40	28.34	18.39	1.51	8.14	10.67	8.67	0.043	0.221	0.348	0.205
Min	36.7	5.51	2.57	2.94	0.00	0.88	1.09	0.49	0.000	0.153	0.179	0.081
CV	0.31	0.41	0.44	0.42	1.51	0.44	0.44	0.52	1.154	0.099	0.172	0.199

Table 2.27: Statistical results of PAHs (ng/m^3) in $PM_{2.5}$ at CNG for winter (W) and summer (S) seasons

CNG(W)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	1.42	0.19	0.07	4.22	1.44	3.26	1.80	0.48	0.13	0.34	0.83	3.98	4.31	4.88	0.77	0.09	1.45	29.65
SD	3.00	0.13	0.19	5.91	1.59	5.02	4.05	0.46	0.37	0.36	1.50	2.48	4.52	6.61	1.74	0.24	2.63	14.36
Max	10.79	0.53	0.66	18.22	5.51	16.09	13.16	1.34	1.29	1.38	5.03	9.93	16.01	21.76	5.43	0.83	7.18	60.07
Min	0.00	0.09	0.00	0.00	0.00	0.03	0.00	0.06	0.00	0.15	0.12	0.36	0.23	0.71	0.00	0.00	0.14	10.98
CV	2.12	0.67	2.62	1.40	1.11	1.54	2.25	0.98	2.82	1.07	1.82	0.62	1.05	1.35	2.26	2.75	1.81	0.48
CNG(S)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	17.85	0.39	4.52	1.30	5.55	1.62	0.29	0.97	0.89	0.32	0.33	1.49	1.06	0.40	0.20	0.00	0.50	37.66
SD	14.20	0.54	5.77	1.38	3.61	1.31	0.21	1.67	1.78	0.33	0.35	0.81	0.69	0.28	0.31	0.00	0.49	20.35
Max	52.66	2.05	20.32	4.87	10.84	3.79	0.77	5.97	5.84	1.35	1.29	3.01	2.50	0.93	0.90	0.00	1.55	80.95
Min	0.28	0.11	0.00	0.00	0.00	0.29	0.00	0.07	0.00	0.17	0.12	0.42	0.06	0.05	0.00	0.00	0.15	15.02
CV	0.80	1.40	1.28	1.06	0.65	0.81	0.72	1.72	1.99	1.03	1.06	0.54	0.65	0.70	1.56	--	0.98	0.54

Table 2.28: Statistical results of chemical characterization (µg/m^3) of PM_{10} at CNG for winter (W) season

CNG (W)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	220	49.6	31.8	0.1	7.4	17.4	14.3	1.2	9.5	1.6	0.4	2.8	4E-3	0.21	1.93	1.70	4.47	9.73	0.09
SD	121	32.0	21.5	0.1	4.9	13.1	11.4	0.8	7.2	0.9	0.2	1.3	2E-3	0.19	1.35	0.93	2.79	6.46	0.07
Max	557	132.3	84.6	0.3	18.5	52.9	55.4	3.9	28.4	4.7	0.9	5.4	1E-2	0.79	6.75	3.70	11.28	27.63	0.34
Min	87	14.4	8.6	0.0	2.3	4.3	3.9	0.4	2.5	0.5	0.2	1.3	3E-3	0.05	0.58	0.63	1.23	2.65	0.02
CV	0.55	0.64	0.68	0.79	0.67	0.75	0.80	0.67	0.76	0.55	0.41	0.46	0.47	0.90	0.70	0.55	0.62	0.66	0.76
CNG (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	3.68	5.97	0.22	0.57	0.08	3.41	0.02	0.02	0.07	0.65	0.02	0.01	0.03	0.04	0.02	8E-4	0.08	0.26	74.1
SD	2.43	4.45	0.14	0.21	0.04	1.91	0.01	0.01	0.04	0.37	0.01	0.01	0.01	0.02	0.01	4E-4	0.06	0.22	3.8
Max	10.48	20.71	0.62	1.03	0.21	8.20	0.05	0.05	0.21	1.73	0.05	0.03	0.06	0.09	0.05	2E-3	0.23	0.91	79.8
Min	0.98	1.87	0.09	0.21	0.01	1.05	0.01	0.01	0.02	0.23	0.01	0.01	0.01	0.02	0.01	5E-4	0.03	0.07	66.4
CV	0.66	0.74	0.64	0.36	0.56	0.56	0.56	0.64	0.64	0.56	0.48	0.46	0.45	0.45	0.59	0.44	0.68	0.84	0.05
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.29: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at CNG for winter (W) season

CNG (W)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	146	34.7	26.4	0.0	5.6	13.7	10.8	0.6	7.0	0.8	0.2	0.8	3E-3	0.13	0.91	0.62	1.77	3.75	0.04
SD	102	22.4	17.8	0.0	4.4	11.9	9.6	0.6	6.1	0.7	0.1	0.4	2E-3	0.13	0.99	0.58	2.15	4.39	0.04
Max	469	92.6	70.2	0.1	16.8	46.5	45.3	2.6	23.4	3.2	0.4	1.6	9E-3	0.63	5.17	2.56	9.67	20.57	0.22
Min	49	10.1	7.1	0.0	1.8	2.3	2.6	0.2	1.4	0.2	0.1	0.2	1E-3	0.02	0.33	0.22	0.48	1.07	0.01
CV	0.70	0.64	0.68	0.92	0.79	0.87	0.89	1.00	0.86	0.90	0.46	0.53	0.49	1.02	1.08	0.95	1.22	1.17	1.10
CNG (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	1.75	2.34	0.05	0.41	0.03	1.21	1E-2	1E-2	0.05	0.38	1E-2	1E-2	2E-2	2E-2	0.02	5E-4	0.04	0.17	78.0
SD	1.99	3.03	0.04	0.18	0.02	1.25	6E-3	8E-3	0.03	0.20	8E-3	5E-3	7E-3	1E-2	0.01	2E-4	0.02	0.14	3.4
Max	7.82	15.05	0.16	0.83	0.10	4.79	3E-2	4E-2	0.11	0.90	4E-2	3E-2	4E-2	6E-2	0.04	1E-3	0.11	0.66	86.0
Min	0.26	0.61	0.00	0.05	0.01	0.34	8E-3	7E-3	0.02	0.14	6E-3	4E-3	1E-2	1E-2	0.01	4E-4	0.02	0.05	71.5
CV	1.14	1.30	0.72	0.43	0.79	1.04	0.39	0.57	0.55	0.52	0.57	0.45	0.42	0.45	0.53	0.42	0.60	0.82	0.04
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.30: Statistical results chemical characterization (µg/m^3) of PM_{10} at CNG for summer (S) season

CNG (S)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	177	18.7	13.1	0.2	4.5	9.6	11.1	1.4	5.3	1.4	1.0	1.8	1E-3	0.13	2.45	3.32	8.69	19.93	0.42
SD	49	8.3	5.5	0.1	1.8	4.6	4.8	0.9	1.9	0.5	0.5	0.9	8E-4	0.09	0.99	1.33	3.37	7.57	0.14
Max	288	40.5	22.2	0.3	8.3	23.8	23.7	5.1	10.3	2.3	2.8	5.1	5E-3	0.53	6.30	5.48	14.23	31.29	0.77
Min	86	3.7	3.5	0.0	1.9	4.2	4.7	0.5	2.2	0.4	0.5	0.9	8E-4	0.07	1.48	1.25	2.83	6.82	0.14
CV	0.28	0.44	0.42	0.37	0.41	0.47	0.43	0.67	0.36	0.37	0.48	0.51	0.63	0.69	0.41	0.40	0.39	0.38	0.35
CNG (S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	3.52	7.09	0.37	0.25	0.15	6.03	7E-3	1E-2	0.05	0.11	0.01	6E-3	2E-2	4E-2	0.01	2E-3	0.11	0.23	65.71
SD	1.40	2.53	0.15	0.09	0.08	2.17	4E-3	9E-3	0.03	0.07	0.02	4E-3	1E-2	2E-2	0.01	7E-4	0.11	0.29	3.27
Max	7.00	11.84	0.68	0.66	0.35	9.53	2E-2	5E-2	0.14	0.32	0.09	2E-2	4E-2	8E-2	0.07	4E-3	0.58	1.40	70.16
Min	1.11	2.87	0.11	0.15	0.02	1.99	4E-3	6E-3	0.02	0.02	0.00	2E-3	5E-3	1E-2	0.00	5E-4	0.03	0.07	58.01
CV	0.40	0.36	0.39	0.39	0.56	0.36	0.54	0.64	0.56	0.62	1.47	0.71	0.47	0.46	1.09	0.49	1.00	1.24	0.05
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.31: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at CNG for summer (S) season

CNG (S)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	79	13.1	10.9	0.0	3.4	7.3	8.6	0.7	4.1	0.7	0.4	0.4	5E-4	0.08	1.13	0.74	1.76	4.11	0.12
SD	24	5.8	4.5	0.0	1.4	3.4	3.7	0.3	1.4	0.3	0.2	0.3	8E-4	0.08	0.45	0.44	0.98	2.30	0.10
Max	157	28.3	18.4	0.1	6.0	18.2	18.4	1.5	7.6	1.5	1.2	1.3	4E-3	0.40	2.22	1.68	4.47	10.06	0.51
Min	37	2.6	2.9	0.0	1.5	3.0	3.5	0.3	1.6	0.3	0.1	0.2	3E-4	0.03	0.38	0.25	0.59	1.40	0.03
CV	0.31	0.44	0.42	0.67	0.40	0.47	0.43	0.48	0.35	0.49	0.67	0.62	1.42	0.98	0.40	0.59	0.56	0.56	0.79
CNG (S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	1.40	1.46	0.09	0.17	0.05	1.23	5E-3	7E-3	2E-2	0.06	7E-3	2E-3	6E-3	8E-3	6E-3	5E-4	0.03	0.10	76.39
SD	0.57	0.81	0.08	0.06	0.04	0.63	3E-3	7E-3	2E-2	0.04	1E-2	3E-3	5E-3	7E-3	9E-3	5E-4	0.07	0.07	2.73
Max	2.76	3.72	0.40	0.37	0.20	2.89	2E-2	3E-2	1E-1	0.20	7E-2	2E-2	3E-2	3E-2	5E-2	3E-3	0.35	0.38	82.48
Min	0.64	0.44	0.02	0.08	0.01	0.40	2E-3	1E-3	7E-3	0.01	8E-4	6E-4	9E-4	2E-3	1E-3	2E-4	0.00	0.04	72.06
CV	0.41	0.56	0.94	0.34	0.79	0.51	0.67	1.04	0.79	0.70	1.90	1.46	0.89	0.81	1.53	0.97	2.17	0.74	0.04
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.32: Correlation Matrix for PM_{10} and its composition at CNG for winter season

CNG (W)	PM_{10}	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
PM_{10}	1.00	0.86	0.82	0.89	0.61	0.80	0.72	0.78	0.30	0.74	0.74	-0.07	0.50	0.89
TC		1.00	1.00	0.99	0.45	0.44	0.33	0.42	0.06	0.36	0.49	-0.12	0.24	0.55
OC			1.00	0.97	0.40	0.40	0.27	0.36	0.02	0.30	0.44	-0.10	0.23	0.50
EC				1.00	0.50	0.51	0.41	0.51	0.12	0.45	0.55	-0.14	0.25	0.60
NO_3^-					0.61	0.95	1.00	0.84	0.39	0.95	0.73	0.07	0.45	0.80
SO_4^{-2}					0.59	0.85		1.00	0.46	0.88	0.82	-0.07	0.37	0.86
NH_4^+					0.64	0.94			0.46	1.00	0.78	0.02	0.42	0.83
Metals					0.58	0.85			0.45		0.76	-0.01	0.70	1.00

Table 2.33: Correlation matrix for $PM_{2.5}$ and its composition at CNG for winter season

CNG (W)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.85	0.81	0.90	0.62	0.85	0.77	0.85	0.49	0.79	0.88	0.04	0.52	0.93
TC		1.00	0.99	0.99	0.44	0.50	0.38	0.48	0.21	0.43	0.57	-0.18	0.38	0.64
OC			1.00	0.97	0.40	0.45	0.31	0.41	0.16	0.36	0.50	-0.21	0.36	0.58
EC				1.00	0.48	0.57	0.46	0.56	0.27	0.50	0.64	-0.15	0.40	0.71
NO_3^-					0.62	0.96	1.00	0.86	0.54	0.96	0.89	0.41	0.54	0.82
SO_4^{-2}					0.59	0.89		1.00	0.58	0.89	0.93	0.17	0.43	0.94
NH_4^+					0.68	0.96			0.57	1.00	0.92	0.38	0.56	0.84
Metals					0.64	0.87			0.64		0.94	0.11	0.52	1.00

Table 2.34: Correlation matrix for PM_{10} and its composition at CNG for summer season

CNG (S)	PM_{10}	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
PM_{10}	1.00	0.50	0.53	0.39	0.57	0.52	0.50	0.28	0.40	0.47	0.74	0.54	0.69	0.93
TC		1.00	0.97	0.94	0.51	0.03	0.08	-0.19	0.05	-0.04	0.61	0.38	0.57	0.21
OC			1.00	0.84	0.48	0.05	0.15	-0.24	0.11	-0.01	0.61	0.49	0.67	0.27
EC				1.00	0.51	-0.02	-0.03	-0.10	-0.05	-0.08	0.55	0.18	0.36	0.11
NO_3^-					0.05	0.74	1.00	0.60	0.27	0.88	0.50	0.69	0.55	0.33
SO_4^{-2}					0.17	0.47		1.00	-0.04	0.60	0.37	0.13	0.07	0.19
NH_4^+					0.07	0.83			0.37	1.00	0.43	0.62	0.44	0.35
Metals					0.47	0.43			0.42		0.53	0.37	0.51	1.00

Table 2.35: Correlation matrix for $PM_{2.5}$ and its composition at CNG for summer season

CNG (S)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.57	0.60	0.48	0.56	0.63	0.79	0.47	0.60	0.65	0.71	0.66	0.61	0.83
TC		1.00	0.97	0.95	0.42	0.00	0.09	-0.17	0.12	-0.05	0.31	0.19	0.33	0.11
OC			1.00	0.84	0.52	0.02	0.17	-0.22	0.19	-0.04	0.32	0.32	0.44	0.19
EC				1.00	0.25	-0.03	-0.02	-0.09	0.02	-0.05	0.27	0.02	0.14	-0.01
NO_3^-					0.45	0.73	1.00	0.61	0.55	0.84	0.52	0.66	0.60	0.77
SO_4^{-2}					-0.14	0.52		1.00	0.18	0.62	0.35	0.07	0.07	0.45
NH_4^+					0.31	0.81			0.57	1.00	0.50	0.55	0.36	0.66
Metals					0.53	0.67			0.71		0.70	0.75	0.60	1.00

2.4.3 Dada Nagar (DDN)

The sampling period was December 22, 2018 – January 12, 2019, for winter and April 27 – May 16, 2019 for summer.

2.4.3.1 Particulate Matter (PM_{10}, $PM_{2.5}$)

Time series of 24-hr average concentrations of PM_{10} and $PM_{2.5}$ are shown for winter (Figure 2.28) and summer (Figure 2.29). Average levels for winter and summer season were 388±190 and 116±32 µg/m^3 (for $PM_{2.5}$) and 598±227 and 297±68 µg/m^3 (for PM_{10}) respectively. The $PM_{2.5}$ levels are 6.5 times higher than the NAQS and PM_{10} is 6.0 times higher than the NAQS in winter. The $PM_{2.5}$ is about two times higher than the NAQS and PM_{10} is three times higher than the national standard in summer. A statistical summary of PM concentrations is presented in Tables 2.39 – 2.42 for the winter and summer seasons. In summer, both PM_{10} and $PM_{2.5}$ levels drop significantly but do not meet the national standards, however, PM_{10} levels was not dropped in same manner as $PM_{2.5}$ and continue to be high in spite of improvement in meteorology and better dispersion. The particles airborne from the soil surface during dust storms in the dry months of summer can contribute significantly to a coarse fraction.

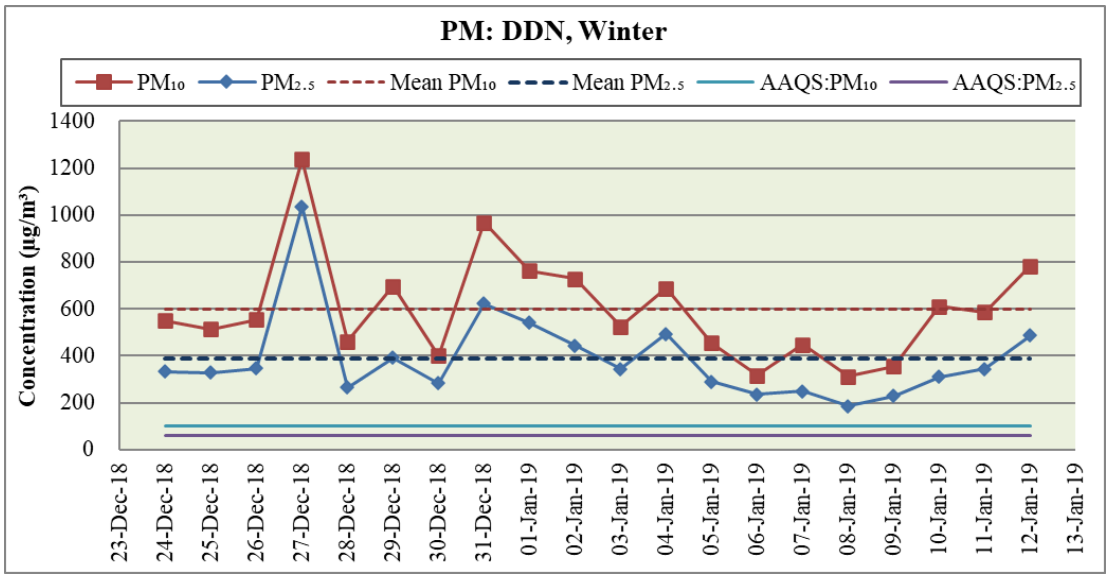


Figure 2.28: PM Concentrations at DDN for Winter Season

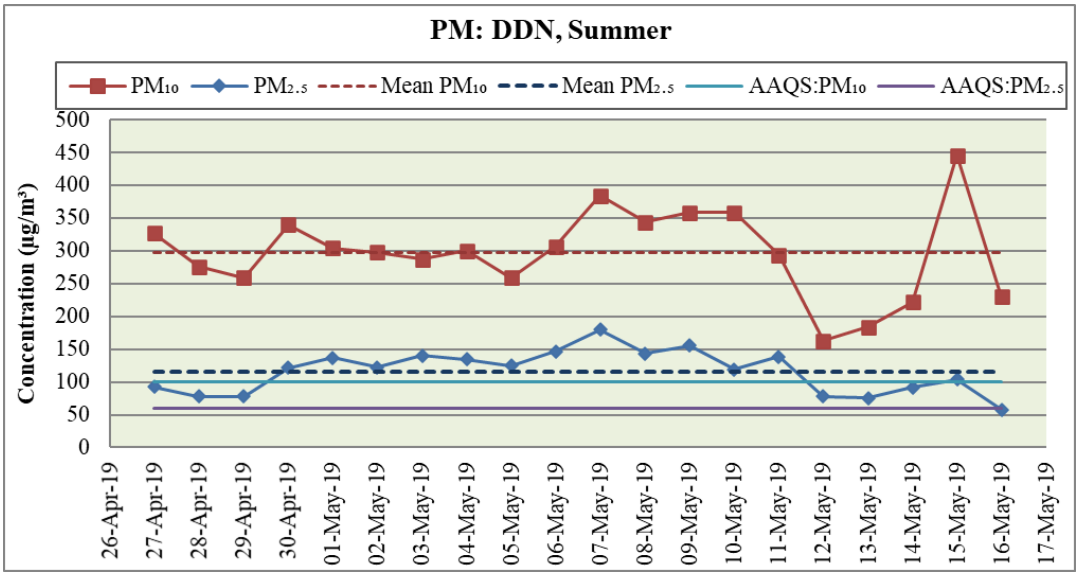


Figure 2.29: PM Concentrations at DDN for Summer Season

2.4.3.2 Gaseous pollutants

Time series of 24-hr average concentrations of SO_2 and NO_2 are shown for winter (Figure 2.30) and summer (Figure 2.31) seasons. It was observed that NO_2 and SO_2 levels were under the NAQ standards. The average of 20 days for winter and summer were 74.3±7.8 and 36.5±8.8 µg/m^3 (for NO_2) and 20.2±4.4 and 5.6±3.8 µg/m^3 (for SO_2) (Table 2.36). The summer concentration of NO_2 and SO_2 dropped significantly than in winter. Although, NO_2 and SO_2 are certainly a matter of concern and these values can largely be attributed to vehicular pollution, DG sets and coal combustion in industries. Variation in NO_2 and SO_2 are due to variability in meteorology and the presence of occasional local sources like DG sets, traffic jams, coal combustion or local open burning etc.

The Mean concentrations of BTX were presented in Figure 2.32 and the statistical summary in Table 2.38. The total BTX level is observed 27.7±14.8 µg/m^3 (Benzene: 4.0 and Toluene: 21.2 µg/m^3) in winter and 45.1±69.4 µg/m^3 (Benzene: 3.8 and Toluene: 40.5 µg/m^3) in summer seasons. The BTX levels were high during summer than the winter. The high levels of toluene in summer suggest the high evaporative losses of solvent uses in industrial processes in the surrounding area.

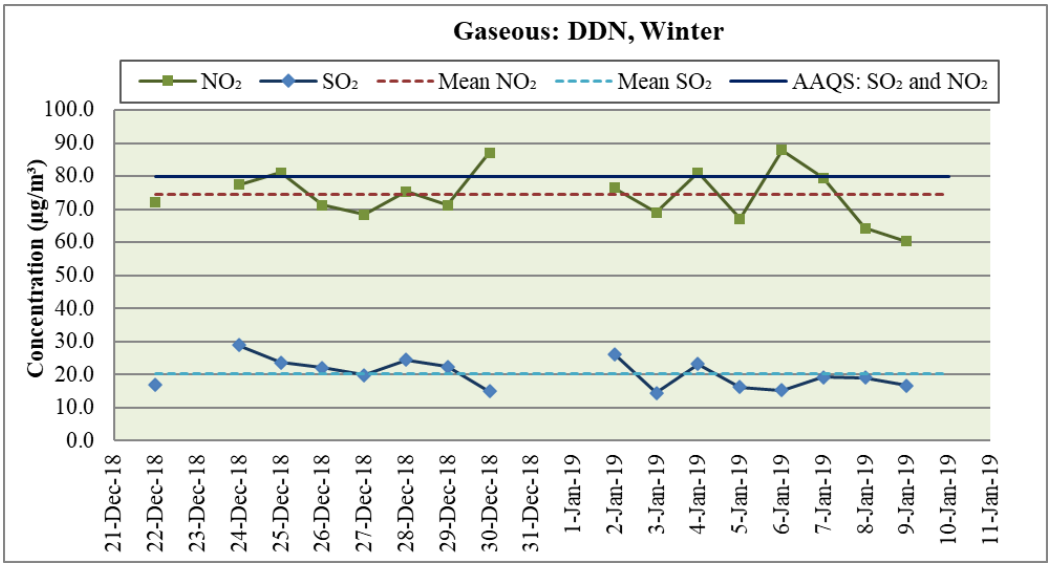


Figure 2.30: SO_2 and NO_2 Concentrations at DDN for Winter Season

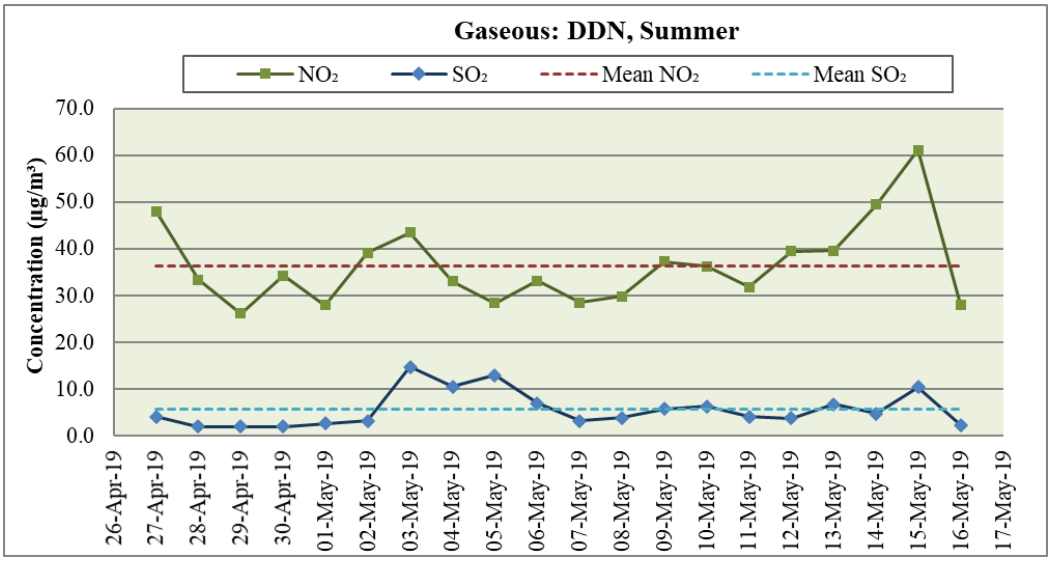


Figure 2.31: SO_2 and NO_2 Concentrations at DDN for Summer Season

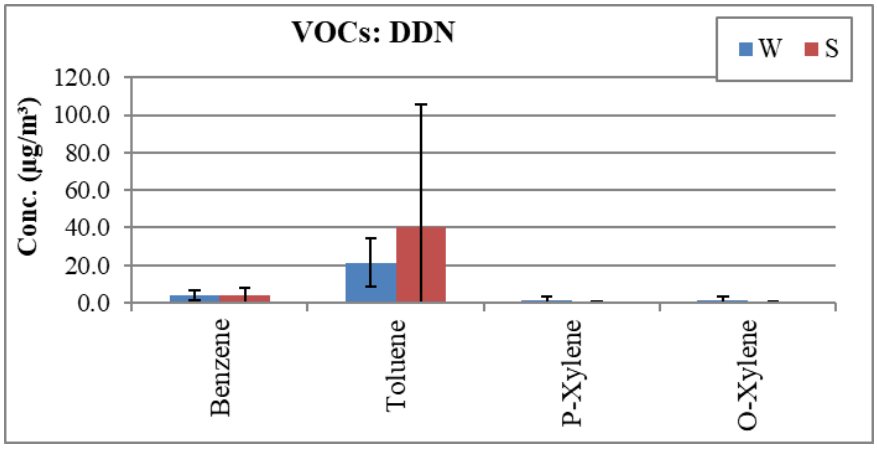


Figure 2.32: VOCs concentration at DDN

2.4.3.3 Carbon Content (EC/OC) in $PM_{2.5}$

Average concentrations of EC, OC (OC1, OC2, OC3 and OC4) and the ratio of OC fraction to TC are shown in Figure 2.33 (a) and (b) for winter and summer seasons. OC is observed slightly higher (winter: 53.4±18.7 and summer: 15.3±4.8 µg/m^3) than the EC (winter: 46.3±17.8 and summer: 13.8±6.2 µg/m^3). It is also observed that the OC and EC are higher in the winter season than in the summer season. A statistical summary of carbon content (TC, EC, OC; OC1, OC2, OC3 and OC4 with fractions OC1/TC, OC2/TC, OC3/TC and OC4/TC) is presented in Table 2.37 for winter and summer seasons. The ratio of OC3/TC is observed higher that indicates the formation of secondary organic carbon in the atmosphere at DDN.

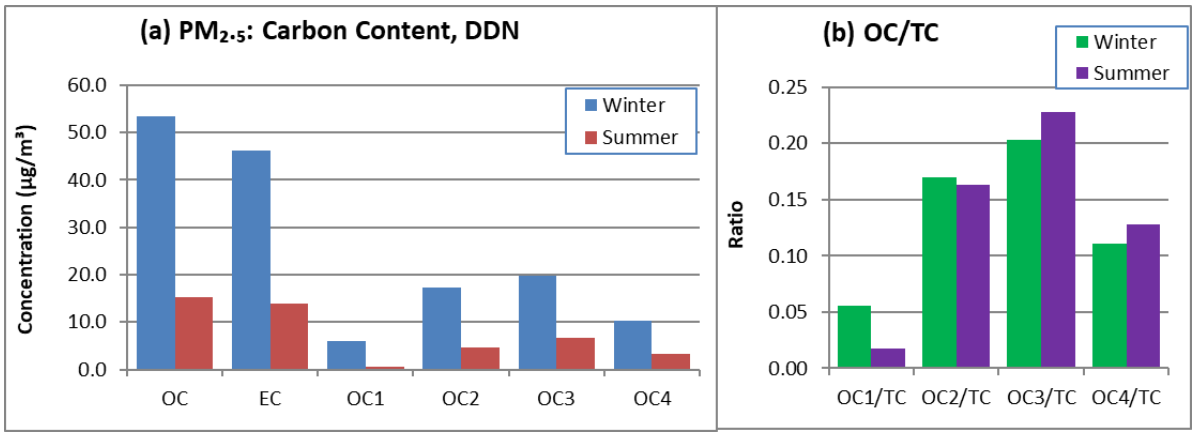


Figure 2.33: EC and OC Content in $PM_{2.5}$ at DDN

2.4.3.4 PAHs in $PM_{2.5}$

Figure 2.34 shows the average measured concentration of PAHs at DDN for winter and summer seasons. A statistical summary of PAHs is presented in Table 2.38 for winter and summer seasons. The PAHs compounds analyzed were: (i) DmP, (ii) AcP, (iii) DEP, (iv) Flu, (v) Phe, (vi) Ant, (vii) Pyr, (viii) BbP, (ix) BeA, (x) B(a)A, (xi) Chr, (xii) B(b)F, (xiii) B(k)F, (xiv) B(a)P, (xv) InP, (xvi) D(a,h)A and (xvii) B(ghi)P. It is observed that Total PAHs concentrations are much higher in winter season (120±65 ng/m^3) compared to summer season (27±23 ng/m^3). Major PAHs are DmP (19.6 ng/m^3), Chr (15.8 ng/m^3), InP (15.3 ng/m^3), B(ghi)P (14.6 ng/m^3) and B(b)F (12.2 ng/m^3) for winter season and B(b)F (4.5 ng/m^3), InP (4.2 ng/m^3), B(ghi)P (4.1 ng/m^3), B(k)F (3.9 ng/m^3) and DmP (3.8 ng/m^3) for summer season.

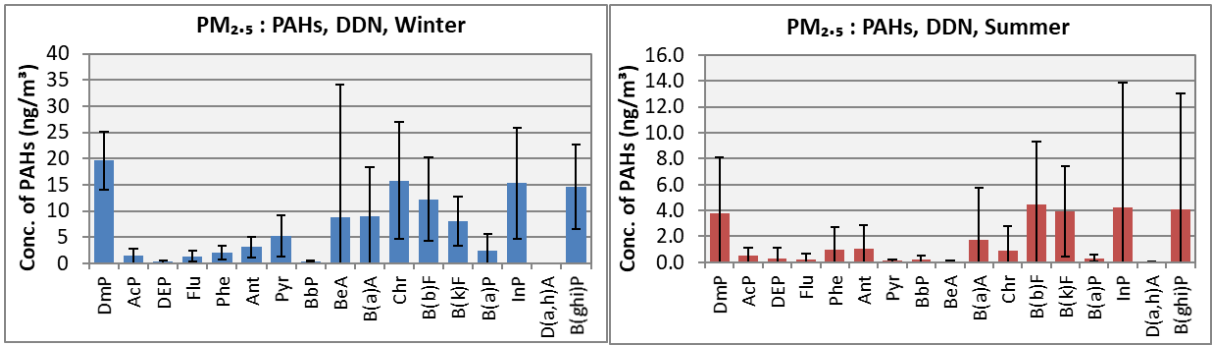


Figure 2.34: PAHs Concentrations in $PM_{2.5}$ at DDN

2.4.3.5 Chemical Composition of PM_{10} and $PM_{2.5}$ and their correlation matrix

Graphical presentations of chemical species are shown for the winter and summer seasons for PM_{10} (Figure 2.35) and $PM_{2.5}$ (Figure 2.36). Statistical summary for particulate matter (PM_{10} and $PM_{2.5}$), its chemical composition [carbon content, ionic species and elements] along with mass percentage (%R) recovered from PM are presented in Tables 2.39 – 2.42 for winter and summer season.

The correlation between different parameters (i.e., PM, TC, OC, EC, F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2} and Metals (elements)) with major species (PM, TC, OC, EC, NO_3^-, SO_4^{-2}, NH_4^+, Metals) for PM_{10} and $PM_{2.5}$ composition is presented in Tables 2.43 – 2.46 for both seasons. It is seen that most of the parameters showed a good correlation (>0.30) with PM_{10} and $PM_{2.5}$. The percentage constituents of the PM are presented in Figure 2.37 (a) and (b) for the winter season and Figure 2.38 (a) and (b) for the summer season.

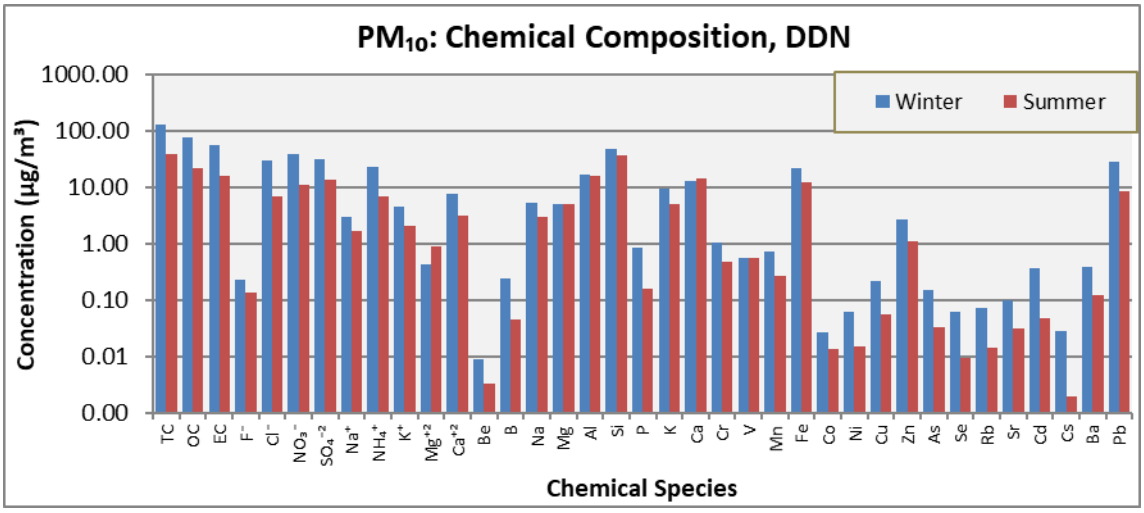


Figure 2.35: Concentrations of species in PM_{10} at DDN

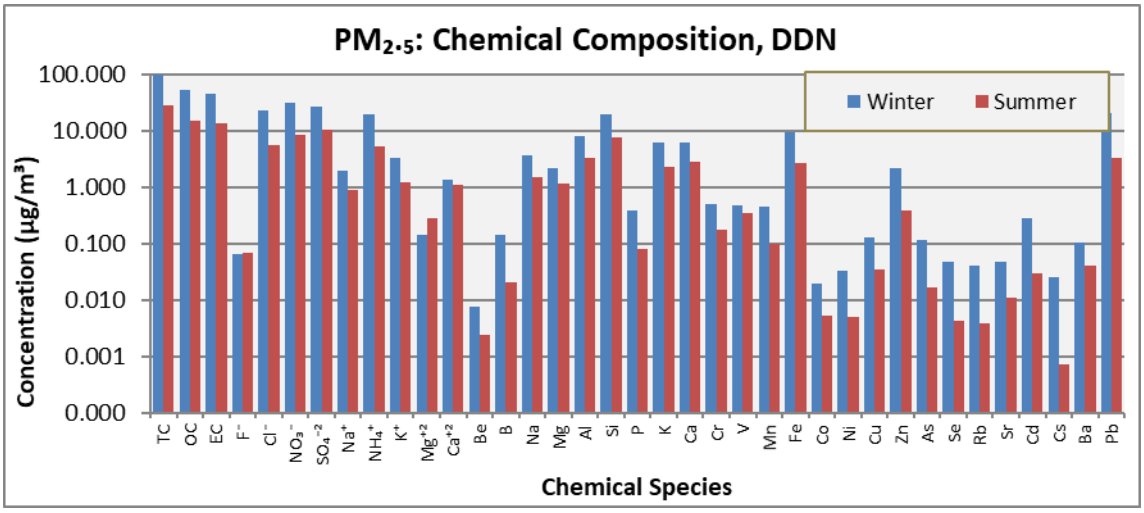


Figure 2.36: Concentrations of species in $PM_{2.5}$ at DDN

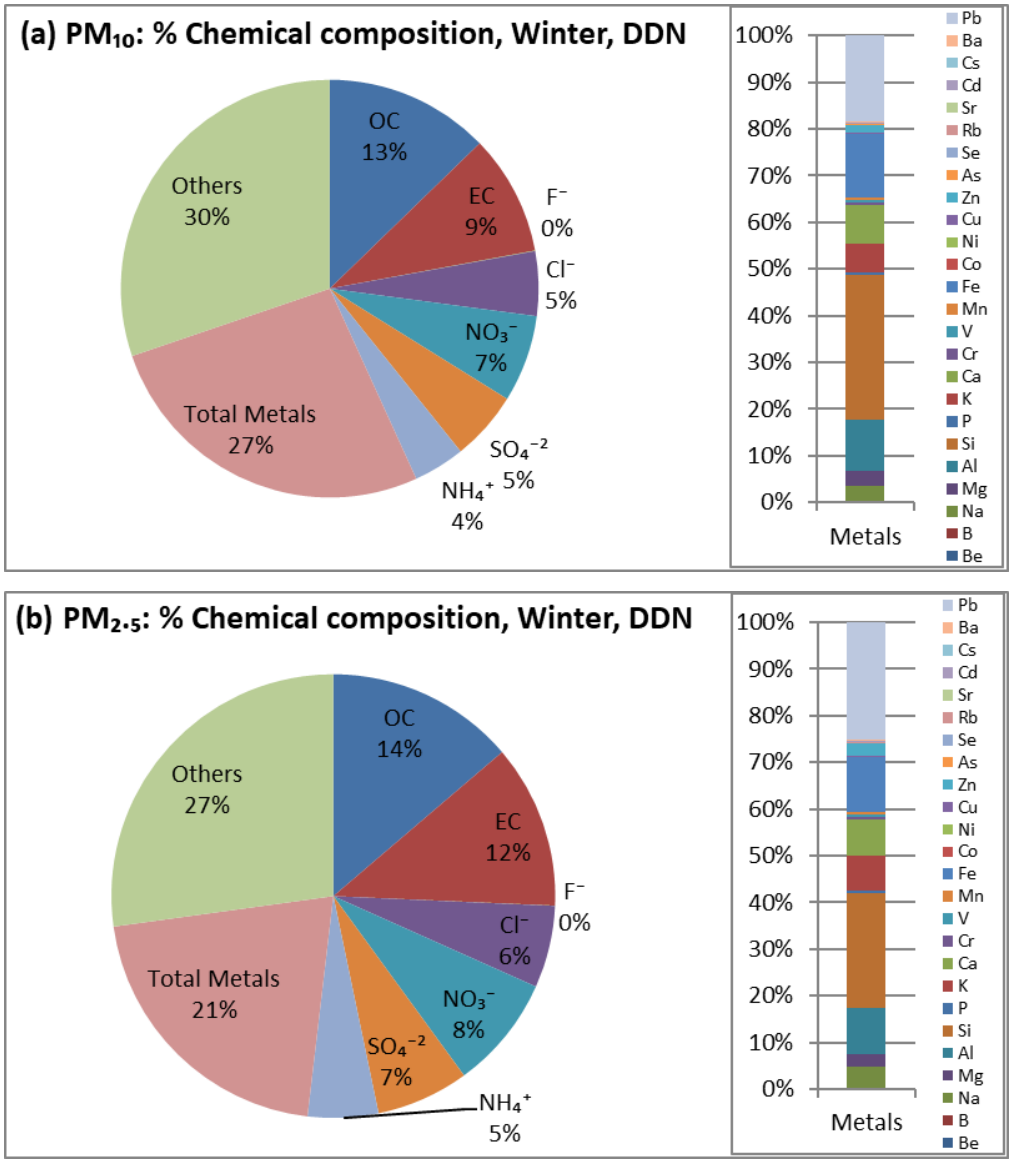


Figure 2.37: Percentage distribution of species in PM at DDN for Winter Season

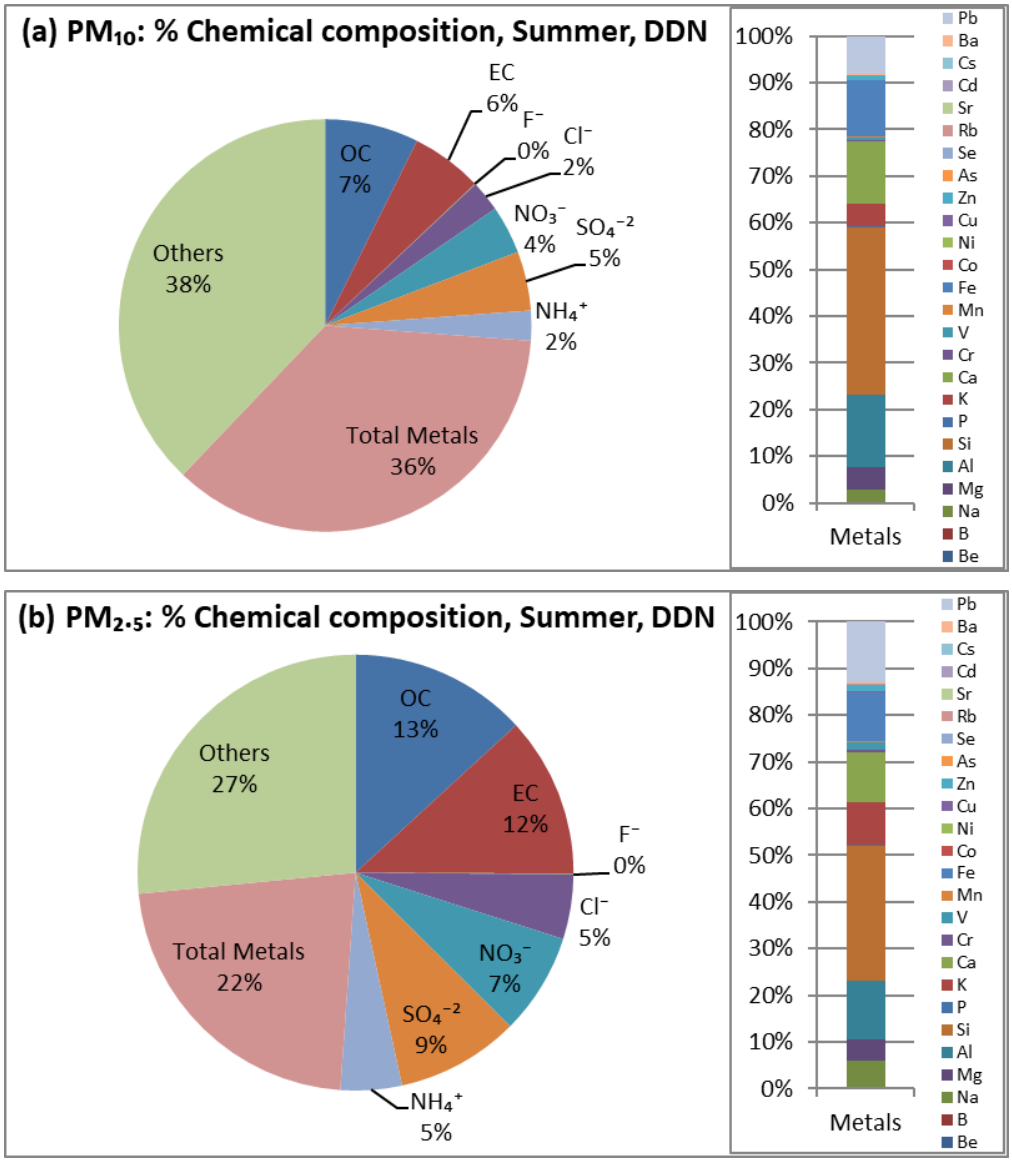


Figure 2.38: Percentage distribution of species in PM at DDN for Summer Season

2.4.3.6 Comparison of PM_{10} and $PM_{2.5}$ Composition

The graphical compositional comparison of $PM_{2.5}$ vs PM_{10} for all species is shown for winter and summer seasons (Figure 2.39) at DDN. The chemical species considered for the comparisons are carbon content (TC, OC and EC), ionic species (F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2}) and elements (Be, B, Na, Mg, Al, Si, P, K, Ca, Cr, V, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, Pb). It is concluded that a significant portion of PM has fine mode during winter (65%) than summer (39%). The major species contributing to fine mode are TC, OC, EC, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Be, V, Cu and Cd; whereas, major species contributing in coarse mode are F^-, Mg^{+2}, Ca^{2+}, Mg, Al, Si, P, Ca, Cr, Fe, Sr and Ba.

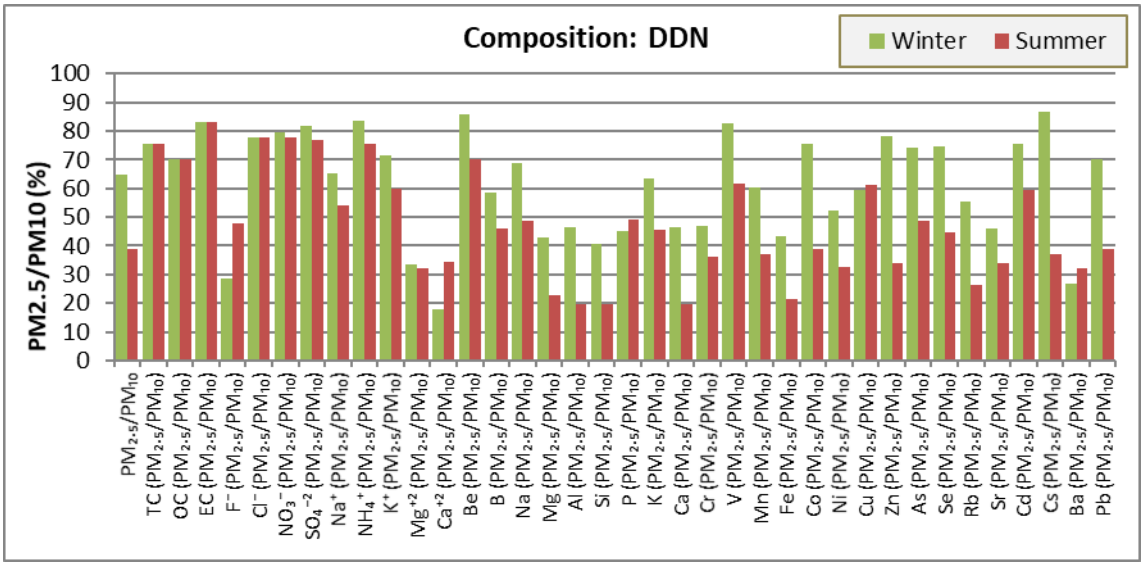


Figure 2.39: Compositional comparison of species in $PM_{2.5}$ Vs PM_{10} at DDN

Table 2.36: Statistical results of gaseous pollutants (µg/m^3) at DDN for winter (W) and summer (S) seasons

DDN (W)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	74.35	20.20	3.96	21.24	1.18	1.30	27.67
SD	7.85	4.36	2.59	12.97	1.86	1.80	14.80
Max	87.96	28.85	11.82	55.82	9.17	7.37	63.66
Min	60.22	14.41	1.38	7.39	0.32	0.05	10.26
CV	0.11	0.22	0.65	0.61	1.58	1.39	0.53
DDN (S)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	36.48	5.64	3.82	40.49	0.38	0.38	45.07
SD	8.80	3.77	3.92	65.22	0.51	0.45	69.44
Max	61.21	14.75	14.22	182.26	1.43	1.31	199.22
Min	26.21	2.00	0.06	0.12	0.01	0.00	0.27
CV	0.24	0.67	1.03	1.61	1.35	1.19	1.54

Table 2.37: Statistical results of carbon contents (µg/m^3) in $PM_{2.5}$ at DDN for winter (W) and summer (S) seasons

DDN (W)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	388.0	99.66	53.37	46.29	5.95	17.18	19.85	10.39	0.055	0.170	0.203	0.111
SD	189.8	36.28	18.70	17.79	3.65	6.99	6.57	2.87	0.017	0.015	0.024	0.026
Max	1036.0	174.05	89.93	84.12	15.56	32.06	34.31	17.01	0.089	0.190	0.263	0.160
Min	186.7	41.19	25.32	15.87	1.78	7.33	8.87	6.58	0.030	0.137	0.160	0.062
CV	0.49	0.36	0.35	0.38	0.61	0.41	0.33	0.28	0.300	0.090	0.116	0.236
DDN (S)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	116.0	29.09	15.29	13.80	0.61	4.73	6.60	3.35	0.018	0.163	0.228	0.128
SD	32.4	10.80	4.79	6.21	0.60	1.74	2.43	1.00	0.013	0.022	0.033	0.051
Max	179.7	58.11	27.81	30.31	2.30	9.38	11.90	5.43	0.041	0.230	0.339	0.240
Min	58.1	14.20	8.56	5.63	0.05	2.20	3.31	0.04	0.003	0.132	0.199	0.001
CV	0.28	0.37	0.31	0.45	0.98	0.37	0.37	0.30	0.748	0.138	0.145	0.397

Table 2.38: Statistical results of PAHs (ng/m^3) in $PM_{2.5}$ at DDN for winter (W) and summer (S) seasons

DDN (W)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	19.62	1.43	0.28	1.33	2.02	3.09	5.22	0.38	8.82	9.01	15.78	12.21	8.08	2.39	15.27	0.00	14.57	119.50
SD	5.56	1.39	0.22	1.07	1.35	1.94	4.01	0.18	25.37	9.35	11.16	8.02	4.68	3.23	10.60	0.00	8.02	64.62
Max	30.34	3.91	0.69	3.42	4.44	6.47	12.53	0.70	85.21	33.09	36.33	28.09	16.07	10.01	33.69	0.00	27.68	257.03
Min	10.13	0.29	0.00	0.16	0.73	0.89	1.06	0.18	0.00	0.28	0.76	1.17	1.66	0.41	2.50	0.00	3.84	40.95
CV	0.28	0.97	0.79	0.80	0.67	0.63	0.77	0.48	2.88	1.04	0.71	0.66	0.58	1.35	0.69	#DIV/0!	0.55	0.54
DDN (S)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	3.75	0.55	0.33	0.21	0.95	1.04	0.10	0.25	0.03	1.70	0.92	4.46	3.93	0.32	4.25	0.02	4.10	26.91
SD	4.35	0.60	0.79	0.48	1.75	1.84	0.14	0.27	0.08	4.04	1.88	4.85	3.52	0.28	9.59	0.05	8.93	23.15
Max	9.38	1.64	2.10	1.30	4.45	5.00	0.34	0.74	0.21	10.87	5.16	10.99	7.95	0.71	25.90	0.14	24.25	76.39
Min	0.17	0.10	0.00	0.00	0.00	0.02	0.00	0.07	0.00	0.16	0.11	0.06	0.05	0.05	0.00	0.00	0.14	1.71
CV	1.16	1.10	2.41	2.25	1.84	1.77	1.35	1.08	2.65	2.37	2.05	1.09	0.90	0.87	2.26	2.65	2.18	0.86

Table 2.39: Statistical results of chemical characterization (µg/m^3) of PM_{10} at DDN for winter (W) season

DDN (W)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	598	76.2	55.8	0.2	29.9	40.3	32.1	3.0	23.8	4.5	0.4	7.8	9E-3	0.25	5.44	5.18	17.14	49.30	0.88
SD	227	26.7	21.4	0.1	12.1	11.1	8.8	1.9	7.5	1.7	0.2	3.2	2E-3	0.10	3.29	3.27	13.34	36.79	0.35
Max	1237	128.5	101.3	0.5	51.8	72.4	52.4	10.2	36.6	8.1	1.0	15.5	1E-2	0.50	16.96	17.00	66.17	182.73	1.55
Min	313	36.2	19.1	0.1	10.4	26.6	17.9	1.2	11.7	2.2	0.2	3.0	6E-3	0.09	1.89	2.06	4.82	17.10	0.40
CV	0.38	0.35	0.38	0.52	0.40	0.27	0.28	0.63	0.31	0.37	0.49	0.41	0.24	0.41	0.60	0.63	0.78	0.75	0.40
DDN (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	9.74	13.28	1.07	0.58	0.75	21.84	0.03	0.06	0.22	2.76	0.16	0.06	0.07	0.10	0.38	0.03	0.40	29.17	70.8
SD	5.06	5.77	0.79	0.22	0.41	13.16	0.01	0.03	0.10	1.23	0.09	0.04	0.03	0.04	0.56	0.01	0.24	21.02	4.9
Max	23.70	27.25	3.90	1.34	1.59	63.98	0.04	0.15	0.41	5.61	0.36	0.14	0.18	0.18	2.34	0.04	0.98	66.97	81.0
Min	3.40	5.92	0.33	0.38	0.15	6.85	0.02	0.03	0.07	0.87	0.04	0.02	0.04	0.06	0.05	0.02	0.09	1.00	60.4
CV	0.52	0.43	0.74	0.37	0.55	0.60	0.25	0.49	0.46	0.45	0.57	0.60	0.48	0.38	1.48	0.21	0.60	0.72	0.07
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.40: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at DDN for winter (W) season

DDN (W)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	388	53.4	46.3	0.1	23.2	32.1	26.2	1.9	19.9	3.2	0.1	1.4	8E-3	0.15	3.74	2.22	7.93	20.07	0.39
SD	190	18.7	17.8	0.1	10.9	10.8	8.2	0.8	6.3	1.4	0.1	1.0	2E-3	0.05	2.02	3.21	10.95	27.38	0.29
Max	1036	89.9	84.1	0.3	47.0	63.4	45.4	4.3	30.4	6.0	0.4	4.8	1E-2	0.26	8.99	15.20	52.41	130.51	1.06
Min	187	25.3	15.9	0.0	8.3	17.3	12.2	0.7	9.9	1.3	0.0	0.2	5E-3	0.07	0.98	0.59	1.84	4.62	0.13
CV	0.49	0.35	0.38	1.18	0.47	0.34	0.31	0.39	0.32	0.43	0.60	0.75	0.25	0.36	0.54	1.45	1.38	1.36	0.73
DDN (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	6.18	6.14	0.50	0.48	0.45	9.49	2E-2	0.03	0.13	2.17	0.12	0.05	0.04	0.05	0.29	3E-2	0.11	20.48	74.8
SD	3.49	4.42	0.75	0.14	0.28	11.24	5E-3	0.02	0.06	0.94	0.06	0.03	0.03	0.02	0.42	7E-3	0.05	14.81	5.3
Max	16.19	21.22	3.53	0.94	1.20	54.08	3E-2	0.12	0.25	4.22	0.20	0.11	0.15	0.11	1.70	4E-2	0.19	49.20	80.9
Min	1.98	2.10	0.12	0.32	0.07	1.80	1E-2	0.02	0.05	0.74	0.04	0.01	0.02	0.03	0.04	2E-2	0.05	0.70	57.6
CV	0.56	0.72	1.49	0.29	0.62	1.18	0.23	0.64	0.43	0.44	0.48	0.54	0.67	0.39	1.47	0.26	0.47	0.72	0.07
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.41: Statistical results chemical characterization (µg/m^3) of PM_{10} at DDN for summer (S) season

DDN (S)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	297	21.8	16.6	0.1	7.2	11.2	13.8	1.7	7.0	2.1	0.9	3.2	3E-3	0.05	3.07	5.19	16.52	38.25	0.16
SD	68	6.8	7.5	0.1	2.9	4.2	5.8	0.4	3.4	0.7	0.4	1.4	3E-4	0.02	0.75	1.56	5.13	11.63	0.06
Max	446	39.7	36.5	0.4	13.2	21.4	22.7	2.6	14.5	4.0	2.0	6.3	4E-3	0.08	4.33	7.59	30.53	70.89	0.27
Min	163	12.2	6.8	0.1	3.2	4.2	5.7	1.0	2.4	1.0	0.3	1.5	3E-3	0.02	1.45	2.91	8.14	18.28	0.06
CV	0.23	0.31	0.45	0.56	0.41	0.37	0.42	0.25	0.49	0.34	0.48	0.45	0.07	0.36	0.25	0.30	0.31	0.30	0.38
DDN (S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	5.07	14.25	0.49	0.58	0.27	12.67	1E-2	0.02	0.06	1.12	0.03	1E-2	1E-2	3E-2	0.05	2E-3	0.12	8.68	62.30
SD	1.35	4.87	0.19	0.18	0.08	3.87	4E-3	0.01	0.03	0.55	0.03	4E-3	7E-3	2E-2	0.03	6E-4	0.06	5.34	3.24
Max	8.05	29.54	0.88	1.11	0.43	24.39	3E-2	0.03	0.11	2.11	0.11	2E-2	3E-2	8E-2	0.10	3E-3	0.29	23.94	69.53
Min	2.79	7.45	0.13	0.36	0.10	7.12	6E-3	0.00	0.02	0.16	0.01	2E-3	4E-3	8E-3	0.01	1E-3	0.03	1.78	56.55
CV	0.27	0.34	0.40	0.31	0.31	0.31	0.32	0.43	0.45	0.49	0.76	0.46	0.48	0.57	0.62	0.30	0.51	0.62	0.05
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.42: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at DDN for summer (S) season

DDN(S)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	116	15.3	13.8	0.1	5.6	8.7	10.6	0.9	5.3	1.2	0.3	1.1	2E-3	0.02	1.50	1.18	3.26	7.54	0.08
SD	32	4.8	6.2	0.0	2.4	3.6	4.6	0.4	2.8	0.5	0.2	0.5	2E-4	0.01	0.59	0.40	1.14	2.95	0.03
Max	180	27.8	30.3	0.1	10.4	18.6	18.6	1.6	12.0	2.0	0.8	2.3	3E-3	0.04	3.19	2.00	6.08	14.68	0.15
Min	58	8.6	5.6	0.0	2.5	3.4	4.2	0.3	1.8	0.5	0.1	0.3	2E-3	0.01	0.62	0.60	1.50	3.13	0.03
CV	0.28	0.31	0.45	0.49	0.43	0.41	0.43	0.40	0.53	0.37	0.53	0.48	0.09	0.43	0.40	0.34	0.35	0.39	0.41
DDN(S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	2.30	2.78	0.18	0.36	0.10	2.70	5E-3	5E-3	0.03	0.38	0.02	4E-3	4E-3	1E-2	0.03	7E-4	0.04	3.39	73.47
SD	0.74	0.99	0.10	0.09	0.05	1.15	2E-3	3E-3	0.02	0.17	0.01	2E-3	1E-3	5E-3	0.02	2E-4	0.02	1.69	2.65
Max	3.53	4.84	0.39	0.57	0.20	5.51	8E-3	1E-2	0.07	0.77	0.04	1E-2	7E-3	2E-2	0.07	1E-3	0.08	6.80	77.89
Min	0.92	1.14	0.04	0.18	0.01	1.08	1E-3	4E-4	0.01	0.14	0.01	5E-4	1E-3	3E-3	0.00	4E-4	0.01	0.91	68.55
CV	0.32	0.36	0.57	0.26	0.52	0.42	0.31	0.62	0.56	0.45	0.52	0.56	0.35	0.47	0.76	0.34	0.46	0.50	0.04
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.43: Correlation matrix for PM_{10} and its composition at DDN for winter season

DDN (W)	1.00	0.63	0.64	0.60	0.65	0.81	0.29	0.20	0.31	0.35	0.82	0.50	0.87	0.96
PM_{10}		1.00	1.00	0.99	0.17	0.43	0.25	0.00	-0.17	0.20	0.69	0.22	0.44	0.47
TC			1.00	0.98	0.15	0.45	0.28	0.03	-0.15	0.22	0.72	0.24	0.45	0.48
OC				1.00	0.19	0.40	0.21	-0.03	-0.21	0.18	0.66	0.19	0.41	0.44
EC					-0.12	0.31	1.00	0.88	0.30	0.66	0.41	0.11	0.25	0.14
NO_3^-					0.00	0.39		1.00	0.52	0.80	0.32	0.26	0.22	0.07
SO_4^{-2}					0.30	0.53			0.53	1.00	0.44	0.44	0.44	0.20
NH_4^+					0.71	0.74			0.32		0.70	0.51	0.86	1.00
Metals	1.00	0.63	0.64	0.60	0.65	0.81	0.29	0.20	0.31	0.35	0.82	0.50	0.87	0.96

Table 2.44: Correlation matrix for $PM_{2.5}$ and its composition at DDN for winter season

DDN (W)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.57	0.59	0.54	0.34	0.80	0.32	0.20	0.42	0.39	0.70	0.13	0.67	0.96
TC		1.00	0.99	0.99	-0.04	0.41	0.27	0.09	0.13	0.23	0.62	0.32	0.08	0.37
OC			1.00	0.98	-0.03	0.42	0.30	0.13	0.17	0.25	0.65	0.34	0.06	0.39
EC				1.00	-0.05	0.40	0.24	0.06	0.10	0.20	0.58	0.29	0.09	0.34
NO_3^-					0.45	0.41	1.00	0.91	0.44	0.76	0.38	0.31	-0.02	0.14
SO_4^{-2}					0.57	0.44		1.00	0.49	0.89	0.36	0.20	0.02	0.03
NH_4^+					0.69	0.65			0.57	1.00	0.53	0.07	0.19	0.21
Metals					0.29	0.71			0.37		0.57	0.03	0.71	1.00

Table 2.45: Correlation matrix for PM_{10} and its composition at DDN for summer season

DDN (S)	PM_{10}	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
PM_{10}	1.00	0.42	0.36	0.46	0.55	0.36	0.50	0.53	0.40	0.45	0.07	0.14	0.55	0.92
TC		1.00	0.98	0.98	-0.03	0.58	0.20	0.29	0.16	0.35	0.40	0.12	0.28	0.09
OC			1.00	0.93	-0.01	0.55	0.13	0.23	0.13	0.26	0.37	0.07	0.25	0.04
EC				1.00	-0.05	0.58	0.26	0.34	0.18	0.42	0.42	0.16	0.31	0.13
NO_3^-					0.28	0.33	1.00	0.84	0.14	0.81	0.12	0.14	0.42	0.32
SO_4^{-2}					0.45	0.25		1.00	0.08	0.91	0.10	0.10	0.56	0.31
NH_4^+					0.20	0.26			-0.08	1.00	0.08	0.07	0.48	0.23
Metals					0.54	0.16			0.40		-0.10	0.08	0.44	1.00

Table 2.46: Correlation matrix for $PM_{2.5}$ and its composition DDN for summer season

DDN (S)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.74	0.67	0.78	0.44	0.70	0.63	0.69	0.63	0.68	0.53	0.03	0.80	0.83
TC		1.00	0.98	0.99	0.36	0.55	0.19	0.32	0.44	0.35	0.29	-0.04	0.44	0.39
OC			1.00	0.93	0.36	0.51	0.11	0.26	0.36	0.26	0.24	-0.04	0.36	0.30
EC				1.00	0.35	0.57	0.25	0.36	0.48	0.41	0.32	-0.04	0.49	0.44
NO_3^-					0.37	0.37	1.00	0.84	0.28	0.81	0.17	0.15	0.67	0.46
SO_4^{-2}					0.38	0.30		1.00	0.15	0.92	0.15	0.16	0.62	0.42
NH_4^+					0.40	0.31			0.11	1.00	0.09	0.06	0.74	0.40
Metals					0.20	0.56			0.74		0.67	0.00	0.73	1.00

2.4.4 Jarib Chowki (JRC)

The sampling period was January 20 – February 11, 2019 for winter and June 07 – 26, 2019 for summer.

2.4.4.1 Particulate Matter (PM_{10}, $PM_{2.5}$)

Time series of 24-hr average concentrations of PM_{10} and $PM_{2.5}$ are shown for winter (Figure 2.40) and summer (Figure 2.41). Average levels for winter and summer season were 186±46 and 57±21 µg/m^3 (for $PM_{2.5}$) and 287±86 and 133±53 µg/m^3 (for PM_{10}) respectively. The $PM_{2.5}$ levels are 3.1 times higher than the NAQS and PM_{10} levels are 2.9 times higher than the NAQS in winter. The $PM_{2.5}$ levels generally meet the standards, while PM_{10} is slightly exceeded by 1.3 times than the NAQS. A statistical summary of PM concentrations is presented in Tables 2.50 – 2.53 for the winter and summer seasons. In summer, $PM_{2.5}$ levels drop significantly and meet the national standards. PM_{10} levels also decreased but slightly exceed NAQS. The particles airborne from the soil surface during dust storms in the dry months of summer can contribute significantly to a coarse fraction.

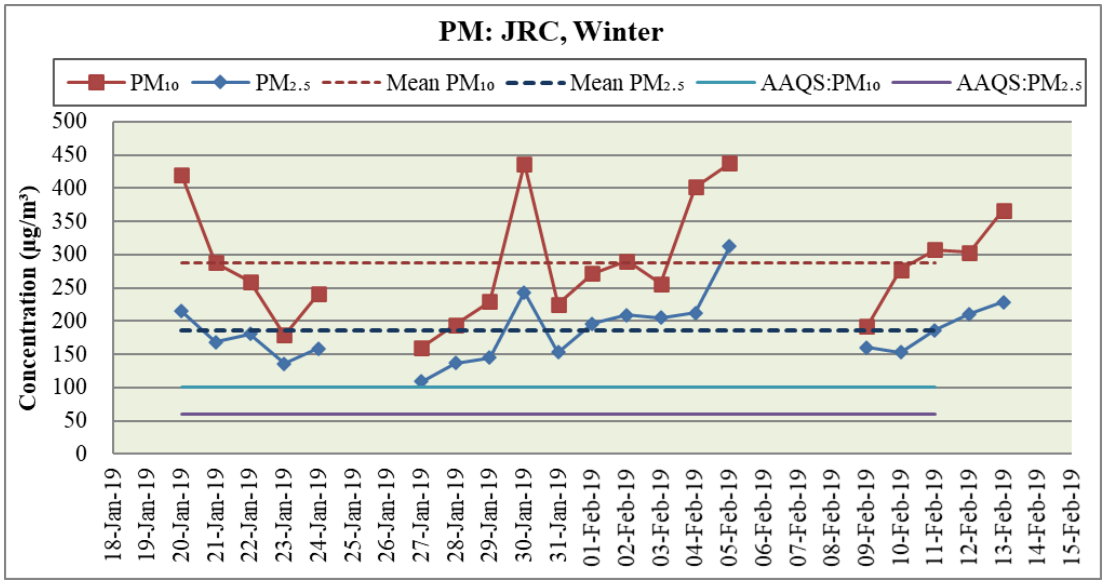


Figure 2.40: PM Concentrations at JRC for Winter Season

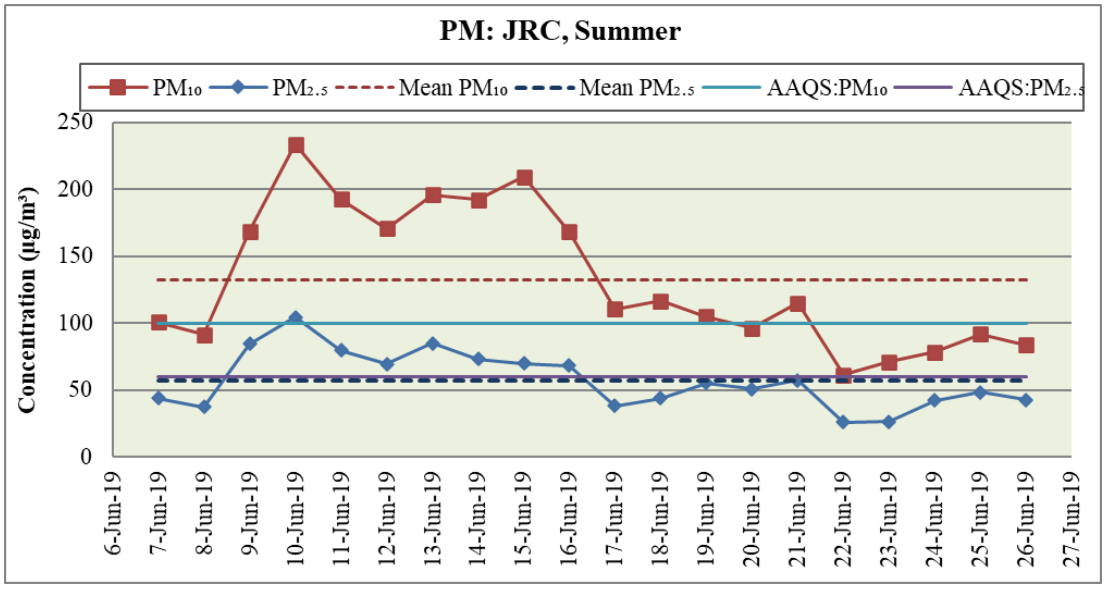


Figure 2.41: PM Concentrations at JRC for Summer Season

2.4.4.2 Gaseous pollutants

Time series of 24-hr average concentrations of SO_2 and NO_2 are shown for winter (Figure 2.42) and summer (Figure 2.43) seasons. It was observed that SO_2 concentrations were low (mostly < 6.0 µg/m^3) and met the air quality standard. NO_2 levels also under the national standard with an average of 20 days at 51.2±11.0 µg/m^3 in winter and 36.3±5.5 µg/m^3 in summer season (Table 2.47). The summer concentration of NO_2 dropped significantly. Although the NO_2 is certainly a matter of concern, these values can largely be attributed to vehicular pollution and DG sets. Variation in NO_2 is due to variability in meteorology and the presence of occasional local sources like DG sets, traffic jams or local open burning etc.

The Mean concentrations of BTX were presented in Figure 2.44 and the statistical summary in Table 2.47. The total BTX level is observed 14.2±10.5 µg/m^3 (Benzene: 4.7 and Toluene: 7.9 µg/m^3) in winter and 7.7±1.5 µg/m^3 (Benzene: 2.3 and Toluene: 3.1 µg/m^3) in summer seasons. The BTX levels were high during winter than in the summer.

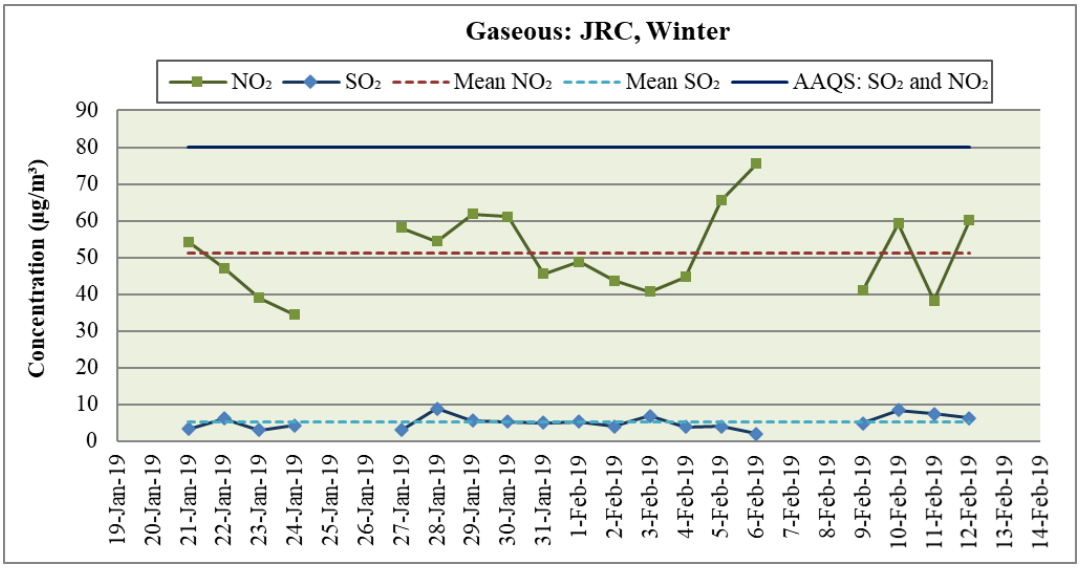


Figure 2.42: SO_2 and NO_2 Concentrations at JRC for Winter Season

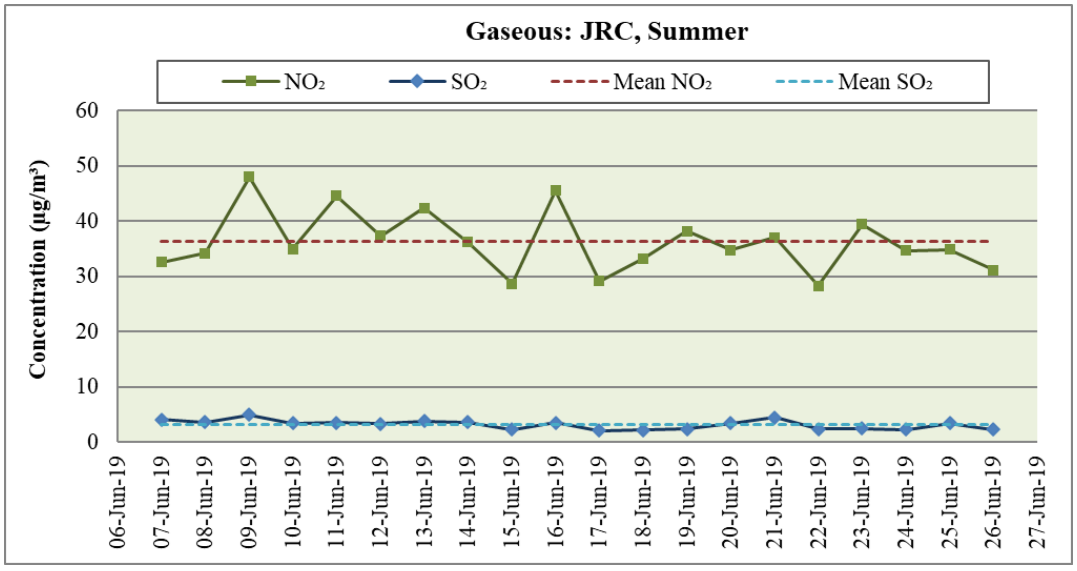


Figure 2.43: SO_2 and NO_2 Concentrations at JRC for Summer Season

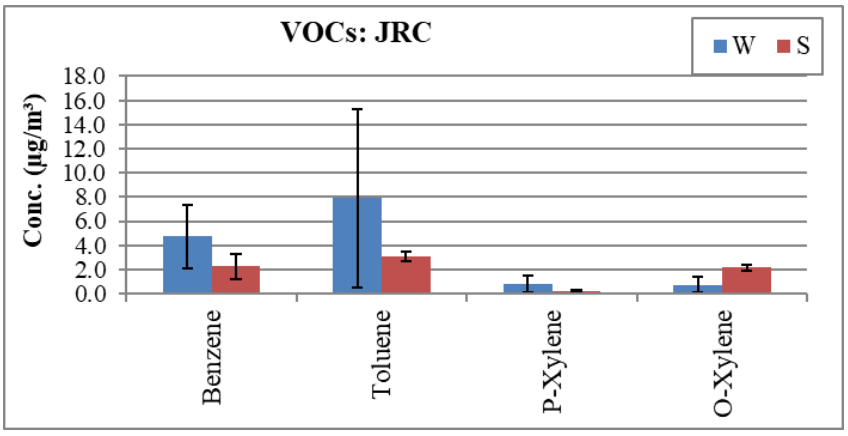


Figure 2.44: VOCs concentration at JRC

2.4.4.3 Carbon Content (EC/OC) in $PM_{2.5}$

Average concentrations of EC, OC (OC1, OC2, OC3 and OC4) and the ratio of OC fraction to TC are shown in Figure 2.45 (a) and (b) for winter and summer seasons. OC is observed higher (winter: 71.1±18.4 and summer: 8.8±2.9 µg/m^3) than the EC (winter: 60.8±15.2 and summer: 6.8±2.6 µg/m^3). It is also observed that the OC and EC are higher in the winter season than in the summer season. A statistical summary of carbon content (TC, EC, OC; OC1, OC2, OC3 and OC4 with fractions OC1/TC, OC2/TC, OC3/TC and OC4/TC) is presented in Table 2.48 for winter and summer seasons. The ratio of OC3/TC is observed higher that indicating the formation of secondary organic carbon in the atmosphere at JRC.

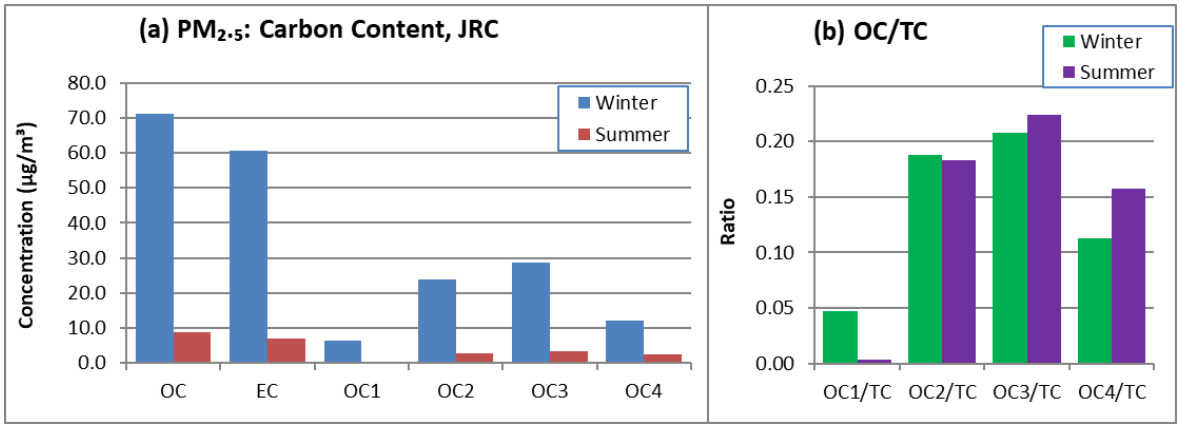


Figure 2.45: EC and OC Content in $PM_{2.5}$ at JRC

2.4.4.4 PAHs in $PM_{2.5}$

Figure 2.46 shows the average measured concentration of PAHs at JRC for winter and summer seasons. A statistical summary of PAHs is presented in Table 2.49 for winter and summer seasons. The PAHs compounds analyzed were: (i) DmP, (ii) AcP, (iii) DEP, (iv) Flu, (v) Phe, (vi) Ant, (vii) Pyr, (viii) BbP, (ix) BeA, (x) B(a)A, (xi) Chr, (xii) B(b)F, (xiii) B(k)F, (xiv) B(a)P, (xv) InP, (xvi) D(a,h)A and (xvii) B(ghi)P. It is observed that Total PAHs concentrations are much higher in winter season (100±56 ng/m^3) compared to summer season (37±14 ng/m^3). Major PAHs are InP (16.8 ng/m^3), B(ghi)P (16.5 ng/m^3), B(b)F (9.9 ng/m^3), B(k)F (9.7 ng/m^3) and BeA (7.0 ng/m^3) for winter season and DmP (12.3 ng/m^3), Ant (5.7 ng/m^3), Flu (3.7 ng/m^3), Phe (3.5 ng/m^3) and B(b)F (2.7 ng/m^3) for summer season.

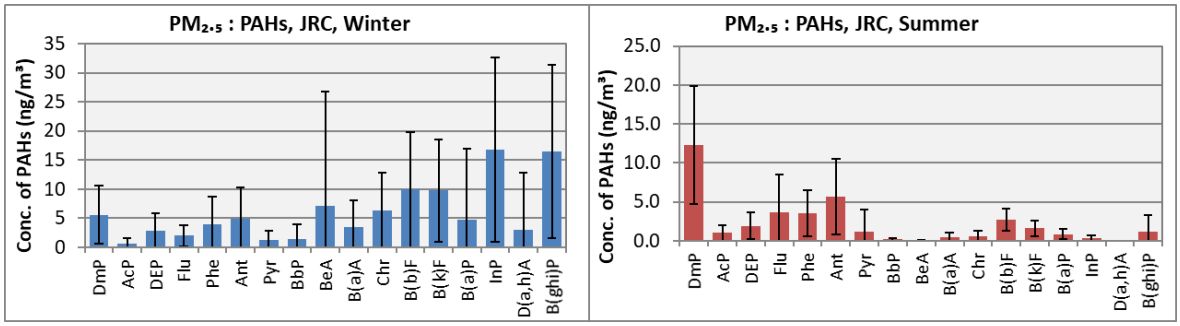


Figure 2.46: PAHs Concentrations in $PM_{2.5}$ at JRC

2.4.4.5 Chemical Composition of PM_{10} and $PM_{2.5}$ and their correlation matrix

Graphical presentations of chemical species are shown for the winter and summer season at JRC for PM_{10} (Figure 2.47) and $PM_{2.5}$ (Figure 2.48). Statistical summary for particulate matter (PM_{10} and $PM_{2.5}$), its chemical composition [carbon content, ionic species and elements] along with mass percentage (% R) recovered from PM are presented in Tables 2.50 – 2.53 for winter and summer season.

The correlation between different parameters (i.e., PM, TC, OC, EC, F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2} and Metals (elements)) with major species (PM, TC, OC, EC, NO_3^-, SO_4^{-2}, NH_4^+, Metals) for PM_{10} and $PM_{2.5}$ composition is presented in Tables 2.54 – 2.57 for both seasons. It is seen that most of the parameters showed a good correlation (>0.30) with PM_{10} and $PM_{2.5}$. The percentage constituents of the PM are presented in Figure 2.49 (a) and (b) for the winter season and Figure 2.50 (a) and (b) for the summer season.

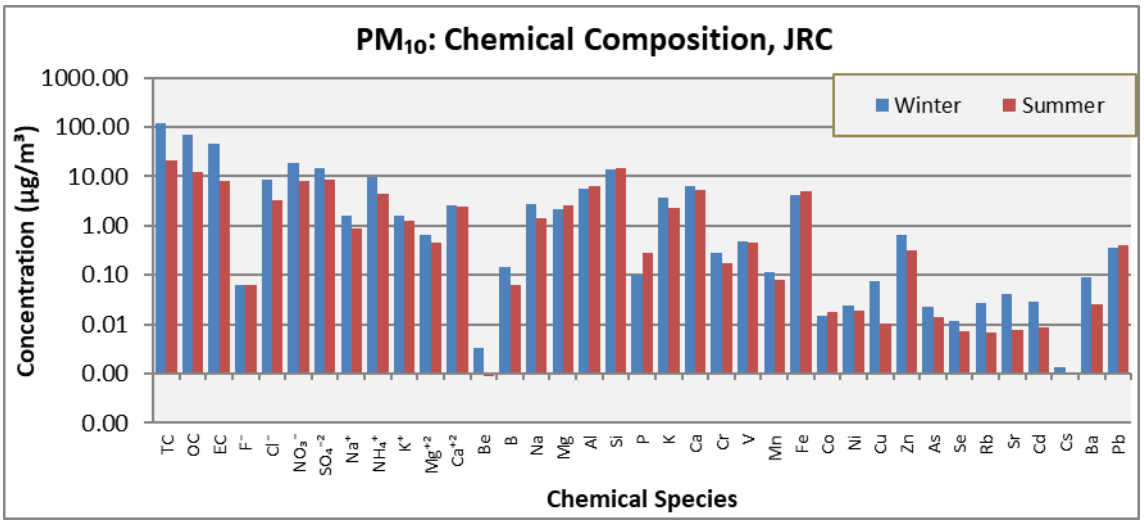


Figure 2.47: Concentrations of species in PM_{10} at JRC

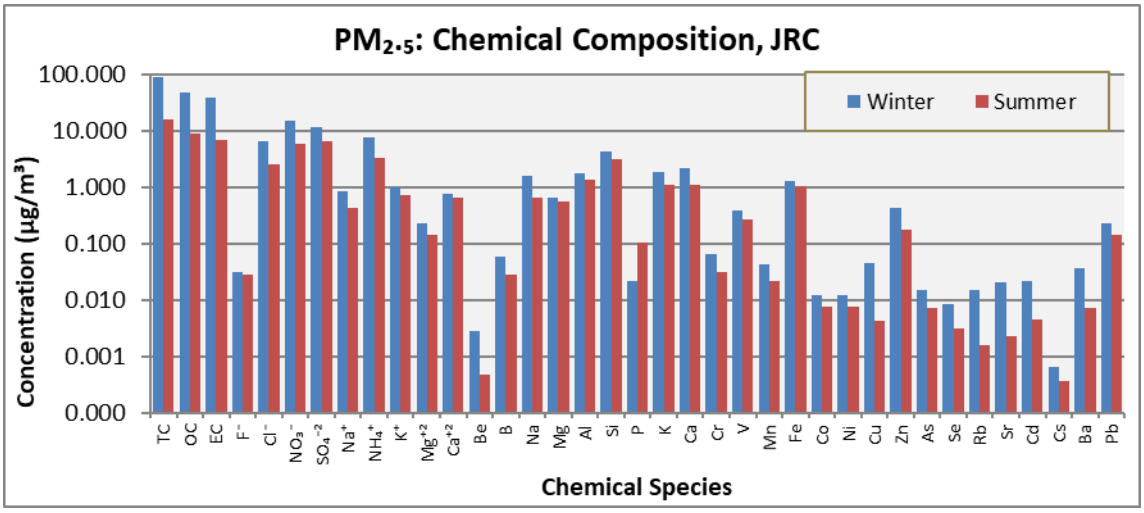


Figure 2.48: Concentrations of species in $PM_{2.5}$ at JRC

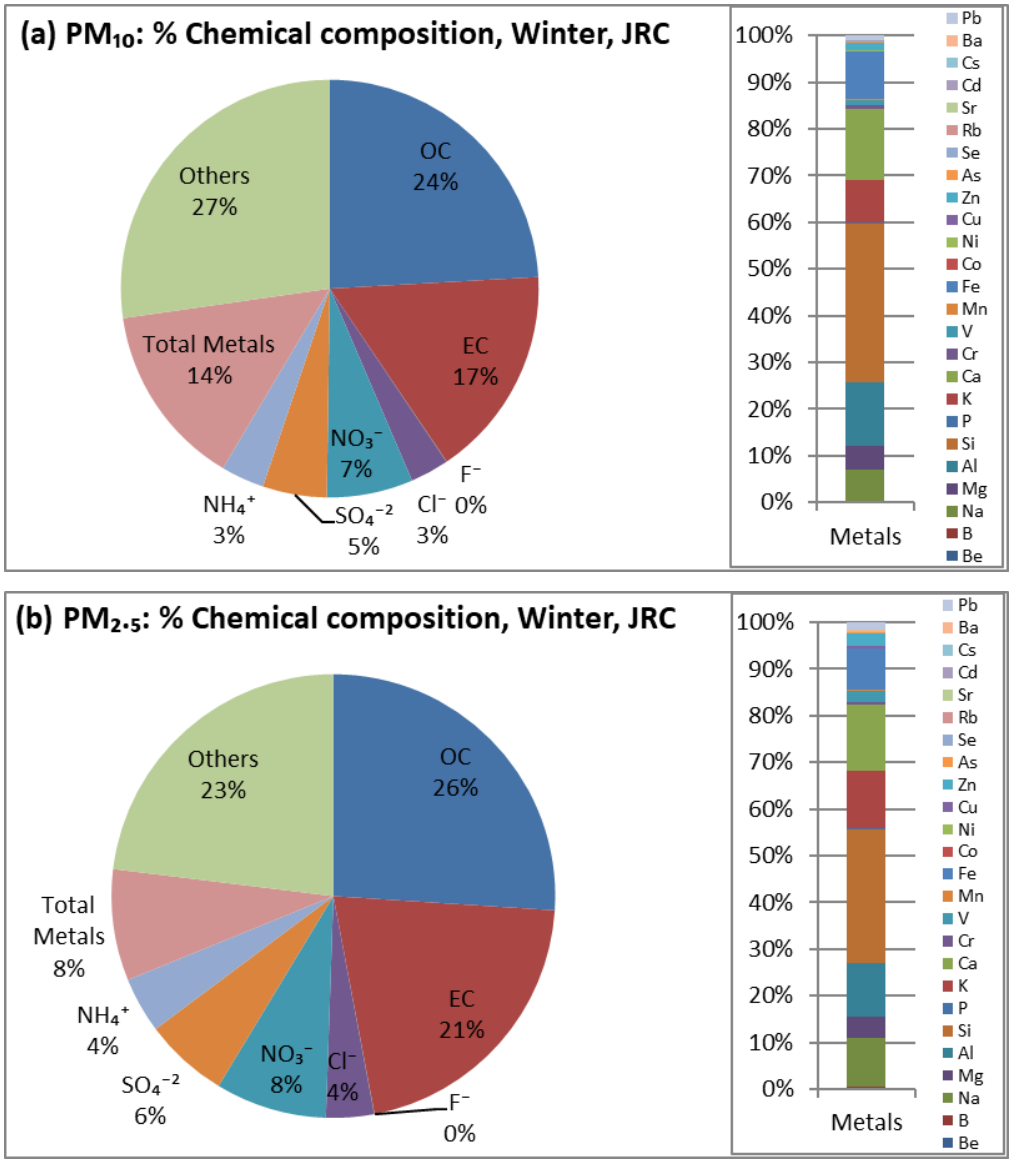


Figure 2.49: Percentage distribution of species in PM at JRC for Winter Season

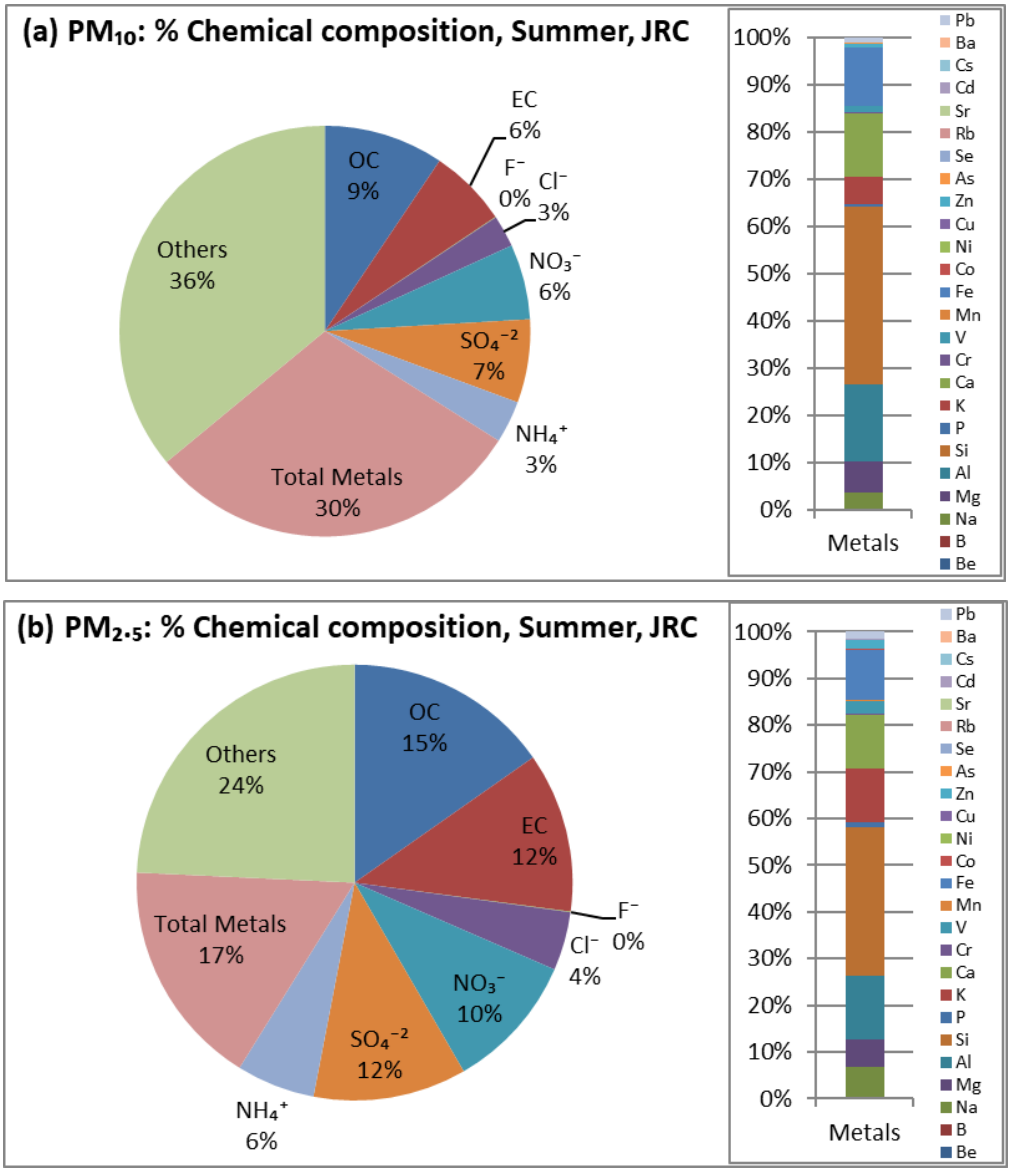


Figure 2.50: Percentage distribution of species in PM at JRC for Summer Season

2.4.4.6 Comparison of PM_{10} and $PM_{2.5}$ Composition

The graphical compositional comparison of $PM_{2.5}$ vs PM_{10} for all species is shown for winter and summer seasons (Figure 2.51) at JRC. The chemical species considered for the comparisons are carbon content (TC, OC and EC), ionic species (F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2}) and elements (Be, B, Na, Mg, Al, Si, P, K, Ca, Cr, V, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, Pb). It is concluded that most portion of PM has fine mode during winter (65%) than summer (43%). The major species contributing to fine mode are TC, OC, EC, F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Be, V, Zn, As and Cd; whereas major species contributing in coarse mode are Ca^{+2}, Mg^{+2}, B, Mg, Al, Si, P, Ca, Cr, Mn, Fe, Sr and Ba.

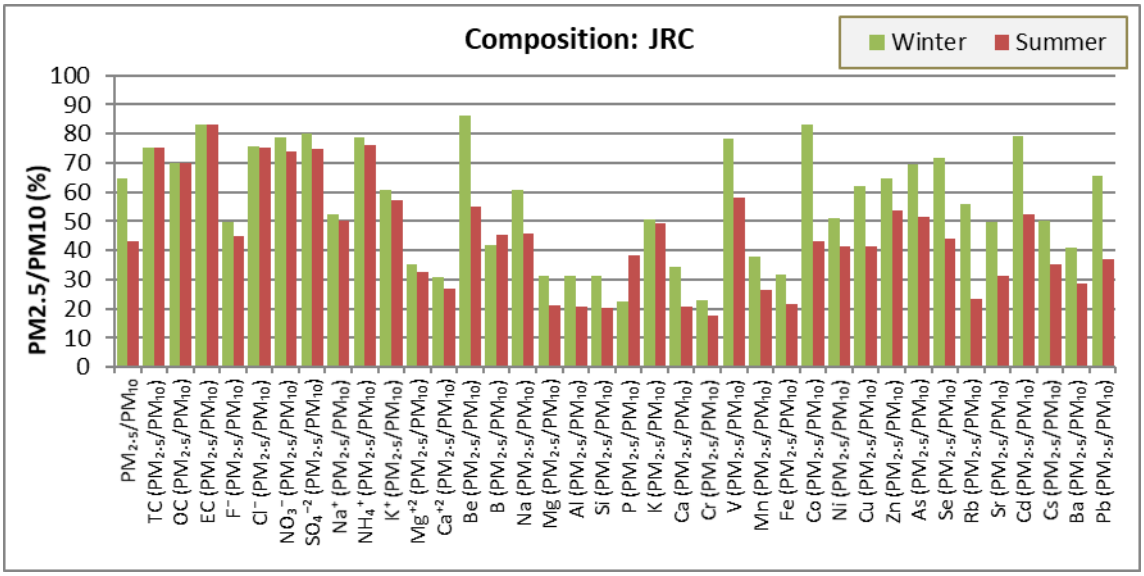


Figure 2.51: Compositional comparison of species in $PM_{2.5}$ Vs PM_{10} at JRC

Table 2.47: Statistical results of gaseous pollutants (µg/m^3) at JRC for winter (W) and summer (S) seasons

JRC (W)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	51.19	5.08	4.72	7.91	0.81	0.74	14.18
SD	11.04	1.88	2.64	7.37	0.66	0.62	10.55
Max	75.56	8.87	11.15	23.20	2.49	2.22	36.88
Min	34.40	2.00	1.13	0.16	0.04	0.02	2.32
CV	0.22	0.37	0.56	0.93	0.82	0.83	0.74
JRC (S)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	36.26	3.21	2.28	3.06	0.24	2.17	7.75
SD	5.51	0.84	1.03	0.42	0.05	0.24	1.51
Max	47.98	5.01	6.23	4.22	0.41	2.71	13.57
Min	28.30	2.12	1.59	2.38	0.17	1.63	6.19
CV	0.15	0.26	0.45	0.14	0.21	0.11	0.19

Table 2.48: Statistical results of carbon contents (µg/m^3) in $PM_{2.5}$ at JRC for winter (W) and summer (S) seasons

JRC (W)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	186.2	131.86	71.08	60.79	6.47	23.97	28.72	11.92	0.047	0.187	0.208	0.113
SD	46.2	33.28	18.39	15.19	2.86	6.53	6.75	3.08	0.018	0.011	0.013	0.022
Max	312.7	165.40	94.15	71.25	11.80	32.52	33.21	16.61	0.085	0.210	0.249	0.154
Min	109.2	22.74	13.65	9.10	0.78	4.45	4.91	3.51	0.014	0.169	0.187	0.075
CV	0.25	0.25	0.26	0.25	0.44	0.27	0.24	0.26	0.389	0.061	0.065	0.194
JRC (S)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	57.4	15.56	8.76	6.80	0.06	2.84	3.44	2.42	0.004	0.183	0.224	0.158
SD	21.2	5.25	2.91	2.56	0.07	1.00	1.18	0.76	0.004	0.015	0.027	0.015
Max	104.3	28.70	18.21	12.19	0.19	5.83	7.41	4.93	0.013	0.209	0.275	0.184
Min	26.1	8.35	5.12	3.23	0.00	1.51	2.15	1.36	0.000	0.163	0.186	0.127
CV	0.37	0.34	0.33	0.38	1.06	0.35	0.34	0.32	1.102	0.081	0.122	0.097

Table 2.49: Statistical results of PAHs (ng/m^3) in $PM_{2.5}$ at JRC for winter (W) and summer (S) seasons

JRC (W)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	5.58	0.62	2.77	2.02	4.00	4.84	1.19	1.37	7.04	3.49	6.26	9.94	9.75	4.66	16.76	2.96	16.46	99.74
SD	5.02	0.87	3.10	1.82	4.65	5.47	1.58	2.55	19.80	4.58	6.61	9.92	8.81	12.27	15.88	9.81	14.92	55.72
Max	18.21	2.87	7.58	5.29	14.18	13.98	4.90	8.93	66.61	12.16	16.45	28.69	27.41	41.60	47.62	32.55	43.67	174.57
Min	0.87	0.11	0.00	0.24	0.00	0.02	0.00	0.13	0.01	0.17	0.19	0.50	0.74	0.05	0.45	0.00	0.14	33.20
CV	0.90	1.41	1.12	0.90	1.16	1.13	1.33	1.85	2.81	1.31	1.06	1.00	0.90	2.63	0.95	3.32	0.91	0.56
JRC (S)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	12.30	1.04	1.90	3.70	3.55	5.66	1.15	0.18	0.04	0.45	0.54	2.68	1.61	0.86	0.34	0.00	1.20	37.20
SD	7.54	1.00	1.69	4.77	2.98	4.85	2.87	0.17	0.11	0.63	0.69	1.44	1.01	0.64	0.41	0.00	2.05	13.88
Max	30.82	2.93	4.85	14.74	7.56	15.09	9.28	0.65	0.36	2.13	1.96	5.77	2.96	2.02	1.05	0.00	6.74	57.77
Min	4.58	0.12	0.00	0.00	0.00	0.02	0.00	0.07	0.00	0.16	0.11	0.69	0.05	0.05	0.00	0.00	0.14	17.55
CV	0.61	0.97	0.89	1.29	0.84	0.86	2.50	0.95	3.16	1.38	1.28	0.54	0.63	0.75	1.19	--	1.70	0.37

Table 2.50: Statistical results of chemical characterization (µg/m^3) of PM_{10} at JRC for winter (W) season

JRC (W)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	287	69.2	47.1	0.1	8.6	19.2	14.2	1.6	9.6	1.6	0.7	2.5	3E-3	0.14	2.66	2.10	5.57	13.88	0.10
SD	86	26.3	18.3	0.1	4.4	7.8	7.1	0.5	4.7	0.5	0.2	1.3	6E-4	0.12	1.15	1.19	2.92	7.28	0.05
Max	438	134.5	85.8	0.2	20.9	38.6	34.0	2.5	22.0	2.8	1.0	5.4	5E-3	0.43	5.32	6.33	14.67	37.11	0.24
Min	160	19.5	11.0	0.0	3.1	7.8	5.4	0.8	3.5	0.6	0.3	1.0	3E-3	0.02	1.14	0.79	1.68	5.25	0.02
CV	0.30	0.38	0.39	0.80	0.52	0.41	0.50	0.31	0.49	0.32	0.33	0.51	0.17	0.82	0.43	0.57	0.52	0.52	0.54
JRC (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	3.68	6.24	0.29	0.48	0.11	4.14	0.01	0.02	0.07	0.66	0.02	0.01	0.03	0.04	0.03	1E-3	0.09	0.36	73.3
SD	1.20	3.04	0.15	0.15	0.04	2.13	0.00	0.01	0.03	0.23	0.01	0.00	0.01	0.01	0.01	4E-4	0.04	0.22	3.6
Max	5.55	14.70	0.52	0.93	0.20	10.65	0.02	0.05	0.13	1.25	0.04	0.02	0.04	0.06	0.06	2E-3	0.19	0.75	78.3
Min	1.19	2.08	0.06	0.14	0.06	1.28	0.01	0.01	0.03	0.34	0.01	0.01	0.01	0.02	0.01	5E-4	0.02	0.14	64.8
CV	0.33	0.49	0.53	0.31	0.34	0.51	0.19	0.44	0.35	0.35	0.36	0.31	0.26	0.26	0.42	0.29	0.48	0.62	0.05
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.51: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at JRC for winter (W) season

JRC (W)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	186	48.5	39.1	0.0	6.5	15.1	11.4	0.8	7.6	1.0	0.2	0.8	3E-3	0.06	1.61	0.65	1.75	4.35	0.02
SD	46	18.4	15.2	0.0	3.4	6.8	6.1	0.4	4.0	0.5	0.1	0.4	7E-4	0.03	1.03	0.49	1.05	2.52	0.01
Max	313	94.1	71.2	0.1	16.5	31.4	27.0	1.7	18.2	2.1	0.4	1.7	5E-3	0.13	4.92	2.33	5.16	11.88	0.04
Min	109	13.6	9.1	0.0	2.5	6.2	4.0	0.4	3.1	0.3	0.1	0.3	2E-3	0.02	0.72	0.31	0.84	2.00	0.01
CV	0.25	0.38	0.39	0.72	0.53	0.45	0.53	0.46	0.53	0.46	0.35	0.50	0.24	0.49	0.64	0.75	0.60	0.58	0.32
JRC (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	1.86	2.16	0.07	0.38	0.04	1.31	1E-2	0.01	0.05	0.43	0.02	8E-3	2E-2	2E-2	0.02	7E-4	0.04	0.24	76.8
SD	0.63	1.33	0.04	0.10	0.02	0.92	2E-3	0.01	0.02	0.15	0.01	3E-3	3E-3	4E-3	0.01	1E-4	0.02	0.14	2.6
Max	2.92	6.68	0.21	0.67	0.13	4.52	2E-2	0.04	0.09	0.87	0.03	1E-2	2E-2	3E-2	0.04	1E-3	0.07	0.57	81.6
Min	0.76	0.85	0.01	0.12	0.02	0.53	1E-2	0.01	0.02	0.20	0.01	4E-3	8E-3	1E-2	0.01	3E-4	0.02	0.10	71.0
CV	0.34	0.62	0.58	0.26	0.54	0.70	0.13	0.55	0.37	0.36	0.40	0.33	0.20	0.21	0.42	0.21	0.43	0.59	0.03
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.52: Statistical results chemical characterization (µg/m^3) of PM_{10} at JRC for summer (S) season

JRC (S)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	133	12.5	10.5	0.1	3.3	7.9	8.7	0.9	4.4	1.2	0.4	2.5	9E-4	0.06	1.39	2.61	6.49	15.00	0.28
SD	53	4.2	3.5	0.0	1.5	3.9	4.4	0.4	1.9	0.5	0.3	1.1	4E-4	0.03	0.80	1.49	3.30	7.73	0.11
Max	234	26.0	21.9	0.1	7.0	14.7	17.3	2.1	7.9	2.3	1.3	5.0	2E-3	0.15	3.46	5.29	12.86	30.01	0.57
Min	61	7.3	6.2	0.0	1.2	2.3	2.9	0.4	1.4	0.5	0.1	1.3	5E-4	0.03	0.51	0.80	2.64	6.55	0.13
CV	0.40	0.33	0.33	0.57	0.45	0.49	0.51	0.48	0.44	0.44	0.61	0.44	0.40	0.47	0.57	0.57	0.51	0.52	0.41
JRC (S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	2.26	5.35	0.18	0.45	0.08	4.87	2E-2	0.02	0.01	0.32	0.01	7E-3	7E-3	7E-3	0.01	1E-3	0.03	0.39	66.39
SD	0.88	2.70	0.09	0.12	0.04	2.54	1E-2	0.01	0.01	0.12	0.01	3E-3	3E-3	4E-3	0.00	4E-4	0.02	0.31	2.95
Max	3.80	10.94	0.33	0.74	0.16	10.55	5E-2	0.05	0.03	0.56	0.03	1E-2	1E-2	2E-2	0.02	2E-3	0.06	1.16	72.49
Min	0.93	2.22	0.06	0.25	0.02	1.97	6E-3	0.01	0.00	0.12	0.00	2E-3	2E-3	3E-3	0.00	4E-4	0.00	0.05	63.01
CV	0.39	0.51	0.49	0.27	0.54	0.52	0.62	0.49	0.66	0.38	0.45	0.42	0.51	0.48	0.43	0.40	0.64	0.79	0.04
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.53: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at JRC for summer (S) season

JRC (S)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	57	8.8	6.8	0.0	2.5	5.8	6.5	0.4	3.3	0.7	0.1	0.7	5E-4	0.03	0.64	0.55	1.34	3.07	0.11
SD	21	2.9	2.6	0.0	1.1	2.9	3.4	0.2	1.5	0.3	0.1	0.4	2E-4	0.02	0.31	0.33	0.77	1.70	0.05
Max	104	18.2	12.2	0.1	5.1	10.8	13.5	0.9	6.1	1.6	0.3	1.4	1E-3	0.08	1.30	1.40	3.38	7.58	0.24
Min	26	5.1	3.2	0.0	0.9	1.6	2.2	0.1	1.1	0.3	0.0	0.1	3E-4	0.01	0.19	0.19	0.54	1.28	0.04
CV	0.37	0.33	0.38	0.35	0.45	0.49	0.53	0.47	0.43	0.49	0.41	0.55	0.31	0.67	0.48	0.60	0.57	0.55	0.49
JRC (S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	1.12	1.10	0.03	0.26	0.02	1.05	8E-3	8E-3	0.00	0.17	0.01	3E-3	2E-3	2E-3	0.00	4E-4	0.01	0.15	76.00
SD	0.38	0.60	0.02	0.08	0.01	0.54	5E-3	2E-3	0.00	0.06	0.00	2E-3	1E-3	9E-4	0.00	1E-4	0.01	0.14	2.54
Max	1.64	2.71	0.09	0.36	0.05	2.52	3E-2	1E-2	0.01	0.29	0.02	6E-3	5E-3	5E-3	0.01	8E-4	0.02	0.47	82.51
Min	0.51	0.45	0.01	0.08	0.01	0.48	2E-3	3E-3	0.00	0.09	0.00	6E-4	4E-4	9E-4	0.00	1E-4	0.00	0.02	72.15
CV	0.34	0.55	0.56	0.29	0.42	0.52	0.73	0.30	0.52	0.35	0.67	0.66	0.63	0.38	0.65	0.37	0.75	1.00	0.03
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.54: Correlation Matrix for PM_{10} and its composition at JRC for winter season

JRC (W)	PM_{10}	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
PM_{10}	1.00	0.77	0.76	0.76	0.19	0.59	0.38	0.39	0.49	0.48	0.50	0.23	0.14	0.66
TC		1.00	0.99	0.99	0.11	0.06	-0.03	-0.01	0.02	0.05	0.25	0.05	-0.36	0.11
OC			1.00	0.96	0.10	0.05	-0.08	-0.05	0.01	0.02	0.23	0.06	-0.38	0.12
EC				1.00	0.13	0.07	0.03	0.04	0.02	0.10	0.27	0.04	-0.33	0.10
NO_3^-					-0.03	0.78	1.00	0.96	0.62	0.94	0.52	0.12	0.52	0.27
SO_4^{-2}					-0.07	0.78		1.00	0.60	0.94	0.40	0.00	0.41	0.23
NH_4^+					0.03	0.79			0.69	1.00	0.42	-0.04	0.43	0.34
Metals					0.25	0.60			0.62		0.42	0.39	0.51	1.00

Table 2.55: Correlation matrix for $PM_{2.5}$ and its composition at JRC for winter season

JRC (W)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.71	0.68	0.73	0.02	0.61	0.53	0.55	0.37	0.63	0.53	0.50	0.68	0.20
TC		1.00	0.99	0.99	-0.33	-0.06	-0.12	-0.11	-0.20	0.00	0.06	0.24	0.25	-0.44
OC			1.00	0.96	-0.35	-0.08	-0.17	-0.15	-0.23	-0.04	0.01	0.16	0.20	-0.45
EC				1.00	-0.30	-0.04	-0.05	-0.05	-0.15	0.05	0.13	0.32	0.31	-0.41
NO_3^-					0.21	0.75	1.00	0.96	0.66	0.93	0.68	0.35	0.66	0.47
SO_4^{-2}					0.14	0.77		1.00	0.63	0.94	0.63	0.29	0.60	0.48
NH_4^+					0.27	0.77			0.66	1.00	0.57	0.24	0.59	0.48
Metals					0.77	0.72			0.69		0.39	0.34	0.31	1.00

Table 2.56: Correlation matrix for PM_{10} and its composition at JRC for summer season

JRC (S)	PM_{10}	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
PM_{10}	1.00	0.68	0.61	0.70	0.83	0.62	0.88	0.77	0.57	0.61	0.66	0.28	0.83	0.97
TC		1.00	0.97	0.95	0.35	0.26	0.55	0.50	0.09	0.28	0.72	-0.17	0.59	0.53
OC			1.00	0.84	0.24	0.34	0.51	0.37	0.15	0.20	0.64	-0.15	0.52	0.46
EC				1.00	0.45	0.13	0.54	0.63	0.00	0.37	0.75	-0.19	0.63	0.57
NO_3^-					0.75	0.73	1.00	0.83	0.61	0.76	0.51	0.41	0.63	0.80
SO_4^{-2}					0.66	0.36		1.00	0.28	0.88	0.60	0.30	0.56	0.68
NH_4^+					0.54	0.49			0.43	1.00	0.37	0.51	0.41	0.52
Metals					0.86	0.59			0.61		0.58	0.29	0.83	1.00

Table 2.57: Correlation matrix for $PM_{2.5}$ and its composition at JRC for summer season

JRC (S)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.80	0.72	0.83	0.63	0.54	0.88	0.83	0.70	0.69	0.80	0.53	0.89	0.93
TC		1.00	0.96	0.95	0.42	0.27	0.57	0.50	0.54	0.33	0.74	0.30	0.62	0.64
OC			1.00	0.84	0.41	0.36	0.52	0.35	0.54	0.24	0.66	0.25	0.55	0.55
EC				1.00	0.38	0.16	0.57	0.63	0.49	0.41	0.76	0.32	0.63	0.69
NO_3^-					0.64	0.71	1.00	0.82	0.73	0.79	0.63	0.48	0.78	0.76
SO_4^{-2}					0.50	0.35		1.00	0.60	0.88	0.65	0.57	0.70	0.70
NH_4^+					0.60	0.50			0.59	1.00	0.44	0.51	0.63	0.52
Metals					0.55	0.48			0.60		0.75	0.50	0.90	1.00

2.4.5 IIT Kanpur (IIT)

The sampling period was December 13, 2018 – January 06, 2019, for winter and March 26 – April 16, 2019, for summer.

2.4.5.1 Particulate Matter (PM_{10}, $PM_{2.5}$)

Time series of 24-hr average concentrations of PM_{10} and $PM_{2.5}$ are shown for winter (Figure 2.52) and summer (Figure 2.53). Average levels for winter and summer season were 196±40 and 66±17 µg/m^3 (for $PM_{2.5}$) and 249±49 and 178±69 µg/m^3 (for PM_{10}) respectively. The $PM_{2.5}$ levels are 3.3 times higher than the NAQS and PM_{10} is 2.5 times higher than the NAQS in winter. The $PM_{2.5}$ levels slightly exceed the standards, while PM_{10} is 1.8 times higher than the NAQS in summer. A statistical summary of PM concentrations is presented in Table 2.61 – 2.64 for the winter and summer seasons. In summer, $PM_{2.5}$ levels drop significantly and are about to meet the national standards. PM_{10} levels also were dropped significantly but continue to be high despite improvement in meteorology and better dispersion. The particles airborne from the soil surface and construction sites during dust storms in the dry months of summer can contribute significantly to a coarse fraction.

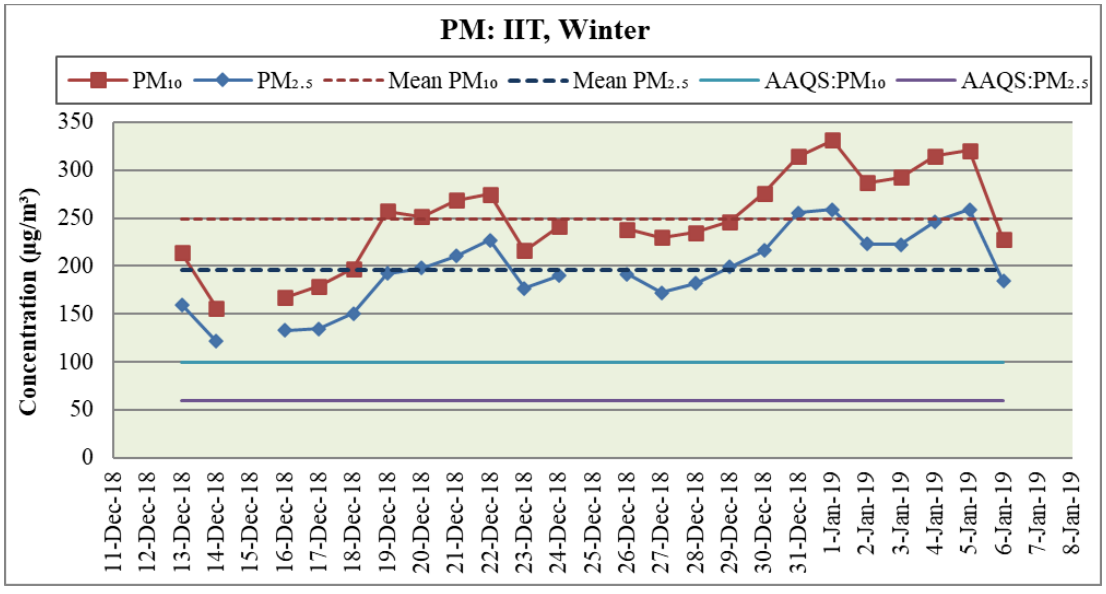


Figure 2.52: PM Concentrations at IIT for Winter Season

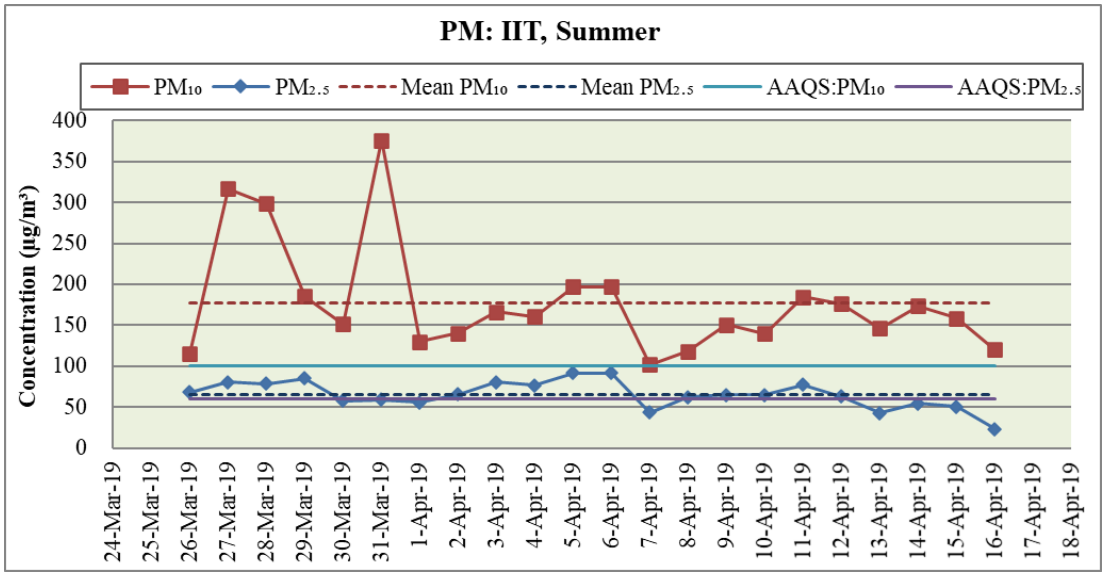


Figure 2.53: PM Concentrations at IIT for Summer Season

2.4.5.2 Gaseous pollutants

Time series of 24-hr average concentrations of SO_2 and NO_2 are shown for winter (Figure 2.54) and summer (Figure 2.55) seasons. It was observed that SO_2 concentrations were low (mostly < 2.0 µg/m^3) and met the air quality standard. NO_2 levels also under the national standard with an average of 20 days at 13.3±2.3 µg/m^3 in winter and 12.0±1.4 µg/m^3 in summer season (Table 2.58). The summer concentration of NO_2 is about in the similar range as in winter. Although, the NO_2 is certainly a matter of concern and these values can largely be attributed to vehicular pollution. Variation in NO_2 is due to variability in meteorology and the presence of occasional local sources like DG sets, etc.

The Mean concentrations of BTX were presented in Figure 2.56 and the statistical summary in Table 2.58. The total BTX level is observed 2.7±1.2 µg/m^3 (Benzene: 1.1 and Toluene: 0.8 µg/m^3) in winter and 6.7±6.6 µg/m^3 (Benzene: 2.2 and Toluene: 3.7 µg/m^3) in summer seasons. The BTX levels were high during summer than in the winter.

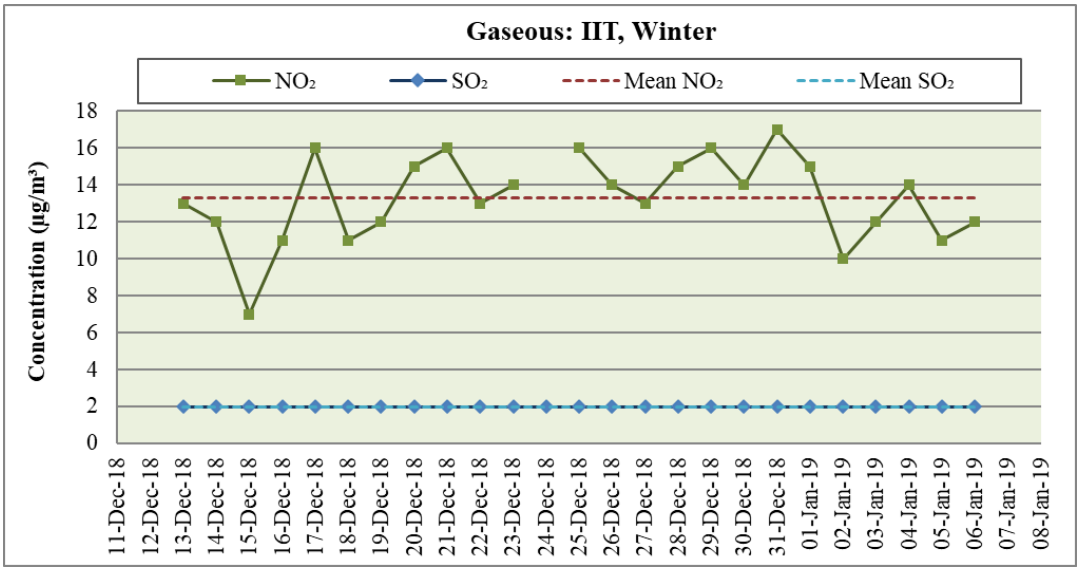


Figure 2.54: SO_2 and NO_2 Concentrations at IIT for Winter Season

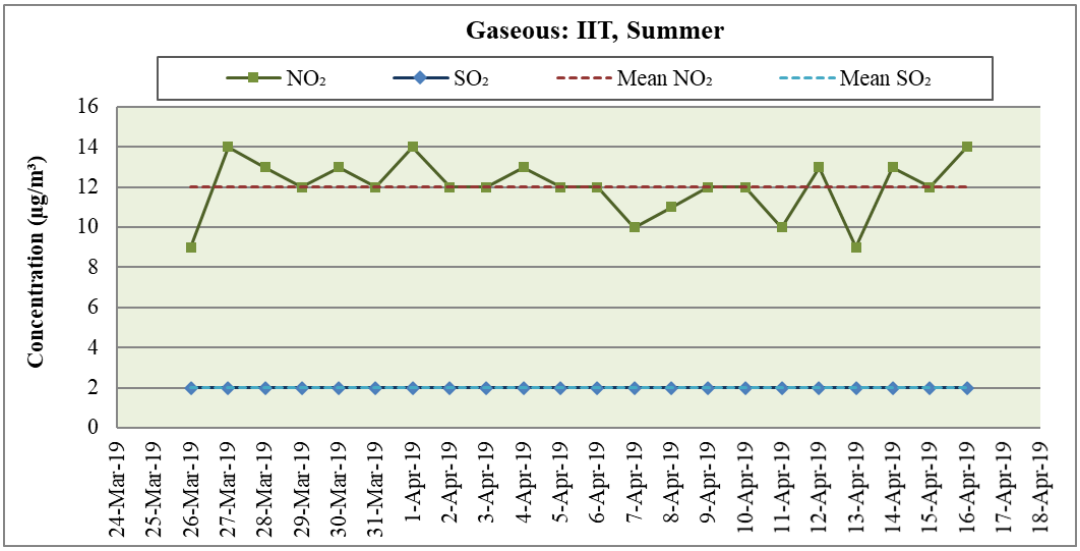


Figure 2.55: SO_2 and NO_2 Concentrations at IIT for Summer Season

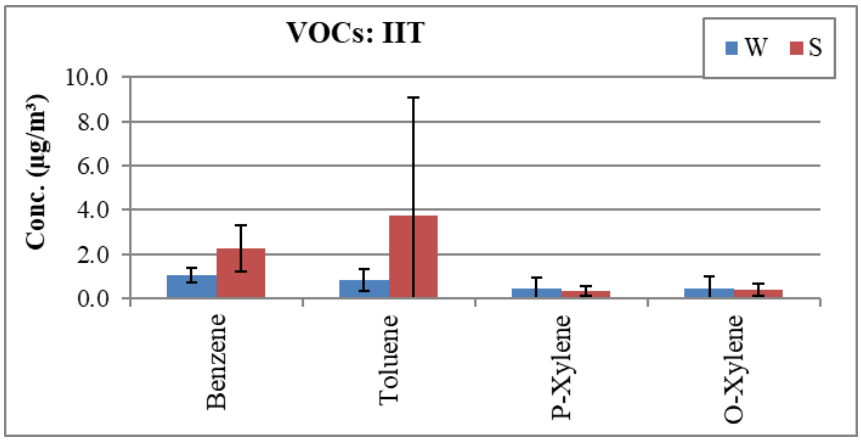


Figure 2.56: VOCs concentration at IIT

2.4.5.3 Carbon Content (EC/OC) in $PM_{2.5}$

Average concentrations of EC, OC (OC1, OC2, OC3 and OC4) and the ratio of OC fraction to TC are shown in Figure 2.57 (a) and (b) for winter and summer seasons. OC is observed slightly higher (winter: 28.6±5.9 and summer: 10.5±3.2 µg/m^3) than the EC (winter: 22.4±4.5 and summer: 9.4±3.5 µg/m^3). It is also observed that the OC and EC are higher in the winter season than in the summer season. A statistical summary of carbon content (TC, EC, OC; OC1, OC2, OC3 and OC4 with fractions OC1/TC, OC2/TC, OC3/TC and OC4/TC) is presented in Table 2.59 for winter and summer seasons. The ratio of OC3/TC is observed higher that indicates the formation of secondary organic carbon in the atmosphere at IIT.

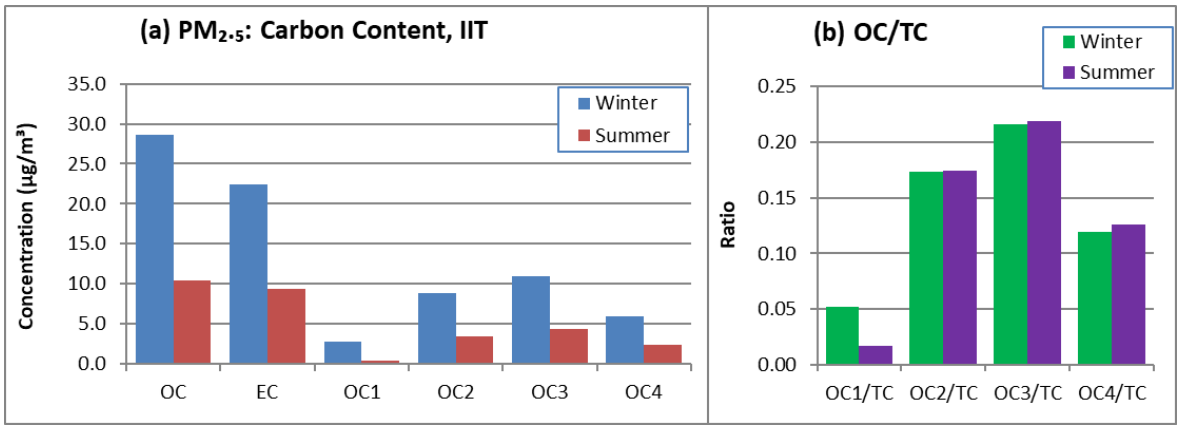


Figure 2.57: EC and OC Content in $PM_{2.5}$ at IIT

2.4.5.4 PAHs in $PM_{2.5}$

Figure 2.58 shows the average measured concentration of PAHs at IIT for winter and summer seasons. A statistical summary of PAHs is presented in Table 2.60 for winter and summer seasons. The PAHs compounds analyzed were: (i) DmP, (ii) AcP, (iii) DEP, (iv) Flu, (v) Phe, (vi) Ant, (vii) Pyr, (viii) BbP, (ix) BeA, (x) B(a)A, (xi) Chr, (xii) B(b)F, (xiii) B(k)F, (xiv) B(a)P, (xv) InP, (xvi) D(a,h)A and (xvii) B(ghi)P. It is observed that Total PAHs concentrations are slightly lower in winter season (27.4±8.1 ng/m^3) compared to summer season (30.4±8.7 ng/m^3). Major PAHs are DmP (5.4 ng/m^3), B(b)F (3.3 ng/m^3), B(k)F (3.1 ng/m^3), B(a)P (2.6 ng/m^3) and Ant (1.9 ng/m^3) for winter season and InP (7.3 ng/m^3), B(ghi)P (5.9 ng/m^3), B(b)F (4.8 ng/m^3), BeA (4.0 ng/m^3) and Chr (1.3 ng/m^3) for summer season.

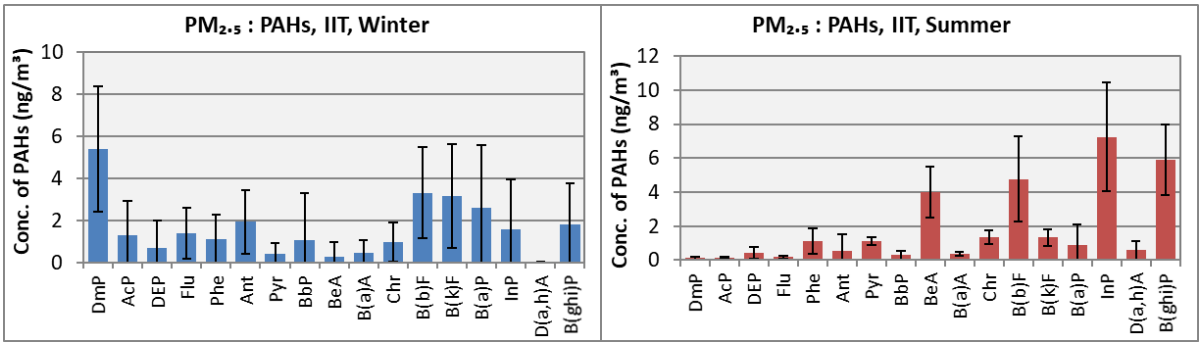


Figure 2.58: PAHs Concentrations in $PM_{2.5}$ at IIT

2.4.5.5 Chemical Composition of PM_{10} and $PM_{2.5}$ and their correlation matrix

Graphical presentations of chemical species are shown for the winter and summer seasons at IIT for PM_{10} (Figure 2.59) and $PM_{2.5}$ (Figure 2.60). Statistical summary for particulate matter (PM_{10} and $PM_{2.5}$), its chemical composition [carbon content, ionic species and elements] along with mass percentage (% R) recovered from PM are presented in Tables 2.61 – 2.64 for winter and summer season.

The correlation between different parameters (i.e., PM, TC, OC, EC, F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2} and Metals (elements)) with major species (PM, TC, OC, EC, NO_3^-, SO_4^{-2}, NH_4^+, Metals) for PM_{10} and $PM_{2.5}$ composition is presented in Tables 2.65 – 2.68 for both seasons. It is seen that most of the parameters showed a good correlation (>0.30) with PM_{10} and $PM_{2.5}$. The percentage constituents of the PM are presented in Figure 2.61 (a) and (b) for the winter season and Figure 2.62 (a) and (b) for the summer season.

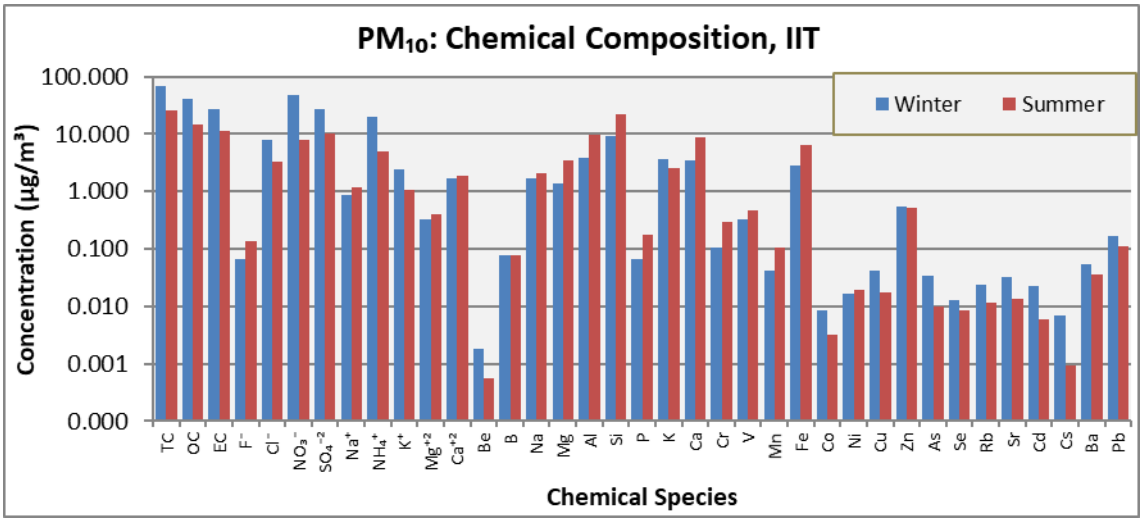


Figure 2.59: Concentrations of species in PM_{10} at IIT

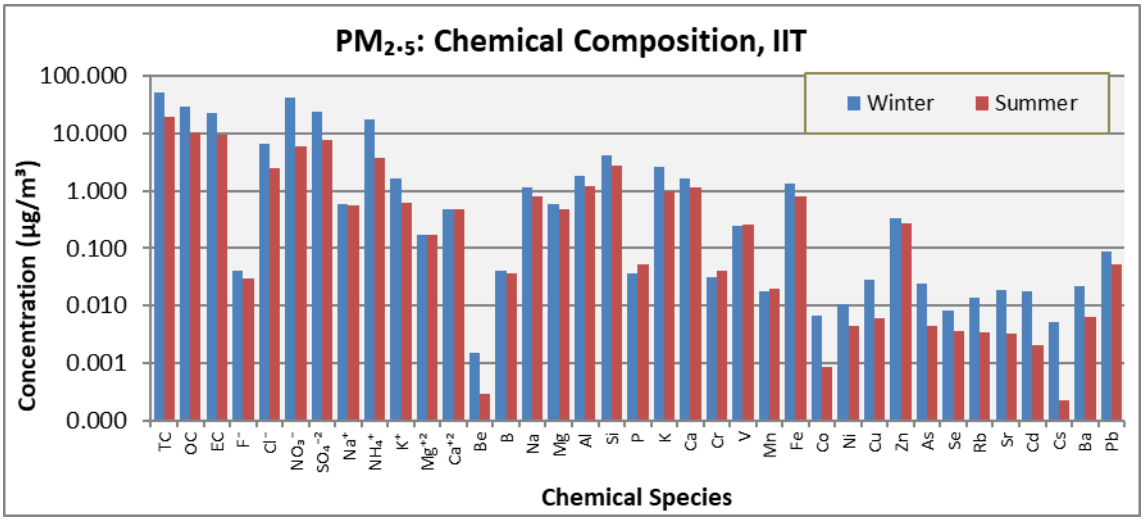


Figure 2.60: Concentrations of species in $PM_{2.5}$ at IIT

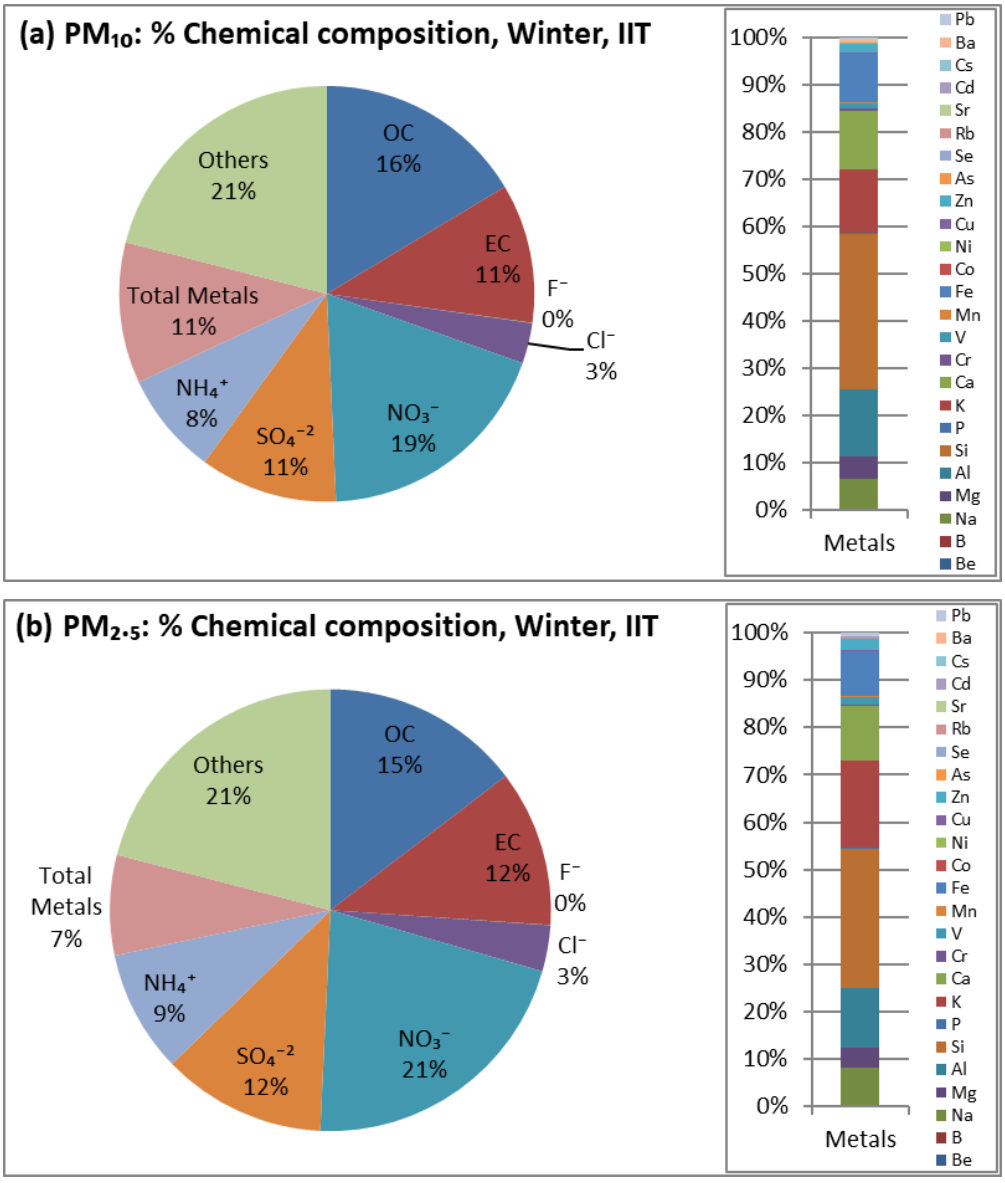


Figure 2.61: Percentage distribution of species in PM at IIT for Winter Season

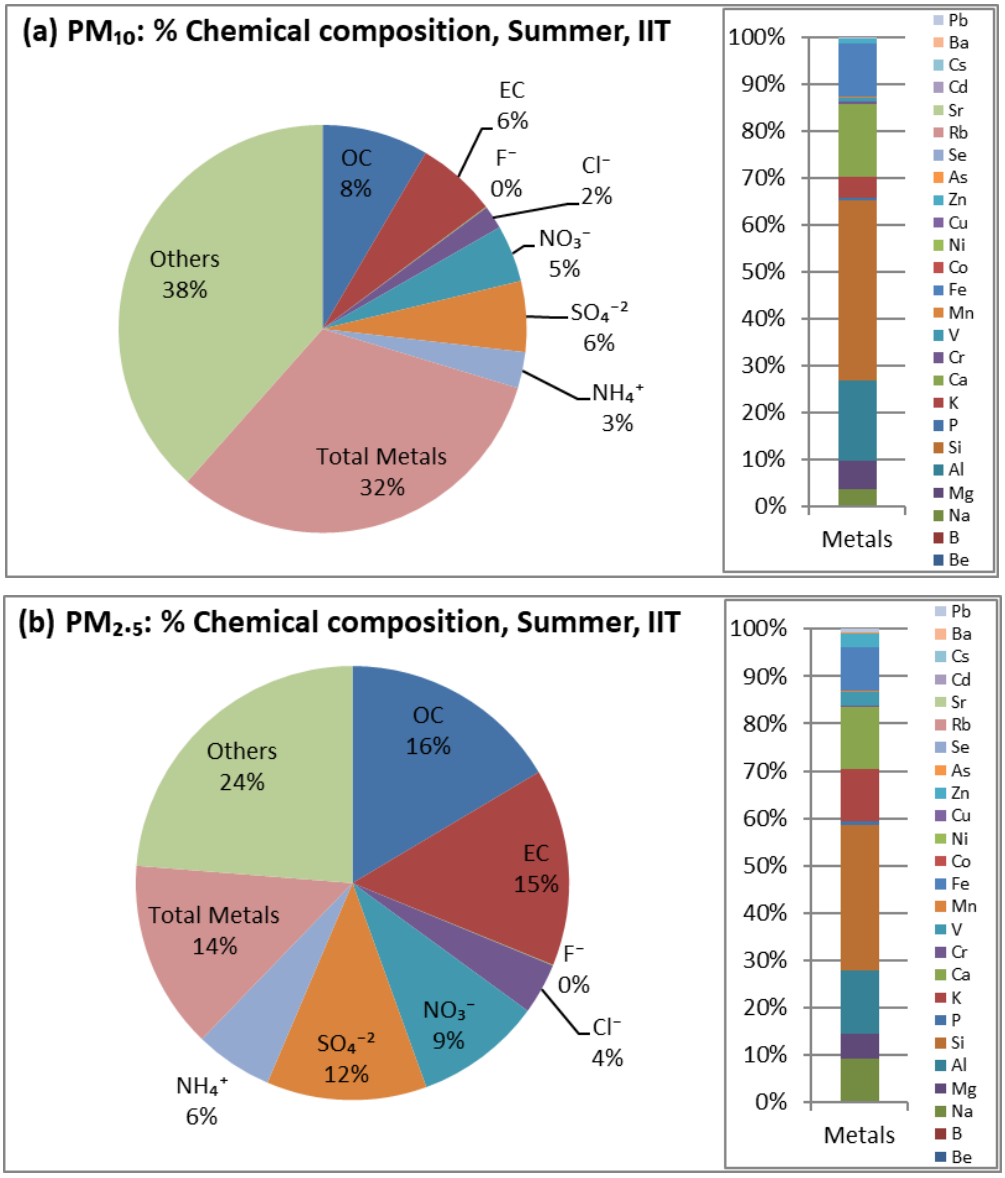


Figure 2.62: Percentage distribution of species in PM at IIT for Summer Season

2.4.5.6 Comparison of PM_{10} and $PM_{2.5}$ Composition

The graphical compositional comparison of $PM_{2.5}$ vs PM_{10} for all species is shown for winter and summer seasons (Figure 2.63) at IIT. The chemical species considered for the comparisons are carbon content (TC, OC and EC), ionic species (F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Ca^{+2}, Mg^{+2}) and elements (Be, B, Na, Mg, Al, Si, P, K, Ca, Cr, V, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, Pb). It is concluded that most portion of PM has fine mode during winter (79%) than summer (36%). The major species contributing to fine mode are TC, OC, EC, Cl^-, NO_3^-, SO_4^{-2}, NH_4^+, K^+, Be, V and Zn; whereas, major species contributing in coarse mode are Ca^{2+}, Be, Mg, Al, Si, Ca, Cr, Mn, Fe and Ba.

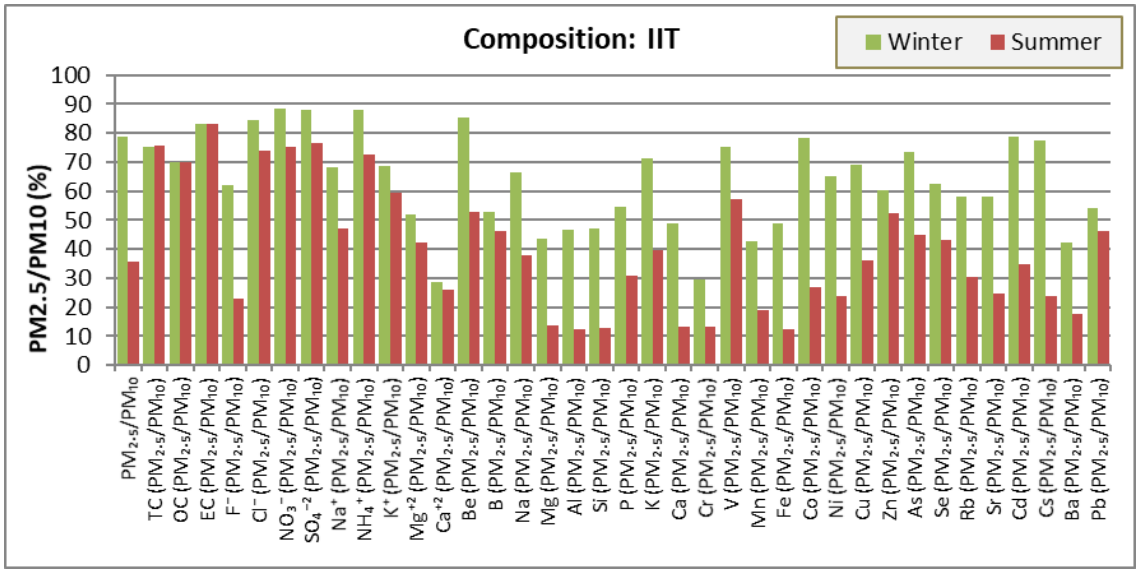


Figure 2.63: Compositional comparison of species in $PM_{2.5}$ Vs PM_{10} at IIT

Table 2.58: Statistical results of gaseous pollutants (µg/m^3) at IIT for winter (W) and summer (S) seasons

IIT (W)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	13.29	2.00	1.06	0.84	0.41	0.43	2.74
SD	2.35	0.00	0.34	0.50	0.54	0.57	1.19
Max	17.00	2.00	1.83	2.43	2.46	2.49	6.11
Min	7.00	2.00	0.61	0.33	0.12	0.03	1.31
CV	0.18	0.00	0.32	0.59	1.32	1.32	0.43
IIT (S)	NO_2	SO_2	Benzene	Toluene	p-Xylene	o-Xylene	Total (BTX)
Mean	12.00	2.00	2.23	3.73	0.34	0.38	6.68
SD	1.45	0.00	1.05	5.34	0.22	0.29	6.60
Max	14.00	2.00	5.45	19.83	0.94	1.18	27.40
Min	9.00	2.00	0.28	0.13	0.00	0.00	0.42
CV	0.12	0.00	0.47	1.43	0.65	0.76	0.99

Table 2.59: Statistical results of carbon contents (µg/m^3) in $PM_{2.5}$ at IIT for winter (W) and summer (S) seasons

IIT (W)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	195.8	51.04	28.62	22.42	2.84	8.87	10.95	5.95	0.052	0.173	0.216	0.119
SD	39.9	9.47	5.88	4.54	2.63	1.91	1.82	0.62	0.035	0.009	0.020	0.018
Max	259.0	69.66	47.41	31.09	14.05	14.10	13.86	7.47	0.202	0.202	0.281	0.163
Min	121.5	33.04	18.87	14.17	0.96	5.84	7.25	4.51	0.020	0.163	0.199	0.078
CV	0.20	0.19	0.21	0.20	0.92	0.21	0.17	0.10	0.668	0.050	0.095	0.155
IIT (S)	$PM_{2.5}$	TC	EC	OC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
Mean	65.5	19.85	10.49	9.37	0.39	3.44	4.30	2.35	0.017	0.174	0.219	0.126
SD	16.8	6.55	3.16	3.48	0.40	1.11	1.34	0.50	0.014	0.014	0.014	0.024
Max	91.8	29.90	15.55	15.85	1.53	5.14	6.45	2.93	0.052	0.208	0.262	0.179
Min	23.5	5.88	3.61	2.27	0.00	1.02	1.54	1.05	0.000	0.147	0.201	0.082
CV	0.26	0.33	0.30	0.37	1.03	0.32	0.31	0.21	0.870	0.080	0.064	0.194

Table 2.60: **Statistical results of PAHs (ng/m^3) in $PM_{2.5}$ at IIT for winter (W) and summer (S) seasons**

IIT(W)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	5.38	1.28	0.71	1.40	1.11	1.94	0.40	1.05	0.27	0.46	0.98	3.31	3.15	2.62	1.56	0.01	1.80	27.42
SD	2.97	1.63	1.29	1.21	1.16	1.51	0.52	2.26	0.69	0.62	0.94	2.15	2.45	2.95	2.38	0.02	1.96	8.13
Max	11.16	4.41	4.43	3.32	4.00	4.40	1.80	8.37	2.39	2.49	2.71	9.33	8.78	10.34	7.89	0.09	6.71	43.34
Min	1.59	0.11	0.00	0.00	0.00	0.03	0.00	0.09	0.00	0.17	0.19	0.50	0.06	0.05	0.00	0.00	0.20	14.64
CV	0.55	1.27	1.80	0.87	1.04	0.78	1.31	2.16	2.59	1.36	0.96	0.65	0.78	1.13	1.52	3.61	1.09	0.30
IIT(S)	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
Mean	0.11	0.15	0.44	0.18	1.14	0.53	1.14	0.29	3.98	0.37	1.33	4.77	1.34	0.89	7.26	0.58	5.91	30.41
SD	0.10	0.03	0.34	0.08	0.75	0.97	0.23	0.25	1.50	0.11	0.40	2.49	0.49	1.19	3.22	0.57	2.06	8.68
Max	0.24	0.19	0.94	0.26	1.58	1.99	1.49	0.62	5.92	0.46	1.71	8.24	1.90	2.68	11.58	1.42	8.36	42.63
Min	0.00	0.11	0.23	0.08	0.02	0.04	0.98	0.06	2.27	0.25	0.92	2.81	0.88	0.21	4.19	0.20	3.85	23.88
CV	0.93	0.20	0.76	0.43	0.65	1.84	0.21	0.88	0.38	0.29	0.30	0.52	0.37	1.34	0.44	0.98	0.35	0.29

Table 2.61: Statistical results of chemical characterization (µg/m^3) of PM_{10} at IIT for winter (W) season

IIT (W)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	249	40.9	27.0	0.1	7.8	47.1	26.7	0.8	20.0	2.4	0.3	1.7	2E-3	0.08	1.71	1.34	3.85	8.99	0.07
SD	49	8.4	5.5	0.0	3.5	13.6	8.4	0.3	6.1	0.6	0.1	0.5	9E-5	0.06	0.55	0.28	1.02	2.28	0.05
Max	331	67.7	37.5	0.1	16.3	70.7	42.1	1.3	28.2	3.7	0.5	2.7	2E-3	0.30	3.11	1.75	5.40	13.07	0.25
Min	156	27.0	17.1	0.0	2.9	22.8	13.8	0.3	9.4	1.2	0.2	0.8	2E-3	0.03	0.99	0.82	1.84	4.80	0.03
CV	0.19	0.21	0.20	0.34	0.45	0.29	0.32	0.36	0.31	0.26	0.31	0.28	0.05	0.81	0.32	0.21	0.26	0.25	0.67
IIT (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	3.71	3.40	0.11	0.33	0.04	2.79	9E-3	2E-2	0.04	0.54	0.03	1E-2	2E-2	3E-2	0.02	7E-3	0.05	0.17	78.9
SD	0.72	0.89	0.03	0.02	0.01	0.58	4E-4	1E-3	0.01	0.16	0.01	4E-3	3E-3	5E-3	0.01	3E-4	0.01	0.05	2.0
Max	4.84	4.92	0.14	0.37	0.06	3.69	1E-2	2E-2	0.07	0.86	0.05	2E-2	3E-2	5E-2	0.04	8E-3	0.09	0.31	82.6
Min	1.96	1.95	0.05	0.30	0.01	1.54	8E-3	1E-2	0.03	0.26	0.02	8E-3	1E-2	2E-2	0.01	6E-3	0.02	0.09	75.7
CV	0.19	0.26	0.24	0.05	0.36	0.21	0.05	0.08	0.26	0.30	0.33	0.33	0.13	0.15	0.30	0.05	0.25	0.33	0.03
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.62: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at IIT for winter (W) season

IIT (W)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	196	28.6	22.4	0.0	6.6	41.6	23.5	0.6	17.5	1.6	0.2	0.5	2E-3	0.04	1.14	0.59	1.80	4.23	0.04
SD	40	5.9	4.5	0.0	3.0	12.6	7.4	0.2	5.6	0.4	0.1	0.2	9E-5	0.03	0.34	0.15	0.56	1.32	0.01
Max	259	47.4	31.1	0.1	13.4	65.0	37.8	1.0	25.7	2.4	0.2	0.9	2E-3	0.14	2.07	0.90	3.15	7.08	0.07
Min	122	18.9	14.2	0.0	2.0	20.5	12.3	0.2	8.0	1.0	0.0	0.0	1E-3	0.01	0.45	0.35	0.70	1.66	0.02
CV	0.20	0.21	0.20	0.46	0.45	0.30	0.31	0.40	0.32	0.25	0.31	0.46	0.05	0.79	0.30	0.25	0.31	0.31	0.35
IIT (W)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	2.64	1.66	0.03	0.25	0.02	1.36	7E-3	1E-2	0.03	0.33	0.02	8E-3	1E-2	2E-2	2E-2	5E-3	0.02	0.09	78.9
SD	0.55	0.46	0.02	0.04	0.01	0.43	4E-4	1E-3	0.01	0.09	0.01	1E-3	1E-3	2E-3	4E-3	3E-4	0.01	0.03	2.5
Max	3.75	2.59	0.09	0.30	0.05	2.30	8E-3	1E-2	0.05	0.51	0.04	1E-2	2E-2	2E-2	3E-2	6E-3	0.04	0.18	84.5
Min	1.28	0.70	0.00	0.16	0.00	0.45	6E-3	9E-3	0.02	0.17	0.02	6E-3	1E-2	2E-2	1E-2	5E-3	0.01	0.05	74.9
CV	0.21	0.28	0.63	0.15	0.50	0.32	0.06	0.12	0.30	0.29	0.27	0.17	0.10	0.11	0.24	0.06	0.31	0.36	0.03
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.63: Statistical results chemical characterization (µg/m^3) of PM_{10} at IIT for summer (S) season

IIT (S)	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	178	15.0	11.3	0.1	3.3	8.0	10.0	1.2	5.1	1.0	0.4	1.9	5E-4	0.08	2.10	3.42	9.63	21.78	0.17
SD	69	4.5	4.2	0.1	1.1	2.5	3.6	0.3	1.6	0.3	0.2	0.7	1E-4	0.03	1.06	2.73	5.47	12.29	0.09
Max	376	22.2	19.1	0.2	5.4	13.3	18.3	1.5	7.8	1.6	1.3	3.3	1E-3	0.14	5.69	14.11	27.54	59.18	0.48
Min	102	5.2	2.7	0.0	1.5	4.1	4.5	0.6	1.8	0.5	0.2	0.8	4E-4	0.03	1.03	1.34	4.18	9.25	0.04
CV	0.39	0.30	0.37	0.44	0.35	0.32	0.36	0.23	0.30	0.27	0.61	0.37	0.27	0.34	0.50	0.80	0.57	0.56	0.54
IIT (S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	2.53	8.87	0.30	0.46	0.11	6.38	3E-3	0.02	0.02	0.51	1E-2	8E-3	1E-2	1E-2	6E-3	9E-4	0.04	0.11	62.49
SD	1.08	4.94	0.21	0.09	0.05	3.53	3E-3	0.01	0.01	0.21	6E-3	6E-3	5E-3	1E-2	4E-3	2E-4	0.02	0.06	4.23
Max	4.91	25.19	0.98	0.75	0.25	17.10	1E-2	0.04	0.05	0.95	2E-2	3E-2	2E-2	4E-2	2E-2	1E-3	0.08	0.30	68.44
Min	0.98	3.67	0.09	0.33	0.04	2.71	7E-4	0.01	0.01	0.24	4E-3	2E-3	4E-3	2E-3	2E-3	5E-4	0.01	0.05	53.20
CV	0.43	0.56	0.69	0.20	0.48	0.55	0.82	0.55	0.58	0.41	0.58	0.73	0.41	0.77	0.67	0.25	0.46	0.50	0.07
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.64: Statistical results of chemical characterization (µg/m^3) of $PM_{2.5}$ at IIT for summer (S) season

IIT(S)	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
Mean	64	10.5	9.4	0.0	2.4	6.0	7.6	0.5	3.7	0.6	0.2	0.5	3E-4	0.04	0.79	0.47	1.19	2.76	0.05
SD	16	3.2	3.5	0.0	0.9	2.1	2.9	0.2	1.2	0.3	0.1	0.1	1E-4	0.02	0.24	0.23	0.43	0.96	0.02
Max	92	15.6	15.8	0.1	4.0	11.4	14.6	0.9	5.8	1.3	0.3	0.8	7E-4	0.07	1.21	1.11	1.93	4.51	0.08
Min	24	3.6	2.3	0.0	1.0	2.9	3.0	0.2	1.3	0.3	0.1	0.2	1E-4	0.01	0.27	0.15	0.39	0.83	0.02
CV	0.25	0.30	0.37	0.39	0.36	0.35	0.38	0.35	0.32	0.42	0.47	0.27	0.37	0.52	0.30	0.48	0.36	0.35	0.33
IIT(S)	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
Mean	1.00	1.16	0.04	0.26	0.02	0.80	9E-4	5E-3	6E-3	0.27	4E-3	4E-3	3E-3	3E-3	2E-3	2E-4	6E-3	0.05	76.27
SD	0.47	0.40	0.02	0.03	0.01	0.28	1E-3	1E-3	3E-3	0.10	2E-3	2E-3	2E-3	2E-3	1E-3	7E-5	3E-3	0.01	2.76
Max	2.11	1.86	0.07	0.33	0.04	1.46	6E-3	7E-3	1E-2	0.45	9E-3	8E-3	7E-3	8E-3	5E-3	4E-4	1E-2	0.08	81.28
Min	0.39	0.35	0.01	0.19	0.01	0.29	2E-4	2E-3	2E-3	0.10	2E-3	9E-4	1E-3	8E-4	8E-4	8E-5	1E-3	0.02	72.42
CV	0.47	0.35	0.44	0.12	0.51	0.35	1.38	0.31	0.50	0.37	0.53	0.51	0.46	0.56	0.51	0.33	0.54	0.29	0.04
% R is the % recovery of mass of collected particle through compositional analysis																			

Table 2.65: Correlation matrix for PM_{10} and its composition at IIT for winter season

IIT (W)	PM_{10}	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
PM_{10}	1.00	0.71	0.50	0.87	0.62	0.80	0.83	0.85	-0.22	0.90	0.48	0.08	0.56	0.64
TC		1.00	0.94	0.86	0.49	0.67	0.32	0.39	-0.36	0.44	0.32	-0.10	0.36	0.28
OC			1.00	0.65	0.32	0.52	0.13	0.14	-0.39	0.23	0.12	-0.19	0.26	0.05
EC				1.00	0.63	0.76	0.54	0.69	-0.22	0.65	0.57	0.06	0.43	0.56
NO_3^-					0.45	0.60	1.00	0.80	-0.14	0.96	0.34	0.27	0.51	0.41
SO_4^{-2}					0.71	0.56		1.00	-0.08	0.87	0.39	0.13	0.43	0.51
NH_4^+					0.53	0.67			-0.24	1.00	0.40	0.20	0.51	0.45
Metals					0.37	0.50			0.16		0.58	-0.05	0.48	1.00

Table 2.66: Correlation matrix for $PM_{2.5}$ and its composition at IIT for winter season

IIT (W)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.71	0.47	0.88	0.62	0.81	0.82	0.89	-0.22	0.91	0.64	-0.25	0.48	0.49
TC		1.00	0.93	0.88	0.47	0.70	0.29	0.43	-0.29	0.46	0.44	-0.42	0.55	0.19
OC			1.00	0.65	0.30	0.53	0.09	0.15	-0.35	0.23	0.22	-0.41	0.45	-0.08
EC				1.00	0.58	0.78	0.49	0.70	-0.14	0.67	0.63	-0.36	0.56	0.51
NO_3^-					0.40	0.58	1.00	0.77	-0.22	0.93	0.45	0.03	0.06	0.23
SO_4^{-2}					0.64	0.59		1.00	-0.10	0.90	0.51	-0.20	0.40	0.52
NH_4^+					0.52	0.66			-0.29	1.00	0.50	-0.08	0.29	0.29
Metals					0.37	0.30			0.37		0.61	-0.22	0.43	1.00

Table 2.67: Correlation matrix for PM_{10} and its composition at IIT for summer season

IIT (S)	PM_{10}	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
PM_{10}	1.00	0.28	0.28	0.28	0.24	0.00	0.44	0.34	0.45	0.53	0.26	0.48	0.17	0.97
TC		1.00	0.99	0.98	-0.23	-0.14	0.51	0.67	0.29	0.64	0.69	-0.23	0.13	0.06
OC			1.00	0.94	-0.21	-0.15	0.48	0.61	0.34	0.57	0.69	-0.21	0.17	0.06
EC				1.00	-0.24	-0.12	0.52	0.72	0.23	0.70	0.66	-0.24	0.10	0.06
NO_3^-					0.04	0.40	1.00	0.62	0.17	0.67	0.45	0.11	-0.06	0.28
SO_4^{-2}					-0.11	0.25		1.00	0.16	0.48	0.30	-0.26	-0.11	0.14
NH_4^+					-0.13	0.09			0.28	1.00	0.53	0.11	-0.05	0.40
Metals					0.32	-0.04			0.41		0.13	0.56	0.18	1.00

Table 2.68: Correlation matrix for $PM_{2.5}$ and its composition at IIT for summer season

IIT (S)	$PM_{2.5}$	TC	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Metals
$PM_{2.5}$	1.00	0.92	0.88	0.92	0.11	0.20	0.66	0.79	0.66	0.69	0.67	-0.06	0.49	0.62
TC		1.00	0.98	0.99	0.17	-0.01	0.55	0.70	0.55	0.68	0.63	-0.15	0.27	0.39
OC			1.00	0.94	0.17	-0.02	0.51	0.63	0.54	0.60	0.65	-0.14	0.24	0.39
EC				1.00	0.17	0.01	0.57	0.75	0.54	0.72	0.60	-0.14	0.28	0.39
NO_3^-					0.38	0.49	1.00	0.63	0.33	0.67	0.35	0.17	0.46	0.08
SO_4^{-2}					0.01	0.26		1.00	0.24	0.45	0.32	-0.10	0.41	0.27
NH_4^+					0.45	0.19			0.50	1.00	0.42	0.21	0.36	0.24
Metals					-0.18	-0.03			0.72		0.56	-0.10	0.49	1.00

2.4.6 Overall Summary and results

The sampling period for winter is December 06, 2018, to February 18, 2019, and April 08, 2019, to June 30, 2019, for the summer season

2.4.6.1 Particulate Matter (PM_{10}, $PM_{2.5}$)

The seasonal comparison is shown for PM_{10} (Figure 2.64), $PM_{2.5}$ (Figure 2.65) and the ratio of $PM_{2.5}$ to PM_{10} (Figure 2.66) for all sites. The overall summary of experimental results for PM is shown for the winter and summer seasons (Table 2.69).

Winter

The overall city average of $PM_{2.5}$ in winter was 238±96 µg/m^3 and PM_{10} was 367±164 µg/m^3. The $PM_{2.5}$ levels are about 4.0 times higher than the national air quality standard (60 µg/m^3) and PM_{10} about 3.7 times higher than the standard (100 µg/m^3). Both $PM_{2.5}$ and PM_{10} levels were highest at DDN, the industrial site at 388 and 598 µg/m^3, followed by levels at RMD (273 and 480 µg/m^3), a commercial cum residential site with high traffic on the nearby national highway. The highest variability was seen at CNG (CV: 0.70) for $PM_{2.5}$ followed by DDN (CV: 0.49) and RMD (CV: 0.48). The levels were quite steady at JRC (CV: 0.25), and IIT (CV: 0.20). The highest variation for PM_{10} was seen at RMD (CV: 0.63) and least at IIT (CV: 0.19).

The ratio of $PM_{2.5}$ to PM_{10} is a useful parameter to indicate the relative abundance of fine particles (i.e., $PM_{2.5}$) and toxicity of particulate matter. The overall city ratio is 0.67 and it was highest at IIT (0.78), followed by JRC (0.66). The relatively high $PM_{2.5}$ at these sites could be attributed by combustion sources and less road dust emission.

Summer

The overall city average of $PM_{2.5}$ levels in summer dropped sharply to 78±23 µg/m^3 also PM_{10} dropped to 205±64 µg/m^3 compared to winter. The $PM_{2.5}$ levels slightly exceed by 1.3 times the standards, while PM_{10} is 2.0 times higher than the standard. $PM_{2.5}$ and PM_{10} levels were highest in DDN (industrial area), 116 and 297 µg/m^3, respectively. The $PM_{2.5}$ and PM_{10} levels were lowest at JRC (57 and 133 µg/m^3); PM_{10} levels exceed the air quality standards.

The highest variability in $PM_{2.5}$ was seen at JRC (CV: 0.37) followed by CNG (CV: 0.31). The highest variation for PM_{10} was seen at JRC (CV: 0.40) and least at DDN (CV: 0.23). The overall

$PM_{2.5}$ to PM_{10} city ratio is 0.40 and it was highest at CNG (0.46). The ratio was similar at other sites.

It is a positive finding that $PM_{2.5}$ levels in summer are expected to almost comply with national standards of 60 µg/m^3 at JRC and IIT, however, in other areas, it is a matter of concern.

The time-series data also reveal that within winter, levels of PM_{10} and $PM_{2.5}$ may show increasing or decreasing patterns. It is seen that levels are highest and increase during the last week of December and the first week of January (Figures 2.4 and 2.52). In the later part of January, more so in February, the levels drop rapidly (Figures 2.16 and 2.28). Typical calm conditions tend to cease in late January and February and wind speed begins to rise, resulting in better dilution and dispersion of the pollutants.

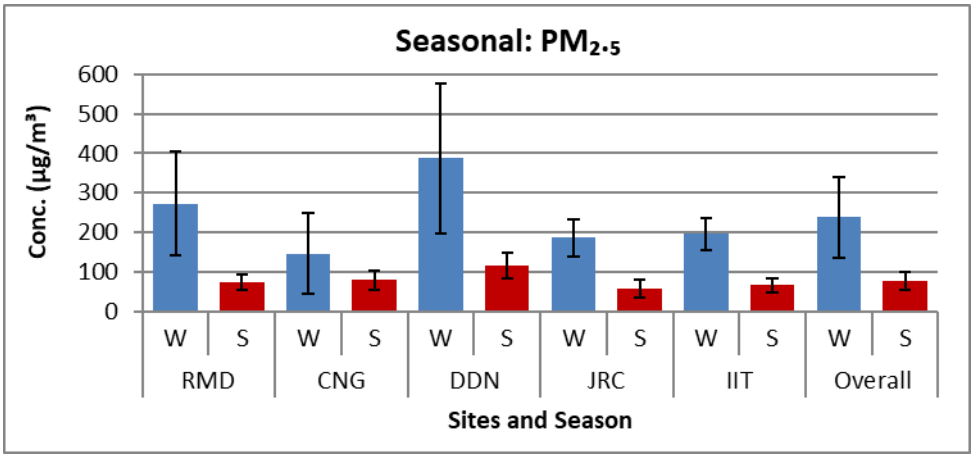


Figure 2.64: Seasonal comparison of PM_{10} levels for all Sites

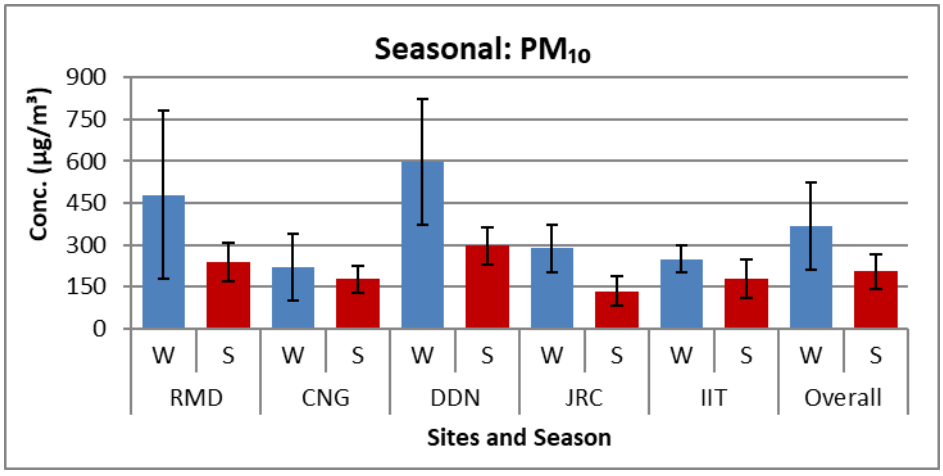


Figure 2.65: Seasonal comparison of $PM_{2.5}$ concentrations for all Sites

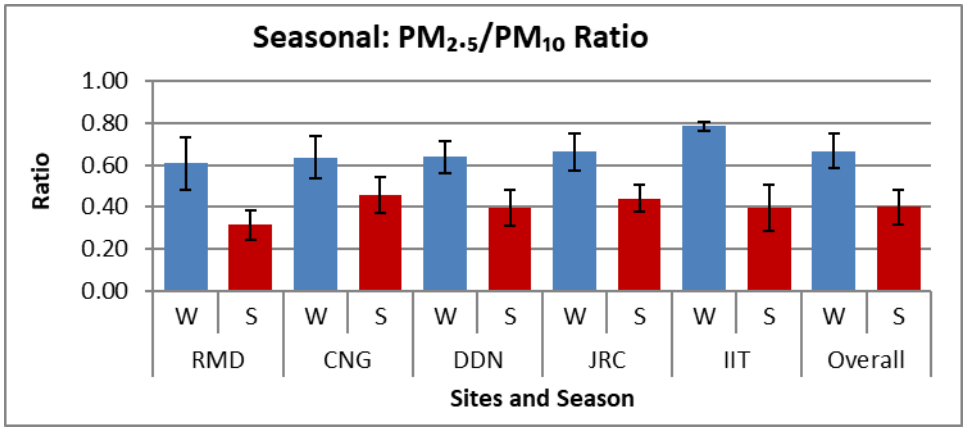


Figure 2.66: Seasonal comparison of $PM_{2.5}$ /PM_{10} ratio

2.4.6.2 Gaseous Pollutants (NO_2 and SO_2)

The seasonal comparison is shown for NO_2 and SO_2 (Figure 2.67). The overall average concentrations with statistical summary are presented in Tables 2.70 and 2.71 for all sites for winter and summer seasons.

The SO_2 levels were quite low (mostly < 5.0 µg/m^3) and were always within the air quality standards (80 µg/m^3) with the highest mean at DDN at 20.2 µg/m^3 in winter and 5.6 µg/m^3 in summer; levels were mostly below 5.0 µg/m^3 in summer at all sites except DDN (Figures 2.67). The SO_2 levels being very low have not been further discussed.

It was observed that NO_2 levels were complying with the air quality standards (80 µg/m^3) during both seasons. The overall city-level average NO_2 levels are 47.7±9.5 µg/m^3 in winter and 34.6±6.3 µg/m^3 in summer. The highest NO_2 concentration was observed at DDN in winter (74.3 µg/m^3) and at RMD in summer (55.1 µg/m^3). At RMD, CNG and DDN, on certain days in winter NO_2 levels exceed the standard. NO_2 is an emerging pollutant that can largely be attributed to vehicular emissions. RMD (commercial area) and DDN (industrial area) are having higher vehicular emissions of NO_2. Levels drop significantly in summer largely due to high wind speeds, convective conditions, large mixing height resulting in better dilution and dispersion of the NO_2.

Although the NO_2 levels meet the national air quality standard (except certain days at DDN and RMD), efforts are required to improve the air quality for NO_2, particularly in the winter season, as it will be difficult to reduce the emission after the fact at a later stage.

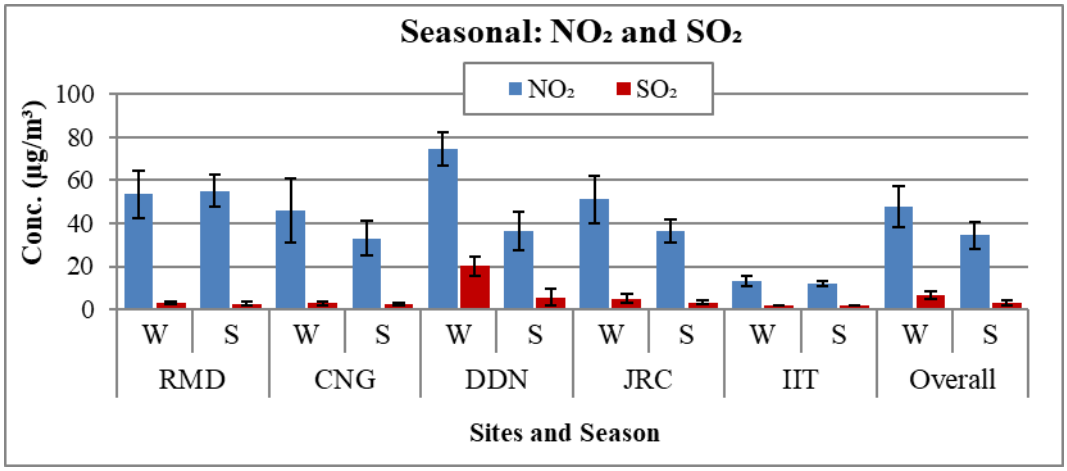


Figure 2.67: Seasonal Comparison of NO_2 and SO_2 levels for all Sites

2.4.6.3 Volatile Organic Compounds (VOCs: BTX)

The seasonal comparison for VOCs (BTX) is shown in Figure 2.68. The overall statistical summary is presented in Tables 2.70 – 2.71 for all sites for the winter and summer seasons.

The overall city-level average of BTX levels is 12.4±8.6 µg/m^3 in winter and 15.1±16.7 µg/m^3 in summer. The highest BTX concentration was observed at DDN in winter (27.7 µg/m^3) and summer (45.1 µg/m^3).

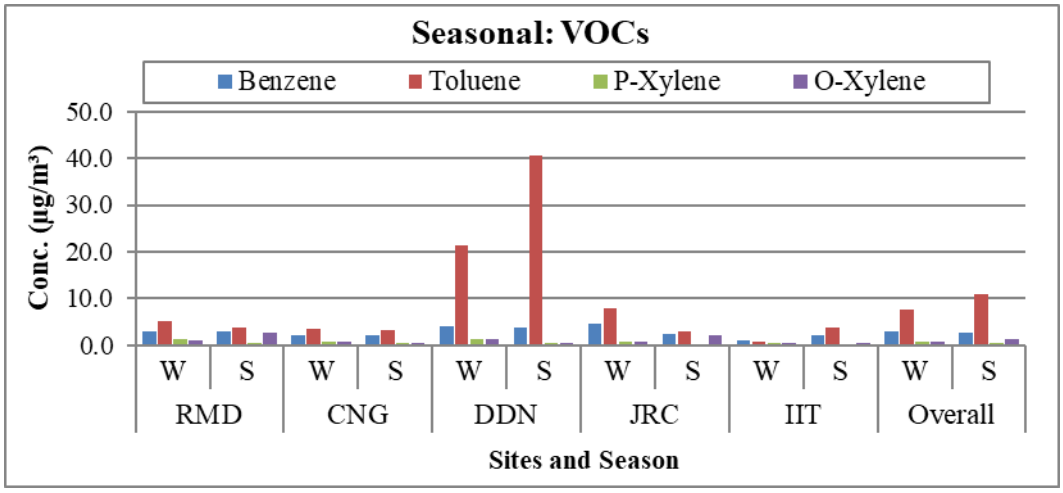


Figure 2.68: Seasonal comparison of VOCs for all Sites

2.4.6.4 Carbon Content (EC/OC) in $PM_{2.5}$

The seasonal comparison for OC and EC is presented in Figure 2.69 for PM_{10} and Figure 2.70 for $PM_{2.5}$. The $PM_{2.5}$ contained a high fraction of TC (OC+EC), 36% in winter and 29% in summer seasons. The OC is observed higher than the EC at each site during winter and summer;

this is generally true that in the atmosphere volatile and semi-volatile organic compounds continuously undergo nucleation, oxidation, condensation and convert into organic particles, whereas EC remains unchanged, as a result, the ratio of OC to EC further increases. However, the ratio of OC3/TC is observed higher than other OCs; this indicates the formation of secondary organic carbon particles in the atmosphere is an important process. It is also observed that the OC and EC are higher in the winter season than in the summer season, probably because of poor dispersion in winter and more combustion sources, including biomass and municipal solid waste (MSW) burning. It is observed that the average TC to $PM_{2.5}$ ratio were maximum (47%) at JRC followed by CNG and minimum (26%) at DDN in winter (Table 2.82) and maximum (31%) at RMD and IIT and minimum (25%) at DDN in summer (Table 2.84).

The overall summary of carbon content (TC, EC, OC; OC1, OC2, OC3 and OC4 with fractions OC1/TC, OC2/TC, OC3/TC and OC4/TC) is presented in Tables 2.72 - 2.73 for winter and summer seasons.

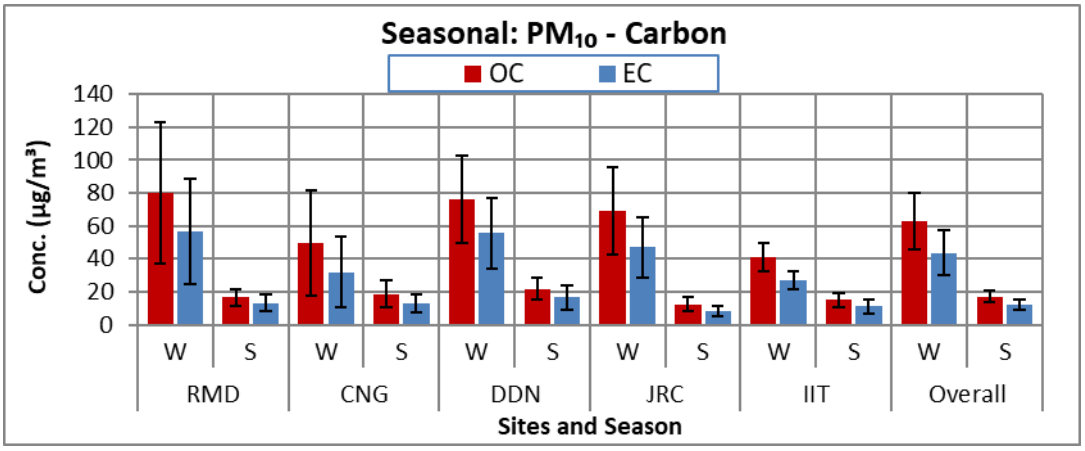


Figure 2.69: Seasonal Comparison of EC and OC in PM_{10} for all Sites

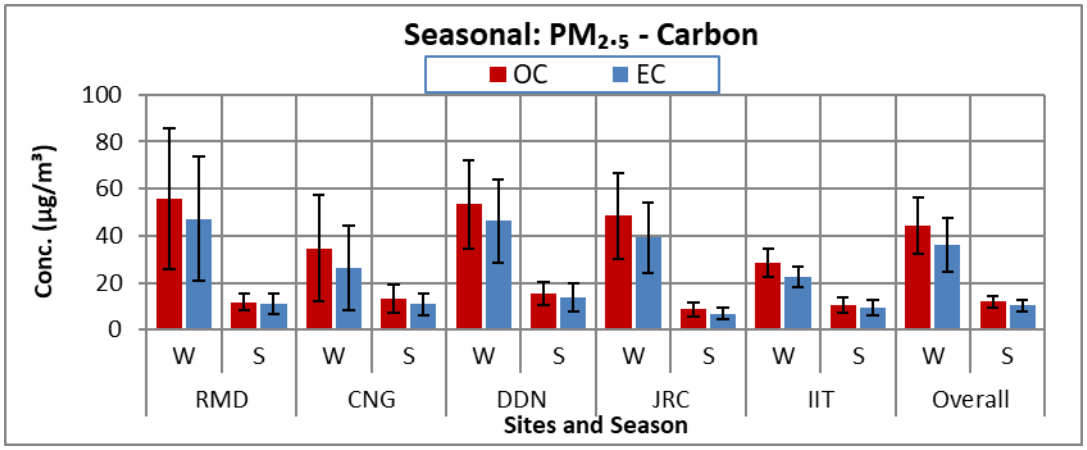


Figure 2.70: Seasonal Comparison of EC and OC in $PM_{2.5}$ for all Sites

2.4.6.5 PAHs in $PM_{2.5}$

The average concentrations of PAHs are shown graphically for the winter season (Figure 2.71) and summer season (Figure 2.72) for all sites along with the overall average concentration for Kanpur. Average concentrations are shown in Tables 2.74 – 2.75 with the standard deviation and coefficient of variation CV for Kanpur City. The PAHs compounds analyzed are (i) DmP, (ii) AcP, (iii) DEP, (iv) Flu, (v) Phe, (vi) Ant, (vii) Pyr, (viii) BbP, (ix) BeA, (x) B(a)A, (xi) Chr, (xii) B(b)F, (xiii) B(k)F, (xiv) B(a)P, (xv) InP, (xvi) D(a,h)A and (xvii) B(ghi)P. Seasonal comparisons for PAHs are shown in Figure 2.73, indicating that the concentrations are significantly higher in the winter season than in the summer season. Major PAHs are DmP, InP, B(ghi)P, B(b)F, B(k)F and Chr. The overall average total PAHs were much higher in winter (105±60 ng/m^3) than in summer (65±35 ng/m^3). B(a)P, although has the annual standard of 1 ng/m^3 and we cannot compare it with levels of 20 days, however levels of B(a)P (winter mean: 3.7 and summer mean: 3.2 ng/m^3) were high and annual standard is most likely to exceed by a fair margin at all sites in the winter season and meet at most sites except at RMD in the summer season.

Literature reported values for InP/(InP + B(ghi)P) ratio are 0.18, 0.37 and 0.56 for gasoline, diesel and coal respectively (Rajput and Lakhani, 2010). The ratio obtained in this study (0.54 in winter and 0.56 in summer) is comparable to the reported values for coal combustion in the winter and summer seasons. It is inferred that the major source of PAHs is coal combustion and other source is diesel vehicles.

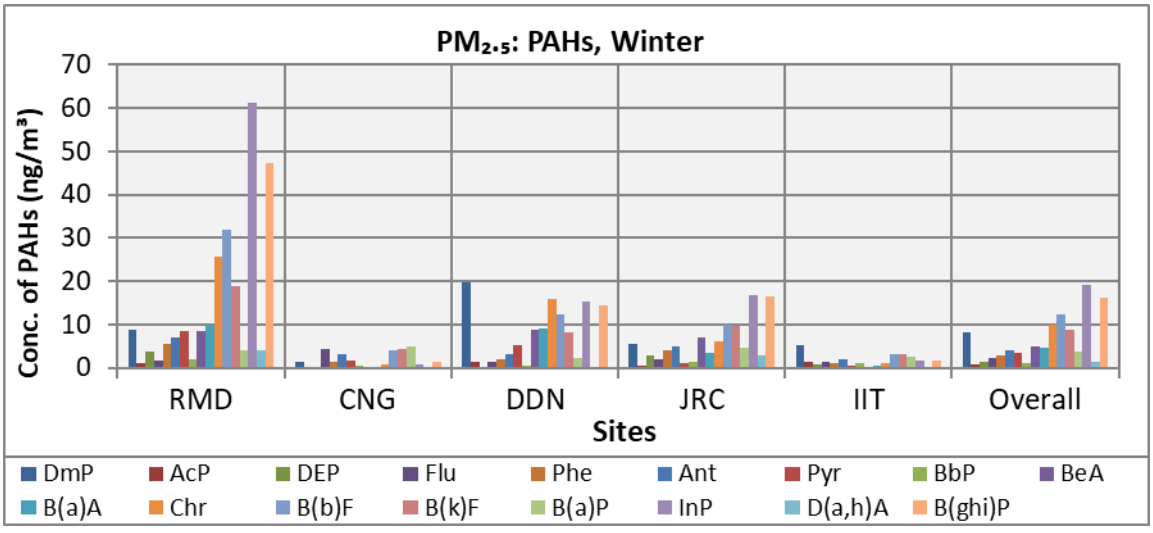


Figure 2.71: Variation in PAHs in $PM_{2.5}$ for winter season

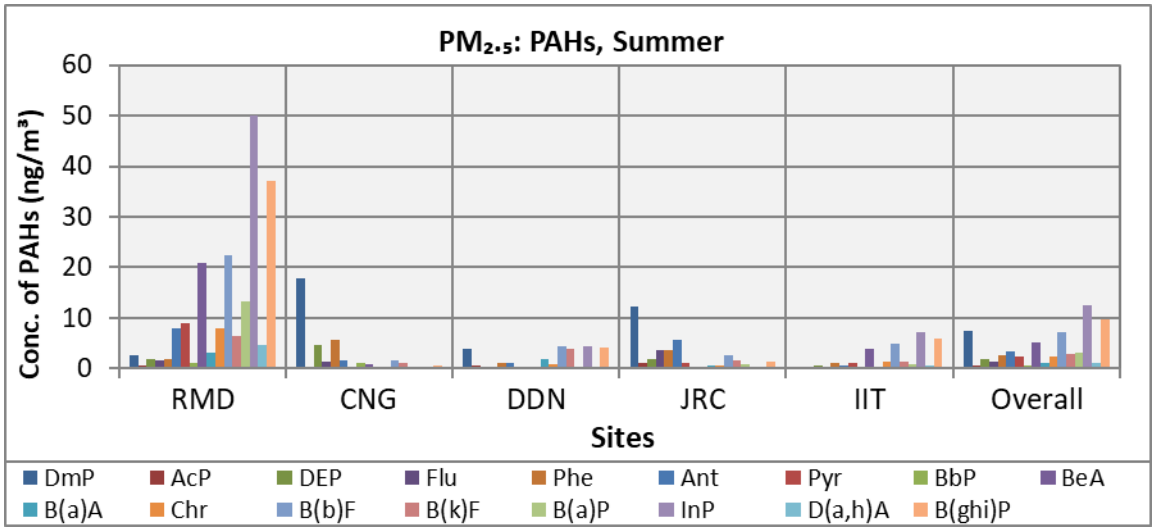


Figure 2.72: Variation in PAHs in $PM_{2.5}$ for summer season

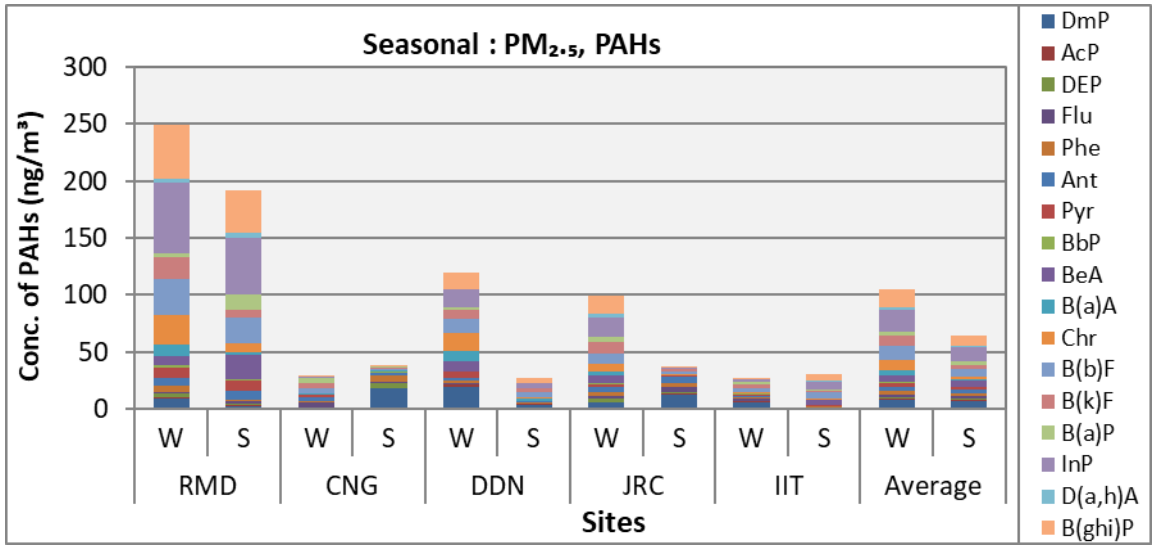


Figure 2.73: Seasonal comparison of PAHs in $PM_{2.5}$

2.4.6.6 Chemical Composition of PM_{10} and $PM_{2.5}$

Graphical presentation for seasonal comparison for chemical species [(a) Anions, (b) Cations and (c) Elements) are shown for PM_{10} (Figure 2.74 (a), (b) and (c)) and $PM_{2.5}$ (Figure 2.75 (a), (b) and (c)). Overall summary of average concentrations for all sites along with overall average, standard deviation (SD) and coefficient of variation (CV) for PM (PM_{10} and $PM_{2.5}$), its composition [carbon content (EC and OC), ionic species (F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Mg^{+2}, Ca^{+2}) and elements (Be, B, Na, Mg, Al, Si, P, K, Ca, Cr, V, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, Pb)] along with mass percentage (%R) estimated in composition are presented in Tables 2.76 – 2.79 for winter and summer seasons.

The statistical summary of the major components (i.e., crustal elements – Si, Ai, Fe, Ca; Secondary ions - NO_3^-, SO_4^{-2}, NH_4^+; TC) in PM_{10} and $PM_{2.5}$ are presented in Tables 2.81 – 2.84 for winter and summer seasons.

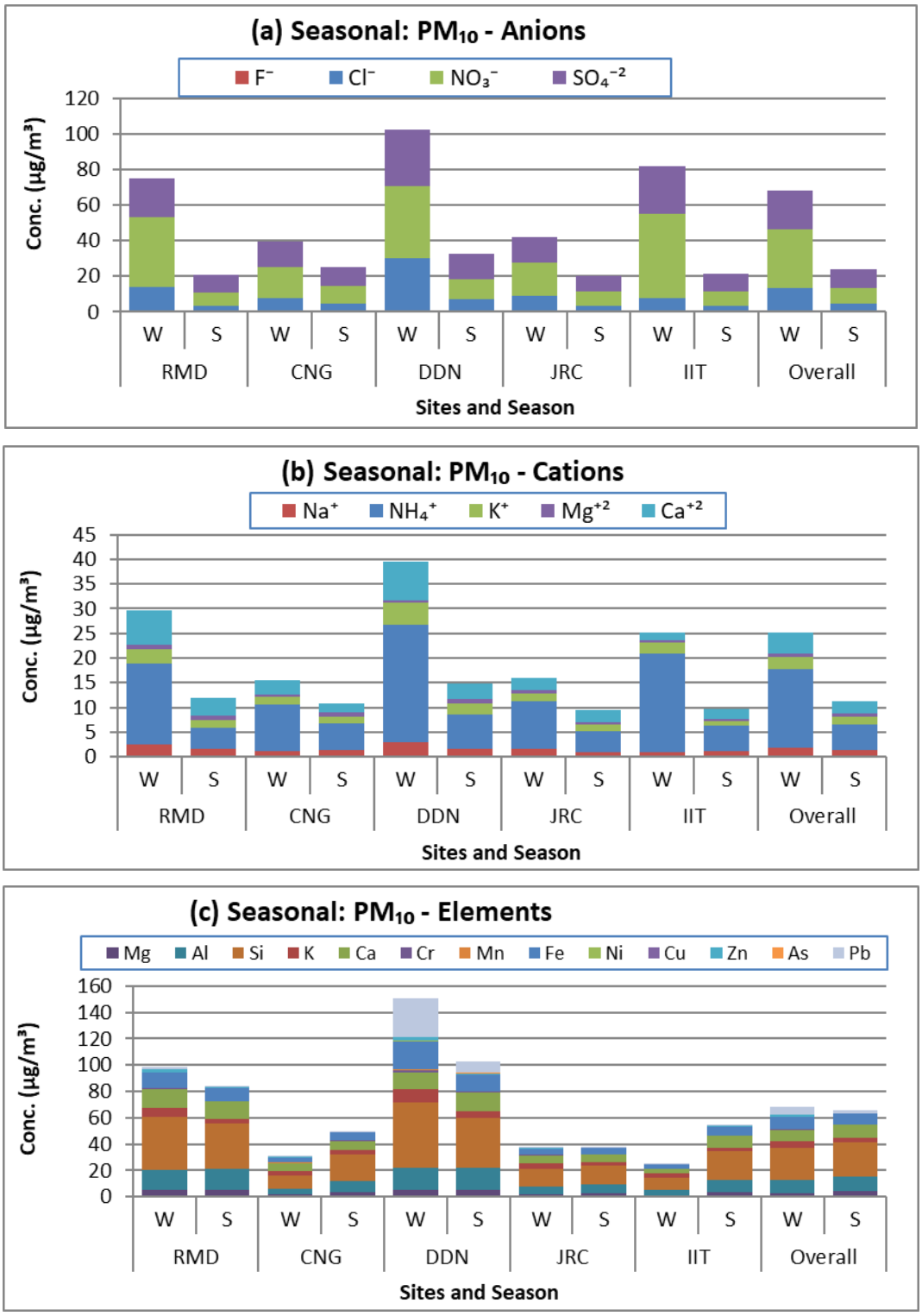


Figure 2.74: Seasonal comparison of ionic and elemental species concentrations in PM_{10} for all sites

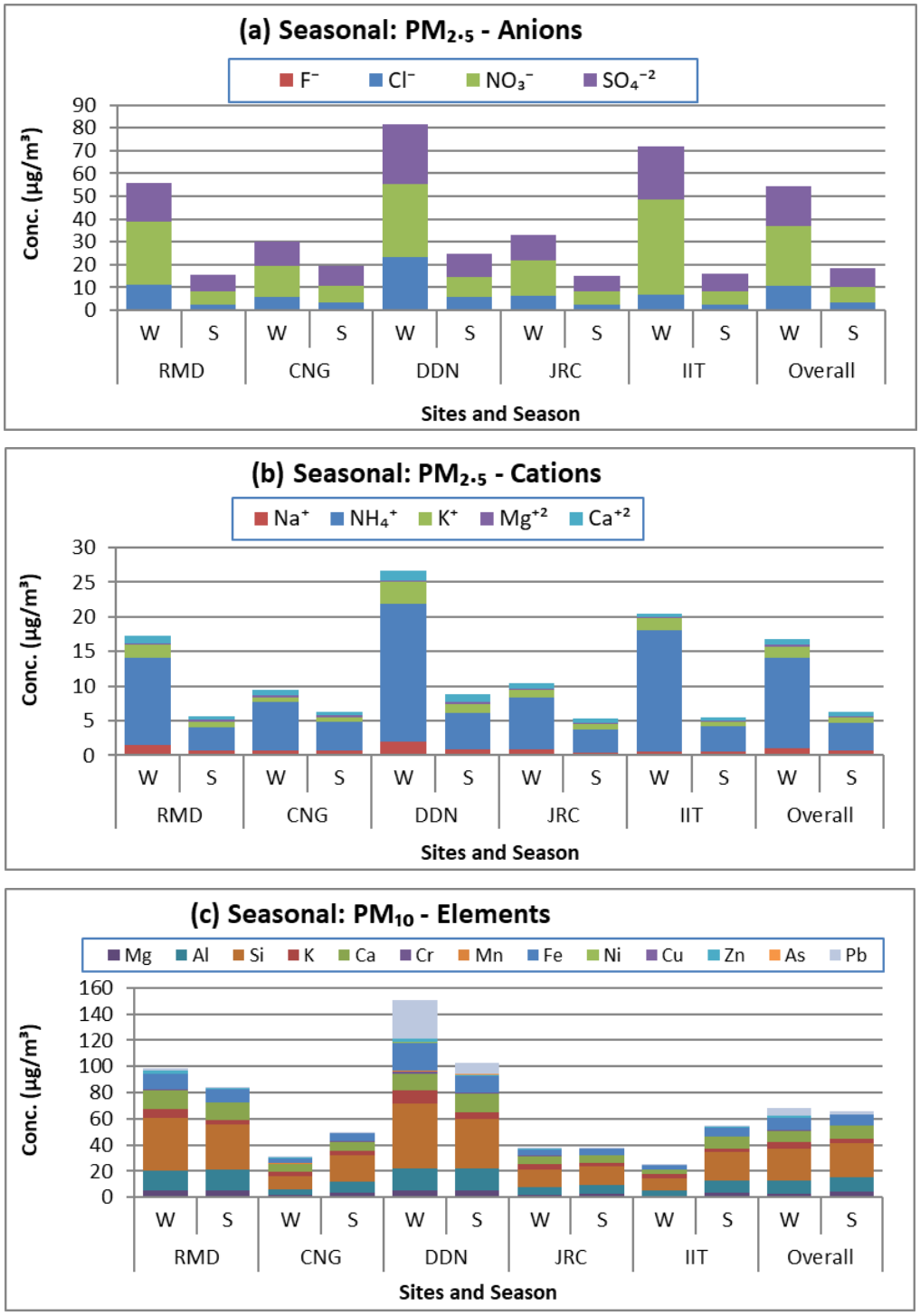


Figure 2.75: Seasonal comparison of ionic and elemental species concentrations in $PM_{2.5}$ for all sites

2.4.6.7 Comparison of PM_{10} and $PM_{2.5}$ Composition

The graphical presentation is the better option for understanding the compositional variation. The major chemical species considered for overall compositional comparisons are carbon (OC and EC), ions (F^-, Cl^-, NO_3^-, SO_4^{-2}, Na^+, NH_4^+, K^+, Mg^{+2}, Ca^{+2}) and elements (Na, Mg, Al, Si, P,

K, Ca, Cr, V, Mn, Fe, Ni, Zn, As, Cd, Ba and Pb). Compositional comparison of $PM_{2.5}$ vs PM_{10} is shown for all major carbon, ions (Figure 2.84) and elements (Figure 2.85) for all sites and both seasons in Kanpur. The overall compositional comparison is also presented in Table 2.80 for all sites.

It is observed that a significant portion of PM has more fine-mode particles during winter (65%) than in summer (38%). The major species contributing to fine mode are TC, EC, OC, Cl^{-}, NO_3^{-}, SO_4^{-2}, NH_4^{+}, K^{+}, Be, B, V, Cu and Cd; whereas, major species contributing in coarse mode are Mg^{+2}, Ca^{+2}, Mg, Al, Si, P, Ca, Cr, Mn, Fe, Sr and Ba (Figures 2.76 and 2.77).

The average ratio ($PM_{2.5}/PM_{10}$) was taken from the previous studies (Puxbaum et al., 2004; Samara et al., 2014; Wang et al., 2014) for EC (0.70) and OC (0.83) to estimate the carbon content in PM_{10}. Therefore, the percentage of EC (70%) and OC (83%) are constant for all sites by converting from levels known in $PM_{2.5}$ and translating these into EC and OC levels of PM_{10}.

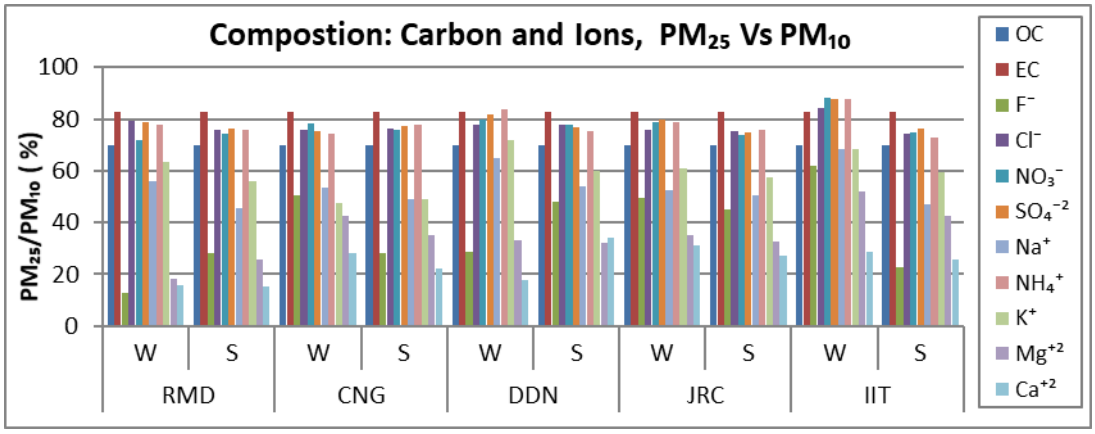


Figure 2.76: Compositional comparison of carbon and ions species in $PM_{2.5}$ Vs PM_{10}

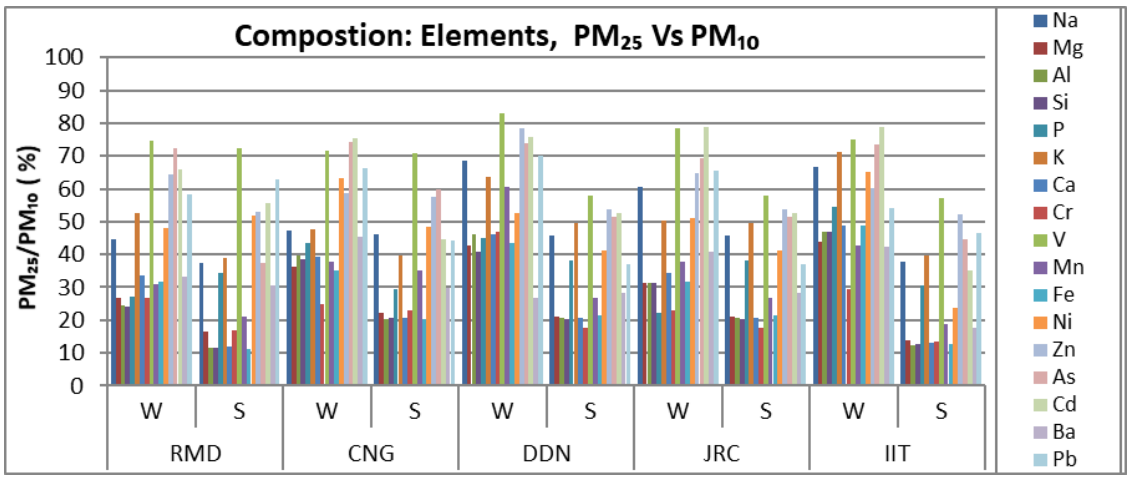


Figure 2.77: Ratio elemental components in $PM_{2.5}$ and PM_{10}

Table 2.69: Overall summary of experimental results of PM (mean±SD µg/m^3)

PM	PM_{10}		$PM_{2.5}$		$PM_{2.5}/PM_{10}$	
Sites	Winter	Summer	Winter	Summer	Winter	Summer
RMD	480±303 (0.63)	239±68 (0.28)	273±132 (0.48)	73±20 (0.27)	0.61±0.13 (0.21)	0.31±0.07 (0.22)
CNG	220±121 (0.55)	177±49 (0.28)	146±102 (0.70)	79±24 (0.31)	0.64±0.10 (0.16)	0.46±0.09 (0.19)
DDN	598±227 (0.38)	297±68 (0.23)	388±190 (0.49)	116±32 (0.28)	0.64±0.08 (0.12)	0.39±0.08 (0.21)
JRC	287±86 (0.30)	133±53 (0.40)	186±46 (0.25)	57±21 (0.37)	0.66±0.09 (0.13)	0.44±0.07 (0.15)
IIT	249±49 (0.19)	178±69 (0.39)	196±40 (0.20)	66±17 (0.26)	0.78±0.02 (0.03)	0.39±0.11 (0.28)
Overall	367±164 (0.45)	205±64 (0.31)	238±96 (0.40)	78±23 (0.29)	0.67±0.07 (0.10)	0.40±0.06 (0.14)
Values show in parenthesis are the coefficient of variation (CV)						

Table 2.70: Overall summary of average concentration (µg/m^3) of gaseous pollutants (SO_2, NO_2 and VOCs) for winter season

Winter	NO_2	SO_2	Benzene	Toluene	P-Xylene	O-Xylene	Total (BTX)
RMD	53.60	2.86	3.08	5.25	1.37	1.17	10.87
CNG	45.92	2.88	2.07	3.38	0.66	0.66	6.77
DDN	74.35	20.20	3.96	21.24	1.18	1.30	27.67
JRC	51.19	5.08	4.72	7.91	0.81	0.74	14.18
IIT	13.29	2.00	1.06	0.84	0.41	0.43	2.74
Overall	47.67	6.60	2.98	7.73	0.89	0.86	12.45
SD	9.48	1.57	1.84	6.47	0.88	0.83	8.62
CV	0.20	0.24	0.62	0.84	0.99	0.96	0.69

Table 2.71: Overall summary of average concentration (µg/m^3) of gaseous pollutants (SO_2, NO_2 and VOCs) for summer season

Summer	NO_2	SO_2	Benzene	Toluene	P-Xylene	O-Xylene	Total (BTX)
RMD	55.07	2.62	3.00	3.70	0.58	2.70	9.99
CNG	33.05	2.58	2.02	3.10	0.48	0.45	6.05
DDN	36.48	5.64	3.82	40.49	0.38	0.38	45.07
JRC	36.26	3.21	2.28	3.06	0.24	2.17	7.75
IIT	12.00	2.00	2.23	3.73	0.34	0.38	6.68
Overall	34.57	3.21	2.67	10.82	0.41	1.22	15.11
SD	6.26	1.21	1.70	14.93	0.27	0.33	16.71
CV	0.18	0.38	0.64	1.38	0.66	0.27	1.11

Table 2.72: Overall summary of average concentration of carbon content in $PM_{2.5}$ for all sites for winter Season

Winter	$PM_{2.5}$	TC	OC	EC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
RMD	272.9	112.3	60.7	51.5	6.90	20.92	22.47	10.45	0.055	0.184	0.204	0.101
CNG	145.9	61.1	34.7	26.4	3.03	12.24	13.09	6.37	0.042	0.199	0.217	0.116
DDN	388.0	99.7	53.4	46.3	5.95	17.18	19.85	10.39	0.055	0.170	0.203	0.111
JRC	186.2	131.9	71.1	60.8	6.47	23.97	28.72	11.92	0.047	0.187	0.208	0.113
IIT	195.8	51.0	28.6	22.4	2.84	8.87	10.95	5.95	0.052	0.173	0.216	0.119
Overall	238	91.2	49.7	41.5	5.04	16.64	19.02	9.02	0.050	0.183	0.210	0.112
SD	86	30.6	15.9	14.8	1.75	5.51	6.43	2.40	0.005	0.010	0.006	0.006
CV	0.36	0.34	0.32	0.36	0.35	0.33	0.34	0.27	0.103	0.057	0.027	0.055

Table 2.73: Overall summary of average concentration of carbon content in $PM_{2.5}$ for all sites for summer season

Summer	$PM_{2.5}$	TC	OC	EC	OC1	OC2	OC3	OC4	OC1/TC	OC2/TC	OC3/TC	OC4/TC
RMD	72.5	23.2	11.9	11.3	0.07	3.94	5.05	2.82	0.002	0.168	0.221	0.129
CNG	79.1	24.0	13.1	10.9	0.22	4.42	5.37	3.09	0.009	0.182	0.225	0.128
DDN	116.0	29.1	15.3	13.8	0.61	4.73	6.60	3.35	0.018	0.163	0.228	0.128
JRC	57.4	15.6	8.8	6.8	0.06	2.84	3.44	2.42	0.004	0.183	0.224	0.158
IIT	65.5	19.9	10.5	9.4	0.39	3.44	4.30	2.35	0.017	0.174	0.219	0.126
Overall	78.1	22.3	11.9	10.4	0.27	3.87	4.95	2.80	0.010	0.174	0.223	0.134
SD	20.3	4.5	2.2	2.3	0.21	0.68	1.06	0.38	0.006	0.008	0.003	0.012
CV	0.26	0.20	0.19	0.22	0.77	0.17	0.21	0.14	0.645	0.045	0.014	0.090

Table 2.74: Overall summary of average concentration (ng/m^3) of PAHs in $PM_{2.5}$ all sites for winter season

Winter	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
RMD	8.73	1.07	3.69	1.69	5.45	6.89	8.49	2.02	8.57	9.97	25.64	31.86	18.91	4.00	61.32	4.06	47.21	249.56
CNG	1.42	0.19	0.07	4.22	1.44	3.26	1.80	0.48	0.13	0.34	0.83	3.98	4.31	4.88	0.77	0.09	1.45	29.65
DDN	19.62	1.43	0.28	1.33	2.02	3.09	5.22	0.38	8.82	9.01	15.78	12.21	8.08	2.39	15.27	0.00	14.57	119.50
JRC	5.58	0.62	2.77	2.02	4.00	4.84	1.19	1.37	7.04	3.49	6.26	9.94	9.75	4.66	16.76	2.96	16.46	99.74
IIT	5.38	1.28	0.71	1.40	1.11	1.94	0.40	1.05	0.27	0.46	0.98	3.31	3.15	2.62	1.56	0.01	1.80	27.42
Overall	8.14	0.92	1.51	2.13	2.81	4.00	3.42	1.06	4.96	4.65	9.90	12.26	8.84	3.71	19.13	1.42	16.30	105.17
SD	4.85	1.02	1.68	2.38	3.29	4.34	3.08	1.53	11.81	5.05	8.22	9.49	7.21	6.35	15.26	3.68	12.41	59.84
CV	0.60	1.11	1.12	1.12	1.17	1.08	0.90	1.45	2.38	1.08	0.83	0.77	0.82	1.71	0.80	2.59	0.76	0.57

Table 2.75: Overall summary of average concentration (ng/m^3) of PAHs in $PM_{2.5}$ for all sites for summer season

Summer	DmP	AcP	DEP	Flu	Phe	Ant	Pyr	BbP	BeA	B(a)A	Chr	B(b)F	B(k)F	B(a)P	InP	D(a,h)A	B(ghi)P	Total PAHs
RMD	2.58	0.57	1.78	1.52	1.95	7.92	8.88	1.15	20.76	3.03	8.01	22.49	6.38	13.29	50.11	4.70	37.13	192.26
CNG	17.85	0.39	4.52	1.30	5.55	1.62	0.29	0.97	0.89	0.32	0.33	1.49	1.06	0.40	0.20	0.00	0.50	37.66
DDN	3.75	0.55	0.33	0.21	0.95	1.04	0.10	0.25	0.03	1.70	0.92	4.46	3.93	0.32	4.25	0.02	4.10	26.91
JRC	12.30	1.04	1.90	3.70	3.55	5.66	1.15	0.18	0.04	0.45	0.54	2.68	1.61	0.86	0.34	0.00	1.20	37.20
IIT	0.11	0.15	0.44	0.18	1.14	0.53	1.14	0.29	3.98	0.37	1.33	4.77	1.34	0.89	7.26	0.58	5.91	30.41
Overall	7.32	0.54	1.79	1.38	2.63	3.35	2.31	0.57	5.14	1.18	2.23	7.18	2.86	3.15	12.43	1.06	9.77	64.89
SD	5.76	0.50	2.02	1.52	2.54	3.09	2.33	0.68	3.01	1.56	1.81	4.06	1.75	3.43	10.84	0.79	8.25	35.39
CV	0.79	0.92	1.13	1.10	0.97	0.92	1.01	1.20	0.59	1.33	0.81	0.57	0.61	1.09	0.87	0.74	0.84	0.55

Table 2.76: Overall summary of average concentration of chemical species in PM_{10} for all sites for winter season

Winter	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
RMD	480	80.0	56.8	0.18	13.70	39.23	21.55	2.56	16.30	3.05	0.71	6.99	1E-2	0.64	5.46	4.85	15.55	40.20	0.84
CNG	220	49.6	31.8	0.08	7.35	17.44	14.27	1.19	9.45	1.61	0.44	2.80	4E-3	0.21	1.93	1.70	4.47	9.73	0.09
DDN	598	76.2	55.8	0.23	29.88	40.32	32.11	2.99	23.76	4.53	0.43	7.84	9E-3	0.25	5.44	5.18	17.14	49.30	0.88
JRC	287	69.2	47.1	0.06	8.60	19.15	14.25	1.61	9.62	1.64	0.66	2.53	3E-3	0.14	2.66	2.10	5.57	13.88	0.10
IIT	249	40.9	27.0	0.07	7.85	47.09	26.73	0.85	19.96	2.37	0.33	1.66	2E-3	0.08	1.71	1.34	3.85	8.99	0.07
Overall	367	63.2	43.7	0.12	13.48	32.65	21.78	1.84	15.82	2.64	0.51	4.36	6E-3	0.26	3.44	3.03	9.32	24.42	0.39
SD	164	17.1	13.7	0.08	9.51	13.45	7.82	0.91	6.31	1.21	0.16	2.84	4E-3	0.22	1.87	1.83	6.47	18.93	0.42
CV	0.45	0.27	0.31	0.63	0.71	0.41	0.36	0.49	0.40	0.46	0.32	0.65	0.69	0.83	0.54	0.60	0.69	0.78	1.07
Winter	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
RMD	6.89	14.02	0.95	0.74	0.31	11.20	0.025	0.041	0.15	2.90	0.054	0.024	0.077	0.118	0.057	0.029	0.24	1.47	71.32
CNG	3.68	5.97	0.22	0.57	0.08	3.41	0.019	0.022	0.07	0.65	0.018	0.014	0.027	0.042	0.023	0.001	0.08	0.26	74.06
DDN	9.74	13.28	1.07	0.58	0.75	21.84	0.027	0.062	0.22	2.76	0.156	0.063	0.072	0.103	0.380	0.029	0.40	29.17	70.78
JRC	3.68	6.24	0.29	0.48	0.11	4.14	0.015	0.024	0.07	0.66	0.022	0.012	0.027	0.042	0.028	0.001	0.09	0.36	73.26
IIT	3.71	3.40	0.11	0.33	0.04	2.79	0.009	0.017	0.04	0.54	0.033	0.013	0.024	0.033	0.023	0.007	0.05	0.17	78.88
Overall	5.54	8.58	0.52	0.54	0.26	8.68	0.019	0.033	0.11	1.50	0.057	0.025	0.045	0.068	0.102	0.013	0.17	6.29	73.66
SD	2.73	4.76	0.45	0.15	0.29	8.10	0.007	0.018	0.07	1.21	0.057	0.022	0.027	0.040	0.156	0.014	0.15	12.81	3.21
CV	0.49	0.56	0.85	0.28	1.14	0.93	0.39	0.55	0.66	0.81	1.01	0.87	0.59	0.59	1.53	1.08	0.84	2.04	0.04

Table 2.77: Overall summary of average concentration of chemical species in $PM_{2.5}$ for all sites for winter season

Winter	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
RMD	273	56.0	47.1	0.02	10.89	28.15	16.93	1.44	12.64	1.94	0.13	1.08	9E-3	0.43	2.44	1.30	3.78	9.66	0.23
CNG	146	34.7	26.4	0.04	5.57	13.68	10.79	0.64	7.00	0.77	0.19	0.79	3E-3	0.13	0.91	0.62	1.77	3.75	0.04
DDN	388	53.4	46.3	0.07	23.23	32.15	26.21	1.94	19.90	3.25	0.14	1.38	8E-3	0.15	3.74	2.22	7.93	20.07	0.39
JRC	186	48.5	39.1	0.03	6.51	15.11	11.40	0.84	7.56	1.00	0.23	0.78	3E-3	0.06	1.61	0.65	1.75	4.35	0.02
IIT	196	28.6	22.4	0.04	6.61	41.65	23.51	0.58	17.54	1.63	0.17	0.47	2E-3	0.04	1.14	0.59	1.80	4.23	0.04
Overall	238	44.2	36.3	0.04	10.56	26.15	17.77	1.09	12.93	1.72	0.17	0.90	5E-3	0.16	1.97	1.08	3.40	8.41	0.14
SD	96	12.0	11.4	0.02	7.37	11.81	6.97	0.59	5.78	0.98	0.04	0.34	3E-3	0.16	1.15	0.70	2.67	6.95	0.16
CV	0.40	0.27	0.31	0.41	0.70	0.45	0.39	0.54	0.45	0.57	0.23	0.38	0.69	0.97	0.58	0.66	0.79	0.83	1.13
Winter	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
RMD	3.62	4.69	0.25	0.55	0.10	3.55	0.019	0.02	0.07	1.87	0.04	0.018	0.030	0.04	0.04	0.024	0.08	0.86	75.60
CNG	1.75	2.34	0.05	0.41	0.03	1.21	0.015	0.01	0.05	0.38	0.01	0.011	0.016	0.02	0.02	0.001	0.04	0.17	77.96
DDN	6.18	6.14	0.50	0.48	0.45	9.49	0.020	0.03	0.13	2.17	0.12	0.047	0.040	0.05	0.29	0.025	0.11	20.48	74.80
JRC	1.86	2.16	0.07	0.38	0.04	1.31	0.012	0.01	0.05	0.43	0.02	0.008	0.015	0.02	0.02	0.001	0.04	0.24	76.82
IIT	2.64	1.66	0.03	0.25	0.02	1.36	0.007	0.01	0.03	0.33	0.02	0.008	0.014	0.02	0.02	0.005	0.02	0.09	78.85
Overall	3.21	3.40	0.18	0.41	0.13	3.38	0.015	0.02	0.06	1.03	0.04	0.019	0.023	0.03	0.08	0.011	0.06	4.37	76.81
SD	1.82	1.93	0.20	0.12	0.18	3.55	0.006	0.01	0.04	0.90	0.04	0.016	0.012	0.01	0.12	0.012	0.04	9.01	1.66
CV	0.57	0.57	1.10	0.28	1.44	1.05	0.38	0.49	0.62	0.87	1.02	0.89	0.50	0.43	1.55	1.12	0.62	2.06	0.02

Table 2.78: Overall summary of average concentration of chemical species in PM_{10} for all sites for summer season

Summer	PM_{10}	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
RMD	239	16.7	13.2	0.11	3.18	7.55	10.05	1.56	4.36	1.57	0.83	3.53	2E-3	0.03	2.94	5.51	15.44	34.59	0.23
CNG	177	18.7	13.1	0.16	4.46	9.64	11.13	1.37	5.31	1.40	1.01	1.83	1E-3	0.13	2.45	3.32	8.69	19.93	0.42
DDN	297	21.8	16.6	0.14	7.18	11.23	13.80	1.68	6.99	2.07	0.89	3.18	3E-3	0.05	3.07	5.19	16.52	38.25	0.16
JRC	133	12.5	8.2	0.06	3.32	7.86	8.70	0.86	4.40	1.25	0.45	2.47	9E-4	0.06	1.39	2.61	6.49	15.00	0.28
IIT	178	15.0	11.3	0.13	3.27	8.02	9.96	1.16	5.09	1.05	0.41	1.87	5E-4	0.08	2.10	3.42	9.63	21.78	0.17
Overall	205	16.9	12.5	0.12	4.28	8.86	10.73	1.32	5.23	1.47	0.72	2.58	2E-3	0.07	2.39	4.01	11.35	25.91	0.25
SD	64	3.6	3.1	0.04	1.70	1.55	1.92	0.33	1.07	0.39	0.27	0.76	1E-3	0.04	0.68	1.27	4.39	10.00	0.10
CV	0.31	0.21	0.25	0.30	0.40	0.18	0.18	0.25	0.20	0.26	0.38	0.30	0.70	0.56	0.28	0.32	0.39	0.39	0.41
Summer	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
RMD	3.73	12.99	0.26	0.43	0.15	10.11	0.005	0.011	0.025	0.477	0.012	0.004	0.012	0.025	0.009	0.001	0.07	0.21	60.03
CNG	3.52	7.09	0.37	0.25	0.15	6.03	0.007	0.014	0.049	0.106	0.012	0.006	0.021	0.041	0.013	0.002	0.11	0.23	65.71
DDN	5.07	14.25	0.49	0.58	0.27	12.67	0.014	0.015	0.057	1.122	0.034	0.010	0.015	0.032	0.049	0.002	0.12	8.68	62.30
JRC	2.26	5.35	0.18	0.45	0.08	4.87	0.018	0.019	0.010	0.324	0.014	0.007	0.007	0.007	0.009	0.001	0.03	0.39	64.33
IIT	2.53	8.87	0.30	0.46	0.11	6.38	0.003	0.019	0.017	0.515	0.010	0.008	0.011	0.014	0.006	0.001	0.04	0.11	62.49
Overall	3.42	9.71	0.32	0.43	0.15	8.01	0.009	0.016	0.031	0.509	0.016	0.007	0.013	0.024	0.017	0.001	0.07	1.93	62.97
SD	1.11	3.81	0.12	0.12	0.07	3.26	0.006	0.003	0.020	0.378	0.010	0.002	0.005	0.013	0.018	0.000	0.04	3.78	2.16
CV	0.33	0.39	0.37	0.28	0.48	0.41	0.65	0.21	0.64	0.74	0.61	0.31	0.41	0.57	1.05	0.30	0.60	1.96	0.03

Table 2.79: Overall summary of average concentration of chemical species in $PM_{2.5}$ for all sites for summer season

summer	$PM_{2.5}$	OC	EC	F^-	Cl^-	NO_3^-	SO_4^{-2}	Na^+	NH_4^+	K^+	Mg^{+2}	Ca^{+2}	Be	B	Na	Mg	Al	Si	P
RMD	73	11.7	11.0	0.03	2.41	5.61	7.69	0.71	3.30	0.88	0.21	0.54	1E-3	0.02	1.09	0.91	1.77	4.01	0.08
CNG	79	13.1	10.9	0.04	3.41	7.31	8.62	0.67	4.13	0.69	0.35	0.41	5E-4	0.08	1.13	0.74	1.76	4.11	0.12
DDN	116	15.3	13.8	0.07	5.57	8.73	10.59	0.91	5.27	1.23	0.29	1.09	2E-3	0.02	1.50	1.18	3.26	7.54	0.08
JRC	57	8.8	6.8	0.03	2.49	5.81	6.52	0.43	3.34	0.71	0.15	0.67	5E-4	0.03	0.64	0.55	1.34	3.07	0.11
IIT	64	10.5	9.4	0.03	2.43	6.02	7.62	0.55	3.70	0.62	0.17	0.48	3E-4	0.04	0.79	0.47	1.19	2.76	0.05
Overall	78	11.9	10.4	0.04	3.26	6.70	8.21	0.65	3.95	0.83	0.23	0.64	9E-4	0.04	1.03	0.77	1.86	4.30	0.09
SD	23	2.5	2.6	0.02	1.36	1.32	1.52	0.18	0.81	0.25	0.08	0.27	9E-4	0.02	0.33	0.29	0.82	1.90	0.03
CV	0.30	0.21	0.25	0.41	0.42	0.20	0.19	0.27	0.21	0.30	0.36	0.42	0.90	0.69	0.32	0.37	0.44	0.44	0.30
Summer	K	Ca	Cr	V	Mn	Fe	Co	Ni	Cu	Zn	As	Se	Rb	Sr	Cd	Cs	Ba	Pb	% R
RMD	1.46	1.54	0.04	0.31	0.03	1.15	0.003	0.006	0.014	0.25	0.00	0.002	0.003	0.006	0.005	0.000	0.022	0.135	75.21
CNG	1.40	1.46	0.09	0.17	0.05	1.23	0.005	0.007	0.024	0.06	0.01	0.002	0.006	0.008	0.006	0.001	0.034	0.102	76.39
DDN	2.30	2.78	0.18	0.36	0.10	2.70	0.005	0.005	0.035	0.38	0.02	0.004	0.004	0.011	0.029	0.001	0.040	3.389	73.47
JRC	1.12	1.10	0.03	0.26	0.02	1.05	0.008	0.008	0.004	0.17	0.01	0.003	0.002	0.002	0.005	0.000	0.007	0.146	76.00
IIT	1.00	1.16	0.04	0.26	0.02	0.80	0.001	0.005	0.006	0.27	0.00	0.004	0.003	0.003	0.002	0.000	0.006	0.052	76.27
Overall	1.45	1.61	0.08	0.27	0.04	1.39	0.004	0.006	0.016	0.23	0.01	0.003	0.004	0.006	0.009	0.000	0.022	0.765	75.47
SD	0.51	0.68	0.06	0.07	0.03	0.75	0.003	0.001	0.013	0.12	0.00	0.001	0.002	0.004	0.011	0.000	0.015	1.468	1.21
CV	0.35	0.42	0.80	0.25	0.73	0.54	0.57	0.21	0.77	0.52	0.63	0.36	0.43	0.57	1.20	0.42	0.69	1.92	0.02

Table 2.80: Ratios of chemical species of $PM_{2.5}$ and PM_{10} for all sites for winter (W) and summer (S) seasons

Sites	RMD		CNG		DDN		JRC		IIT		Overall	
Season	W	S	W	S	W	S	W	S	W	S	W	S
PM_{10}	480	239	220	177	598	297	287	133	249	178	367	205
$PM_{2.5}$	273	73	146	79	388	116	186	57	196	64	238	78
$PM_{2.5}/PM_{10}$	57	30	66	45	65	39	65	43	79	36	65	38
TC ($PM_{2.5}/PM_{10}$)	75	76	75	75	75	76	75	75	75	76	75	76
OC ($PM_{2.5}/PM_{10}$)	70	70	70	70	70	70	70	70	70	70	70	70
EC ($PM_{2.5}/PM_{10}$)	83	83	83	83	83	83	83	83	83	83	83	83
F^- ($PM_{2.5}/PM_{10}$)	13	28	51	28	29	48	50	45	62	23	32	33
Cl^- ($PM_{2.5}/PM_{10}$)	79	76	76	76	78	78	76	75	84	74	78	76
NO_3^- ($PM_{2.5}/PM_{10}$)	72	74	78	76	80	78	79	74	88	75	80	76
SO_4^{-2} ($PM_{2.5}/PM_{10}$)	79	77	76	77	82	77	80	75	88	76	82	77
Na^+ ($PM_{2.5}/PM_{10}$)	56	46	54	49	65	54	52	50	68	47	59	49
NH_4^+ ($PM_{2.5}/PM_{10}$)	78	76	74	78	84	75	79	76	88	73	82	75
K^+ ($PM_{2.5}/PM_{10}$)	64	56	47	49	72	60	61	57	69	59	65	56
Mg^{+2} ($PM_{2.5}/PM_{10}$)	18	26	42	35	33	32	35	33	52	42	34	33
Ca^{+2} ($PM_{2.5}/PM_{10}$)	16	15	28	22	18	34	31	27	29	26	21	25
Be ($PM_{2.5}/PM_{10}$)	83	48	82	43	86	70	86	55	85	53	84	58
B ($PM_{2.5}/PM_{10}$)	67	54	60	59	58	46	42	45	53	46	61	52
Na ($PM_{2.5}/PM_{10}$)	45	37	47	46	69	49	61	46	66	38	57	43
Mg ($PM_{2.5}/PM_{10}$)	27	16	36	22	43	23	31	21	44	14	35	19
Al ($PM_{2.5}/PM_{10}$)	24	11	40	20	46	20	31	21	47	12	37	16
Si ($PM_{2.5}/PM_{10}$)	24	12	39	21	41	20	31	20	47	13	34	17
P ($PM_{2.5}/PM_{10}$)	27	34	43	30	45	49	22	38	54	31	37	35
K ($PM_{2.5}/PM_{10}$)	53	39	48	40	63	45	50	49	71	40	58	42
Ca ($PM_{2.5}/PM_{10}$)	33	12	39	21	46	20	35	21	49	13	40	17
Cr ($PM_{2.5}/PM_{10}$)	27	17	25	23	47	36	23	18	29	13	34	24
V ($PM_{2.5}/PM_{10}$)	75	72	72	71	83	62	78	58	75	57	77	63
Mn ($PM_{2.5}/PM_{10}$)	31	21	38	35	60	37	38	27	43	19	49	30
Fe ($PM_{2.5}/PM_{10}$)	32	11	35	20	43	21	32	22	49	13	39	17
Co ($PM_{2.5}/PM_{10}$)	79	61	77	73	76	39	83	43	78	27	78	47
Ni ($PM_{2.5}/PM_{10}$)	48	52	63	49	52	33	51	41	65	24	54	38
Cu ($PM_{2.5}/PM_{10}$)	47	55	68	49	59	61	62	42	69	36	58	52
Zn ($PM_{2.5}/PM_{10}$)	64	53	59	58	78	34	65	54	60	52	69	45
As ($PM_{2.5}/PM_{10}$)	72	37	74	60	74	49	69	52	73	45	73	49
Se ($PM_{2.5}/PM_{10}$)	77	42	78	35	74	45	72	44	62	43	74	42
Rb ($PM_{2.5}/PM_{10}$)	39	27	60	27	56	26	56	23	58	30	51	27
Sr ($PM_{2.5}/PM_{10}$)	33	23	52	21	46	34	50	31	58	25	44	26
Cd ($PM_{2.5}/PM_{10}$)	66	55	75	45	76	59	79	53	79	35	75	54
Cs ($PM_{2.5}/PM_{10}$)	83	30	66	33	87	37	50	35	77	24	83	33
Ba ($PM_{2.5}/PM_{10}$)	33	31	45	30	27	32	41	28	42	18	33	30
Pb ($PM_{2.5}/PM_{10}$)	58	63	66	44	70	39	66	37	54	46	69	40

Table 2.81: Mean of major components: PM_{10}, winter (µg/m^3)

Winter	PM_{10}	Crustal (Si + Al + Fe + Ca)	Ratio Crustal/PM_{10}	Sec Ions (NO_3^- + SO_4^{-2} + NH_4^+)	Ratio Sec Ions/PM_{10}	TC	Ratio TC/PM_{10}
RMD	480	81.0	0.169	77.1	0.161	136.8	0.285
CNG	220	23.6	0.107	41.2	0.187	81.4	0.369
DDN	598	101.6	0.170	96.2	0.161	132.0	0.221
JRC	287	29.8	0.104	43.0	0.150	116.4	0.405
IIT	249	19.0	0.076	93.8	0.376	67.9	0.272
Overall	367	51.0	0.125	70.2	0.207	106.9	0.311
SD	164	37.7	0.042	26.7	0.096	30.8	0.075
CV	0.45	0.74	0.34	0.38	0.46	0.29	0.24

Table 2.82: Statistical summary of major components: $PM_{2.5}$, winter (µg/m^3)

Winter	$PM_{2.5}$	Crustal (Si + Al + Fe + Ca)	Ratio Crustal/$PM_{2.5}$	Sec Ions (NO_3^- + SO_4^{-2} + NH_4^+)	Ratio Sec Ions/$PM_{2.5}$	TC	Ratio TC/$PM_{2.5}$
RMD	273	21.69	0.079	57.72	0.212	102.8	0.377
CNG	146	9.06	0.062	31.47	0.216	61.1	0.419
DDN	388	43.64	0.112	78.26	0.202	99.7	0.257
JRC	186	9.57	0.051	34.07	0.183	87.6	0.470
IIT	196	9.05	0.046	82.70	0.422	51.0	0.261
Overall	238	18.60	0.070	56.84	0.247	80.4	0.357
SD	96	15.00	0.027	23.93	0.099	23.2	0.095
CV	0.40	0.81	0.38	0.42	0.40	0.29	0.27

Table 2.83: Statistical summary of major components: PM_{10}, summer (µg/m^3)

Summer	PM_{10}	Crustal (Si + Al + Fe + Ca)	Ratio Crustal/PM_{10}	Sec Ions (NO_3^- + SO_4^{-2} + NH_4^+)	Ratio Sec Ions/PM_{10}	TC	Ratio TC/PM_{10}
RMD	239	73.1	0.306	22.0	0.092	29.9	0.125
CNG	177	41.7	0.236	26.1	0.147	31.9	0.180
DDN	297	81.7	0.275	32.0	0.108	38.5	0.129
JRC	133	31.7	0.239	21.0	0.158	20.7	0.156
IIT	178	46.7	0.263	23.1	0.130	26.3	0.148
Overall	205	55.0	0.264	24.8	0.127	29.4	0.148
SD	64	21.4	0.029	4.5	0.027	6.6	0.022
CV	0.31	0.39	0.11	0.18	0.21	0.22	0.15

Table 2.84: Statistical summary of major components: $PM_{2.5}$, summer (µg/m^3)

Summer	$PM_{2.5}$	Crustal (Si + Al + Fe + Ca)	Ratio Crustal/$PM_{2.5}$	Sec Ions (NO_3^- + SO_4^{-2} + NH_4^+)	Ratio Sec Ions/$PM_{2.5}$	TC	Ratio TC/$PM_{2.5}$
RMD	73	8.5	0.117	16.6	0.229	22.7	0.312
CNG	79	8.6	0.108	20.1	0.253	24.0	0.303
DDN	116	16.3	0.140	24.6	0.212	29.1	0.251
JRC	57	6.6	0.115	15.7	0.273	15.6	0.271
IIT	64	5.9	0.093	17.3	0.272	19.9	0.312
Overall	78	9.2	0.115	18.9	0.248	22.2	0.290
SD	23	4.1	0.017	3.6	0.027	5.0	0.028
CV	0.30	0.45	0.15	0.19	0.11	0.23	0.10

2.4.7 Statistical Summary

For the comparison of winter and summer air quality levels, box plots and Student t-test statistics were used. These are discussed in the following sections.

2.4.7.1 Box Plot Distribution

Statistical box plots are shown in Figures 2.78 to 2.83 for all sites for $PM_{2.5}$, PM_{10}, NO_2 and SO_2, EC and OC for winter (W) and summer (S) season. These figures show the mean, median, 25% quartile, 75% quartile and outliers of the data distribution. The outlier values could be possibly due to the local activities (i.e., DG sets emission, biomass burning, traffic congestion etc.) near the monitoring stations. The RMD and DDN sites show the largest variability and high pollution level, whereas residential areas show low variability in PM_{10} and $PM_{2.5}$. The same trend and pattern are applicable for NO_2, OC and EC. It is to be noted that variability is much higher in winter than in summer.

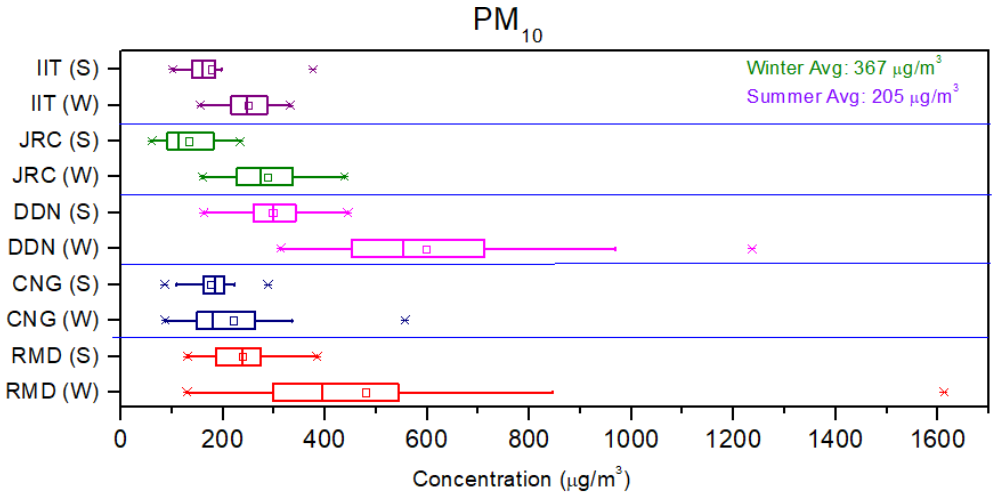


Figure 2.78: Box plot distribution for PM_{10} (winter and summer)

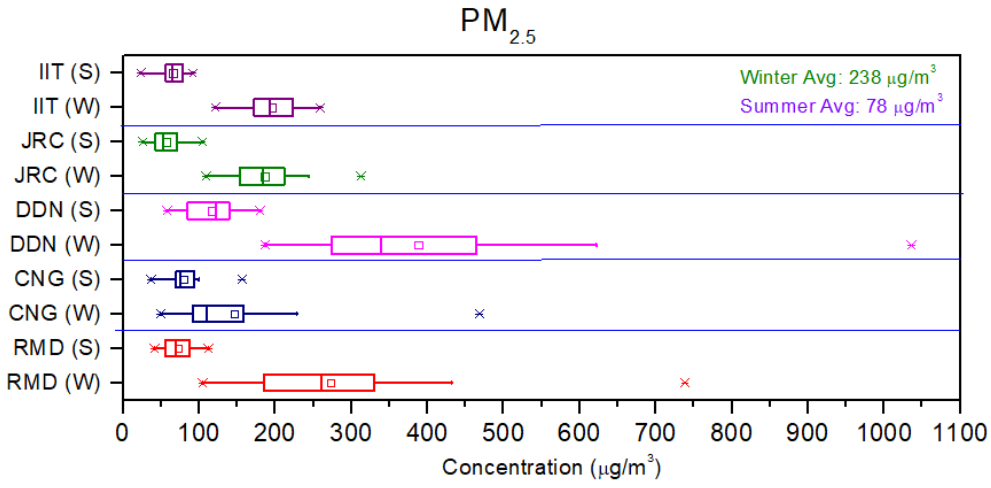


Figure 2.79: Box plot distribution for $PM_{2.5}$ (winter and summer)

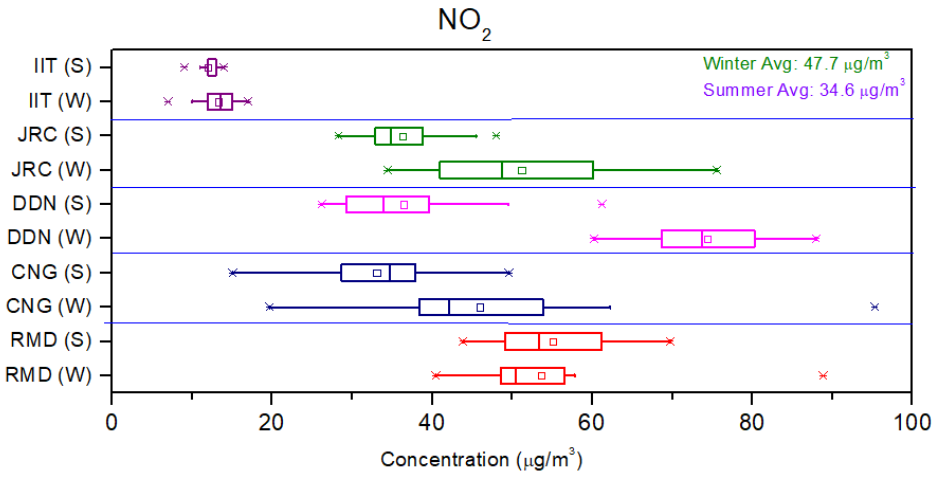


Figure 2.80: Box plot distribution for NO_2 (winter and summer)

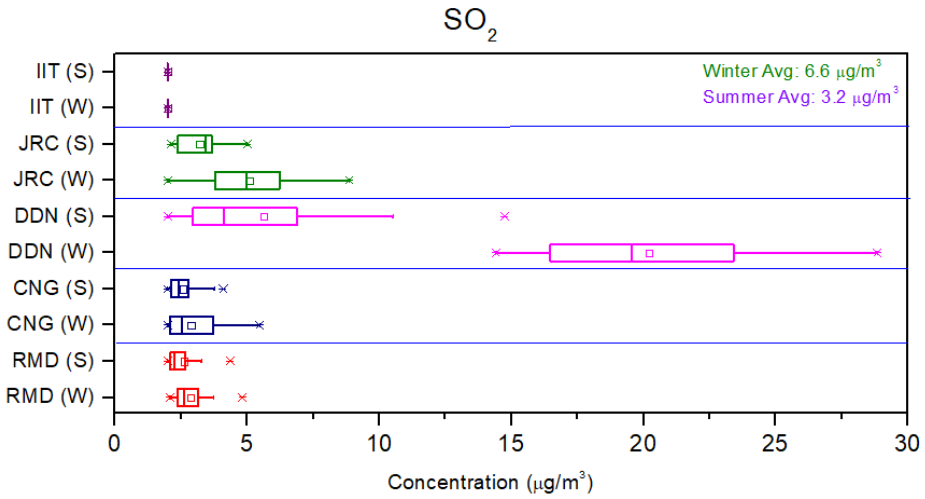


Figure 2.81: Box plot distribution for SO_2 (winter and summer)

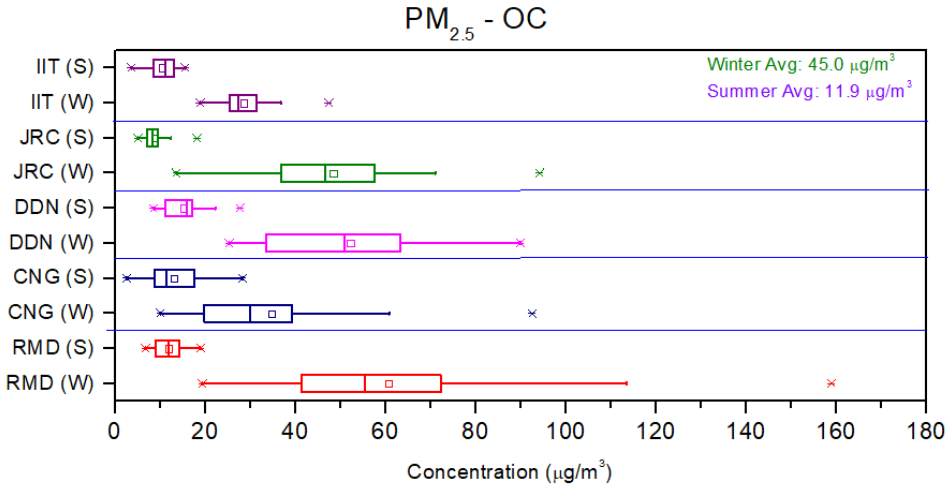


Figure 2.82: Box plot distribution for OC (winter and summer)

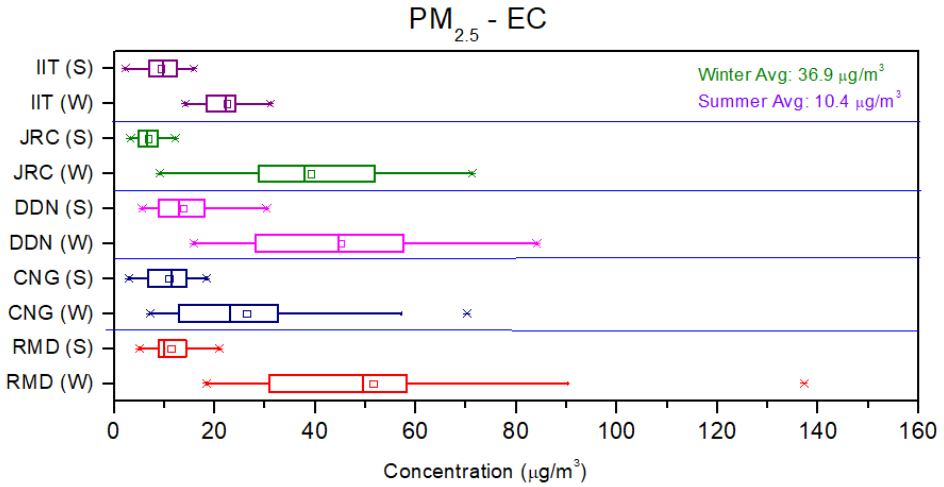


Figure 2.83: Box plot distribution for EC (winter and summer)

2.4.7.2 Statistics of t-Test for Seasonal Comparison

Student t-test statistics are performed at 5% level of significance to estimate if winter levels are higher (or lower) than summer levels for PM_{10}, $PM_{2.5}$, NO_2, SO_2 and carbon content (EC and OC). It is observed from Table 2.85 that in winter, $PM_{2.5}$, OC and EC levels are significantly higher at all sites, PM_{10} levels are higher at all sites except CNG, NO_2 levels are higher at all sites except RMD and SO_2 levels are higher at DDN and JRC. There is no significant difference in PM_{10} levels at CNG, in NO_2 levels at RMD and in SO_2 levels at RMD, CNG and IIT in summer and winter.

The information on the seasonal composition of PM can assist in identifying the various sources contributing to the ambient pollution level.

Table 2.85: Statistical Comparison Winter vs Summer

Parameter / Site	PM_{10}	$PM_{2.5}$	OC	EC	NO_2	SO_2
RMD	↑	↑	↑	↑	↔	↔
CNG	↔	↑	↑	↑	↑	↔
DDN	↑	↑	↑	↑	↑	↑
JRC	↑	↑	↑	↑	↑	↑
IIT	↑	↑	↑	↑	↑	↔

↔ No significant difference; ↑ (Levels higher in winter); ↓ (Levels lower in winter)

* No pollutant showed lower concentration in winter

2.5 Interpretations and Inferences

Based on the extensive air quality measurements in the summer and winter months and critical analyses of air quality data, the following inferences and insights are drawn for developing a causal relationship between emission and impact through receptor modeling (Chapters 4). The season-wise, site-specific average air concentration of PM_{10}, $PM_{2.5}$ and their compositions and gaseous pollutants (Tables 2.69 – 2.79 and 2.81 – 2.85) have been referred to bring the important inferences to the fore.

- Particulate pollution is the main concern in the city where PM_{10} levels are 2.2 – 6.0 times higher than the national air quality standards in the winter season and 1.3 – 3.0 times in the summer season. $PM_{2.5}$ levels are 2.4 – 6.5 times higher than the national standard in the winter season. In the summer, $PM_{2.5}$ levels exceed by 1.1 – 1.9 times the national standards except at JRC where $PM_{2.5}$ meets the standard.

- The chemical composition of PM_{10} and $PM_{2.5}$ carries the signature of sources and their harmful contents. The chemical composition is variable depending on the size fraction of particles and the season. The PM levels and chemical composition are discussed separately for two seasons.

PM_{10} (winter and summer)

The overall average concentration of PM_{10} was 367±164 µg/m^3 in winter and 205±64 µg/m^3 in summer against the acceptable level of 100 µg/m^3. The highest levels were observed at DDN (598±227 µg/m^3) and lowest at CNG (220±121 µg/m^3) in winter. In summer, the highest levels were at DDN (297±68 µg/m^3) and the lowest at JRC (133±53 µg/m^3).

In winter, crustal component (Si + Al + Fe + Ca) accounts for about 13% (much less compared to 26% in summer). This suggests soil and road dust have reduced significantly in PM_{10} in winter. The coefficient of variation (CV) is about 0.34 (of the fraction of crustal component), which suggests the crustal source contributes consistently even in winter, though much less than in summer.

In summer, the crustal component (Si + Al + Fe + Ca) accounts for about 26% of total PM_{10}. This suggests airborne soil and road dust are the major sources of PM_{10} pollution in summer. The coefficient of variation (CV) is about 0.11 (of the fraction of crustal component), which suggests the sources are consistent and uniform all around the city,

forming a layer that envelops the city. RMD has the highest crustal fraction (around 31% of total PM_{10}). It is difficult to pinpoint the crustal sources as these are widespread and present all around in Kanpur and are more prominent in summer when soil and dust are dry and high-speed winds make the particles airborne. It was observed that in summer, the atmosphere looks light brownish, which can be attributed to the presence of large amounts of soil dust particles in the atmosphere.

In winter, the other important component is the combustion-related total carbon (TC = EC + OC), which account for about 31% of total PM_{10} and secondary particles (NO_3^- + SO_4^{-2} + NH_4^+) accounts for about 21%; both fractions of secondary particles and combustion-related carbons have increased and account for 52% of PM_{10}.

In summer, the combustion-related total carbon (EC+OC) account for 15% of total PM_{10} and secondary particles (NO_3^- + SO_4^{-2} + NH_4^+) accounts for about 13%.

The Cl^- content in PM_{10} in winter is consistent and varies between 3 – 5%, an indicator of the burning of municipal and plastic solid waste (MSW); poly vinyl chloride (PVC) is a significant part of MSW. The highest Cl^- content is observed at DDN at 30 µg/m^3 compared to the overall city level of 13.5 µg/m^3. The Cl^- content in PM_{10} in summer is consistent at 1.3 – 2.5%. The high level at DDN signifies some local burning of waste either in industrial processes or as means of disposal of solid waste.

The lead (Pb) levels are highly variable, with city average of 6.29 µg/m^3 in winter and 1.93 µg/m^3 in summer. The maximum levels were at DDN in winter (29.2 µg/m^3) and summer (8.7 µg/m^3). The high levels of Pb signify the industrial emissions from lead smelting units the city. DDN is an industrial site having several lead smelting units.

$PM_{2.5}$

The overall average concentration of $PM_{2.5}$ is 238±96 µg/m^3 in winter and 78±23 µg/m^3 in summer and against the acceptable level of 60 µg/m^3. The highest levels are observed at DDN (388±190 µg/m^3) and lowest at CNG (146±102 µg/m^3) in winter. In summer, the highest levels were at DDN and the lowest at JRC.

The crustal component (Si + Al + Fe + Ca) accounts for about 7% in winter and 11% in summer in total $PM_{2.5}$. The CV is about 0.15 in summer, which suggests the source is consistent all around the city though relatively small in winter.

In winter, the important components are the combustion-related total carbon (TC=EC+OC), which account for 36% of total $PM_{2.5}$ and secondary particles ($NO_3^- + SO_4^{-2} + NH_4^+$) accounts for 25%; both secondary particles and combustion-related carbon are consistent contributors to $PM_{2.5}$ at about 61%. The highest TC level was observed at RMD (103 µg/m^3) and secondary particles at IIT (about 83 µg/m^3).

In summer, the combustion-related total carbon (EC+OC) account for 29% and secondary particles accounts for 25%; both secondary particles and combustion-related carbon are consistent contributors to $PM_{2.5}$ at about 54%. The highest TC was at DDN and secondary particles at CNG.

The Cl^- content in $PM_{2.5}$ was consistent in the winter and summer seasons and varied between 3 – 6%, which is an indicator of the burning of MSW. This is relatively lower in summer than in winter.

The maximum Pb levels were at DDN in winter (20.5 µg/m^3) and summer (3.39 µg/m^3). The high levels of Pb signify the industrial emissions from lead smelting units the city.

Potassium levels

In general, potassium levels are high and variable for PM_{10} (3.7 to 9.7 µg/m^3) in winter and drop in summer to 2.3 to 5.1 µg/m^3. In $PM_{2.5}$, potassium levels in winter vary between 1.8 to 6.2 µg/m^3. In general, the potassium levels are 2.0 µg/m^3 in urban areas. Potassium is an indicator of biomass burning and high levels and variability (CV ~ 0.60) show day-to-day variation in winter.

NO_2 levels

NO_2 levels in winter are higher than those in summer at all sites and the levels meet the national air quality standard of 80 µg/m^3, except some days at RMD and DDN. The highest NO_2 levels were at DDN in winter, an industrial site and at RMD in summer, a traffic site. In addition, high levels of NO_2 are expected to undergo chemical transformation to form fine secondary particles in the form of nitrates, adding to high levels of existing PM_{10} and $PM_{2.5}$.

SO_2 levels (less than 6.0 µg/m^3 except for DDN) in the city were well within the air quality standard.

General inferences

In winter, $PM_{2.5}$, OC and EC levels are significantly higher at all sites, PM_{10} levels are higher at all sites except CNG, NO_2 levels are higher at all sites except RMD and SO_2 levels are higher at DDN and JRC. In general, air pollution levels in ambient air (barring traffic intersections) are uniform across the city, suggesting the entire city is stressed under high pollution; in a relative sense, DDN is most polluted, followed by RMD. JRC and IIT are the least polluted areas.

It is to be noted that OC3/TC ratio (OC3 refers to carbon content of higher molecular weight organic compounds) is above 0.20 and the highest among the ratio of the fraction of OC to TC. It suggests a significant component of secondary organic aerosol is formed in the atmosphere due to condensation and nucleation of volatile to semi-volatile organic compounds, which suggests emissions within and outside of Kanpur.

Total PAH levels (17 compounds; particulate phase) in winter is high (relatively to levels generally seen in urban areas) at 105 ng/m^3 and B(a)P at 3.71 ng/m^3 (annual standard is one ng/m^3); the comparison with the annual standard is not advisable due to different averaging times. PAH levels in summer drop significantly to about 65 ng/m^3. The highest PAH levels were observed at RMD (winter 250 ng/m^3 and in summer 192 ng/m^3).

The total BTX levels are slightly higher in summer (15.1±16.7 µg/m^3) than in winter (12.4±8.6 µg/m^3). The emission rate is expected to be high in summer due to higher temperature, but not much difference in the concentration is due to better dispersion and large ventilation coefficient in summer. The benzene generally meets the annual national standard (5 µg/m^3) in winter and in summer.

In a broad sense, the air quality is worse in winter than in summer as air contains a much larger contribution of combustion products in winter than in summer.

In a broad sense, fractions of secondary particles of both PM_{10} and $PM_{2.5}$ in two seasons were consistent and needed to be controlled for better air quality in Kanpur. Combustion sources, vehicles, coal, biomass burning and MSW burning are other consistent sources in winter and require a strategy to control these sources. In summer, air quality cannot be improved unless we find effective control solutions for soil and road dust, fly ash re-suspension. The possible effective mixture of control options is discussed in Chapter 6.

3 Emission Inventory

3.1 Introduction

Emission inventory (EI) is a basic necessity for planning air pollution control activities. EI provides a reliable estimate of total emissions of different pollutants, their spatial and temporal distribution, and identification and characterization of main sources. This information on EI is an essential input to air quality models for developing strategies and policies. In this chapter, the emission inventory of the study area for the year 2020 is presented.

3.2 Methodology

The stepwise methodology adopted for this study is presented in Figure 3.1.

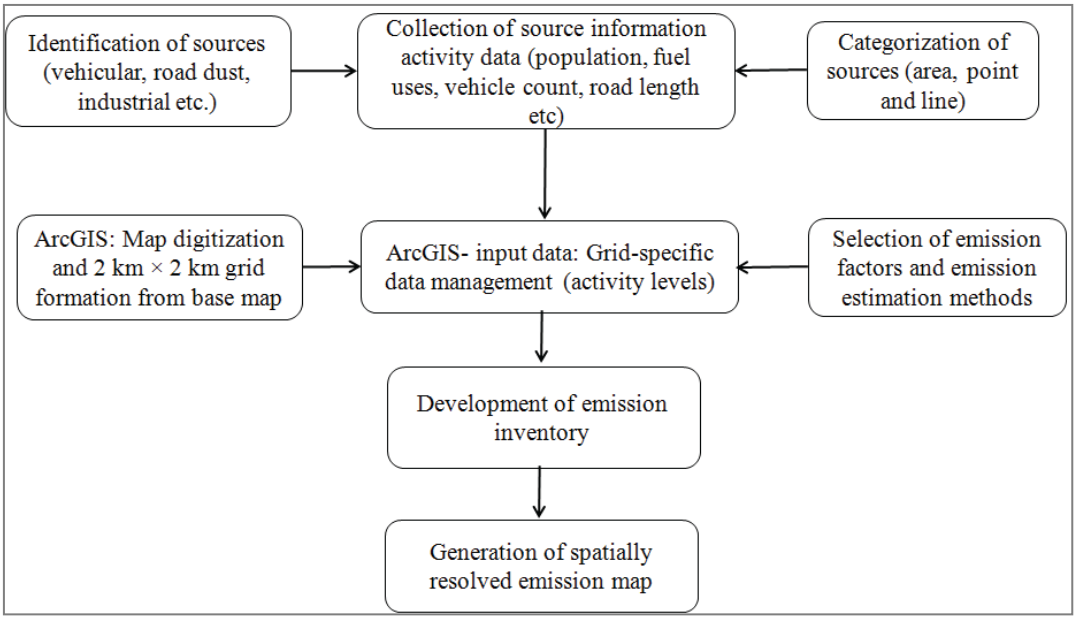


Figure 3.1: Stepwise Methodology adopted for the Study

3.2.1 Data Collection

The primary and secondary data were collected by the IITK team. For example, construction and demolition data were collected by field survey and validated by satellite imagery. Road dust sampling at 19 locations was conducted. A physical survey of industrial areas was also done. The main sources of secondary data collection are from UPPCB, Census of India, CPCB website, AAI (Airport Authority of India), Indian Railways, Central Electricity Authority

(CEA), Transport Department, and Toll Plazas. The information has also been collected through the Internet by visiting various websites. Although all possible efforts have been made to collect the data, some information/data could be missing.

3.2.2 Digital Data Generation

The land-use map of the study area is prepared in terms of settlements, agriculture, road network, water bodies, etc. (Figure 3.2 to Figure 3.12).

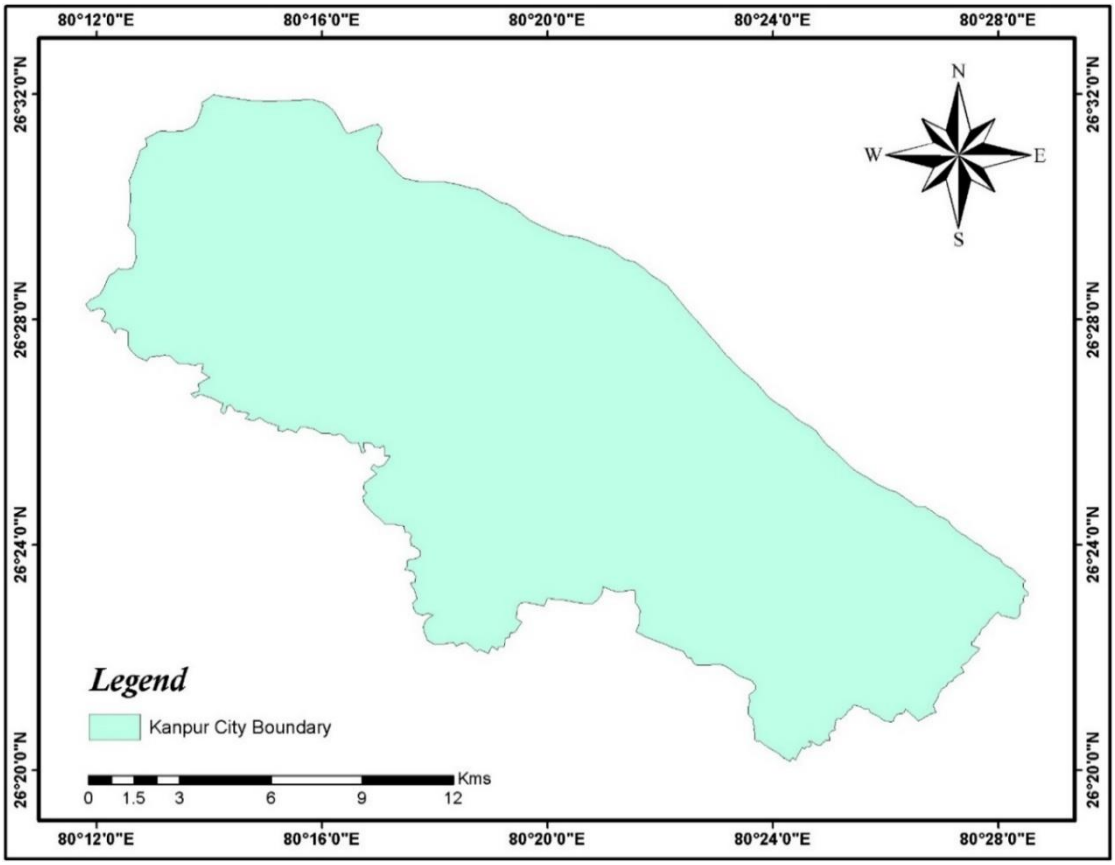


Figure 3.2: Kanpur City Boundary

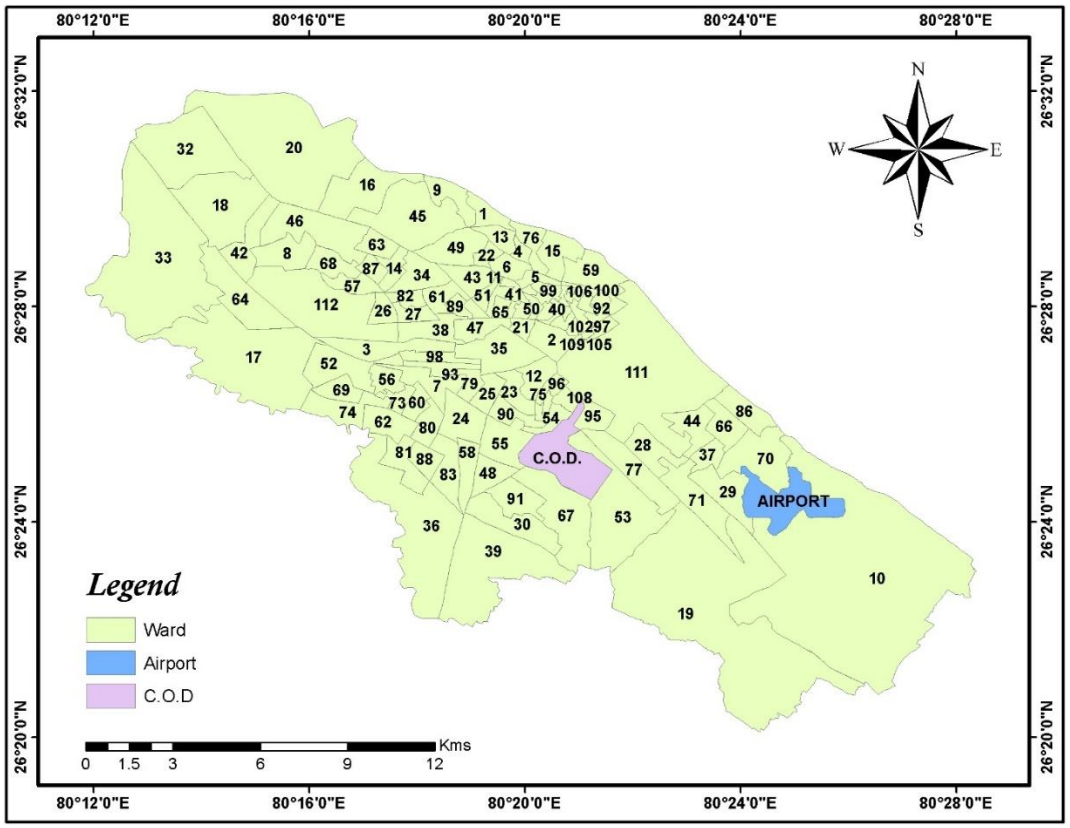


Figure 3.3: Ward Map

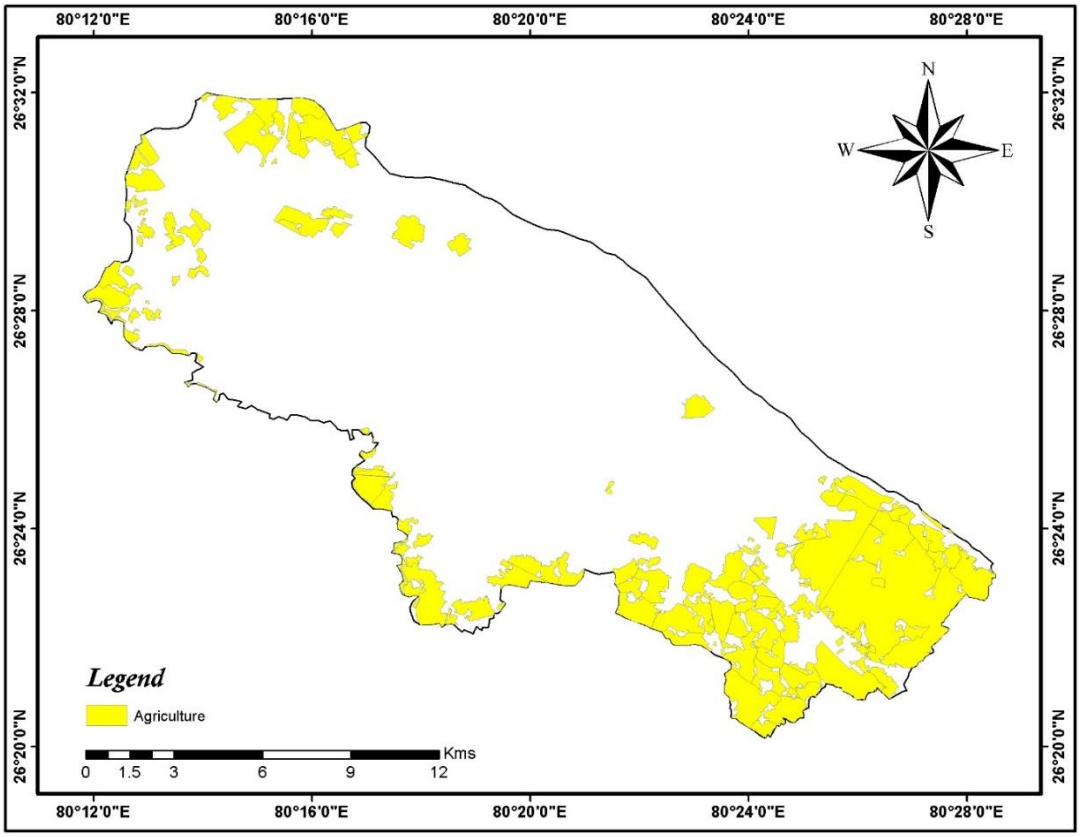


Figure 3.4: Agricultural Area Map

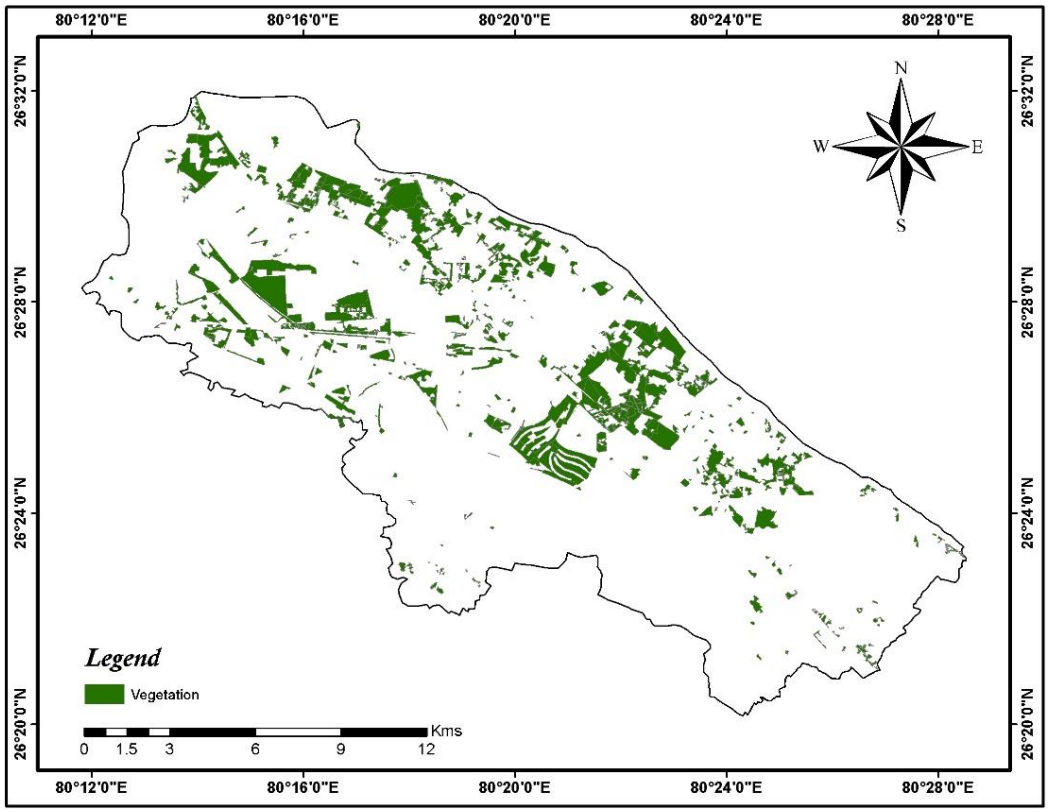


Figure 3.5: Green Area Map

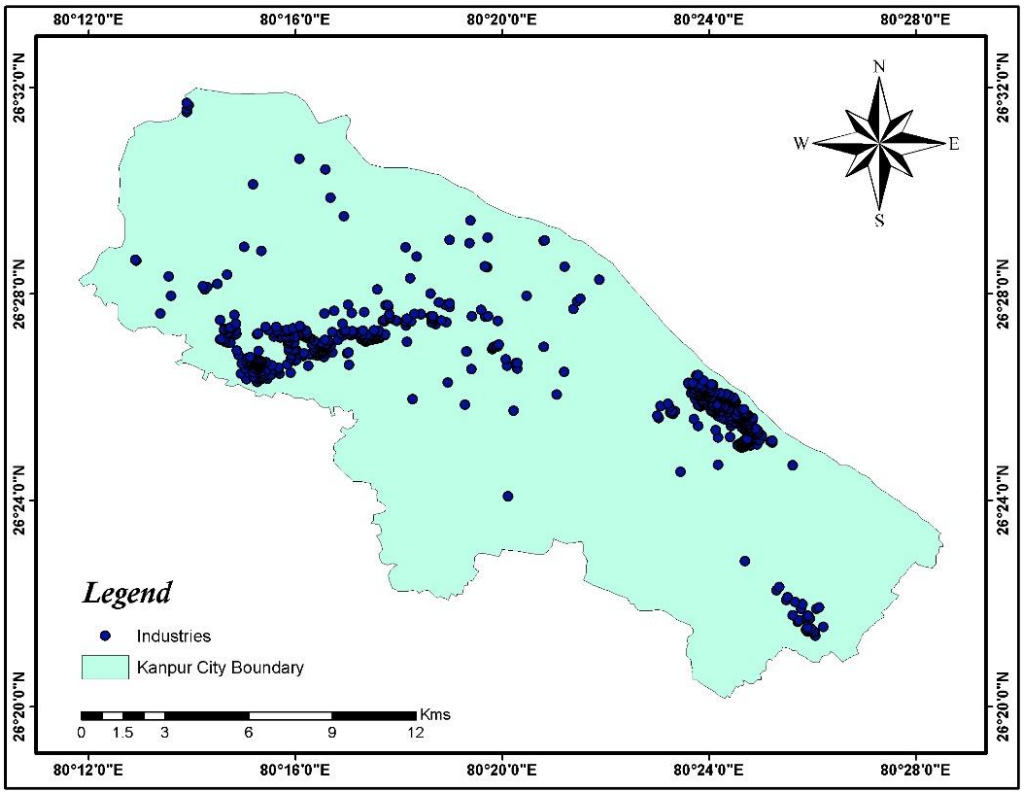


Figure 3.6: Industrial Area Map

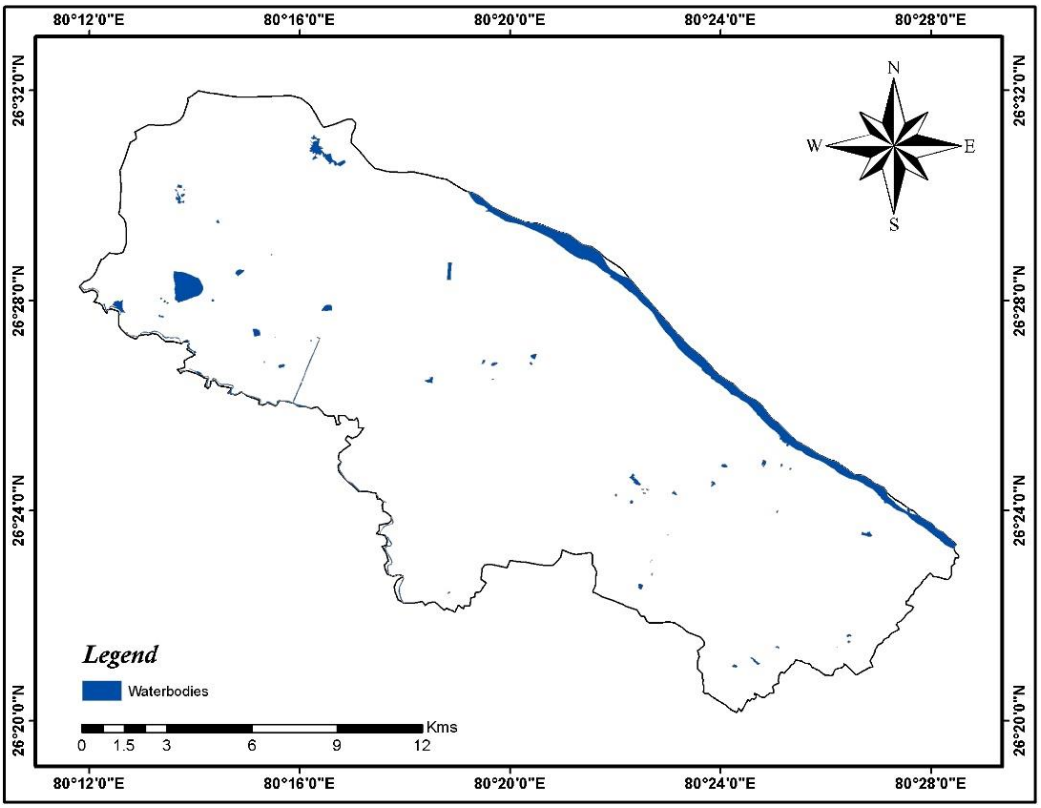


Figure 3.7: Waterbodies Area Map

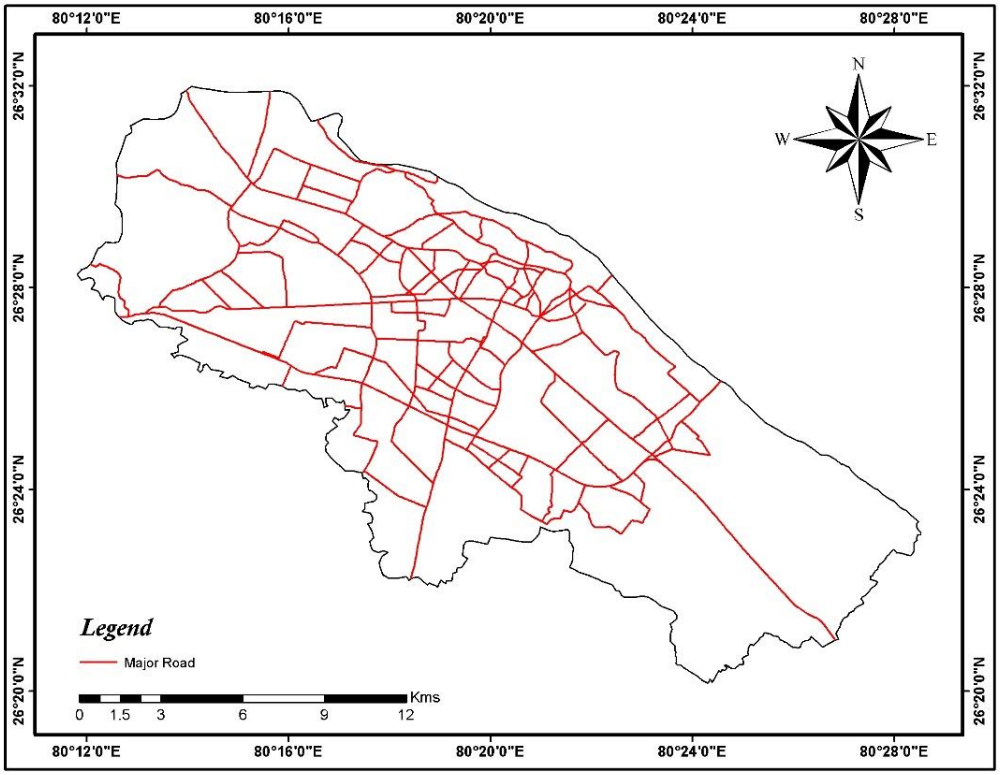


Figure 3.8: Major Road Network Map

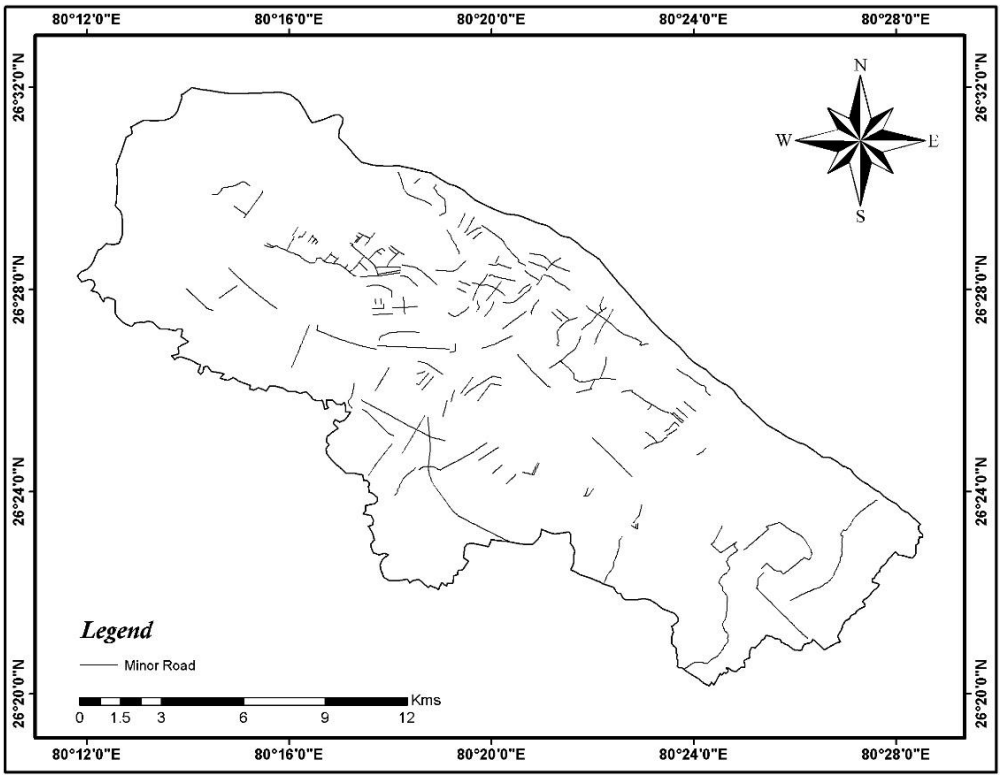


Figure 3.9: Minor Road Network Map

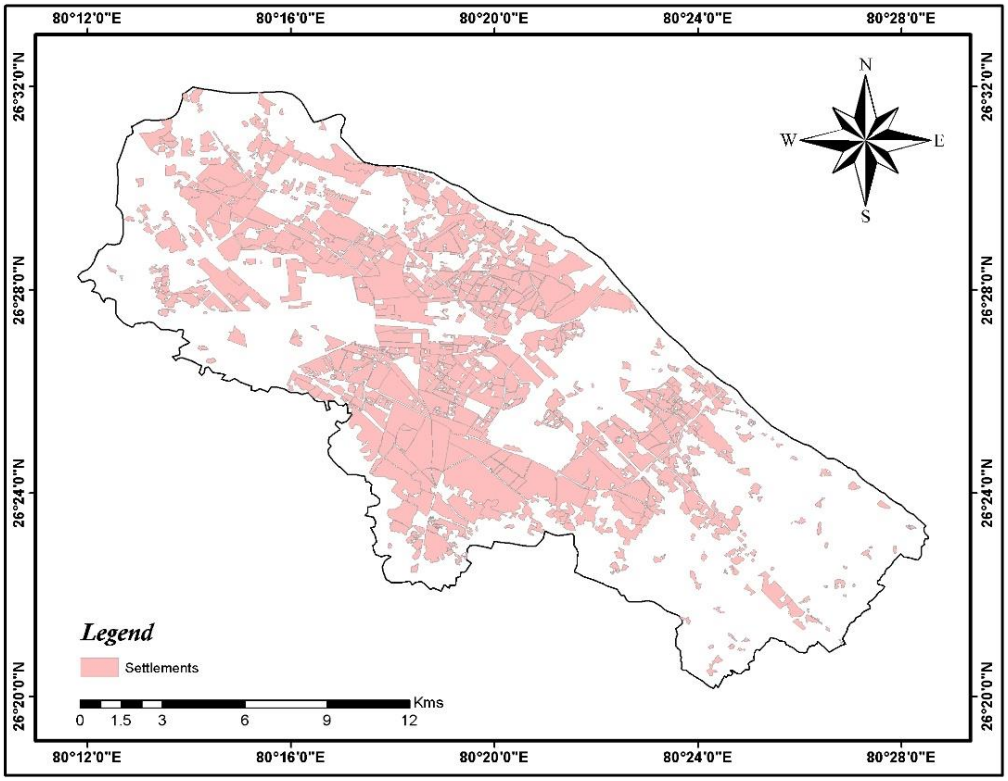


Figure 3.10: Settlement Area Map

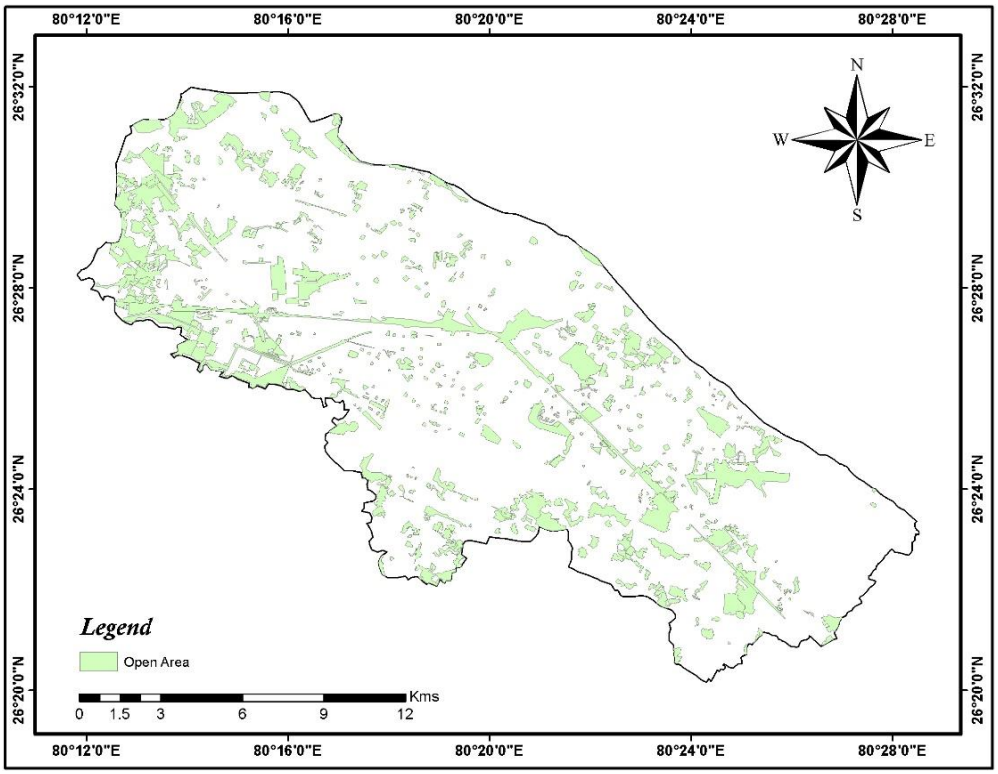


Figure 3.11: Open Area Map

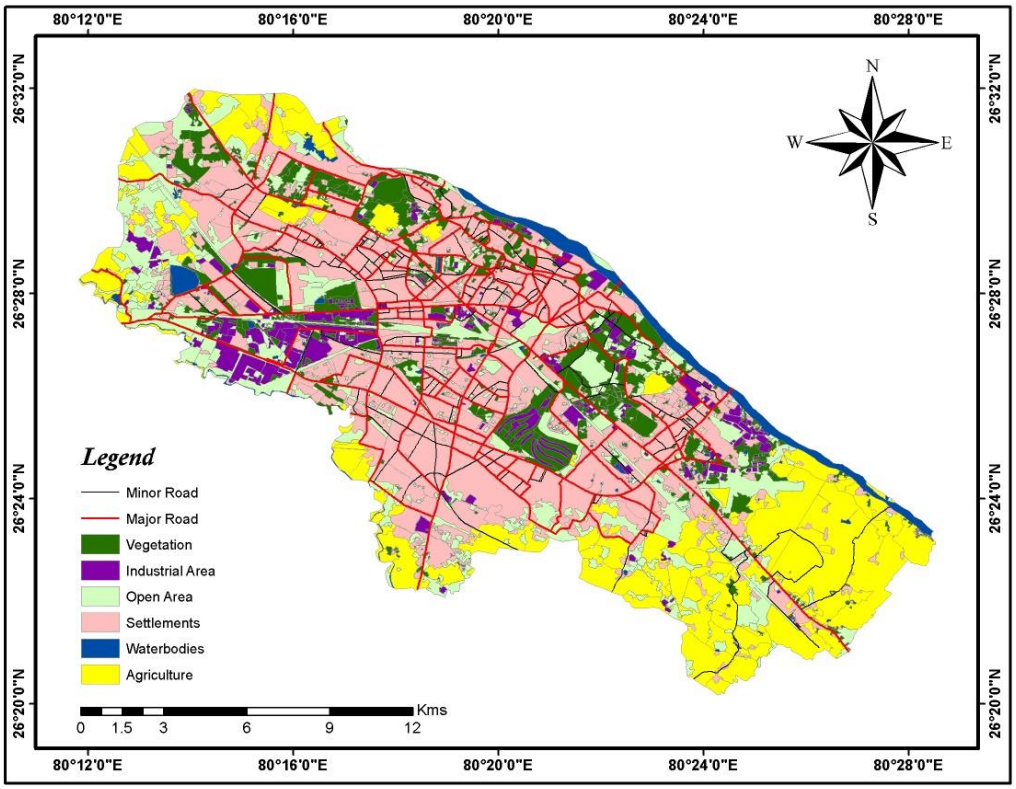


Figure 3.12: Land-use Map of Kanpur city

At the time of the development of the emission inventory, a suitable coding system was adopted to avoid confusion and misrepresentation of results and interpretation. The emissions have been

calculated for Kanpur city. The Grid map of Kanpur with grid identity numbers is shown in Figure 3.13. The entire study area was divided into grid cells of 2 km x 2 km.

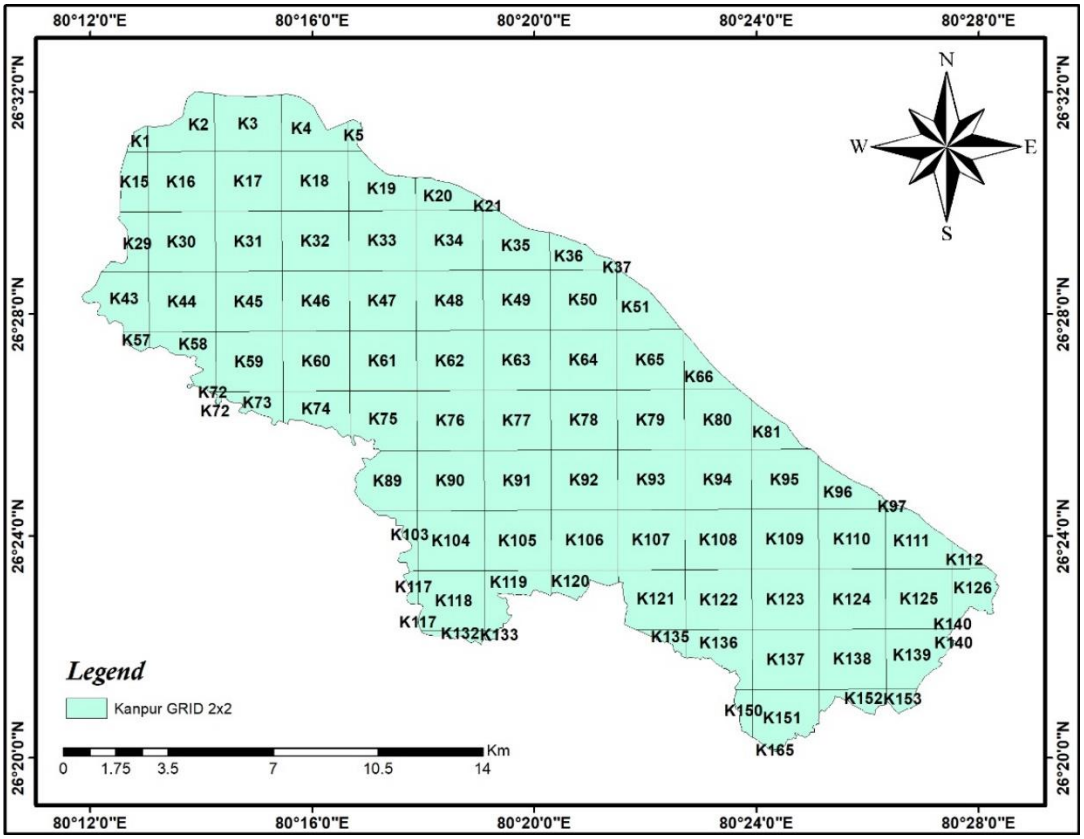


Figure 3.13: Grid Map of Kanpur showing Grid Identity Numbers

3.2.3 Emission Factor

An emissions factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the mass of pollutant per unit mass of raw material, volume, distance traveled, or duration of the activity (e.g., grams of particulate emitted per kilogram of coal burnt). Such factors facilitate the estimation of emissions from various sources of air pollution. In most cases, these factors are simply averaging of all available data of acceptable quality and are generally assumed to be representative of long-term averages for all facilities in the source category. The emission factors used in the report are mentioned in Annexure 1.

The general equation for emissions estimation is:

$$E = A \times EF \times (1 - ER/100) \qquad (3.1)$$

Where:

E = Emissions;

A = Activity rate;

EF = Emission factor, and

ER = Overall emission reduction efficiency, %

3.2.4 Domestic Sector

The interior boundaries in the map (Figure 3.14) show the administrative boundaries of wards in Kanpur City. The Kanpur City consists of 112 wards as shown in Figure 3.14. The fuel consumption pattern shows 82% LPG consumption (CRISIL report), wood (10%), dung (1%), coal (2%), Kerosene (4%) and crop residue (1%). The slum area details have been obtained from Kanpur Nagar Nigam and an on-field survey is conducted by the IITK team. There are approximately 380 areas identified as slums and below the poverty line. The majority of the slum area are using wood and dung as a fuel source for cooking. Although they have been given LPG cylinders, due to their economic conditions the refilling is not frequent. The ward-wise population density of Kanpur city is given in Figure 3.15. Ward number 78, 84, 94, 99, 100, 101, 105, 107 and 110 shows a high population density of 2.5 lakhs per square km.

After obtaining the area of wards, the emission density for each ward is calculated for different pollutants (PM_{10}, $PM_{2.5}$, SO_2, NOx, and CO). The emission factors are given by CPCB (2011) and AP-42 (USEPA, 2000) were used for each fuel type.

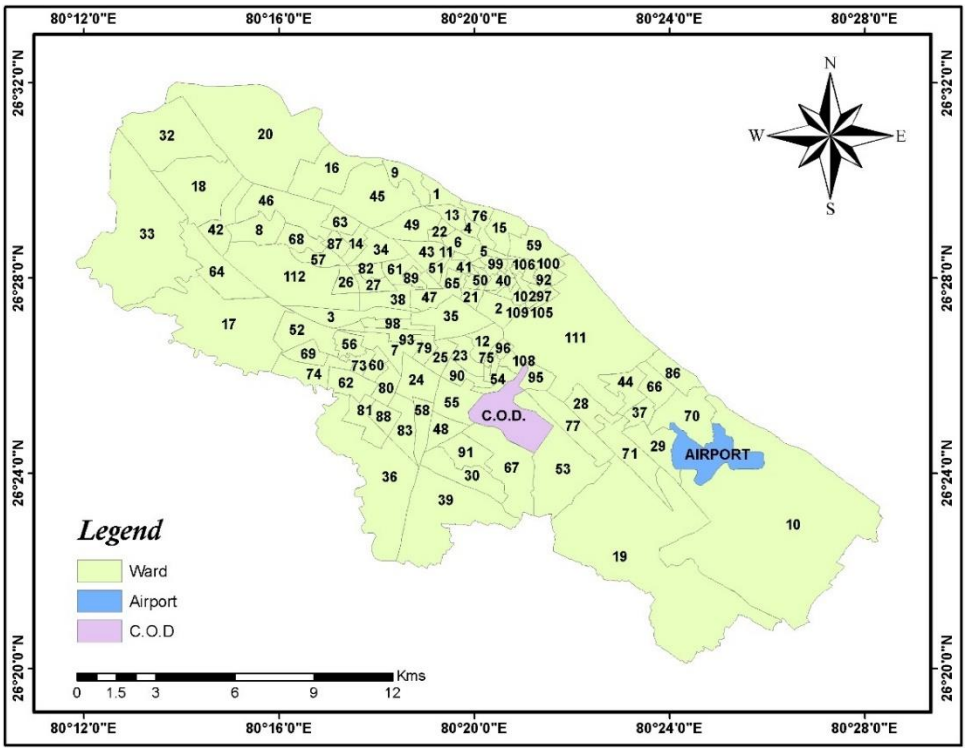


Figure 3.14: Wards in Kanpur City

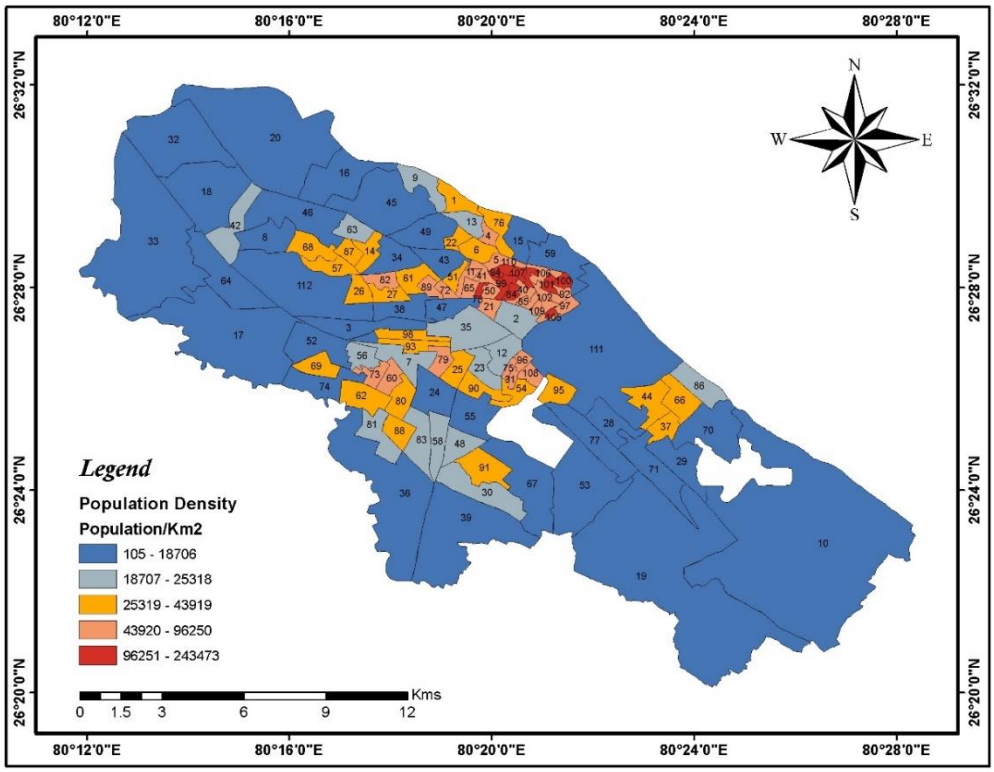


Figure 3.15: Map showing Population density of Kanpur city

The overall emission from domestic sources is presented in Figure 3.16. The emission contribution from different fuel types to different pollutants is shown in Figure 3.17 to Figure 3.21. For spatial distribution of different pollutants (Figure 3.22 to Figure 3.26), emission per capita, in each ward and village was calculated, as activity data was available based on per capita.

The emission density in terms of kg/day/m^2 in each ward was calculated based on population and area of the ward for different pollutants (PM_{10}, $PM_{2.5}$, SO_2, NOx, and CO); see below.

$$\text{Emission Density (kg/day/m}^2\text{)} = \text{Emission of Ward (kg/day)} / \text{Ward Area (m}^2\text{)} \qquad (3.2)$$

For calculating emission in a grid that may contain more than one ward, the area of the fraction of each ward falling inside that grid was calculated, and with the help of emission density of the ward, the missions were calculated, see below.

$$Grid.Emission = \sum_{i=1}^{N} (\text{area of fraction ward i in grid X emission density of ward, i}) \qquad (3.3)$$

Where N= no. of wards in the grid

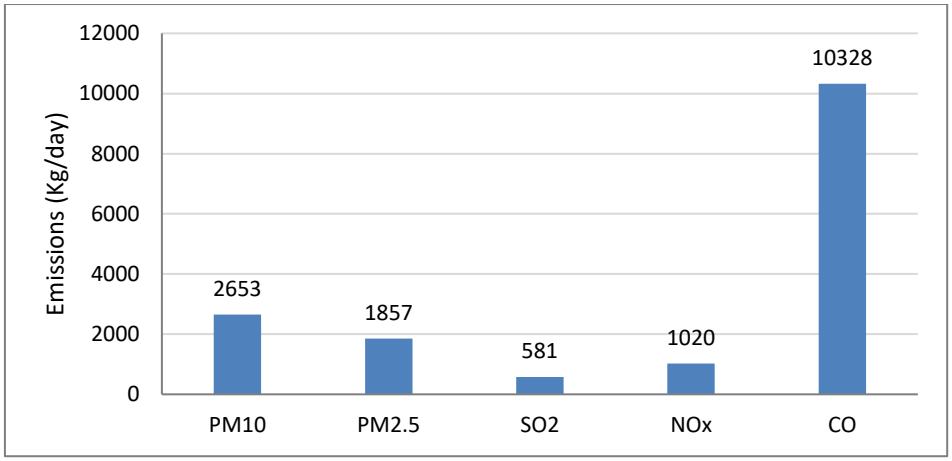


Figure 3.16: Emission Load from Domestic Sector (kg/day)

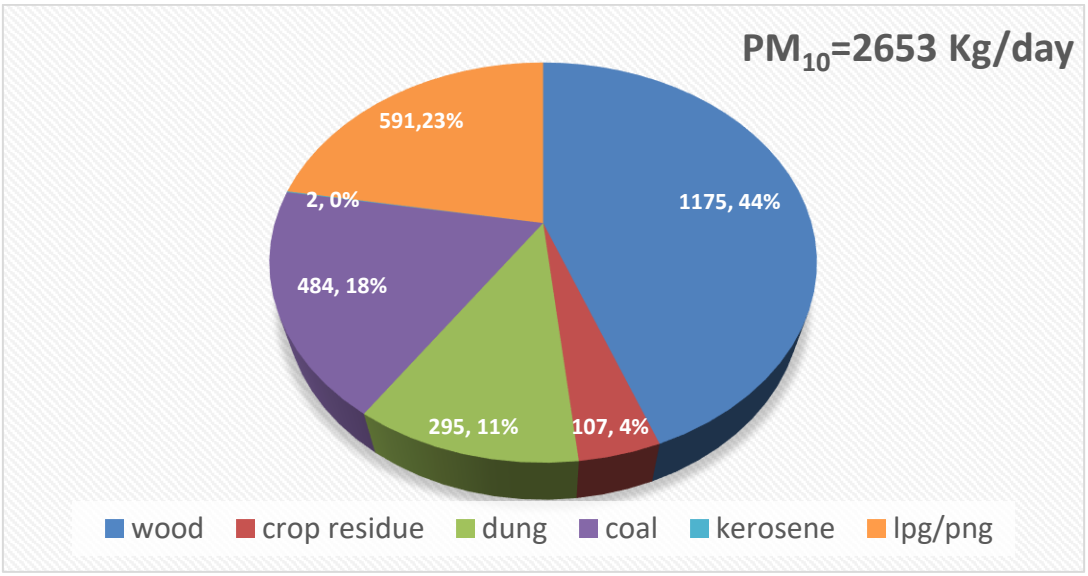


Figure 3.17: PM_{10} Emission load from Domestic Sector (Kg/day, %)

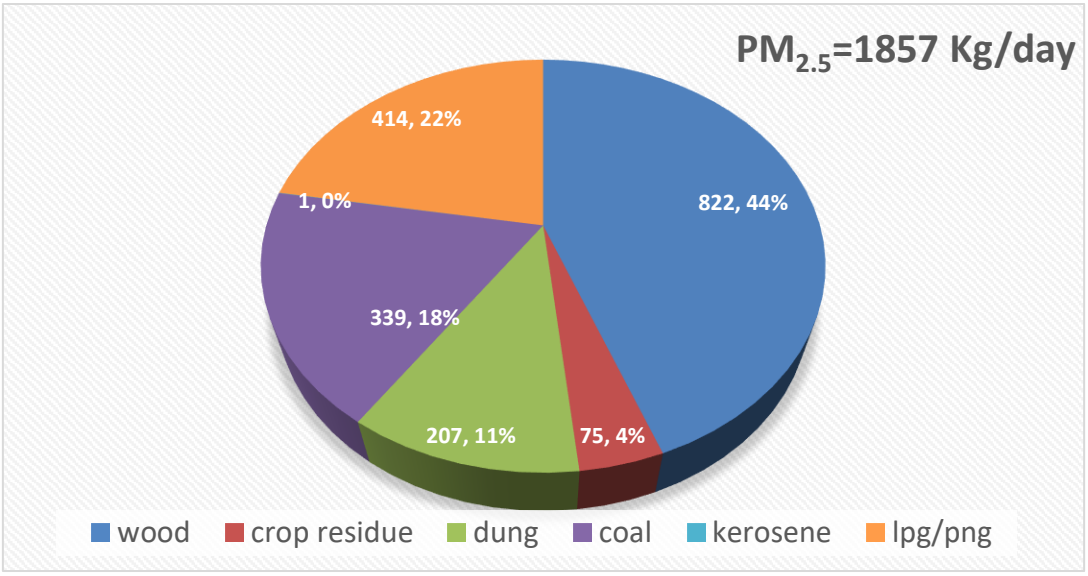


Figure 3.18: $PM_{2.5}$ Emission load from Domestic Sector (Kg/day, %)

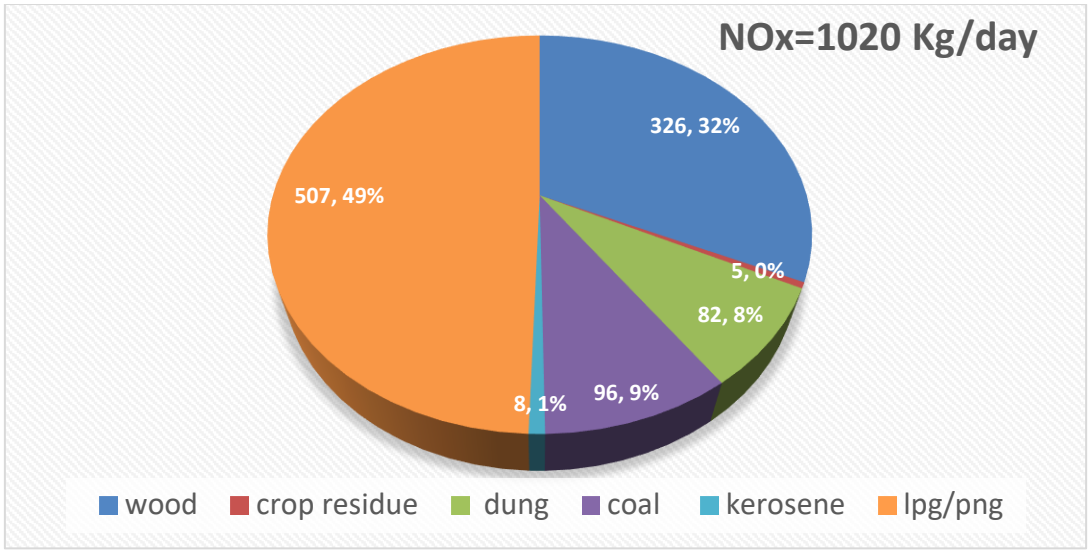


Figure 3.19: NOx Emission load from Domestic Sector (Kg/day, %)

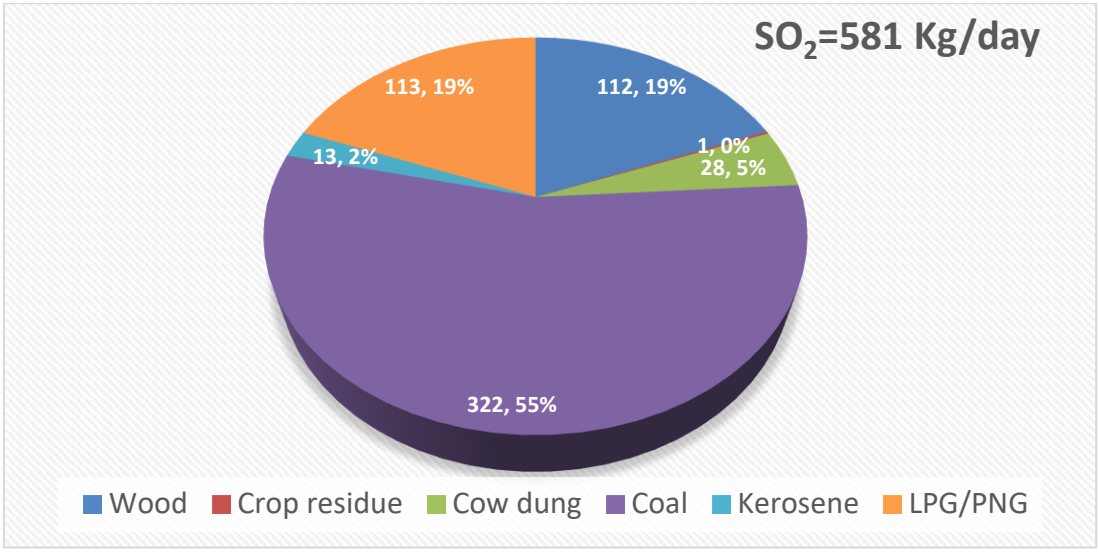


Figure 3.20: SO_2 Emission load from Domestic Sector (Kg/day, %)

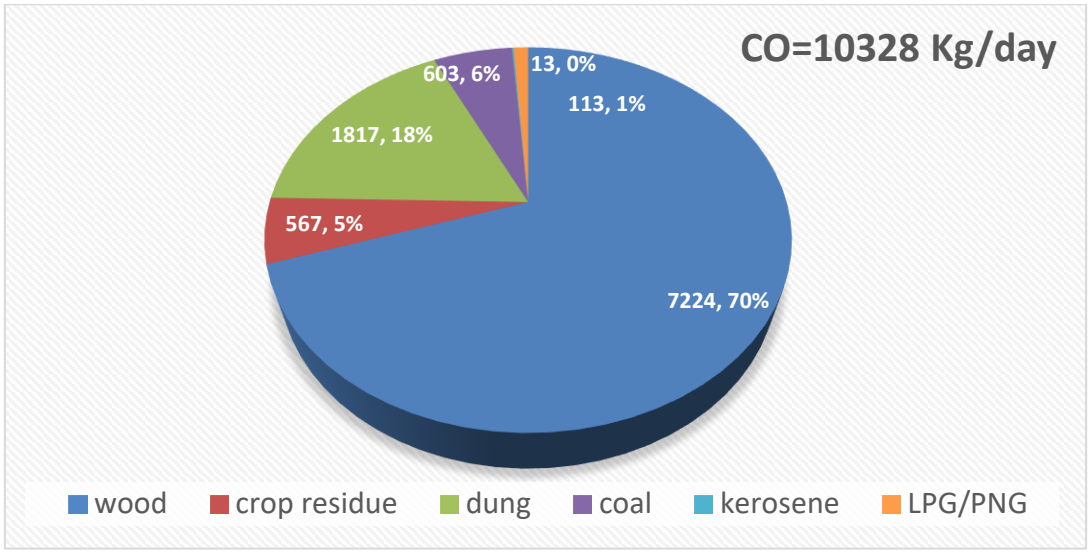


Figure 3.21: CO Emission load from Domestic Sector (Kg/day, %)

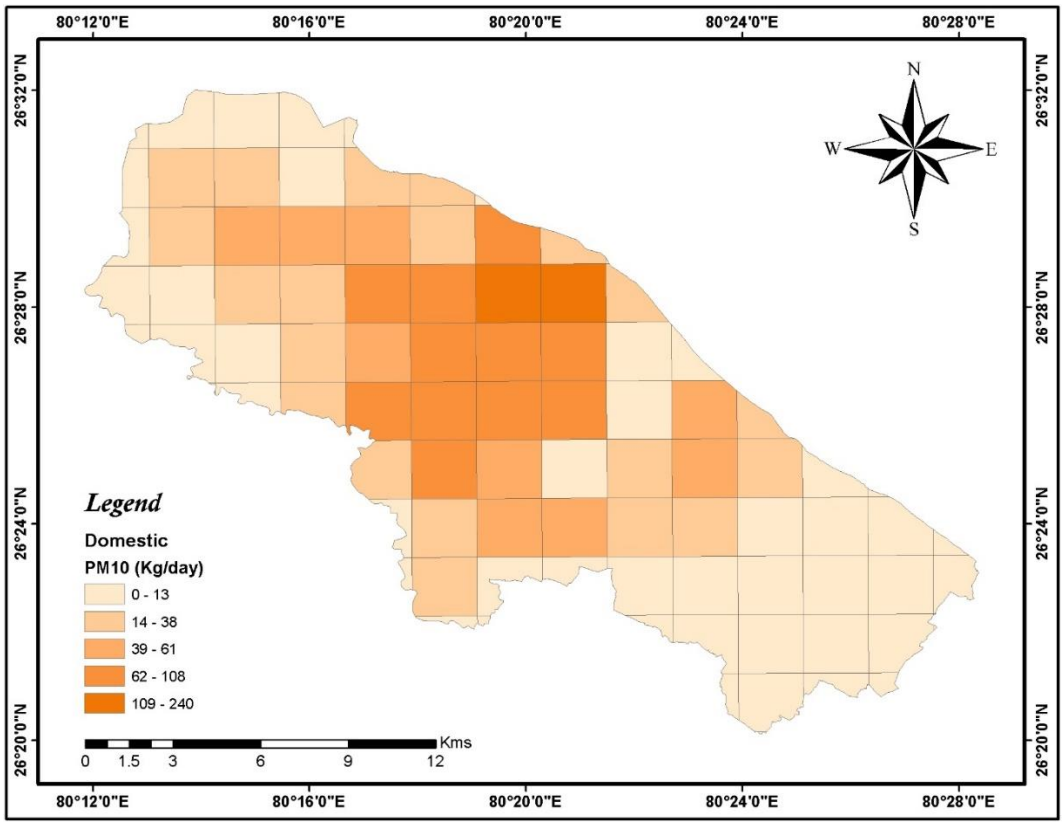


Figure 3.22: Spatial Distribution of PM_{10} Emissions from Domestic Sector

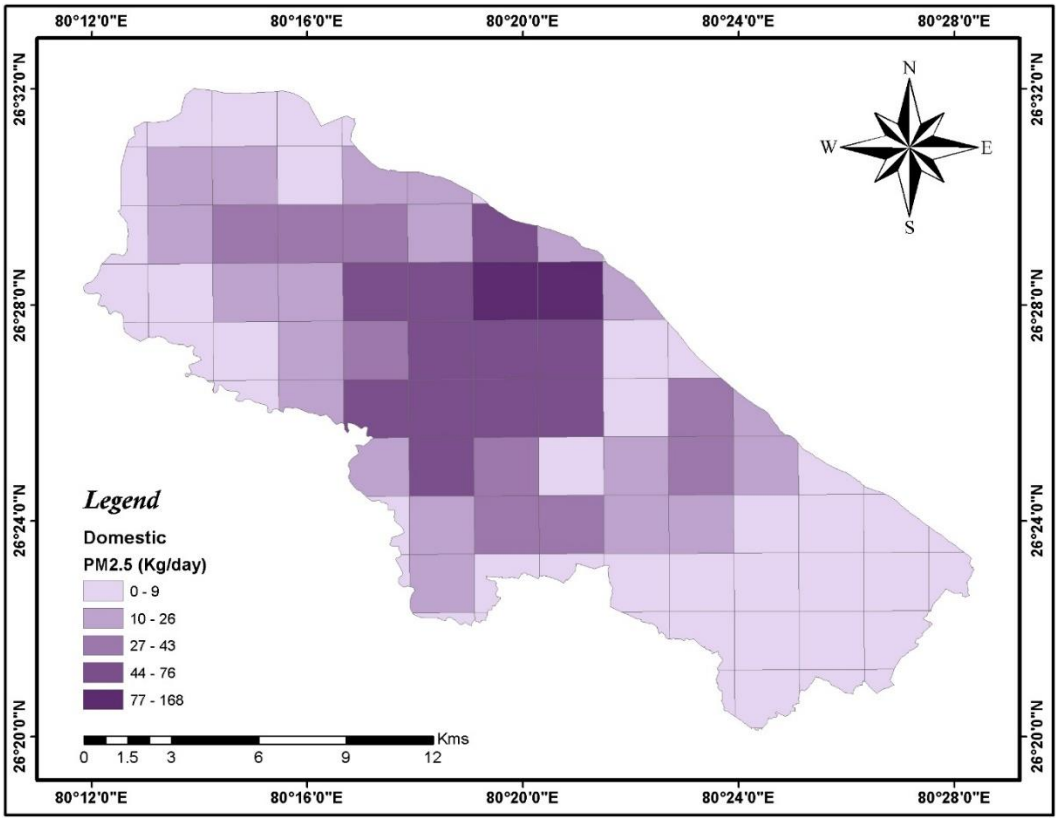


Figure 3.23: Spatial Distribution of $PM_{2.5}$ Emissions from Domestic Sector

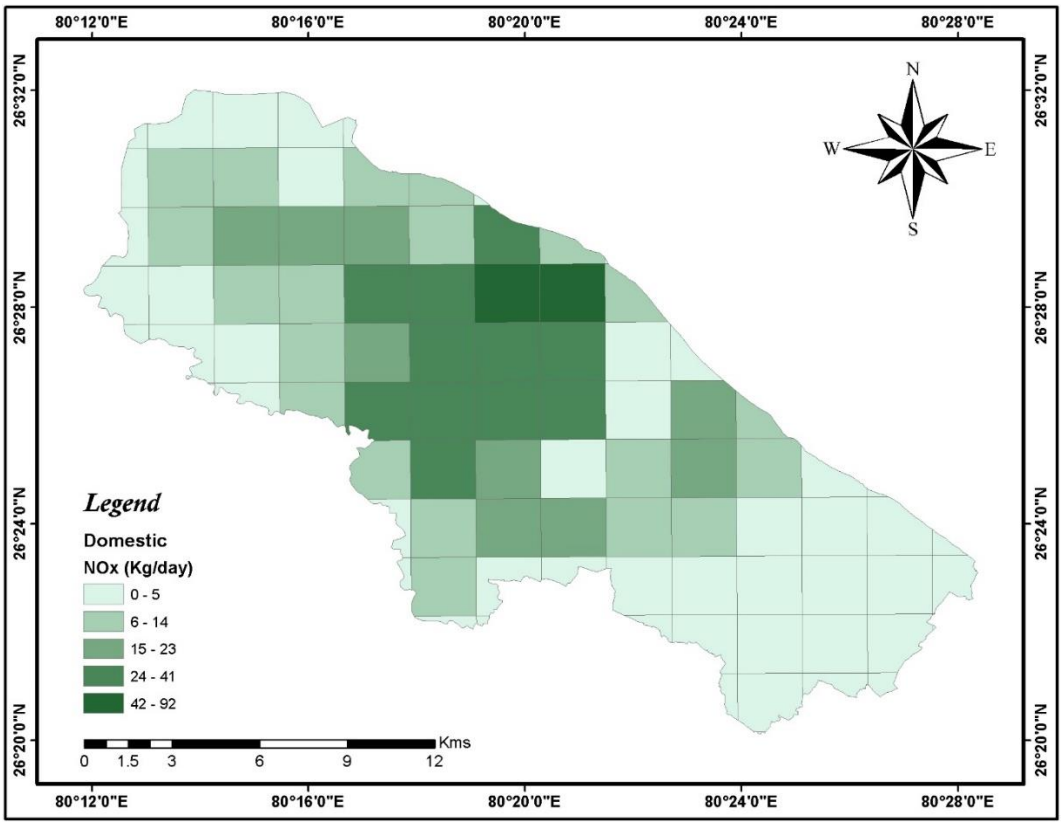


Figure 3.24: Spatial Distribution of NOx Emissions from Domestic Sector

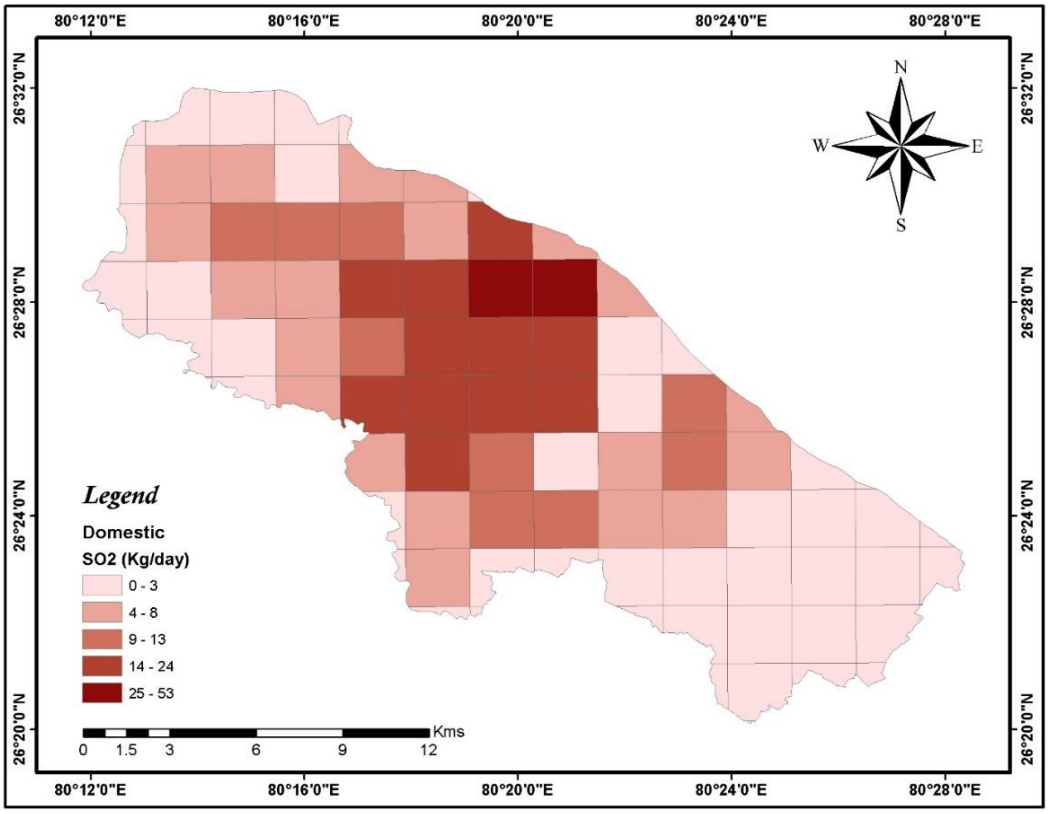


Figure 3.25: Spatial Distribution of SO_2 Emissions from Domestic Sector

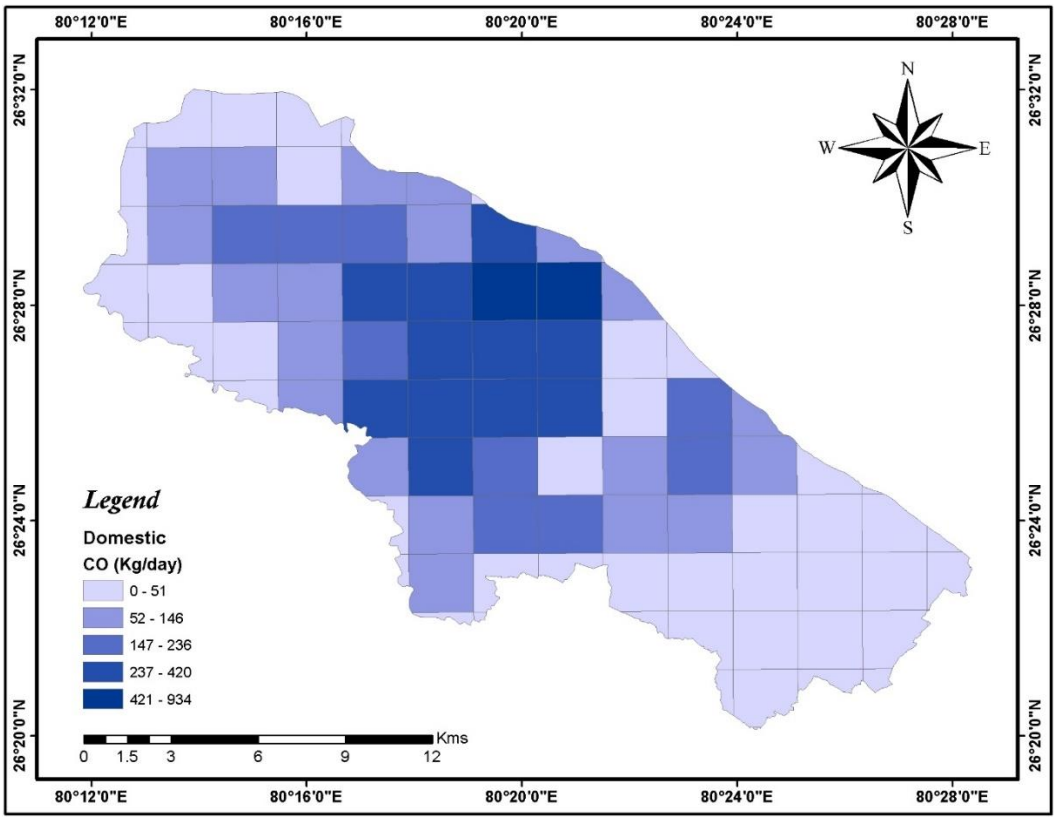


Figure 3.26: Spatial Distribution of CO Emissions from Domestic Sector

3.2.5 Construction and Demolition

A detailed survey was undertaken to assess construction and demolition activities. The satellite imagery was also used to identify the construction activities. The major construction activities include buildings (including residential housing and apartments) information was obtained from Kanpur Nagar Nigam, PWD, CPWD, and a detailed survey were done. Nearly at all the construction sites, the construction material and their debris (lying open, without cover) are being stored outside the construction premises, near the road (Figure 3.27). The areas under construction activities were calculated based on survey data and GIS. The construction and demolition sites in Kalyanpur are given in Figure 3.28. The location of construction and demolition sites at Kanpur city is given in Figure 3.29. The emission factors given by AP-42 (USEPA, 2000) were used for estimating the construction and demolition emissions.

Figure 3.27: Construction material and debris near constructuion sites

Figure 3.28: Kalyanpur location showing the dumping of construction material

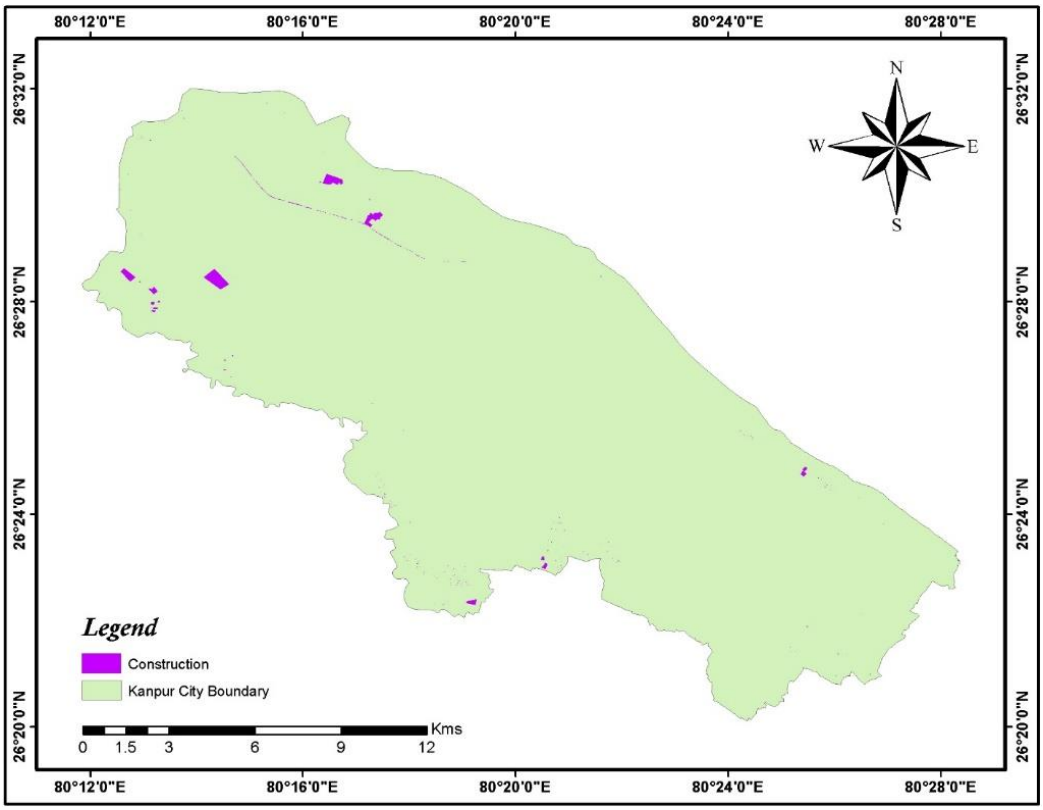


Figure 3.29: Construction/Demolition Sites

Total emissions from construction and demolition activities are presented in Figure 3.30. The spatially resolved map of construction and demolition activities is shown in Figure 3.31 to Figure 3.32.

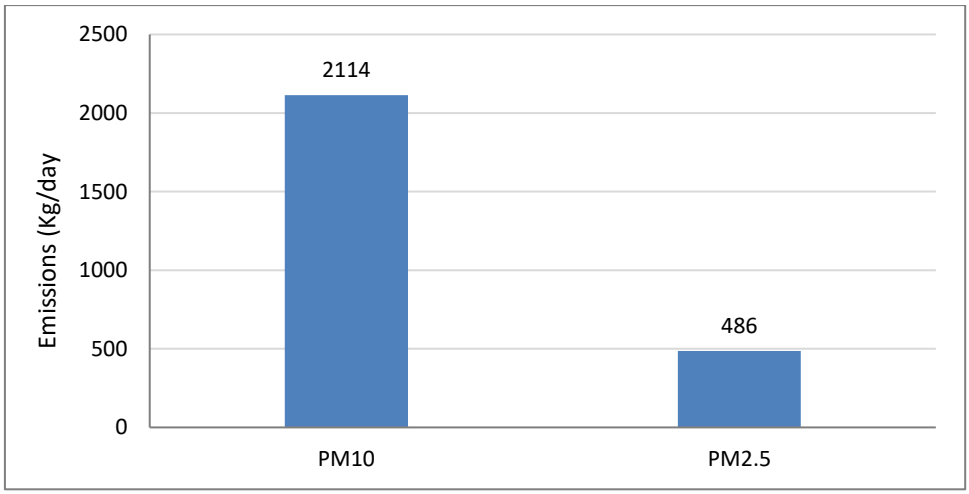


Figure 3.30: Emission Load from Construction and Demolition activities (kg/day)

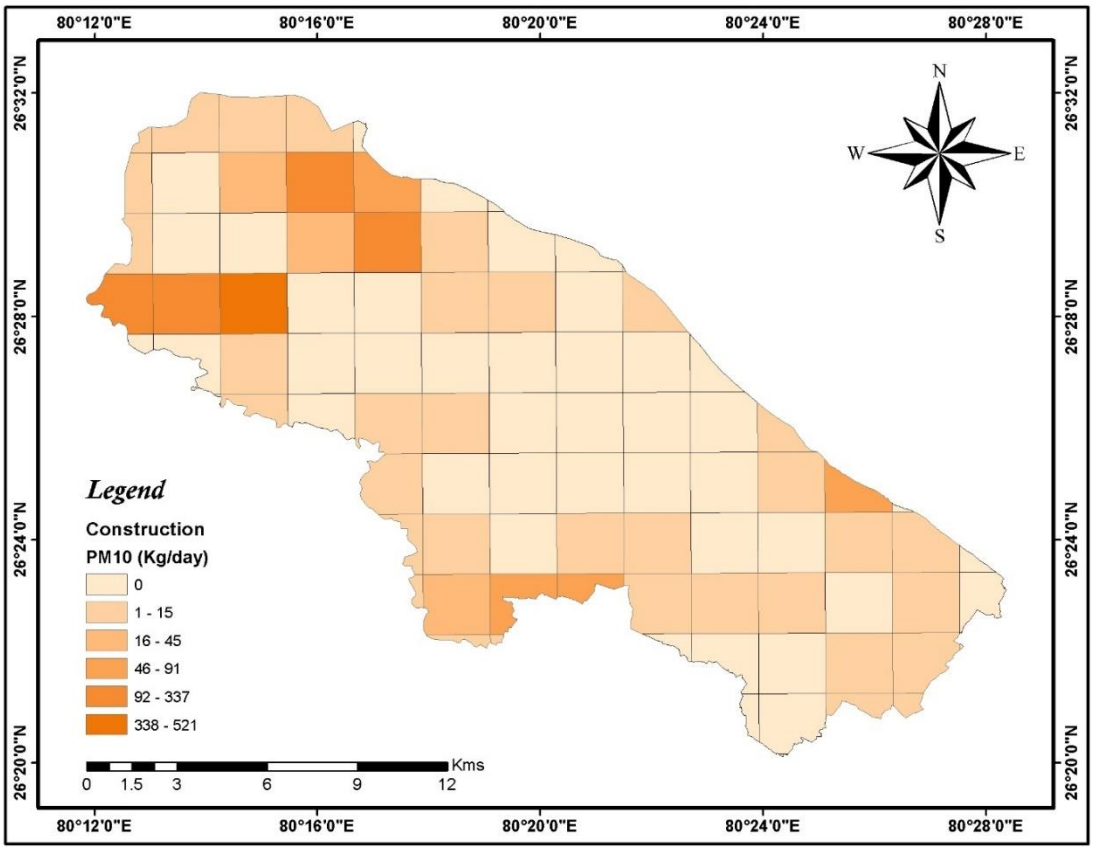


Figure 3.31: Spatial Distribution of PM_{10} Emissions from Construction/Demolition

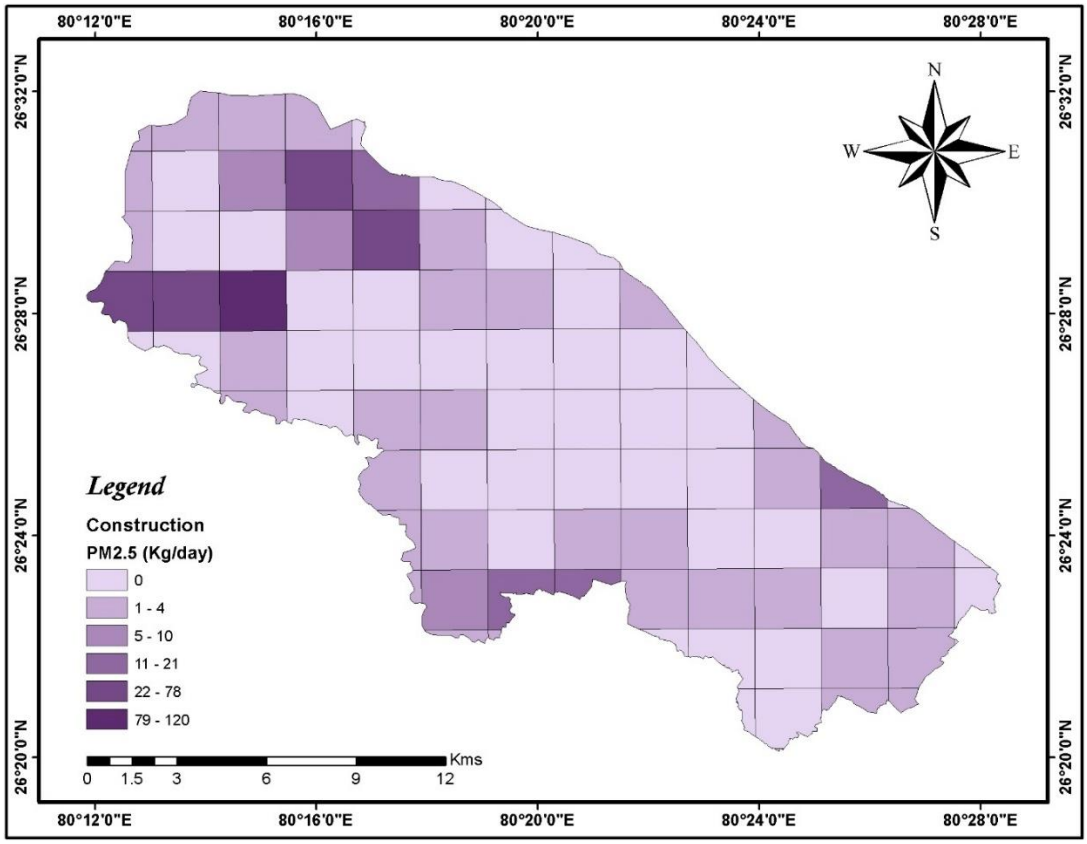


Figure 3.32: Spatial Distribution of $PM_{2.5}$ Emissions from Construction/Demolition

3.2.6 Diesel Generator Sets (DG sets)

The location of the DG set is shown in Figure 3.33. The industries use DG sets as a backup, approximately 860 DG sets are installed in industries (source: consent data). During the industrial survey, it was found out that DG sets operate for two hours per day. Most of the industries use diesel as fuel to generator sets. The calculation is based on Eq (3.1), where ER, overall efficiency reduction was taken as zero. The CPCB (2011) emission factors were used for emission estimation. The total emissions from DG sets are shown in Figure 3.34, the spatial distribution of emissions from DG Sets is shown in Figure 3.35 to Figure 3.39.

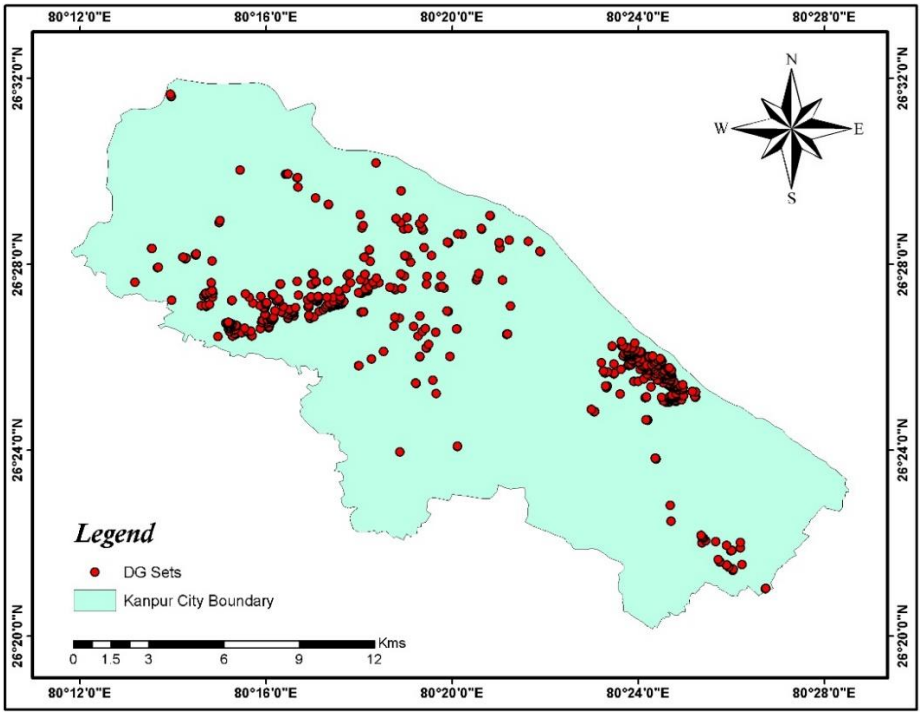


Figure 3.33: Location of Industrial DG Sets

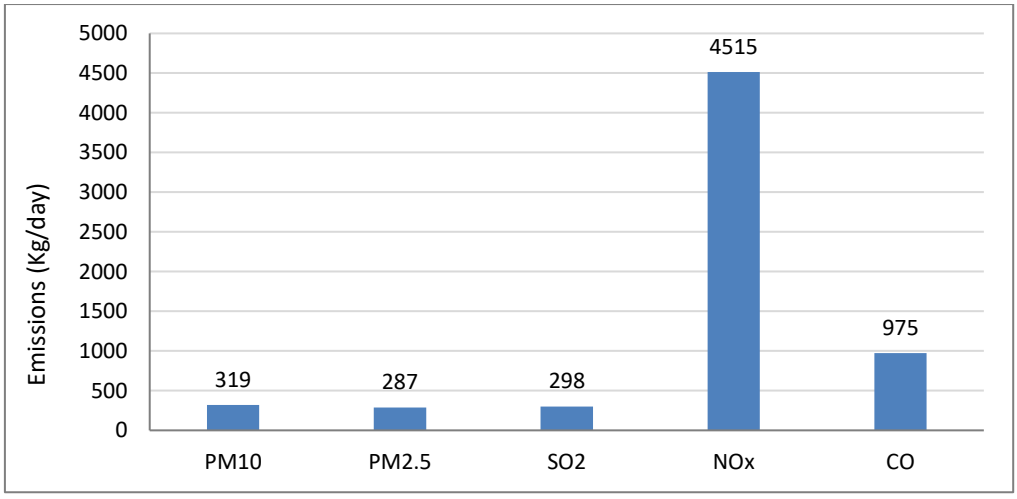


Figure 3.34: Emission Load (kg/day) from DG sets

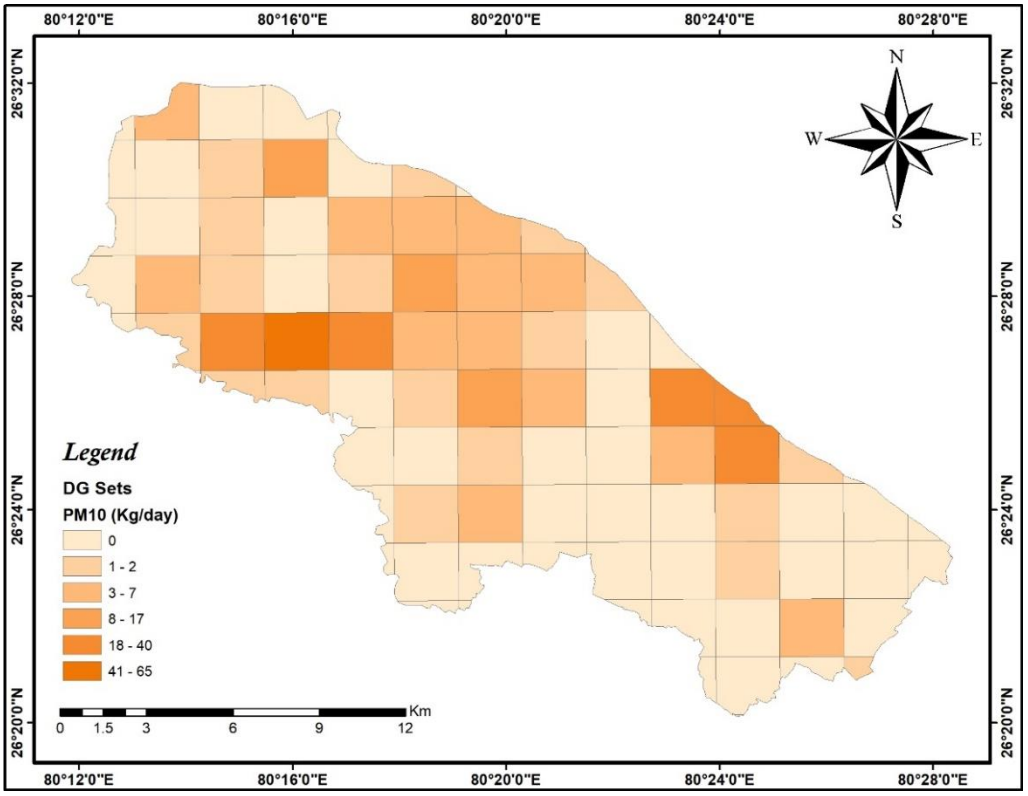


Figure 3.35: Spatial Distribution of PM_{10} Emissions from DG Sets

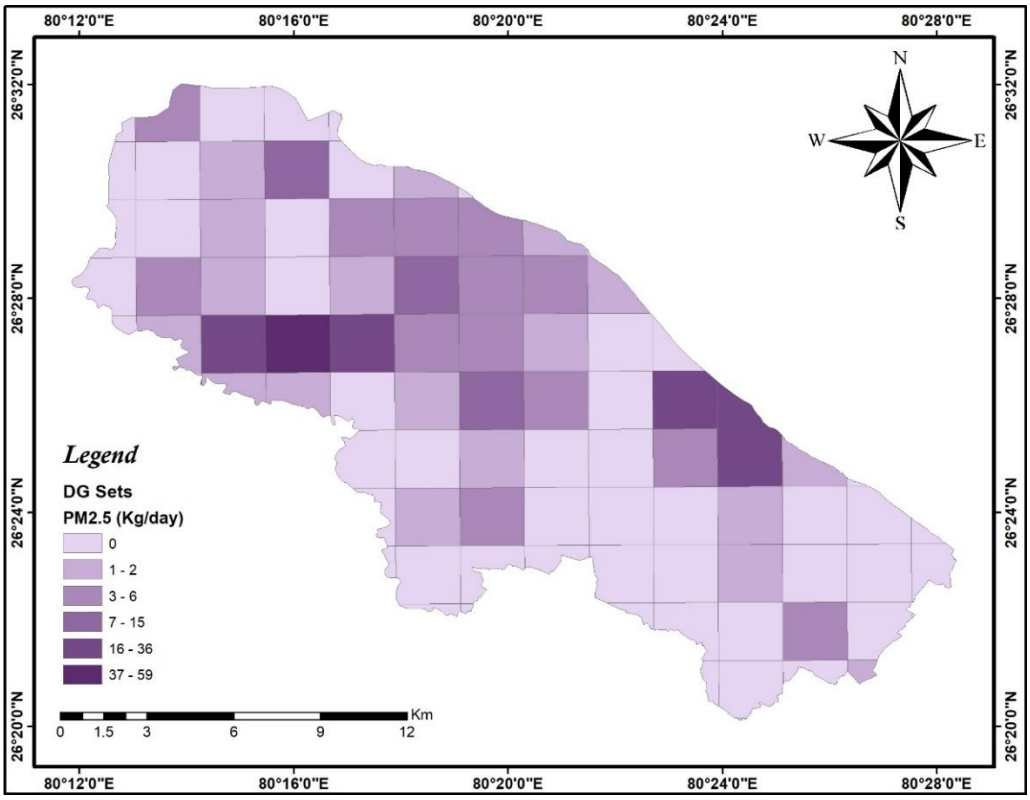


Figure 3.36: Spatial Distribution of $PM_{2.5}$ Emissions from DG Sets

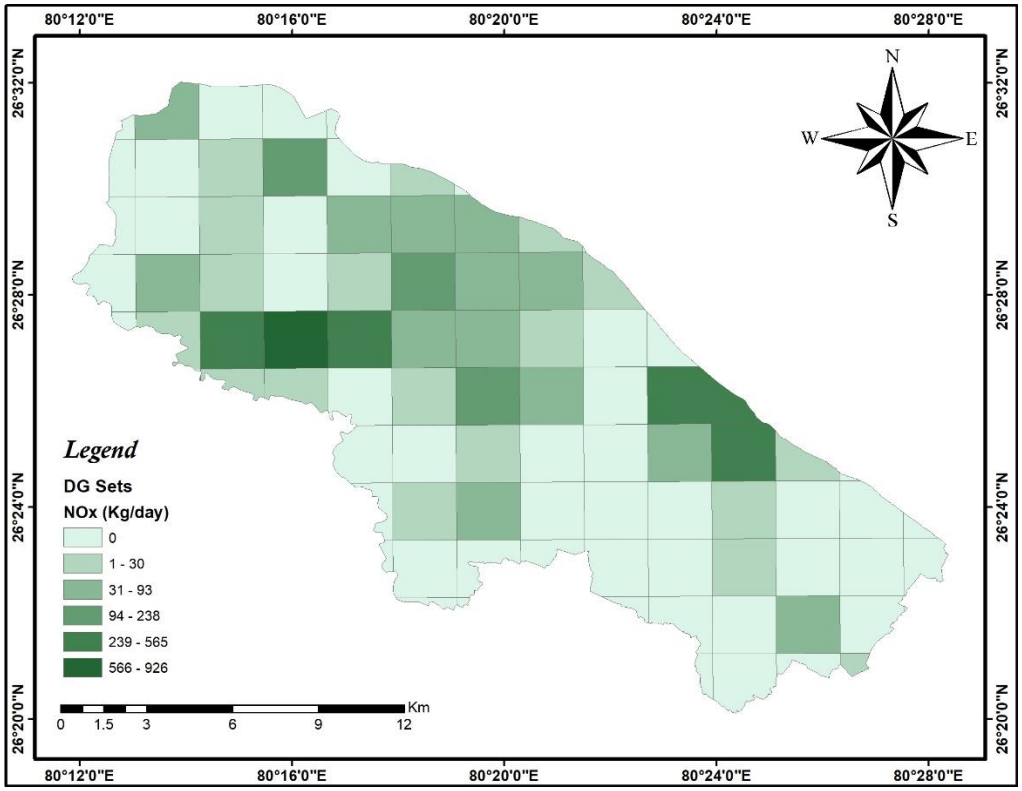


Figure 3.37: Spatial Distribution of NOx Emissions from DG Set

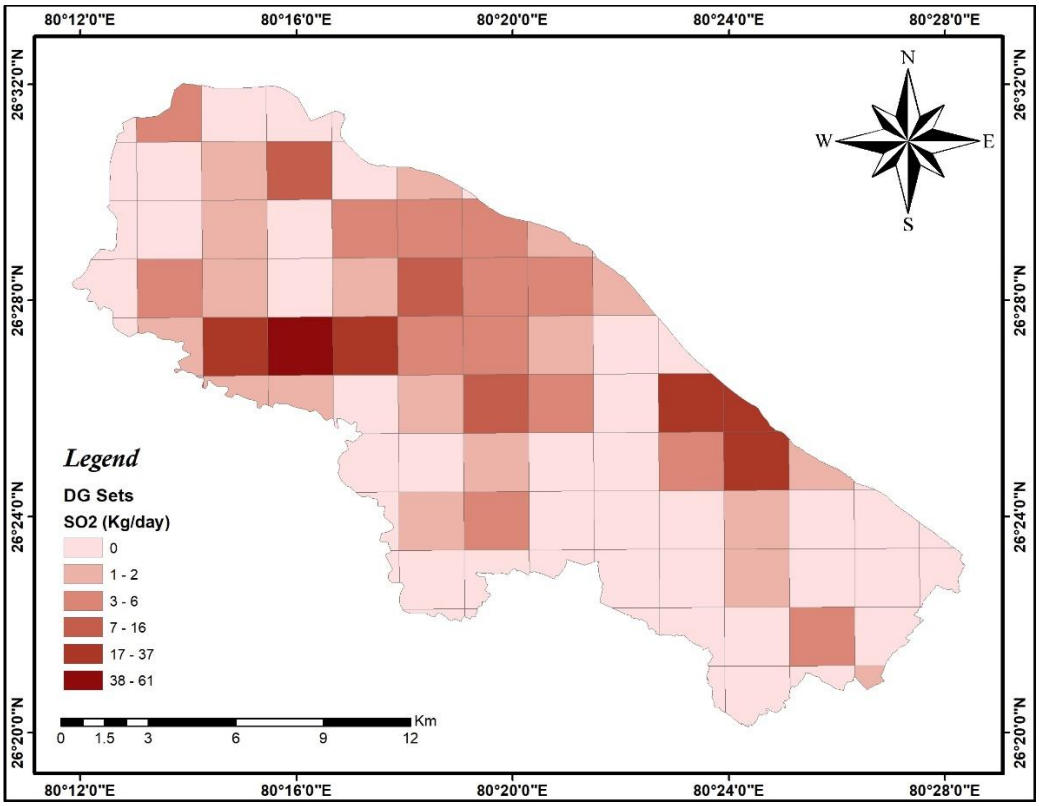


Figure 3.38: Spatial Distribution of SO_2 Emissions from DG Set

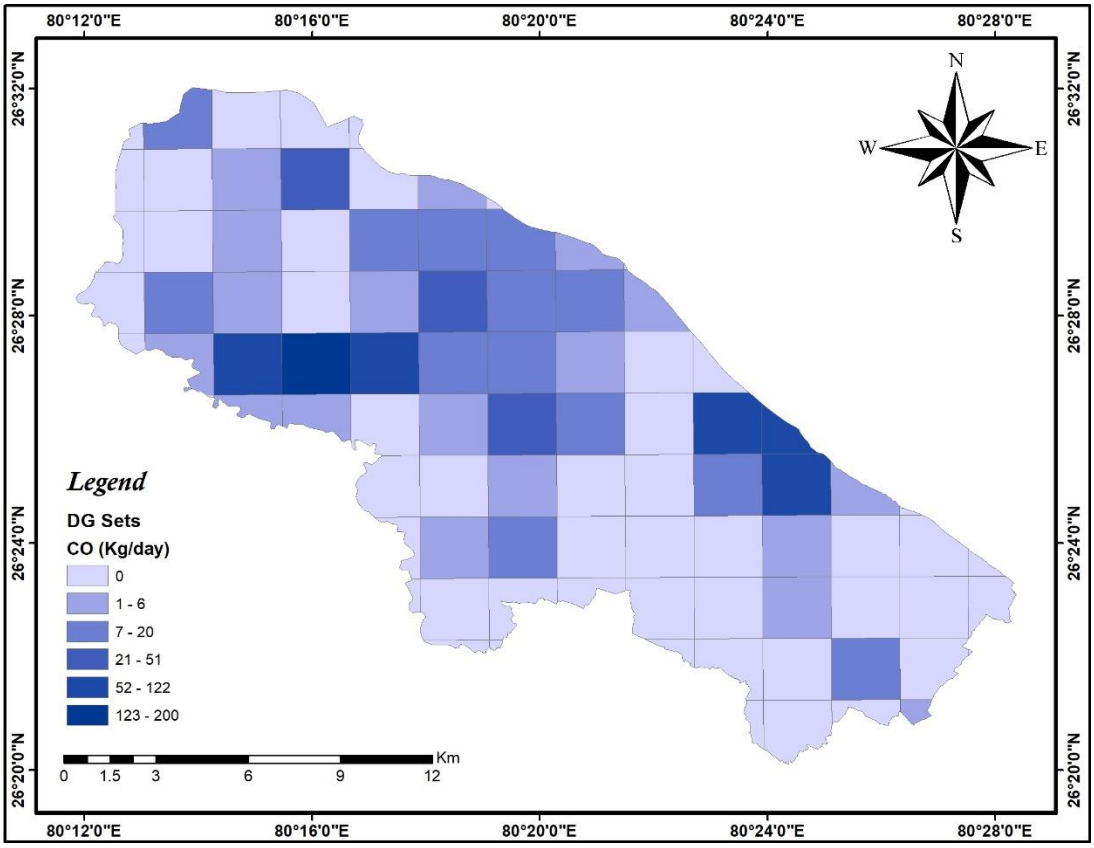


Figure 3.39: Spatial Distribution of CO Emissions from DG Sets

3.2.7 Hotels and restaurants

The primary survey was conducted by the IITK team to identify the hotels and restaurants of more than sitting capacity of ten persons and other eating joints

During the field survey, it was observed that hotels, restaurants, etc. use coal as fuel in tandoors. The total number of big hotel and restaurant enterprises was approximately 800 (Figure 3.40). It was observed that coal/wood is being used as fuel in the tandoor, the common fuel other than wood is LPG. The average consumption of wood/coal in each establishment is estimated to be 30 kg per day based on a primary survey. The fuel consumption for each fuel type was estimated for each grid. In most of the cases, it was found that there were no control devices installed at these activities. The emissions of various parameters such as SO_2, NOx, PM_{10}, $PM_{2.5}$, and CO were estimated from the activity data from each fuel type and then were summed up in each grid cell. The emission factors given by CPCB (2011) were used. The overall emission from this area source (Hotels/Restaurants) is shown in Figure 3.41. The spatial distribution of emissions from hotels/restaurants is shown in Figure 3.42 to Figure 3.46.

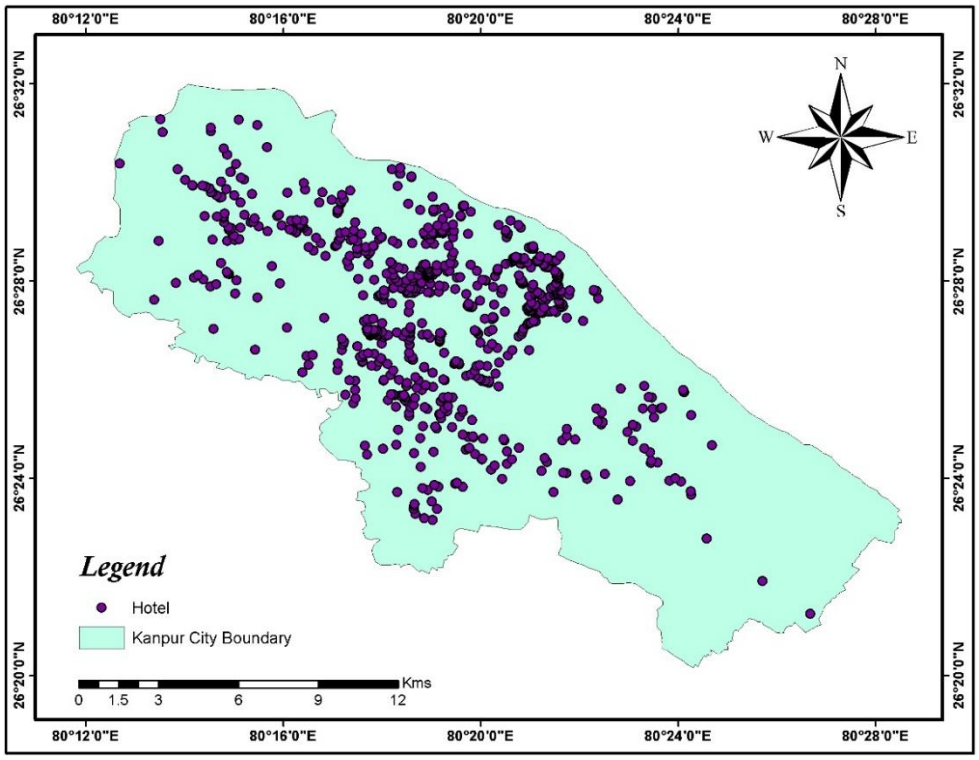


Figure 3.40: Location of Hotels and Restaurants

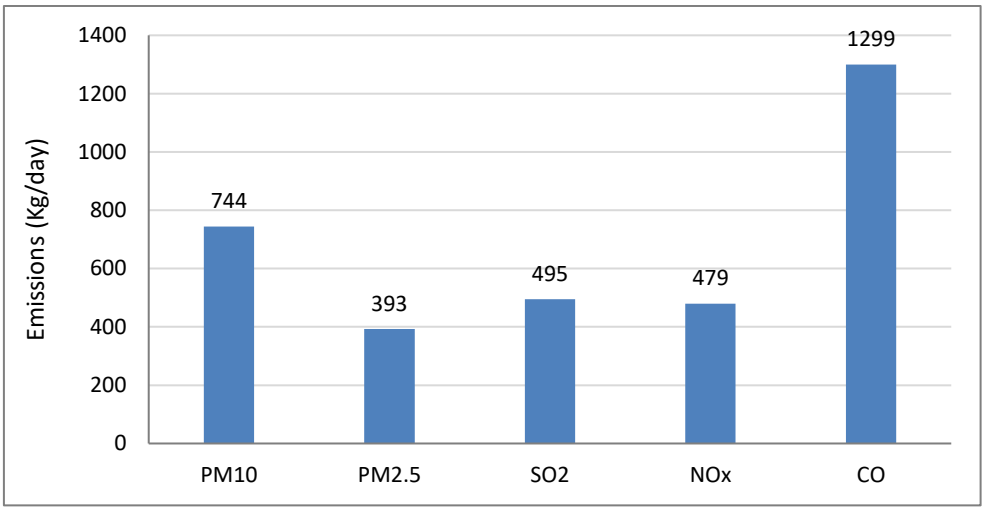


Figure 3.41: Emission Load from Hotels and Restaurants

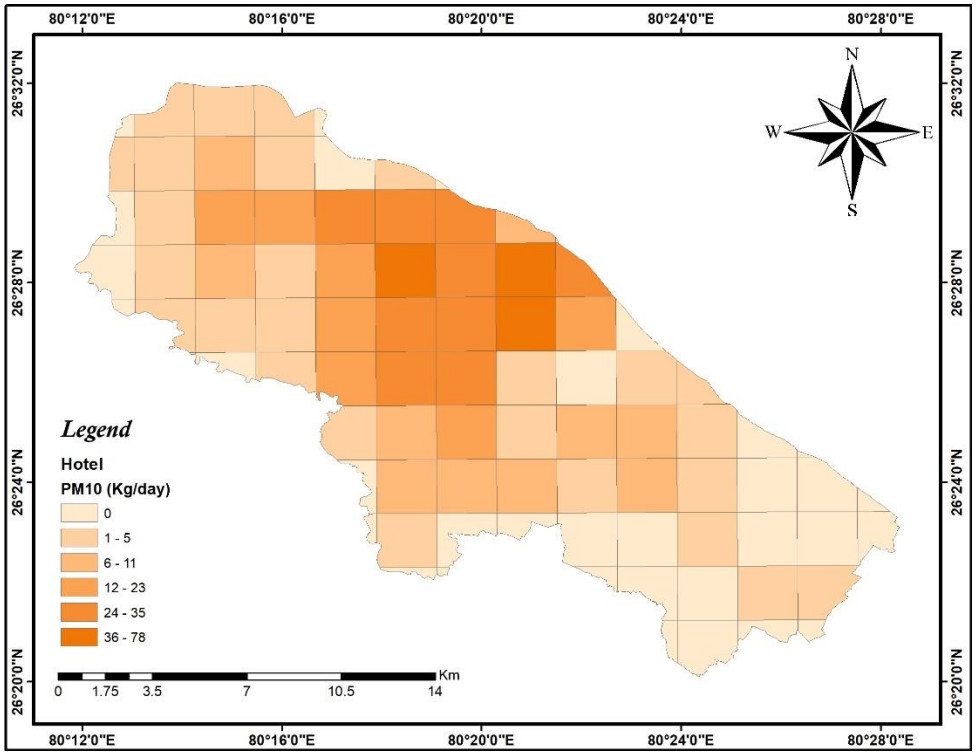


Figure 3.42: Spatial Distribution of PM_{10} Emissions from Hotels and Restaurants

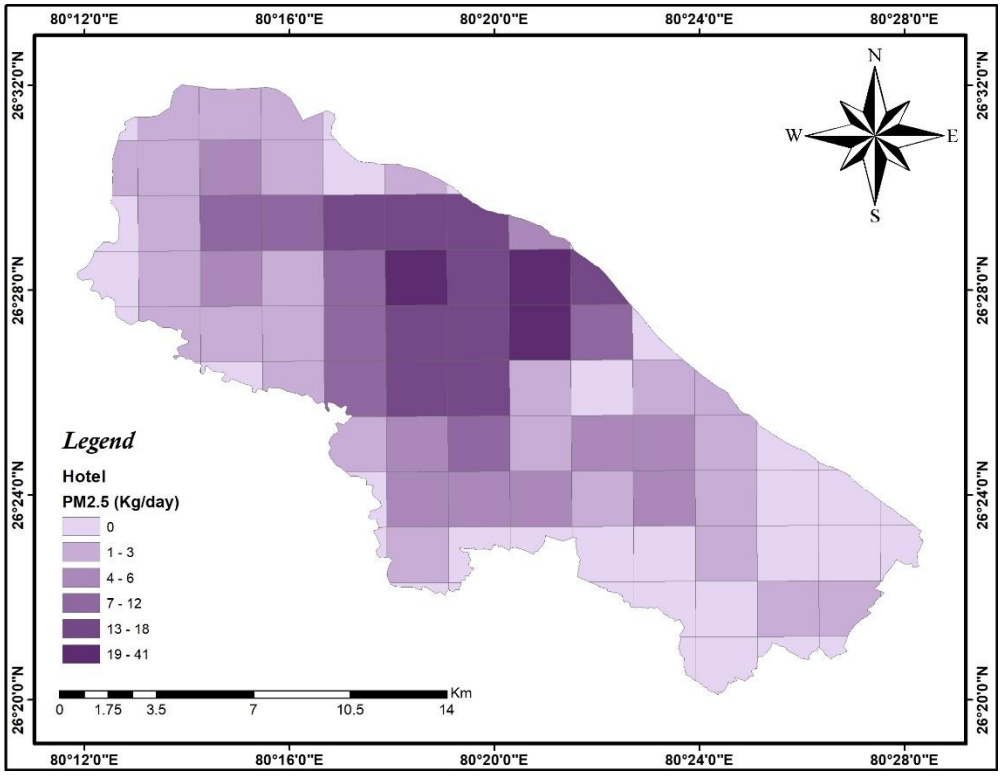


Figure 3.43: Spatial Distribution of $PM_{2.5}$ Emissions from Hotels and Restaurants

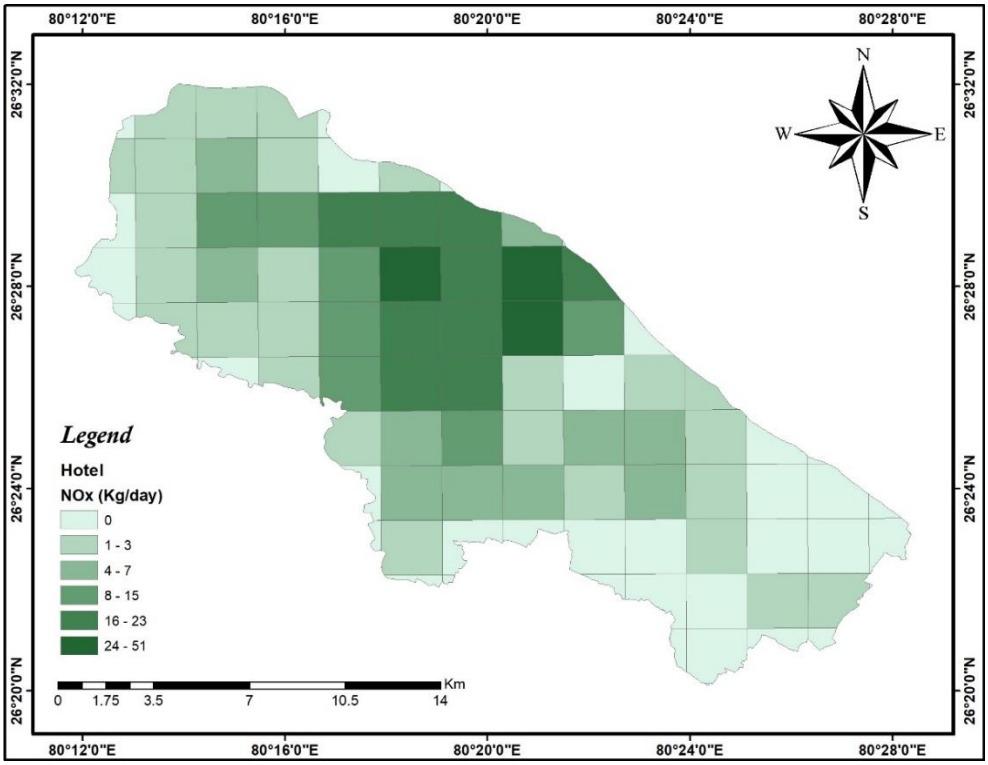


Figure 3.44: Spatial Distribution of NO_X Emissions from Hotels and Restaurant

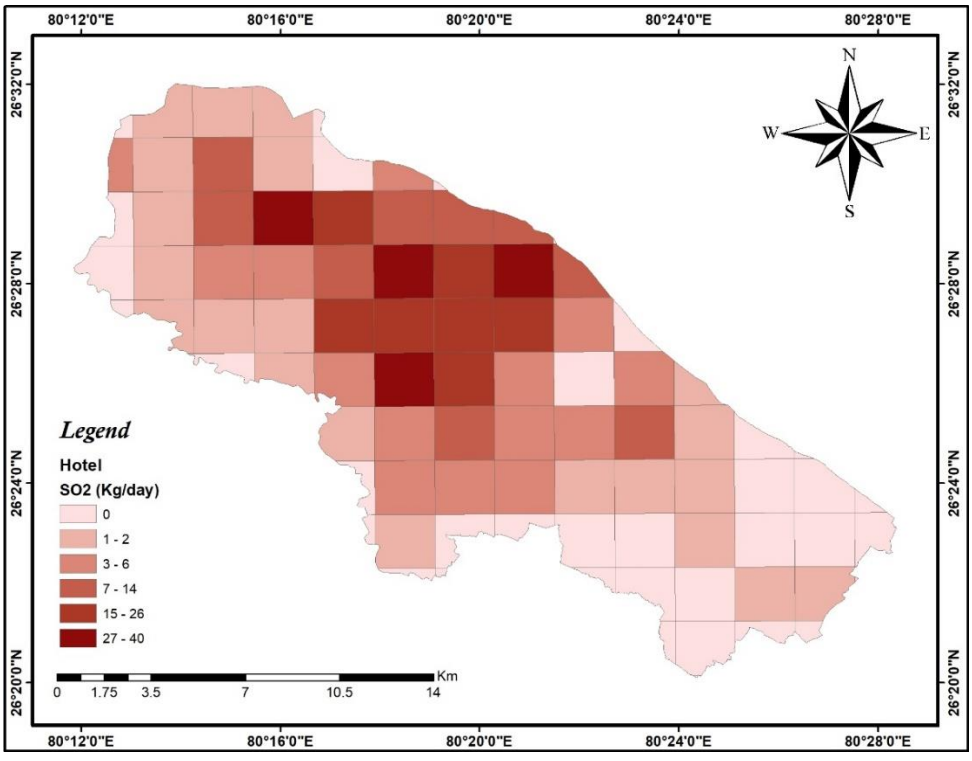


Figure 3.45: Spatial Distribution of SO_2 Emissions from Hotels and Restaurants

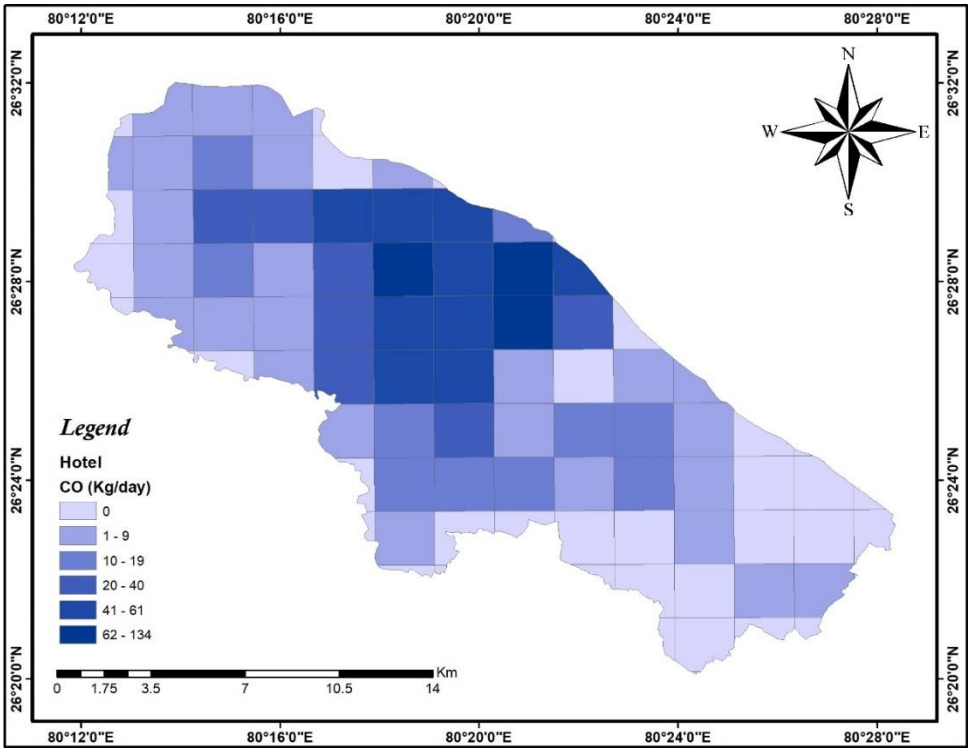


Figure 3.46: Spatial Distribution of CO Emissions from Hotels and Restaurant

3.2.8 Municipal Solid Waste burning

Open burning activities are broadly classified into refuse and biomass burning. The refuse or municipal solid waste (MSW) burning depends on solid waste generation and the extent of disposal and infrastructure for collection. The contribution of MSW burning may surprise many persons. This emission is expected to be large in the regions of economically lower strata of the society which do not have proper infrastructure for collection and disposal of MSW. The MSW collection efficiency is 80% in Kanpur city (CPCB annual report, 2018), several events of MSW burning have been observed during the city survey. The survey was conducted for weekdays and weekends and the frequency of MSW events is calculated in the low-, middle- and higher-income areas. The MSW burning at different location of Kanpur city is shown in Figure 3.47.

Figure 3.47: MSW Burning in several parts of Kanpur city

The emission factors are given by CPCB (2011) and AP-42 (USEPA, 2000) were used for estimating the emission from MSW burning using the same procedure of emission density in a ward or village. The emissions from MSW burning are presented in Figure 3.48 and spatial distribution in Figure 3.49 to Figure 3.53.

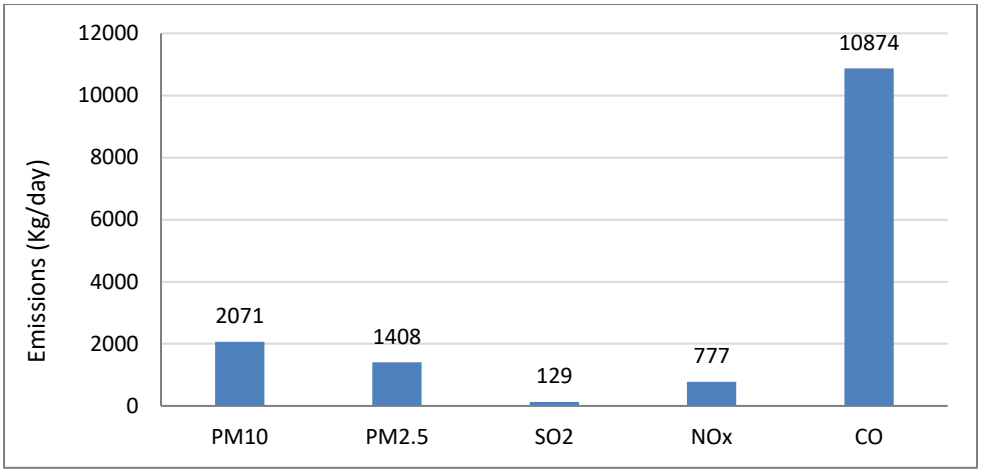


Figure 3.48: Emission Load from MSW Burning

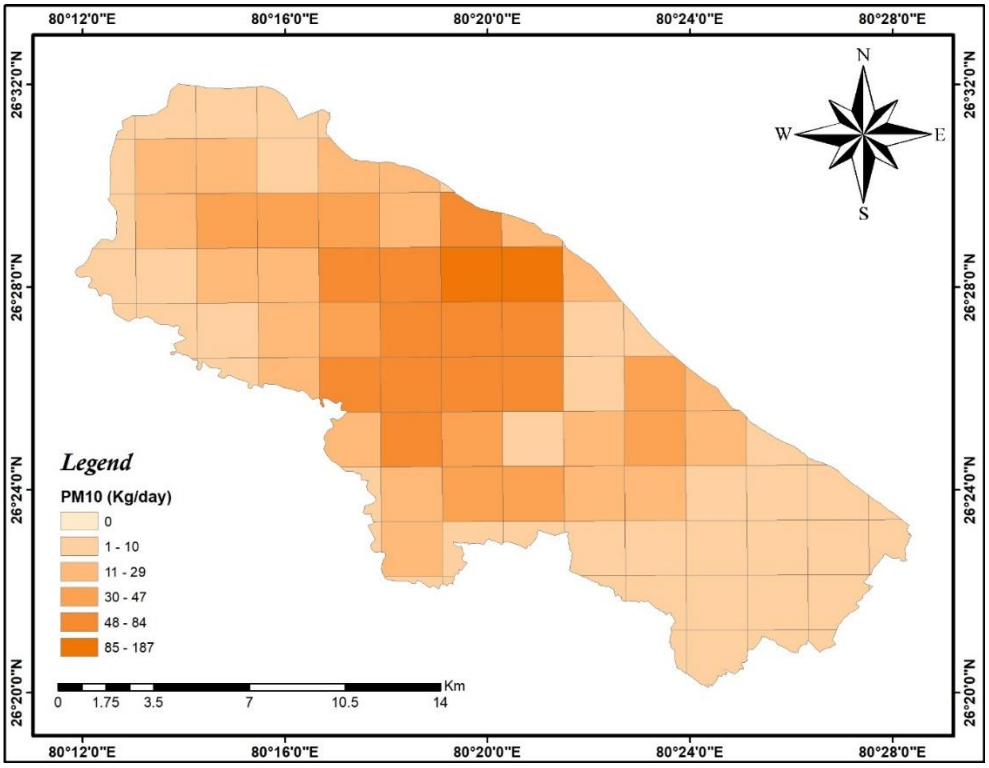


Figure 3.49: Spatial Distribution of PM_{10} Emissions from MSW Burning

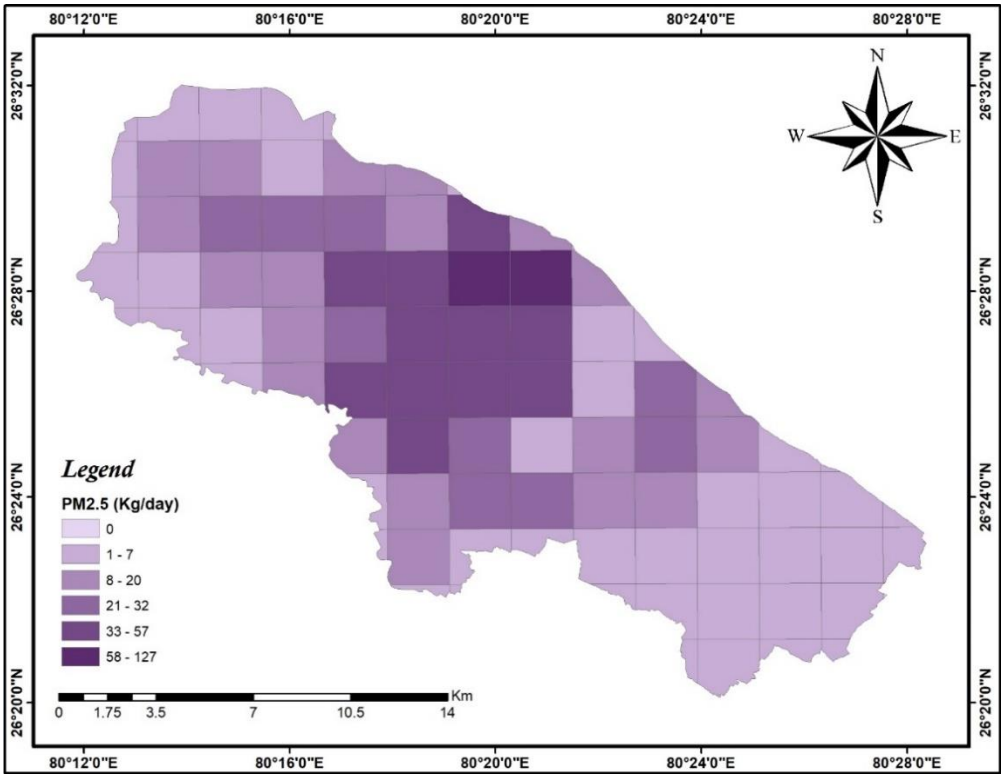


Figure 3.50: Spatial Distribution of $PM_{2.5}$ Emissions from MSW Burning

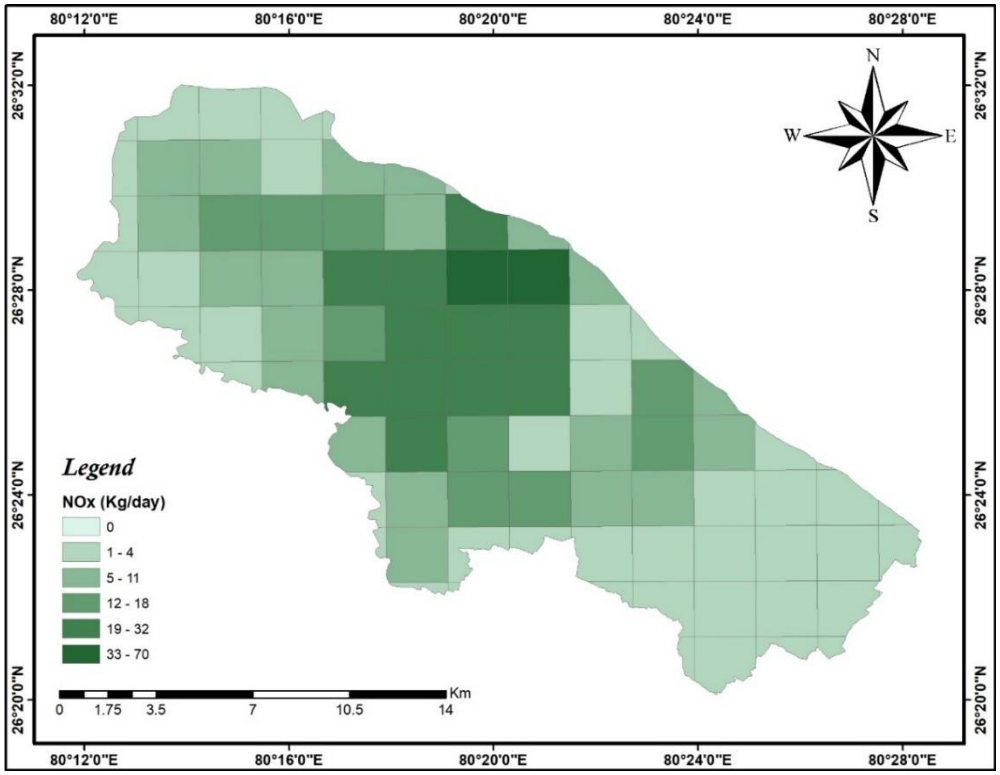


Figure 3.51: Spatial Distribution of NO_X Emissions from MSW Burning

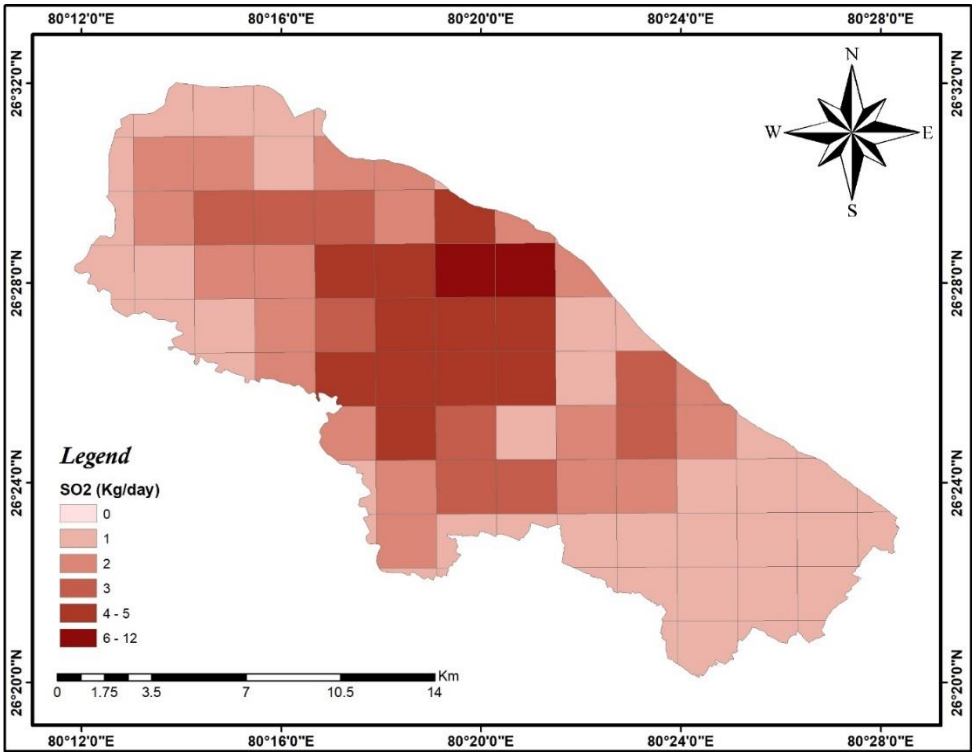


Figure 3.52: Spatial Distribution of SO_2 Emissions from MSW Burning

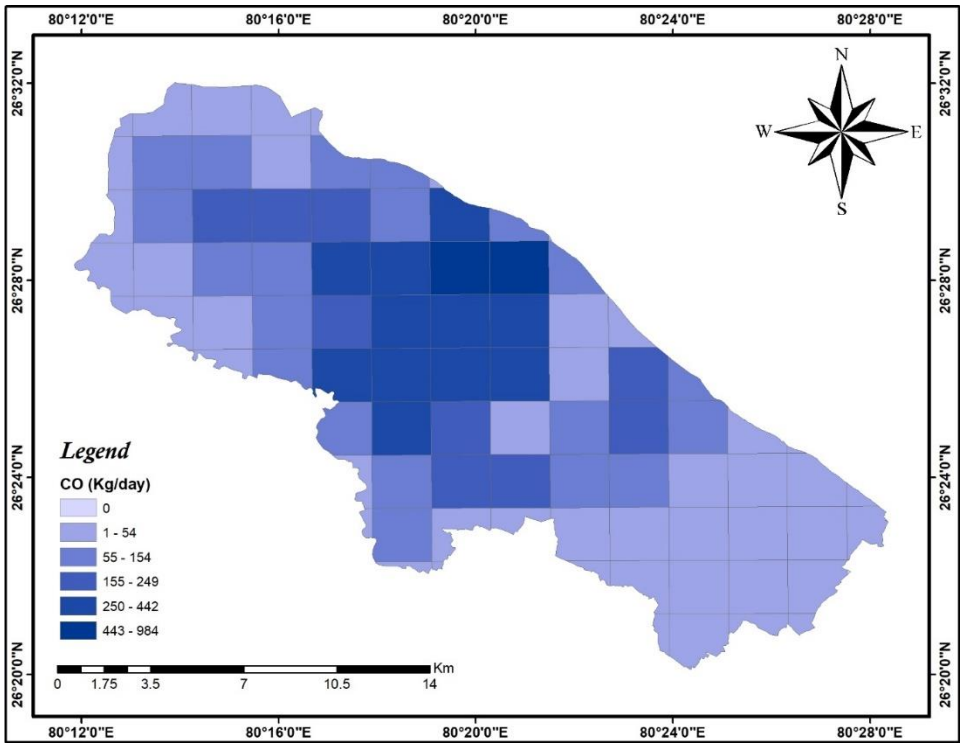


Figure 3.53: Spatial Distribution of CO Emissions from MSW Burning

3.2.9 Open Area

The open areas referred to open grounds/fields with no specific land use, mostly use for social events. The Emission Load for Open Area in Kanpur City is given in Figure 3.54. Open area contribution to PM_{10} is 121 kg/day, other pollutants are negligible. The spatial distribution of PM_{10} is given in Figure 3.55.

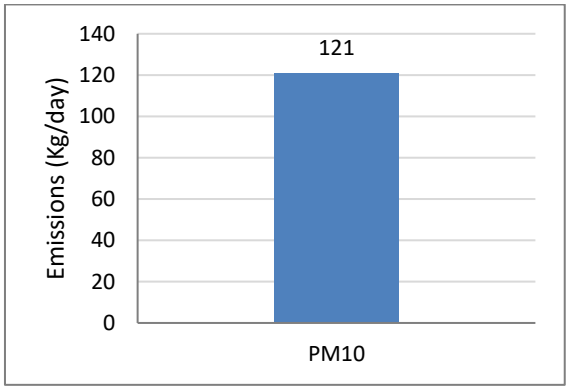


Figure 3.54: Emission Load from Open Area (kg/day)

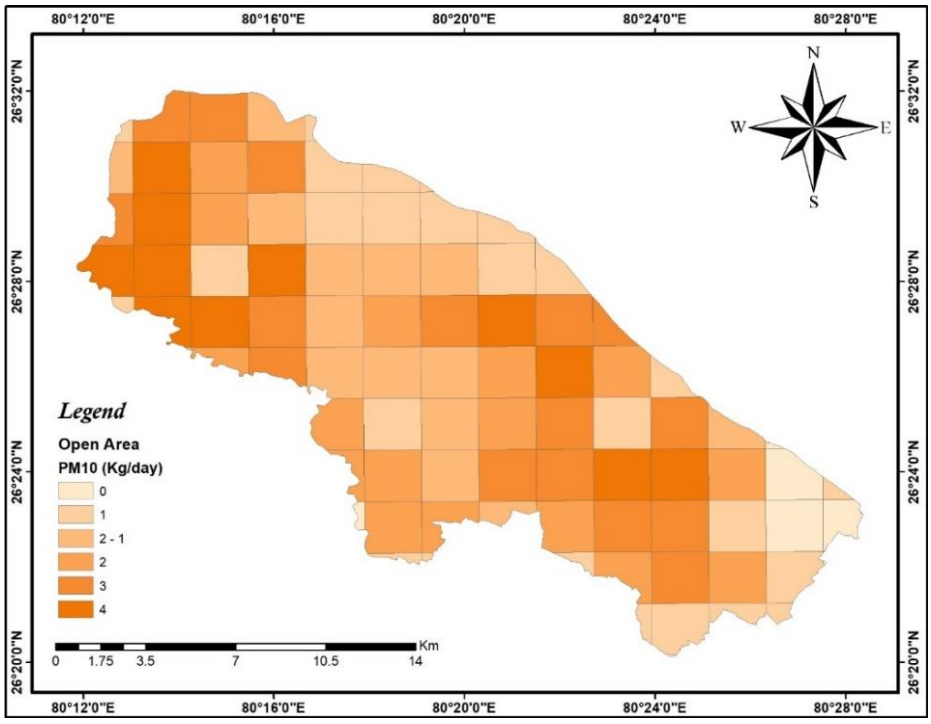


Figure 3.55: Spatial Distribution of PM_{10} Emissions from Open Area

3.2.10 Hospitals

A detailed survey was undertaken to estimate the emission from hospitals in Kanpur City. There are approximately 200 hospitals present in the city. The locations of Hospitals in Kanpur Nagar are given in Figure 3.56. The emission load from hospitals is given in Figure 3.57.

Maximum emissions for the hospitals are of NOx from DG sets. The Spatial distribution of emissions from Hospitals is given in Figure 3.58 to Figure 3.62.

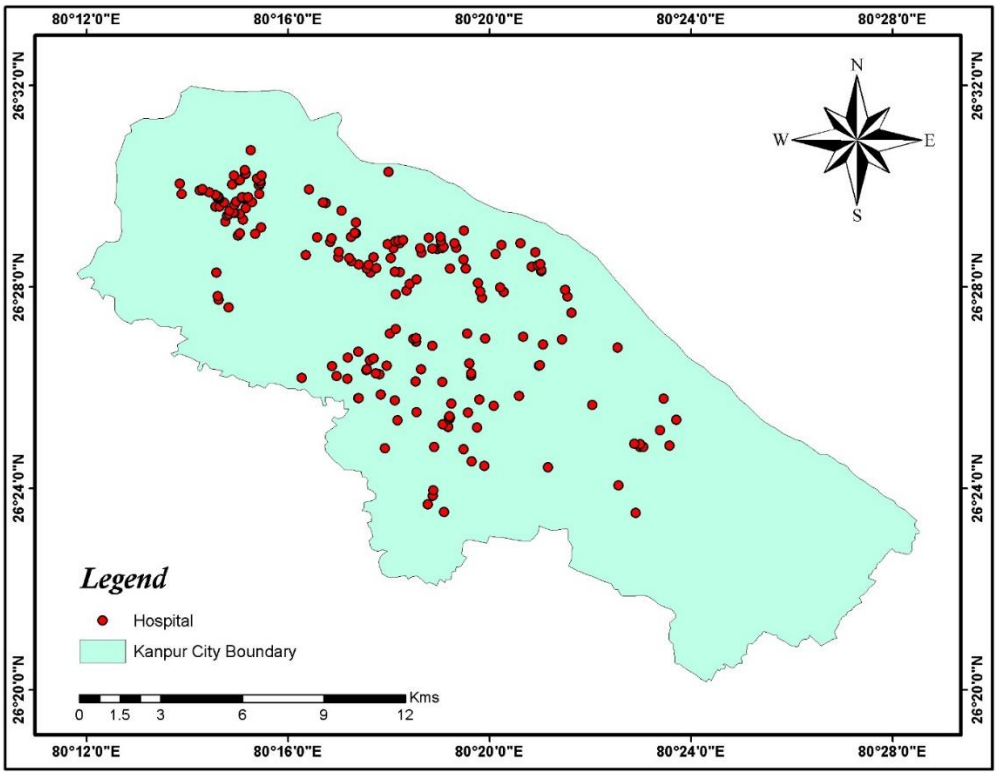


Figure 3.56: Locations of Hospitals in Kanpur City

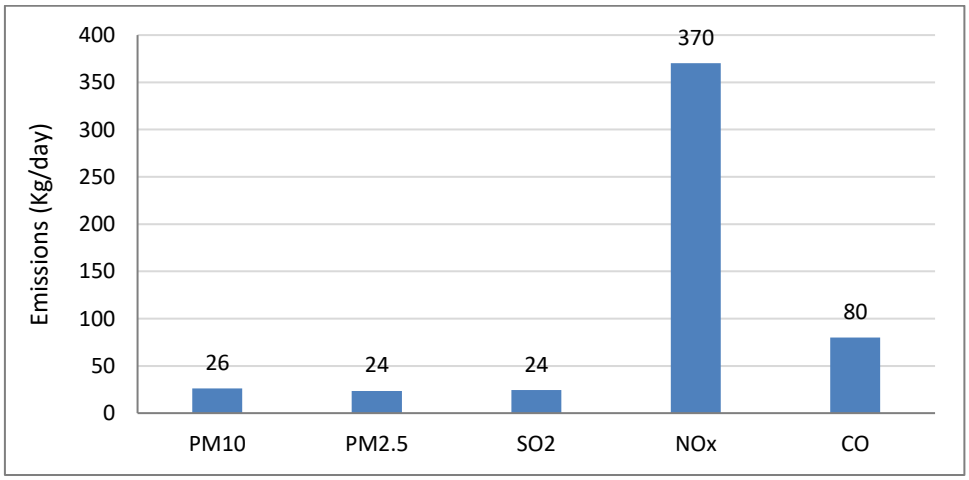


Figure 3.57: Emission Load from Hospitals (kg/day)

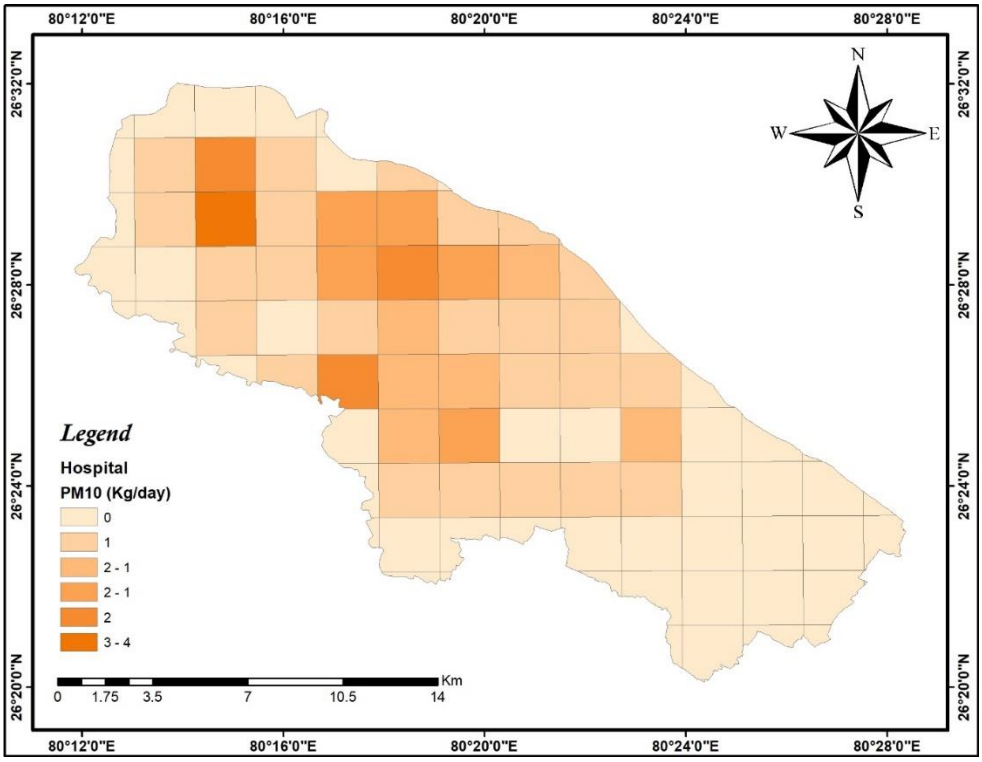


Figure 3.58: Spatial Distribution of PM_{10} Emissions from Hospitals

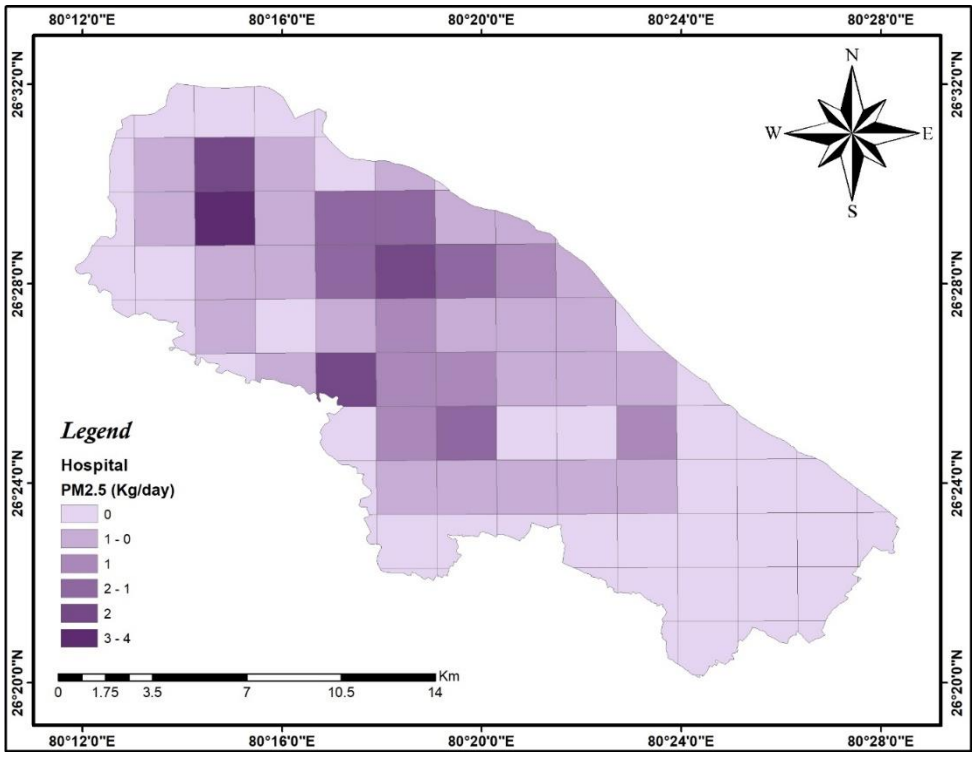


Figure 3.59: Spatial Distribution of $PM_{2.5}$ Emissions from Hospitals

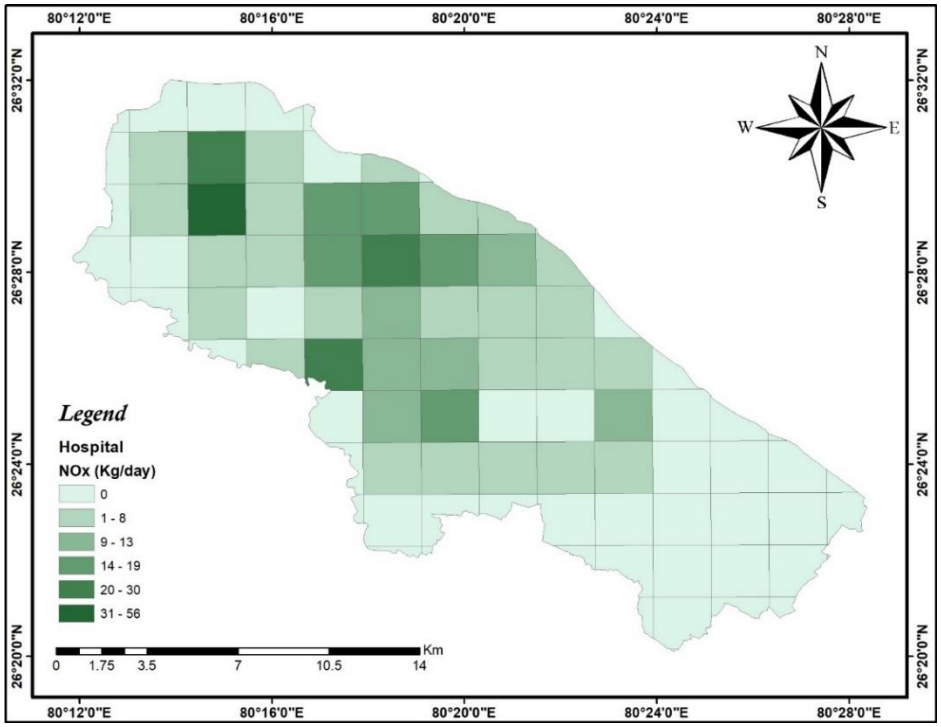


Figure 3.60: Spatial Distribution of NOx Emissions from Hospitals

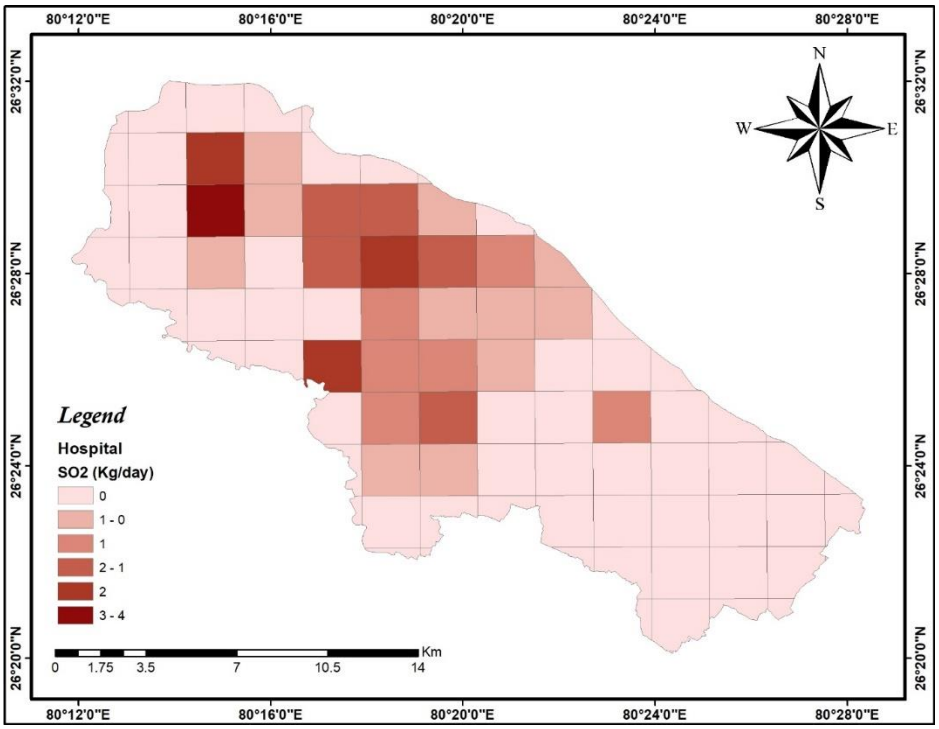


Figure 3.61: Spatial Distribution of SO_2 Emissions from Hospitals

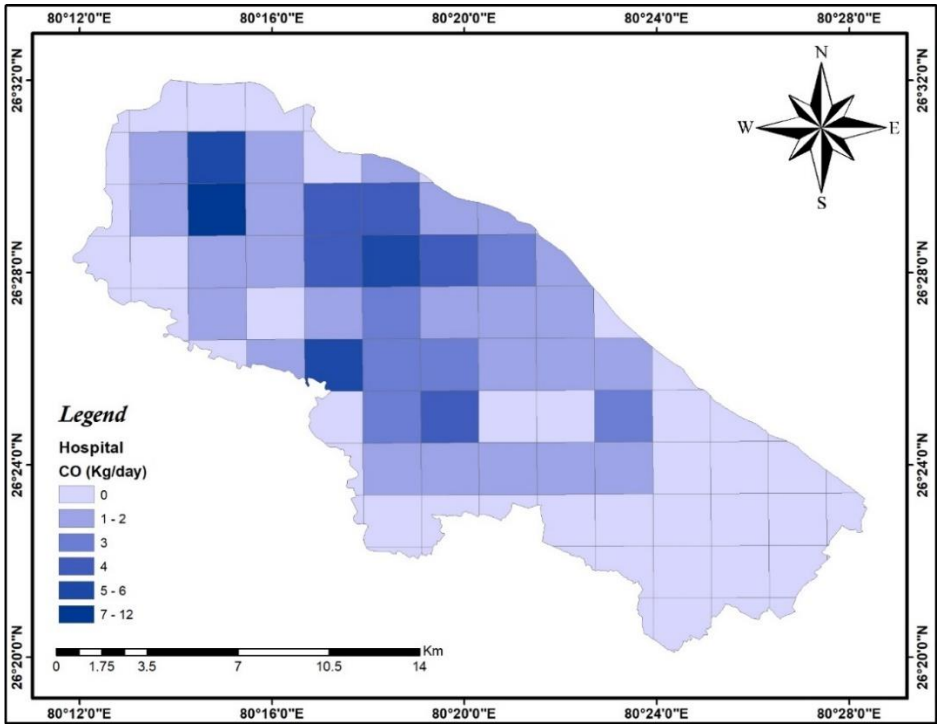


Figure 3.62: Spatial Distribution of CO Emissions from Hospitals

3.2.11 Industries

There are approximately 720 industrial units in Kanpur City (Figure 3.63) having 250 boilers/baby boilers (with size e.g., 2TPH) that are operational in Kanpur city and contribute to particulate as well as in gaseous emissions. The overall emissions estimated from the different types of boilers, furnaces, etc are presented in Table 3.1. The large contribution is from the boilers that majorly use wood/coal as fuel in them. Also, the lead smelting furnaces (around 45 in numbers) are being used in the manufacturing of lead ingots at Kanpur city that contributes to emissions. These lead industries are located in Panki industrial area and a few are on Dada Nagar area. The industries are categorized based on stack height as area source (stack height < 20 m) and as a point source with stack height more than 20m.

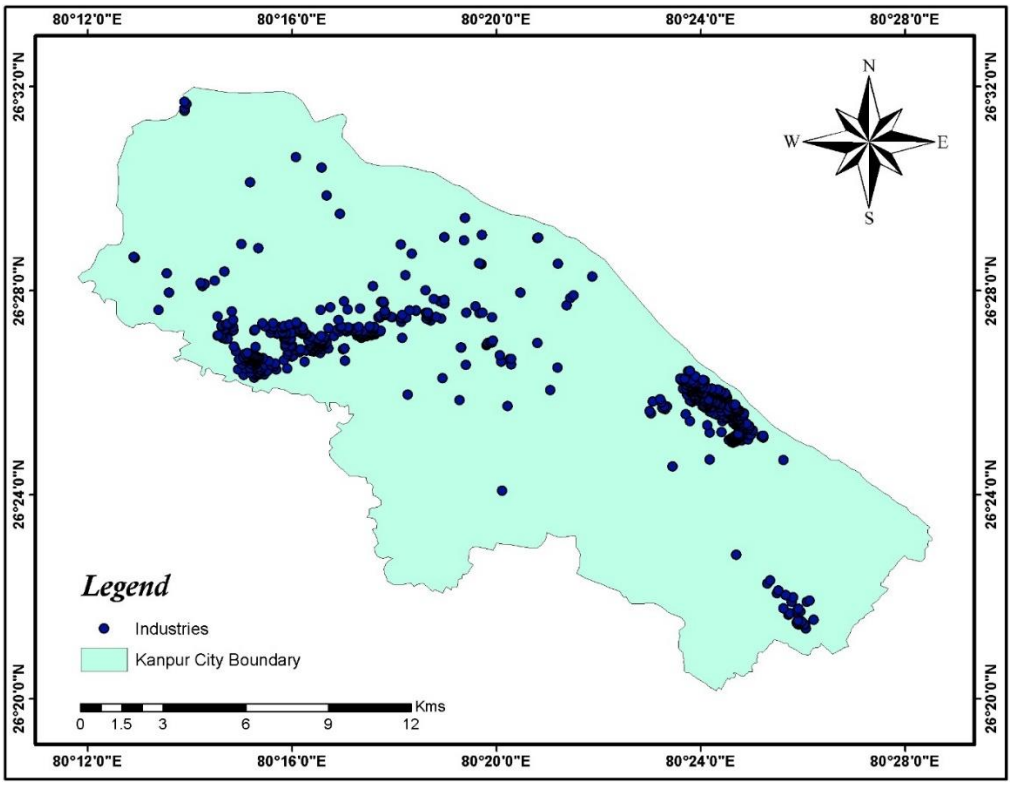


Figure 3.63: Location of Industries

Table 3.1: Furnace/Boiler Details in Kanpur City (emissions in kg/day) (Source: Consent Data, UPPCB)

Boiler/Furnace Type	Fuel used in Boiler/Furnace	No of Furnaces/ Boilers	PM10	PM2.5	NOx	SO2	CO
			kg/day	kg/day	kg/day	kg/day	kg/day
Baby Boilers	Wood, Coal, Charcoal	212	341	307	734	634	57
Boiler	Coal, LDO, Rice Husk, Diesel	38	329	296	549	487	1413
Induction Furnace	Electricity	1	1	1	0	0	0
Uncategorised boiler/furnace	Coal, Wood, H.S.D.	403	2794	2515	7450	6250	2608
AFBC Boiler	Coal	1	812	731	1760	1520	40
Furnace	Coal	6	5	5	11	10	0.25
Low Temperature Furnace	H.S.D.	1	6	5	53	151	5
Oil fired Boiler	H.S.D.	1	4	3	33	94	3

Lead Melting Furnace	Coal, Wood	43	77	70	106	88	448
Thermic Fluid Heater	Coal, Wood	15	29	26	61	52	14
Cupola Furnace	Coal	2	2	1	3	3	0
Total		**723**	**4400**	**3960**	**10760**	**9289**	**4588**

Industries as Area Source

There are around 57 industries categorized as area source in Kanpur City. The location of industries as area source is given in Figure 3.64. Figure 3.65 presents the overall emissions from industries (stack height < 20 m) as an area source. The boiler/baby boilers are majorly falling under this category. The spatial distribution of emissions from industries (area source) is presented in Figure 3.66 to Figure 3.70.

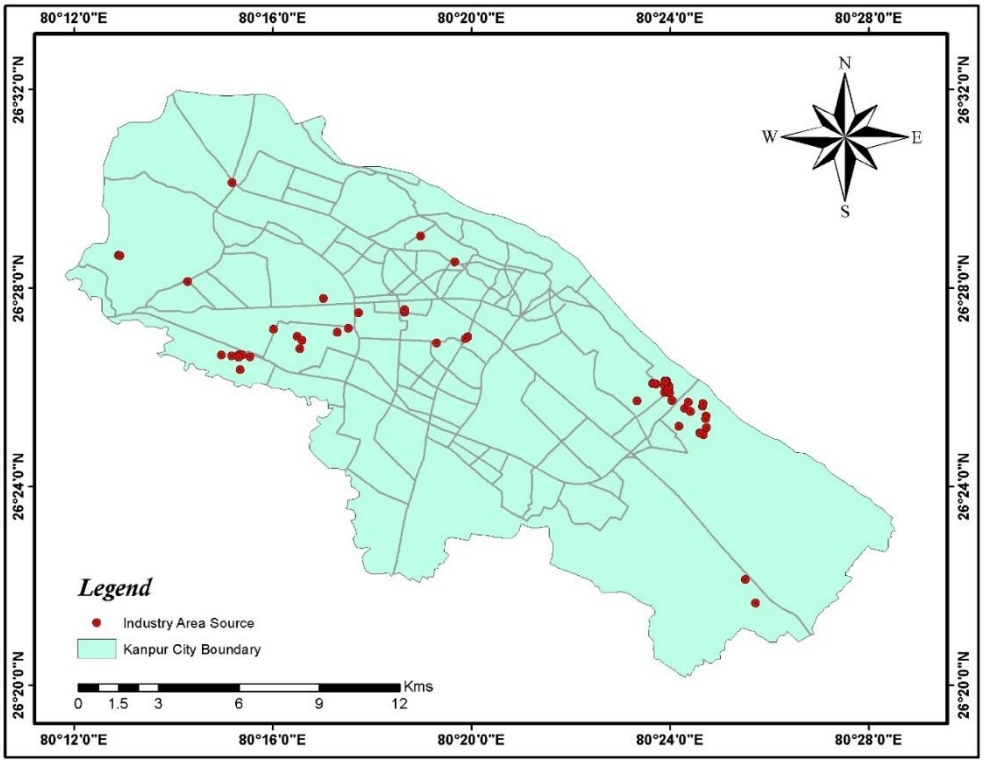


Figure 3.64: Location of Industries as area source

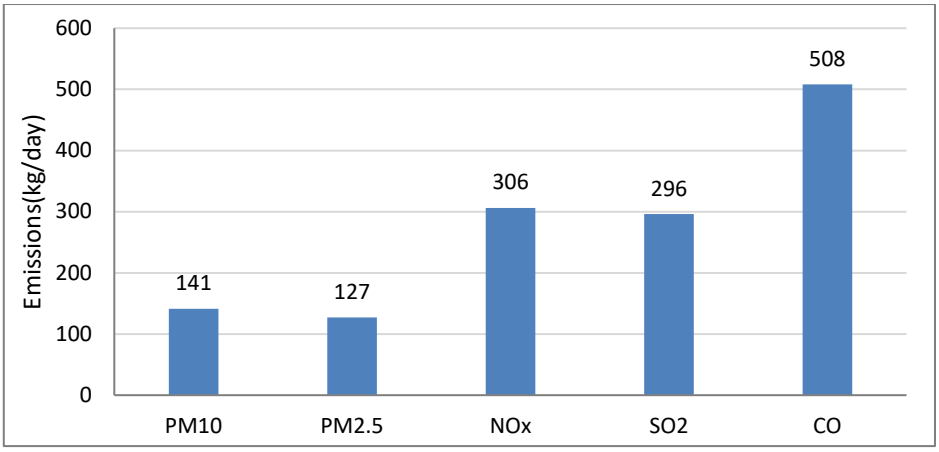


Figure 3.65: Emission Load from Industries as Area Source

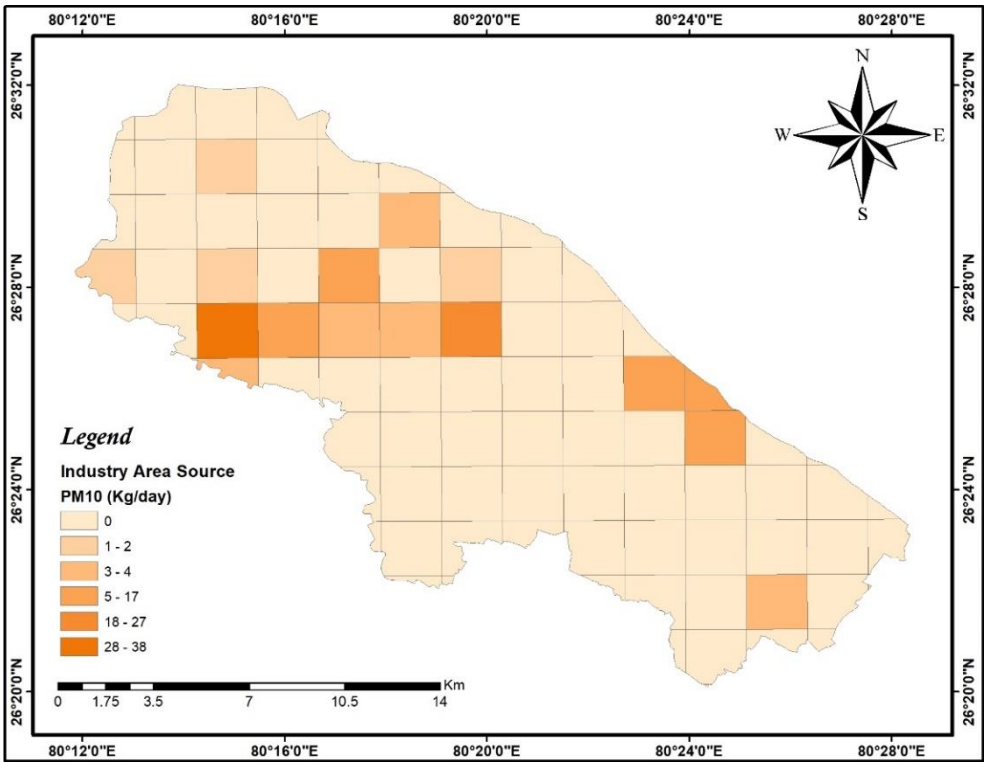


Figure 3.66: Spatial Distribution of PM_{10} Emissions from Industries as area source

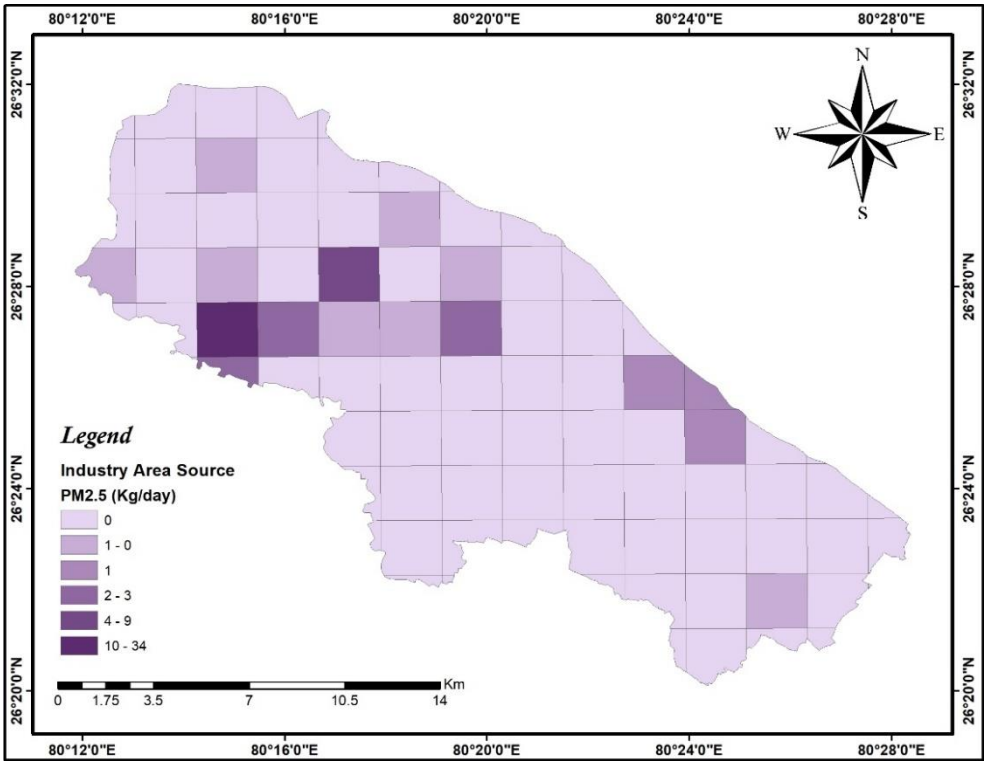


Figure 3.67: Spatial Distribution of $PM_{2.5}$ Emissions from Industries as area source

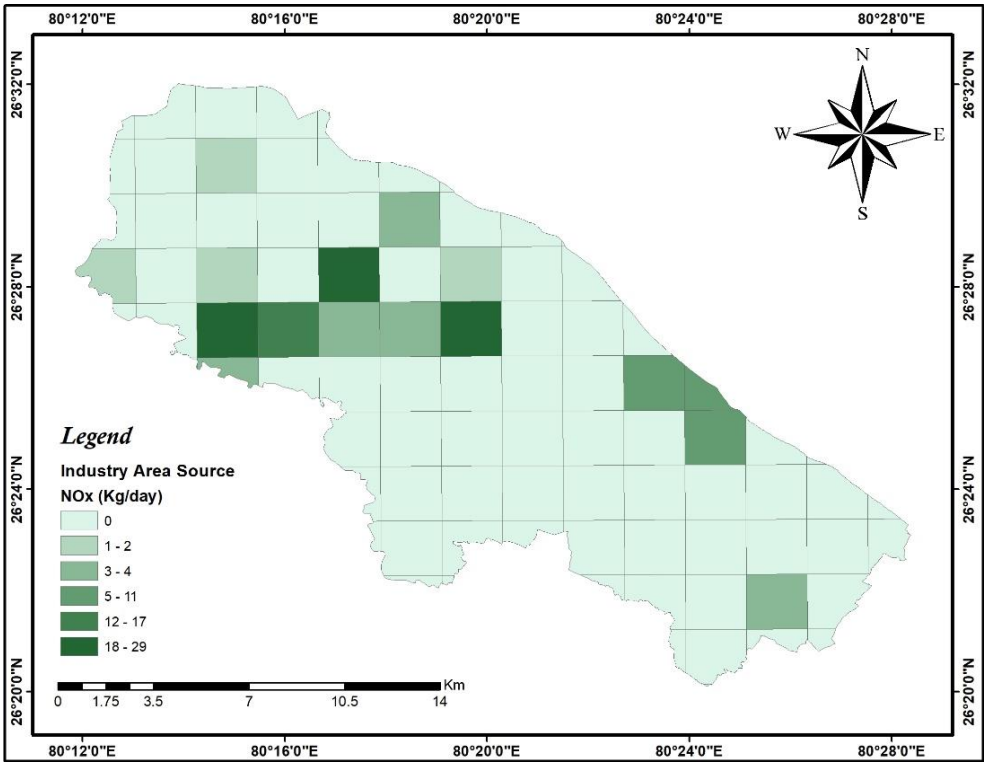


Figure 3.68: Spatial Distribution of NO_x Emissions from Industries as area source

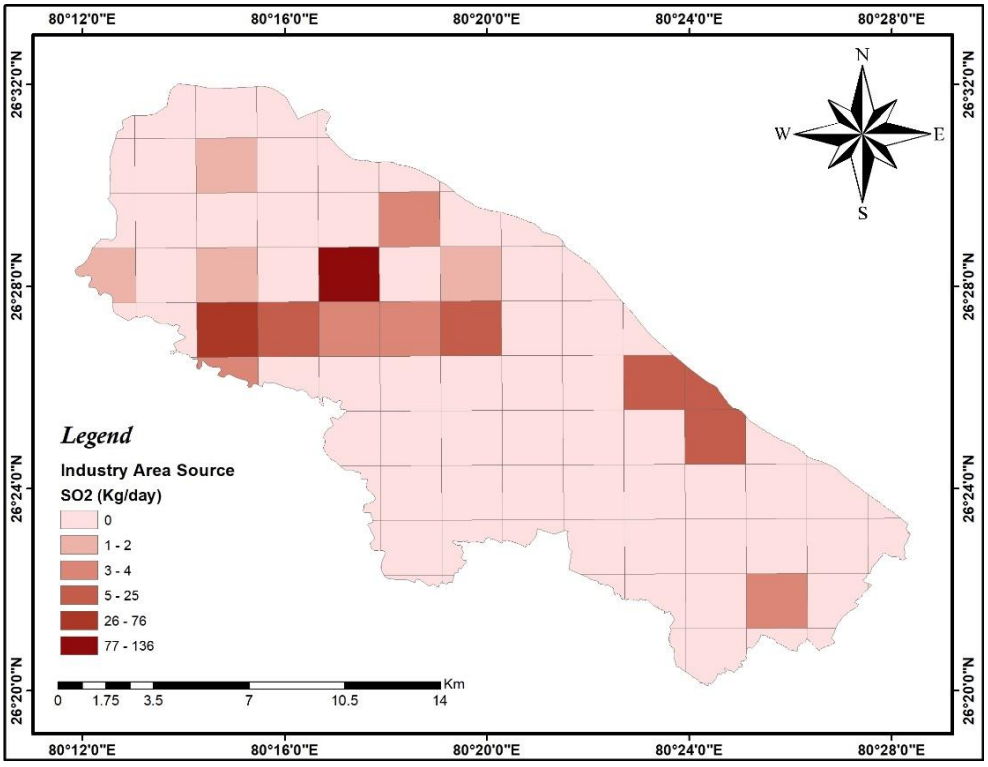


Figure 3.69: Spatial Distribution of SO_2 Emissions from Industries as area source

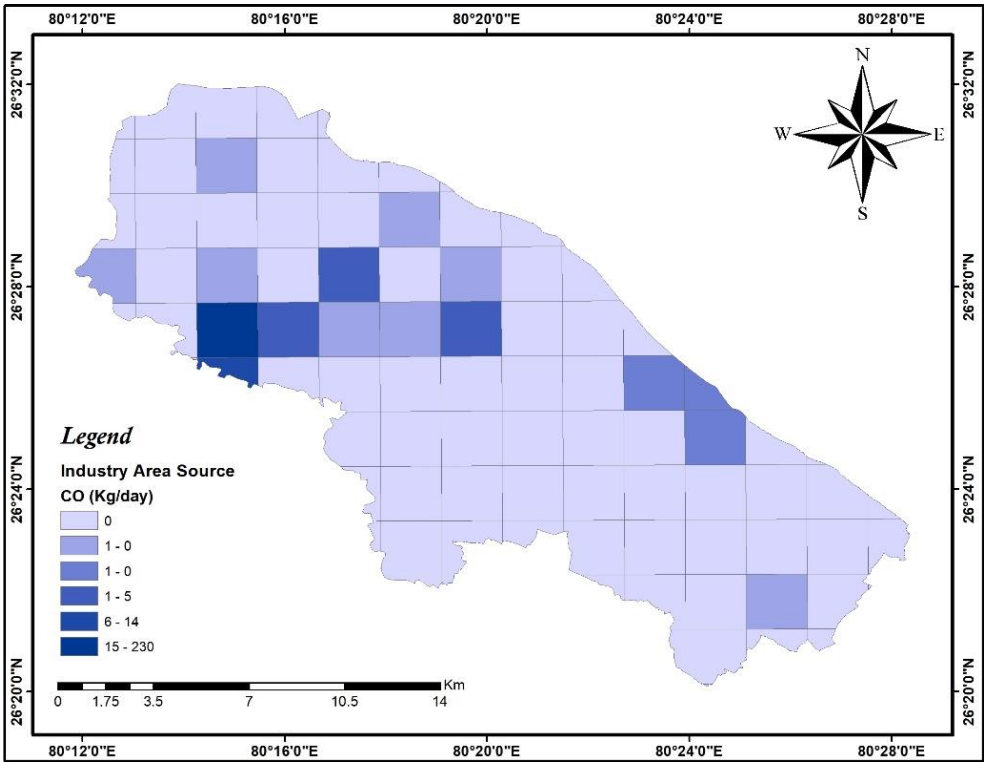


Figure 3.70: Spatial Distribution of CO Emissions from Industries as area source

Industries as Point Source

There are approximately 670 industries that are having chimney height equal to or more than 20 meters (Figure 3.71). The information on stacks, fuel, and its consumption was obtained from UPPCB. The AP-42 (USEPA, 2000) emission factors were used to calculate the emission. The emission of pollutants from large industries is shown in Figure 3.72.

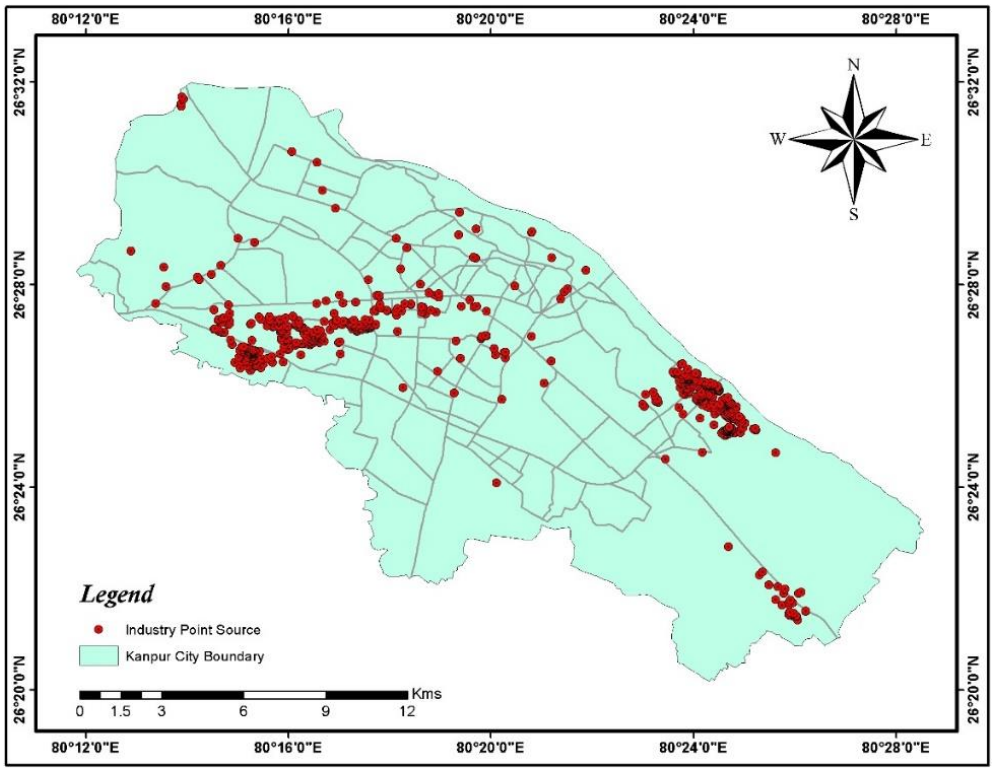


Figure 3.71: Location of Industries as point source

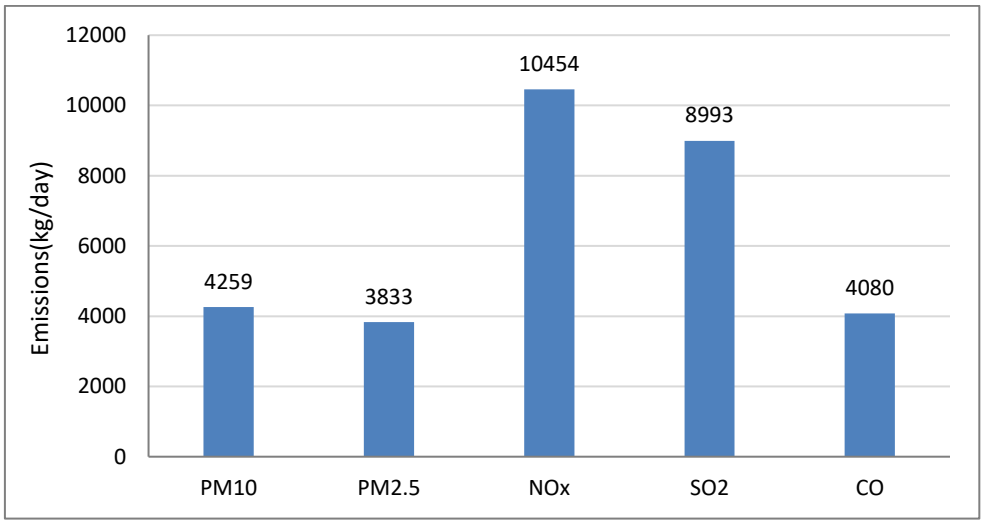


Figure 3.72: Emission Load from Industrial Point Source

The spatial distribution of emissions from industries as point source is presented in Figure 3.73 to Figure 3.77.

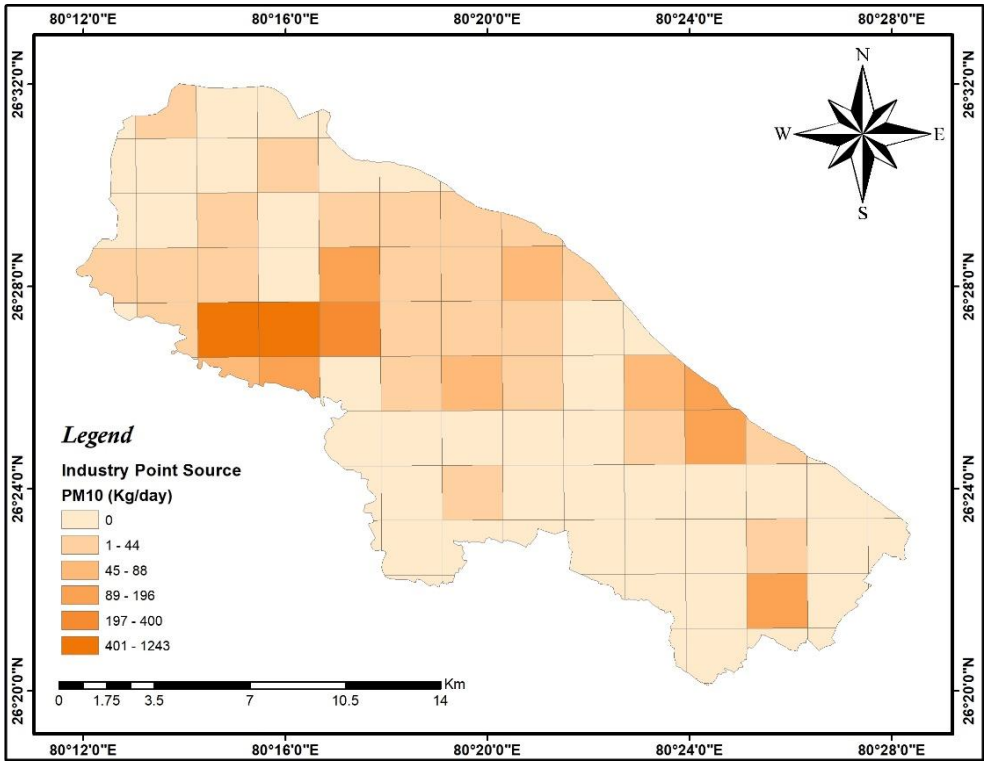


Figure 3.73: Spatial Distribution of PM_{10} Emissions from Industries as point source

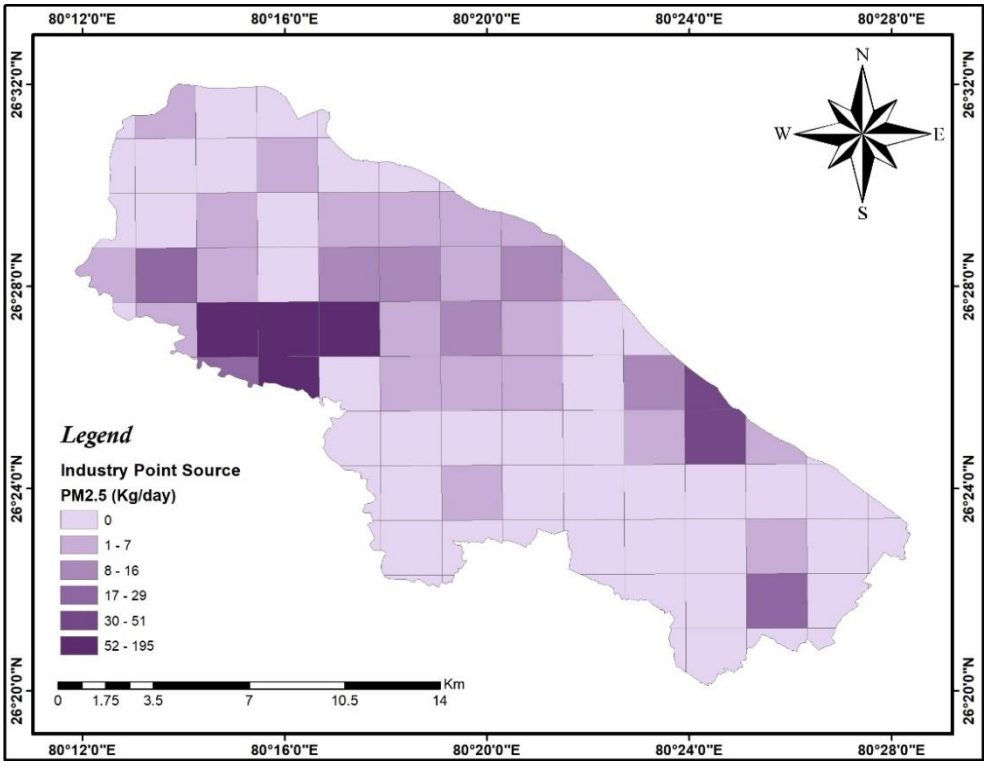


Figure 3.74: Spatial Distribution of $PM_{2.5}$ Emissions from Industries as point source

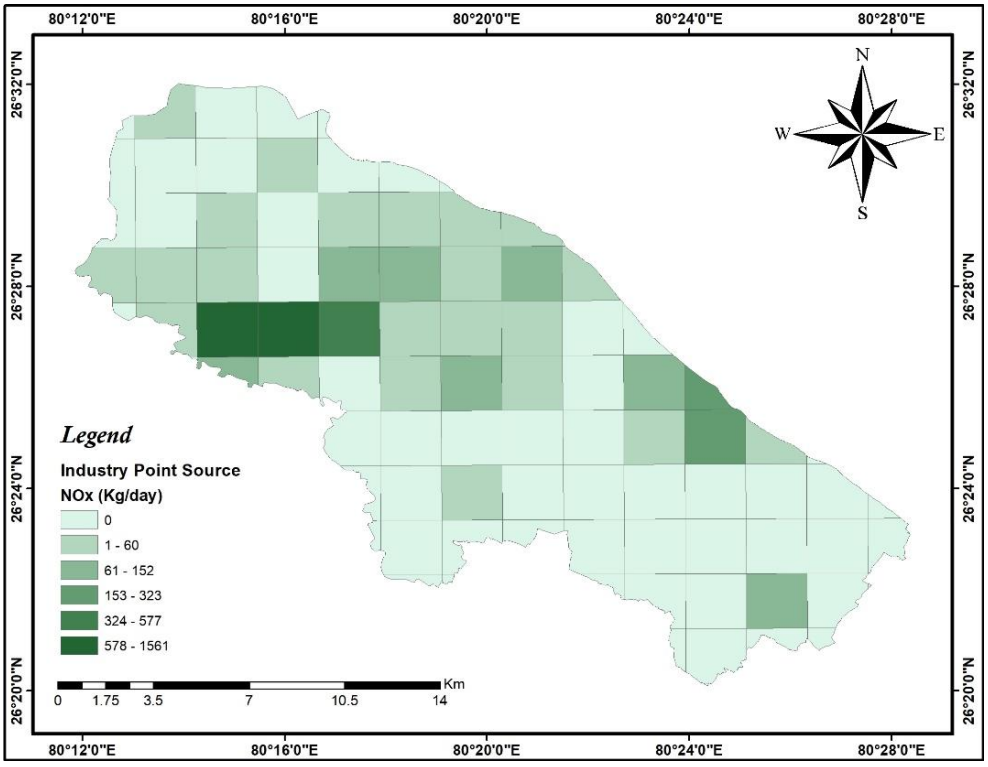


Figure 3.75: Spatial Distribution of NOx Emissions from Industries as point source

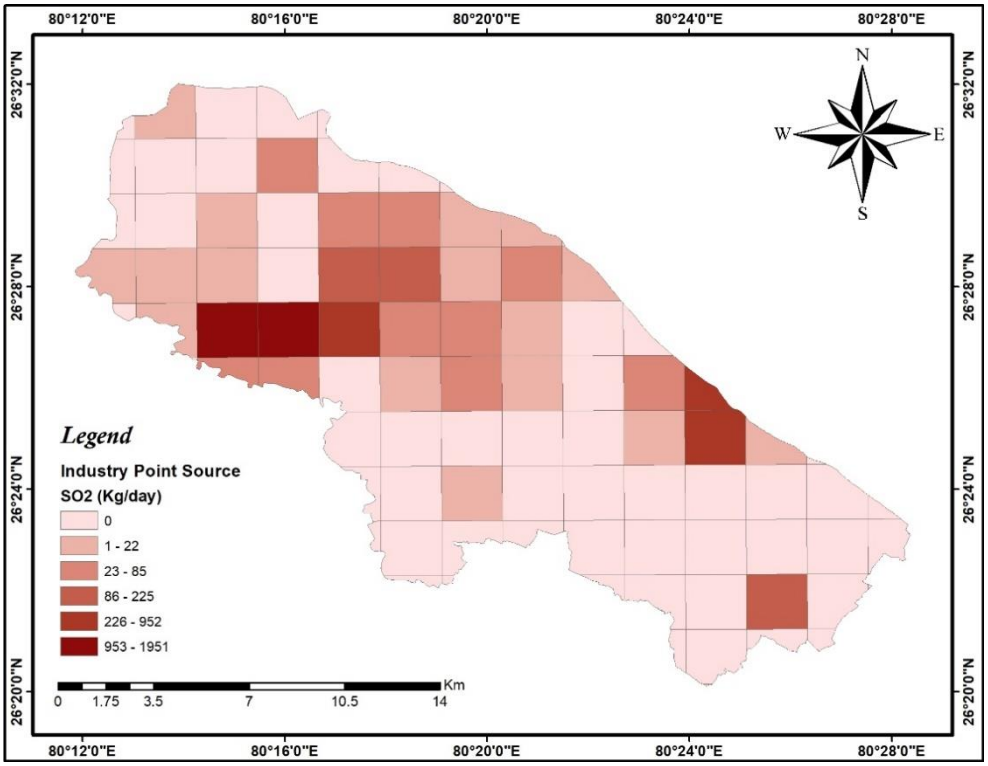


Figure 3.76: Spatial Distribution of SO_2 Emissions from Industries as point source

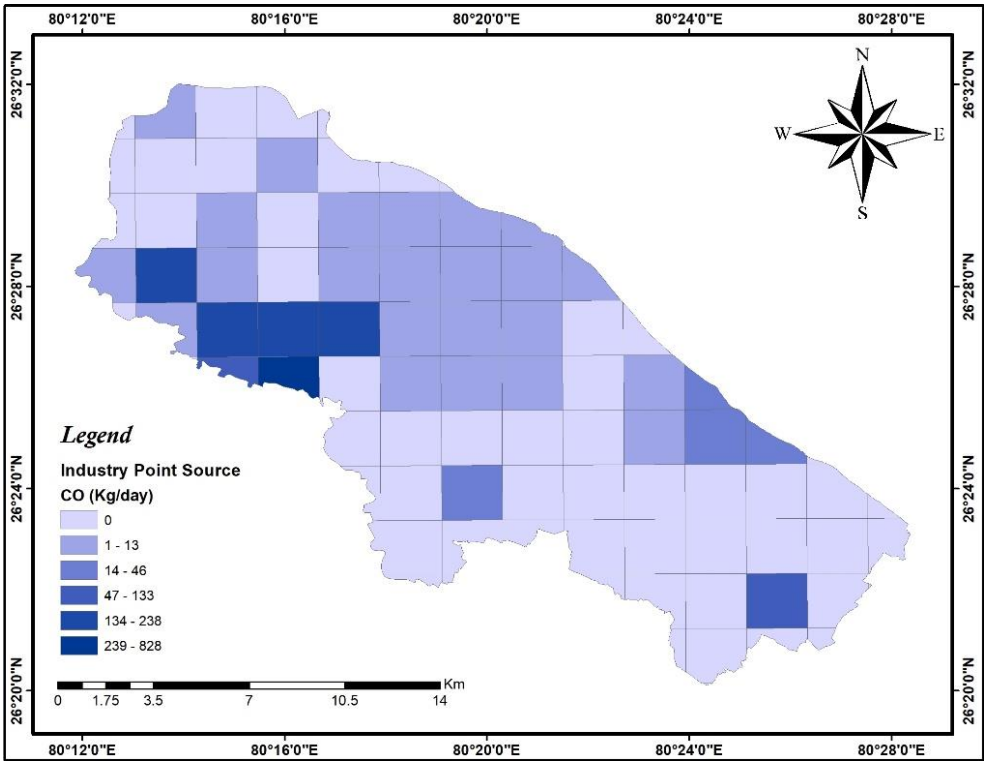


Figure 3.77: Spatial Distribution of CO Emissions from Industries as point source

3.2.12 Parking Lot Survey

To obtain the prevalence of vehicle technology types operating in the city and fuel used, parking lot questionnaire surveys (engine technology and capacity, vehicle age, fuel use, etc.) were done at 10 locations (Kalyanpur, BadaChauraha, Tatmill, Ramadevi, Vijaynagar, Dadanagar, Zsquare, Mallroad, Kanpur Central, Rave Moti)) in the city of Kanpur. ARAI (2011) and CPCB (2011) emission factors were used to calculate the emissions. The parking lane survey results for 2Ws, 3Ws, and 4Ws in terms of engine size and year of manufacturing is presented in Figure 3.78 to Figure 3.80. This information is vital in calculating the emission from vehicles on the road. The emission factors vary considerably for engine size, fuel uses, and age of the vehicles.

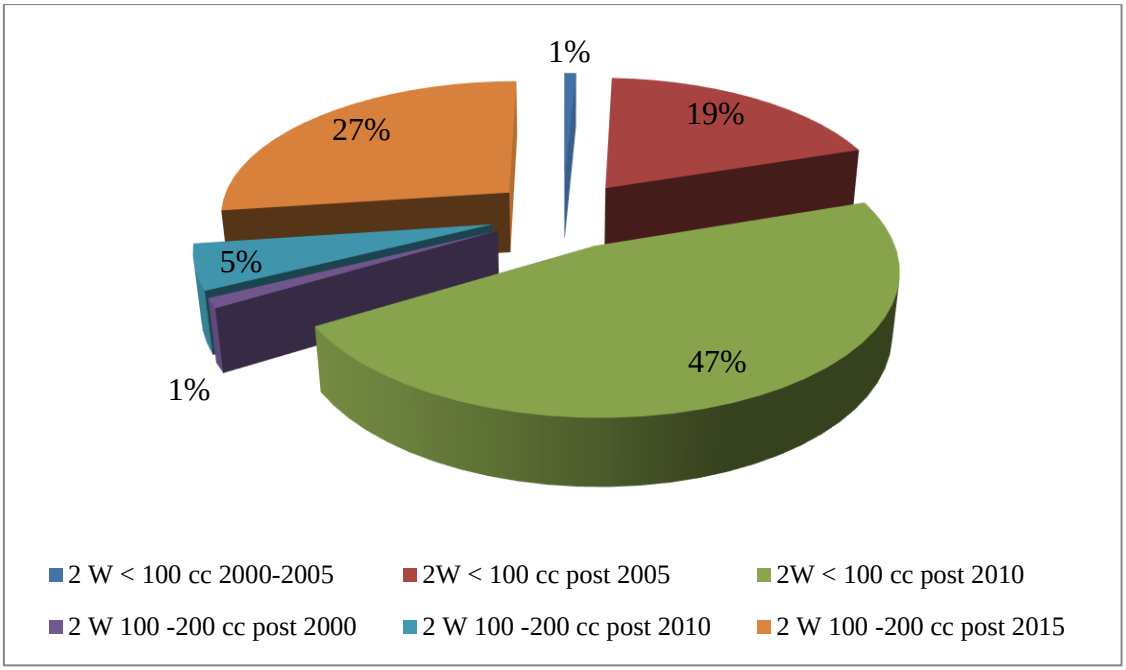


Figure 3.78: **Distribution of 2-Ws in the study area (parking lot survey)**

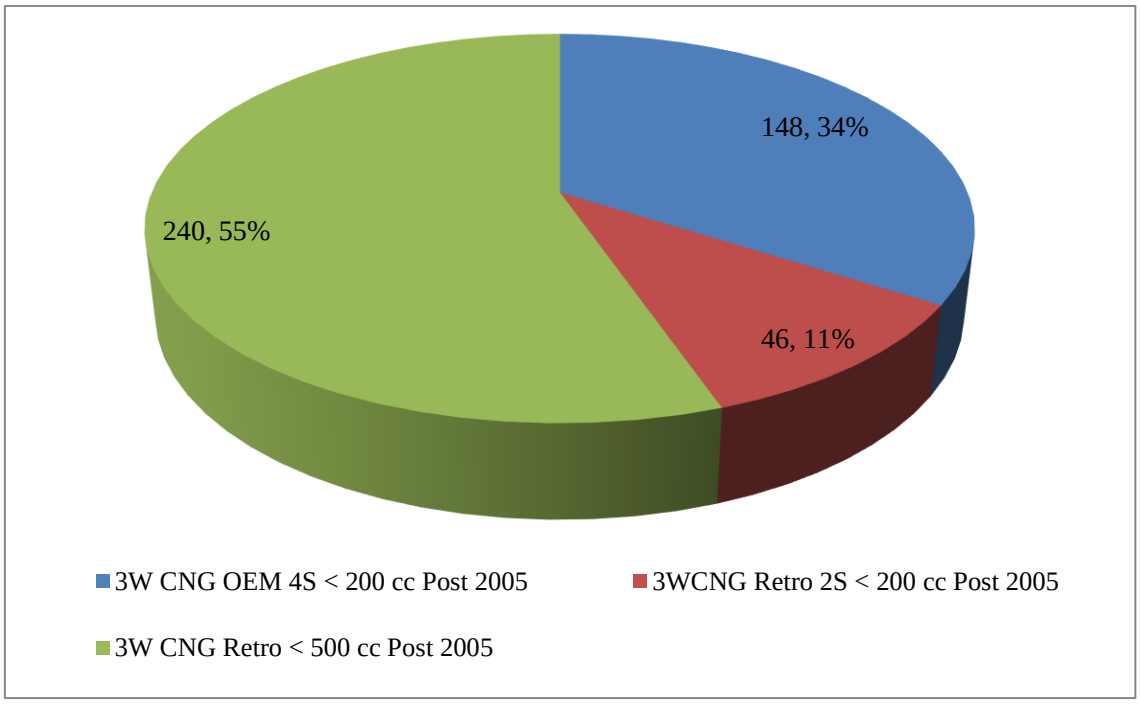


Figure 3.79: **Distribution of 3-Ws in the study area (parking lot survey)**

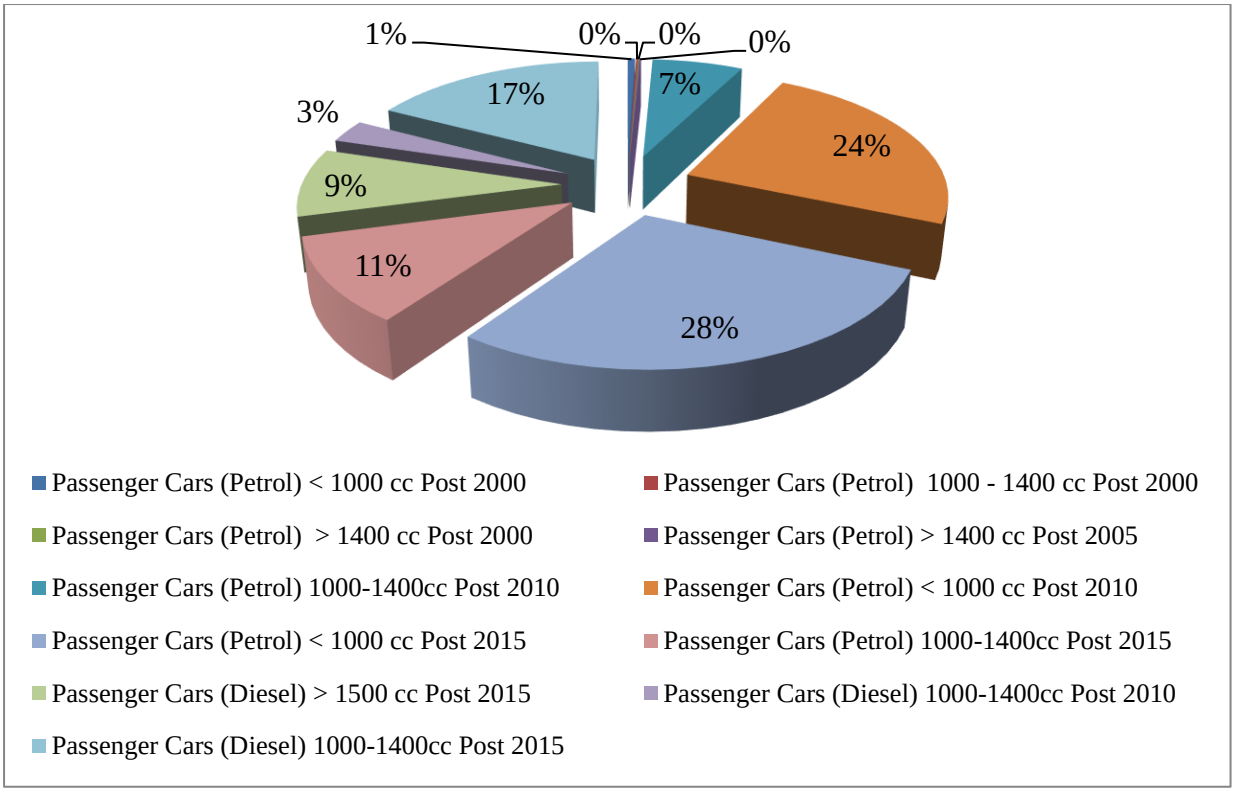


Figure 3.80: **Distribution of 4-Ws in the study area (parking lot survey)**

3.2.13 Vehicular - Line Sources

The average daily flow of vehicles in each hour for 2Ws, 3Ws, 4Ws, LCVs, Buses, and Trucks at 19 locations were obtained by video recording at crossings (Figure 3.81). From these 19 traffic locations, the data were extrapolated for the remaining grid cells. Road lengths in each cell for major and minor roads were calculated from the digitized maps using the ArcGIS tool, ArcMap, and extracted into the grids. The information on traffic flow from traffic counts was translated into the vehicles on the roads in each grid. Wherever it was feasible, either traffic flow was taken directly from the traffic data, and for interior grids, traffic from medium roads going the highways was taken to flow in the interior part of the city. The emissions from each vehicle category for each grid are estimated and summed up.

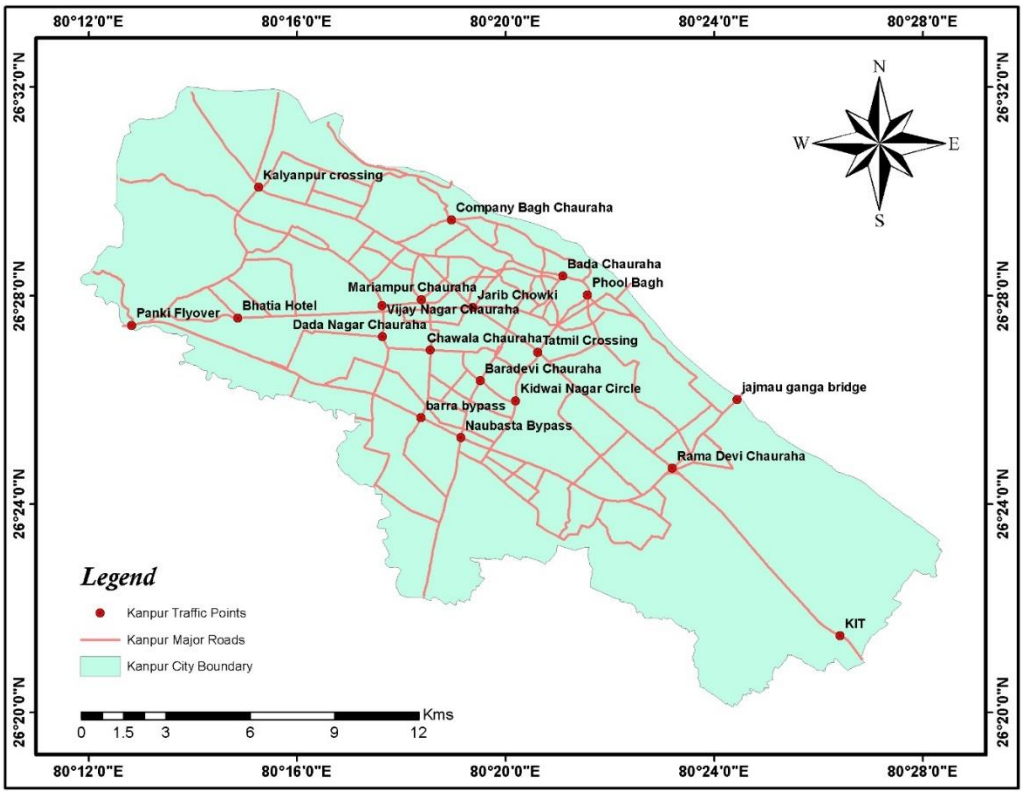


Figure 3.81: Traffic location considered for vehicle emission in the city of Kanpur.

The emissions from railway locomotives are not taken into considerations, as the emissions are negligible in comparison with the vehicles and other sources.

The emission contribution of each vehicle type in the city of Kanpur city is presented in Figure 3.82 to Figure 3.86.

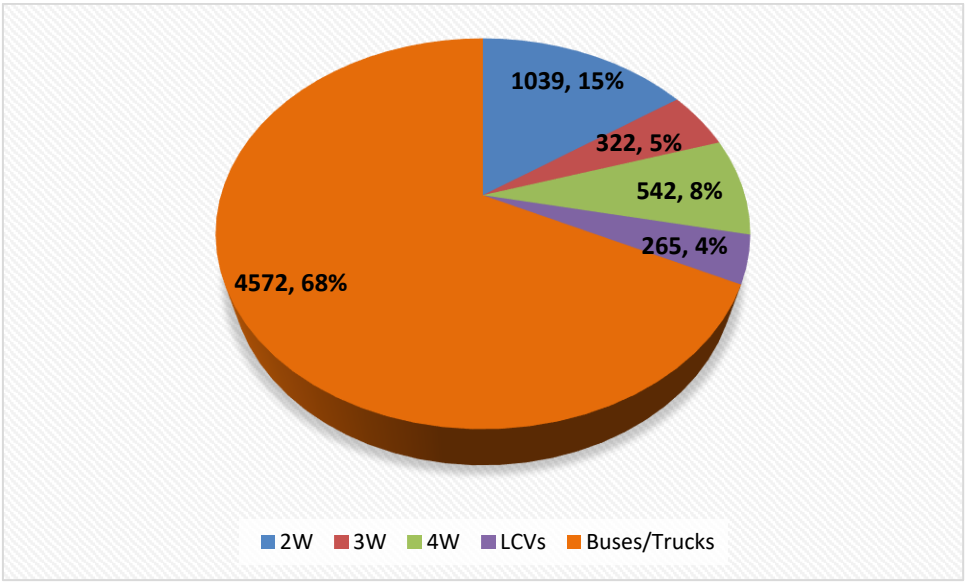


Figure 3.82: PM_{10} Emission Load contribution of each vehicle type (kg/day)

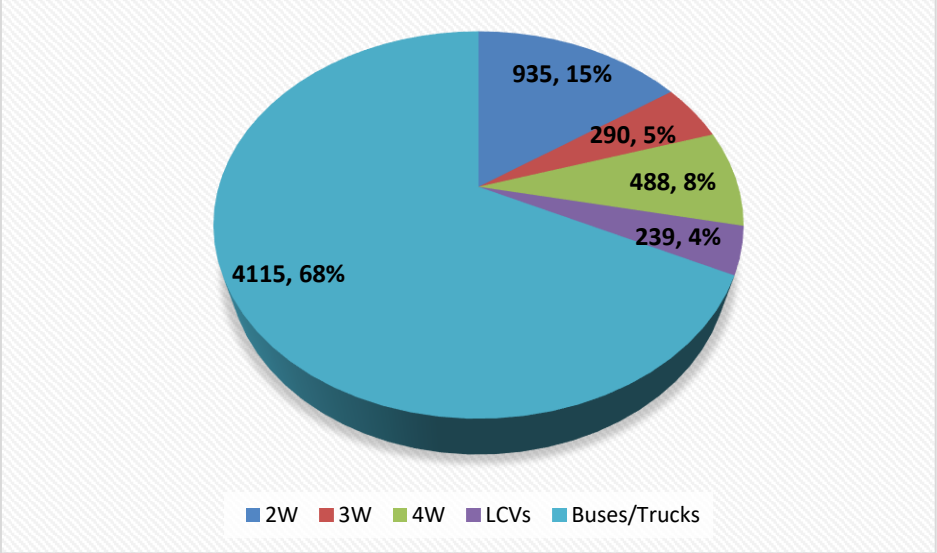


Figure 3.83: $PM_{2.5}$ Emission Load contribution of each vehicle type (kg/day)

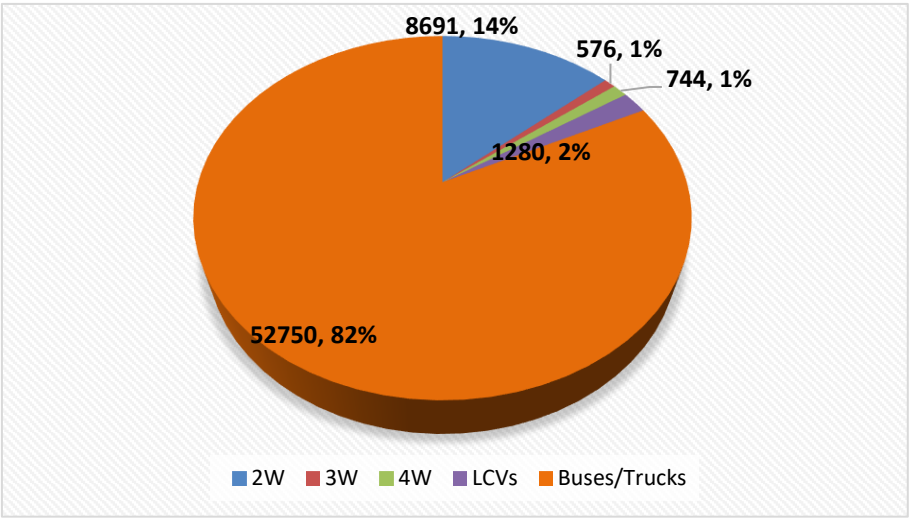


Figure 3.84: NO_x Emission Load contribution of each vehicle type (kg/day)

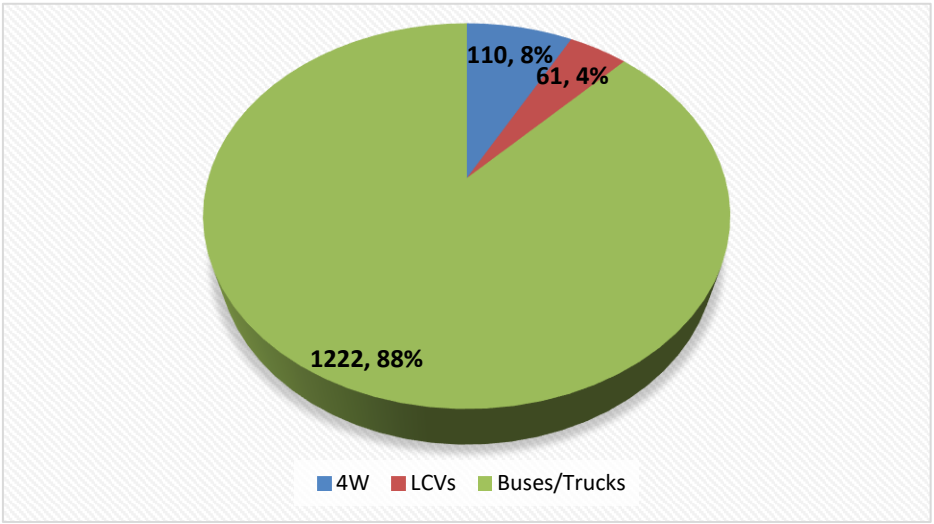


Figure 3.85: SO_2 Emission Load contribution of each vehicle type (kg/day)

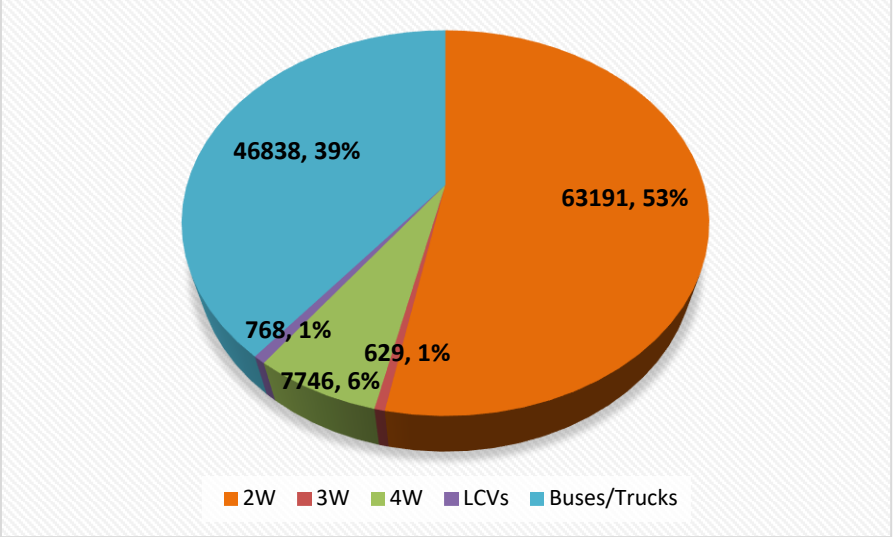


Figure 3.86: CO Emission Load contribution of each vehicle type (kg/day)

The emission from vehicles is shown in Figure 3.87. The spatial distribution of emissions from vehicles is presented in Figure 3.88 to Figure 3.92.

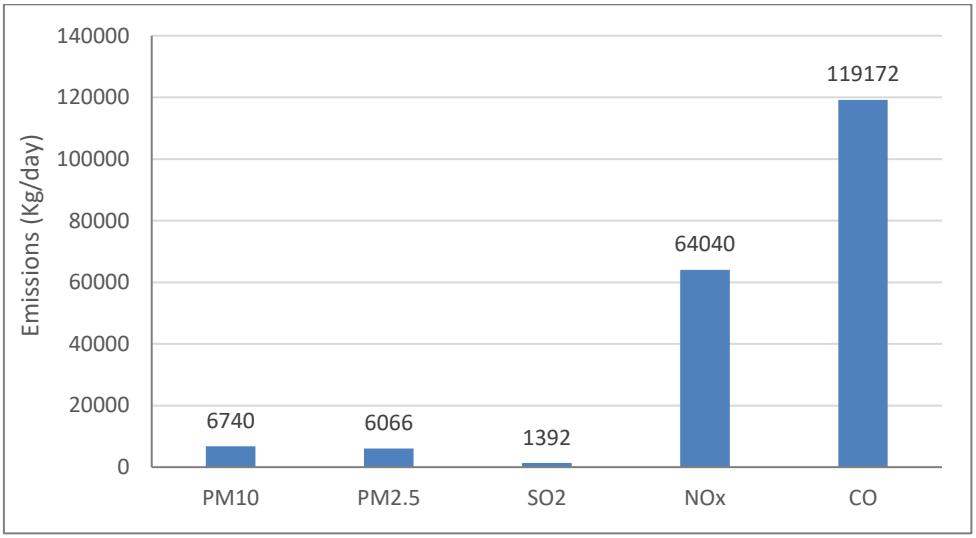


Figure 3.87: Emission Load from Vehicles (kg/day)

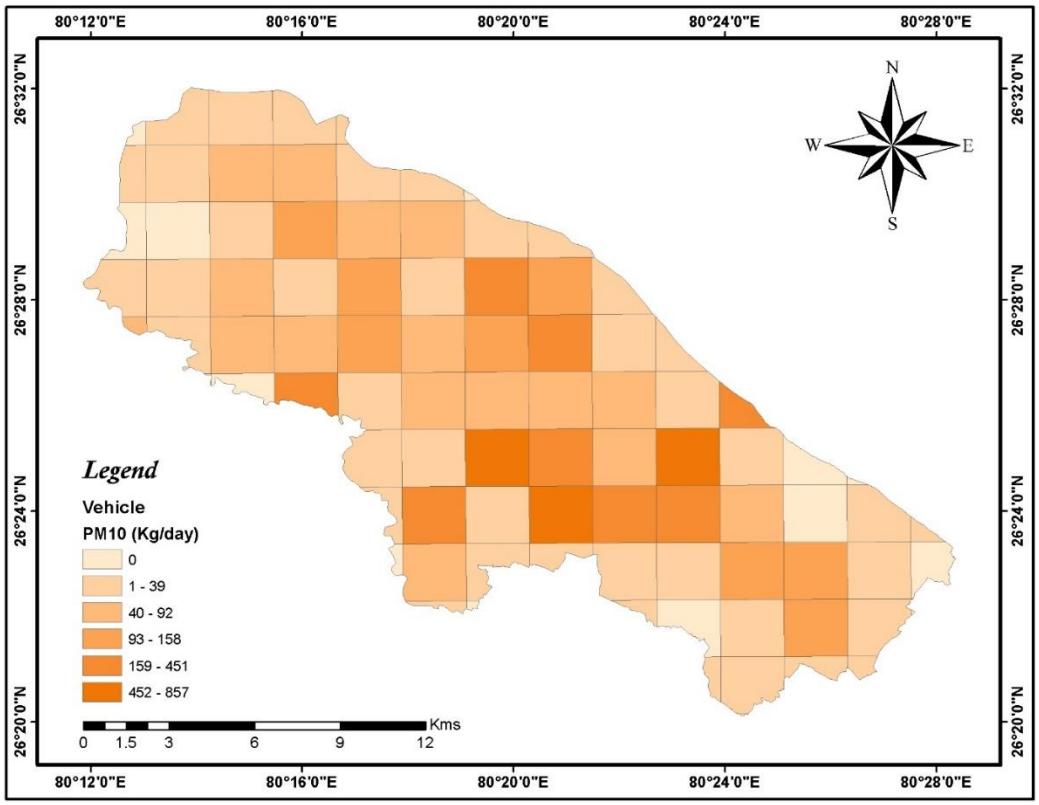


Figure 3.88: Spatial Distribution of PM_{10} Emissions from Vehicles

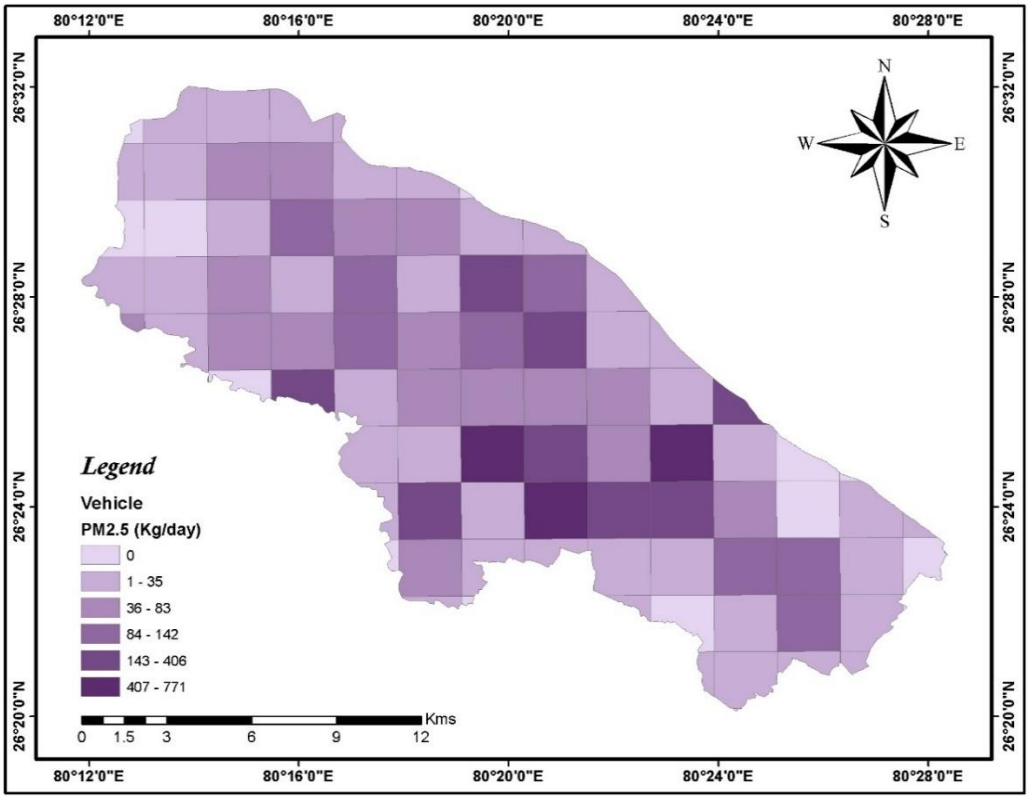


Figure 3.89: Spatial Distribution of $PM_{2.5}$ Emissions from Vehicles

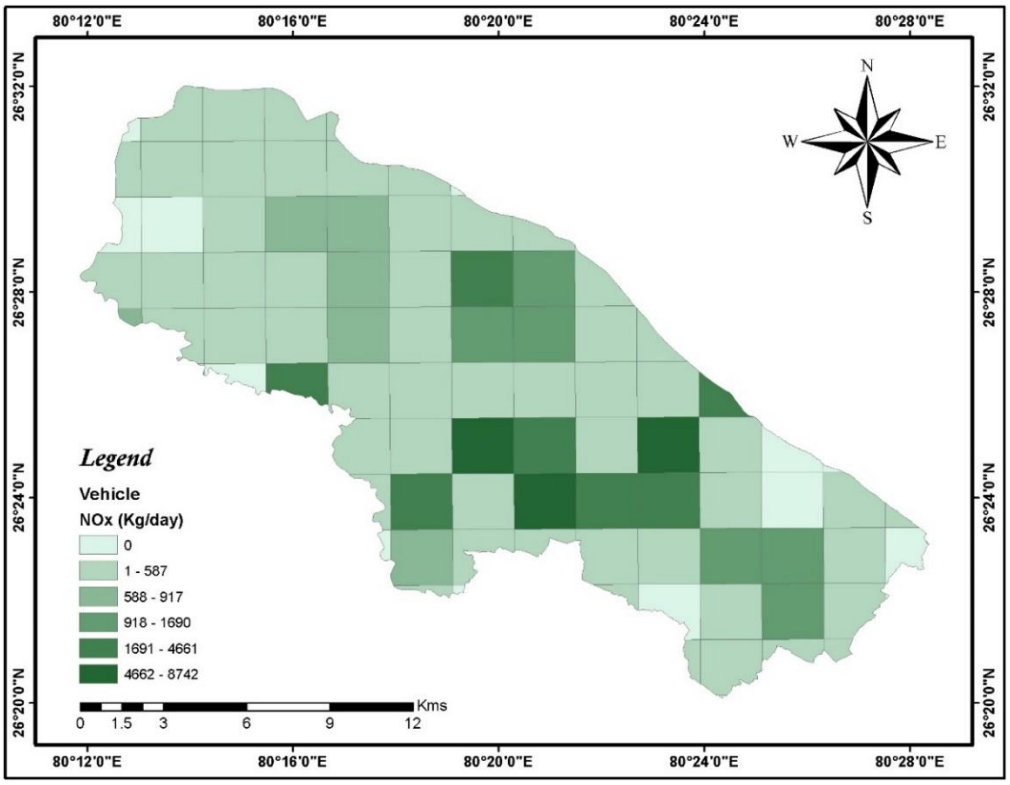


Figure 3.90: Spatial Distribution of NOx Emissions from Vehicles

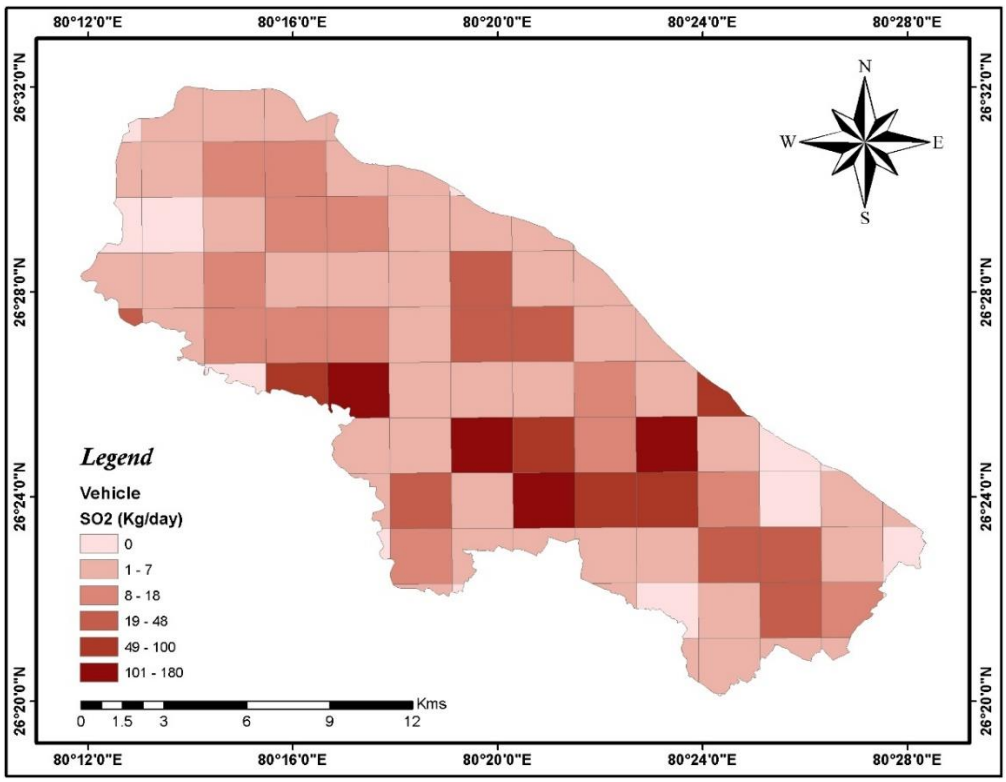


Figure 3.91: Spatial Distribution of SO_2 Emissions from Vehicles

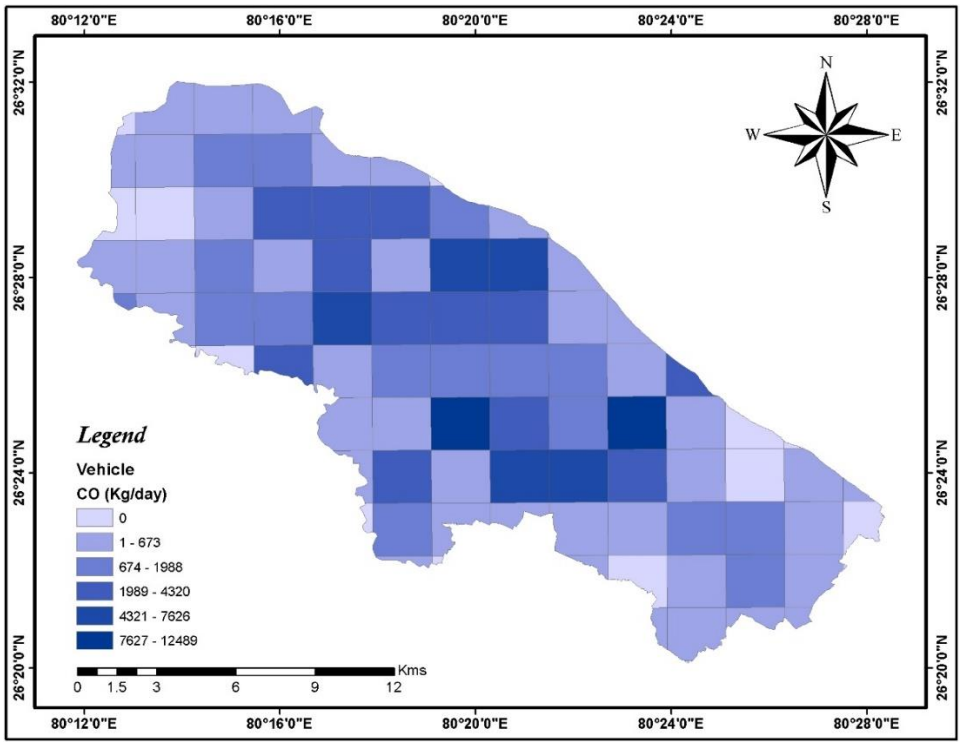


Figure 3.92: Spatial Distribution of CO Emissions from Vehicles

3.2.14 Vehicle Congestion

Kanpur is the biggest city in the state and is the main center of commercial and industrial activities. The Large-scale units are located in Panki, Dadanagar, and Kalpi road areas. Commercial activities and high population density need better road infrastructure and smooth traffic movement. With the high population growth and changing travel & traffic characteristics, transportation problems are aggravating in the city of Kanpur. The city is predominantly dependent upon private buses and tempos for intra-city passenger travel.

The yawning gap between demand and supply of transport infrastructure is steadily increasing. Capital-intensive transport infrastructure development is imperative for medium and long-term solutions. Kanpur is facing the problem of regulating inter-city traffic together with city traffic. The railway network passing through the city has resulted in a large number (16) of rail level crossings. The congestion is evident all along the G.T. Road and at all those places where the railway network cuts the road network (Figure 3.93). In the past, some remedial measures were exercised by constructing six Roads Over Bridges (Murray Crossing, Jhakkarkati, Narender Mohan Setu, Govind Puri, Dada Nagar, and Panki) and a by-pass on the southern end of the city to ease the traffic congestion. The spurt in city population and motorized vehicles (3.3 lakh to 5.4 lakh) has compounded the problem further. The problem of pollution and air quality deteriorating, when the rail level crossings are closed, besides generating long queues of traffic

leading to congestion and traffic jams are some of the major problems. Kanpur city is connected to an industrial estate at Dada Nagar and Panki through Dada Nagar tri-junction and Vijay crossing. High traffic movement on this corridor causes frequent traffic jams. Due to the heterogeneous composition of autos, tempos, rickshaws, cycles, two-wheelers, cars and other small good vehicles, traffic movement is very slow. There is no division of routes for fast and slow vehicles which causes congestion and increases traffic problems. The road network within the city is not developed enough to cater to these requirements.

It can be seen from Figure 3.94 that, Kanpur has several unorganized clusters of vehicle repairing shops in Kalyanpur, Govindnagar, Bakarmandi, Bajariya, Harsh Nagar and Transport Nagar. In the physical survey, it is observed that reused engine oil is being again put into several vehicles during servicing and break down of vehicles. Many paint shops paint the vehicle in open areas. The debris, oils and grease are directly thrown on open roadside creating pollution.

Figure 3.93: Heavy Traffic Congestion on Highways/Roads

Figure 3.94: Pollution from Unorganised automobile service centres in Kanpur city

The typical Traffic conditions at different locations in Kanpur City are given in Figure 3.95 and Figure 3.96. Consequently, the major Traffic bottlenecks are mentioned in Table 3.2. The colour coding used here is Red, Orange, and Green indicating the slow traffic to fast traffic movement respectively. The major issue is the slow traffic movement that refers to the congestion conditions on the road. Hence decongestion plan for the major Traffic Bottleneck intersections of Kanpur city is recommended. Haphazard parking of vehicles on roads should be stopped. Proper signage for parking signboards/ No Parking should be erected at identified locations. Strict actions should be taken against those vehicle owners who park their vehicles on roads. The carriageway of all roads should be widened to the maximum extent by removing encroachments. Removal of encroachment will result in smooth and efficient vehicular movement using all the available road width and minimize congestion. All main crossings and tri-sections need to be equipped with traffic lights and glow signs to regulate the movement of traffic. Tempo boarding/alighting should be displayed but it would not be allowed within 50 m reach of the intersection.

Table 3.2: Major Traffic Bottleneck at Kanpur City

Ramadevi	Rajiv puram crossing, Kakadev
Tatmill chauraha	Survodya Nagar crossing
Jakarkati bridge	Shastri Nagar crossing
Bans mandi crossing at GT road	Vijay Nagar
Afim Koti	Darshan Purva
Jarib chowki	Kidwai Nagar crossing

Gumati railway crossing	Saket Nagar crossing
Coca cola crossing	Bada Chauraha
Chhapeda Pulia	Deputy Padav
Rawatpur crossing	Ghanta ghar
Gurudev crossing	Moolgangh chauraha
Kalyanpur crossing	Kanpur Central

Day	Ramdevi	Tat mill chauraha	Jakarkatti bridge	Bans mandi crossing at GT road	afim koti	Jarib chowki	Gumati railway crossing	Coca cola crossing	Chhapeda Pulia	Rawatpur crossing	Gurudev crossing	Kalyanpur crossing
Sunday	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm
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Monday	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
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Tuesday	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
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Wednesday	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
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Thursday	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
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Friday	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm
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Saturday	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
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	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm
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	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm

Figure 3.95: Typical Traffic conditions at different locations in Kanpur City

Rajiv puram crossing, Kakadev	Survodya Nagar crossing	Shastri Nagar crossing	Darshan Purva	Vijay Nagar	Kidwai Nagar crossing	Saket Nagar crossing	Bada Chauraha	Deputy Padav	Ghanta ghar	Moolgangh chauraha
8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm
12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm
2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm
4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm
6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm
8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
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12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm
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8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm
12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm
2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm
4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm
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8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm
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8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm
12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm
2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm
4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm
6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm
8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm
12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm
2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm
4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm
6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm
8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am	8am-10am
10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm	10am-12pm
12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm	12pm-2pm
2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm	2pm-4pm
4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm	4pm-6pm
6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm	6pm-8pm

Figure 3.96: Typical Traffic conditions at different locations in Kanpur City (Explain legend)

3.2.15 Paved and Unpaved Road Dust

Dust emissions from paved and unpaved roads vary with the 'silt loading' present on the road surface and the average weight of vehicles traveling on the road. The term silt loading (sL) refers to the mass of the silt-sized material (equal to or less than 75 μm in physical diameter) per unit area of the travel surface. The quantity of dust emissions from the movement of vehicles on a paved or unpaved road can be estimated using the following empirical expression:

$$E_{ext} = [\, k\,(sL)^{0.91} \times (W)^{1.02} \,]\,(1 - P/4N) \quad (3.4)$$

Where

E = particulate emission factor (having units matching the units of k),

sL = road surface silt loading (grams per square meter) (g/m^2), and

W = average weight (tons) of the vehicles traveling the road.

E_{ext} = annual or other long-term average emission factor in the same units as k,

P = number of "wet" days with at least 0.254 mm (0.01 in) of precipitation during the averaging period, and

N = number of days in the averaging period.

k: constant (a function of particle size) in g VKT^{-1} (Vehicle Kilometer Travel).

The road dust sampling locations are given in Figure 3.97. The silt loads (sL) samples from 19 locations were collected (Figure 3.98). Then mean weight of the vehicle fleet (W) was estimated by giving the weightage to the percentage of vehicles of all types with their weight. Then emission rate (g VKT^{-1}) was calculated based on Eq (3.4). VKT for each grid was calculated by considering the tonnage of each road. Then finally, the emission loads from paved and unpaved roads were found out by using Eq (3.4). There is a need to clean the road on regular basis. The road dust deposition can be seen in Figure 3.99. It can be seen the roads are broken in patches causing higher road dust emissions (Figure 3.100). In the winter and monsoon season, it is less due to moisture and dew atmospheric conditions. The emission load from road dust in Kanpur city is given in Figure 3.101. The Spatial distribution of Emissions from Road Dust Re-suspension is presented in Figure 3.102 to Figure 3.103.

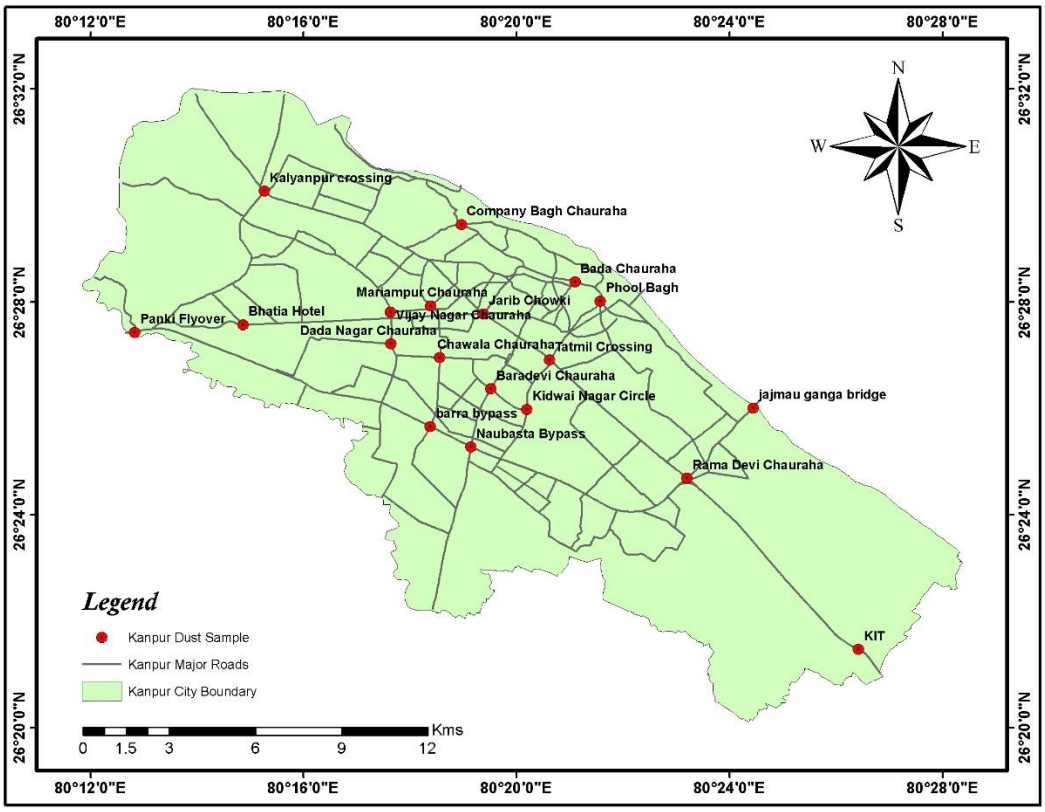


Figure 3.97: Road Dust Sampling Location

Figure 3.98: Road Dust Sampling in the City of Kanpur

Figure 3.99: Road dust deposition on the paved road

Figure 3.100: Broken roads causing higher road dust emissions

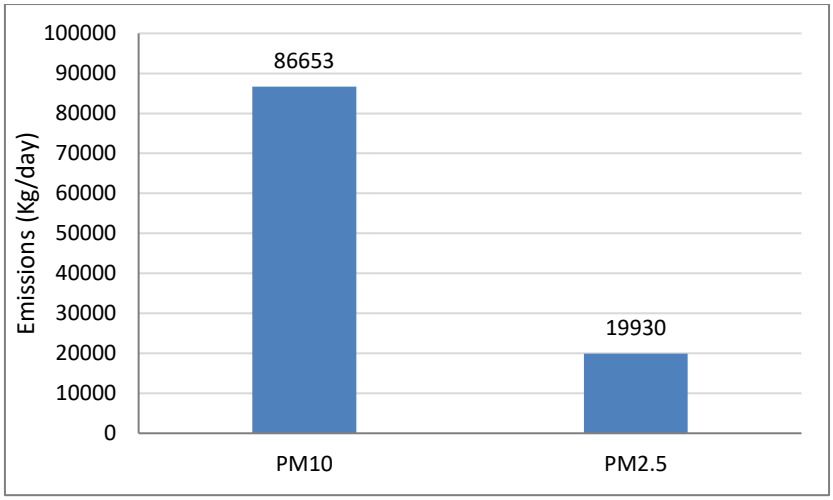


Figure 3.101: Emissions from road dust in Kanpur city (Kg/day)

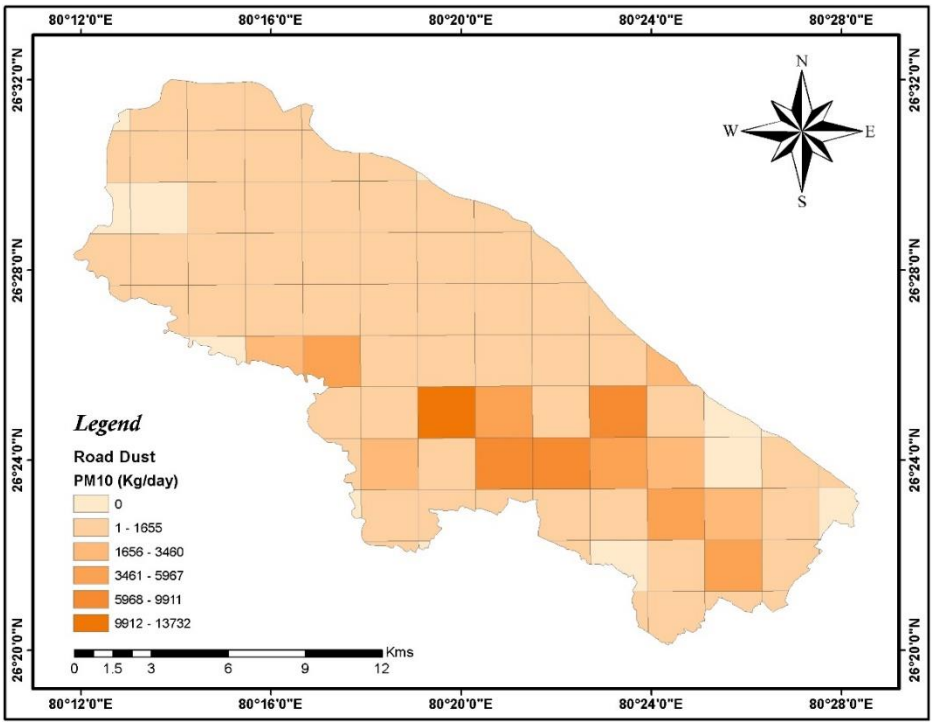


Figure 3.102: Spatial Distribution of PM_{10} Emissions from Road Dust Re-suspension

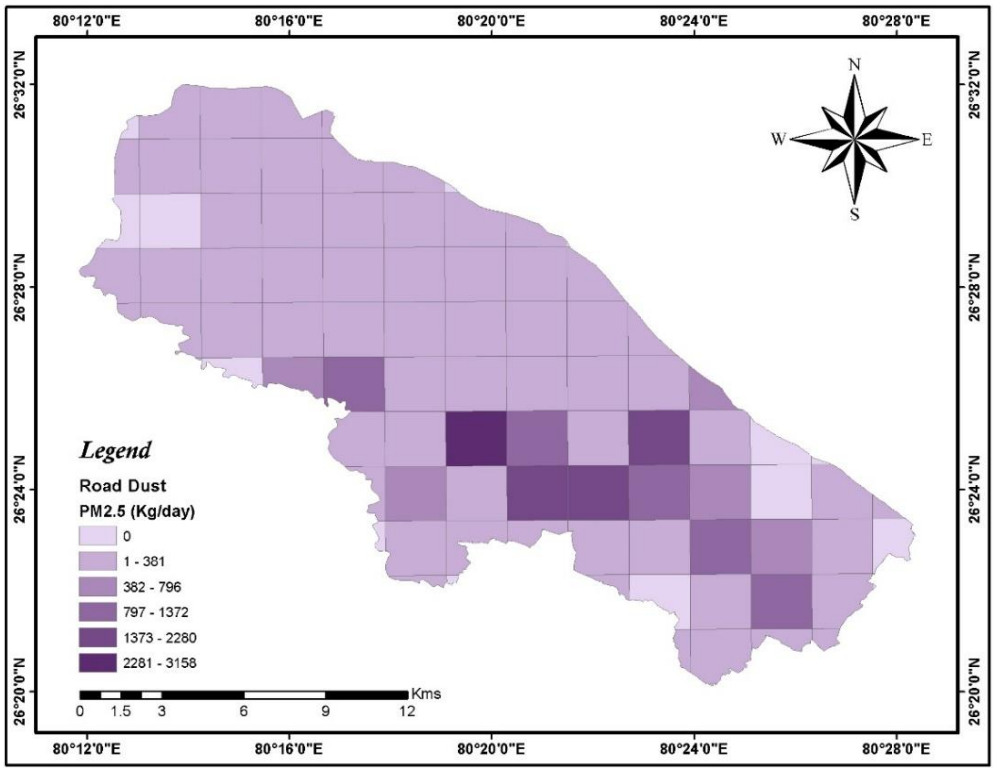


Figure 3.103: Spatial Distribution of $PM_{2.5}$ Emissions from Road Dust Re-suspension

3.3 City Level Emission Inventory

The overall baseline emission inventory for the entire city is presented in Table 3.3. The pollutant-wise contribution is shown in Figure 3.104 to Figure 3.107. The spatial distribution of pollutant Emissions from all sources is presented in Figure 3.108 to Figure 3.113.

Table 3.3: Kanpur City Level Inventory (kg/day)

Sources	PM_{10}	$PM_{2.5}$	SO_2	NOx	CO
Domestic	2653	1857	581	1020	10328
MSW	2071	1408	129	777	10874
Hotel	744	393	495	479	1299
Construction	2114	486	0	0	0
DG Sets	319	287	298	4515	975
Industries	4400	3960	9289	10760	4588
Hospital	26	24	24	370	80
Open Area	121	0	0	0	0
Vehicle	6740	6066	1392	64040	119172
Road Dust	86653	19930	0	0	0
Total	**105841**	**34411**	**12208**	**81961**	**147316**

The total PM_{10} emission load in the city is estimated to be 106 t/d. The top four contributors to PM_{10} emissions are road dust (82%), vehicles (6%), industries (4%) and construction (2%); these are based on annual emissions. Seasonal and daily emissions could be highly variable. The estimated emission suggests that there are many important sources and a composite emission abatement including most of the sources will be required to obtain the desired air quality.

$PM_{2.5}$ emission load in the city is estimated to be 34 t/d. The top four contributors to $PM_{2.5}$ emissions are road dust (58 %), vehicles (18 %), industries (12%), and domestic fuel burning (6 %); these are based on annual emissions. Seasonal and daily emissions could be highly variable.

NOx emissions load in the city is estimated to be 82 t/d. Nearly 78 % of emissions are attributed to vehicular emissions followed by industries (13%) and DG set (6%). Vehicular emissions that occur at ground level, probably making it the most important emission. NOx apart from being a pollutant itself is an important component in the formation of secondary particles (nitrates) and ozone. NOx from vehicles and industry are potential sources for controlling NOx emissions.

SO_2 emission load in the city is estimated to be 12 t/d. Industry account for 76 percent of the total emission. Vehicles contribute 11% followed by Hotels and Restaurants (4%).

The estimated CO emission is about 147 t/d. Nearly 81 % emission of CO is from vehicles, followed by industries (3%), domestic (7%), and about 7 % MSW burning. Vehicles could be the main target for controlling CO for improving air quality with respect to CO.

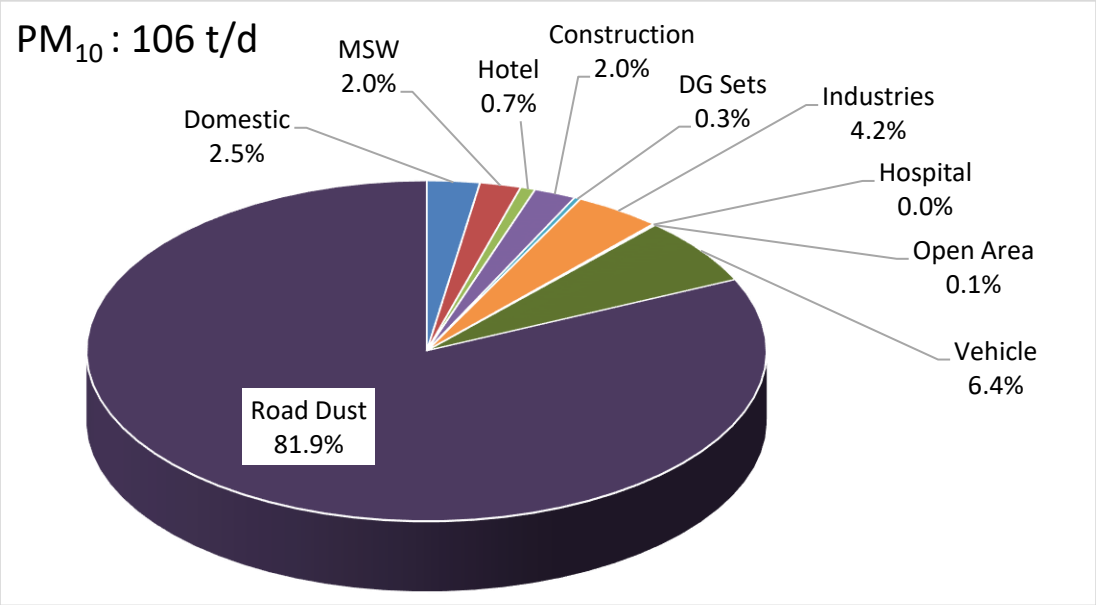


Figure 3.104: PM_{10} Emission Load of Different Sources

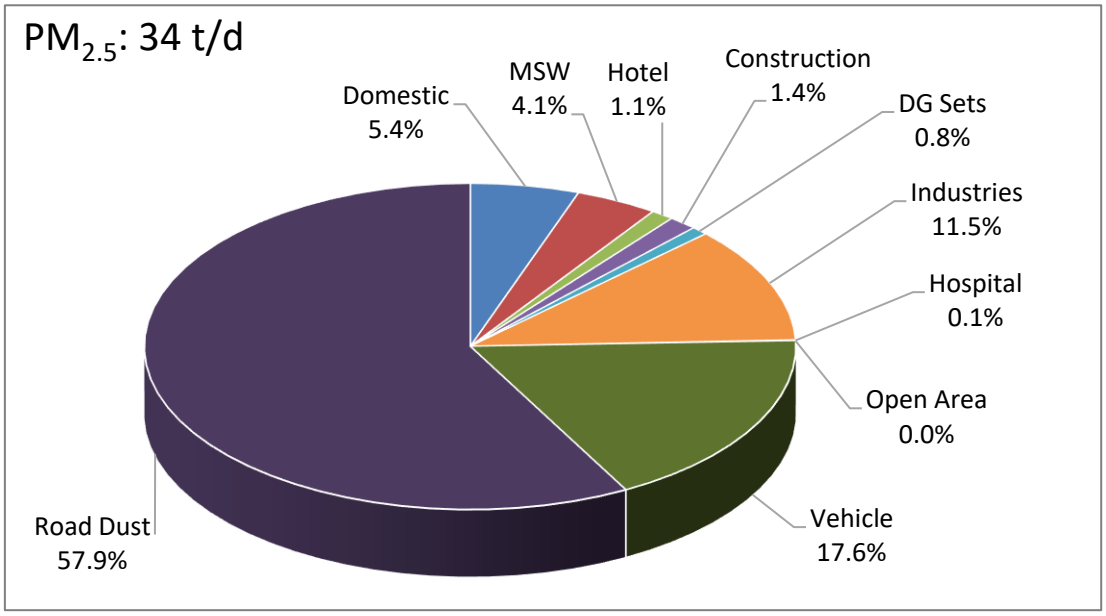


Figure 3.105: $PM_{2.5}$ Emission Load of Different Sources

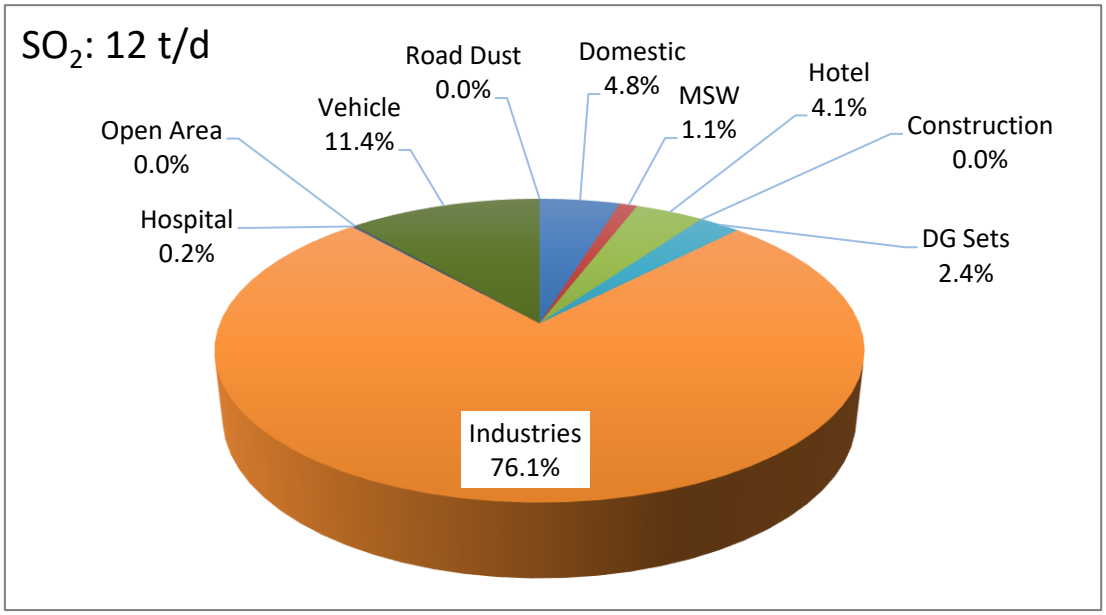


Figure 3.106: SO_2 Emission Load of Different Sources

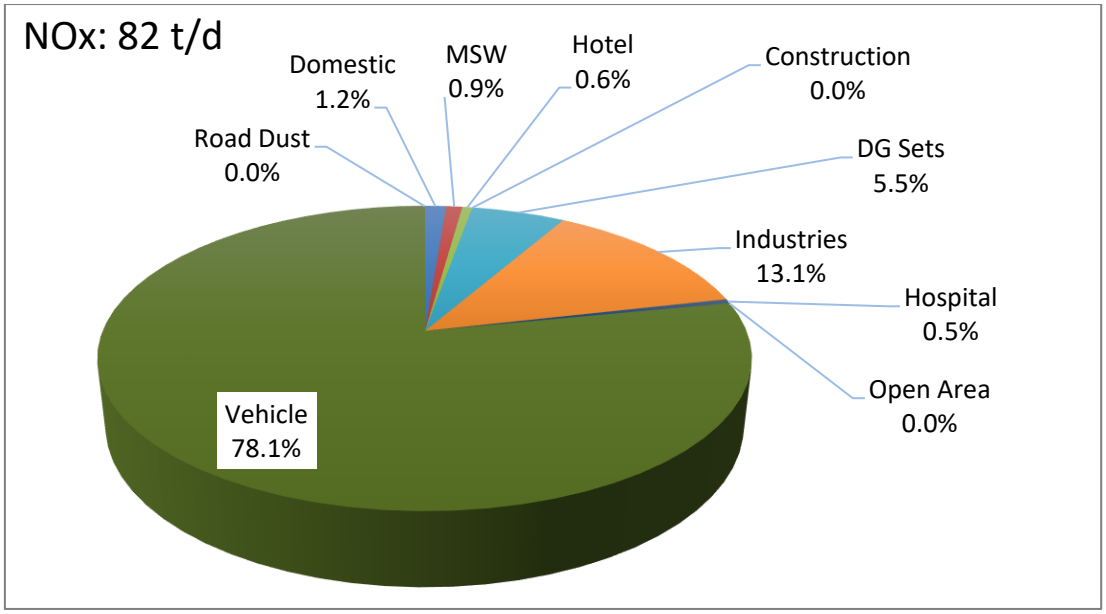


Figure 3.107: NOx Emission Load of Different Sources

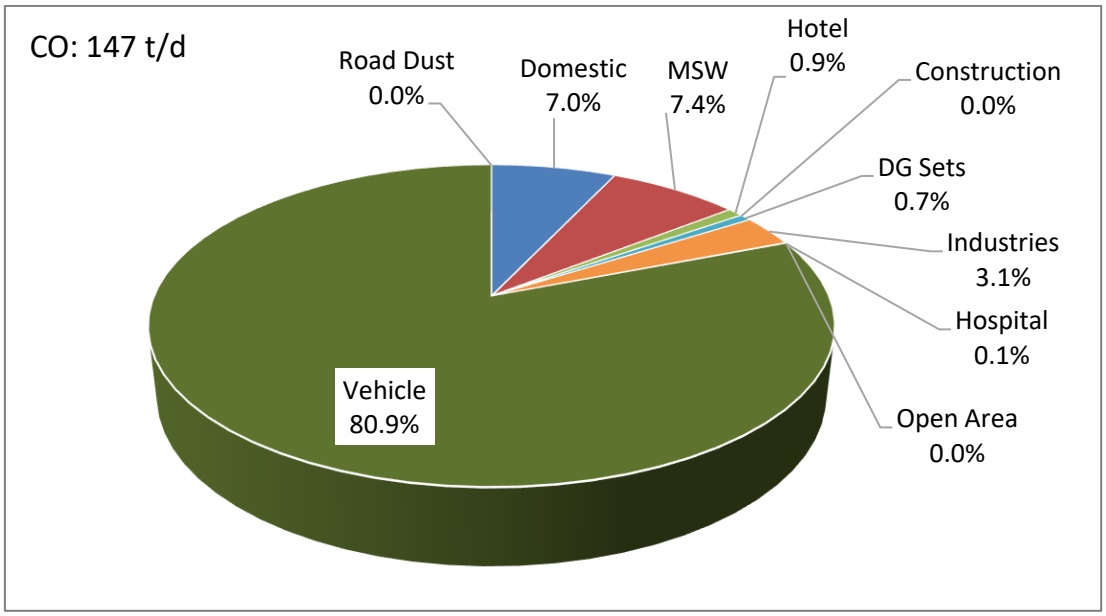


Figure 3.108: CO Emission Load Contribution of Different Sources

Spatial variation of emission quantity suggests that for PM_{10}, $PM_{2.5}$, CO, SO_2, and NOx, the central downtown area, North-east of the city show higher emissions than other parts.

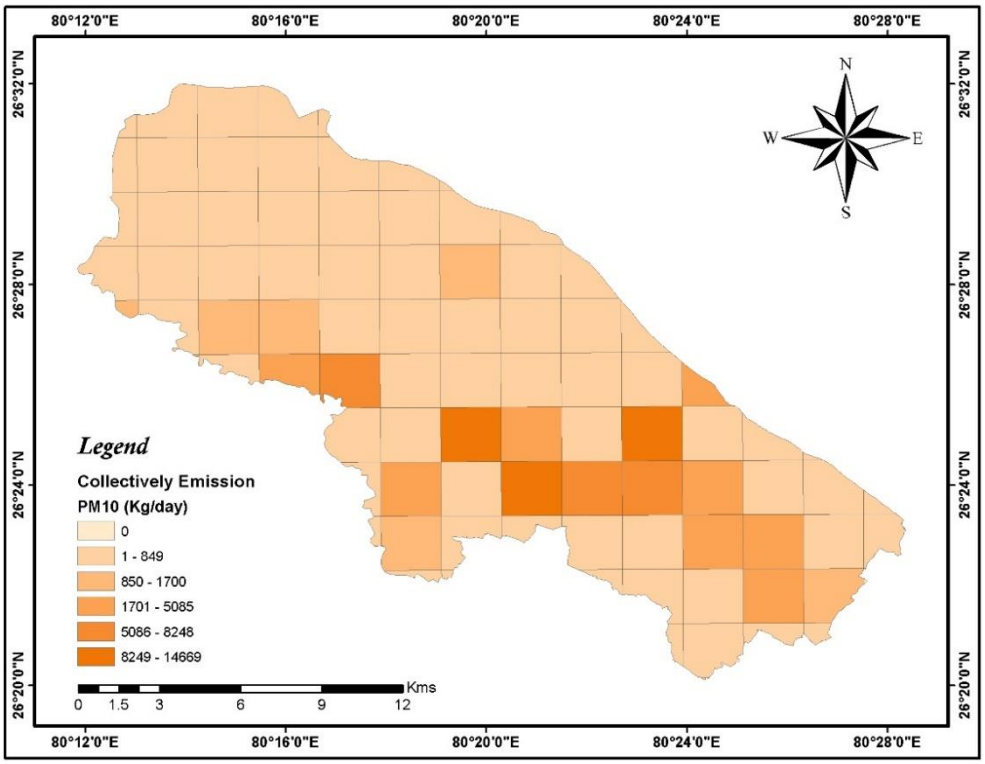


Figure 3.109: Spatial Distribution of PM_{10} Emissions in the City of Kanpur

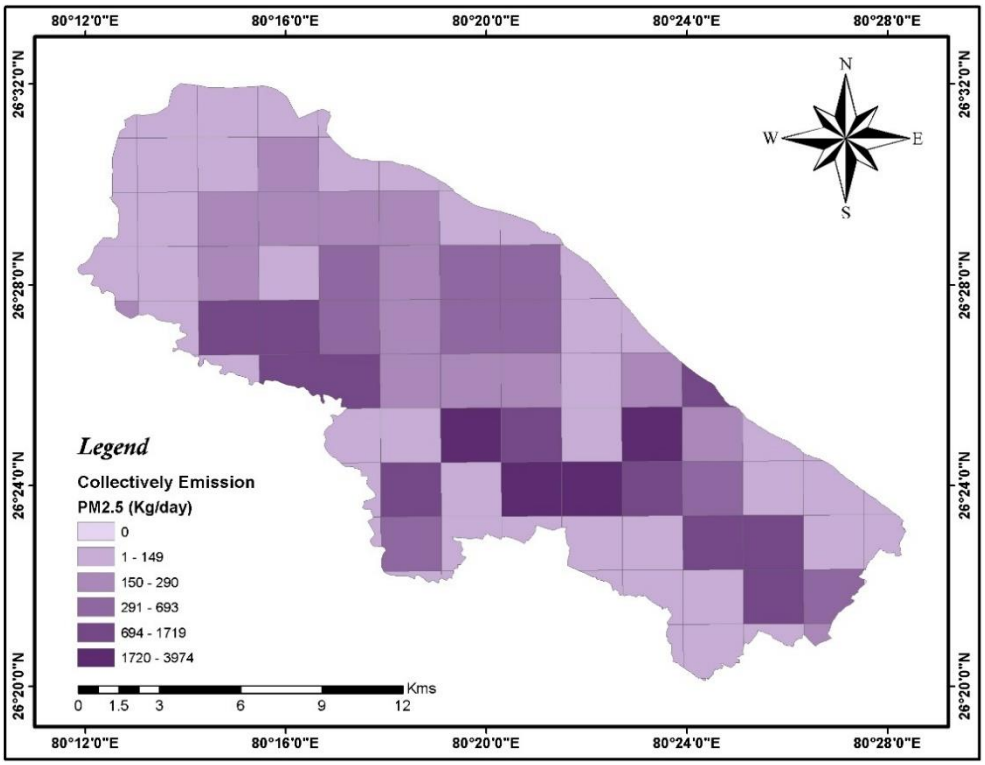


Figure 3.110: Spatial Distribution of $PM_{2.5}$ Emissions in the City of Kanpur

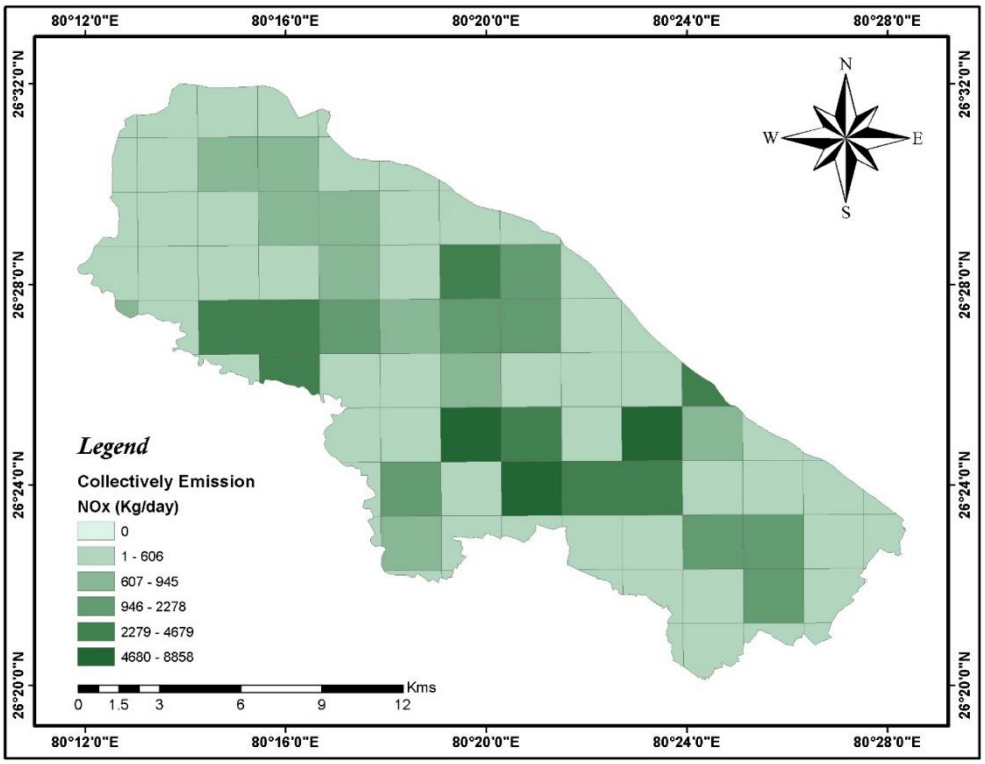


Figure 3.111: Spatial Distribution of NOx Emissions in the City of Kanpur

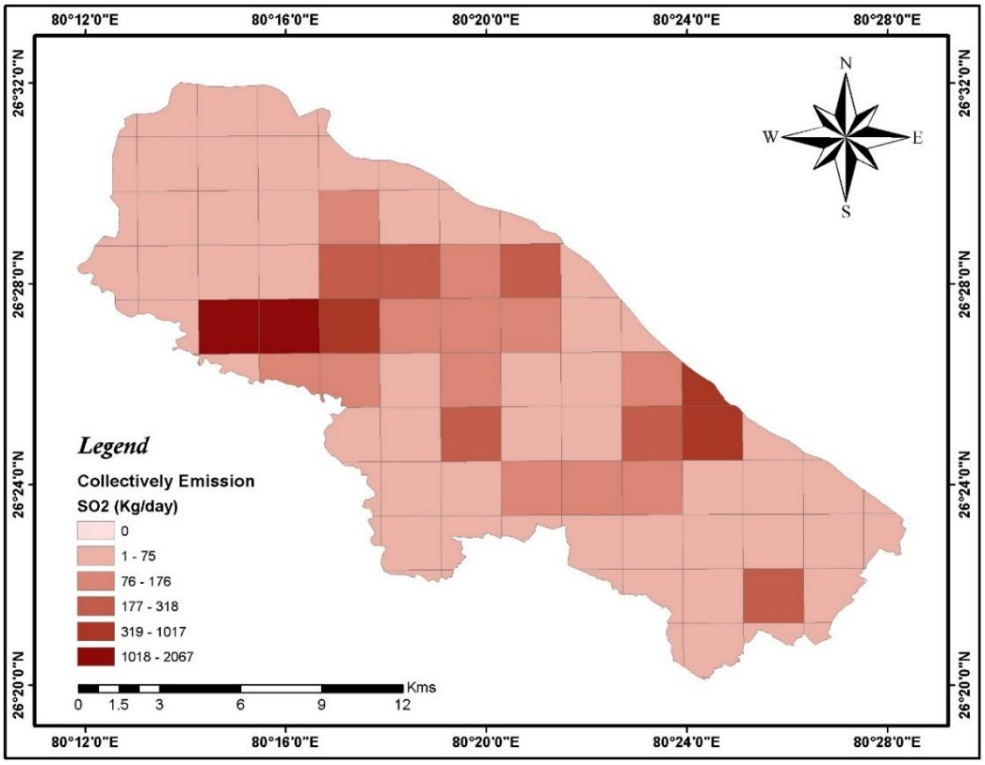


Figure 3.112: Spatial Distribution of SO_2 Emissions in the City of Kanpur

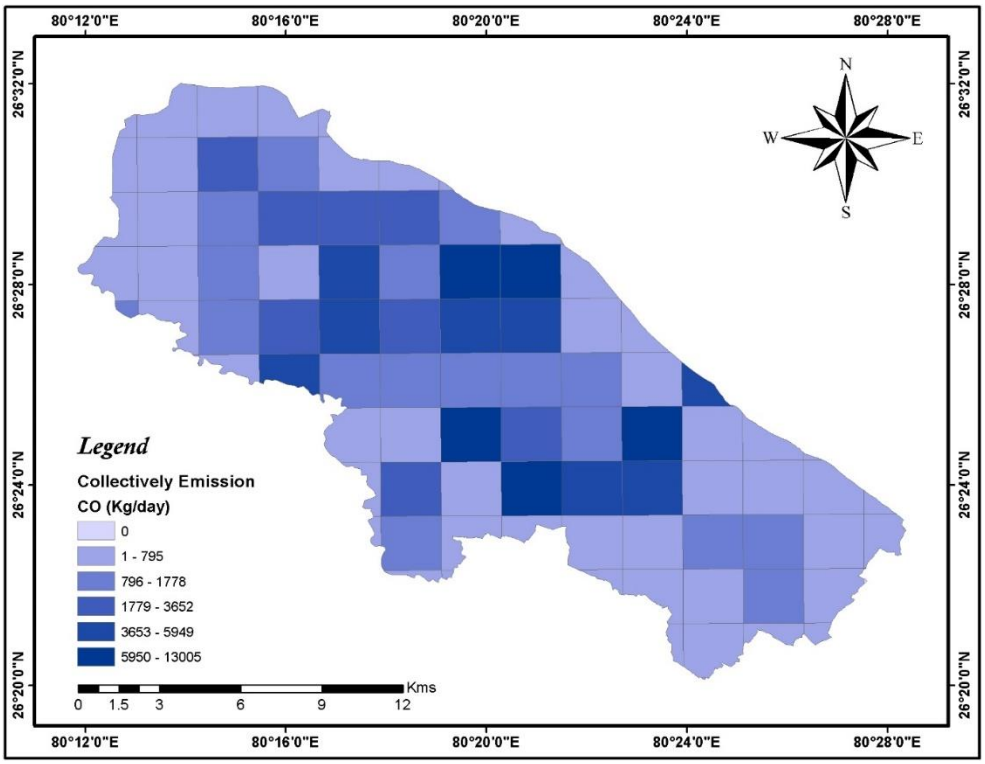


Figure 3.113: Spatial Distribution of CO Emissions in the City of Kanpur

4 Receptor Modelling and Source Apportionment

4.1 Receptor Modeling

In a complicated urban atmosphere, to identify and quantify the contribution of multiple emitting sources to air quality is challenging. However, recent advancements in the chemical characterization of PM have made it possible to apportion the sources contributing to air pollution, especially that of PM. Receptor modeling using source fingerprinting (chemical composition) can be applied quantitatively to know the sources of origin of particles. Mathematical models are frequently used to identify and to adopt the source reductions of environmental pollutants. There are two types of modeling approaches to establish source receptor linkages:

1. Dispersion Modeling and
2. Receptor source Modeling.

The focus of modeling in this chapter is receptor modeling. The receptor model begins with observed ambient airborne pollutant concentrations at a receptor and seeks to apportion the observed concentrations between several source types based on the knowledge of the compositions of the sources and receptor materials (Cooper and Watson, 1980; Watson, 1984; Javitz et al., 1988). There are two generally recognized classes of receptor Models:

- Chemical elemental balance or chemical mass balance (CEM/CMB), and
- Multivariate or a statistical.

In this Chapter, CMB technique has been attempted to fully understand the contribution of each source to ambient air PM_{10} and $PM_{2.5}$ concentrations. Positive matrix factorization (PMF) was used to get possible sources in the study area. However, the extensive emission inventory undertaken in this study gave a good idea of possible sources in the study area.

While (CEM/CMB) methods apportion sources using extensive quantitative source emission profiles, statistical approaches infer source contribution without a prior need of quantitative source composition data (Watson et al., 1994). The CMB method assumes that there is linearity in the concentration of aerosol and their mass is conserved from the time a

chemical species is emitted from its source to the time it is measured at a receptor. That is, if p sources are contributing M_j mass of particulates to the receptor (Watson et al., 2004),

$$m = \sum_{j=1}^{p} M_j$$

$$F'_{ij} = F_{ij}$$

Where, m is the total mass of the particulate collected on a filter at a receptor site, F'_{ij} is the fraction of chemical species *i* in the mass from source j collected at the receptor and F_{ij} is the fraction of chemical i emitted by source *j* as measured at the source. The mass of the specific species, m_i, is given by the following:

$$m_i = \sum_{i=1}^{p} M_{ij} = \sum_{i=1}^{p} F'_{ij} M_j$$

Where, M_{ij} is the mass of element *i* contributed to the receptor from source *j*. Dividing both sides of the equation by the total mass of the deposit collected at the receptor site, it follows that

$$C_i = \sum_{j=1}^{p} F_{ij} S_j$$

Where, C_i is the concentration of chemical component i measured at the receptor (air filter) and S_j is the source contribution; that is, the ratio of the mass contributed from source j to the total mass collected at the receptor site.

If the C_i and F_{ij} at the receptor for all p of the source types suspected of affecting the receptor are known, and p≤n (n = number of the species), a set of n simultaneous equations exist from which the source type contribution S_j may be calculated by least square methods. The software used for apportioning the sources is PMF5.0, developed by USEPA (2004).

4.2 PMF Modeling: Source Apportionment of PM_{10} and $PM_{2.5}$

USEPA's PMF5.0 (USEPA, 2014) is a multivariate factor analysis tool that solves a matrix of speciated data of samples into two matrices: factor contributions (S) and source profiles (F). The resolved source profiles were interpreted to identify the contributing sources at the receptor based on the reported source profiles and emissions inventories. The PMF model

derives the source contributions and profiles through minimizing the critical parameter that is called objective function Q (given below) (USEPA, 2014).

$$Q = \sum_{k=1}^{n}\sum_{i=1}^{m}\left[\frac{C_{ik} - \sum_{j=1}^{P} F_{ij}S_{jk}}{u_{ik}}\right]^2$$

Where *m* is the number of chemical species, *n* is the number of samples, and *P* is the number of source factors/profiles.

Ambient PM_{10} and $PM_{2.5}$ observations with chemical composition were used for apportionment of sources for about 200 samples each for PM_{10} and $PM_{2.5}$, collected during 2018-2019 in winter and summer.

The PMF identified contributing sources by minimizing the objective function Q within 10% uncertainty. The results with the lowest Q_{robust} are analyzed in terms of R-square and percent mass (predicted to measured). The results showed the R-square was above 0.98 for both PM_{10} and $PM_{2.5}$ and the percent mass accounted was over 80%.

The apportioned factors are assigned to the sources based on their fingerprint species contributing to the factor collected from the literature. The mean contributions of species in the source profiles for PM_{10} and $PM_{2.5}$ are presented in Figures 4.1 – 4.2. The results of PMF5.0 at each location for each season are described in Section 4.3.

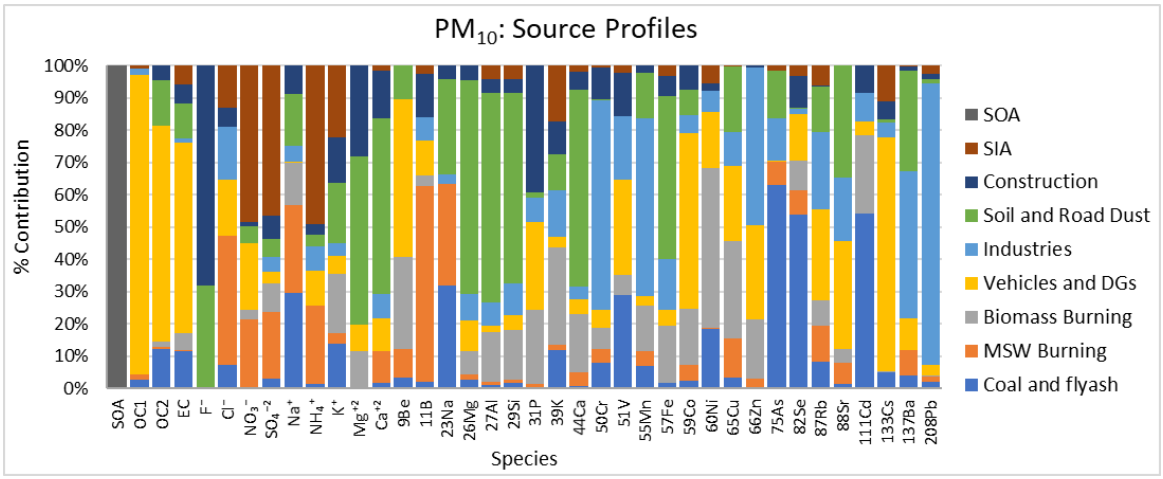


Figure 4.1: PMF-based Source profiles for PM_{10}

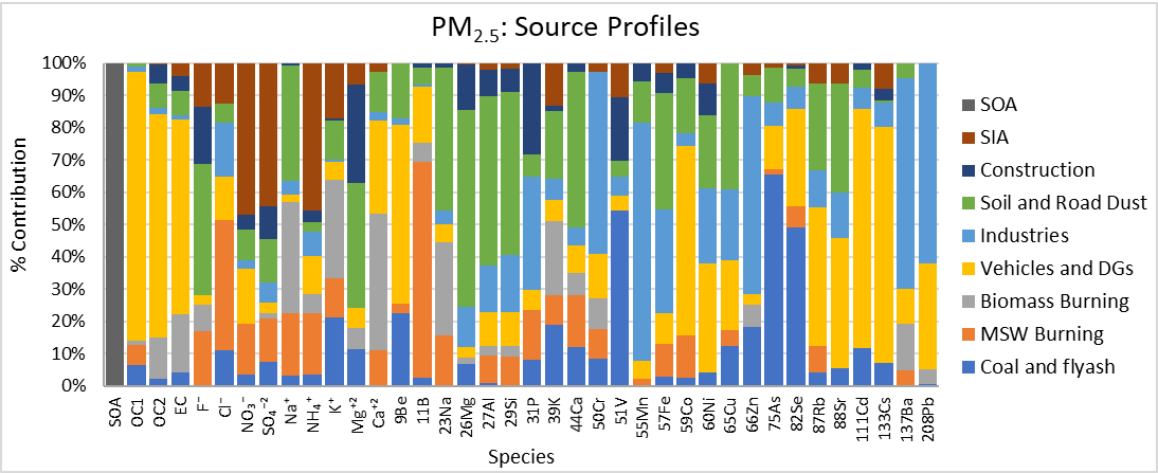


Figure 4.2: PMF-based Source profiles for $PM_{2.5}$

HYSPLIT Model (NOAA, 2013) was run for back trajectory analysis to assist in the interpretation of results and to indicate how the sources located in the upwind of Kanpur could impact air quality in Kanpur.

4.3 PMF Modeling Results and interpretation

It may be noted that vehicles and diesel generators (DGs) include all vehicles powered by gasoline, diesel, natural gas, DGs, LPG from domestic cooking. The Coal and fly ash source include coal and residual oil combustion and fly ash. The factors of similar nature are considered as a single entity for better clarity. The SOA is dealt separately as a sum of OC3 and OC4 multiplied by a factor of 1.6 (Nagar et al., 2017).

The statistical summary of performance and acceptability of PMF model for PM_{10} and $PM_{2.5}$ for winter and summer is given in Tables 4.1 to 4.4.

4.3.1 Ramadevi (RMD)

4.3.1.1 Winter Season [sampling period: Jan 09 – Feb 01, 2019]

PM_{10} (winter)

The average PM_{10} concentration was 480 µg/m^3. Figure 4.3 (a), (b), (c) represents PM_{10} contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively, at RMD. It is observed that the major source contributing to PM_{10} was vehicles and DGs (121 µg/m^3 ~ 25%) followed by soil and road dust (93 µg/m^3 ~ 19%) and SOA (75

μg/m^3 ~ 16%). The other significant sources are biomass burning (12%), municipal solid waste (MSW) burning (9.5%), secondary inorganic aerosols (SIA; 6.6%), construction material (4.0%), industrial emission (4.0%) and coal and fly ash (4.0%).

$PM_{2.5}$ (winter)

The average $PM_{2.5}$ concentration was 273 μg/m^3 (i.e., about 0.57 of PM_{10}). Figure 4.4 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively, at RMD. It is observed that the major source contributing to $PM_{2.5}$ was vehicles and DGs (91 μg/m^3 ~ 33%) followed by SOA (52 μg/m^3 ~ 19%) and MSW burning (40 μg/m^3 ~ 15%). Other sources are soil and road dust (12%), SIA (8%), industrial emissions (5%), biomass burning (4%), coal and fly ash (3%) and construction material (1%).

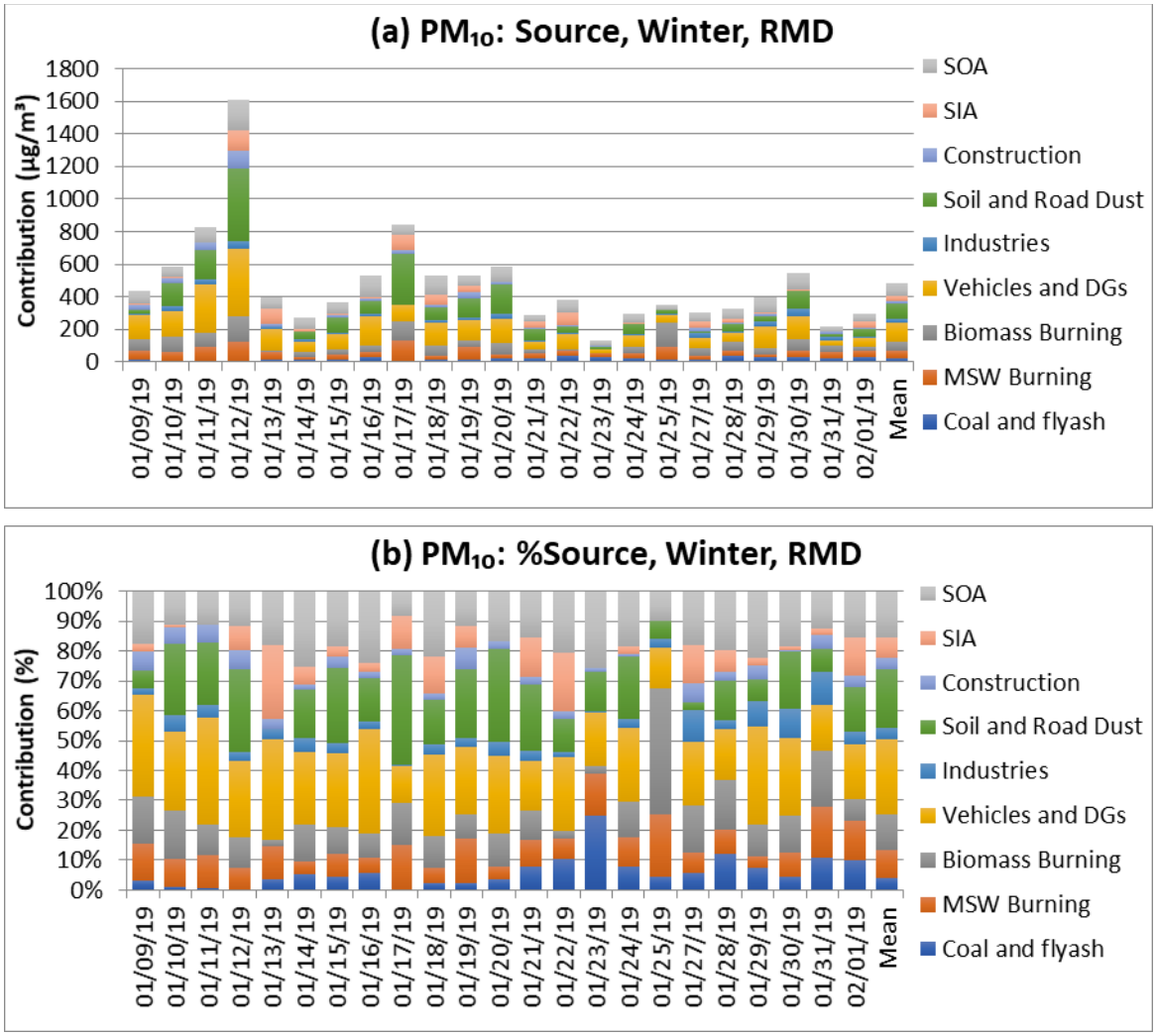
HYSPLIT back trajectories (Figure 4.5) indicate that wind is flowing mostly from the NW direction and partly from SE direction. Winds can pick up the pollutants on the way, especially from large sources and tall emitting sources, but these contributions have not been quantified.

Inferences

- The vehicles and DGs contribute significantly to PM_{10} (25%) and $PM_{2.5}$ (33%). It includes gasoline, diesel, natural gas, DGs, LPG from domestic cooking.
- SOA has a major contribution in PM_{10} (16%) and $PM_{2.5}$ (19%) that is formed from precursor VOCs emitted from various long-distanced sources (i.e., biomass burning, fueling stations, vehicles, solvent industries, MSW burning, brick kilns, etc.).
- The MSW burning has a major contribution to PM_{10} (9%) and $PM_{2.5}$ (15%) at RMD. This emission is expected to be large from regions of economically lower strata of society that do not have proper infrastructure for the collection and disposal of solid waste.
- Soil and road dust contribution is higher in PM_{10} (19%) compared to $PM_{2.5}$ (12%). The consistent levels during the winter season may be due to low wind speed (more calm conditions). It can be seen the high fraction of $PM_{2.5}$ in PM_{10} (about 0.57 of PM_{10}).
- The SIA contributes to PM_{10} (7%) and $PM_{2.5}$ (8%). These particles are expected to source from precursor gases (SO_2 and NO_x) emitted from far distances. However,

the contribution of NO_x from local sources, especially vehicles and power plants, can also contribute to nitrates. For sulfates, the major contribution can be attributed to large power plants and refineries from long distances.

- Biomass burning also has a significant contribution. This emission is expected from regions of economically lower strata of society where they used wood/dungs for cooking the food and crop residue burning in the nearby areas.



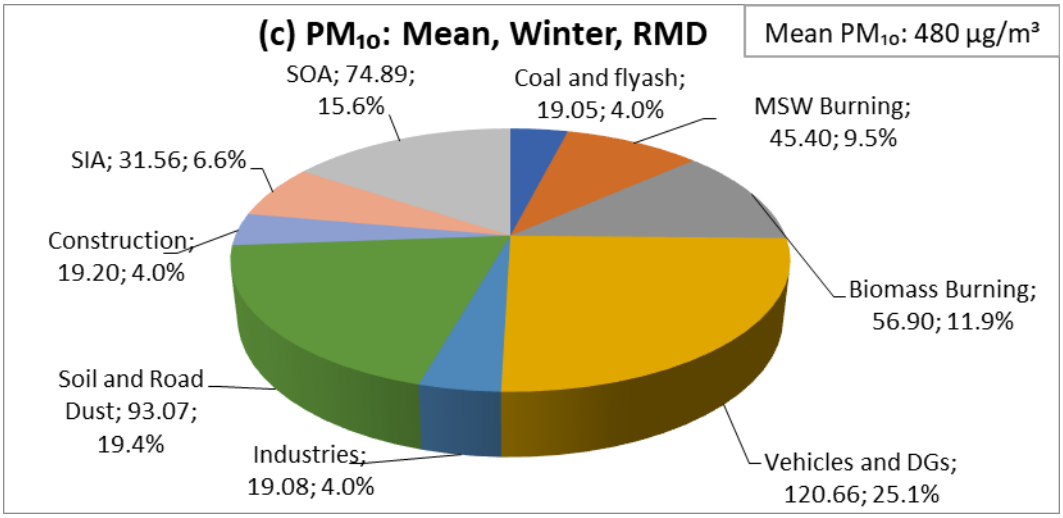
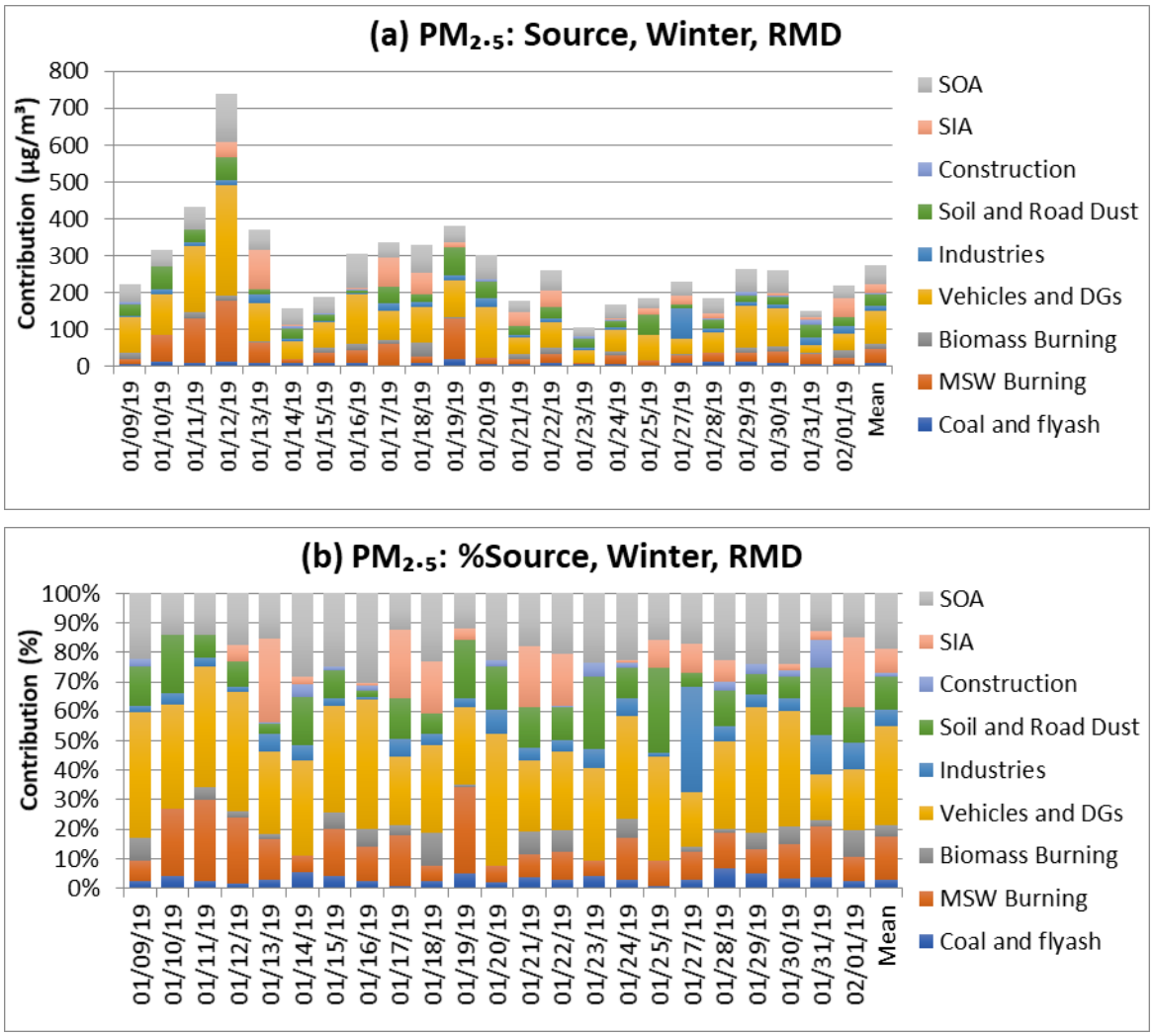


Figure 4.3: PMF modeling for PM_{10} at RMD for winter season



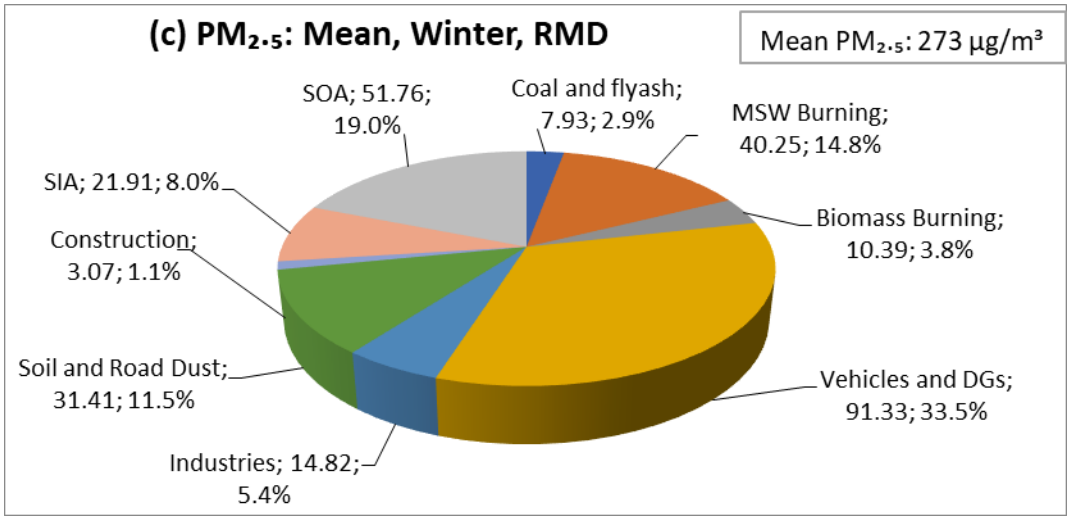


Figure 4.4: PMF modeling for $PM_{2.5}$ at RMD for winter season (MSW burning includes burning of plastic core wires to recover metal)

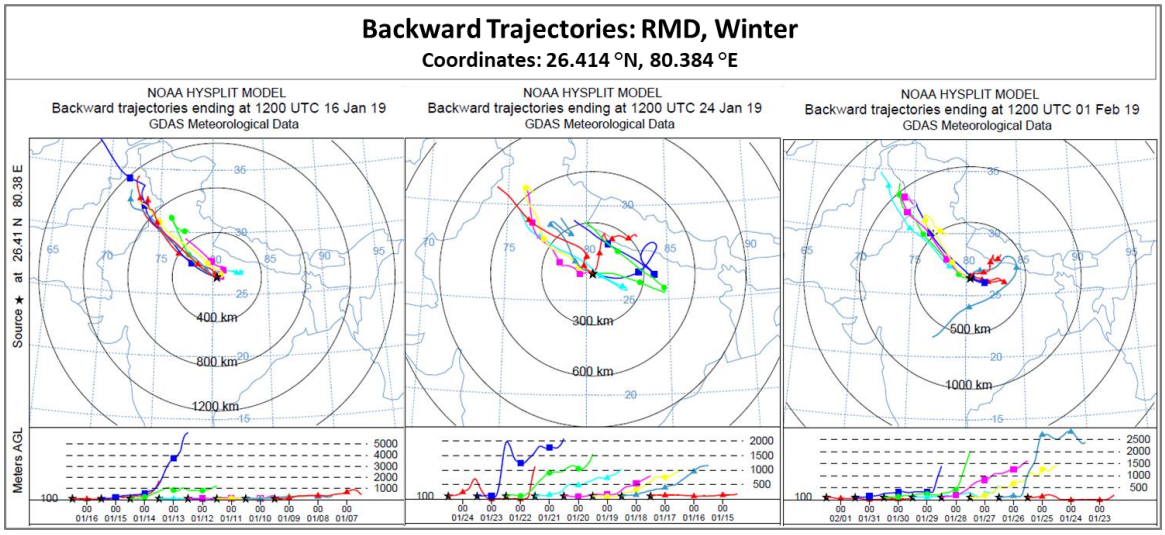


Figure 4.5: Backward trajectories at RMD for winter season

4.3.1.2 Summer Season [sampling period: May 19 – Jun 05, 2019]

PM_{10} (summer)

The average PM_{10} concentration was 239 µg/m^3. Figure 4.6 (a), (b), (c) represents PM_{10} contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively, at RMD. It is observed that the major PM_{10} source contributing was soil and road dust (153 µg/m^3 ~ 64%) followed by biomass burning (17 µg/m^3 ~ 7.3%) and SOA (17

µg/m^3 ~ 7.1%) in PM_{10}. Other sources are SIA (5.3%), construction material (5.2%), coal and fly ash (4.7%), MSW burning (3.2%), industrial (1.8%), and vehicles and DGs (1.6%) in PM_{10}.

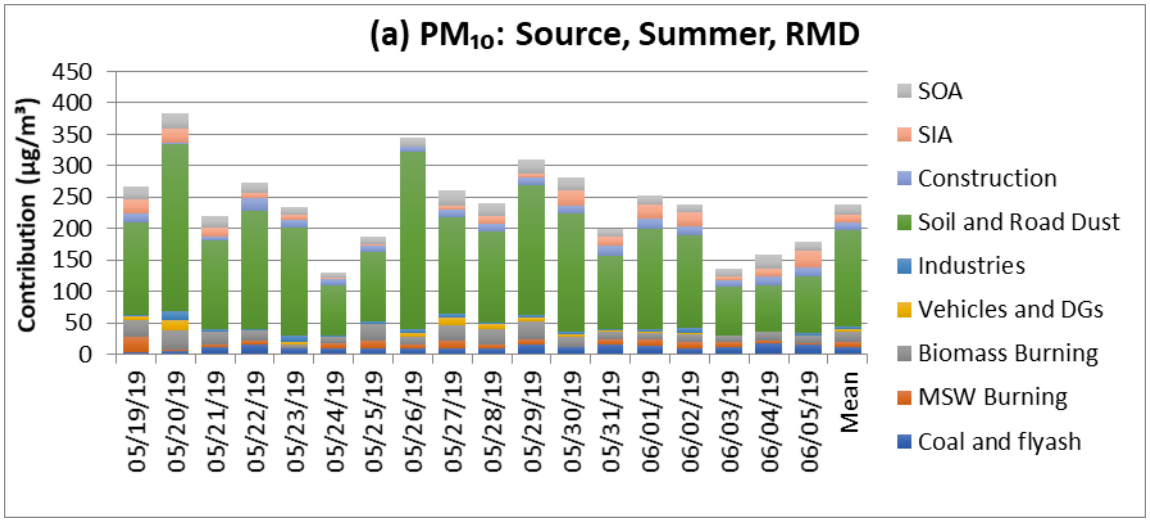
$PM_{2.5}$ (summer)

The average $PM_{2.5}$ concentration was 73 µg/m^3; the $PM_{2.5}/PM_{10}$ ratio is about 0.30. Figure 4.7 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively, at RMD. It is observed that the major source contributing to $PM_{2.5}$ was soil and road dust (18 µg/m^3 ~ 25%) followed by biomass burning (13 µg/m^3 ~ 17%) and SOA (12 µg/m^3 ~ 16%). coal and fly ash (26%). Other significant sources are construction material (15.2%), MSW burning (8.3%), SIA (8.1%), vehicles and DGs (4.7%) and industrial (3.2%).

HYSPLIT back trajectories (Figure 4.8) show that most of the time wind is mostly from NW and partly from east direction, and wind mass travels over the Thar Desert in Rajasthan and part of Punjab and Haryana before entering Kanpur. These winds pick up the pollutants on the way, especially from tall emitting sources.

Inferences

The major sources contributing to PM_{10} and $PM_{2.5}$ have dramatically changed. Soil and road dust and construction have become the major PM_{10} and $PM_{2.5}$ sources. It was observed that the atmosphere in summer looked white to gray, indicating the presence of large amounts of dust which may be due to high speeds of wind and very dry conditions, which makes the dust airborne. The occasional dust storm can also contribute to road/soil dust resuspension.



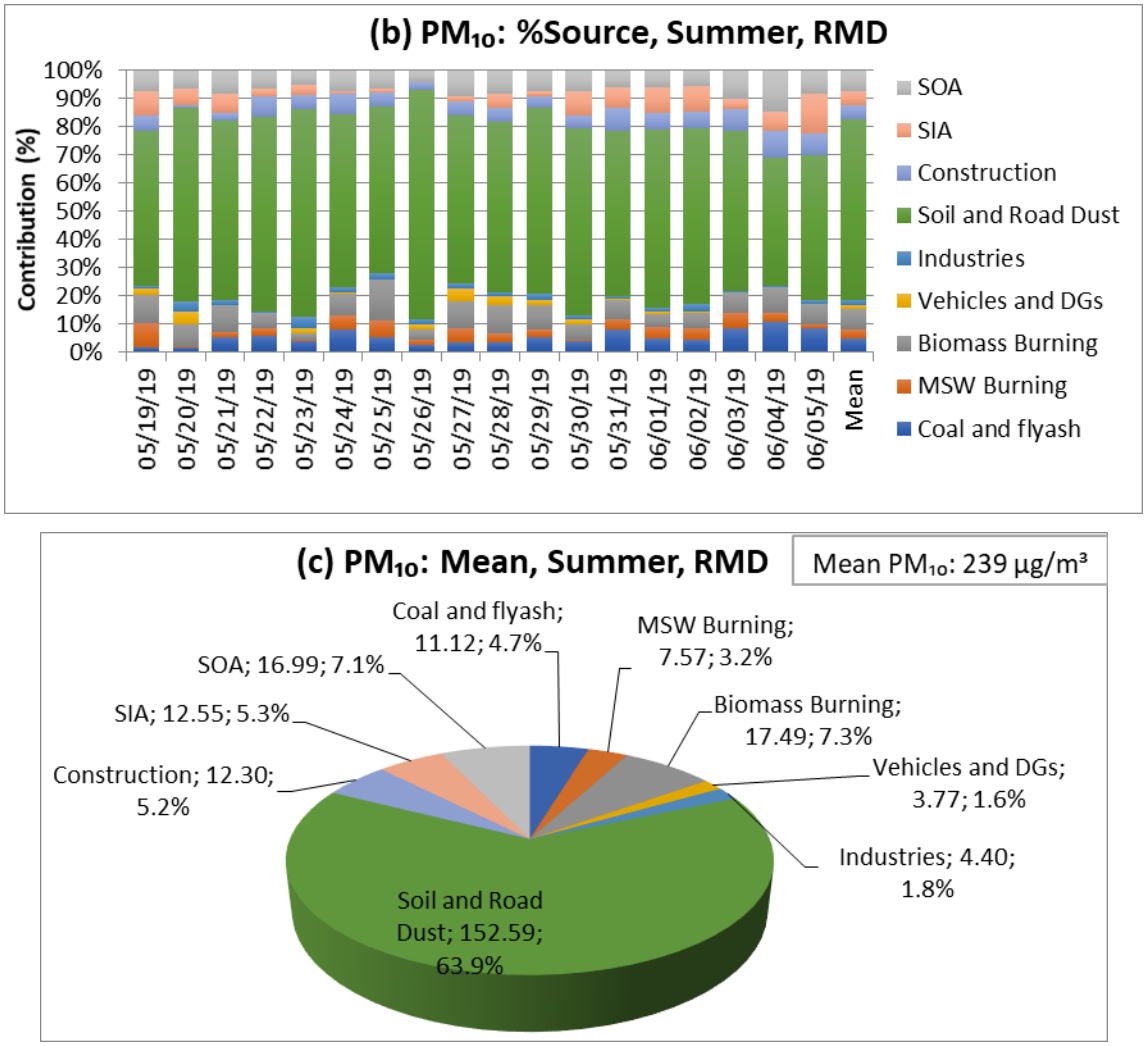
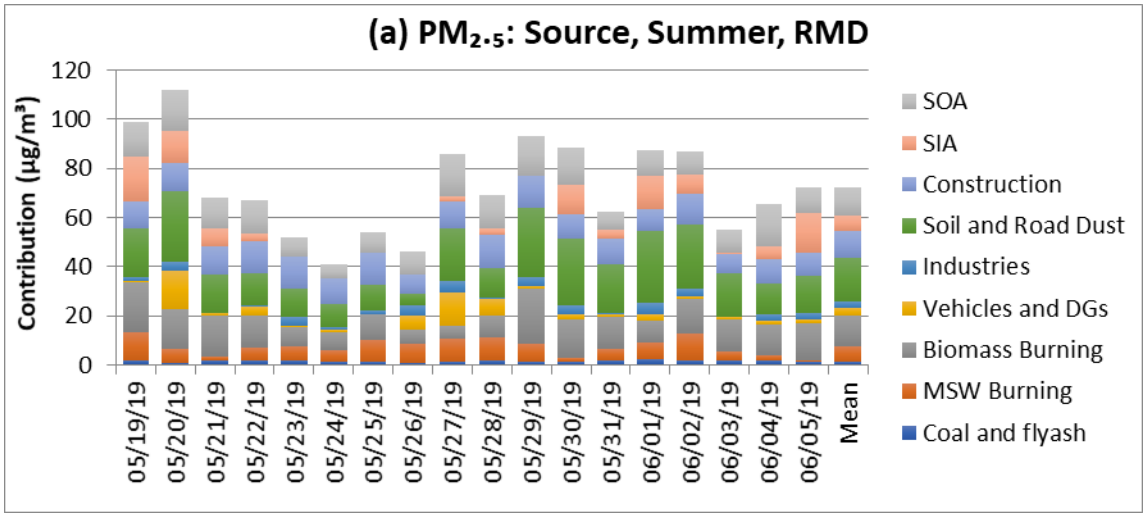


Figure 4.6: PMF modeling for PM_{10} at RMD for summer season



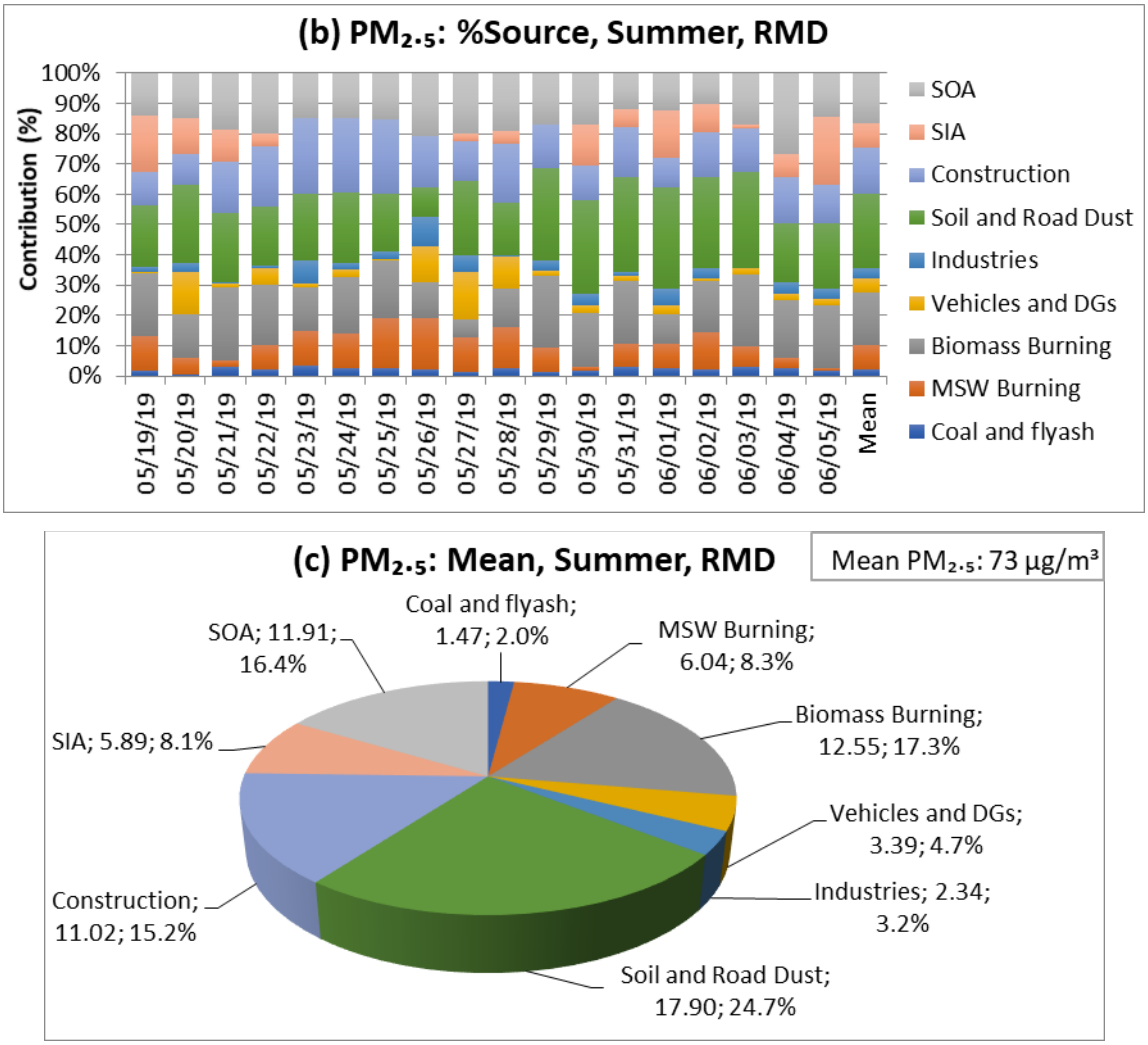


Figure 4.7: PMF modeling for $PM_{2.5}$ at RMD for summer season

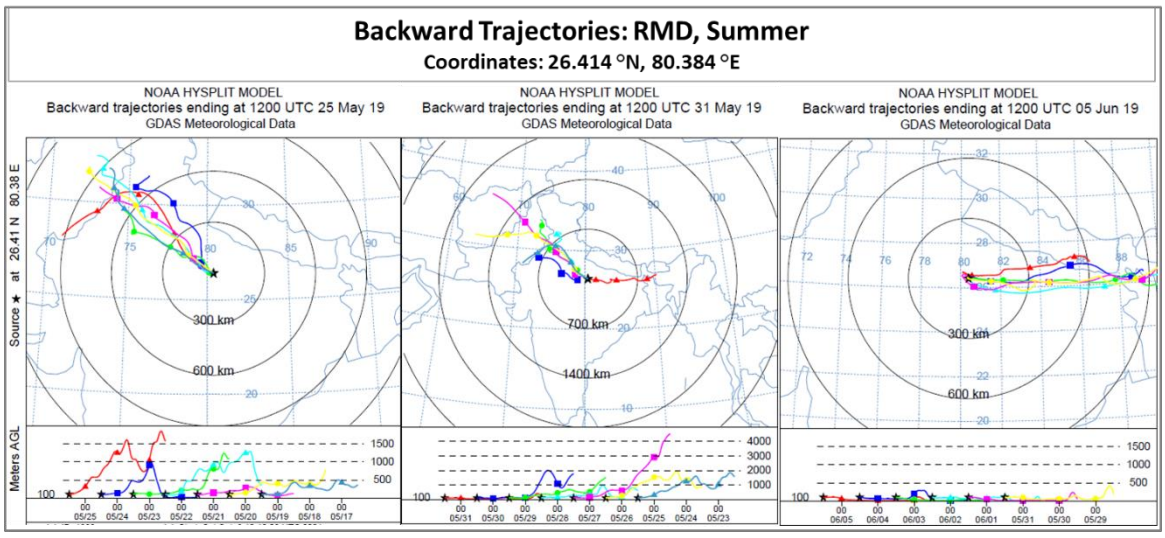


Figure 4.8: Backward trajectories at RMD for summer season

4.3.2 Chunniganj (CNG)

4.3.2.1 Winter Season [sampling period: Feb 04 – Mar 02, 2019]

PM_{10} (winter)

The average PM_{10} concentration was 220 µg/m^3. Figure 4.9 (a), (b), (c) represents PM_{10} contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage respectively at CNG. It is observed that the major PM_{10} source contributing was vehicles and DGs (66 µg/m^3 ~ 30%) followed by SOA (43 µg/m^3 ~ 19%) and soil and road dust (25 µg/m^3 ~ 11%) in PM_{10}. The other significant sources are SIA (9.9%), MSW burning (9.1%), biomass burning (8.7%), industrial emission (5.6%), construction material (3.1%) and coal and fly ash (2.9%). The contribution of coal and fly ash was the lowest in PM_{10}.

$PM_{2.5}$ (winter)

The average $PM_{2.5}$ concentration was 146 µg/m^3 (i.e., about 0.66 of PM_{10}). Figure 4.10 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage respectively at CNG. It is observed that the major source contributing to $PM_{2.5}$ was vehicles and DGs (52 µg/m^3 ~ 36%) followed by SOA (30 µg/m^3 ~ 21%) and SIA (21 µg/m^3 ~ 15%). Other predominant sources are soil and road dust (12.7%), MSW burning (8.1%), coal and fly ash (2.8%), industrial emission (2.6%) and biomass burning (2.1%). The contribution of construction material was estimated at about 1% in $PM_{2.5}$.

HYSPLIT back trajectories (Figure 4.11) show that wind is mostly from NW and wind mass travels over the states of Punjab, Haryana, Delhi and part of Rajasthan before entering Kanpur. These winds pick up the pollutants on the way, especially from large and tall emitting sources.

Inferences

The major sources contributing to PM_{10} and $PM_{2.5}$ have dramatically changed. Vehicles and DGs and industrial emissions are the major contributing sources to both PM_{10} and $PM_{2.5}$. MSW burning, SOA, SIA, soil/road dust and biomass burning are the consistent sources contributing to PM_{10} and $PM_{2.5}$ and slightly changed. The industrial emissions and MSW

burning are exceptionally high at CNG, indicating irregular waste generated from industries that succeed for open burning.

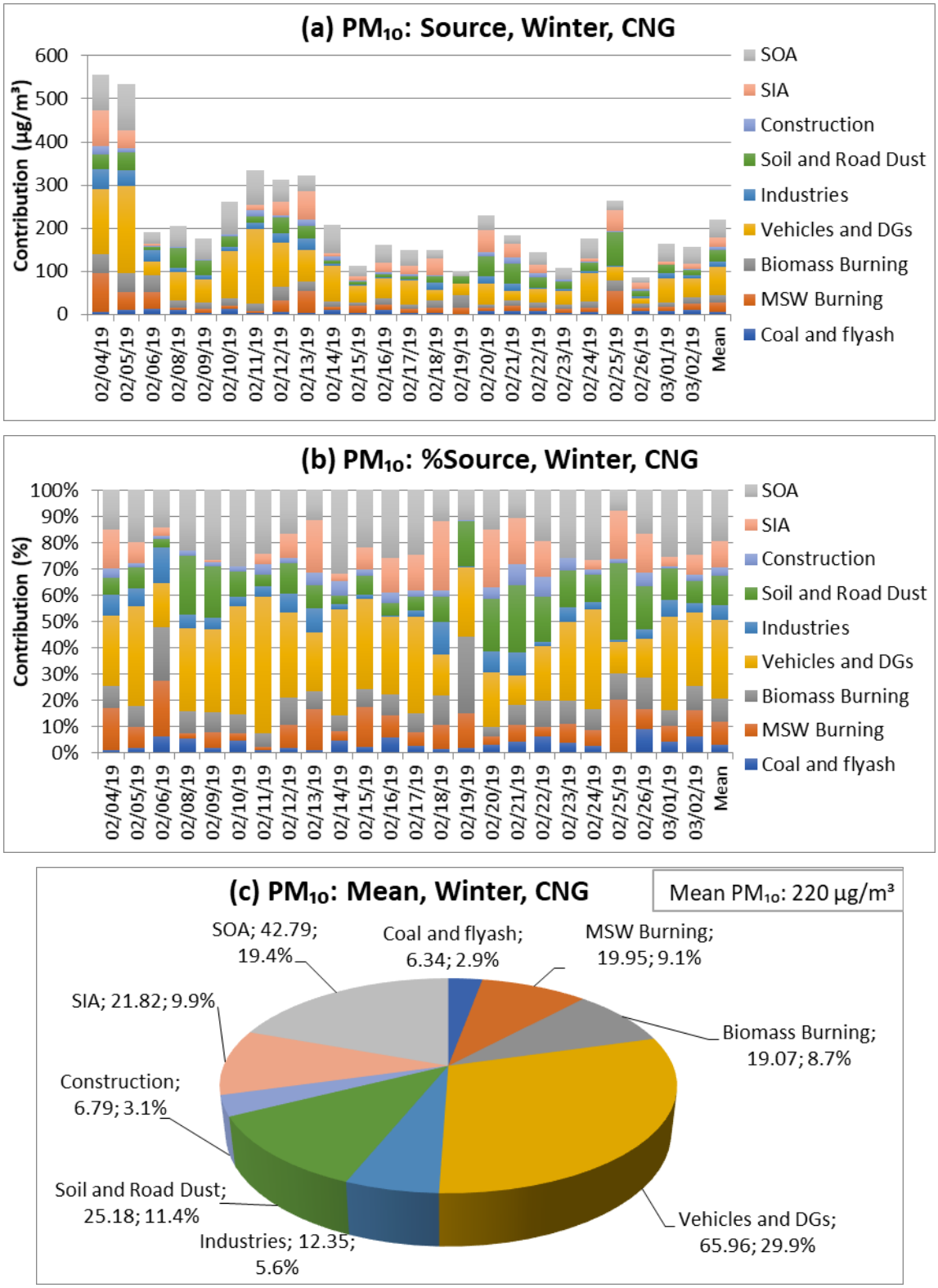


Figure 4.9: PMF modeling for PM_{10} at CNG for winter season

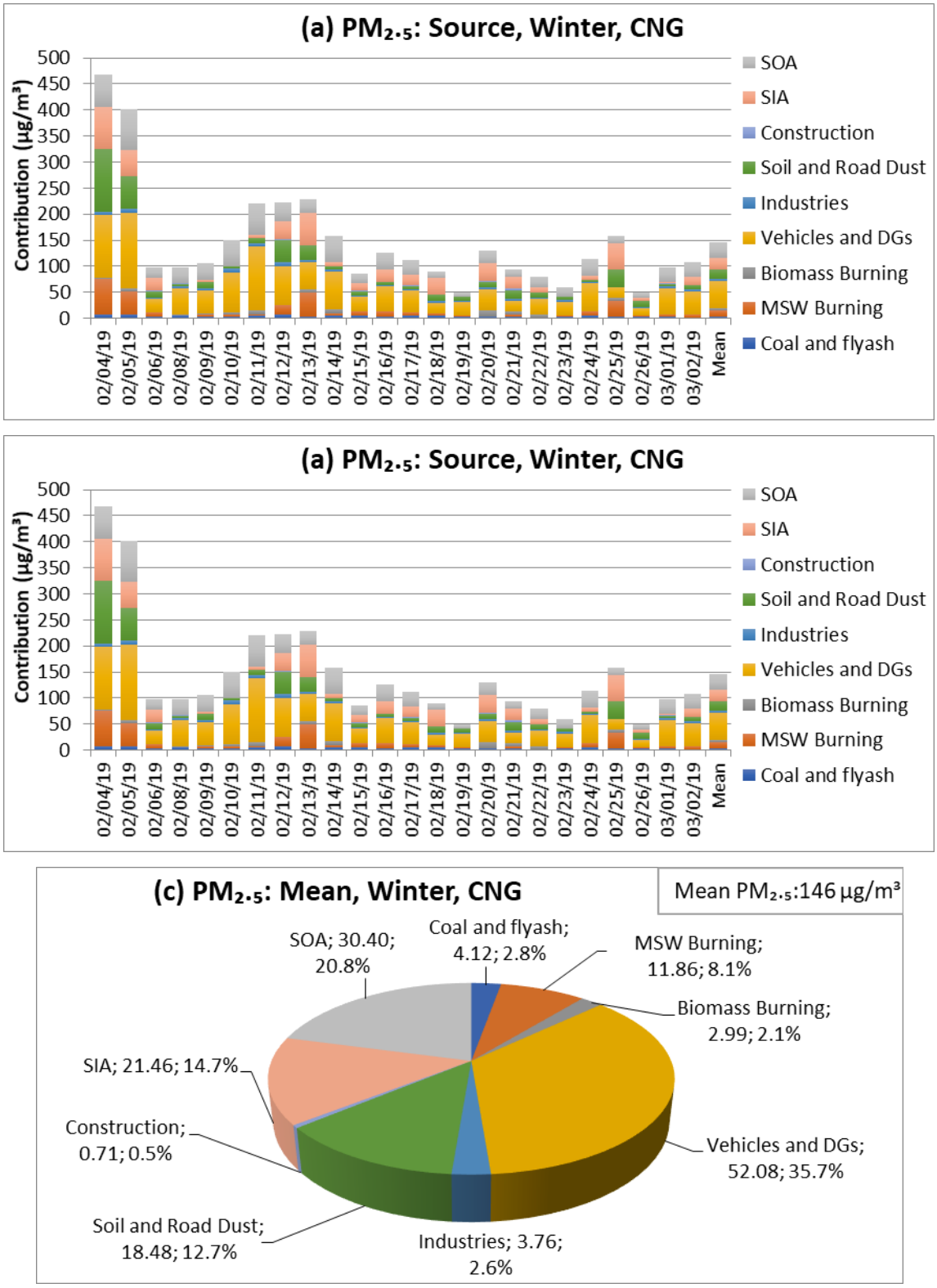


Figure 4.10: PMF modeling for $PM_{2.5}$ at CNG for winter season

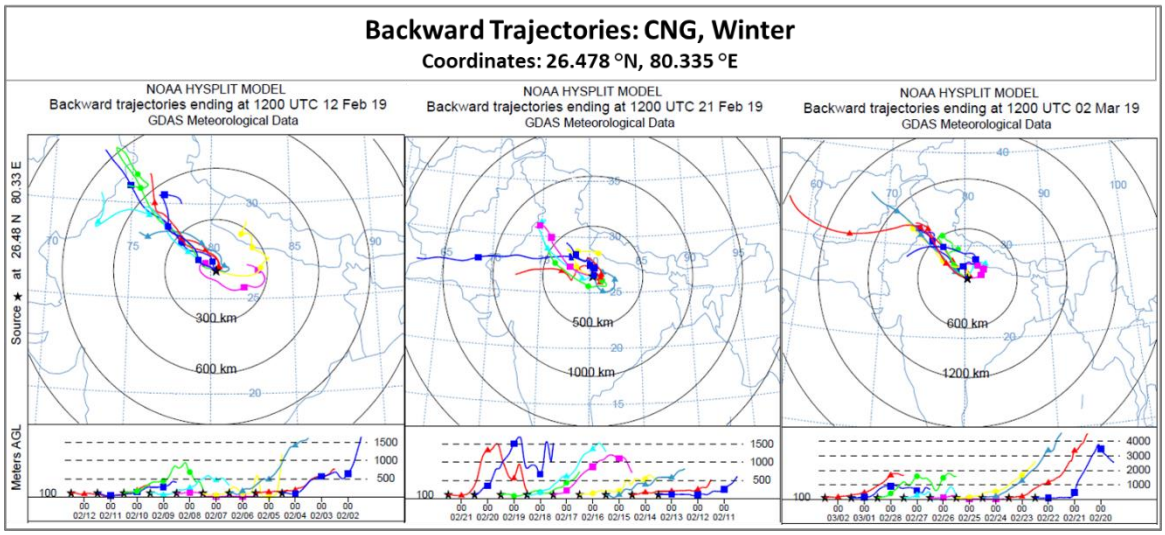


Figure 4.11: Backward trajectories at CNG for winter season

4.3.2.2 Summer Season [sampling period: Apr 01 – 24, 2019]

PM_{10} (summer)

The average PM_{10} concentration was 177 µg/m^3. Figure 4.12 (a), (b), (c) represents PM_{10} contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage respectively at CNG. It is observed that the major PM_{10} source contributing was soil and road dust (71 µg/m^3 ~ 40%) followed by construction material (24 µg/m^3 ~ 14%) and biomass burning (20 µg/m^3 ~ 11%). The other significant sources are SOA (10.6%), SIA (7.5%), MSW burning (6.7%), industrial (4.0%) and vehicles and DGs (3.9%). The contribution of coal and fly ash is lowest at 2.1% in PM_{10}.

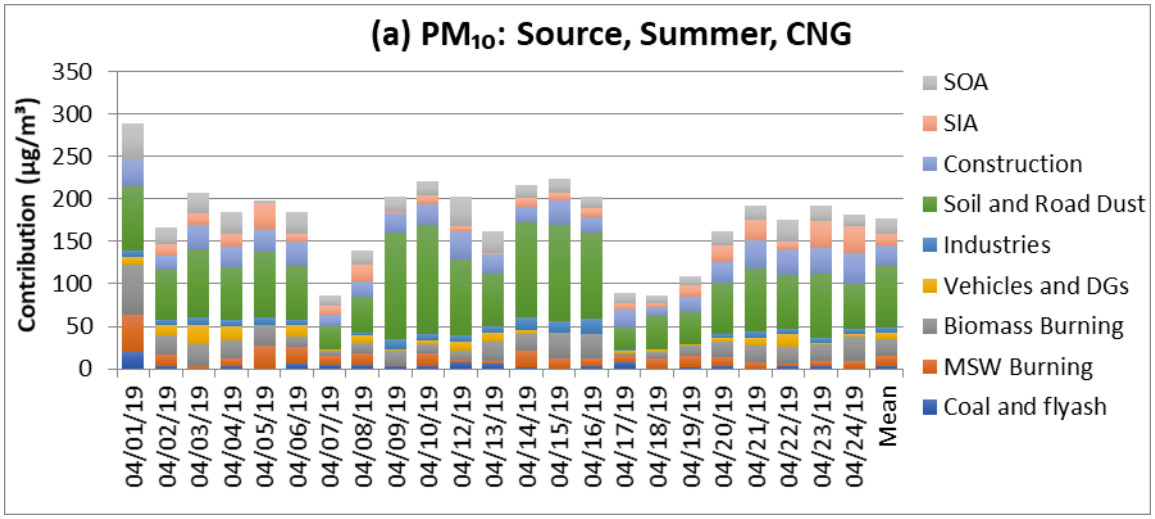
$PM_{2.5}$ (summer)

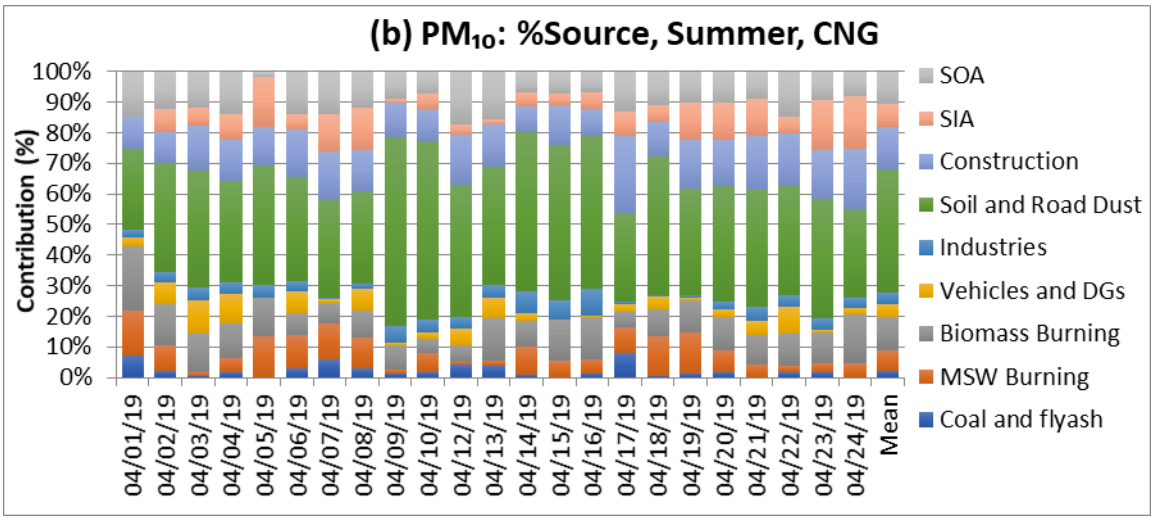
The average $PM_{2.5}$ concentration was 79 µg/m^3 ($PM_{2.5}/PM_{10}$ is 0.45). Figure 4.13 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage respectively at CNG. It is observed that the major source contributing to $PM_{2.5}$ was soil and road dust (15 µg/m^3 ~ 19%) followed by SOA (13 µg/m^3 ~ 17%) and MSW burning (12 µg/m^3 ~ 15%). Other significant sources are construction material (14.6%), biomass burning (10.3%), vehicles and DGs (8.3%), SIA (7.8%) and industrial emissions (7.3%). The contribution of coal and fly ash is lowest at 1.1% in $PM_{2.5}$.

HYSPLIT back trajectories (Figure 4.14) show that wind is mostly from NW and E. Wind mass travels over the Thar Desert in Rajasthan and part of states of Punjab and Haryana before entering Kanpur. These winds pick up the pollutants on the way, especially from large and tall emitting sources.

Inference

Soil/Road dust, construction and SOA are the major contributors in summer both for PM_{10} and $PM_{2.5}$; at the same time, vehicles and DGs, biomass burning and construction material are prominent both in PM_{10} and $PM_{2.5}$. It is a bit surprising that these sources consist of the major portion of PM. In winter, the wind speed is generally low and mostly about to calm conditions. Therefore, fine mode particles retain in the atmosphere. In the area of about 50 km radius, there are several brick kiln units operated and caused emissions.





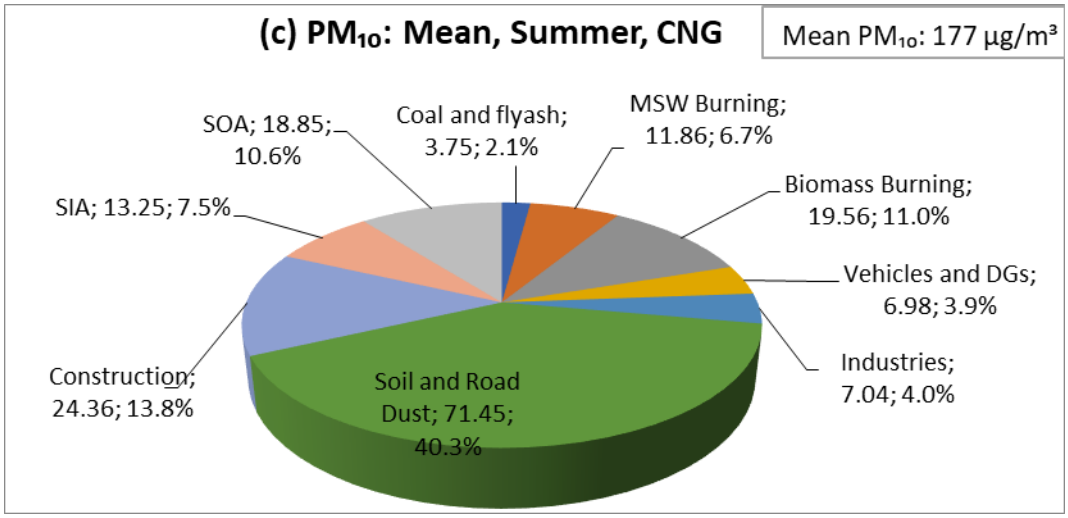
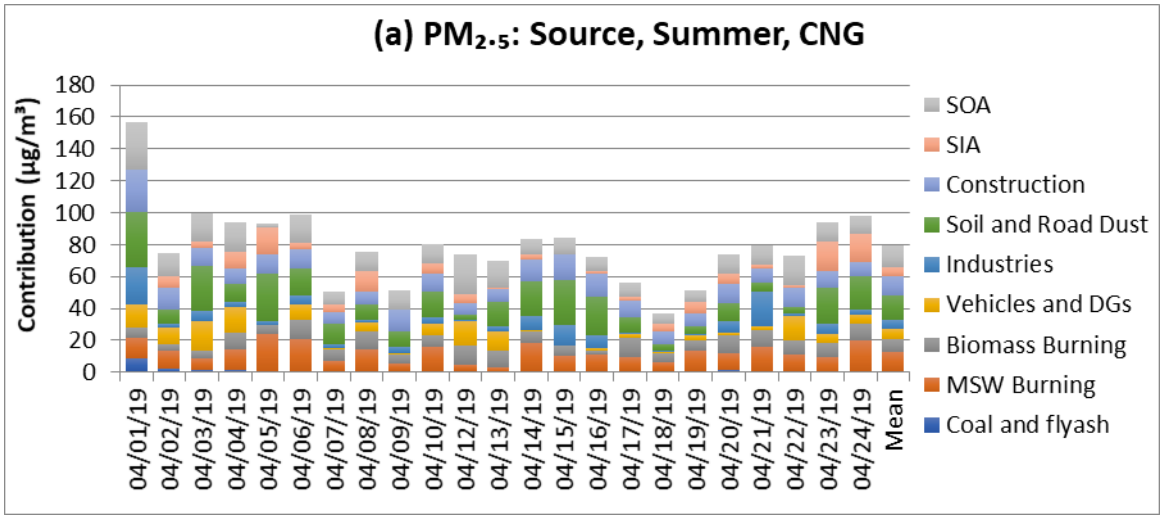
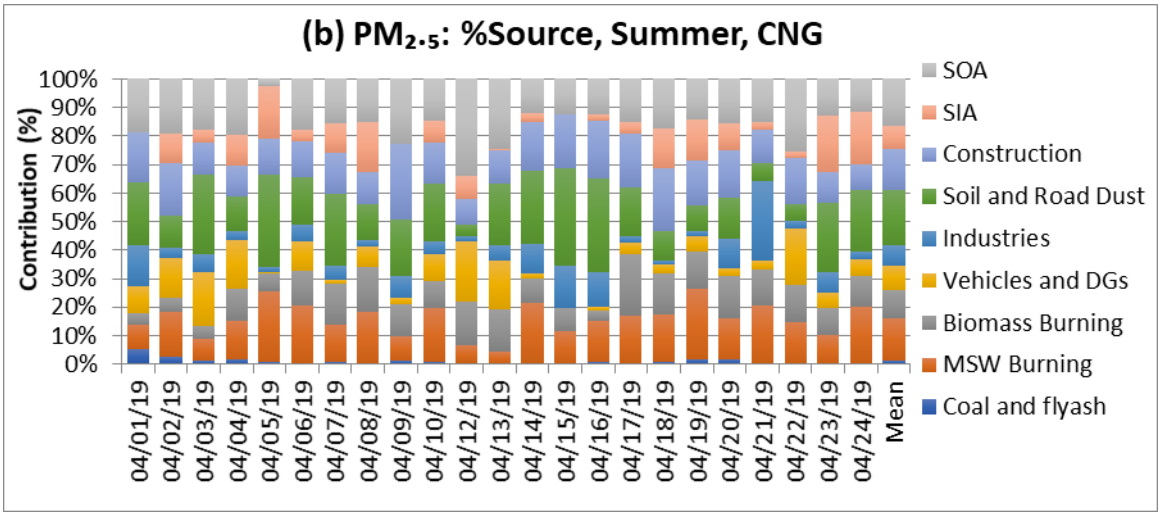


Figure 4.12: PMF modeling for PM_{10} at CNG for summer season





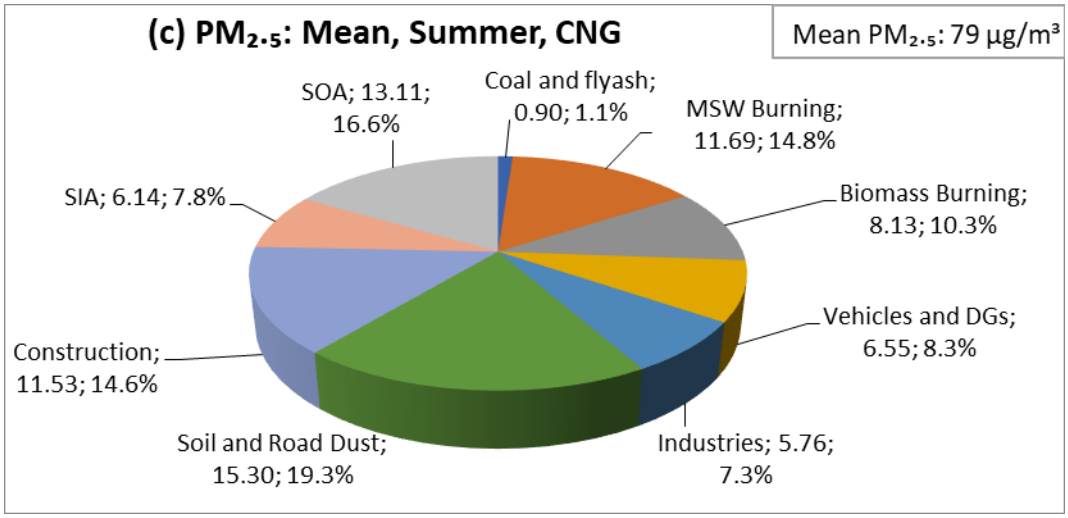


Figure 4.13: PMF modeling for $PM_{2.5}$ at CNG for summer season

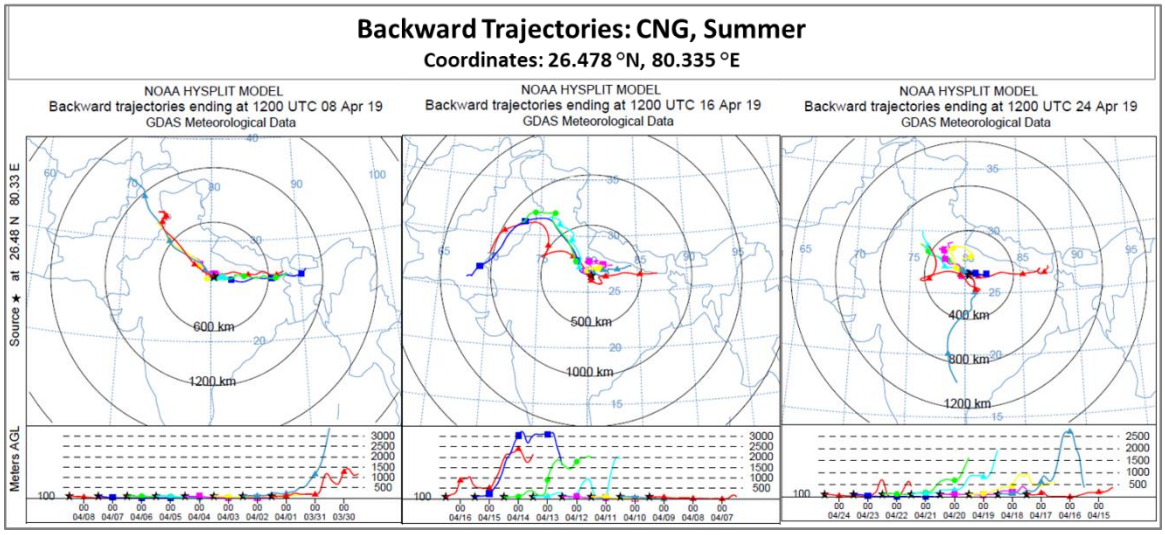


Figure 4.14: Backward trajectories at CNG for Summer Season

4.3.3 Dada Nagar (DDN)

4.3.3.1 Winter Season [sampling period: Dec 22, 2018 – Jan 12, 2019]

PM_{10} (winter)

The average PM_{10} concentration was 598 µg/m^3. Figure 4.15 (a), (b), (c) represents PM_{10} contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively, at DDN. It is observed that the major PM_{10} source contributing was vehicles and DGs (112 µg/m^3 ~ 19%) followed by soil and road dust (86 µg/m^3 ~ 14%) and industrial

emission (80 µg/m^3 ~ 13%). The other significant contributing sources are biomass burning (13.4%), SOA (11.6%), MSW burning (9.2%), SIA (9.0%), coal and fly ash (6.1%) and construction material (3.7%).

$PM_{2.5}$ (winter)

The average $PM_{2.5}$ concentration was 388 µg/m^3 (i.e., about 0.65 of PM_{10}). Figure 4.16 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively, at DDN. It is observed that the major source contributing to $PM_{2.5}$ was vehicles and DGs (106 µg/m^3 ~ 27%) followed by industrial emission (63 µg/m^3 ~ 16%) and soil and road dust (53 µg/m^3 ~ 14%). Other major sources are SOA (12.5%), MSW burning (10.7%), SIA (9.0%), coal and fly ash (6.9%) and biomass burning (2.2%). The contribution of the construction material was lowest at 1.5% in $PM_{2.5}$.

HYSPLIT back trajectories (Figure 4.17) show that most of the time wind is mostly from NW dirction. The wind mass travels over Punjab, Haryana, Delhi and part of Rajasthan before entering Kanpur. These winds pick up the pollutants on the way, especially from large and tall emitting sources.

Inferences

The major sources contributing to PM_{10} and $PM_{2.5}$ have dramatically changed. Industrial emissions are the second most contributor at DDN after vehicles and DGs. The sampling site was in the middle of the industrial area, which had large trucks ferrying raw material and finishes products. The MSW burning and industrial emissions also contribute a significant amount at DDN that indicates irregular management of waste generated from industries that succeed in open burning.

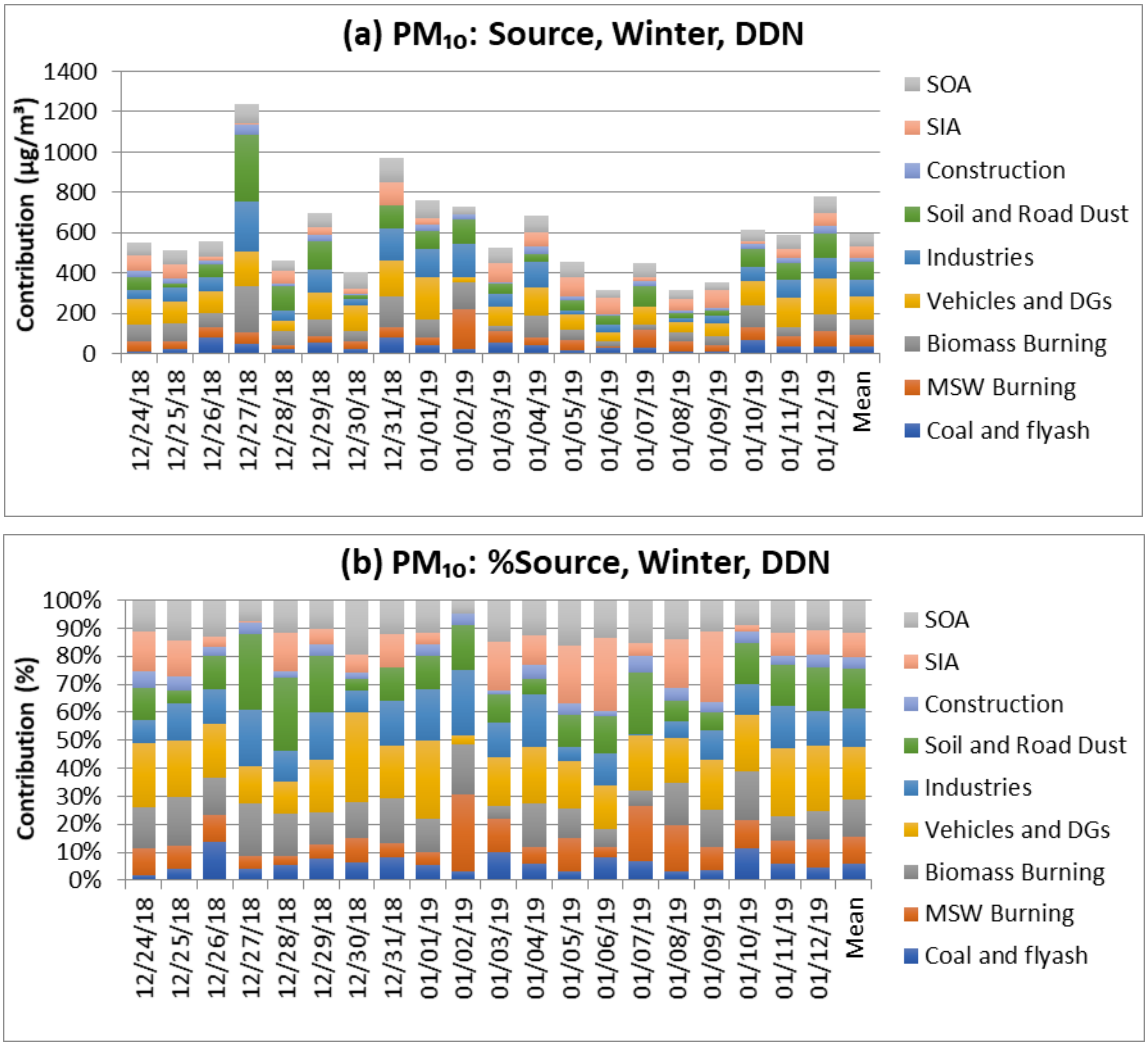


Figure 4.15: PMF modeling for PM_{10} at DDN winter season

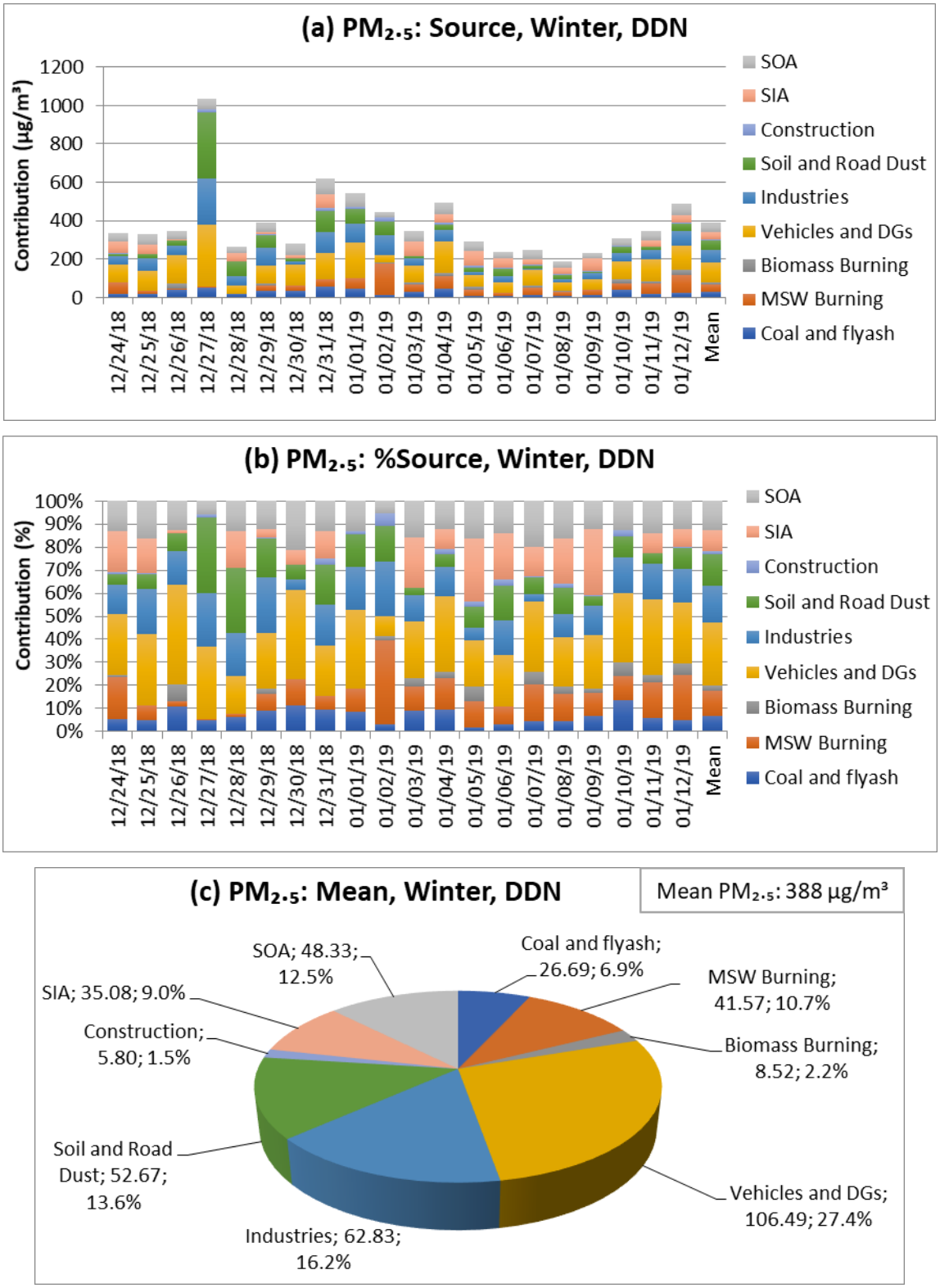


Figure 4.16: PMF modeling for $PM_{2.5}$ at DDN, winter season

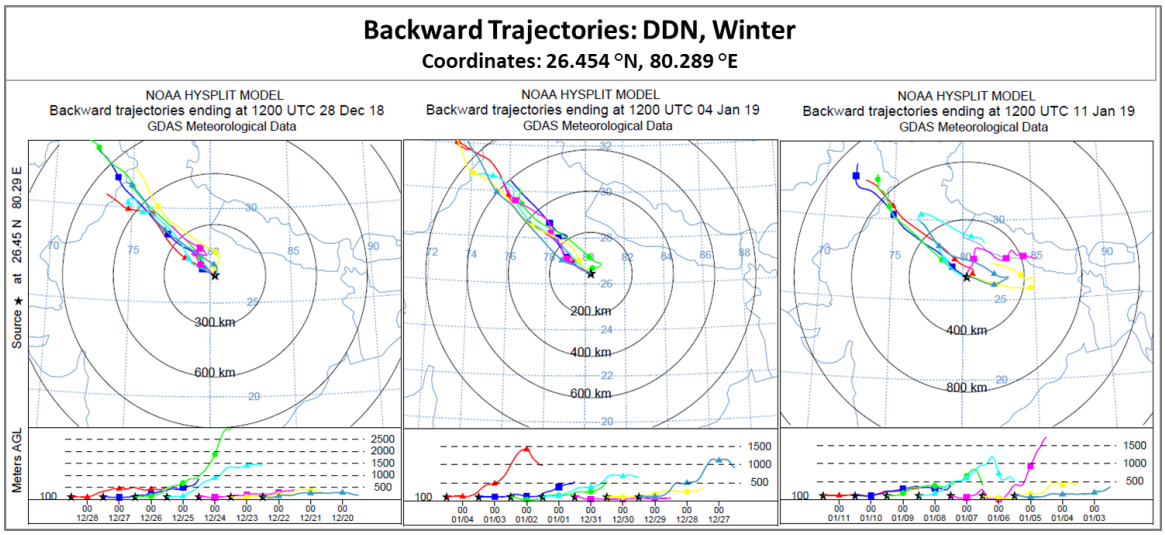


Figure 4.17: Backward trajectories at DDN for winter season

4.3.3.2 Summer Season [sampling period: April 27 - May 16, 2019]

PM_{10} (summer)

The average PM_{10} concentration was 297 µg/m^3. Figure 4.18 (a), (b), (c) represents PM_{10} contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively, at DDN. It is observed that the major PM_{10} source contributing was soil and road dust (150 µg/m^3 ~ 51%) followed by biomass burning (29 µg/m^3 ~ 10%) and industrial emission (26 µg/m^3 ~ 9%) in PM_{10}. The other significant sources are SOA (7.6%), SIA (5.4%), vehicles and DGs (5.2%), MSW burning (4.4%), construction material (4.1%) and coal and fly ash (4.0%). The contribution of coal and fly ash the was lowest in PM_{10}.

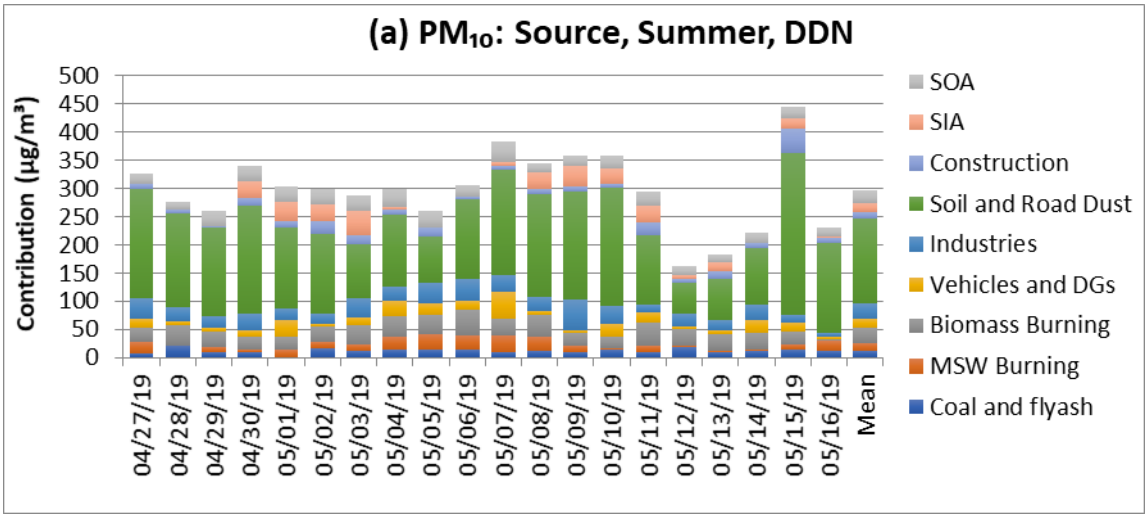
$PM_{2.5}$ (summer)

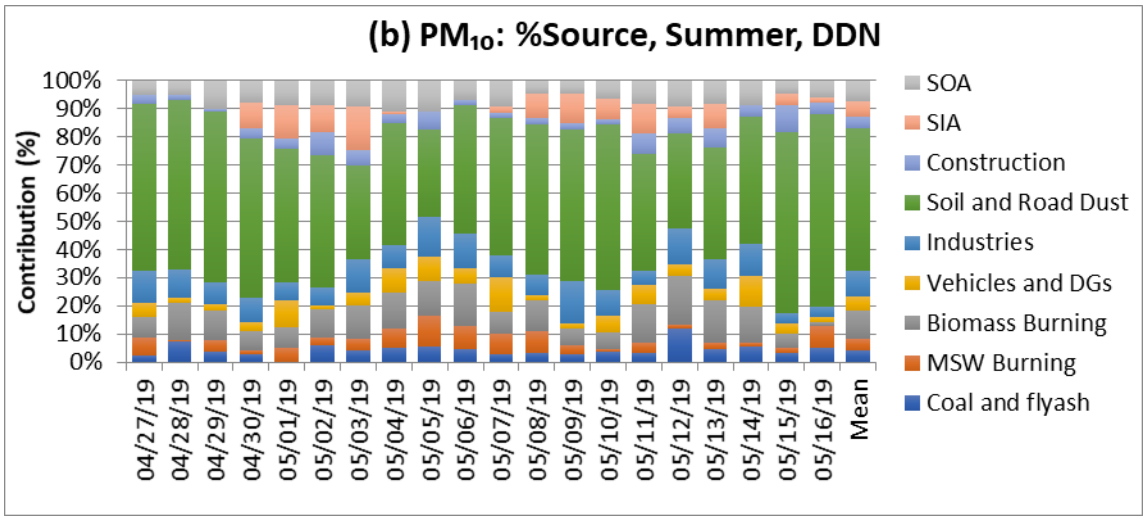
The average $PM_{2.5}$ concentration was 116 µg/m^3 (i.e., about 0.39 of PM_{10}). Figure 4.19 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively, at DDN. It is observed that the major source contributing to $PM_{2.5}$ was soil and road dust (29 µg/m^3 ~ 25%) followed by biomass burning (20 µg/m^3 ~ 17%) and SOA (15 µg/m^3 ~ 13%). Other significant sources are industrial emission (11.7%), MSW burning (9.7%), SIA (8.5%), vehicles and DGs (7.4%), construction material (3.7%) and coal and fly ash (3.2%) in $PM_{2.5}$.

HYSPLIT back trajectories (Figure 4.20) show that wind is mainly from NW to SW and sometimes from the east. The wind mass travels over different states and the Thar Desert and Rajasthan before entering Kanpur. These winds pick up the pollutants on the way, especially from large sources.

Inference

Soil and road dust is major contributors in summer both for PM_{10} and $PM_{2.5}$. Biomass is the second major contributor to PM_{10} and $PM_{2.5}$ followed by industrial emission. The loose particles are airborne with high-speed wind from the desert, open barren fields, open dumping sites of fly ash, no control at construction sites caused the high contribution to PM. The sampling site was in the middle of the industrial area, which had large trucks ferrying raw material and finishes products. The industrial emissions and MSW burning also contribute a significant amount at DDN that indicates irregular management of waste generated from industries that succeed in open burning.





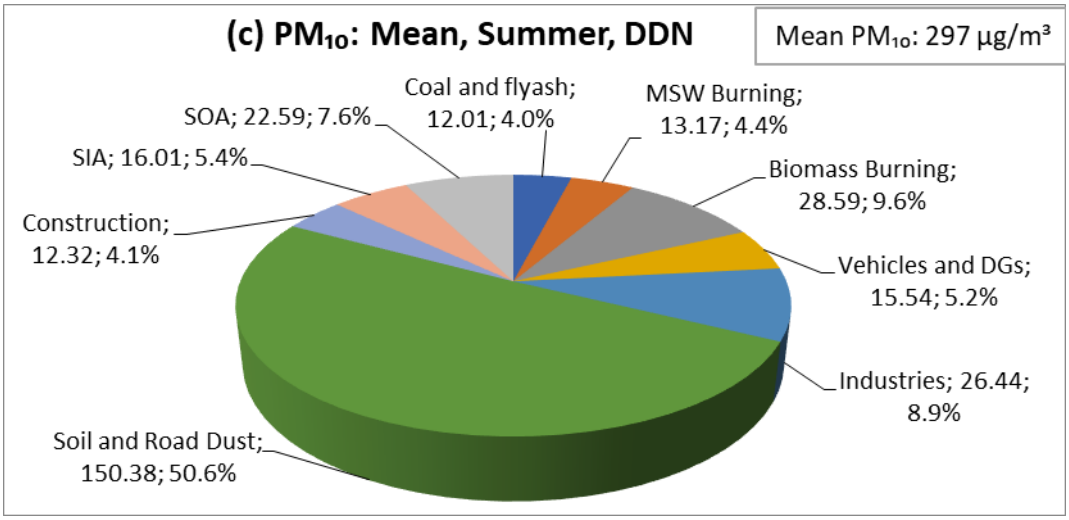
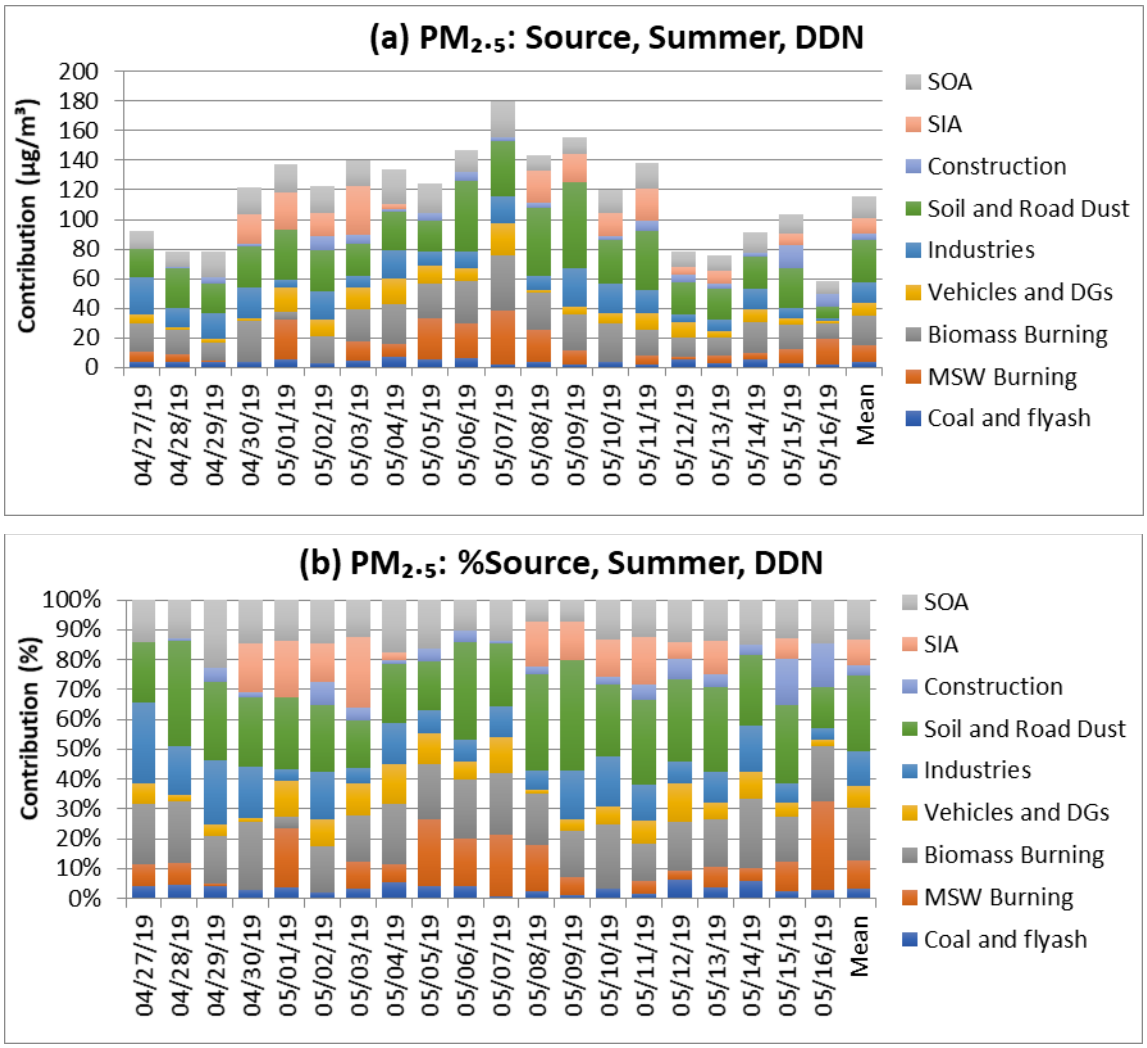


Figure 4.18: PMF modeling for PM_{10} at DDN for summer season



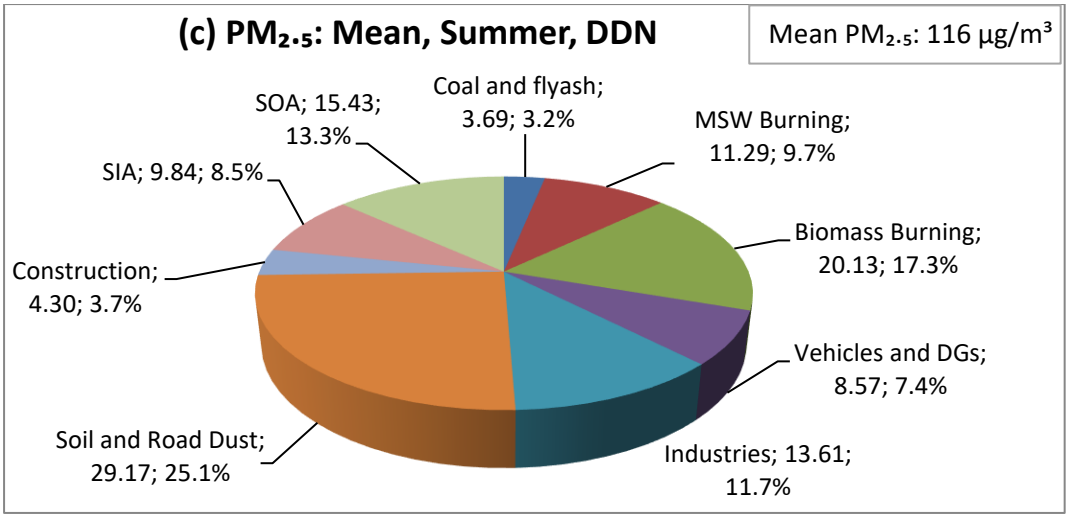


Figure 4.19: PMF modeling for $PM_{2.5}$ at DDN for summer season

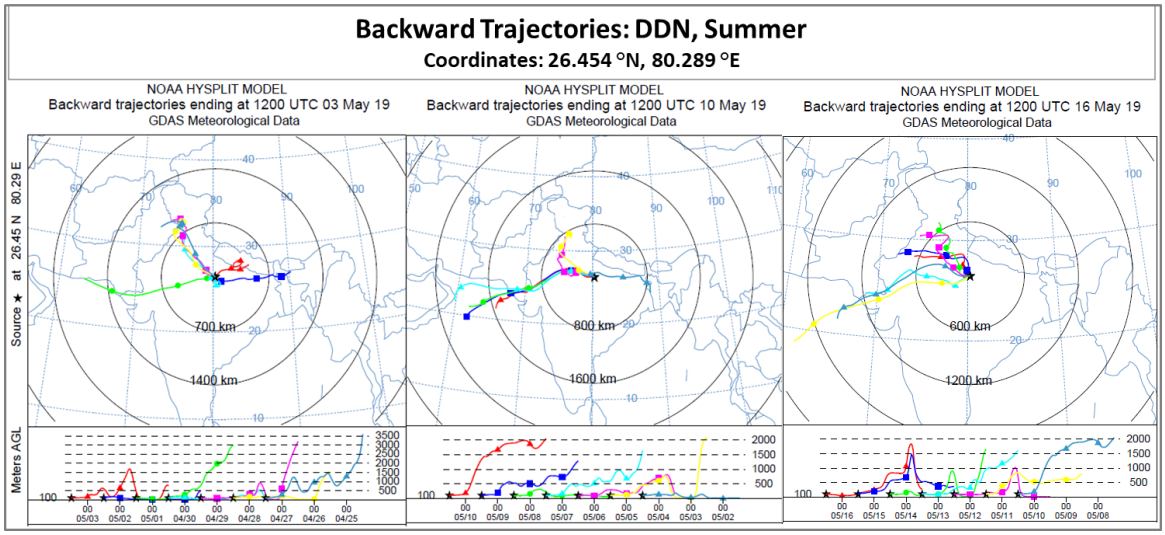


Figure 4.20: Backward trajectories at DDN for summer season

4.3.4 Jarib Chowki (JRC)

4.3.4.1 Winter Season [sampling period: Jan 20 – Feb 11, 2019]

PM_{10} (winter)

The average PM_{10} concentration was 287 µg/m^3. Figure 4.21 (a), (b), (c) represents PM_{10} contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage respectively at JRC. It is observed that the major contributing source was SIA vehicles and DGs (88 µg/m^3 ~ 31%) followed by SOA (64 µg/m^3 ~ 22%) and soil and road dust (39

$\mu g/m^3$ ~ 14%). The other significant contributing sources are biomass burning (10.2%), SIA (8.8%), MSW burning (7.1%), coal and fly ash (3.9%), industrial emission (1.8%) and construction material (1.7%).

$PM_{2.5}$ (winter)

The average $PM_{2.5}$ concentration was 186 $\mu g/m^3$ (i.e., about 0.65 of PM_{10}). Figure 4.22 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage respectively at JRC. It is observed that the major source contributing to $PM_{2.5}$ was vehicles and DGs (66 $\mu g/m^3$ ~ 36%) followed by SOA (44 $\mu g/m^3$ ~ 24%) and SIA (24 $\mu g/m^3$ ~ 13%). Other significant sources are soil and road dust (10.1%), MSW burning (7.4%), biomass burning (4.8%), industrial emission (2.4%) and coal and fly ash (2.3%). The contribution of the construction material was less than 1% in $PM_{2.5}$.

HYSPLIT back trajectories (Figure 4.23) show that wind is mostly from NW and sometimes from the east direction. Wind mass travels over to neighboring districts, states of Punjab, Haryana, Delhi and Rajasthan before entering into Kanpur. These winds pick up the pollutants on the way, especially from large and tall emitting sources.

Inference

The major sources contributing to PM_{10} and $PM_{2.5}$ have dramatically changed. It is to be noted that at JRC, vehicles and DGs, SOA and SIA contribute about 60% (in PM_{10}) and 70% (in $PM_{2.5}$) and MSW burning about 7% are consistent. The MSW burning contributes a significant amount at JRC that indicates irregular management of waste generated from commercial activities that succeed for open burning. It may be noted that this site is near a traffic junction which has high traffic load and congestion that caused high emission.

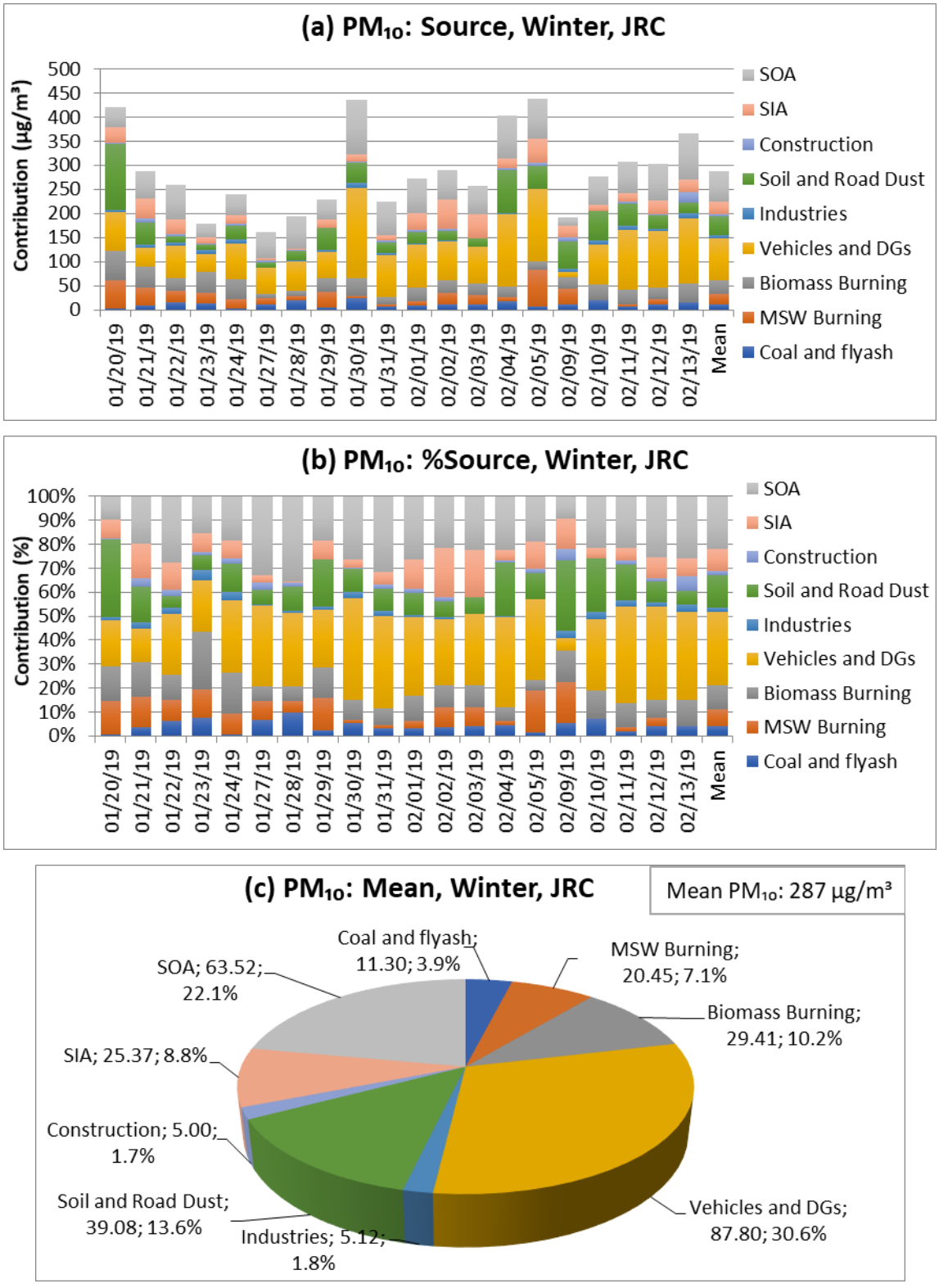


Figure 4.21: PMF modeling for PM_{10} at JRC for winter season

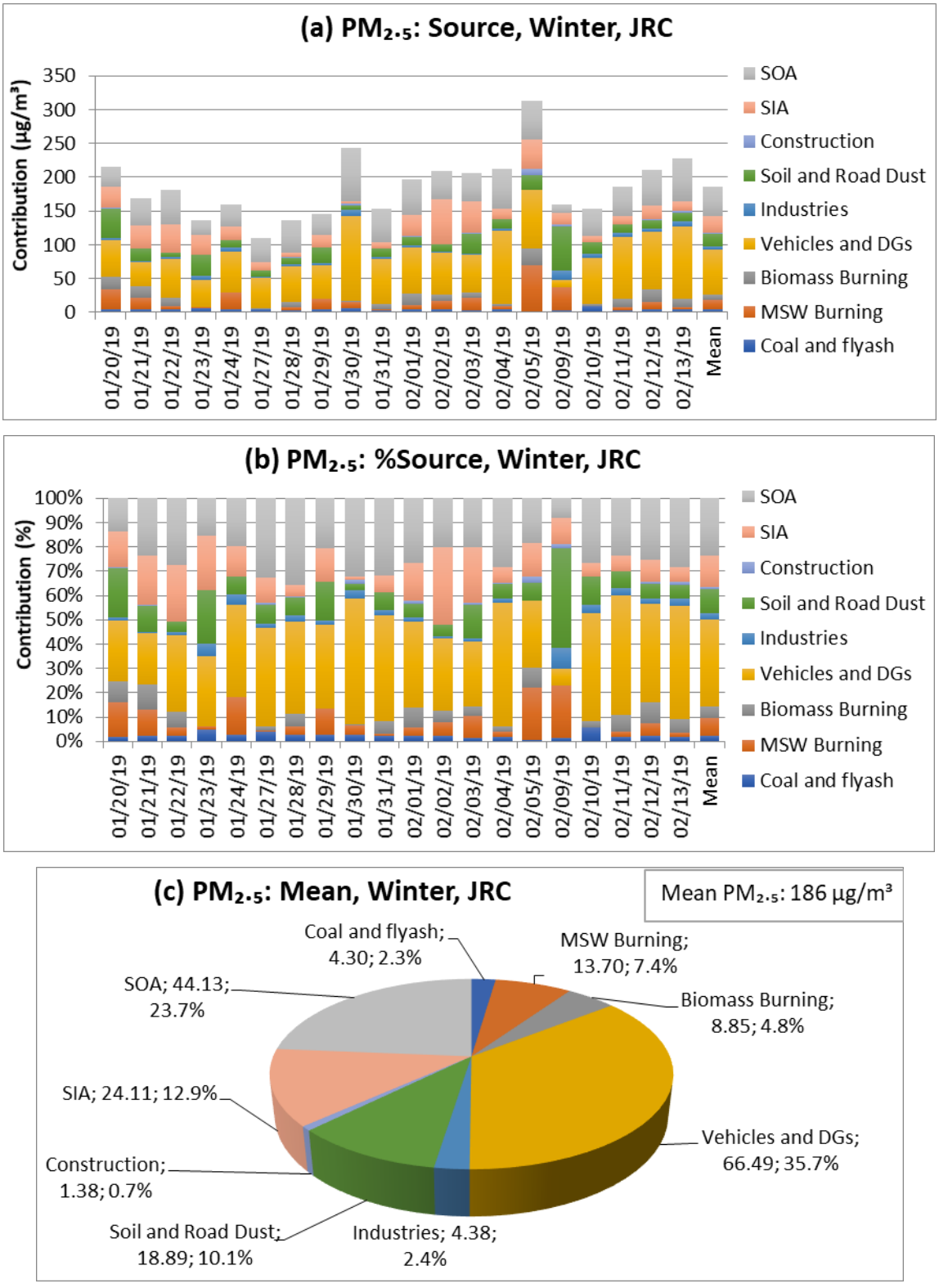


Figure 4.22: PMF modeling for $PM_{2.5}$ at JRC for winter season

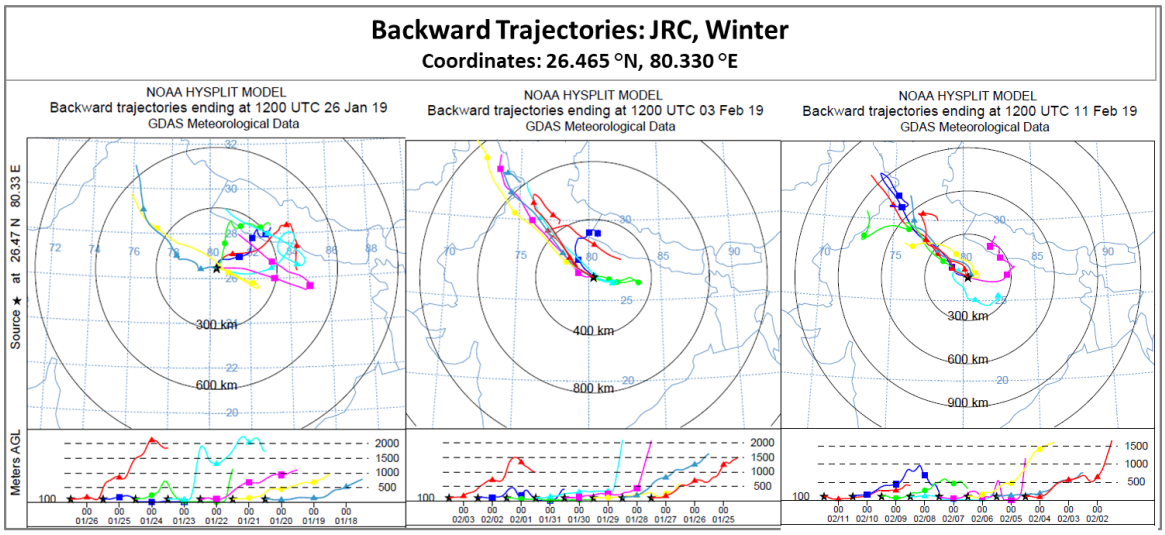


Figure 4.23: Backward trajectories at JRC for winter season

4.3.4.2 Summer Season [sampling period: Jun 07 – 26, 2019]

PM_{10} (summer)

The average PM_{10} concentration was 133 µg/m^3. Figure 4.24 (a), (b), (c) represents PM_{10} contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage respectively at JRC. It is observed that the major PM_{10} source contributing was soil and road dust (43 µg/m^3 ~ 32%) followed by biomass burning (24 µg/m^3 ~ 18%) and construction material (14 µg/m^3 ~ 11%). The other significant sources are SOA (9.7%), SIA (8.9%), vehicles and DGs (7.8%), MSW burning (5.8%) and coal and fly ash (4.6%). The contribution of the industrial emissions was lowest at 2.0% in PM_{10}.

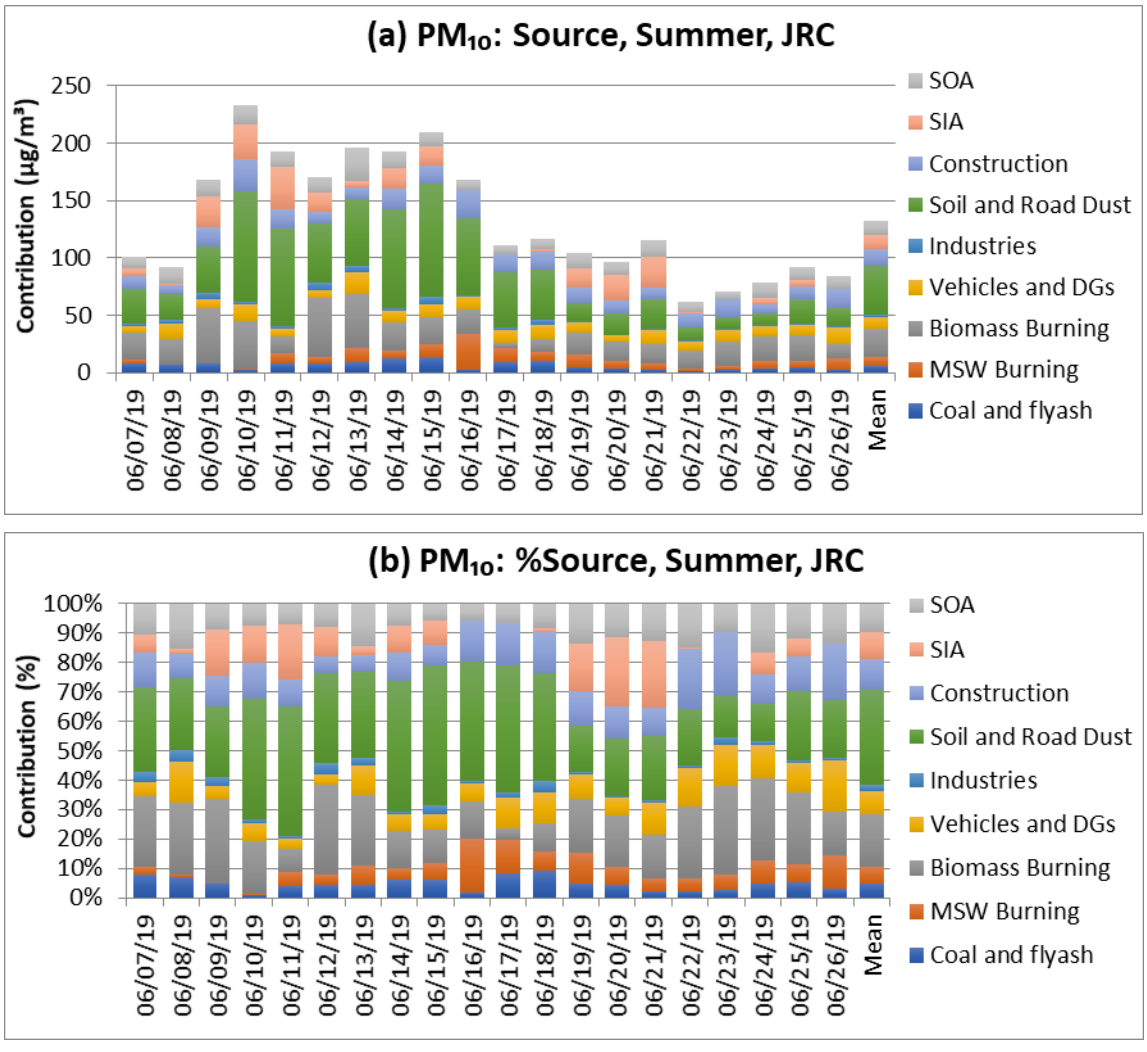
$PM_{2.5}$ (summer)

The average $PM_{2.5}$ concentration was 57 µg/m^3 (i.e., about 0.43 of PM_{10}). Figure 4.25 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage respectively at JRC. It is observed that the major source contributing to $PM_{2.5}$ was soil and road dust (14 µg/m^3 ~ 24%) followed by biomass burning (9 µg/m^3 ~ 16%) and SOA (8 µg/m^3 ~ 15%). Other significant sources are construction material (13.9%), MSW burning (11.2%), SIA (8.0%), vehicles and DGs (7.1%), coal and fly ash (2.9%) and industrial emissions (2.1%).

HYSPLIT back trajectories (Figure 4.26) show that wind is not stable in any particular direction and wind mass travel over to neighboring districts and the state of Rajasthan before entering into Kanpur. These winds pick up the pollutants on the way, especially from large and tall emitting sources.

Inference

Soil and road dust and construction are major contributors in summer both for PM_{10} and $PM_{2.5}$. The loose particles are airborne with high-speed wind from the desert, open barren fields, open dumping sites of fly ash, no control at construction sites caused the high contribution to PM. The biomass burning, MSW burning and vehicles contribute a significant amount at JRC that indicates irregular management of waste generated from commercial activities that succeed for open burning. It may be noted that this site is near a traffic junction which having high traffic load and congestion that caused high emissions.



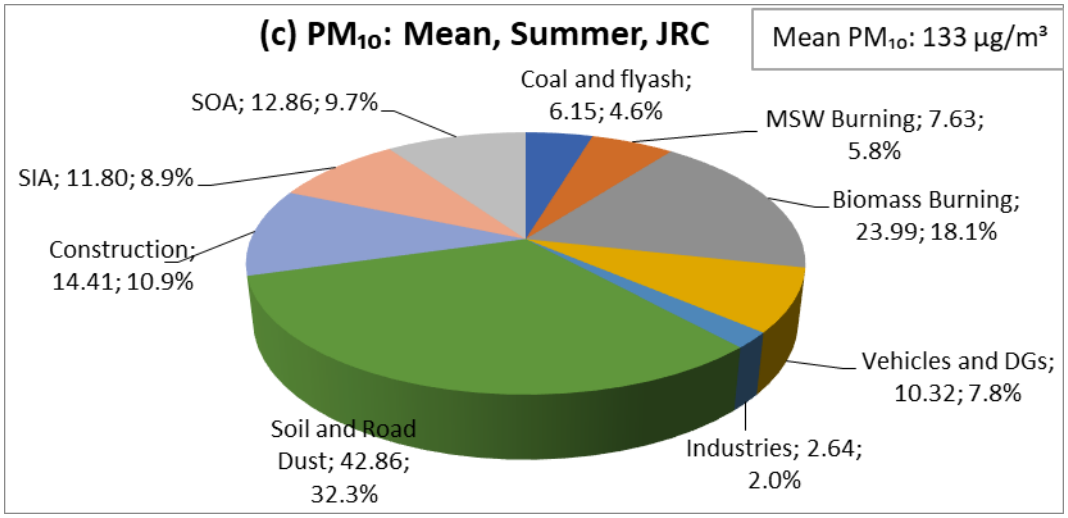
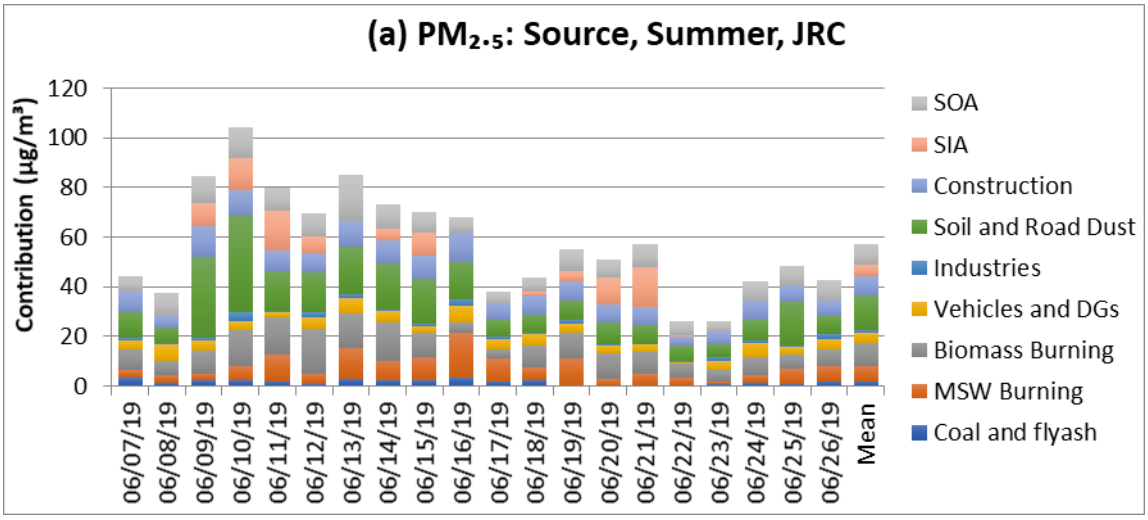
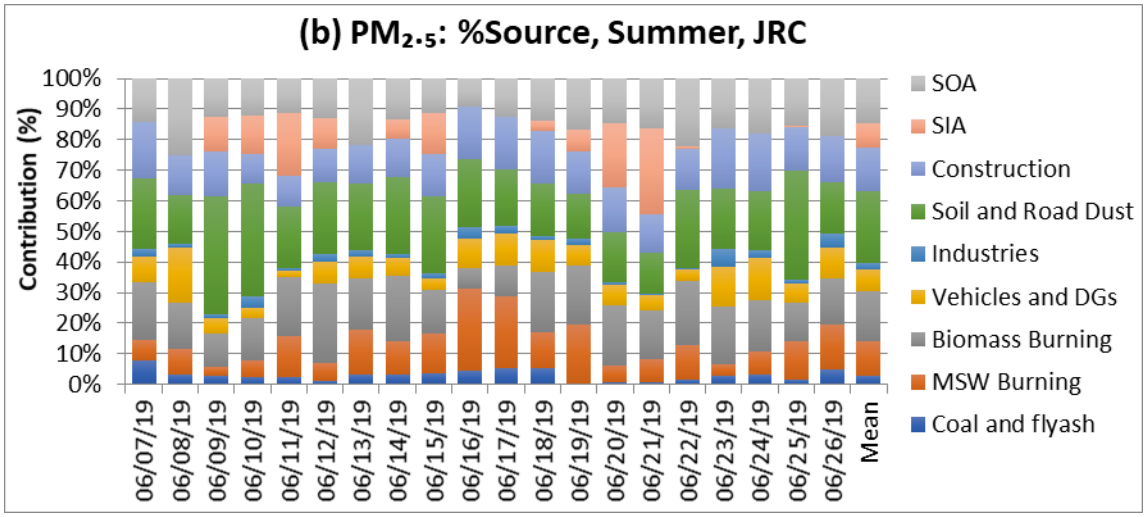


Figure 4.24: PMF modeling for PM_{10} at JRC for summer season





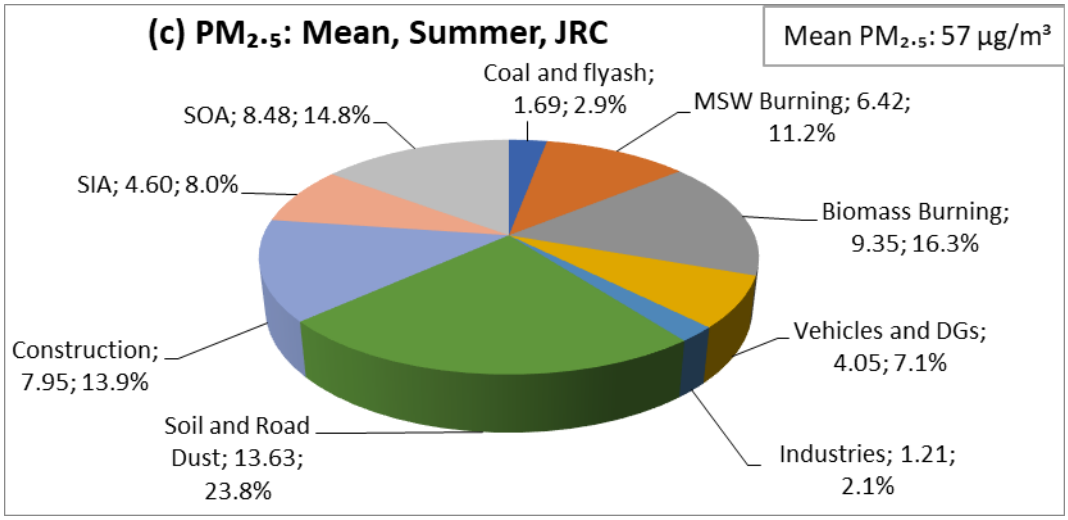


Figure 4.25: PMF modeling for $PM_{2.5}$ at JRC for summer season

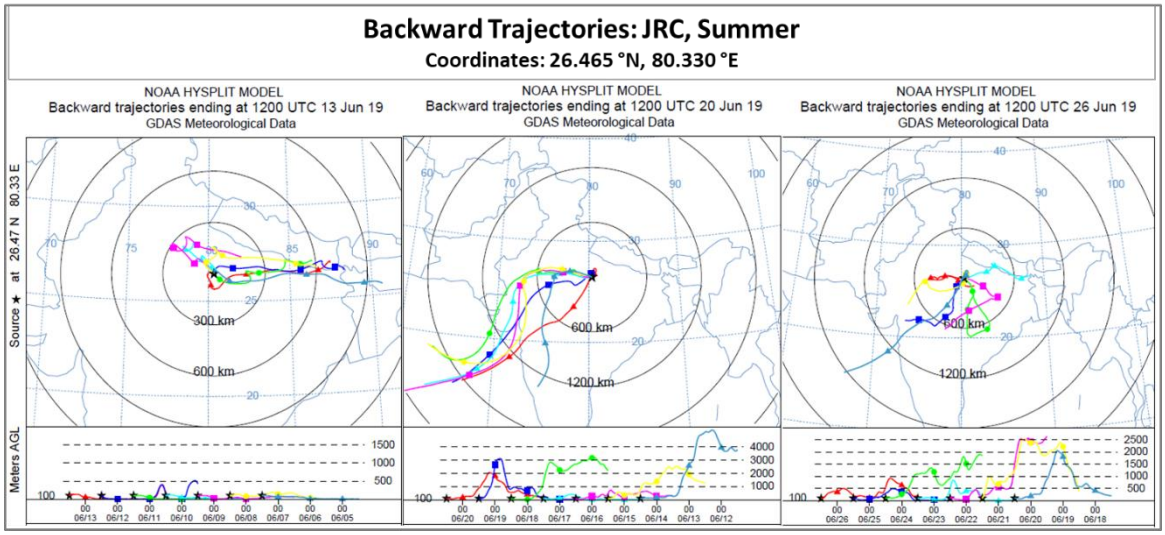


Figure 4.26: Backward trajectories at JRC for summer season

4.3.5 IIT Kanpur (IIT)

4.3.5.1 Winter Season [sampling period: Dec 13, 2018 – Jan 06, 2019]

PM_{10} (winter)

The average PM_{10} concentration was 249 µg/m^3. Figure 4.27 (a), (b), (c) represents PM_{10} contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively at IIT. It is observed that the major PM_{10} source contributing was SIA (114

μg/m^3 ~ 46%) followed by vehicles and DGs (45 μg/m^3 ~ 18%) and SOA (38 μg/m^3~ 15%) The other significant contributing sources are soil and road dust (9.7%), coal and fly ash (4.6%), MSW burning (2.4%), biomass burning (1.9 %) and construction material (1.6%) in PM_{10}. The contribution of industrial emission was lowest at 0.7% in PM_2

$PM_{2.5}$ (winter)

The average $PM_{2.5}$ concentration was 196 μg/m^3 (i.e., about 0.79 of PM_{10}). Figure 4.28 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively at IIT. It is observed that the major source contributing to $PM_{2.5}$ was SIA (95 μg/m^3 ~ 49%) followed by vehicles and DGs (34 μg/m^3 ~ 17%) and SOA (27 μg/m^3 ~ 14%). Other significant sources are soil and road dust (10.7%), MSW burning (2.9%), coal and fly ash (2.6%), biomass burning (1.8%) and construction material (1.4%). The contribution of industrial emission was lowest at 0.9% in $PM_{2.5}$.

HYSPLIT back trajectories (Figure 4.29) show that most of the time wind is mostly from NW and sometimes from east. The wind mass travels over Punjab, Haryana and Rajasthan before entering Kanpur. These winds pick up the pollutants on the way, especially from large sources.

Inference

SIA (46 – 49%) is the major source followed by vehicular contribution (18 – 17%) for both PM_{10} and $PM_{2.5}$. It is a bit surprising that SIA particles have such a high contributor to PM_{10} and $PM_{2.5}$. Contributions of SOA also are high for both PM_{10} and $PM_{2.5}$. The high contribution of SOA and SIA indicates the formation of these particles at long-distanced sources in the upwind direction such as a brick kiln, biomass burning, coal combustion in power plants. Vehicles and DGs also major contributors could be contributed from nearby GT road having high traffic loads.

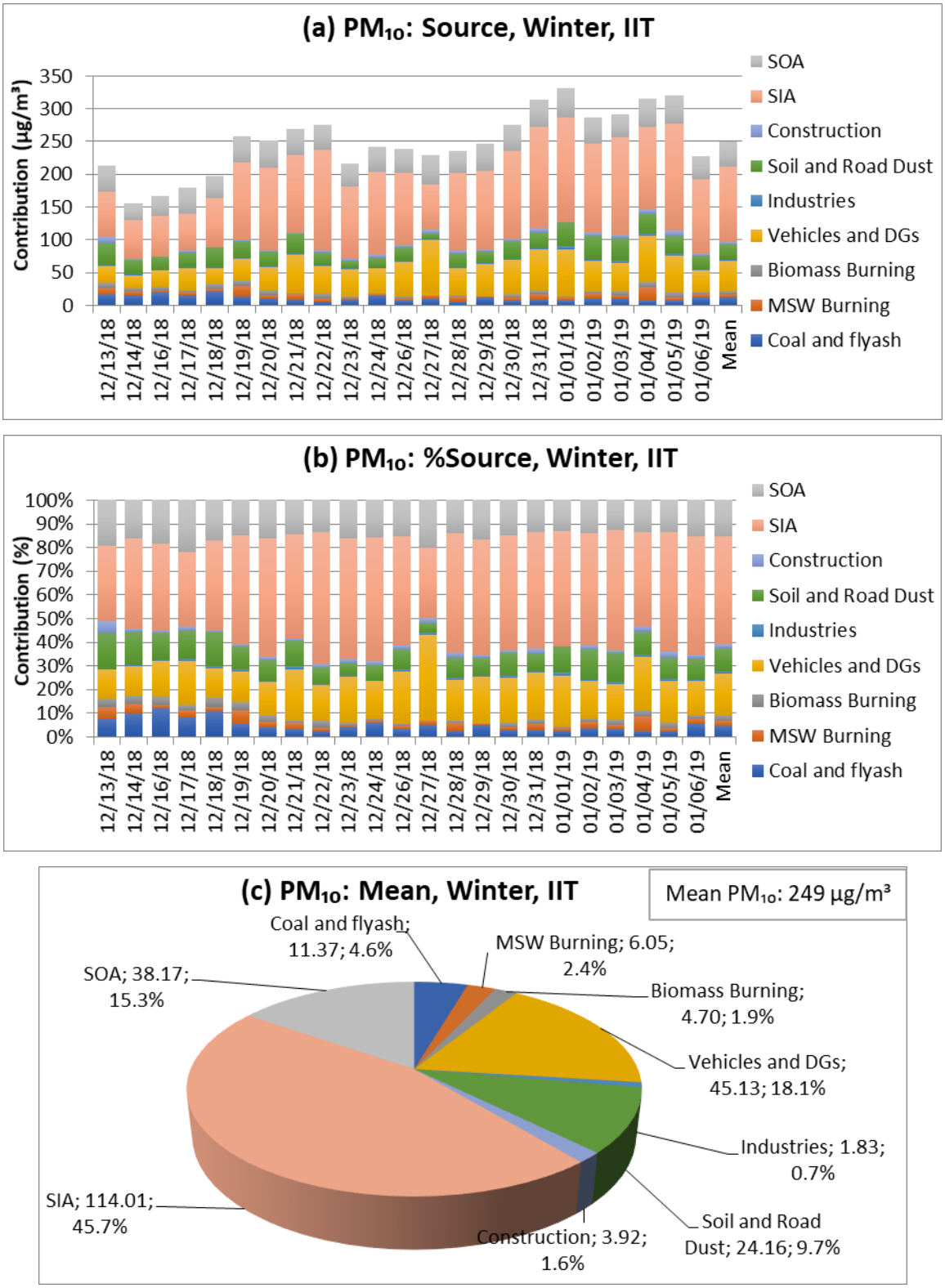


Figure 4.27: PMF modeling for PM_{10} at IIT for winter season

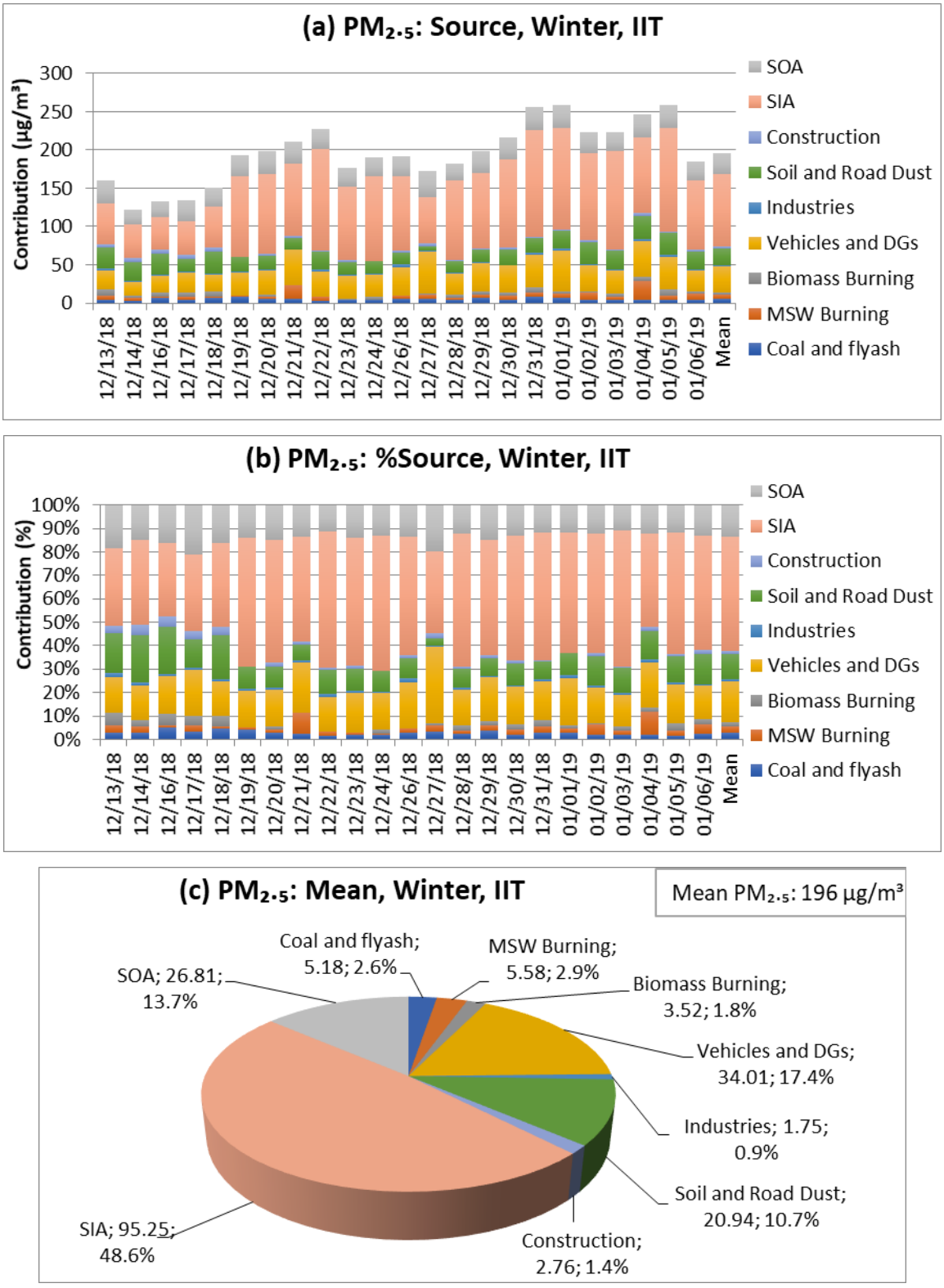


Figure 4.28: PMF modeling for $PM_{2.5}$ at IIT for winter season

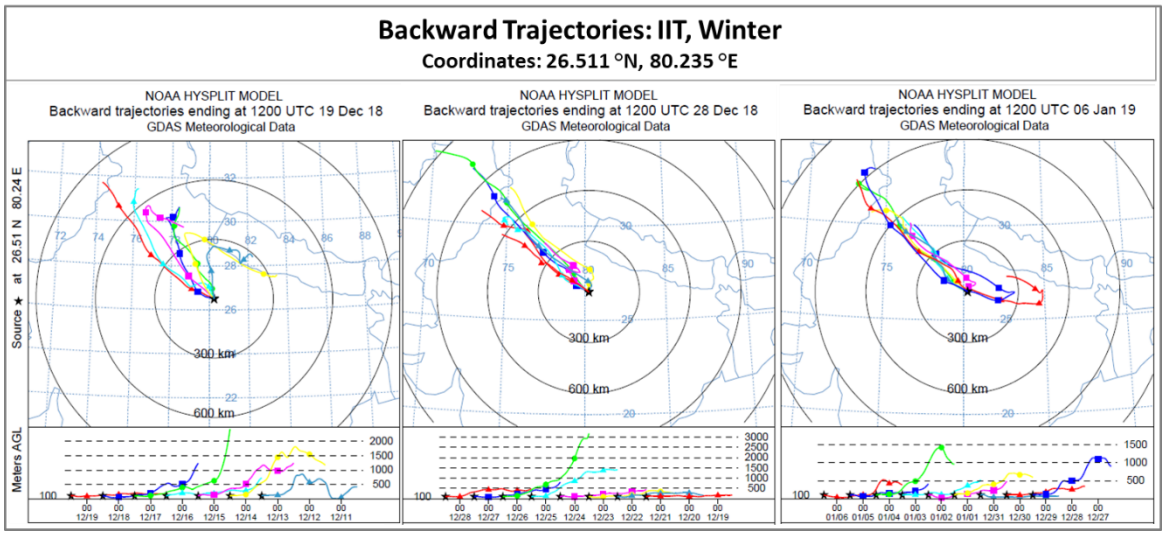


Figure 4.29: Backward trajectories at IIT for winter season

4.3.5.2 Summer Season [sampling period: Mar 26 – Apr 16, 2019]

PM_{10} (summer)

The average PM_{10} concentration was 178 µg/m^3. Figure 4.30 (a), (b), (c) shows PM_{10} concentration contribution of sources, percent contribution of sources and summary of sources (average over about 20 days) at IIT. It is observed that the major PM_{10} source contributing was soil and road dust (87 µg/m^3 ~ 49%) followed by SIA (19 µg/m^3 ~ 10.7%) and SOA (15 µg/m^3 ~ 8.4%). The other significant contributing sources are construction material (8.4%), coal and fly ash (7.3%), biomass burning (6.5%), vehicles and DGs (3.8%), MSW burning (3.2%) and industrial emission (2.8%) in PM_{10}.

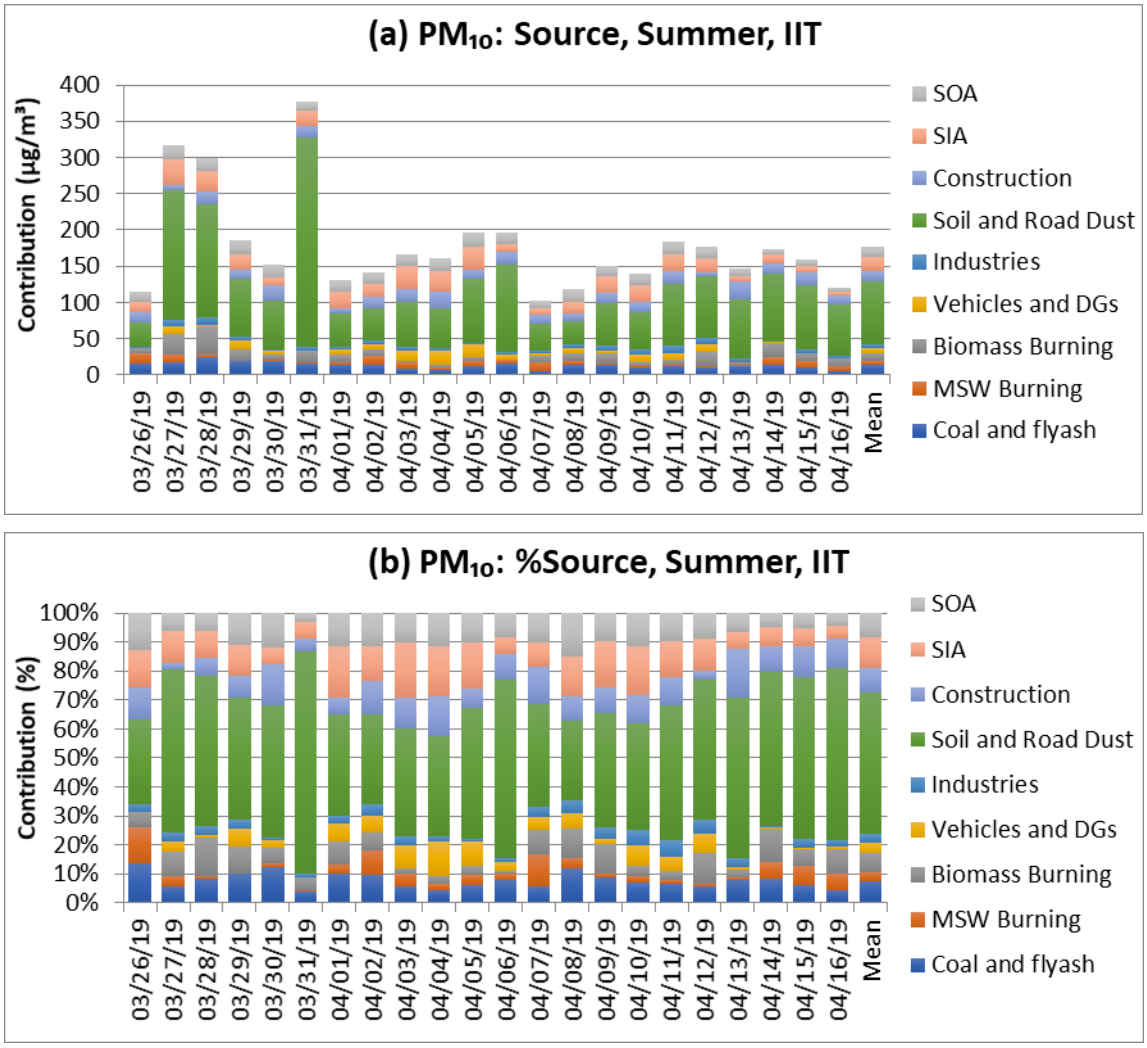
$PM_{2.5}$ (summer)

The average $PM_{2.5}$ concentration was 64 µg/m^3. Figure 4.31 (a), (b), (c) represents $PM_{2.5}$ contribution of sources in terms of concentration, percent contribution of sources and overall contribution (average over about 20 days) in terms of concentration and percentage, respectively at IIT. It is observed that the major source contributing to $PM_{2.5}$ was soil and road dust (10.7 µg/m^3 ~ 16.8%) followed by SOA (10.4 µg/m^3 ~ 16.4%) and SIA (10.3 µg/m^3 ~ 16.1%). Other significant sources are biomass burning (12.5%), construction material (12.0%), coal and fly ash (8.2%), vehicles and DGs (7.9%), MSW burning (7.7%) and industrial emission (2.4%). The contribution of the industrial emission was lowest in $PM_{2.5}$.

HYSPLIT back trajectories (Figure 4.32) show that wind is mostly from NW and partly from the east direction. The wind mass travels over the states of Punjab, Haryana, Rajasthan and the Thar Desert before entering Kanpur. These winds pick up the pollutants on the way, especially from large sources.

Inference

Soil and road dust and construction material are combinedly major contributors in summer both for PM_{10} and $PM_{2.5}$. The loose particles are airborne with high-speed wind from the desert, open barren fields, open dumping sites of fly ash, no control at construction sites caused the high contribution to PM. Secondary particles also the second major contributors to PM_{10} and $PM_{2.5}$ formed from precursor gases (VOCs, SO_2 and NO_2) from long-distanced sources (brick kilns, coal combustions, biomass burning, MSW, etc.).



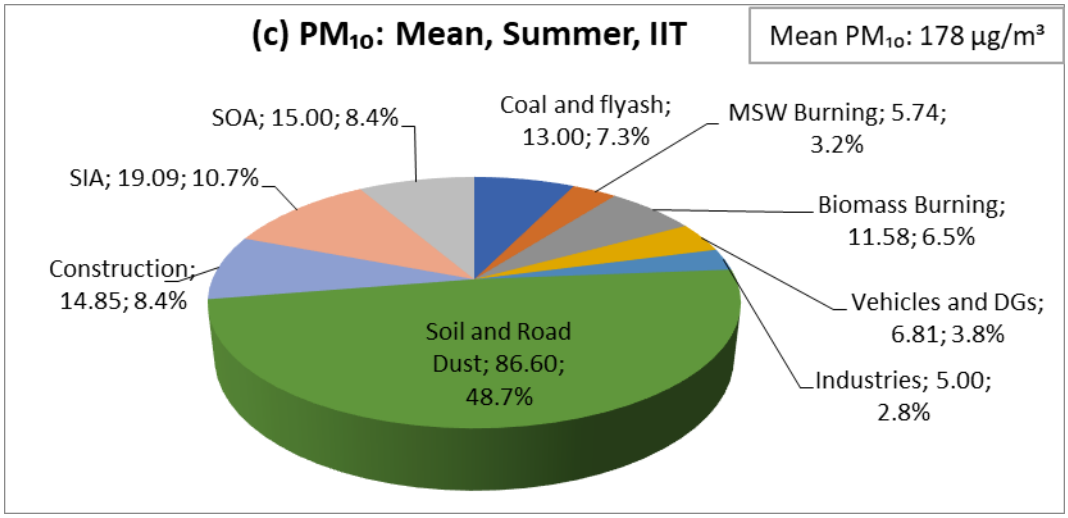
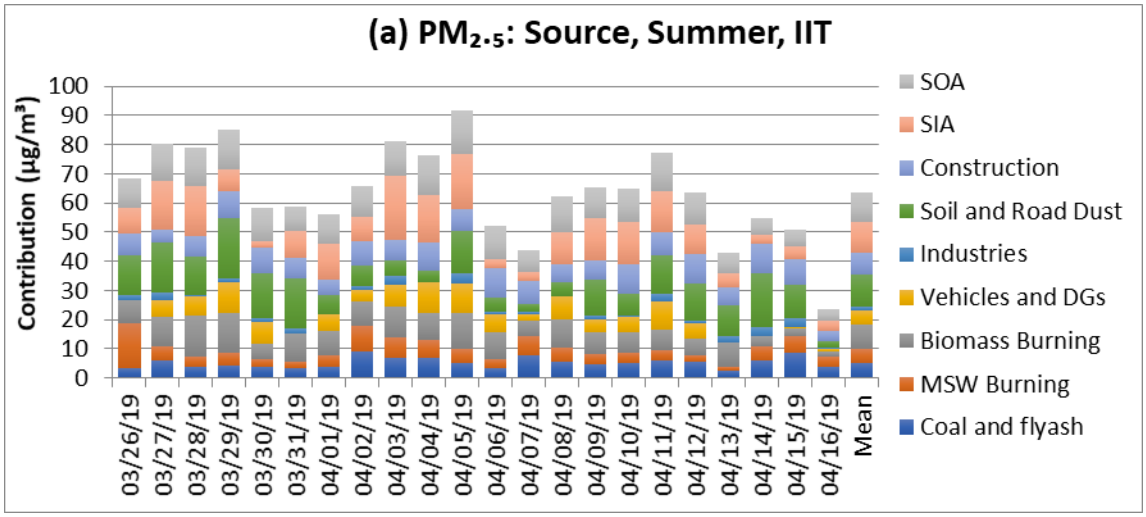
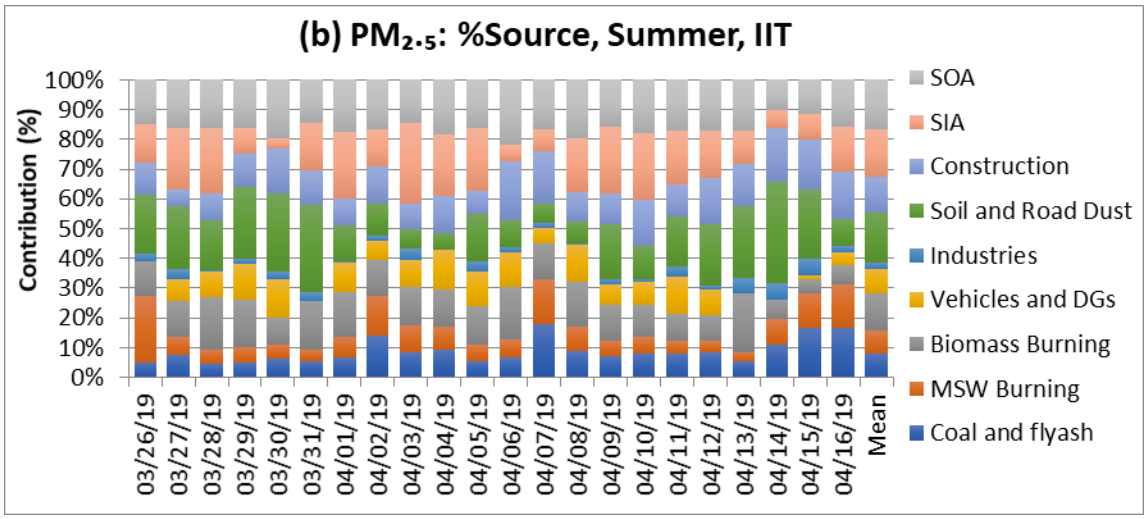


Figure 4.30: PMF modeling for PM_{10} at IIT for summer season





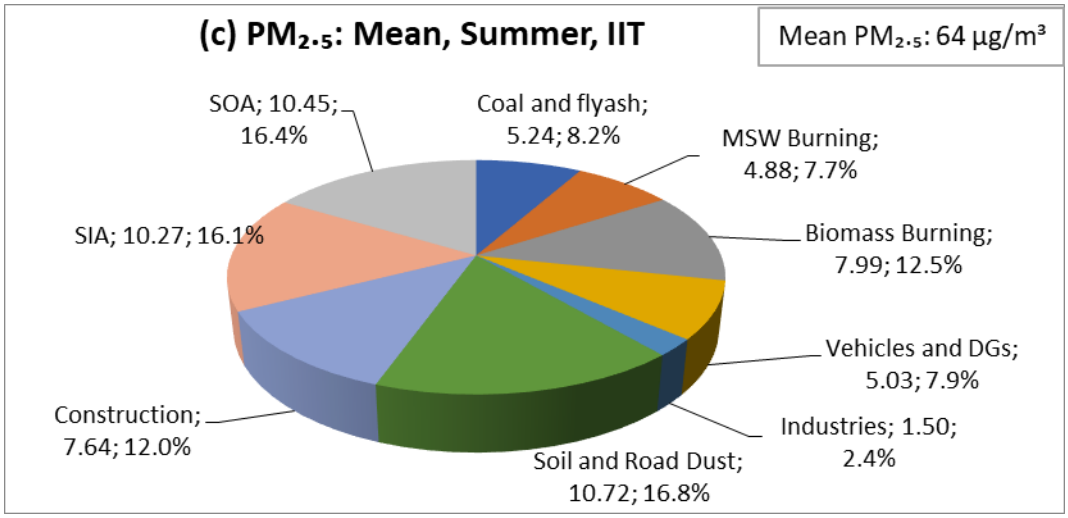


Figure 4.31: PMF modeling for $PM_{2.5}$ at IIT for summer season

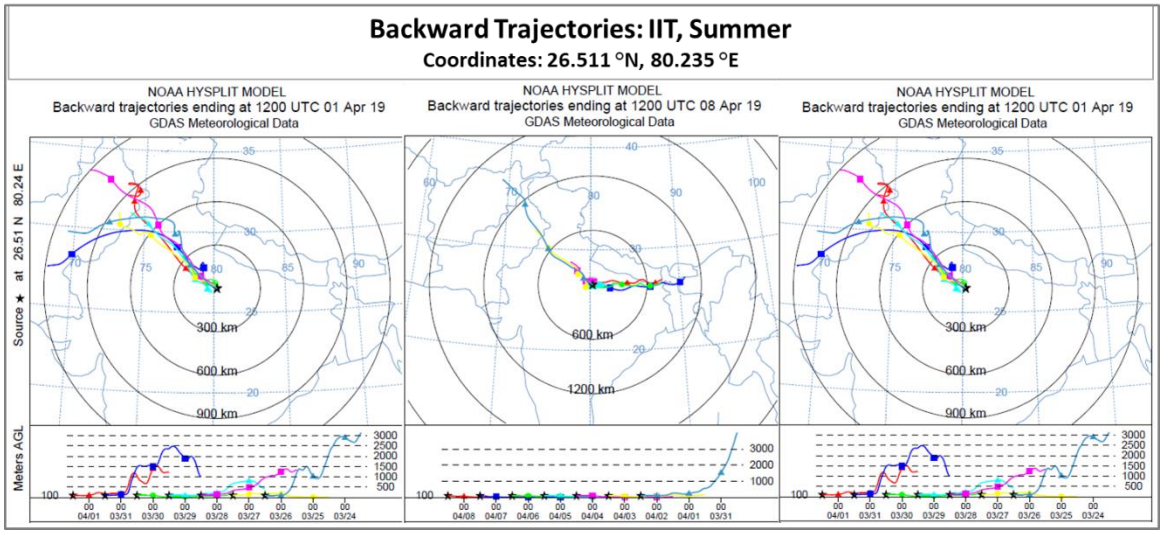


Figure 4.32: Backward trajectories at IIT for summer season

4.4 Long-range transport and contribution

HYSPLIT back trajectories show that most of the time wind is from north-west (winter) and north-west and east (summer) and sometimes from south-west. Wind mass as it travels over some part of Thar desert and states of Punjab, Haryana, Delhi before entering Kanpur may pick up the pollutants on the way, especially from large sources (e.g., soil, brick kilns and CRB) and tall emitting sources (industries and power plants); however, these contributions have not been quantified. There is no assessment made on emissions upstream of Kanpur and their contribution in Kanpur.

4.5 Overall Summary and Source Apportionment at a Glance

The overall summary of PMF modeling results is shown in Figure 4.33 and Figure 4.34. Tables 4.1 - 4.4 provide a summary with overall statistics. The main highlights of PMF results are summarized below.

- Ranges of source contributions to PM_{10} are: soil and road dust (10 – 64%), coal and fly ash (2 – 7%), vehicles and DGs (2 – 31%), MSW burning (2 – 9%), biomass burning (2 – 18%), industrial (1 – 14%), construction material (2 – 14%), secondary inorganic aerosol (SIA; 5 – 46%) and secondary organic aerosol (SOA; 7 – 22%).
- Ranges of source contributions to $PM_{2.5}$ are: soil and road dust (10 – 25%), coal and fly ash (1 – 8%), vehicles and DGs (5 – 36%), MSW burning (3 – 15%), biomass burning (2 – 17%), industrial (1 – 16%), construction material (0.5 – 15%), SIA (8 – 49%) and SOA (12 – 24%).
- The percentage contribution of vehicles and DGs (PM_{10}: 24.5 – 4.5% and $PM_{2.5}$: 29.9 – 7.1%), SIA (PM_{10}: 16.0 – 7.6% and $PM_{2.5}$: 18.7 – 9.7), SOA (PM_{10}: 16.8 – 8.7% and $PM_{2.5}$: 17.9 – 15.5), and industrial (PM_{10}: 5.2 – 3.9% and $PM_{2.5}$: 5.5 – 5.3%) are higher during winter season compared to summer season both in PM_{10} and $PM_{2.5}$.
- The percentage contribution of soil and road dust (PM_{10}: 47.2 – 13.7% and $PM_{2.5}$: 20.3 – 11.7%), construction (PM_{10}: 8.5 – 2.8% and $PM_{2.5}$: 13.5 – 1.1%), coal and fly ash (PM_{10}: 4.6 – 4.3% and $PM_{2.5}$: 3.5 – 3.5%) and biomass burning (PM_{10}: 10.5 – 9.2% and $PM_{2.5}$: 14.8 – 2.9%) are higher during summer season compared to winter season both in PM_{10} and $PM_{2.5}$.
- The percentage contribution of MSW burning is higher during the winter season compared to the summer season in PM_{10} (7.5% – 4.7%) and during the summer season compared to the winter season in $PM_{2.5}$ (10.3 – 8.8%).

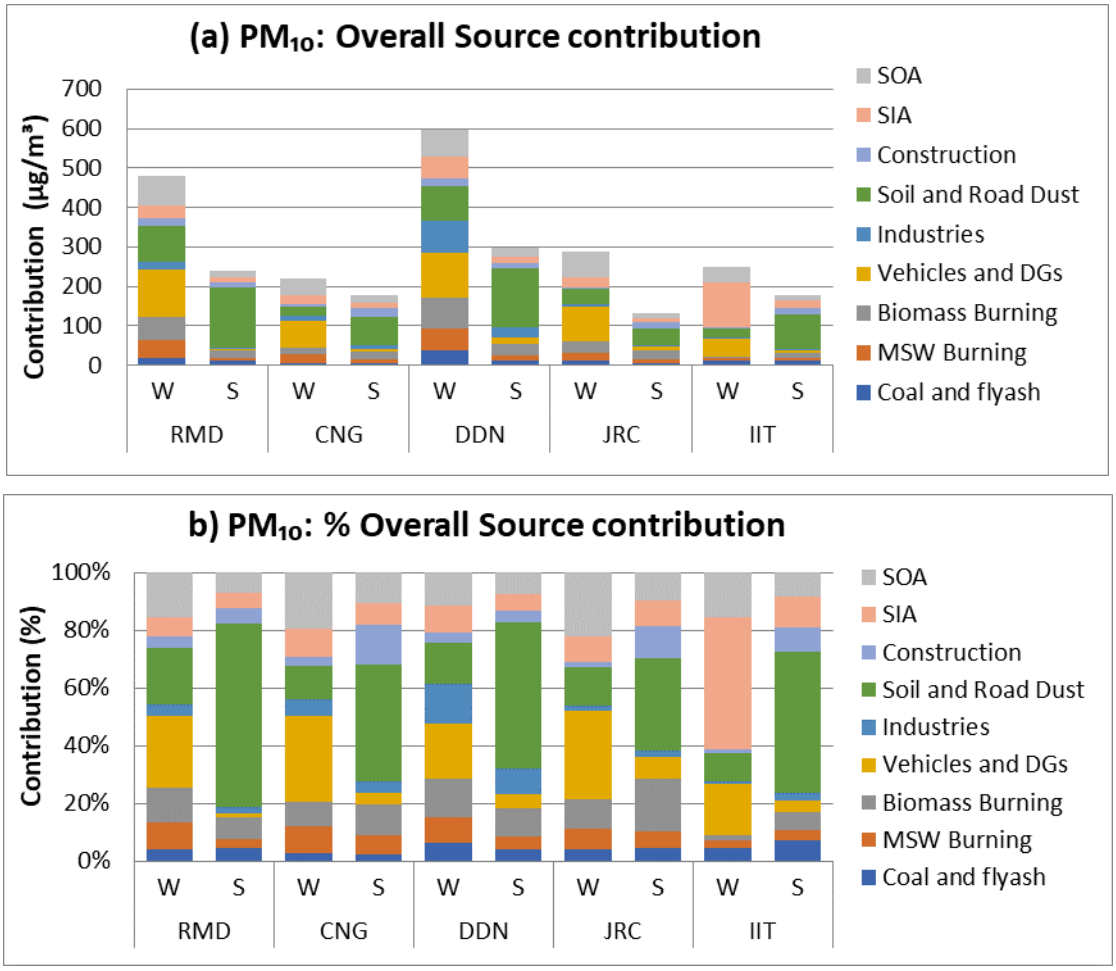
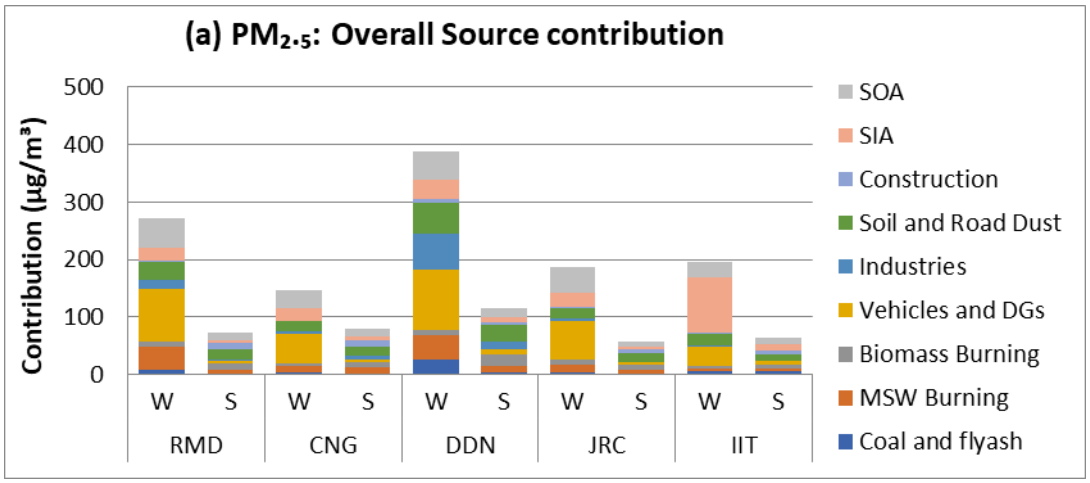


Figure 4.33: Overall results of PMF modeling for PM_{10}



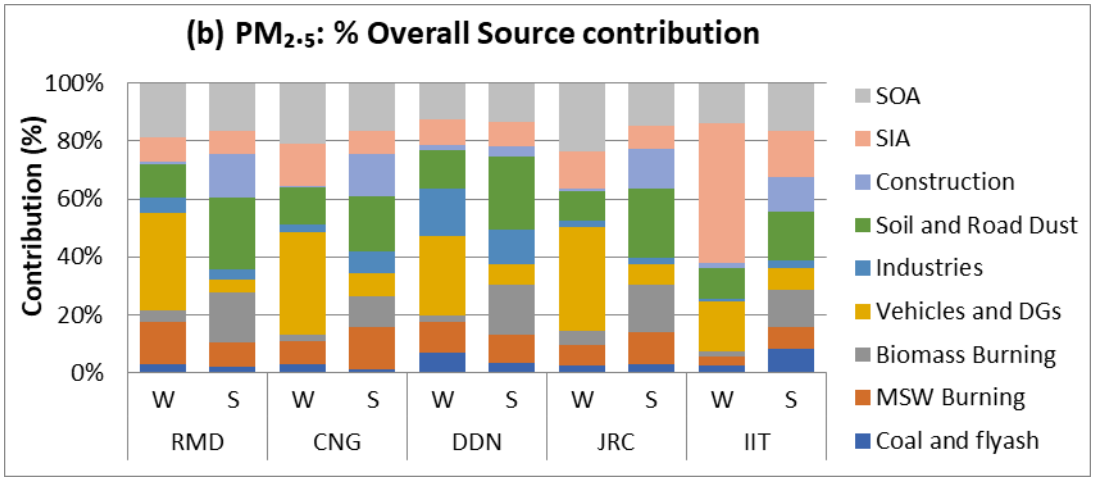


Figure 4.34: Overall results of PMF modeling for $PM_{2.5}$

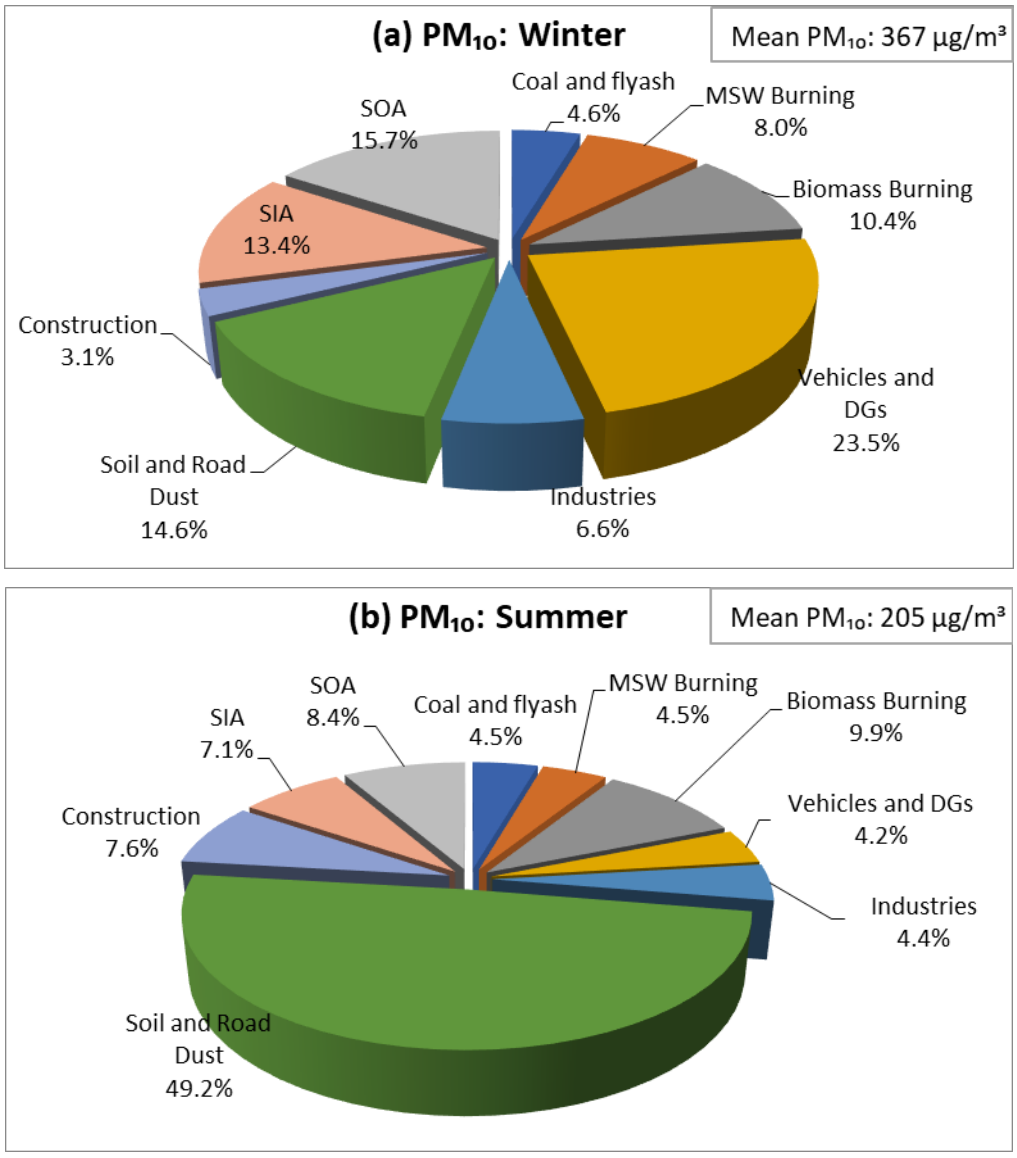


Figure 4.35: Overall source contribution to PM_{10} in (a) winter and (b) summer

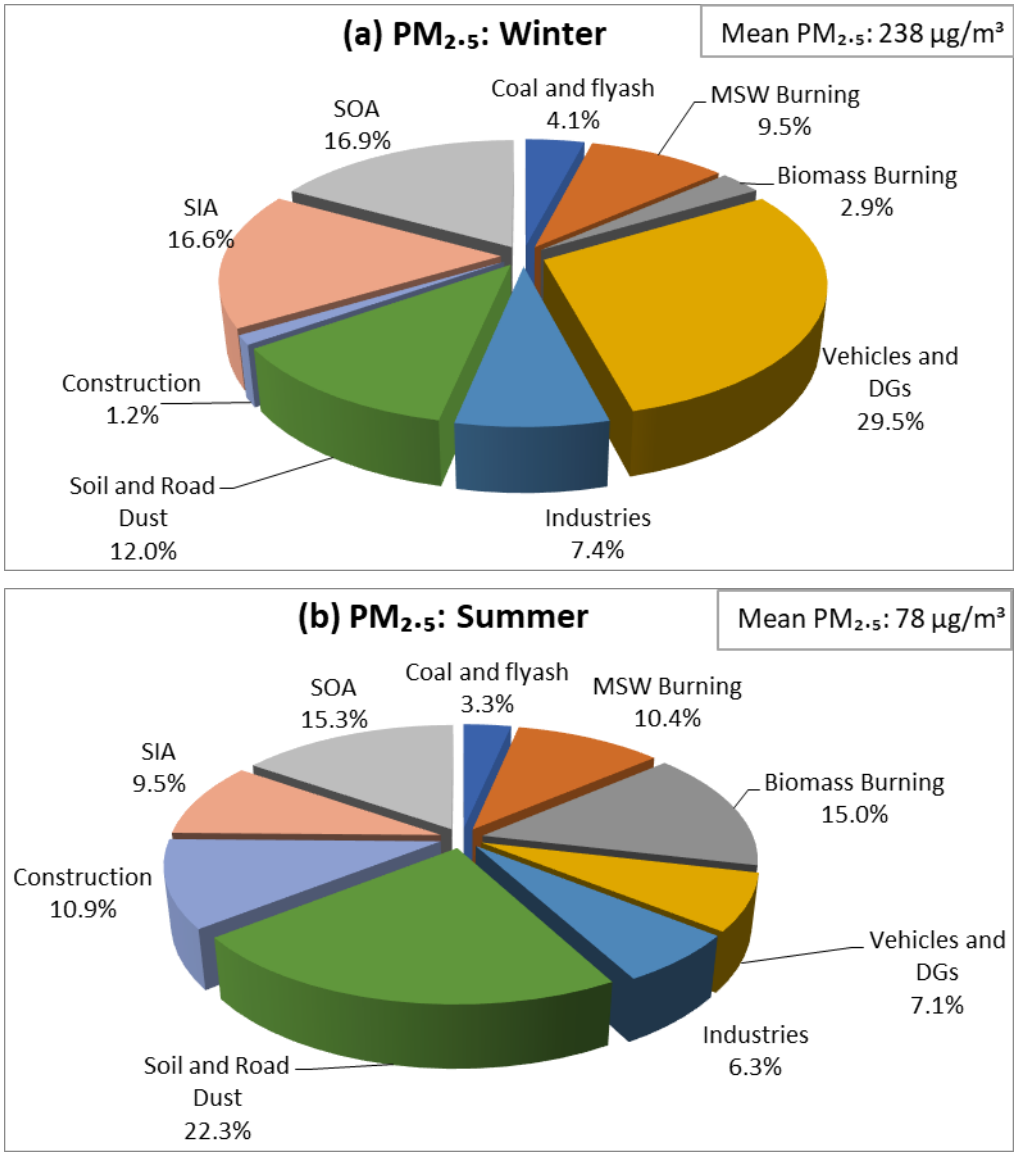


Figure 4.36: Overall source contribution to $PM_{2.5}$ in (a) winter and (b) summer

Table 4.1: Statistical summary of the source apportionment in PM_{10} for winter season

Site location	Parameter	Measured PM_{10} ($\mu g/m^3$)	Calculated PM_{10} ($\mu g/m^3$)	% Mass	% Source Contribution								
					Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	Mean	480	474	101.0	4.0	9.5	11.9	25.1	4.0	19.4	4.0	6.6	15.6
	SD	303	278	8.1	5.4	4.5	7.9	7.0	3.0	9.3	2.1	6.8	5.1
	CV	0.63	0.59	0.08	1.36	0.48	0.67	0.28	0.76	0.48	0.54	1.03	0.32
	Max	1612	1535	114.0	24.7	21.1	42.0	35.9	11.2	36.9	7.6	24.8	25.8
	Min	130	148	79.4	0.0	3.8	2.2	12.3	0.2	0.0	0.0	0.0	8.1
CNG	Mean	220	229	104.5	2.9	9.1	8.7	29.9	5.6	11.4	3.1	9.9	19.4
	SD	121	126	5.1	2.3	5.6	5.3	10.3	3.6	7.3	2.0	7.9	6.7
	CV	0.55	0.55	0.05	0.79	0.62	0.61	0.34	0.64	0.63	0.64	0.80	0.35
	Max	557	576	121.1	9.1	21.2	29.3	51.9	13.5	29.5	8.0	26.6	31.9
	Min	87	89	97.0	0.0	1.2	3.5	11.4	0.6	3.2	0.5	0.0	7.9
DDN	Mean	598	595	100.0	6.1	9.2	13.4	18.8	13.8	14.3	3.7	9.0	11.6
	SD	227	212	5.7	3.1	5.9	4.1	6.0	5.5	6.6	1.4	7.8	3.2
	CV	0.38	0.36	0.06	0.50	0.64	0.31	0.32	0.40	0.46	0.38	0.86	0.28
	Max	1237	1091	109.3	13.9	27.5	18.7	32.1	23.0	27.0	6.1	26.0	19.5
	Min	313	305	86.8	1.9	3.4	4.8	3.5	0.1	3.8	0.3	0.0	4.8
JRC	Mean	287	287	100.3	3.9	7.1	10.2	30.6	1.8	13.6	1.7	8.8	22.1
	SD	86	82	3.3	2.4	5.7	4.5	9.4	1.2	8.1	1.6	5.3	6.8
	CV	0.30	0.29	0.03	0.61	0.80	0.44	0.31	0.68	0.60	0.94	0.60	0.31
	Max	438	436	108.4	9.6	17.4	23.8	42.6	4.2	32.8	6.3	20.9	35.3
	Min	160	153	95.1	0.4	0.0	4.2	5.3	0.0	5.0	0.0	0.7	9.2
IIT	Mean	249	252	101.3	4.6	2.4	1.9	18.1	0.7	9.7	1.6	45.7	15.3
	SD	49	49	3.7	2.9	1.6	1.2	5.2	0.3	3.0	0.9	7.3	2.4
	CV	0.19	0.20	0.04	0.65	0.65	0.62	0.29	0.35	0.31	0.58	0.16	0.15
	Max	331	334	108.3	12.3	6.3	4.1	36.3	1.3	15.5	4.5	55.7	21.8
	Min	156	164	91.7	2.3	0.4	0.0	12.2	0.2	3.9	0.1	29.7	12.4

Table 4.2: Statistical summary of the source apportionment in PM_{10} for summer season

Site location	Parameter	Measured PM_{10} ($\mu g/m^3$)	Calculated PM_{10} ($\mu g/m^3$)	% Mass	% Source Contribution								
					Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	Mean	239	248	104.6	4.7	3.2	7.3	1.6	1.8	63.9	5.2	5.3	7.1
	SD	68	66	4.5	2.6	2.2	2.8	1.5	1.1	8.1	2.2	3.8	2.2
	CV	0.28	0.27	0.04	0.56	0.69	0.38	0.95	0.59	0.13	0.43	0.72	0.32
	Max	384	373	113.1	10.9	8.9	14.4	4.5	4.2	81.4	9.7	14.5	14.4
	Min	131	148	97.2	1.4	0.3	2.4	0.0	0.2	45.8	0.5	0.0	4.0
CNG	Mean	177	182	102.9	2.1	6.7	11.0	3.9	4.0	40.3	13.8	7.5	10.6
	SD	49	51	3.1	2.2	4.4	3.8	3.3	2.1	9.4	3.7	5.1	3.6
	CV	0.28	0.28	0.03	1.03	0.66	0.34	0.84	0.52	0.23	0.27	0.68	0.34
	Max	288	303	110.3	8.0	15.1	20.6	11.1	8.8	61.7	24.9	17.3	17.4
	Min	86	86	98.7	0.0	0.9	4.8	0.0	0.3	26.2	8.5	0.0	1.7
DDN	Mean	297	299	101.2	4.0	4.4	9.6	5.2	8.9	50.6	4.1	5.4	7.6
	SD	68	63	4.3	2.4	3.0	4.1	3.4	3.3	10.7	2.5	4.9	2.1
	CV	0.23	0.21	0.04	0.59	0.68	0.42	0.64	0.37	0.21	0.60	0.92	0.27
	Max	446	425	111.6	12.0	11.0	17.4	12.5	14.9	68.5	9.6	15.4	11.1
	Min	163	181	94.8	0.0	0.6	1.4	1.5	3.4	31.0	1.1	0.0	4.6
JRC	Mean	133	139	105.1	4.6	5.8	18.1	7.8	2.0	32.3	10.9	8.9	9.7
	SD	53	54	5.9	2.3	4.3	7.8	4.0	1.2	11.3	4.5	7.8	3.5
	CV	0.40	0.39	0.06	0.49	0.75	0.43	0.51	0.61	0.35	0.42	0.88	0.36
	Max	234	243	118.2	9.1	18.5	30.5	17.3	3.9	47.3	21.8	23.4	16.5
	Min	61	59	96.6	0.9	0.4	4.1	3.5	0.3	12.9	5.3	0.0	5.5
IIT	Mean	178	181	102.2	7.3	3.2	6.5	3.8	2.8	48.7	8.4	10.7	8.4
	SD	69	69	4.2	2.7	3.4	3.5	3.3	1.4	12.3	3.6	4.6	3.0
	CV	0.39	0.38	0.04	0.37	1.06	0.54	0.86	0.51	0.25	0.43	0.43	0.36
	Max	376	391	108.9	13.6	12.4	13.2	12.0	5.8	76.7	16.8	19.0	14.9
	Min	102	106	95.3	3.9	0.2	0.8	0.0	0.6	27.5	2.4	4.5	3.2

Table 4.3: Statistical summary of the source apportionment in $PM_{2.5}$ for winter season

Site location	Parameter	Measured $PM_{2.5}$ ($\mu g/m^3$)	Calculated $PM_{2.5}$ ($\mu g/m^3$)	% Mass	% Source Contribution								
					Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	Mean	273	274	101.5	2.9	14.8	3.8	33.5	5.4	11.5	1.1	8.0	19.0
	SD	132	125	6.0	1.5	7.1	3.4	8.5	7.0	6.8	2.3	9.3	5.3
	CV	0.48	0.46	0.06	0.50	0.48	0.89	0.25	1.29	0.59	2.06	1.16	0.28
	Max	738	709	111.9	6.6	29.4	11.4	44.8	35.6	28.9	9.7	28.6	30.4
	Min	104	113	90.8	0.5	4.9	0.0	15.7	1.0	2.2	0.0	0.0	11.8
CNG	Mean	146	149	103.8	2.8	8.1	2.1	35.7	2.6	12.7	0.5	14.7	20.8
	SD	102	99	5.2	1.8	5.5	2.6	11.7	1.4	6.5	0.9	10.9	7.2
	CV	0.70	0.67	0.05	0.63	0.67	1.29	0.33	0.55	0.51	1.91	0.74	0.34
	Max	469	454	113.2	8.3	20.0	9.0	55.9	5.9	25.5	3.0	36.3	33.4
	Min	49	55	96.8	0.6	0.4	0.0	12.6	0.8	2.4	0.0	0.0	9.3
DDN	Mean	388	389	100.4	6.9	10.7	2.2	27.4	16.2	13.6	1.5	9.0	12.5
	SD	190	187	3.1	3.2	7.9	2.5	7.9	5.9	8.0	1.4	9.2	3.8
	CV	0.49	0.48	0.03	0.47	0.74	1.13	0.29	0.37	0.59	0.94	1.02	0.30
	Max	1036	1019	106.2	13.6	36.7	7.6	43.0	23.9	33.1	5.4	28.5	21.5
	Min	187	183	95.9	1.8	0.3	0.0	8.4	3.2	3.1	0.0	0.0	5.3
JRC	Mean	186	187	100.4	2.3	7.4	4.8	35.7	2.4	10.1	0.7	12.9	23.7
	SD	46	46	1.9	1.1	6.7	3.4	11.2	1.9	8.8	0.8	7.8	7.0
	CV	0.25	0.25	0.02	0.50	0.91	0.72	0.31	0.80	0.87	1.07	0.60	0.30
	Max	313	311	104.2	5.6	21.6	10.0	51.9	8.6	41.0	2.8	31.6	35.8
	Min	109	108	96.7	0.7	0.0	0.0	6.9	0.0	2.7	0.0	1.3	8.1
IIT	Mean	196	198	101	2.6	2.9	1.8	17.4	0.9	10.7	1.4	48.6	13.7
	SD	40	42	3	1.0	2.3	1.5	3.9	0.4	4.3	1.3	9.2	2.7
	CV	0.20	0.21	0.03	0.37	0.82	0.86	0.22	0.49	0.40	0.94	0.19	0.20
	Max	259	264	107	5.2	9.8	5.1	32.4	2.1	20.4	4.6	58.3	21.0
	Min	122	126	91	1.4	0.5	0.0	13.5	0.5	3.1	0.0	31.4	11.0

Table 4.4: Statistical summary of the source apportionment in $PM_{2.5}$ for summer season

Site location	Parameter	Measured $PM_{2.5}$ ($\mu g/m^3$)	Calculated $PM_{2.5}$ ($\mu g/m^3$)	% Mass	% Source Contribution								
					Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	Mean	73	76	105.5	2.0	8.3	17.3	4.7	3.2	24.7	15.2	8.1	16.4
	SD	20	18	6.9	0.7	4.9	5.0	4.9	2.5	6.3	4.8	7.1	3.9
	CV	0.27	0.23	0.07	0.36	0.59	0.29	1.05	0.79	0.26	0.32	0.87	0.24
	Max	112	112	122.1	3.3	16.9	24.4	15.8	9.7	33.5	24.9	22.4	26.8
	Min	41	50	98.7	0.6	0.8	6.1	0.3	0.0	9.6	9.8	0.0	10.4
CNG	Mean	79	82	104.4	1.1	14.8	10.3	8.3	7.3	19.3	14.6	7.8	16.6
	SD	24	25	5.9	1.2	5.6	4.6	6.8	6.2	8.8	4.4	6.6	6.1
	CV	0.31	0.30	0.06	1.02	0.38	0.44	0.83	0.85	0.46	0.30	0.84	0.37
	Max	157	166	117.6	5.3	24.9	21.4	21.0	28.2	34.1	26.7	19.9	34.1
	Min	37	38	92.9	0.0	4.5	3.3	0.0	1.3	4.2	9.0	0.0	2.4
DDN	Mean	116	120	103.9	3.2	9.7	17.3	7.4	11.7	25.1	3.7	8.5	13.3
	SD	32	33	4.5	1.5	8.4	4.2	4.0	6.2	6.3	4.3	7.8	3.3
	CV	0.28	0.28	0.04	0.47	0.87	0.24	0.53	0.53	0.25	1.16	0.92	0.25
	Max	180	190	115.6	6.4	29.4	23.1	13.2	26.8	37.3	15.3	23.9	22.9
	Min	58	67	99.0	0.8	0.0	4.1	1.2	3.5	13.7	0.0	0.0	7.3
JRC	Mean	57	63	112.3	2.9	11.2	16.3	7.1	2.1	23.8	13.9	8.0	14.8
	SD	21	21	8.2	1.9	6.4	4.5	4.0	1.5	7.2	2.9	8.6	4.1
	CV	0.37	0.33	0.07	0.64	0.57	0.28	0.56	0.69	0.30	0.21	1.07	0.28
	Max	104	107	133.0	7.8	26.6	26.0	17.9	5.9	38.2	19.4	27.9	25.2
	Min	26	28	101.2	0.4	3.0	6.6	2.2	0.3	13.3	9.6	0.0	9.2
IIT	Mean	64	65	102.6	8.2	7.7	12.5	7.9	2.4	16.8	12.0	16.1	16.4
	SD	16	16	4.4	4.1	4.7	3.9	4.7	1.7	8.1	3.8	6.7	2.5
	CV	0.25	0.24	0.04	0.49	0.62	0.31	0.60	0.73	0.48	0.31	0.42	0.15
	Max	92	88	111.0	17.9	22.5	19.8	13.7	5.8	33.7	19.4	27.3	21.8
	Min	24	26	92.9	4.7	3.0	5.0	0.0	0.0	5.2	5.6	3.3	10.3

Table 4.5: Concentration apportionment: winter PM_{10} (Concentration in $\mu g/m^3$)

Site location	PM_{10} ($\mu g/m^3$)	Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	480	19.1	45.4	56.9	120.7	19.1	93.1	19.2	31.6	74.9
CNG	220	6.3	19.9	19.1	66.0	12.3	25.2	6.8	21.8	42.8
DDN	598	36.5	55.0	80.3	112.3	82.7	85.6	22.3	53.9	69.3
JRC	287	11.3	20.5	29.4	87.8	5.1	39.1	5.0	25.4	63.5
IIT	249	11.4	6.0	4.7	45.1	1.8	24.2	3.9	114.0	38.2
Overall	367	16.9	29.4	38.1	86.4	24.2	53.4	11.4	49.3	57.7
SD	164	11.9	20.2	30.4	31.5	33.4	33.4	8.6	38.2	16.3

Table 4.6: Percentage apportionment: winter PM_{10}

Site location	PM_{10} ($\mu g/m^3$)	Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	480	4.0	9.5	11.9	25.1	4.0	19.4	4.0	6.6	15.6
CNG	220	2.9	9.1	8.7	29.9	5.6	11.4	3.1	9.9	19.4
DDN	598	6.1	9.2	13.4	18.8	13.8	14.3	3.7	9.0	11.6
JRC	287	3.9	7.1	10.2	30.6	1.8	13.6	1.7	8.8	22.1
IIT	249	4.6	2.4	1.9	18.1	0.7	9.7	1.6	45.7	15.3
Overall	367	4.3	7.5	9.2	24.5	5.2	13.7	2.8	16.0	16.8
SD	164	1.2	3.0	4.5	5.9	5.2	3.7	1.1	16.7	4.1

Table 4.7: Concentration apportionment: winter $PM_{2.5}$ (Concentration in µg/m^3)

Site location	$PM_{2.5}$ (µg/m^3)	Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	273	7.9	40.3	10.4	91.3	14.8	31.4	3.1	21.9	51.8
CNG	146	4.1	11.9	3.0	52.1	3.8	18.5	0.7	21.5	30.4
DDN	388	26.7	41.6	8.5	106.5	62.8	52.7	5.8	35.1	48.3
JRC	186	4.3	13.7	8.8	66.5	4.4	18.9	1.4	24.1	44.1
IIT	196	5.2	5.6	3.5	34.0	1.7	20.9	2.8	95.3	26.8
Overall	238	9.6	22.6	6.9	70.1	17.5	28.5	2.7	39.6	40.3
SD	96	9.6	17.0	3.4	29.2	25.8	14.5	2.0	31.6	11.1

Table 4.8: Percentage apportionment: winter $PM_{2.5}$

Site location	$PM_{2.5}$ (µg/m^3)	Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	273	2.9	14.8	3.8	33.5	5.4	11.5	1.1	8.0	19.0
CNG	146	2.8	8.1	2.1	35.7	2.6	12.7	0.5	14.7	20.8
DDN	388	6.9	10.7	2.2	27.4	16.2	13.6	1.5	9.0	12.5
JRC	186	2.3	7.4	4.8	35.7	2.4	10.1	0.7	12.9	23.7
IIT	196	2.6	2.9	1.8	17.4	0.9	10.7	1.4	48.6	13.7
Overall	238	3.5	8.8	2.9	29.9	5.5	11.7	1.1	18.7	17.9
SD	96	1.9	4.4	1.3	7.8	6.2	1.4	0.4	17.0	4.8

Table 4.9: Concentration apportionment: summer PM_{10} (Concentration in $\mu g/m^3$)

Site location	PM_{10} ($\mu g/m^3$)	Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	239	11.1	7.6	17.5	3.8	4.4	152.6	12.3	12.6	17.0
CNG	177	3.8	11.9	19.6	7.0	7.0	71.5	24.4	13.2	18.8
DDN	297	12.0	13.2	28.6	15.5	26.4	150.4	12.3	16.0	22.6
JRC	133	6.2	7.6	24.0	10.3	2.6	42.9	14.4	11.8	12.9
IIT	178	13.0	5.7	11.6	6.8	5.0	86.6	14.9	19.1	15.0
Overall	205	9.2	9.2	20.2	8.7	9.1	100.8	15.6	14.5	17.3
SD	64	4.0	3.2	6.5	4.5	9.8	48.9	5.0	3.0	3.7

Table 4.10: Percentage apportionment: summer PM_{10}

Site location	PM_{10} ($\mu g/m^3$)	Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	239	4.7	3.2	7.3	1.6	1.8	63.9	5.2	5.3	7.1
CNG	177	2.1	6.7	11.0	3.9	4.0	40.3	13.8	7.5	10.6
DDN	297	4.0	4.4	9.6	5.2	8.9	50.6	4.1	5.4	7.6
JRC	133	4.6	5.8	18.1	7.8	2.0	32.3	10.9	8.9	9.7
IIT	178	7.3	3.2	6.5	3.8	2.8	48.7	8.4	10.7	8.4
Overall	205	4.6	4.7	10.5	4.5	3.9	47.2	8.5	7.6	8.7
SD	64	1.9	1.6	4.6	2.3	2.9	11.9	4.0	2.3	1.5

Table 4.11: Concentration apportionment: summer $PM_{2.5}$ (Concentration in µg/m^3)

Site location	$PM_{2.5}$ (µg/m^3)	Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	73	1.5	6.0	12.6	3.4	2.3	17.9	11.0	5.9	11.9
CNG	79	0.9	11.7	8.1	6.6	5.8	15.3	11.5	6.1	13.1
DDN	116	3.7	11.3	20.1	8.6	13.6	29.2	4.3	9.8	15.4
JRC	57	1.7	6.4	9.3	4.0	1.2	13.6	7.9	4.6	8.5
IIT	64	5.2	4.9	8.0	5.0	1.5	10.7	7.6	10.3	10.4
Overall	78	2.6	8.1	11.6	5.5	4.9	17.3	8.5	7.3	11.9
SD	23	1.8	3.2	5.1	2.1	5.2	7.1	2.9	2.5	2.6

Table 4.12: Percentage apportionment: summer $PM_{2.5}$

Site location	$PM_{2.5}$ (µg/m^3)	Coal and flyash	MSW Burning	Biomass Burning	Vehicles and DGs	Industries	Soil and Road Dust	Construction	SIA	SOA
RMD	73	2.0	8.3	17.3	4.7	3.2	24.7	15.2	8.1	16.4
CNG	79	1.1	14.8	10.3	8.3	7.3	19.3	14.6	7.8	16.6
DDN	116	3.2	9.7	17.3	7.4	11.7	25.1	3.7	8.5	13.3
JRC	57	2.9	11.2	16.3	7.1	2.1	23.8	13.9	8.0	14.8
IIT	64	8.2	7.7	12.5	7.9	2.4	16.8	12.0	16.1	16.4
Overall	78	3.5	10.3	14.8	7.1	5.3	21.9	11.9	9.7	15.5
SD	23	2.8	2.8	3.2	1.4	4.1	3.7	4.7	3.6	1.4

4.6 Interpretations and Inferences

Based on the PMF modeling results (Figures 4.33 to 4.36) and their critical analyses, the following inferences and insights are drawn to establish quantified source-receptor impacts and pave the path for preparing an action plan. Tables 4.5 to 4.12 show season-wise, site-specific average source contribution to PM_{10} and $PM_{2.5}$, and these tables are frequently referred to bring the important inferences to the fore.

- The sources of PM_{10} and $PM_{2.5}$ contributing to ambient air quality are different in summer and winter.
    - In winter, % contribution of PM_{10} – $PM_{2.5}$ sources (given in parenthesis) to the ambient air level are: vehicles and DGs (24.5 – 29.9%), secondary organic aerosol (SOA; 16.8 – 17.9%), secondary inorganic aerosol (SIA; 16.0 – 18.7%), soil and road dust (13.7 – 11.7%), coal and fly ash (15 – 16%; includes ash from burning of residual oil), biomass burning (9.2 – 2.9%), MSW burning (7.5 – 8.8%), industrial (5.2 – 5.5%) and construction material (2.8 – 1.1%). It is noteworthy, in winter, major sources for PM_{10} and $PM_{2.5}$ are generally the same.
    - In summer, % contribution of PM_{10} - $PM_{2.5}$ sources (given in parenthesis) to the ambient air level are: soil and road dust (47.2 – 21.9%), biomass burning (10.5 – 14.8%), construction (8.5 – 11.9%), SOA (8.7 – 15.5%), SIA (7.6 – 9.7%), MSW burning (4.7 – 10.3%), vehicles and DGs (4.5 – 7.1%), industrial (3.9 – 5.3%), and coal and fly ash (4.6 – 3.5%; includes burning of residual oil). It is noteworthy, in summer also, the major sources for PM_{10} and $PM_{2.5}$ are generally the same.
- The most consistent sources for PM_{10} and $PM_{2.5}$ in both seasons are SOA, and vehicles and DGs. The other sources on average may contribute more (or less), but their contributions are variable from one day to another.
- The high presence of soil and dust, construction, MSW burning, biomass burning and vehicles (in PM_{10}) at most the sites envelop the entire region.
- In summer, soil and road dust, coal and fly ash and construction activities contribute 60% to PM_{10} and 37% to $PM_{2.5}$. It is observed that in summer, the atmosphere looks brownish indicating the presence of large amounts of dust. In winter, the contributions of coal and fly ash, soil and road dust and construction material reduce significantly

both in PM_{10} and $PM_{2.5}$ (by 21 and 16%) when winds are low and prevalent atmospheric conditions are calm.

- Vehicles and DGs (including domestic) is the highest contributing source that indicates the slow-moving traffic with high congestions on the major roads.
- SIA and SOA are the most significant contributors to PM_{10} and $PM_{2.5}$. High and consistent contributions of secondary aerosols suggest the high emissions of precursors gases from different sectors, i.e., combustion sources, industries, brick kilns, biomass, MSW burning, domestic at far distances at regional levels from the receptor sites.
- The contribution of the biomass burning in summer is at 15% (for $PM_{2.5}$) and 11% (for PM_{10}) and in winter at 9% (for PM_{10}) and 3% (for $PM_{2.5}$). The presence of sizeable biomass is inconsistent in winter and summer, indicates the contribution from nearby areas and is impacted by meteorology.
- The contribution of MSW burning is higher in the summer than in the winter. In winter, the contribution of MSW burning is very high at RMD in PM_{10} – $PM_{2.5}$ (9.5 – 14.8%) followed by DDN (9.2 – 10.7%). In summer, contribution of MSW burning varied 3 - 7% in PM_{10} and 8 - 15% in $PM_{2.5.}$
- The Industrial contribution is high in winter months (5.2 – 5.5%) in PM_{10} − $PM_{2.5}$. The maximum contribution was in winter at DDN, (an industrial site); $PM_{2.5}$ (16.2%) and PM_{10} (13.8%). It is also highest at DDN in summer.

Directions for PM control

- Soil and road dust

  In summer, this source contributes about 47% to PM_{10}. The silt load on most of the roads is very high and silt can become airborne with the movement of vehicles. The estimated PM_{10} emission from road dust is about 87 tons per day. Similarly, soil from the open fields gets airborne in summer. The potential control options can be sweeping and watering of roads, better construction and maintenance, growing plants, grass, etc., to prevent re-suspension of dust.

- Vehicular and DG sets pollution

  This source is the largest source in winter and the most consistently contributing source to PM_{10} and $PM_{2.5}$ in winter and summer. Various control options include

the implementation of BS-VI, introduction of electric and hybrid vehicles, traffic planning and restriction of movement of vehicles, retro-fitment in diesel exhaust, improvement in public transport, etc. These options are further discussed in Chapter 6.

- Coal and fly ash

  Coal and fly ash contribute about 4% to PM_{10} and unless sources contributing to fly ash are controlled, one cannot expect improvement in air quality. It appears these sources are more fugitive than regular point sources. Fly ash emissions from hotels, restaurants, tandoors and brick kilns within a 50 km radius also cause large emissions and require better housekeeping, fly ash disposal and improved zigzag technologies in brick kilns.

- Biomass burning

  Biomass burning should be minimized if not completely stopped. Possibly, it could be switched to cleaner fuel for domestic fuel, local bakeries and hotels, industries, and other local thermal energy-consuming industries. All biomass burning in Kanpur should be banned and strictly implemented.

- MSW burning

  One of the reasons for the burning of MSW/plastic waste is the lack of infrastructure for timely collection of MSW and people conveniently burn or it may smolder slowly for a long time. In this regard, infrastructure for collection and disposal of MSW has to improve and the burning of MSW should be completely banned.

- Industrial sources

  The industrial unit in the DDN must comply with the norms notified by the government. There might be some unauthorized industries in the surroundings of DDN and RMD that must be enforced to close such units. At DDN, a significant contribution is from lead smelting industries having high uncontrolled emissions. These industries must comply the norms and shift to other industrial clusters outside the city in a phased manner.

- Secondary particles

What are the sources of secondary particles (organic and inorganic), the major contributors to Kanpur's PM? These particles are expected to source from precursor gases (organic gases, SO_2 and NO_x) which are chemically transformed into particles in the atmosphere. Mostly the precursor gases are emitted from far distances from large sources. For sulfates, the major contribution can be attributed to large power plants, refineries and brick kilns. However, the contribution of NO_x from local sources, especially vehicles and power plants can also contribute to nitrates. VOCs are the major Emissions from coal combustion, biomass burning, MSW burning, solvent uses, fueling stations, vehicles, DGs are the major contributors to form organic aerosol. Behera and Sharma (2010) for Kanpur have concluded that secondary aerosol (SIA and SOA) accounted for a significant mass of $PM_{2.5}$ (about 47% - 50% with SIA 32 – 33%). Any particulate control strategy should also include control of primary precursor gases.

The effectiveness of the pollution control options and selection of an optimal mix of control options are analyzed in Chapter 6.

5 Dispersion Modeling

5.1 Introduction

The current state-of-the-science, comprehensive meteorological and regulatory air dispersion modeling systems have been used in the study to conduct the dispersion modeling. The American Meteorological Society / Environmental Protection Agency Regulatory Model (AERMOD) has been used to assess the impact from short-range transport (<50 km) on $PM_{2.5}$ emitting from the sources within the Kanpur City,

5.1.1 AERMOD

AERMOD is a dispersion model having the ability to characterize the planetary boundary layer (PBL) through both surface and mixed layer scaling. This model is a complete and powerful air dispersion modeling package that seamlessly incorporates the following popular United States Environmental Protection Agency (EPA) air dispersion models into one integrated interface:

- AERMOD
- ISCST3
- ISC-PRIME

The AERMOD modeling system consists of one main program (AERMOD) and two pre-processors (AERMET and AERMAP). AERMOD uses terrain, boundary layer, and source data to model pollutant transport and dispersion for calculating temporally averaged air pollution concentrations.

The approach for modeling using AERMOD is shown in Figure 5.1. Onsite hourly meteorological data was generated by the WRF model. The model run was performed for a defined study period (the year 2018). The output of the WRF model was fed as the input of AERMOD in the pre-processor RAMMET and AERMET of the model. The observed meteorological data was collected from the UPPCB monitoring station located at Sanjay Palace, Kanpur and compared with the WRF results for validation.

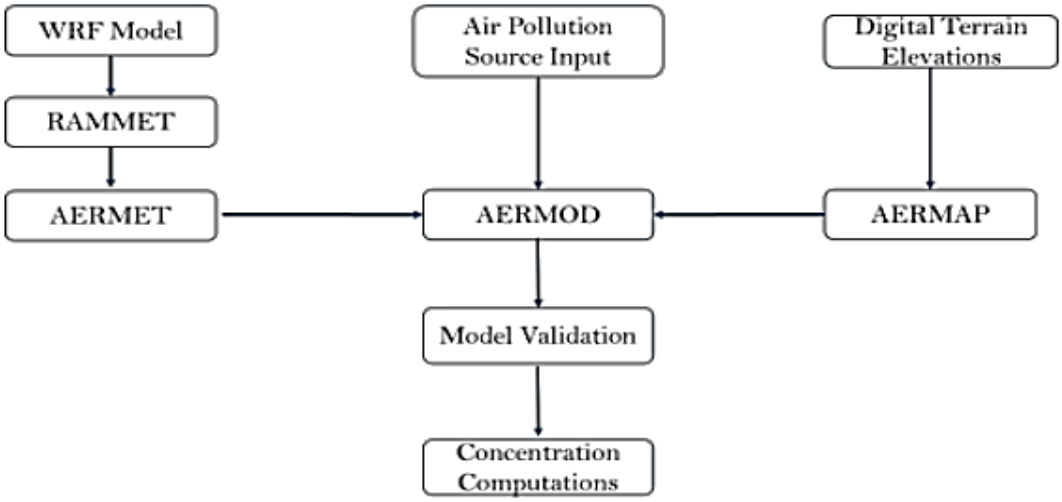


Figure 5.1: Approach for Dispersion Modelling using AERMOD

The meteorological parameters from the WRF model (wind speed, wind direction, rainfall, temperature, humidity, pressure, ceiling height, global horizontal radiation, and cloud cover) with one-hour resolution were organized in a spreadsheet. This spreadsheet was reprocessed in AERMET, which is the meteorological pre-processor of AERMOD. The terrain data at 90 m resolution of Shuttle Radar Topography Mission (SRTM) was used in AERMAP, which is also the pre-processor of AERMOD. This provided a physical relationship between terrain features and the behaviour of air pollution plumes and generated location and height data for each receptor location. AERMOD was further used to model air quality in the study for the prediction of pollutants concentration from different sources within Kanpur City.

5.2 Meteorological Data

In evaluating the emission dispersion using the AERMOD, the meteorological dataset was generated using the WRF model (version 3.6.1) (Wang et al., 2007; Peckham et al., 2015) from January 01, 2018, to December 31, 2018. The frequency distribution and frequency count data were obtained by processing the hourly surface file in AERMET. The AERMET program is a meteorological pre-processor that prepares hourly surface data and upper-air data for use in the USEPA air quality dispersion model, AERMOD.

The wind rose plots for all months of 2018 are shown in Figure 5.2. The predominant wind blowing direction was observed to be northwest in all the months. Also, a relatively high wind speed was observed in the summer season.

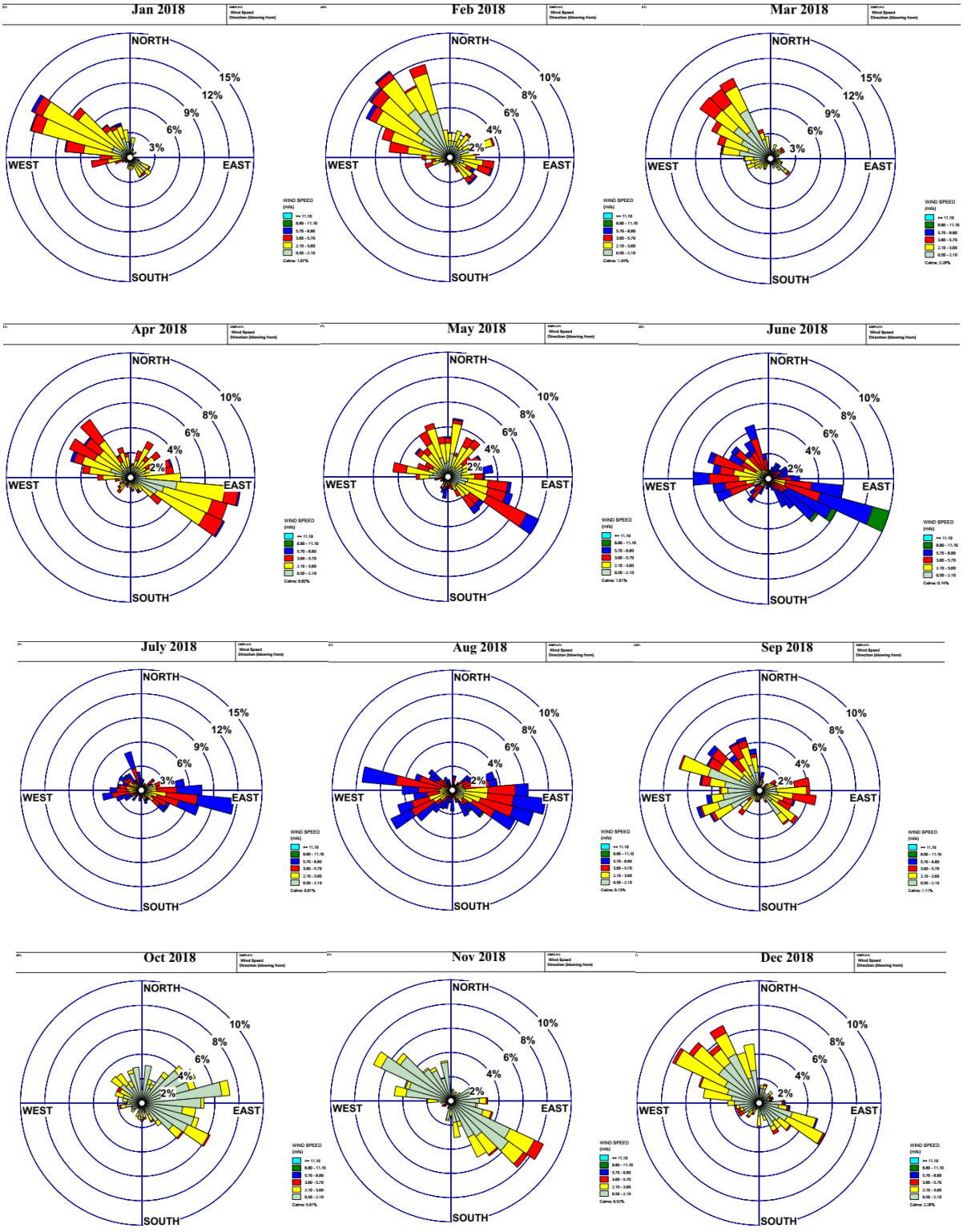


Figure 5.2: Wind Rose Plots for months of 2018

The modeled wind speed and ambient temperature data were validated using the data obtained from the UPPCB's ambient air quality monitoring station located at Nehru Nagar, Kanpur. In addition, the 24-hour moving average from hourly wind speed data for all months, 2018 was also plotted (Figure 5.3).

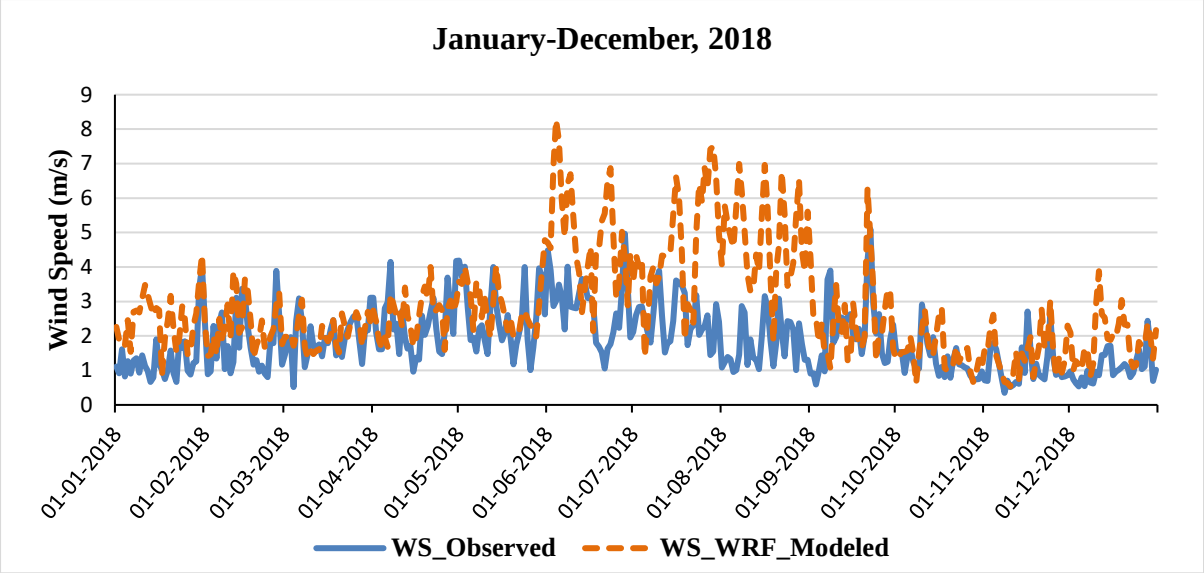


Figure 5.3: Time-Series Plot of 24-hour mean WS (Observed vs. Modeled) for 2018

The Pearson's correlation coefficient (r), normalized mean square error (NMSE), and fractional bias (FB) were calculated for winter and summer month's hourly wind speed data to assess the model performance (Table 5.1). The quality of an ideal and perfect model is to have both the fractional bias and normalized mean square error equal to zero. The performance of a model can be deemed as acceptable if, NMSE ≤ 0.5, and -0.5 ≤ FB ≤ +0.5.

Table 5.1: Statistical summary of wind speed for WRF validation

Months	Observed (m/s)	Modeled (m/s)	NMSE	FB	R
January	1.34	2.45	0.50	-0.59	0.61
February	1.81	2.29	0.19	-0.23	0.56
March	1.95	2.08	0.06	-0.07	0.55
April	2.29	2.61	0.13	-0.13	0.33
May	2.50	2.50	0.12	-0.14	0.46
June	2.84	4.93	0.55	-0.54	-0.14
July	2.51	4.57	0.65	-0.58	-0.08
August	1.77	4.81	1.25	-0.92	0.28
September	2.15	2.50	0.34	-0.15	0.27
October	1.29	1.52	0.16	-0.16	0.49
November	1.11	1.53	0.40	-0.32	0.59
December	1.08	1.88	0.53	-0.54	0.35

The model performed satisfactorily for predicting wind speeds in the months of February, March, April, May, September, October and November while overestimating the wind speeds

in January, June, July, August and December. Furthermore, the time-series plot of observed 24 hourly ambient temperature values with modeled values shows a good agreement for all months except winter seasons 2018, which are shown in Figure 5.4. The statistical parameters assessing the performance of the model are listed in Table 5.2.

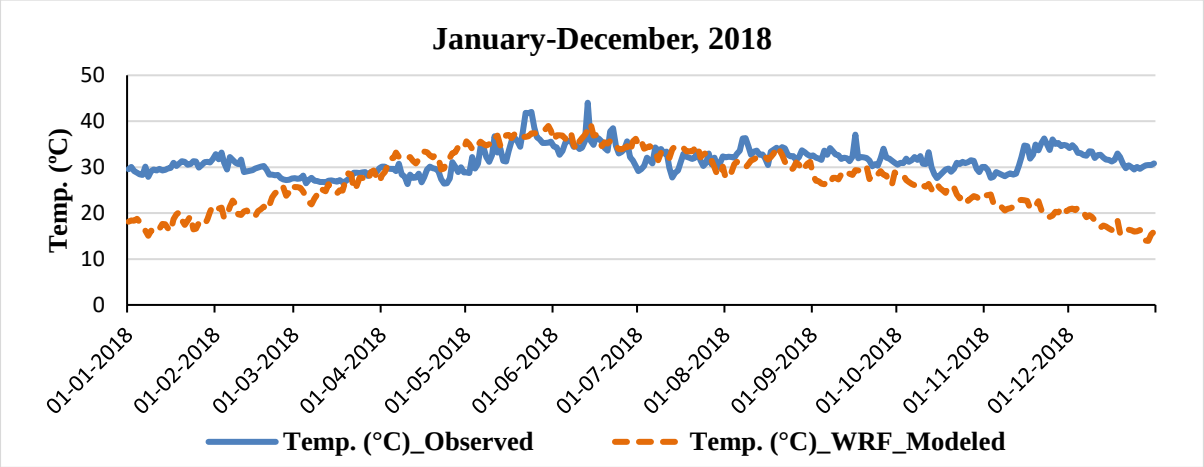


Figure 5.4: Time-Series Plot of Ambient Temperature Data for 2018

Table 5.2: Statistical summary of ambient temperature for WRF validation

Months	Temp.(°C) Observed	Temp.(°C) WRF Modeled	NMSE	FB	R
January	30.05	17.76	0.29	0.51	0.48
February	29.69	21.78	0.12	0.31	-0.59
March	27.71	25.79	0.01	0.07	0.56
April	28.79	32.00	0.01	-0.11	0.15
May	34.62	34.62	0.01	-0.05	0.56
June	34.87	35.81	0.00	-0.03	0.38
July	31.42	32.97	0.01	-0.05	-0.12
August	33.11	30.98	0.01	0.07	0.15
September	32.23	28.08	0.02	0.14	-0.04
October	30.48	25.30	0.04	0.19	0.19
November	32.19	21.51	0.17	0.40	-0.50
December	31.74	17.51	0.37	0.58	0.85

It is concluded that model performance to predict wind speed is acceptable. The correlation coefficient is statistically significant and other performance parameters FB and NMSE are acceptable for the months having an acceptable coefficient of correlation.

The model performance for the prediction of temperature is also acceptable for all months except winter seasons 2018 (Table 5.2). The differences in winter temperature statistics may occur due to some error in sensor or calibration at Nehru Nagar, Kanpur station.

5.3 Digital Elevation Model (DEM) and receptor grid network

The Digital Terrain Elevation Model (DEM) is the most critical information required for complex terrain. The terrain affects the dispersion significantly. DEM is required to predict wind flow patterns and dispersion. AERMOD processes DEM data and creates an elevation and height scale (the terrain height and location that has the greatest influence on dispersion) for each receptor in the domain. The terrain is the vertical dimension of the land surface. Gridded terrain elevations for the proposed modeling domain were derived from 3 arc-second digital elevation models (DEMs) produced by the United States Geological Survey (USGS). The processed terrain elevation data is shown in Figure 5.5. Receptor locations were defined using a set of non-uniform cartesian grid networks, uniform polar grid networks, and discrete cartesian grid networks. Five non-uniform cartesian grid networks (Figure 5.6 and Table 5.3) were employed to assess the impact within the Kanpur City boundary and two discrete cartesian receptors (Figure 5.7) were used to assess the impact at the locations where the manual ground observations were being recorded. A total of 577 receptors (Figure 5.8) were defined for the analysis of ground-level $PM_{2.5}$ concentrations.

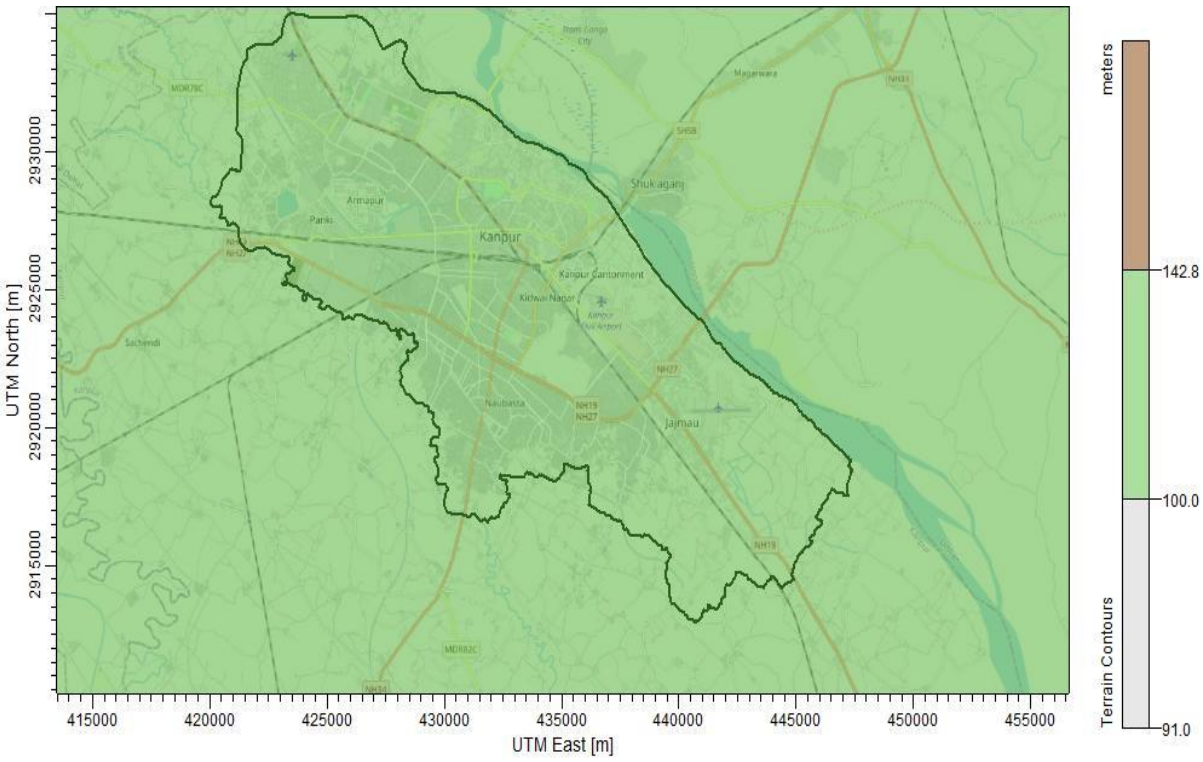


Figure 5.5: Terrain Contour Map of the Kanpur City

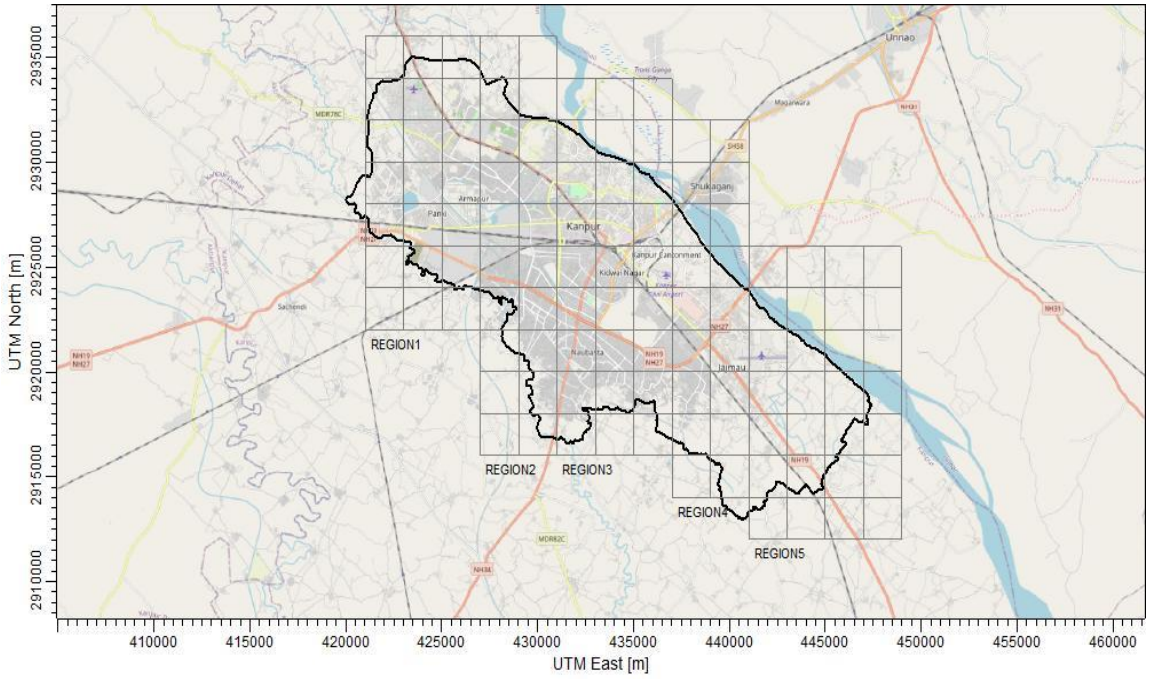


Figure 5.6: Non-Uniform Cartesian Grid Receptor Network

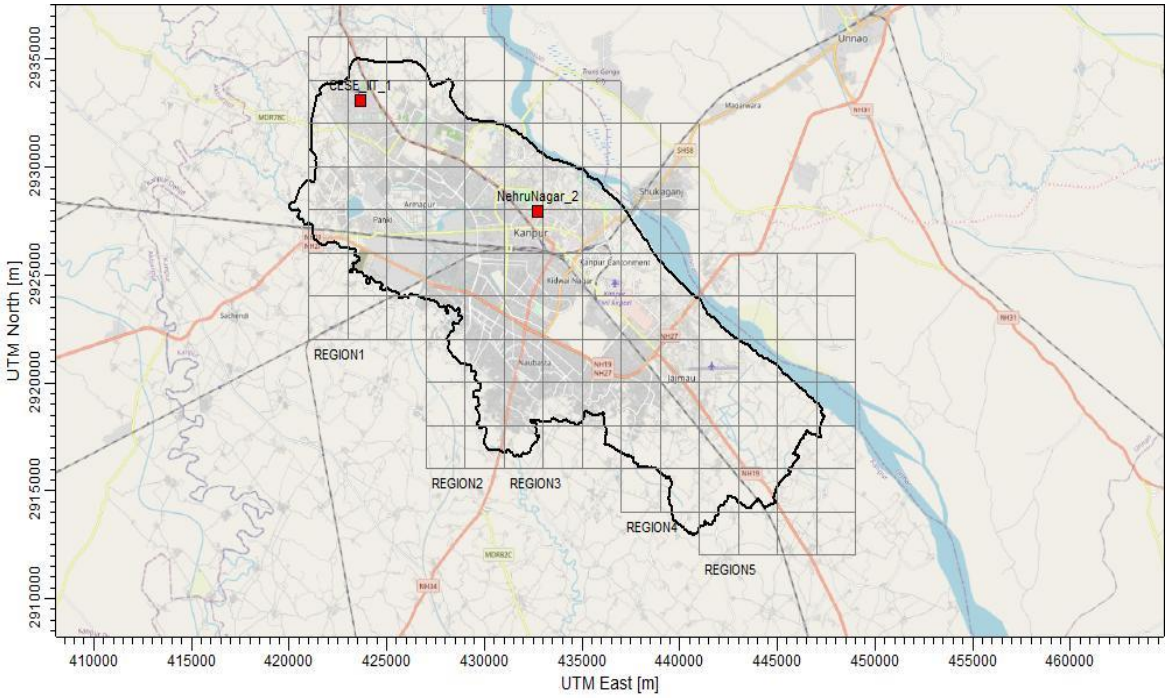


Figure 5.7: Discrete Cartesian Receptor (red squares show where air quality is monitored)

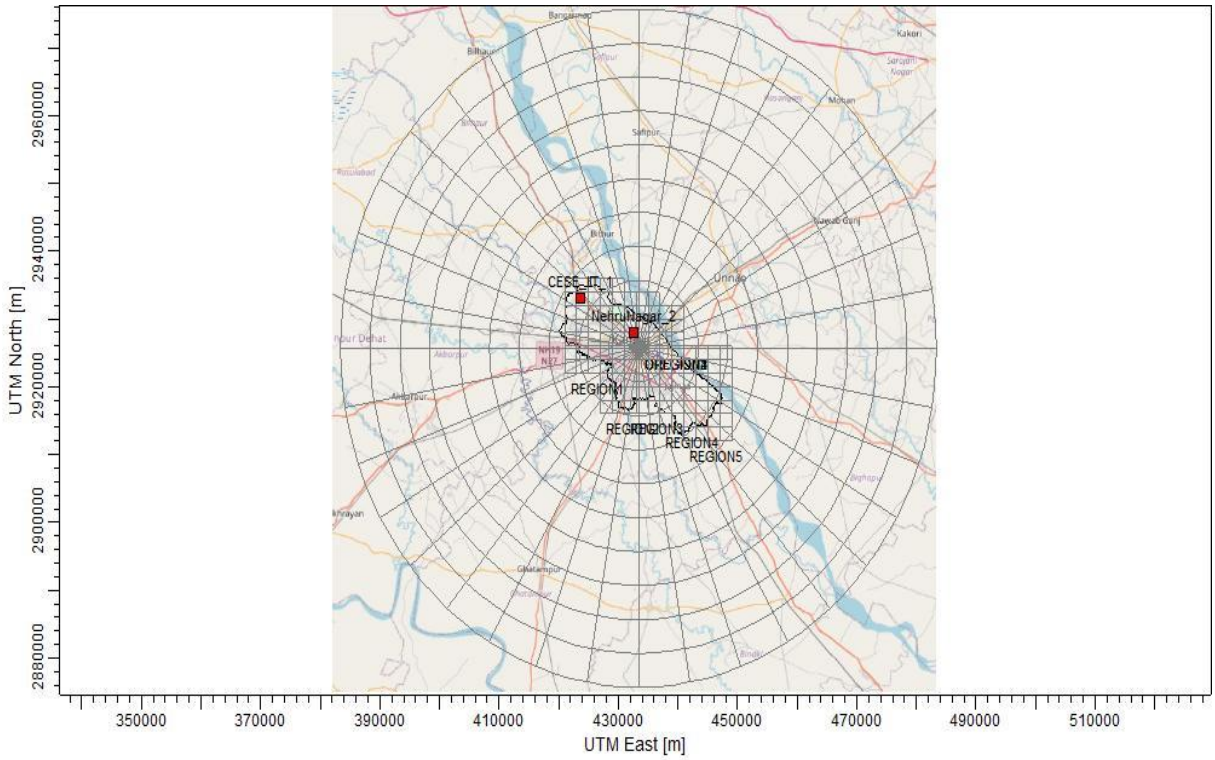


Figure 5.8: Total Receptor Network

Table 5.3: Receptor Networks defined for Impact Assessment

Receptor Type	No. of Networks	No. of Receptors
Uniform Cartesian Grid	0	-
Non-Uniform Cartesian Grid	5	-
REGION 1	-	32
REGION 2	-	33
REGION 3	-	40
REGION 4	-	30
REGION 5	-	40

5.4 Evaluation of Dispersion Modeling Results

The air dispersion modeling was done with complex terrain (using the elevation heights in Kanpur City). By this approach, all the elevations of terrain were accounted for, and the air dispersion reflected more accurate results as compared to flat terrain. The model was run considering only the sources within Kanpur City.

The time-series and scatter plot of 24-hour average $PM_{2.5}$ concentration observed at the UPPCB's continuous ambient monitoring station located at Nehru Nagar, IIT Kanpur and the modeled $PM_{2.5}$ concentrations considering all the major sources of $PM_{2.5}$ was plotted (Figure 5.9 and Figure 5.10) and it was observed that the model predicted well with a root mean square error of 88.48 (Nehru Nagar), 113.66 (IIT) $\mu g/m^3$ (Table 5.4 and Table 5.5). During winter, high concentrations of $PM_{2.5}$ were observed, which the model could not account for. It appeared that there was a significant contribution of sources located outside the Kanpur City, including the formation of secondary aerosols from distantly located emission sources.

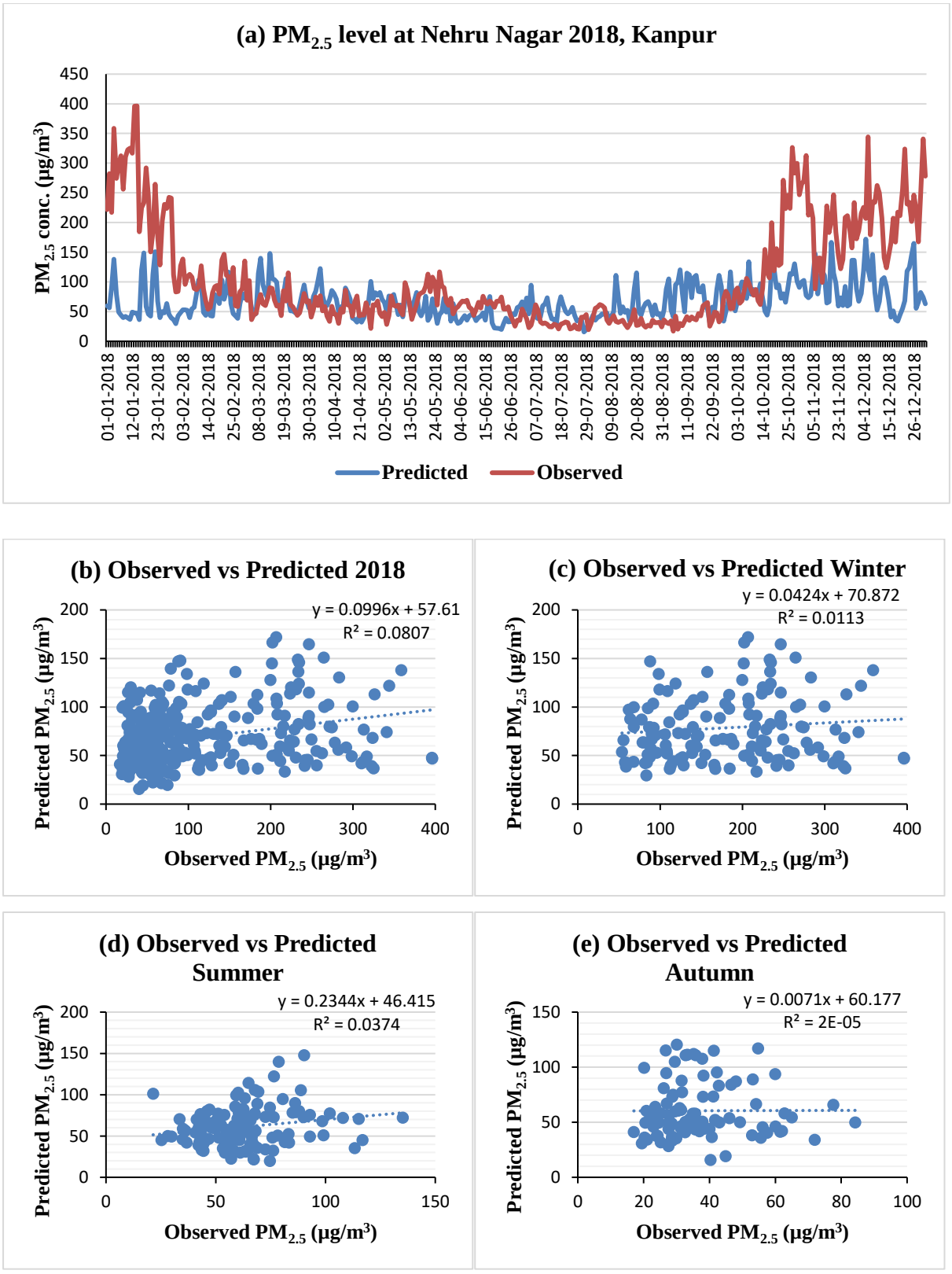


Figure 5.9: (a) Time series plot and (b-e) scattered plot for observed vs. predicted $PM_{2.5}$ levels at Nehru Nagar in 2018

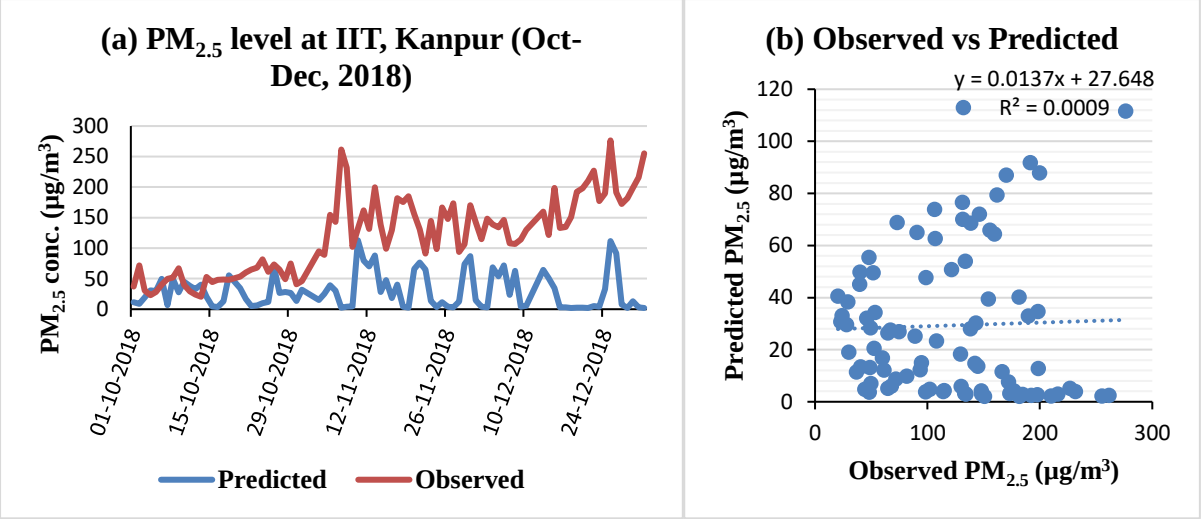


Figure 5.10: (a) Time series plot and (b) scattered plot for observed vs. predicted $PM_{2.5}$ levels at IIT in 2018

Table 5.4: Statistical parameters for validation of model for $PM_{2.5}$ at Nehru Nagar

Months	Observed Mean	Predicted Mean	Difference
January	248.59	63.03	185.56
February	96.13	62.65	33.48
March	68.42	77.42	-9.00
April	54.41	68.57	-14.15
May	71.27	57.92	13.35
June	56.61	40.20	16.41
July	32.26	48.54	-16.28
August	36.52	54.28	-17.76
September	42.85	79.11	-36.25
October	148.95	87.78	61.17
November	186.87	95.23	91.65
December	220.77	86.92	133.85

Table 5.5: Statistical parameters for validation of model for $PM_{2.5}$

Parameters	Nehru Nagar	IIT
Observed Mean $PM_{2.5}$, µg/m^3	127.14	120.15
Predicted Mean $PM_{2.5}$, µg/m^3	67.97	29.29
Root Mean Square Error (RMSE), µg/m^3	88.48	113.66
Normalised Mean Square Error (NMSE)	1.11	3.67
Fractional Bias (FB)	0.42	1.22
Pearson Correlation Coefficient (R)	0.28	0.03

It is seen (Figure 5.9 (b)) that the modeled and observed $PM_{2.5}$ concentrations show a significant linear association (R^2 =0.081) (for over 350 data points). In this study, three seasons have taken such as winter includes (January, February, October, November and December) summer (March, April, May and June) and autumn (July, August and September) months. However, the noteworthy point is that the model under-predicts the concentration by a factor of almost 2 times at Nehru Nagar and 4 times at IIT respectively. The probable reasons for underestimation by the model are because of (i) over-prediction of wind speed by the WRF model, (ii) inventory may be incomplete and some sources may be missing, and (iii) there is a substantial contribution of sources present outside the Kanpur City. Since the linear association in the model-computed and observed levels is significant, the model could be used for decision-making and useful insights.

The deficit in the model and measured (referred to as unidentified) $PM_{2.5}$ levels were highest during the January and December months. Also, it is worth noting that there was a sudden spike in these unidentified concentrations of $PM_{2.5}$ during the last week of October, the first and last week of November. This episodic spike in the unidentified $PM_{2.5}$ concentrations with an average value was almost 137 $\mu g/m^3$ in the city, which can be attributed to the influx from the surrounding regions outside the city.

5.5 Region-wise impact assessment

Kanpur City was divided into five regions (Figure 5.11) for a better assessment of the impacts from different sources, which could enable efficient planning of mitigation strategies in these regions. Major localities in these regions are given in Table 5.6. Dispersion modeling was carried out using state-of-the-art models to apportion the contribution of sources (sector-wise; industries, power plants, brick kilns, vehicles, open fires, dust, domestic, etc.) to air pollution in Kanpur City.

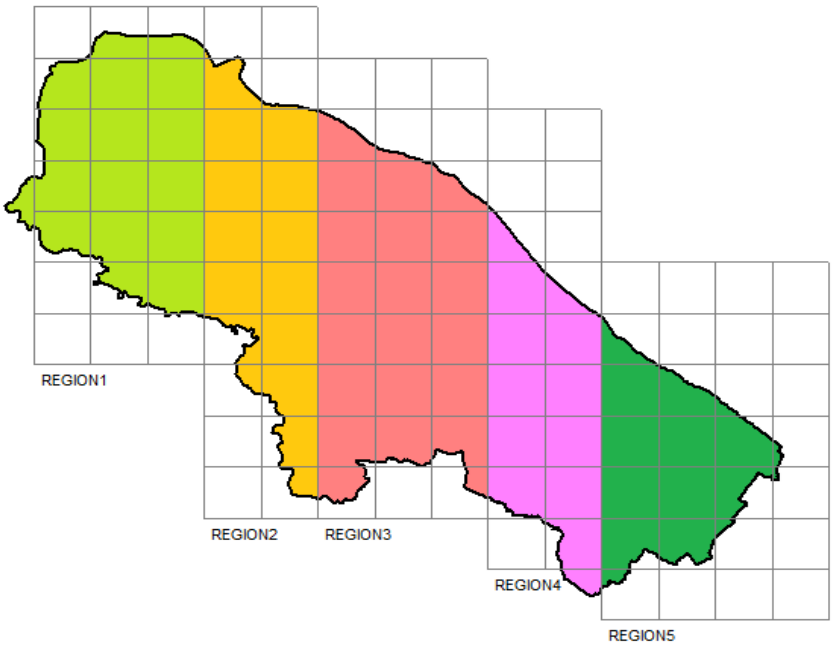


Figure 5.11: Demarcation of Five Regions for Impact Assessment

Table 5.6: Major Localities in Different Regions of Kanpur

Region 1	Region 2	Region 3	Region 4	Region 5
IIT	CSJM	Moti Jheel	Cantt.	Chakeri
Kalyanpur	Rawatpur	Fasalganj	Lalbangla	Karauli
Panki	Kakadev	Govind Nagar	Jajmau	UPSIDC Industrial Area
Armapur	Ratanlal Nagar	Naubasta	Shyam Nagar	Rooma
	Dadanagar	Chunniganj	Ramadevi	

The highest 24-hour average $PM_{2.5}$ concentrations were plotted and tabulated for these regions in the year of 2018 in Figure 5.12 and Table 5.7. The monthly average $PM_{2.5}$ levels are given in Figure 5.13 and Table 5.8 and percentage contribution from the different sources is given in Table 5.9. The modelled concentration in region 3 had the average $PM_{2.5}$ concentration of 692.25 ± 185.03 µg/m^3 derived from the peak 24-hour concentrations (in the region) followed by region 4 with 516.43 ± 173.01 µg/m^3 and region 5 with 454.87 ± 146.11 µg/m^3 and least in Region 1 at 263.86 ± 63.51 µg/m^3. The highest 24-hour average $PM_{2.5}$ concentrations were observed during the winters (November to February), while the lowest during the peak summer month (June) and start of monsoon month (July).

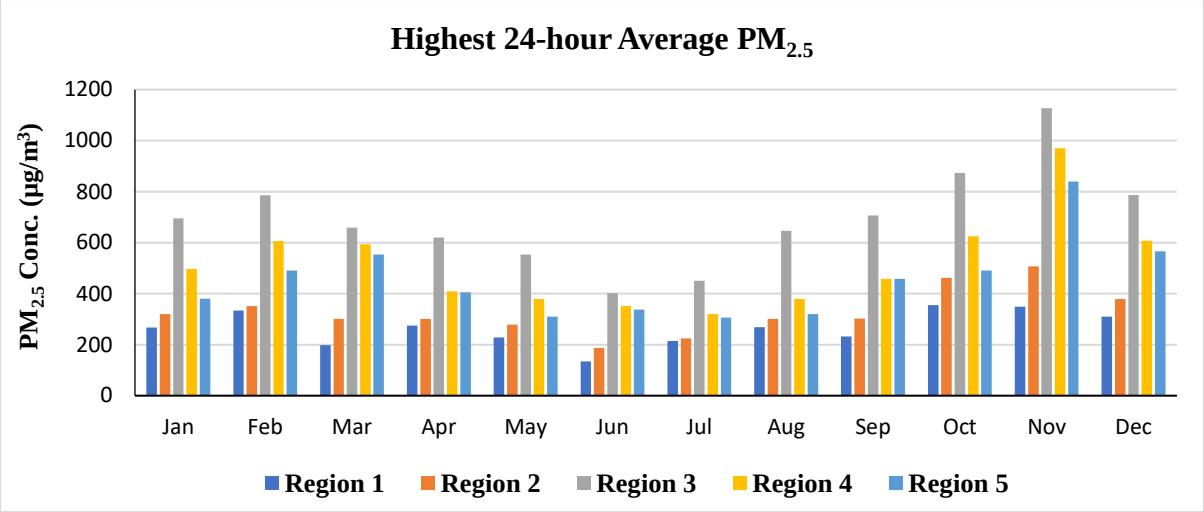


Figure 5.12: Region-wise highest 24-hour average $PM_{2.5}$ levels in 2018

It was observed that the $PM_{2.5}$ concentration in the ambient air increases as the winter season approaches. During peak summer and monsoon seasons, the $PM_{2.5}$ concentration was minimum and increased steadily with the fall in temperature, which promoted stable atmospheric conditions and reduced dispersion of pollutants. From the annual average plot, the envelope of $PM_{2.5}$ concentration was seen to be elongated along the prevailing wind direction (N-W).

Table 5.7: Region and Month-wise highest 24-hour $PM_{2.5}$ levels in 2018 (Modelled)

Months	Concentration (µg/m^3)				
	Region 1	**Region 2**	**Region 3**	**Region 4**	**Region 5**
January	267.44	320.23	695.31	497.14	379.74
February	333.83	350.95	786.36	606.77	490.94
March	197.73	301.26	659.27	593.67	554.12
April	274.98	300.70	619.97	408.64	405.02
May	228.44	278.54	553.21	378.78	309.92
June	134.65	187.53	401.09	351.52	337.49
July	214.80	224.24	450.75	320.19	306.15
August	268.38	301.42	646.07	379.56	320.07
September	232.16	301.87	706.75	457.97	457.97
October	354.76	461.54	874.09	624.60	491.16
November	348.54	506.74	1126.72	970.56	839.71
December	310.56	378.64	787.43	607.73	566.13

Table 5.8: Region-wise monthly average $PM_{2.5}$ levels from all sources in 2018

Months	Concentration (µg/m^3)				
	Region 1	Region 2	Region 3	Region 4	Region 5
January	23.86	45.96	83.80	92.18	72.09
February	29.66	53.04	89.03	92.10	65.23
March	24.25	48.12	89.99	101.38	80.45
April	44.46	56.02	78.01	67.39	37.57
May	36.20	51.56	73.71	64.39	34.35
June	18.26	28.09	47.12	48.47	34.67
July	26.24	36.33	54.55	51.05	32.48
August	26.74	35.96	54.34	51.09	32.26
September	30.56	49.01	79.94	81.19	55.87
October	55.30	78.64	107.48	90.58	46.00
November	50.71	75.59	116.12	111.57	73.49
December	35.18	59.50	100.56	104.83	73.82

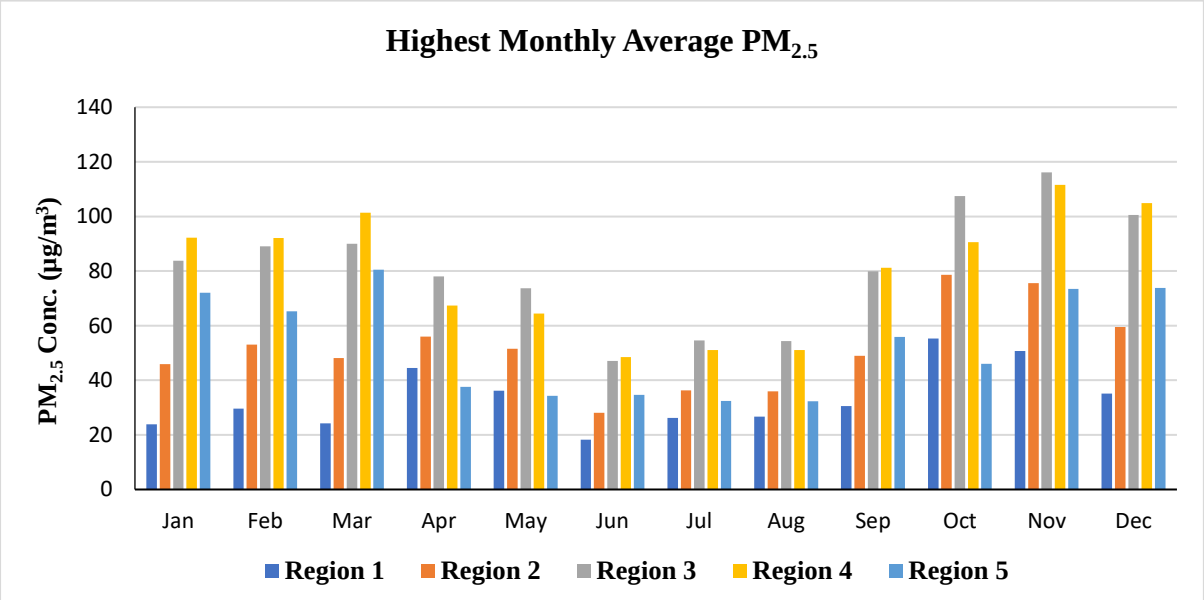


Figure 5.13: Region-wise Monthly average $PM_{2.5}$ levels in 2018

Table 5.9: $PM_{2.5}$ percentage contribution from different sources

Sources	Contribution (%)					
	Region 1	**Region 2**	**Region 3**	**Region 4**	**Region 5**	**Overall**
CONSTRUC	4.55	2.64	0.96	0.46	0.5	1.39
DGSETS	1.48	1.35	0.62	0.6	0.82	0.86
DOMESTIC	6.5	7.29	7.04	4.27	2.92	5.56
HOSPITAL	0.14	0.12	0.08	0.04	0.03	0.07
HOTEL	1.32	1.56	1.58	0.92	0.52	1.19
INDUSTRY	25.34	18.4	6.19	4.12	5.3	9.45
MSW	4.93	5.53	5.34	3.24	2.21	4.22
ROADDUST	38.67	46	58.84	66.72	71.44	59.06
VEHICLE	17.07	17.1	19.35	19.64	16.27	18.2

5.5.1 Summary

The highest contributing source among all was road dust in all the regions followed by vehicular emissions in regions 3, 4 and 5. Industries were the second-highest contributors in regions 1 and 2.

Domestic sources were the third-highest contributors in regions 3 and 4, where the residential population is concentrated. Construction sources were the highest contributors in region 1, where the construction hotspots are located. MSW burning was higher in regions 2 and 3 compared to other regions (Table 5.9). The rank of different sources based on their $PM_{2.5}$ contribution in all the regions is given in Table 5.10.

Overall, the top contributors to $PM_{2.5}$ were road dust (59.06%), vehicles (18.2%), industry (9.45%), domestic sources (5.56%), and MSW (4.22%).

Table 5.10: Rank to sources in different regions based on their contribution to $PM_{2.5}$

Rank	Region 1	Region 2	Region 3	Region 4	Region 5	Overall
1	Road Dust	Road Dust	Road Dust	Road Dust	Road Dust	Road Dust
2	Industry	Industry	Vehicle	Vehicle	Vehicle	Vehicle
3	Vehicle	Vehicle	Domestic	Domestic	Industry	Industry
4	Domestic	Domestic	Industry	Industry	Domestic	Domestic
5	MSW	MSW	MSW	MSW	MSW	MSW
6	Construction	Construction	Hotel	Hotel	DG Sets	Construction
7	DG Sets	Hotel	Construction	DG Sets	Hotel	Hotel

5.5.2 The combined impact of all the sources

The highest 24-hour average, monthly average, and period average $PM_{2.5}$ concentration plots for all sources in the Kanpur City are given in Figure 5.14, Figure 5.15 and Figure 5.16, respectively. The highest values of $PM_{2.5}$ concentration were obtained from road dust, industrial, and vehicular sources. Hospital area, hotel, and DG sets sources contributed the least to the $PM_{2.5}$ concentration (

). In Kanpur City, the standard annual average $PM_{2.5}$ concentration is exceeded mostly in the area surrounding the National Highway 19 (NH-19) (Figure 5.16).

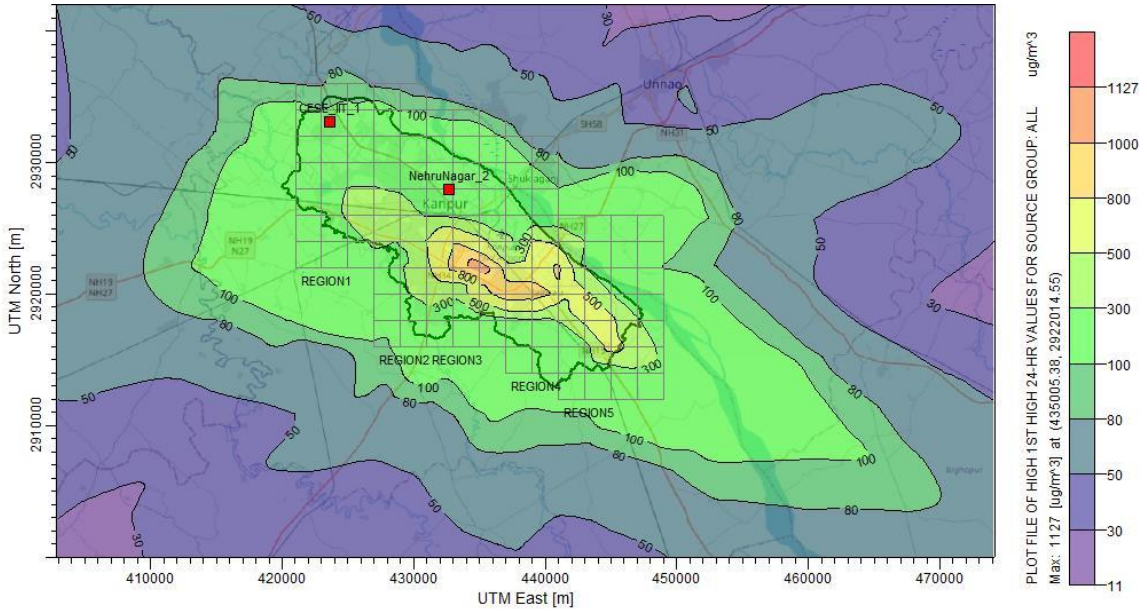


Figure 5.14: Highest 24-hour Average $PM_{2.5}$ Levels from All Sources

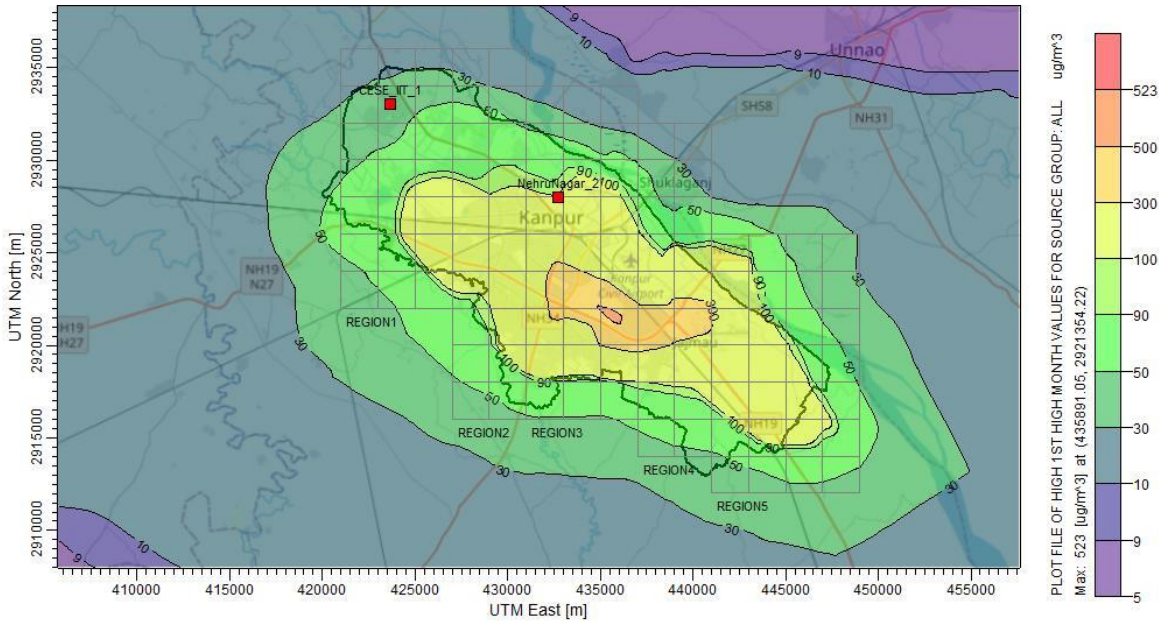


Figure 5.15: Monthly Average $PM_{2.5}$ Levels for critical month (All Sources)

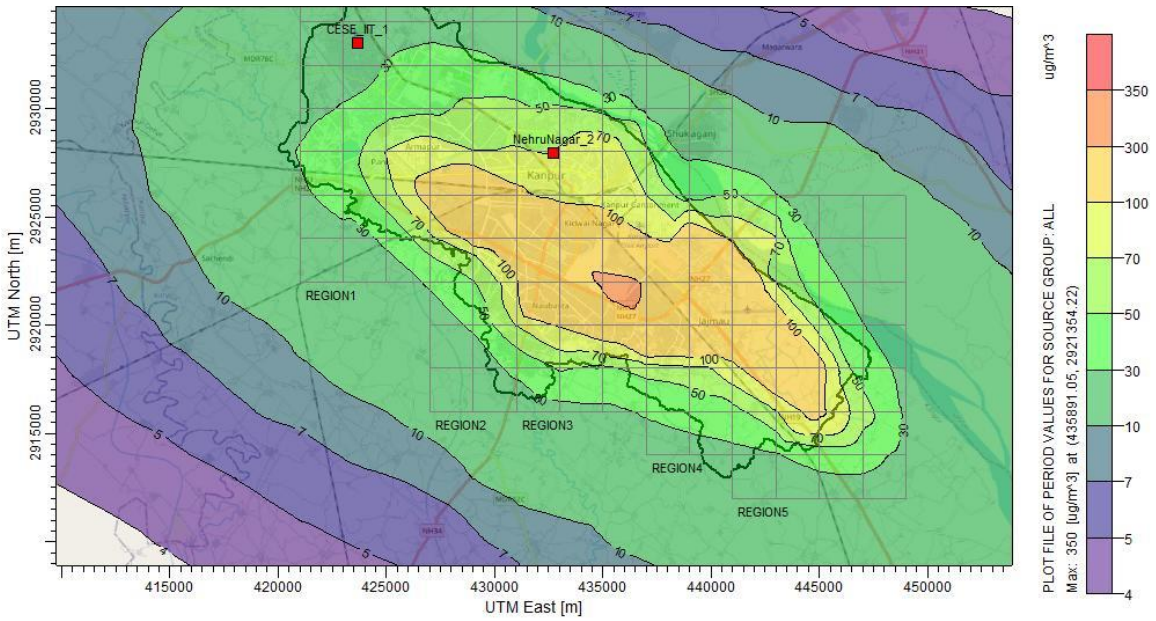


Figure 5.16: Annual Average $PM_{2.5}$ Levels from All Sources

5.6 Scenario Analysis

(Develop and demonstrate control measures (three scenarios) on air quality improvements)

The study has considered three scenarios to assess the improvement in the air quality of Kanpur City. Maximum 24-hour average $PM_{2.5}$ concentration is the parameter considered to analyze different scenarios. In recent years CPCB focused on all types of pollution sources and tried to cut down the concentration of pollution sources as they are the contributors to $PM_{2.5}$ concentration in the city. The three scenarios are presented below.

5.6.1 Scenario: Baseline Scenario

Table 5.11 represents the current status of modeled air quality (maximum $PM_{2.5}$ concentration) in different regions of Kanpur when no intervention has been taken.

Table 5.11: Highest 24-hour Average $PM_{2.5}$ Levels ($\mu g/m^3$) in Different Regions

Months	Concentration ($\mu g/m^3$)				
	Region 1	Region 2	Region 3	Region 4	Region 5
January	267.44	320.23	695.31	497.14	379.74
February	333.83	350.95	786.36	606.77	490.94
March	197.73	301.26	659.27	593.67	554.12
April	274.98	300.70	619.97	408.64	405.02
May	228.44	278.54	553.21	378.78	309.92
June	134.65	187.53	401.09	351.52	337.49
July	214.80	224.24	450.75	320.19	306.15
August	268.38	301.42	646.07	379.56	320.07
September	232.16	301.87	706.75	457.97	457.97
October	354.76	461.54	874.09	624.60	491.16
November	348.54	506.74	1126.72	970.56	839.71
December	310.56	378.64	787.43	607.73	566.13

5.6.2 Scenario 1: 25% Reduction in All Sources Emissions

Table 5.12 and Figure 5.17 represents the status of air quality (maximum $PM_{2.5}$ concentration) in different regions of Kanpur when the emissions from all sources are reduced by 25%.

Table 5.12: Scenario 1 Highest 24-hour Average $PM_{2.5}$ Levels ($\mu g/m^3$) in Different Regions

Months	Scenario 1-Concentration ($\mu g/m^3$)				
	Region 1	Region 2	Region 3	Region 4	Region 5
January	200.40	240.10	521.47	372.86	284.78
February	250.05	263.07	589.76	455.11	368.13
March	148.29	225.98	494.48	445.20	415.58
April	206.23	225.45	464.93	306.48	303.76
May	171.28	208.91	414.90	284.08	232.44
June	100.99	140.65	300.81	263.64	253.12
July	161.10	168.18	338.06	240.14	229.52
August	201.27	226.06	484.54	284.66	240.05
September	174.11	226.40	529.99	343.48	343.48
October	265.66	346.15	655.56	468.56	368.36
November	261.40	380.04	845.07	727.79	629.35
December	232.92	283.98	590.56	455.81	424.60

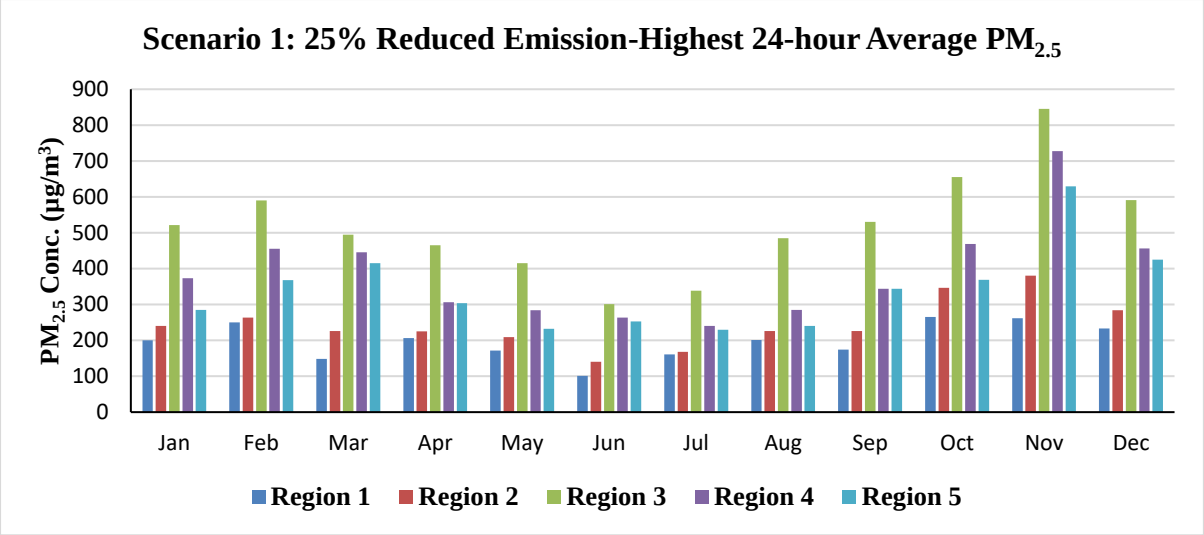


Figure 5.17: Scenario 1, 25% Reduced Emission-Highest 24-hour Average $PM_{2.5}$

5.6.3 Scenario 2: 50% Reduction in Reduction in All Sources Emissions

Table 5.13 and Figure 5.18 represents the status of air quality (maximum $PM_{2.5}$ concentration) in different regions of Kanpur when the emissions from all sources are reduced by 50%.

Table 5.13: Scenario 2 Highest 24-hour Average $PM_{2.5}$ Levels (µg/m^3) in Different Regions

Months	Scenario 2- Concentration (µg/m^3)				
	Region 1	Region 2	Region 3	Region 4	Region 5
January	133.60	160.06	347.65	248.57	189.85
February	166.70	175.38	393.17	303.41	245.42
March	98.86	150.66	329.65	296.80	277.06
April	137.49	150.30	309.96	204.32	202.50
May	114.18	139.27	276.60	189.38	154.96
June	67.32	93.77	200.54	175.76	168.75
July	107.40	112.12	225.37	160.09	153.01
August	134.18	150.70	323.03	189.78	160.04
September	116.08	150.94	353.32	228.98	228.98
October	177.11	230.77	437.04	312.37	245.58
November	174.27	253.36	563.38	485.19	419.56
December	155.28	189.32	393.71	303.87	283.06

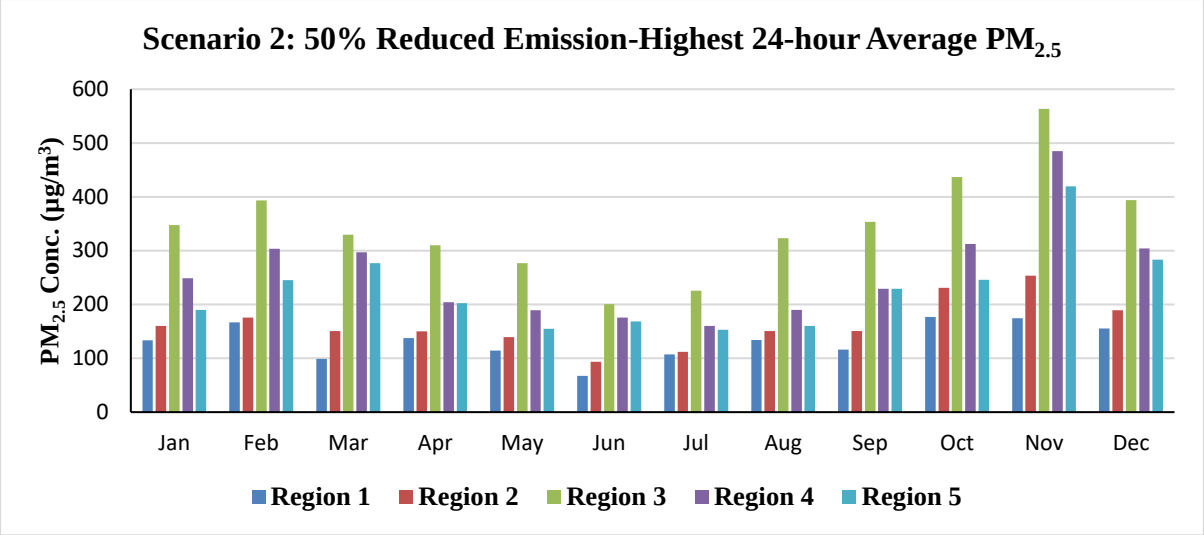


Figure 5.18: Scenario 2, 50% Reduced Emission-Highest 24-hour Average $PM_{2.5}$

5.6.4 Scenario 3: 75% Reduction in All Sources Emissions

Table 5.14 and Figure 5.19 represents the status of air quality (maximum $PM_{2.5}$ concentration) in different regions of Kanpur when the emissions from all sources are reduced by 75%.

Table 5.14: Scenario 3 Highest 24-hour Average $PM_{2.5}$ Levels ($\mu g/m^3$) in Different Regions

Months	Scenario 3 - Concentration ($\mu g/m^3$)				
	Region 1	Region 2	Region 3	Region 4	Region 5
January	66.83	80.09	174.10	124.32	94.97
February	83.41	87.75	196.90	151.76	122.75
March	49.46	75.36	165.12	148.44	138.59
April	68.79	75.21	155.22	102.17	101.28
May	57.13	69.72	138.54	94.72	77.51
June	33.68	46.91	100.45	87.92	84.41
July	53.74	56.13	112.87	80.09	76.54
August	67.13	75.41	161.77	94.92	80.06
September	58.08	75.56	176.95	114.55	114.55
October	88.60	115.52	218.85	156.24	122.82
November	87.17	126.74	282.18	242.66	209.85
December	77.69	94.73	197.16	151.99	141.59

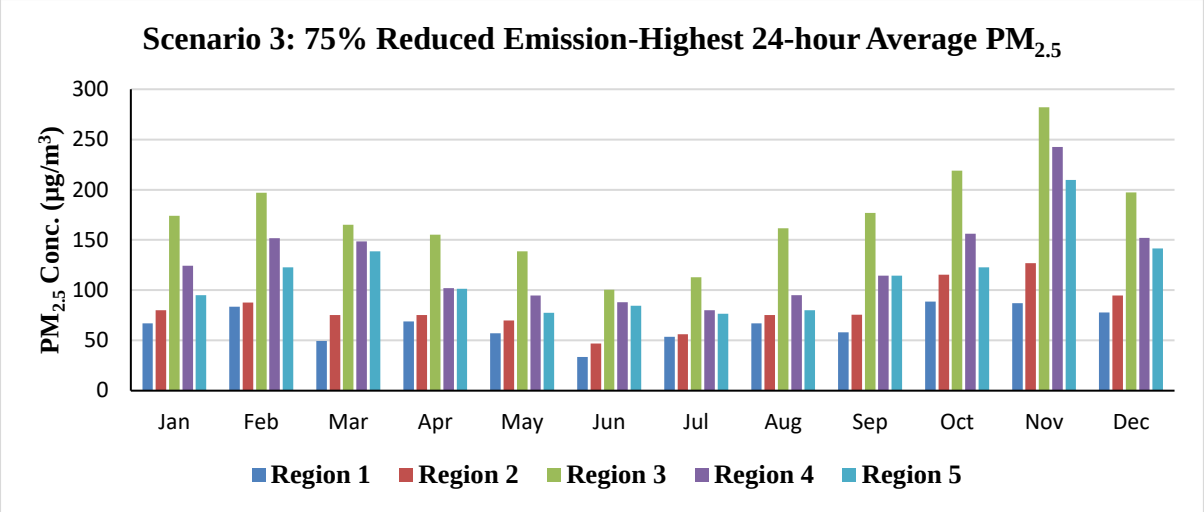


Figure 5.19: Scenario 3, 75% Reduced Emission-Highest 24-hour Average $PM_{2.5}$

The overall improvement in air quality for $PM_{2.5}$ under the three scenarios will be close to 25% in Scenario 1, 50% in Scenario 2 and 75% in Scenario 3 in the peak 24- hourly concentration (Figure 5.20). Since the maximum contribution is from road dust, the maximum advantage will be by improving road conditions. Sweeping, road washing and paved shoulders will be effective ways to control road dust emissions.

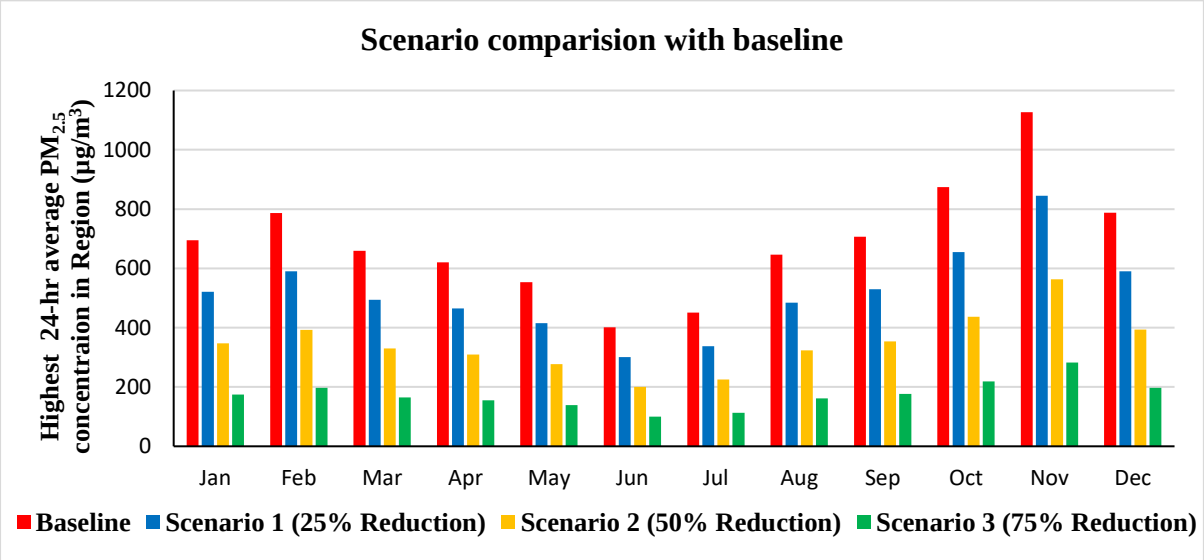


Figure 5.20: Air Quality Improvement in Scenarios 1, 2 and 3 in Peak 24-hour Average $PM_{2.5}$ Levels

5.7 Summary of the Dispersion Modeling and interpretations

The major findings from the dispersion modeling are summarized below:

The highest 24-hour average $PM_{2.5}$ concentration plots for all sources with air quality improvement in Scenarios 1, 2 and 3 are given in Figure 5.21, Figure 5.22 and Figure 5.23 respectively.

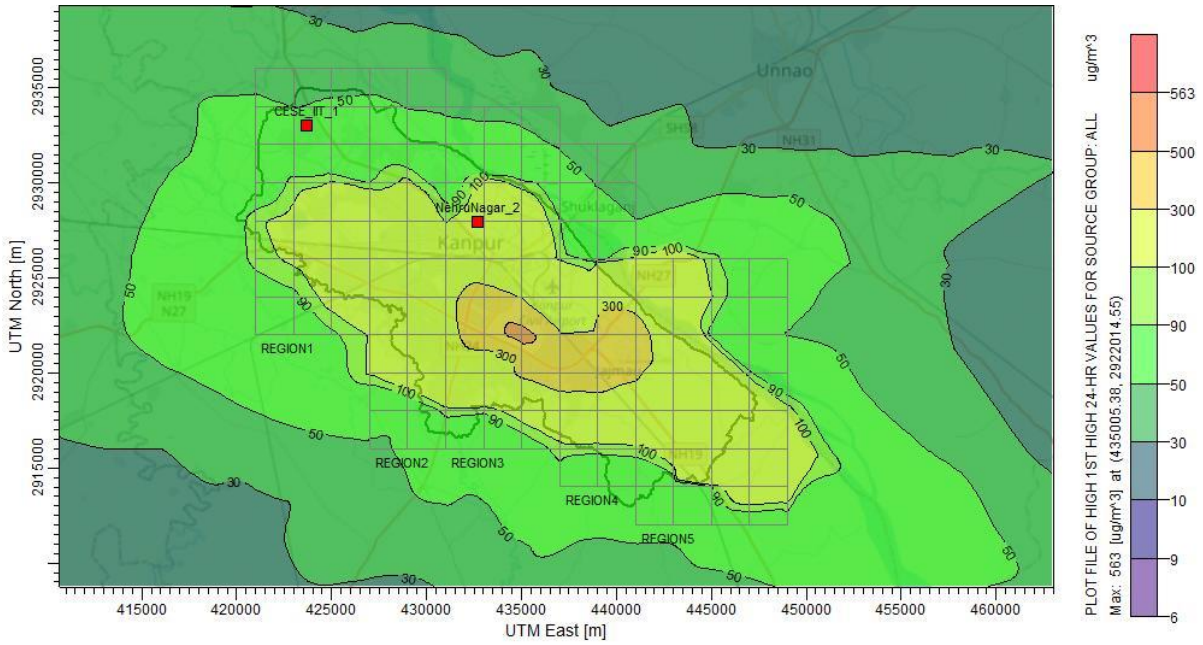


Figure 5.21: Highest 24-hour Average $PM_{2.5}$ Levels from All Sources (Scenarios 1)

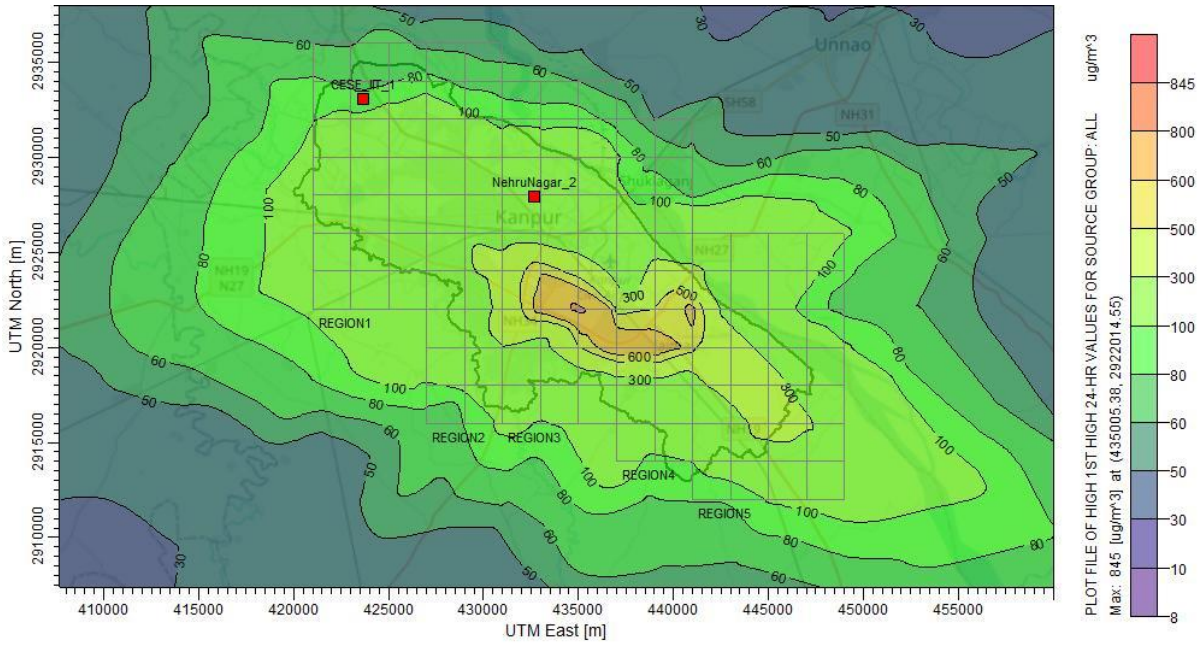


Figure 5.22: Highest 24-hour Average $PM_{2.5}$ Levels from All Sources (Scenarios 2)

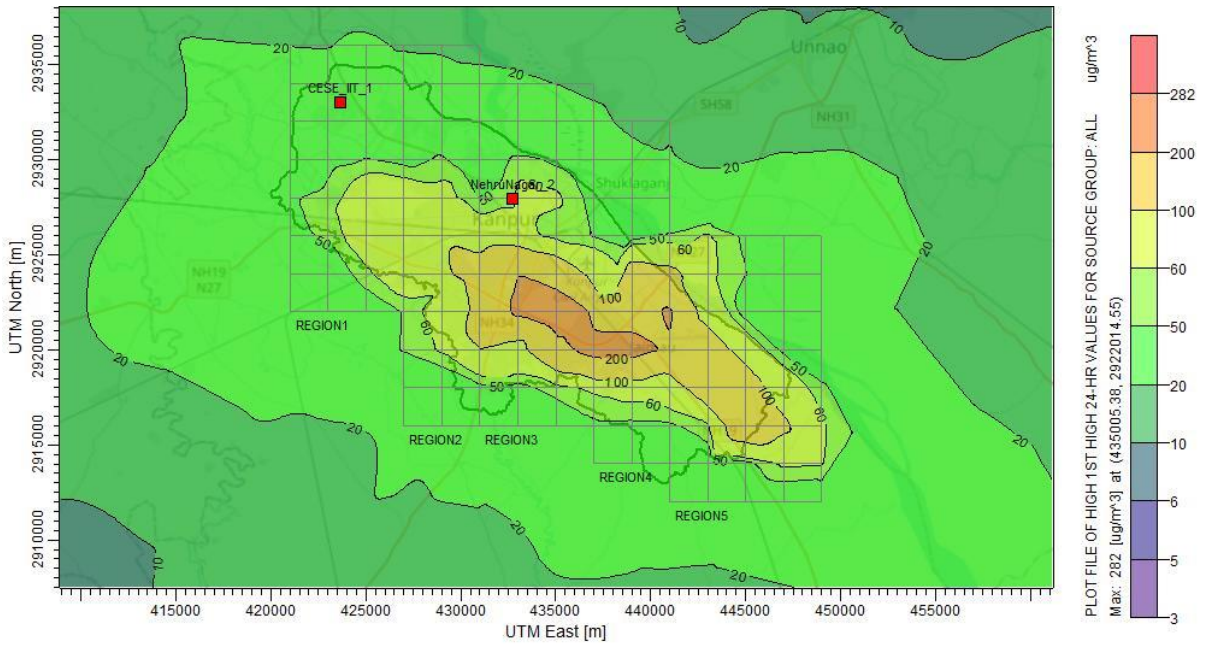


Figure 5.23: Highest 24-hour Average $PM_{2.5}$ Levels from All Sources (Scenarios 3)

The WRF (Weather Research and Forecasting) model for meteorology parameters was validated against the measured data from UPPCB continuous air quality monitoring station, Nehru Nagar, Kanpur. The model performed satisfactorily with a statistically significant correlation coefficient (r = 0.44; n = 365) for predicting wind speeds in the year 2018. In general, the wind speeds were overestimated by a factor of 1.5 times.

Furthermore, the time-series plot of observed 24 hourly ambient temperature levels with modeled levels showed a good agreement (r = 0.37; n = 365) for all months of 2018. In general, the temperature was underestimated by a factor of 1.15 times. It was concluded that the WRF model provided realistic meteorology and the WRF outputs were used in air quality modeling.

The $PM_{2.5}$ modeled and observed levels over one year showed a linear association (r = 0.28 n= 358). It is noteworthy that the model under-predicts the concentration by a factor of 1.5 times at Nehru Nagar receptor. The probable reasons for underestimation by the model are (i) over prediction of wind speed by the WRF model in some months, (ii) inventory may be incomplete and some sources may be missing, and (iii) there is a substantial contribution of sources present outside the Kanpur City. Since the linear association in the model-computed and observed levels is very good, the model could be used for decision-making and useful insights.

The deficit in the model and measured (referred to as unidentified) $PM_{2.5}$ levels at Nehru Nagar were highest during the January and December months. Also, it is worth noting that there was a sudden spike in these unidentified concentrations of $PM_{2.5}$ during the last week of October,

the first and last week of November. This episodic spike in the unidentified $PM_{2.5}$ concentrations with an average value was almost 137 $\mu g/m^3$ in the city, which can be attributed to the influx from the surrounding regions outside the city.

For better insight, Kanpur City was divided into five regions (Figure 5.11). The modelled concentration in region 3 had the average $PM_{2.5}$ concentration of 692.25 ± 185.03 $\mu g/m^3$ derived from the peak 24-hour concentrations (in the region) followed by region 4 with 516.43 ± 173.01 $\mu g/m^3$ and region 5 with 454.87 ± 146.11 $\mu g/m^3$ and least in Region 1 at 263.86 ± 63.51 $\mu g/m^3$.

Regions 3 and 4 are densely populated and region 1 and 2 has a major industrial area. The highest 24-hour average $PM_{2.5}$ concentrations were computed for the winter month's November of the year 2018. The highest 24-hour average $PM_{2.5}$ concentrations were observed during the winter months (November and December) while the lowest was during the summer (June and July).

The highest contributing source was road dust in all the regions followed by vehicular emissions in regions 3, 4 and 5. Industries were the second-highest contributors in regions 1 and 2. Domestic sources were the third-highest contributors in regions 3 and 4, where the residential population is concentrated.

Overall, city-level contributors to $PM_{2.5}$ were road dust (59.06%), vehicles (18.2%), industry (9.45%), domestic sources (5.56%), and MSW (4.22%).

From the annual average plots, it is seen that $PM_{2.5}$ envelops a large area that gets elongated along the prevailing wind direction (N-W) within Kanpur City. The annual standard for $PM_{2.5}$ concentration (40 $\mu g/m^3$) is exceeded in the area surrounding industries, main roads and the National Highway.

6 Control options, Analyses and Prioritization for Actions

6.1 Air Pollution Scenario in the City of Kanpur

The city of Kanpur has a complex urban environment concerning air pollution sources and faces severe air pollution of PM_{10} and $PM_{2.5}$. There are several prominent sources within and outside Kanpur city contributing to PM_{10} and $PM_{2.5}$ in ambient air. Chapter 3 presents the emission inventory and Chapter 4 describes the contributions of sources to the ambient air concentrations. Based on the comprehensive source apportionment study, the sources of PM_{10} and $PM_{2.5}$ contributing to ambient air quality are different in summer and winter. The highlights of the source apportionment study are presented below.

In winter, % contribution of PM_{10} – $PM_{2.5}$ sources (given in parenthesis) to the ambient air level are: vehicles and DGs (24.5 – 29.9%), secondary organic aerosol (SOA; 16.8 – 17.9%), secondary inorganic aerosol (SIA; 16.0 – 18.7%), soil and road dust (13.7 – 11.7%), coal and fly ash (15 – 16%; includes ash from burning of residual oil), biomass burning (9.2 – 2.9%), MSW burning (7.5 – 8.8%), industrial (5.2 – 5.5%) and construction material (2.8 – 1.1%). It is noteworthy, in winter, major sources for PM_{10} and $PM_{2.5}$ are generally the same.

In summer, % contribution of PM_{10} - $PM_{2.5}$ sources (given in parenthesis) to the ambient air level are: soil and road dust (47.2 – 21.9%), biomass burning (10.5 – 14.8%), construction (8.5 – 11.9%), SOA (8.7 – 15.5%), SIA (7.6 – 9.7%), MSW burning (4.7 – 10.3%), vehicles and DGs (4.5 – 7.1%), industrial (3.9 – 5.3%), and coal and fly ash (4.6 – 3.5%; includes burning of residual oil). It is noteworthy, in summer also, the major sources for PM_{10} and $PM_{2.5}$ are generally the same.

Although sources contributing to summer and winter air pollution are different, the overall action plan should include control of all sources regardless of the season. This chapter presents various air pollution control options and their effectiveness in improving air quality. At the end of the chapter, a time-sensitive action plan is presented.

6.2 Controlling of sources within the city

6.2.1 Hotels/Restaurants/Banquet Halls

The total number of big hotels and restaurants was approximately 800, mainly situated in the central part of the city and along the GT Road. It was observed that coal/wood is being used as fuel in the tandoor, the common fuel other than wood is LPG. The PM emission in the form of flyash contributes to air pollution from this source.

The banquet halls also use diesel generator sets at the time of power failure and coal especially in tandoor and other cooking. In grid-wise distribution of Kanpur City, the prominent locations of Banquet halls using the DG sets were found in the highlighted grids K59, K60, K80, and K95 (Figure 6.1). Although small and uncluttered banquets halls are there in some other grids, the majority of emissions are from these four grids (Table 6.1).

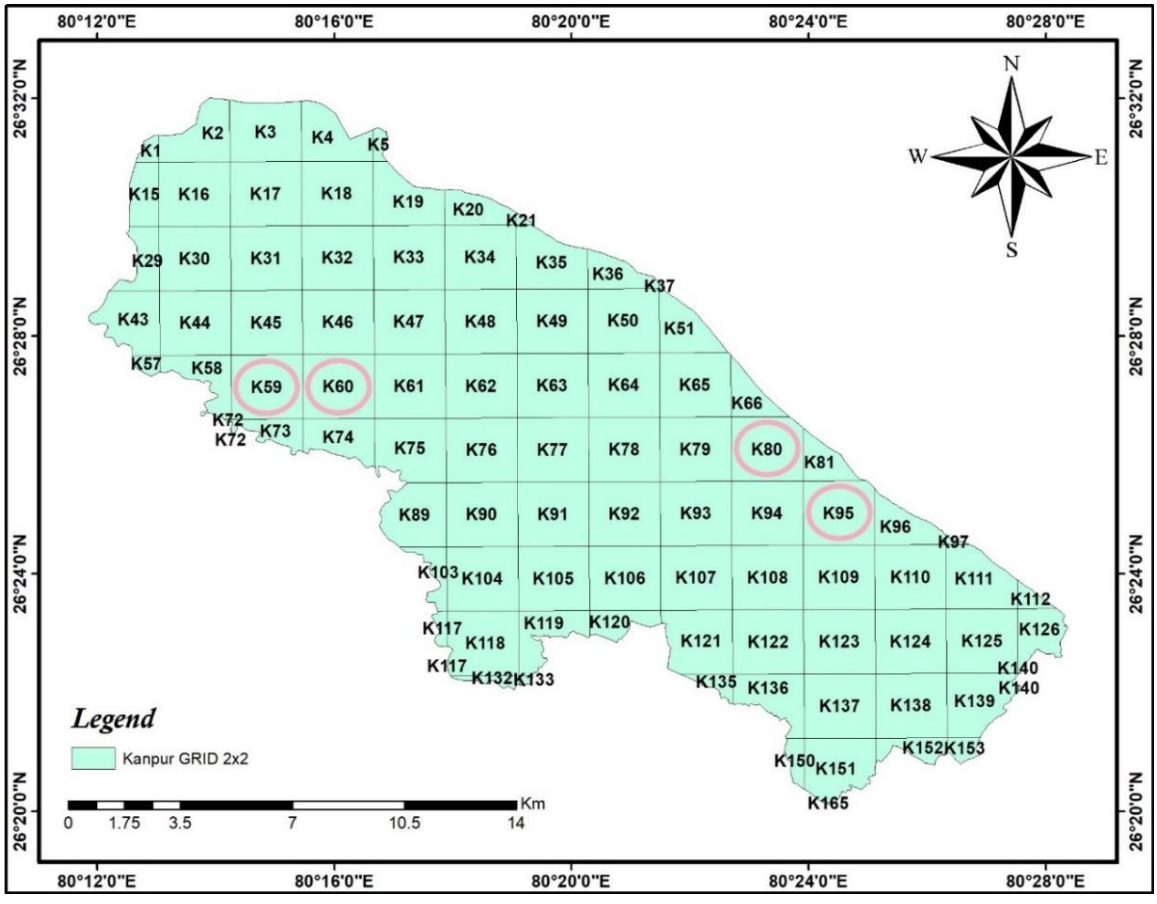


Figure 6.1: Banquet Halls prominent in highlighted grids of Kanpur City

Table 6.1: Grid wise location and description for Banquet Halls in Kanpur City

Sr. No.	Priority Grids	Locations in Grids	Source Description	Remarks
1	K59	Panki	DG sets are used at the time of power failure, encroachment of road	DG sets should be under the designated norms, meet stack height requirements, and use only BSVI fuel. In long-term DG sets of 10 KVA and bigger should be shifted to PNG.
2	K60	Panki Powerhouse colony		
3	K80	Lal Bangla, KDA colony		
4	K95	Jajmau, Chakeri		

It is also seen that the ash/residue from the tandoor and other activities are indiscriminately disposed of near the roadside. This contributes to road dust emissions. The Kanpur Municipal Corporation should enforce coal-free cooking in the hotels and restaurants, banquet halls and marriage places. For example, the coal burnt in bhatti/tandoor near roadside restaurants is shown in Figure 6.2. The ash must be stored in hole-free bags and disposed of. One may consider linking the commercial license to clean fuel, which may be enforced by Kanpur Municipal Corporation, Department of Food, Civil Supplies and Consumer Affairs, and oil Companies (Indian Oil, HP, etc.). A 70% reduction of PM_{10} (744 kg/d) and $PM_{2.5}$ (393 kg/d) emission from the sources can be achieved by stopping the use of coal/wood, and dung cakes.

Figure 6.2: Coal combustion in batti/tandoor at roadside restaurant

It is proposed that (i) all restaurants with a sitting capacity of more than 10 should not use coal/wood in any form and shift fully to electric or gas-based appliances (ii) DG sets should be under the designated norms, meet stack height requirements and use only BSVI fuel with DPF. (iii) DG sets of 2KVA and smaller (operating at ground level) should be banned and one can use an inverter or solar-based generators, and in the long-term, DG sets of 10 KVA and bigger should shift to PNG.

6.2.2 Municipal Solid Waste (MSW) Burning

MSW and other residue burning are rampant in Kanpur (Figures 6.3 – 6.5). In winter, the overall $PM_{2.5}$ contribution from MSW burning is 9.5% (Figure 4.36, Chapter 4) and stopping this burning is the simplest way to reduce $PM_{2.5}$ levels. Any form of garbage burning should be strictly stopped and strictly monitored for its compliance. The Kanpur Municipal Corporation should have the provision of penalty and fine to deter the people from burning any residue and improve the collection and disposal of the MSW.

Proper disposal of MSW will require the development of infrastructure (including access to remote and congested areas) for effective collection of MSW and disposal at the scientific landfill site. The Kanpur municipal corporation should prioritize the MSW collection mechanism starting systematically in each ward with an emphasis on public awareness. Special attention is required for fruits and vegetable markets, commercial areas, mandis and high-rise residential buildings. Industrial waste burning is dealt with separately.

Figure 6.3: Solid waste burning in the Kalyanpur area near railway station

Figure 6.4: Solid waste burning in the Dada Nagar area

Figure 6.5: Solid waste burning in the Navin Nagar and Saraimita areas

In the gridded distribution of Kanpur City, the prominent MSW burning was found in the highlighted grids, K49, K50, K75, and K90 (Figure 6.6). Localities, where incidents of MSW burning are frequent, are Gol Chauraha, Bakarmandi, Kalyanpur Chauraha, Vijay Nagar Chauraha, CTI, Ghantaghar and Colnelganj (Figures 6.3 – 6.5). Market areas where there is the practice of MSW burning, the majority of emissions are from these four grids (Table 6.2). However, small residue burning is a common practice at several locations in Kanpur.

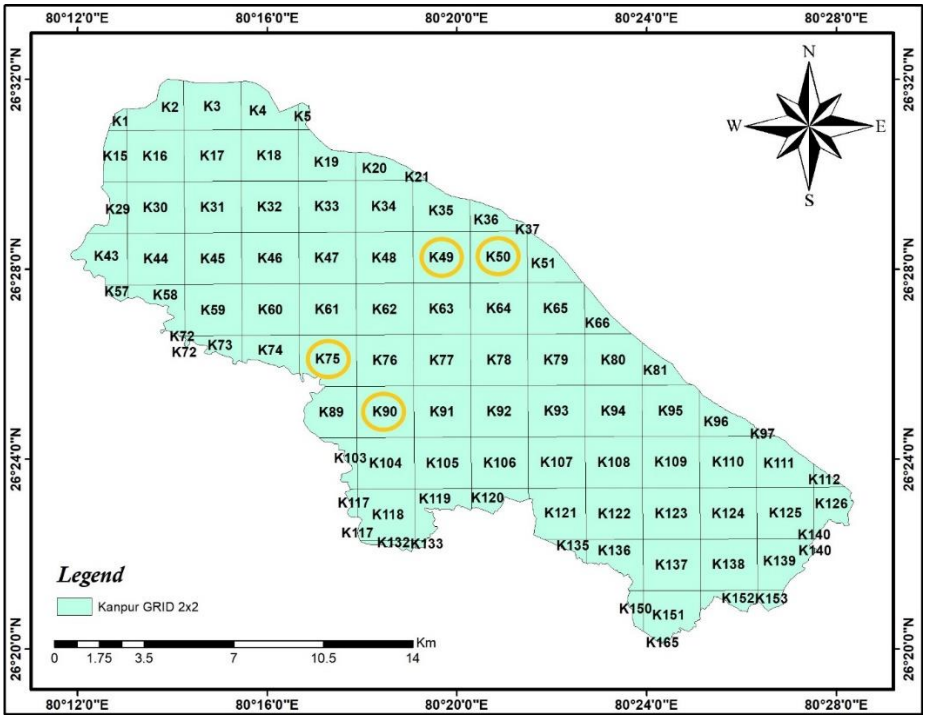


Figure 6.6: MSW burning prominent in the highlighted grids of Kanpur City

Table 6.2: Grid wise location and description for MSW burning in Kanpur City

Sr. No.	Priority Grid	Locations in Grids	Source Description	Remarks
1	K49	Harsh Nagar, Brahm Nagar	Refuse burning near residential areas	The burning of municipal solid waste must be stopped completely. Regular collection and segregation of solid waste. Hefty fines on those burning solid waste. Mass balance of waste generated collected and disposed of.
		Rambaugh, Colnelganj	Indiscriminate burning of solid waste near the roadside, open areas, and unauthorized dumping of solid waste on the roadside.	
2	K50	Mool Ganj, General Ganj		
3	K75	Barra, Ratanlal Nagar		
4	K90	Jarauli Phase 1, Damodar Nagar, Sanjay Gandhi Nagar		

A mechanism should be developed to carry out a mass balance of MSW generation, collection and disposal on a weekly and monthly basis. Major commercial areas identified for this issue were Parade Bazar, Shivalaya Market, Sisamau Bazar, Phool Bagh, Birhana Road, Chawala Market, Bakarmandi, Jawahar Nagar, Gumti Market, Dada Nagar, P. Road, Fazalganj, Naramau, Lal Bangla, Kakadeo, Nayaganj, Kalyanpur, Keshav Puram, Arya Nagar, Swaroop Nagar, Mall Road, Ashok Nagar, Panki, Kidwai Nagar, Barra, 80 feet road, Shastri Nagar, Kalpi Road, Jajmau. Major residential areas (having high density) were Rawatpur, Barra, Swaroop Nagar, Kidwai Nagar, Pandu Nagar, Naubasta, Shastri Nagar, Khyora, Lal Bangla, Nawabganj, Ramadevi, Fazalganj, Chaman Ganj, Yashoda Nagar.

The residential area having moderate population density was Rai Purwa, Vishnupur, Harjinder Nagar, Lajpat Nagar. Residential Areas having low population density were Bakar Ganj, Collector Ganj, Prem Nagar, Munshi Purwa, Nehru Nagar, Armapur Estate, Tilak Nagar, Gandhi Nagar, Khalasi Line, Ratanlal Nagar.

Desilting and cleaning of municipal drains by Kanpur Municipal Corporation should be undertaken on a regular interval, as the silt with biological activities can cause emission of air pollutants like H_2S, NH_3, VOCs, etc.

The official MSW dumping sites are located in Bhaunti and Panki and these sites have mountains of undisposed garbage. The MSW treatment and disposal sites should be developed and operated in complying with MSW waste management rules. The treatment and rightful

disposal of fresh waste should not take more than 7 days i.e. as storage becomes a major source of VOCs.

Sensitize people and media through workshops and literature distribution to prevent waste burning and its unauthorized disposal; this activity may be undertaken by Kanpur Municipal Corporation, UPPCB, and NGOs and municipal corporators.

The banning of MSW waste burning can reduce the emissions by 100% of PM_{10} (2071 kg/d) and $PM_{2.5}$ (1408 kg/d).

Helpline Number (For reporting complaints pertaining to air pollution viz., open burning, fugitive emission due to construction activities, etc.) should be created and advertised.

6.2.3 Brick Kilns

Brick kilns are one of the major contributors to air pollution from surrounding areas of Kanpur. The information on the number of the brick kilns and activity data were collected from CPCB and UPPCB and through satellite imagery. There are approximately 300 brick kilns in the airshed of Kanpur (Brick Kilns Summary and list, UPPCB, May 2019) (Figure 6.7). Although the brick kilns are outside the Kanpur city boundary, it is important to consider these brick kilns, as they contribute to the city's air pollution. Wood and coal are the prominent fuels being used in these brick kilns.

It has been found that 50% of the brick kilns were on Zig Zag technology and the remaining on conventional (Bull-trench) technology (emissions vary for two technologies).

Although brick kilns constitute a major economic activity and drive the construction industry, this sector needs to come under the formal sector with the best available technology with modern pollution control equipment.

The conversion of all remaining Brick Kilns to Zig-Zag technology can reduce emissions by 9.2 tons/d for PM_{10} and 6.4 tons/d for $PM_{2.5}$.

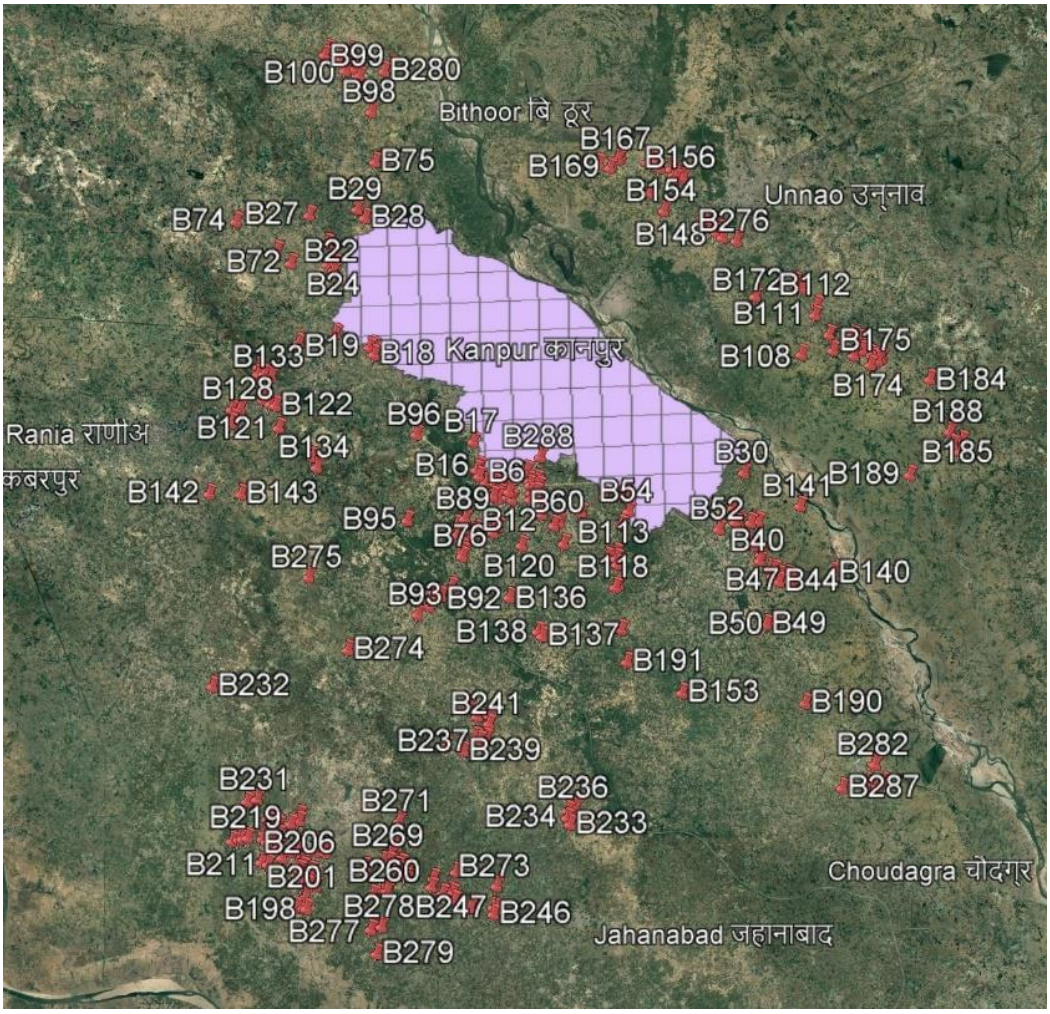


Figure 6.7: Location of Brick Kilns around borders of Kanpur City

6.2.4 Construction and Demolition

The construction and demolition (C&D) emission can be classified as temporary or short-term. In a developing urban area, these temporary or short-term construction activities are frequent. This source is one of the significant ground-level emission sources. Nearly at all the construction sites, the construction material and their debris (lying open, without cover) are being stored outside the construction premises, near the road. The flyover construction at the COD crossing, Panki thermal power plant, and elevated Kanpur metro were major construction activities identified during the study period. It is recommended that ongoing building construction activities should have the flagstaff till 10 m in height.

Every C&D activity should fully comply with C&D Waste Management Rules, 2016. A C&D waste recycling facility must be created, which is a common practice in large cities. The control measures for emission should include:

- Wet suppression
- wind speed reduction (for large construction sites)
- Waste should be properly disposed of and not stored on the premises or on the roadside.
- Proper handling and storage of raw material: covered the storage and provide the windbreakers.
- Vehicle cleaning and specific fixed wheel washing on leaving the site and damping down of haul routes.
- The actual construction area is covered by a fine screen.
- No storage (no matter how small) of construction material near roadside (up to 10 m from the edge of the road).

The above control measures should be coordinated and supervised under Kanpur Development Authority, Uttar Pradesh Housing Board, Kanpur Municipal Corporation, Urban Development Department, PWD, and UPPCB. In the gridded distribution of Kanpur City, prominent construction and demolition activities were seen in the highlighted grids K18, K33, K43, and K45 (Figure 6.8). Although there were small constructions in other grids also, the majority of emissions are from these four grids. The description of these grids is given in Table 6.3.

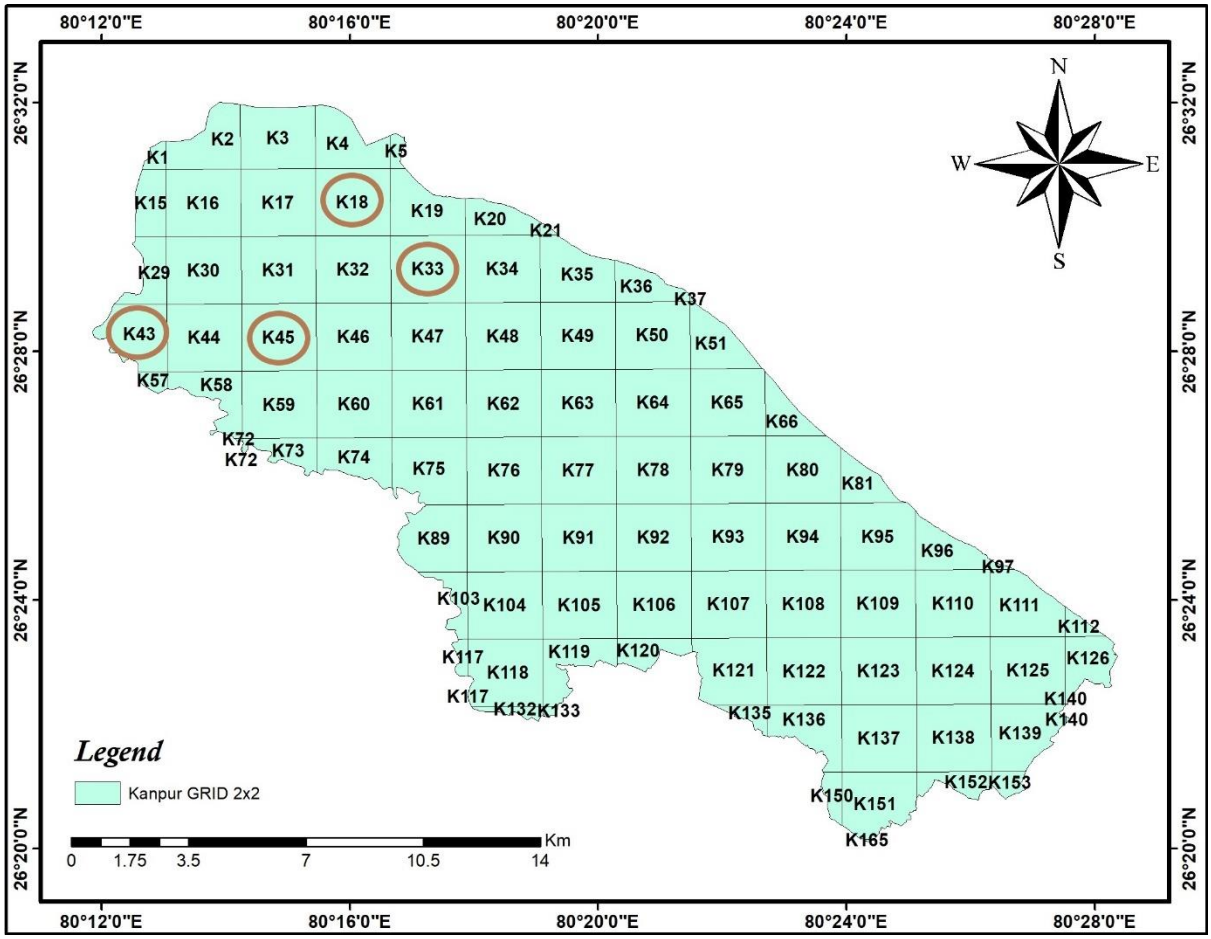


Figure 6.8: Construction and demolition prominent in the highlighted grids

Table 6.3: Grid wise location and description for Construction and demolition

Sr. No.	Priority grid	Locations in Grids	Source description	Remarks
1	K18	Kalyanpur (on GT Road)	Metro development project causing Construction Dust	Improved construction & demolition practices should be adopted.
			Indiscriminate dumping of construction material/debris (Boulders, Bricks)	Proper facility for construction material dumping
2	K33	Rawatpur Crossing	Metro development project causing Construction Dust	Improved construction & demolition practices should be adopted.
			Due to metro construction, the road is in bad condition. The road is having large potholes and the road is damaged.	
			Construction and demolition practice along the roadside	

Sr. No.	Priority grid	Locations in Grids	Source description	Remarks
3	K43	Bahera	Indiscriminate dumping of construction material/debris (Boulders, Bricks)	
4	K45	Panki	Indiscriminate dumping of construction material/debris (Boulders, Bricks)	
		Panki Powerhouse	The old power plant is being demolished. Panki power plant is in the construction phase, the fugitive dust emission is due to improper storage and handling of construction material.	

The suggested control measures will reduce the emission by 50% in PM_{10} (2114 kg/day) and 72% in $PM_{2.5}$ (486 kg/day). This will also reduce the road dust and fly ash contribution to ambient air concentration.

6.2.5 Household

Although in Kanpur, 82% of the households use LPG (CRISIL report) for cooking, the remaining 18 % uses wood, crop residue, dung, kerosene, and coal for cooking (Census-India, 2012). The Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil, HP, etc.) may formulate a time-bound plan for every household to have LPG. In the gridded distribution of Kanpur City, the prominent densely populated areas were found in highlighted grids K49, K50, K75, and K90 (Figure 6.9). Although there were other populated areas as well, they occasionally use wood/coal, but the majority of the emissions are from these four grids. The description of these grids is given in Table 6.4.

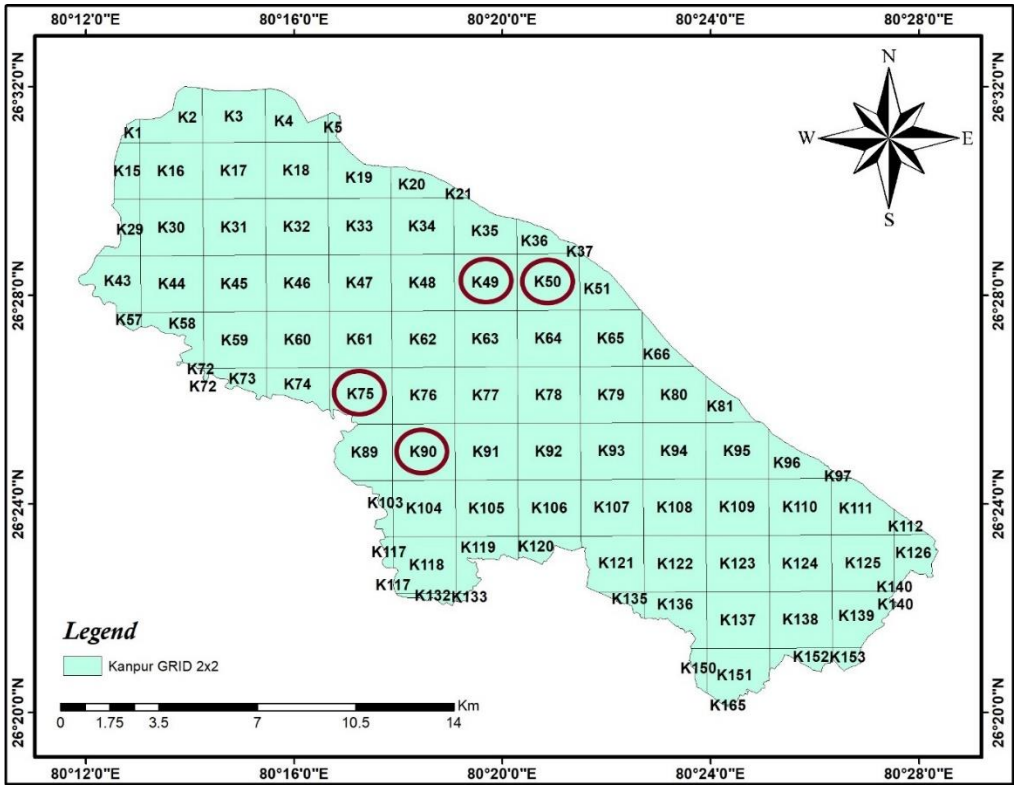


Figure 6.9: Domestic sector prominent in the highlighted grids of Kanpur City

Table 6.4: Grid wise location and description for Domestic sector in Kanpur using fuel other than LPG

Sr. No.	Priority Grid	Locations in Grids	Source Description
1	K49	Harsh Nagar, Brahm Nagar, Chamanganj, Colonel Ganj	Burning of wood and dung as fuel, LPG is commonly used, coal is also used as domestic fuel
2	K50	General Ganj, Moolganj, Civil Lines	wood and dung are used as fuel, LPG is commonly used
3	K75	Barra, Ratanlal Nagar, Tatyatope Nagar	coal is used as domestic fuel;
4	K90	Jarauli Phase 1, Sanjay Gandhi Nagar, Damodar Nagar	wood and dung are used as fuel, coal is also burnt as domestic fuel

The LPG should be made available to the remaining 18% of households to make the city 100% LPG-fuelled. By 2030, planning should be done that as many households as a possible shift to electric cooking. For new societies, buildings should have a good infrastructure for PNG.

This action is expected to reduce 82% of PM_{10} (2653 kg/day) and 81% of $PM_{2.5}$ (1857 kg/d) emissions from domestic sector.

6.2.6 Soil and Road Dust

It has been observed that the soil and road dust emission and its contribution to ambient air concentration are consistent and it is one of the largest sources of PM_{10} and $PM_{2.5}$ emissions. The silt load, important factor PM emissions from the road varied from 8.2 to 62.7 g/m^2 which is very high. The industrial area, where heavy vehicle movement is seen, also shows the high road dust emission. It is suggested that high traffic density roads should be properly maintained, paved from one end to another, have sidewalks through interlocking blocks for the pedestrians, proper drainage from the road, shrubs should be planted on-road divider. Out of the total road network, 70 percent of surface quality is poor.

The following control measures are suggested to reduce the dust emissions from the major roads:

1. Convert all unpaved, partially paved roads to fully paved roads. PWD (Public Works Department) and city administration should act immediately to reduce the pollution load from road dust.
2. Municipal Council should carry out vacuum-assisted sweeping. The efficiency of vacuum-assisted sweeping should be 90% (Amato et al., 2010) and this should be part of the specification with no leakages of collected dust vacuum trucks. If the sweeping is done twice a month, the road dust emission will be reduced by 42% (PM_{10}= 86653 kg/day and $PM_{2.5}$= 19930 kg/day).
3. If the silt road is greater than 3 gm/m^2, the vacuum-assisted sweeping should be carried out along with washing by the municipal council and the UPPCB should have the surveillance of this action.
4. NHAI should ensure that the silt load on GT Road and all highways maintained by them should have a silt load of less than 3 gm/m^2.
5. The condition of the roads must be maintained properly with no potholes and shoulders paved by interlocking concrete to have a proper sidewalk.
6. The truck carrying construction material, or any airborne material should be covered.
7. Vacuum sweeping of roads with high silt load locations (Fazalganj, GT Road,

Chunni Ganj, Kakadeo, Rawatpur, Kalyanpur, Deendayal Nagar, Dadanagar, CTI, Barra, Shyam Nagar, Avas Vikas, Govind Nagar, Maswanpur, Vijay Nagar, Galla Mandi, Jareeb Chowki, NH-34, VIP Road, Mall Road, NH-27) should be carried out at least four times a month also carpeting of shoulders, maintenance of the road, dividers, and kerbs should be carried out at regular intervals. This activity should have proper documentation including the quantity of dust collected from the roads.

8. Shrubs and perennial forages, or grass covers should be planted on the medians wherever possible.

In the gridded distribution of Kanpur City, the prominent bad roads with high silt load were found in highlighted grids K91, K94, K106, and K107 (Table 6.5). Other nearby grids K76, K77, K80, K90, K93, K95, K105, K108, and K109, which were also influenced by the priority grids have the areas like Saket Nagar, Kidwai Nagar, Lal Bangla, Vasant Vihar, Sadullahpur, Jajmau, Hanspuram, Harjendar Nagar, and Ahirwan respectively, also need attention along with priority grids (Figures 6.10 and 6.11).

Figure 6.10: Road Dust prominent on various roads

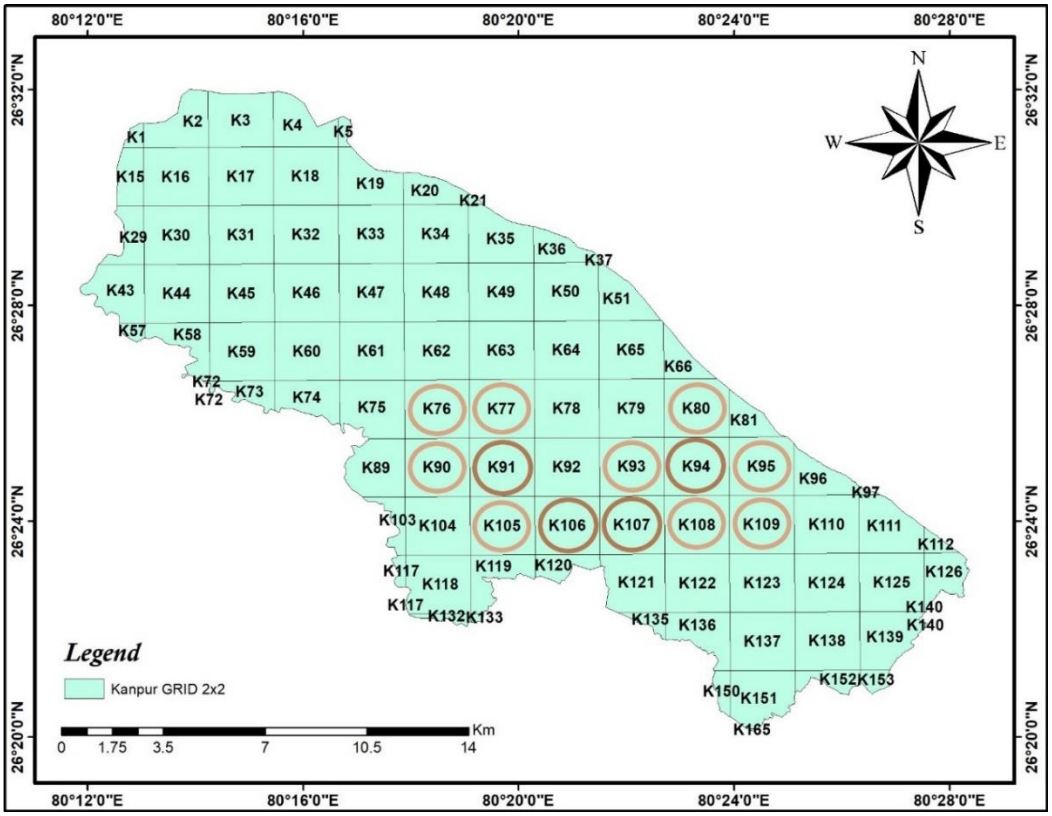


Figure 6.11: Road Dust prominent in the highlighted grids

Table 6.5: Grid wise location and description for Road Dust

Sr. No.	Priority Grid	Locations in Grids	Source description	Remarks
1	K91	Pashupati Nagar, Shankaracharya Nagar	Connecting Roads are broken, potholes and heavy silt load.	Nearby grids K76, K77, K90 and K105 Should also be considered.
			Kanpur Jhansi Highway Bridge roads are in okay condition, but silt load is high.	
			Kanpur Jhansi Highway side-road/parallel throughout are broken, potholes with heavy silt load and potholes.	
2	K94	Krishna Nagar, Gandhi Nagar	The presence of broken roads and may be considered unpaved roads.	Road's condition should be maintained properly.
		Ramadevi Chauraha	Ramadevi chauraha road under the bridge is in bad condition with potholes and a high silt load. This leads to traffic jams.	Nearby grids K80, K93, K95, 107, 108, and K109 Should also be considered.

Sr. No.	Priority Grid	Locations in Grids	Source description	Remarks
3	K106	Swarna Jayanti Vihar	Connecting roads are broken, maybe considered unpaved	Nearby grids K91 K105, and K108 Should also be considered.
		Koyala Nagar	Kanpur Jhansi Highway Bridge roads are in okay condition but the silt load is high.	
4	K107	Daheli Sujanpur	Construction and demolition practice along the roadside, causing high silt load.	
		Jawahar Puram	Road condition is not maintained properly, presence of potholes on road.	
		Shyam Nagar	Heavy dust accumulation on the roadside	

The above control measures should be coordinated and supervised by Kanpur Development Authority, Uttar Pradesh Housing Board, Kanpur Municipal Corporation, National Highway Authority, PWD, and State Forest Department (for increasing green cover and plantation) as per their jurisdictions.

For example, the quality of the road, silt load with less than 3.0 gm/m^2 and interlocked concrete shoulder undertaken at Hyderabad can be seen and employed in Kanpur (Figure 6.12)

Figure 6.12: Quality of dust-free Roads, footpaths and divider with dust control (Courtesy Greater Hyderabad Municipal Corporation)

6.2.7 Vehicle Emission Control, Congestion and Traffic Management

The vehicle emission contribution is significant for CO, NOx, PM_{10}, and $PM_{2.5}$. There is a relatively large contribution of diesel vehicles (trucks, buses, LCVs, cars, etc.) to PM_{10}, $PM_{2.5}$ and NOx. The source apportionment results show that Rama Devi, Jhkarkatti, and Dada Nagar have very large vehicle contributions (27 – 36% in winter in $PM_{2.5}$; Figure 4.34, Chapter 4) with an overall contribution of vehicles in the city is 30% of $PM_{2.5}$ in winter. Out of about 12.8 tonne/d emission of $PM_{2.5}$ from vehicles, over 80% is from diesel vehicles, especially from trucks and buses. Therefore, control measures have to focus on advanced technological intervention for diesel vehicles like Diesel Particulate Filter (DPF). The general recommendations for vehicular emission control are enumerated below (specific recommendations are discussed later).

1. Retro-fitment of DPF: These filters have a PM emission reduction efficiency of 60-90%. If the diesel vehicles entering and those in the city are equipped with DPF, there is a possible reduction of 40% of PM2.5 emissions. This option must be explored as Bharat stage VI fuel is available and this technology can be adopted.
2. Industries should encourage employing trucks and heavy-duty vehicles of Bharat stage VI or IV with DPF for transportation of the raw and finished products at and from the industry.
3. By the end of 2024, a target of 50% of the total registration of vehicles in the city should be EVs in the sector of 2Ws, 3Ws and passenger cars. A suitable subsidy or tax break may be considered to the individuals opting for EVs. Charging infrastructure should come up quickly at multiple places, including public buildings and parking lots and battery swapping facilities should be planned to avoid long charging periods especially for two-wheelers.
4. Emissions from in-use vehicles also depend on the maintenance and upkeep of vehicles. In this regard, it is suggested that each vehicle manufacturing company should have its authorized service centres in sufficient number to cater to the need of their vehicles in the city. The automobile manufacturing company-owned service centres (AMCOSC) should be fully equipped for complete inspection and maintenance of vehicles ensuring vehicles conform to emission norms and fuel economy after servicing. Every vehicle at least once a year should undergo a thorough check-up and compliance with pollution control devices and their proper functioning from an authorized centre.

5. The current official PUC centres in Kanpur are 15 *(Refer: Transport Department, Government of India)*. The number of PUC centres should increase to 90 based on the thumb rule of 3 PUC centres per ten thousand registered vehicles. Maintenance and calibration of equipment must be ensured by regular surveillance.
6. Restriction on plying and phasing out of 10 years old commercial diesel-driven vehicles.
7. Check the overload vehicles: Expedite installation of weigh-in-motion bridges and machines at all entry points to Kanpur to ensure that vehicles are not overloaded. There should be random checks on suspicious heavily loaded vehicles and a severe penalty is levied if they are found overloaded.
8. UPSRTC should plan and install multiple electric charging facilities in its depots (in Kanpur and other destinations) to quickly move towards electric buses.
9. The local public transport in the city should also move to electric buses. It is suggested that buses should be medium size of 30 seating capacity and provide better frequency for easy maundering in the city to avoid difficult turning and congestion.
10. Route rationalization: Improvement of availability by rationalizing routes and fleet enhancement with requisite modifications. Ensure integration of the existing metro system with bus service.
11. IT systems in buses, bus stops, and control centre and passenger information systems should be introduced for the reliability of bus services and monitoring.
12. The public transport system is inadequate. The large intracity passenger demand is met mostly by tempos and autorickshaws. The tempo movements are undisciplined, and they form multiple lanes, stop as per their will in the middle of the road and hardly follow any traffic rules; this leads to congestion and safety hazard. There should be designated places where tempos can stop to drop and take passengers/commuters. There is no tempo terminal facility thus these mushroomed up at one place completely blocking the road at the terminus.
13. The intersections are very poorly designed. There is a need to improve the intersections of roads at many places of Kanpur City. The traffic signal, wherever installed, does not function properly which leads to slow traffic movement and reduced road safety. Steps shall be taken to install traffic signals on all the major intersections and traffic police shall enforce smooth traffic.
14. Buses and trucks parked at G.T. Road between Jarib Chowki and Gol Chouraha should be stopped.

15. Other than a few roads, there is a lack of footpath availability and marking of zebra crossing for the pedestrian movements and people are forced to walk on the road. Proper footpaths and ease of crossing should be available for the pedestrians.

Decongestion of Roads

Kanpur is one of the most densely populated cities in the country. It is the main centre of commercial and industrial activities in the state. A chaotic, undisciplined, and poorly managed traffic is the norm in the city (Figure 6.13). Driving in the opposite direction of main traffic, a culture of me first, parking in no-parking areas and on-street parking are the major causes of traffic congestion and pose a safety hazard. The slow movement of vehicles results in much higher emissions than vehicles at smooth cruising speed. The large vehicles (Trailers and Trucks) majorly operate in the areas of Panki, Dadanagar, Kalpi road, and most of GT road and require specific attention including installation of DPF.

Figure 6.13: Traffic Chaos and Congestion on the roads

A real-deriving survey was undertaken to examine the vehicle speed pattern starting from IIT Gate (9:50 AM), Rawatpur, Gol chaurah, Jarib chowki, Ghantaghar, Nai sadak, Parade, Mall road, Tatmill, Vijay Nagar (12:30 pm) (Figure 6.14). During this peak morning time, the

average speed of the vehicle was only about 13.7 kilometre per hour with frequent braking and accelerating with no cruising period. The low speeds lead to a longer time on road causing large emissions. Further, under such driving conditions, emissions are often much higher than specified BS norms.

To increase the average speed and get full advantage of BS-VI, decongestion, removing encroachments from the roads, stopping unauthorized and improper parking is essential. The off-street parking is inadequate in the city causing jams and permanent congestion because of on-street haphazard parking.

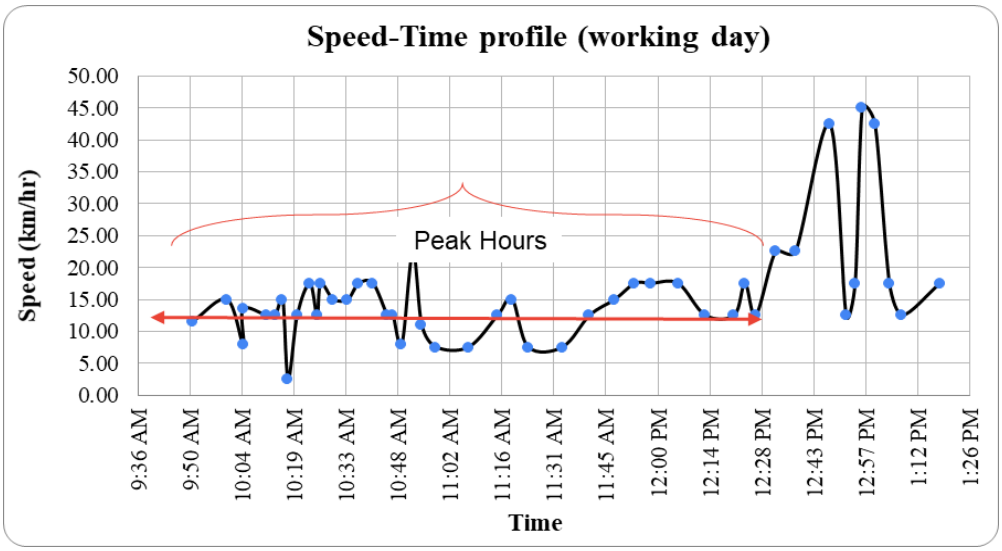


Figure 6.14: The speed - time profile during peak hours (mean speed 13.67 km/hr)

The criss-cross railway network passing through the middle of the city severely aggravates the traffic woes of commuters and ordinary citizens. There are 12 major and 4 small level crossings in the city (Figure 15).

Figure 6.15: Major Railway crossing along GT Road

It was observed that once a train is to pass some 6-7 crossings are closed at the same time which leads to severe traffic congestion not only at side roads but also on GT road. The specific points that will help in decongestion are elaborated below.

- Heavy encroachment by shopkeepers and street vendors is observed in the commercial area and in residential areas, and vehicles are parked on the road. The parked vehicles take up to 40% of the road width, although one-third of the roads are more than 30 m wide. This reduces road utilization by about 50 percent.
- The unauthorized vehicle service centres located near the road make things worse as the vehicle is parked on-road while servicing and repairing and oil and grease spillage can be seen, some of the areas where these unorganized shops can be seen are IIT-Kanpur Gate, Bakarmandi, Harsh Nagar, Fazalganj, Govindnagar, Naubasta.
- Jhakakarkati bus stand is located in the center of the city (near Kanpur Central Railway Station), inter and intra city bus movements become heavy in this area and there is heavy traffic congestion because of road configuration and the narrow flyover opening on the entrance of the bus stand. The nearby area of this bus stand is tightly jammed as the buses used to stop on-roads and within 10-15 minutes, traffic jam reaches to 400-500 meters on all sides.

  It is recommended that the Jhakarkatti bus stand is shifted to some other location at the

outer periphery of city limits. It is proposed that the city should have three different modern bus terminals to cater movement of inter-city buses in three different directions (to Lucknow, to Pryagraj and Kannauj).

- The Rawatpur railway station area is congested and it is a common site for inter and intra-city buses, which are parked randomly and pick up the passengers. This bus stop at Rawatpur should be discontinued and suitably relocated as it is causing serve congestion.
- Heavy-duty vehicles and buses which are destined for other cities pass through major roads within Kanpur city and create heavy congestion. The important point of congestions is Naubasta Chaburah. For example, vehicles coming from Jhansi and going towards Hamirpur or vice versa can be avoided by constructing flyovers at Naubasta Chaburah and similarly a connecting flyover for vehicles coming/going from Hamirpur. As a result of connecting flyovers, other major connecting routes within the city will also decongest.
- Areas that are adjacent to the market centres like P.Road, Parade, Shivalay, Naveen Market, and Gumti experience heavy traffic congestion due to the unregulated parking and encroachment by local shop owners. The Gumti and P. Road are commercial and mixed-use areas and encroachments along the road and of corridors are common and leave no space even for pedestrians. The on-street parking has to be removed and if required multistorey parking is developed (discussed later).

During the traffic recording and survey done by IIT Kanpur, the following major intersections are identified as traffic bottlenecks (Table 6.6 and Figure 6.16).

Table 6.6: Major Traffic Bottleneck at Kanpur City

Ramadevi	Rajiv puram crossing, Kakadev
Tatmill chauraha	Survodya Nagar crossing
Jakarkati bridge	Shastri Nagar crossing
Bans mandi crossing at GT road	Vijay Nagar
Afim koti	Darshan Purva
Jarib chowki	Kidwai Nagar crossing
Gumati railway crossing	Saket Nagar crossing
Coca cola crossing	Bada Chauraha
Chhapeda Pulia	Deputy Padav
Rawatpur crossing	Ghanta ghar
Gurudev crossing	Moolganj chauraha
Kalyanpur crossing	Kanpur Central

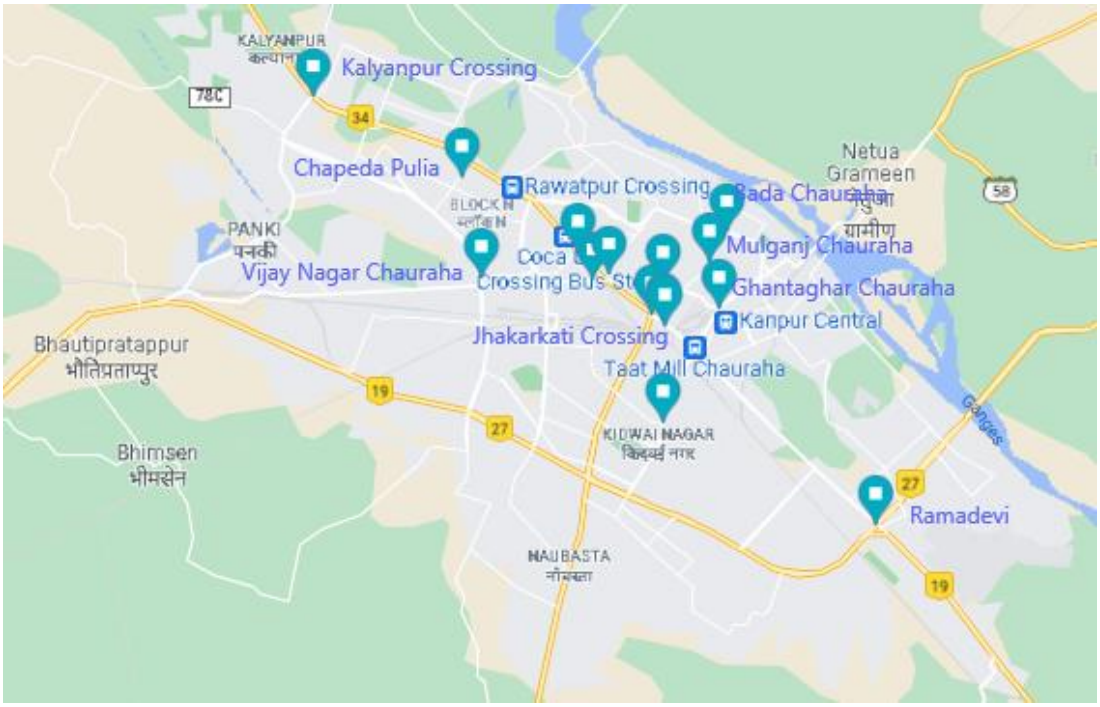


Figure 6.16: Location of traffic bottlenecks

The surveyed areas for traffic congestion were plotted in GIS and shown in grids (Figure 6.17), the prominent vehicular moments were found prominent in highlighted grids K49, K90, K94, and K106. Other prioritized grids for the vehicular moment were observed in the areas of grids K17, K31, K32, K33, K44, K45, K47, K48, K49, K58, K59, K62, K63, K74, K75, K76, K77, K78, K79, K81, K90, K91, K92, K93, K94, K106, K107, and K108 have the areas like Kalyanpur, Maswanpur, Sharada Nagar, Gangaganj Colony, Panki, Vijay Nagar, Narainpurawa, Chamanganj, Fazalganj, Anwar Ganj, Gujaini, Barra, Saket Nagar, Juhi, Babu Purawa, Kanpur Cantonment, Ashrafabad, Jarauli, Pashupati Nagar, Bada Chauraha, Devaki Nagar, Shyam Nagar, Lal Bangla, Swarna Jayanti Vihar, Daheli Sujanpur, and Harjendar Nagar respectively, which also need decongestion for smooth traffic operation. The description of these grids are given in Table 6.7.

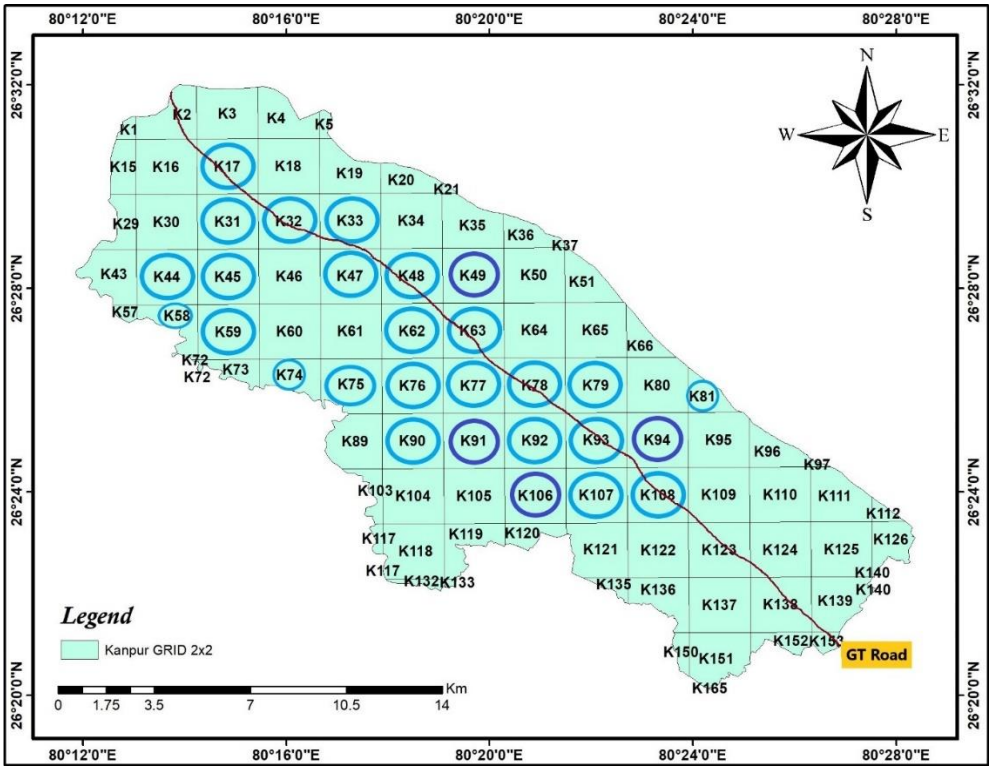


Figure 6.17: Vehicular moment prominent in the highlighted grids of Kanpur City

Table 6.7: Grid wise location and description congested Vehicular moment in Kanpur City

Sr. No.	Priority Grid	Locations in Grids	Source Description	Remarks
1	K49	Jarib Chowki	Traffic congestion on road, cars, Bus movement towards the city. Frequent stopping on roads also causes jams, No traffic Management.	Following Grids should be considered for smooth traffic flow K17, K32, K33, K47, K48, K49, K63, K62, K77, K78, K79, K93, K94, K108, K81, K91, K107, K106, K92, K90, K76, K75, K74, K59, K31, K45, K44, and K58.
			the heterogeneous composition of Autos, Tempos, Rickshaws, Cycles, two-wheelers,	We need to decongest the above grids to have a smooth flow of traffic in the city.
			unauthorized parking of 3Ws on roads causing heavy traffic jams.	Remove on-road unauthorized parking from the above-mentioned grids
2	K91	Naubasta Bypass	Heavy movement of trucks and Buses. Roadside parking. No traffic management.	

Sr. No.	Priority Grid	Locations in Grids	Source Description	Remarks
3	K94	Ramadevi Chauraha	Heavy movement of trucks and Buses. Roadside parking. No traffic management.	
4	K106	Kanpur Jhansi Highway	Heavy movement of trucks and Buses. Roadside parking. No traffic management.	

Parking spaces

The off-street parking is inadequate in the city. Probably similar to the city of Agra, over 55% of major roads are taken by on-street parking causing jams and permanent congestion.

There must be no Parking zone (up to 50 m including auto, electric and hand-pulled rickshaw) near the intersections (Figure 6.18) it will help the smooth traffic flow. Certain parking policies in congestion areas (high parking costs, at city centers, only parking should be limited for physically challenged people.

The city should strictly follow Recommendations from IRC 12-2015 of prohibiting on-street parking as detailed below:

- Near Intersections: the capacity of an intersection is greatly reduced if vehicles are allowed to park on the approaches. Visibility is also adversely affected & safety is reduced. It is the general practice to prohibit parking for a distance of about 50 m on the approaches to a major intersection.
- Narrow Streets: Narrow streets with heavy traffic require that all possible measures should be taken to remove obstacles to traffic flow. Prohibition of parking can have a salutary effect on traffic flow & congestion. In the busy street of the central area, it is generally desirable to prohibit parking on two-way streets with less than 5.75 m width & one-way streets less than 4 m width.
- Pedestrian Crossings: Desirable to prohibit parking within about 8.0 m from the pedestrian crossings.
- Structures: Structures such as bridges, tunnels and underpasses generally have a road way width less than the highway and for this reason, it is desirable to prohibit parking on them.

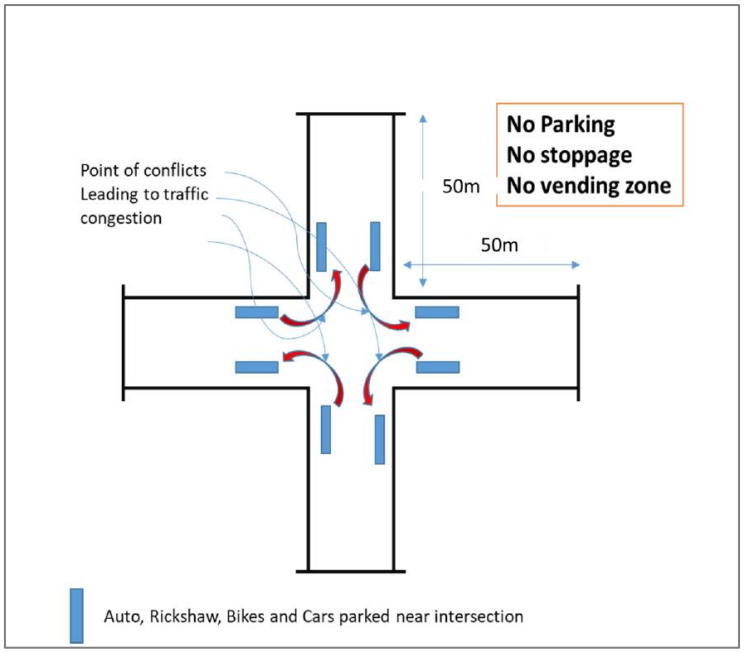


Figure 6.18: Conflicts due to on-street parking near intersections

There are modern technologies to facilitate multilevel car parking systems and the city should consider multilevel car parking systems in near future.

Automated Multilevel Car Parking Systems

Automated Car Parking Systems are much in vogue - a method of automatically parking and retrieving cars that typically use a system of pallets and lifts and signaling devices for retrieval. They serve advantages like safety, saving of space, time and fuel (since one does not have to drive around for locating space) but also need to have an extra and a very detailed assessment of the parking required, space availability and traffic flow. These can be further categorized into fully automatic or semi-automatic systems.

Dependent/Stack System: This allows two passenger cars to be parked one above the other (Figure 6.19). Its single post saves space and offers flexibility. Besides a platform (curved at the ends to allow the car to roll on/roll off conveniently) there is an operating control pendant that can be located anywhere in the garage, basement, and outdoor structure for operation from a safe distance.

Figure 6.19: Multi-level car parking (example)

Puzzle Car Parking Systems: Here the cars move vertically and horizontally like a puzzle, till the car required comes to the lower level where it is driven out (Figure 6.20). Installed in basements, rooftops, under stilts, open grounds, terraces, driveways, etc the system is designed in the form of a matrix of rows and columns such as 2 x 2 or 2 x 3, etc in which out of the total number of available spots, a certain number of spots are kept vacant to enable horizontal and vertical movement of remaining spots.

Available in the range of two to six levels, all the cars are independent of each other and the system can be installed in a phased manner.

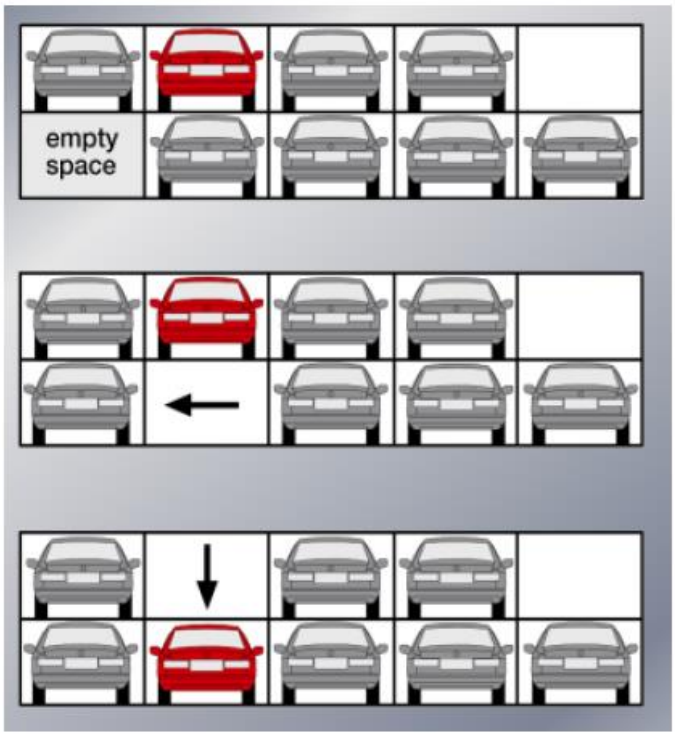


Figure 6.20: Puzzle Car parking system

Parking prices

Since on-street parking has been a major concern within the region, strict guidelines need to be adopted to discourage private vehicles in the settlements. In some areas, parking charges of Rs. 50 per hour needs to be introduced in the city. Also, the building norms must have the mandatory provision of parking at everyone's house. Unauthorized on-street parking must be penalized and strict monitoring of compliance of defined rules to be enforced. "No parking zone" and no-vending zones signs should be placed at required locations exhibiting parking issues and they should also be painted on roads with clear markings.

The introduction of one-way traffic routes (e.g., Sisamau Bazar, Chawla Market) can play a vital role in the decongestion plan. Stretches like Narauna Market, Birhana Road, Gumti, and Jawahar Nagar in Kanpur have their effective road widths reduced due to on-street parking. Mostly, the parking is done on the walkways, and there is insufficient street space for pedestrians, cyclists, and public transport. At some places, there do exist parking places but still, people prefer to park on-street because of lower convenience and high prices at designated parking.

GT Road

There are about 14 major railway crossings along the GT road and they are the major traffic bottlenecks. The commuters tend to barge into the wrong/opposite lane further aggravating the congestion. Motorists show complete indiscipline (Figure 6.21). The high frequency of railway traffic through these crossings results in long queues of the vehicle on both sides of the boom barrier. Further, at few places, there is no median dividing the roads approaching these crossings. It is therefore recommended that the medians should be extended till the boom barrier and there should be the presence of traffic police so that no vehicle comes in the wrong direction; if necessary one-way road spikes can be installed (Figure 6.22).

Figure 6.21: A typical traffic due to vehicle in the wrong lane

Figure 6.22: One-way traffic spike strips

- The proposal of foot-over bridges across the main areas along GT road, possibly with escalators should be provided.
- Two major railway crossings just 400 m apart are Kalyanpur and Baghiya are major traffic bottlenecks both due to the large volume of traffic and narrow roads. The high

frequency of railway traffic through several railway crossings results in long queues of the vehicle on both sides of the boom barrier spilling over the main road. The commuters tend to barge into the wrong/opposite lane further aggravating the congestion. Since it is no possible to have the flyovers at all crossings a system of smooth U-turns and approach to railway crossing is proposed (Figure 6.23). This system can be employed at several locations on the GT road.

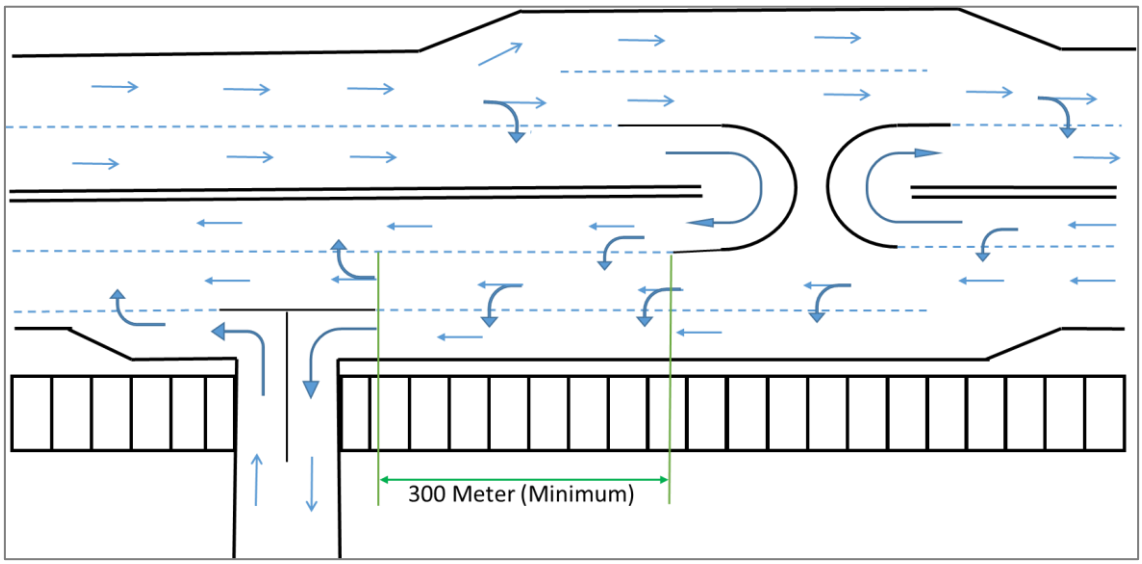


Figure 6.23: U-turn and smooth traffic at Levels crossings.

In addition, there is a requirement of at least 6 ROB's between Jarib Chowki and Kalyanpur and also at Shyam Nagar, Dada Nagar, Govind Nagar and one running parallel to Govind Puri Railway Bridge.

Promoting Public Transport Travel

Increasing the efficiency of public transport can deliver benefits of enhanced road capacities, accessibility and safety, and security. Thus, it is proposed to improve the efficiency of the existing public transport system and bring in a new fleet of low-floor electric buses. The size of these buses (e.g. a 30-seater minibusses) should be decided to keep in mind the limited road width available at several locations in the city. Since the oversized buses tend to occupy most of the carriageway and further leads to congestion at bottlenecks while turning.

6.2.8 Industries

Besides PM pollution (discussed later), ambient air samples collected at Dada Nagar industrial area during the winter months show very high levels of lead (in PM_{10}: 29 µg/m^3 and $PM_{2.5}$: 20 µg/m^3); these levels are not acceptable given the toxicity of lead. There are more than 35 lead smelting units and are claimed to have control devices installed. The devices are inadequate or poorly operated with very low collection efficiency.
Given that these lead units are in the highly populated mixed land-use area, it is suggested that these industries shift to other areas with low population density and with highly efficient capture devices and suitable disposal of collected lead particles.

It is also observed that the majority of industries use coal as fossil fuel in the industries. Since the industrial area is in the middle of the city, the industry should shift to PNG or LDO or other cleaner fuels in a time-bound manner possibly in one year.

In the gridded distribution of Kanpur City, the prominent locations of Industries were found in highlighted grids K47, K59, K60, K63, K80, and K95 (Figure 6.24). Although there were small industries scattered all around Kanpur City, the majority of emissions are from these six grids. The description of these grids is given in Table 6.8.

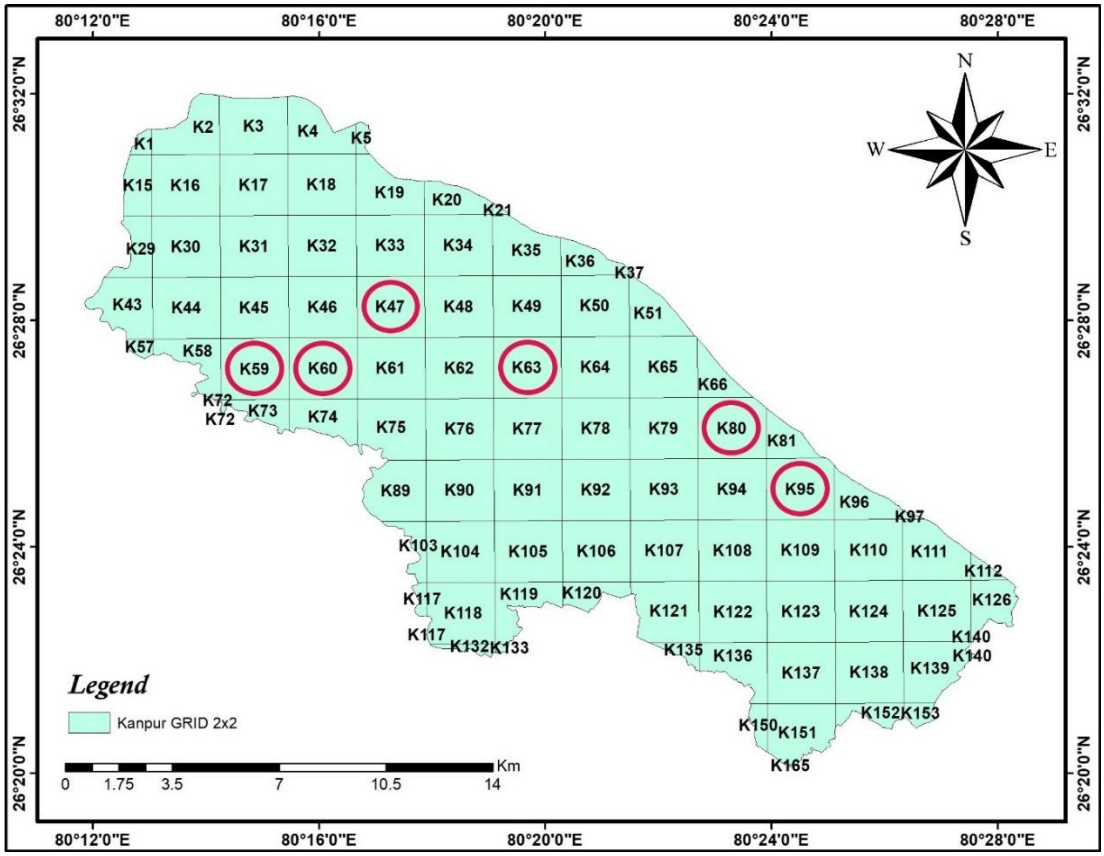


Figure 6.24: Industrial areas prominent in the highlighted grids of Kanpur City

Table 6.8: Grid wise location and description for Industrial areas in Kanpur City

Sr. No.	Priority grid	Name/Identity of Source	Source Description	Remark
1	**K47**	Naveen Nagar, Double Pulia, Vijay Nagar, Pandu Nagar	Coal as fuel is a major source of high emissions, Boiler of high-capacity causes emission	Shift to cleaner fuels. All industries in Kanpur should only use natural gas or electricity as a primary energy source.
				Installation by major air polluting industries in Kanpur of continuous real-time stack monitoring stations
			The industrial area also lying-in adjacent grid no. K61	Strict surveillance of industries needs to be done
2	**K59**	Panki industrial area	The boiler of high-capacity causes emission	
			Coal as fuel is a major source of high emissions	

Sr. No.	Priority grid	Name/Identity of Source	Source Description	Remark
3	**K60**	Nauraiya Khera, Dabauli	Multiple DG sets are used	
			Coal as fuel is a major source of high emissions	
4	**K63**	Fazalganj Industrial Estate, Param Purwa Juhi	Coal as fuel is a major source of high emissions	
			Multiple DG sets are used	
5	**K80**	Lal Bangla, Chebil Purwa		
6	**K95**	Jajmau, Gaukheda, Chakeri		

A coordinated effort under the supervision of UPPCB and Industries Departments is suggested to implement the following control measures:

- The majority of industries use multi-cyclones as air pollution control devices. It is recommended that these cyclones should be replaced by baghouses for effective control of particulate emission.
- Ensuring compliance with emission standards in industries: All industries causing Air, Water, and Noise pollution shall be made compliant w.r.t environmental regulations.
- Strict action to stop unscientific disposal of industrial waste in the surrounding area.
- Industrial waste burning should be stopped immediately which is seen in the industrial area especially packing materials.
- The area and road in front of the industry should be free from any storage or disposal of any waste or raw material.
- The industry should follow best practices to minimize fugitive emission within the industry premises; all leakages, transfer points, loading and unloading, material handling within the industry should be controlled.
- Adequate and quality electric supply should be available to the industries for an effective industrial operation and avoidance of the DG sets.
- It is seen that industrial waste (hazardous) is mixed with MSW and burnt in several parts of Kanpur. It is recommended that no industrial waste should be mixed with MSW rather disposed of at TSDF for hazardous waste disposal.

- There are industries with induction furnaces, which is a very pollution process, with almost no pollution control devices. The maximum emissions occur when the furnace lids and doors are opened during charging, back charging, alloying, oxygen lancing (if done), poking, slag removal, and tapping operations. These emissions escape from sides and top the building.
- To address the pollution caused by fugitive emissions using induction furnaces a fume gas capturing device has been developed and commercially available. A side-based suction (Figures 6.25 – 6.27) is far more effective than top suction, which interferes with the movement of the crane.

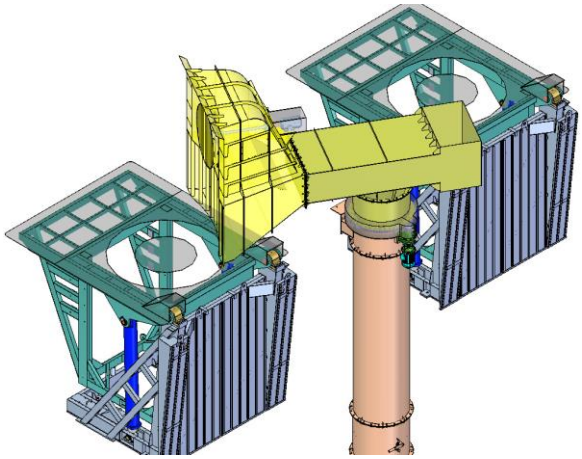


Figure 6.25: Proposed Suction Hood (Pic courtesy: Electrotherm)

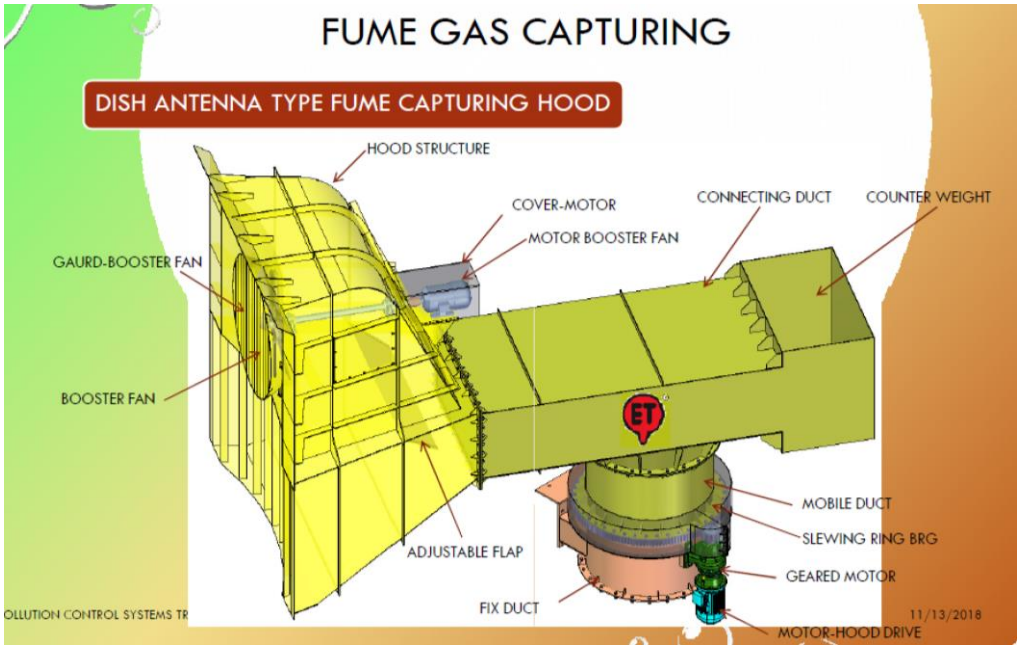


Figure 6.26: **Side-based Suction Hood (Pic courtesy: Electrotherm)**

Figure 6.27: Working of side-based Suction Hood

- It is recommended that fume gas capturing hood followed by baghouse should be used to control air pollution.

The economics of the side-based suction hood for an induction furnace:

Assume capacity 8 tons per batch
Running time = 8 hrs.
Capital Cost of Suction Hood= Rs. 40 lakhs
Electricity cost for Running for one year = Rs. 26.5 lakhs
Running + Capital Cost for ten years = Rs. 3.0 crore
Per year operational cost (including maintenance) = Rs. 30 lakhs
Turnover of the company per year = Rs. 3 crore

Pollution control cost is 10% of turnover. Which is somewhat high and may raise the question of the economic viability of the industry, especially when other such industries in the country do not do such a level of investment. The industry will need some support in terms of soft loans or even some subsidies.

It is seen that waste is burnt in industrial areas (Panki Industrial Area Site, Dada Nagar Co-operative Industrial Estate, Jajmau). Hazardous waste (oil, grease, and paint, packaging material) is dumped and burned on the roads in the areas like Fazalganj and Dadanagar, where the trucks are being repaired. Industrial waste burning must be stopped under the supervision of UPPCB. It is also seen that solid waste (all types) is dumped and stored just outside the premises of the industry; this is not acceptable and it looks unpleasant and at times spills over the road. It is recommended that there should be a separate industrial non-hazardous dumpsite for industrial waste, and they should not be allowed to dispose of the waste on roads or in front

of the industry. Strict compliance and surveillance are required that hazardous waste goes to TSDF under the supervision of Kanpur Municipal Corporation and UPPCB.

6.3 Summary of Actions and Control Options

It may be noted that air polluting sources are plenty and efforts are required for every sector/source. In addition, there is a need to explore and implement various options for controlling air pollutants. A list of potential control options (technical, administrative and management) based on the above discussion that includes interventions is presented in Table 6.9 for $PM_{2.5}$ and PM_{10}.

6.4 Strengthening of UPPCB Kanpur Regional Office

- New manpower recruitment for sampling, analysis, assessment, and surveillance
- Automated Stack Testing Kit
- The surveillance team should work in two shifts (day and night)
- Strict action against visible emission
- Proper documentation of violation of emission norms
- Capacity-building should be done through regular training of personals
- Laboratory Upgradation

Table 6.9: A Glance of Control Options and Action Plan for City of Kanpur (for details read section 6.2)

Source	Control Action	Responsible authorities	Time Frame (within specified time)
Hotels/ Restaurants/ Banquet Halls	All Restaurants small or large should not use coal and shift to gas-based or electric (for sitting capacity of more than 10 persons) appliances.	Kanpur Municipal Corporation	1 year
	Link Commercial license to clean fuel	Kanpur Municipal Corporation, Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	1 year
	Ash/residue from the tandoor and other activities should not be disposed of near the roadside. Requires ward-level surveillance.	Kanpur Municipal Corporations	1 year
Domestic Sector	LPG to all. Slums and about 15% of populations are still using wood, biomass and dung as cooking fuel.	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	1 year
	No new building complex or society be allowed without PNG supply distribution network	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	1 year

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	By 2030, the city may plan to shift to electric cooking (common in western countries) or PNG at the minimum	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	10 years
Municipal Solid Waste (MSW) Burning	Any type of garbage burning should be strictly stopped. Current waste collection and surveillance are poor.	Kanpur Municipal Corporation	Immediate
	Surveillance is required that hazardous waste goes to TSDF.	Kanpur Municipal Corporation, UPPCB	
	Desilting and cleaning of municipal drains	Kanpur Municipal Corporation	
	Waste burning in Industrial areas should be stopped.	UPSIDC, UPPCB	
	Daily, Monthly mass balance of MSW generation and disposal	Kanpur Municipal Corporation	
	Sensitize people and media through workshops and literature distribution as not to burn the waste.	Kanpur Municipal Corporation, UPPCB, and NGO	
Construction and Demolition	Wet suppression	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	Immediate

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Wind speed reduction (for large construction sites)	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	Enforcement of C&D Waste Management Rules. The waste should be sent to construction and demolition processing facility	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	Immediate
	Proper handling and storage of raw material: covered the storage and provide the windbreakers.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	Vehicle cleaning and specific fixed wheel washing on leaving the site and damping down of haul routes.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	The actual construction area should be covered by a fine screen.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	No storage (no matter how small) of construction material near roadside (up to 10 m from the edge of the road)	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	Builders should leave 25% area for green belt in residential colonies to be made mandatory.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD	
	Sensitize construction workers and contract agencies through workshops.	Kanpur Development Authority, Kanpur Municipal Corporation, Urban Development Department, PWD, UPPCB, and NGO	
Road Dust	The silt load in Kanpur varies from 8.2 to 62.7 g/m^2. The silt load on each road should be reduced under 3 gm/m^2. Regular vacuum sweeping should be done on the road having a silt load above 3 $gm/m^{2.}$	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, PWD, UPPCB (for silt load compliance)	Immediate
	Convert unpaved roads to paved roads. Maintain pothole-free roads.	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, PWD, UPPCB to carry out surveillance	

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Implementation of truck loading guidelines; use appropriate enclosures for haul trucks and gravel paving for all haul routes.	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, PWD	
	Increase green cover and plantation. Undertake to the green of open areas, community places, schools, and housing societies.	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, State Forest Department, PWD	
	vacuum-assisted sweeping is carried out four times a month on major roads with road washing.	Kanpur Development Authority, Kanpur Municipal Corporation, National Highway Authority, PWD	
Vehicles	Diesel vehicles entering the city should be equipped with DPF which will bring a reduction of 40% in emissions (This option can be implemented with vehicles of BS-IV category as well)	State Transportation Department	3 years
	Industries must be encouraged to use BS-VI or BS-IV (with DPF) vehicles for transportation of raw and finished products	Industrial Associations and State transport Department	Immediate

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Restriction on plying and phasing out of 10 years old commercial diesel-driven vehicles.	Transport Department	2 years
	Introduction of cleaner fuels (CNG/ LPG) for all vehicles (other than 2-W).	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.)	2 years
	Check overloading: Expedited installation of weigh-in-motion bridges and machines at all entry points to Kanpur.	Transport Department, Traffic Police, Kanpur, NHAI, Toll agencies	Six-months
	Electric/Hybrid Vehicles should be encouraged; New residential and commercial buildings to have charging facilities. All new city buses should be electric.	Transport Department, Kanpur City Transport Services Ltd	1 year
	Bus stop and their parking should be rationalized to ensure more efficient utilization. The depots should include well-equipped maintenance workshops. Adequate charging stations.	Transport Department, Kanpur City Transport Services Ltd	1year

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Enforcement of bus lanes and keeping them free from obstruction and encroachment.	Kanpur Municipal Corporation, Kanpur City Transport Services Ltd	1 year
	Ensure integration of the upcoming metro system with bus services.	Kanpur Metro Rail Corporation, Kanpur Development Authority, Kanpur Municipal Corporation, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	1 year
	Route rationalization: Improvement of availability by rationalizing routes and fleet enhancement with requisite modification.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	1 year
	IT systems in buses, bus stops, and control centers, and passenger information systems for the reliability of bus services and monitoring.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	1 year
	Movement of materials (raw and product) within city should be allowed between 10 PM to 5 AM.	Transport Department, Kanpur, Kanpur Development Authority, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	1 year
Industries and DG Sets	Ensuring emission standards in industries. Shifting of polluting industries.	UPPCB, Industries Department	1 year

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Strict action to stop unscientific disposal of hazardous waste in the surrounding area	Municipal council and UPPCB	
	There should be separate Treatment, Storage, and Disposal Facilities (TSDFs) for hazardous waste.	Industrial Associations, UPSIDC, Industries Department, UPPCB	2 years
	Industrial waste burning should be stopped immediately	Industrial Associations, UPSIDC, UPPCB	Immediate
	Following best practices to minimize fugitive emission within the industry premises, all leakages within the industry should be controlled	Industrial Associations, UPSIDC, UPPCB	Immediate
	Area and road in front of the industry should be the responsibility of the industry	Industrial Associations, UPSIDC, UPPCB	
	Category A Industries (using coal and other dirty fuels)		
	About 707 boilers and furnaces in Kanpur are running over coal, wood, and other dirty solid fuels which should be shifted to natural gas and electricity	Department of Food, Civil Supplies and Consumer Affairs and Oil Companies (Indian Oil/HP, etc.), Industrial Associations, UPPCB	2 years

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Almost all rotary furnaces having significant emissions are running on coal that needs to be shifted to natural gas and electricity	Industrial Associations, UPPCB	2 years
	Multi-cyclones should be replaced by baghouses. Ensure installation and operation of air pollution control devices in industries.	Industrial Associations, UPPCB	2 years
	Category B Industries (Induction Furnace)		
	Recommended Fume gas capturing hood followed by Baghouse should be used to control air pollution	Industrial Associations, UPPCB	2 years
	Diesel Generator Sets		
	Strengthening of grid power supply, uninterrupted power supply to the industries	State Energy Department, JVVNL	2 years
	Renewable energy should be used to cater to the need of office requirements in the absence of power failure to stop the use of DG Set	Industrial Associations	2 years
	Dada Nagar area had very high lead levels. There are more than 35 secondary lead smelting units in the	UPPCB	1 year

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	area. Given that these lead units are in the highly populated mixed land-use area, it is suggested that these industries shift to other areas with low population density and with highly efficient capture devices and suitable disposal of collected lead particles.		
Decongestion of Roads at high traffic areas	Strict action on roadside encroachment. Disciplined movement of tempos to stop only at designated spots. Action on driving in the wrong lane	Kanpur Development Authority, Kanpur Municipal Corporations, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	6 months
	Disciplined Public transport (designate one lane stop).	Kanpur City Transport Services Ltd., Traffic Police, Kanpur	
	Removal of the free parking zone. No parking within 50 m of any major crossing and or chaurahs, rotaries. Strictly follow Indian Road Congress guidelines	Kanpur Development Authority, Kanpur Municipal Corporation, Kanpur City Transport Services Ltd, Traffic Police, Kanpur	
	Examine the existing framework for removing broken vehicles from roads and create a system for	Kanpur Development Authority, Kanpur City Transport Services Ltd, NHAI, Traffic Police, Kanpur	

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	speedy removal and ensure minimal disruption to traffic.		
	Synchronize traffic movements or introduce intelligent traffic systems for lane-driving.	Kanpur Development Authority, Kanpur City Transport Services Ltd, NHAI, Traffic Police, Kanpur	
	Mechanized multi-story parking at bus stands, railway stations, and big commercial areas. Remove at least 50 percent of on-street parking in the city	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, NHAI, Traffic Police, Kanpur	
	Identify traffic bottleneck intersections and develop a smooth traffic plan. For example, Ramadevi, Tatmill, Afimkothi, Jarib chowki, and Rawatpur crossing are the main bottlenecks for traffic.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, Traffic Police, Kanpur	
	Parking policy in congestion area (high parking cost, at city centers, only parking is limited for physically challenged people, etc).	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, NHAI, Traffic Police, Kanpur	

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	Jhakarkati Bus Stand causes extreme congestion and increased emissions and should be decongested at priority. It is recommended that the city should relocate these bus stations to the outskirts of the city.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, Traffic Police, Kanpur	
	The important point of congestions is Naubasta Chaburah. For example, vehicles coming from Jhansi and going towards Hamirpur or vice versa can be avoided by constructing flyovers at Naubasta Chaburah and similarly a connecting flyover for vehicles coming/going from Hamirpur. As a result of connecting flyovers, other major connecting routes within the city will also decongest.	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, Traffic Police, Kanpur, NHAI	2 years
	The high frequency of railway traffic through several railway crossings results in long queues of the vehicle on both sides of the boom barrier spilling over the main road. The commuters tend to barge into the wrong/opposite lane further aggravating the	Kanpur Development Authority, Kanpur City Transport Services Ltd, Kanpur Municipal Corporations, Traffic Police, Kanpur, NHAI, Kanpur metro	1 year

Source	Control Action	Responsible authorities	Time Frame (within specified time)
	congestion. Since it is not possible to have the flyovers at all crossings a system of smooth U-turns and approach to railway crossing is proposed (Figure 6.23). This system can be employed at several locations on the GT road.		
*The above steps should not only be implemented in Kanpur municipal limits rather these should be extended to up to at least 25 km beyond the boundary. This will need support from the central government.			

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ANNEXURE 1

Table showing the Emission Factors (EF) used while estimating the emissions:

Source		Units	PM_{10}	$PM_{2.5}$	NOx	SO_2	CO
Cremation		g/kg	6.53	5.88	1.81	0.62	40.18
Domestic	Wood	g/kg	5.04	4.54	1.40	0.48	31.00
	Crop residue	kg/ton	11.00	9.90	0.49	0.12	58.00
	Dung	g/kg	5.04	4.54	1.40	0.48	31.00
	Coal	g/kg	13.20	4.60	3.99	13.30	24.92
	Kerosene	g/lit	0.61	0.55	2.50	4.00	62.00
	LPG	g/lit	2.10	2.10	3.60	0.40	2.00
Medical Incinerators		g/kg	2.33	2.10	1.78	1.09	2.95
DG Set		g/kwh	1.33	1.20	18.80	1.24	4.06
Industrial Area	LDO	g/lit	2.37	2.13	6.60	33.91	0.60
	HSD	g/lit	1.49	1.34	6.60	18.84	0.60
	LPG	g/kg	2.1	1.89	1.80	0.4	0.252
	Natural gas	kg/$(10)^6$ m^3	121.6	109.4	1600	9.6	1344
	Coal(cyclone)	g/kg	10.15	1.05	11.00	9.50	0.25
	Coal(scrubber)	g/kg	7.35	5.25	11.00	9.50	0.25
	Dal mill	kg/hr	85.00	-	-	-	-
Industrial Stack	LDO	g/lit	2.37	2.13	6.60	33.91	0.60
	HSD	g/lit	1.49	1.34	6.60	18.84	0.60
	LPG	g/kg	2.1	1.89	1.80	0.4	0.252
	Natural gas	kg/$(10)^6$ m^3	121.6	109.4	1600	9.6	1344
	Coal(cyclone)	g/kg	10.15	1.05	11.00	9.50	0.25
	Coal(scrubber)	g/kg	7.35	5.25	11.00	9.50	0.25
Vehicle	2 wheelers(BS-iii)	g/km	0.0365	0.03285	0.0107	0.00	2.37
	2 wheelers (BS-iv)	g/km	0.0365	0.03285	0.0107	0.00	1.00
	3 wheelers (CNG)	g/km	0.0096	0.00864	0.2550	0.00	1.00
	4 wheelers (BS-iii)(p)	g/km	0.0016	0.00144	0.0477	0.00	0.84
	4 wheelers (BS-iv)(p)	g/km	0.0013	0.00117	0.0358	0.00	0.06
	4 wheelers (BS-iii)(d)	g/km	0.0083	0.00747	0.14	0.00	0.3
	4 wheelers (BS-iv)(d)	g/km	0.0008	0.00072	0.1008	0.00	0.06
	4 wheelers (CNG)	g/km	0.0038	0.00342	0.2942	0.00	0.06
	LCV(CNG)	g/km	0.0297	0.02673	0.4549	0.00	3.66
	LCV(Diesel)	g/km	0.0339	0.03051	0.1692	0.00	3.66
	Bus (CNG)	g/km	0.0225	0.02025	0.4956	0.00	3.72
	Bus (Diesel)	g/km	0.0214	0.01926	0.5211	0.00	3.92
	Truck	g/km	0.03	0.027	0.6887	0.00	4.13
Power Plant	Coal	kg/ton	0.95	0.42	11.00	9.50	0.25
	Natural Gas	kg/$(10)^6$ m^3	121.60	109.40	4480	9.60	1344
	LDO	g/lit	2.37	2.13	6.60	33.91	0.60
	HSD	g/lit	1.49	1.34	6.60	18.84	0.60
Tandoor		kg/day	14.00	7.00	3.99	9.50	24.92
Construction		ton/acre/mth	1.2	1.08	-	-	-