Real-Time Source Apportionment and Forecasting for Advance Air Pollution Management in Delhi

Winter Season Report (Revised)

Submitted to

Delhi Pollution Control Committee
Delhi Government

IIT Kanpur, IIT Delhi, TERI, New Delhi, Airshed, Kanpur

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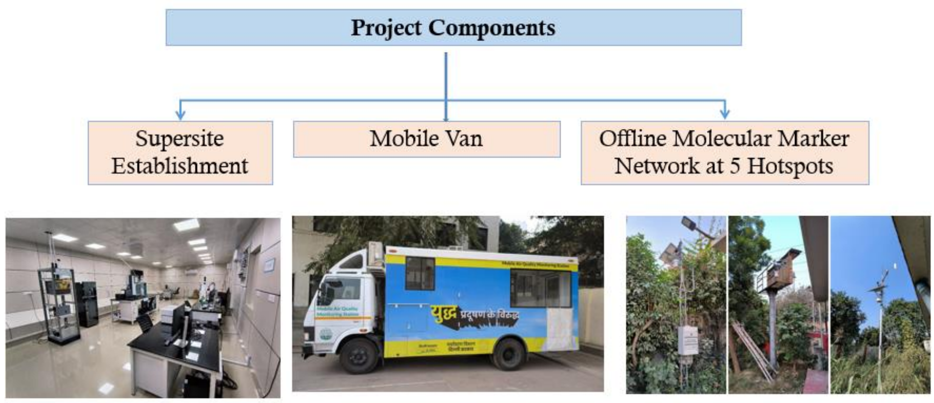
Executive Summary

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.). Being a national capital and major center of tourism, commerce, industry and education, Delhi has experienced a significant growth in recent years. The burgeoning population coupled with rapid growth in terms of vehicles, construction, and energy consumption has resulted in serious air pollution concerns in Delhi.

Understanding the air pollution sources is important to control and prevent $PM_{2.5}$ emissions. This requires the identification and contribution of the sources (source apportionment) at ambient air breathing level air quality in in space and time. In previous studies, typical ambient sampling devices collect integrated average samples of long durations and sent off to the laboratory for a time-consuming and labor-intensive analysis; this invariably provided low temporal resolution of 6-12 months which was not effective in taking short- or long-term actions.

Thus, there is a need of the hour that one should move from low temporal resolution source apportionment to high-resolution source apportionment studies i.e., real-time source apportionment. This enhancement will provide instant results and quick decision-making for the timely control of air pollution emissions.

To address the air pollution issues of the City of Delhi, the Delhi Pollution Control Committee (DPCC), Govt. of NCTD sponsored the project ‘Real-Time Source Apportionment and Forecasting for Advance Air Pollution Management in Delhi’ to the Indian Institute of Technology Kanpur (IITK) led consortium of IIT Delhi, The Energy Research Institute and Airshed Planning Professional, Kanpur.



The project had the following main objectives:

1. Establish state-of-the-art *supersite* capable of monitoring $PM_{2.5}$, NO_2, NOx, CO, SO_2, Ozone, elemental carbon, organic carbon, PAHs, elements, ions, secondary inorganic and organic aerosols, molecular markers, and other organic compounds.

2. Daily, weekly, monthly and seasonal interpretation of air quality to establish detailed and reliable source-receptor linkages for real-time source apportionment and suggest a higher level of controls at major sources, for example, road dust, industrial emissions, and alternative fuels, household emissions and other non-point sources.

3. ***Forecasting***: air quality and air quality index (AQI) at multiple locations, identify and locate the potential contributing sources within and outside Delhi, and control of potential sources wherever feasible.

4. Develop state-of-the-art mobile air quality laboratory for source apportionment at multiple locations to daily and weekly interpretation of air quality, source apportionment, and further strengthen local and far distant sources.

A supersite at Sarvodaya Bal Vidyalaya, Rouse Avenue, New Delhi was developed which is capable of measurement of $PM_{2.5}$, NO_2, NO_x, CO, SO_2, Ozone, elemental carbon, organic carbon, PAHs, elements, ions, secondary inorganic and organic aerosols, molecular markers, and other organic compounds.

Winter is the most critical season where levels of $PM_{2.5}$ exceed the national air quality standards (NAAQS) by a factor of five to six on certain days. It was observed that there are significant variations over the 24-hour cycle in hourly concentration and certain episodic periods of high concentrations were observed. Therefore, for effective control of $PM_{2.5}$.

The real-time source apportionment of $PM_{2.5,}$ results show secondary inorganic aerosols (SIA), which are mostly expected travel from far distances, contribution to be the highest. The average of winter season's source apportionment shows SIA (32 percent) and biomass burning (24 percent; within and outside Delhi) contribute the most followed by vehicles at 17 percent. On certain contribution of SIA, biomass burning, and vehicles can contribute up to, 60, 50 and 40 percent and others can exceed 35 percent. It suggests all sources withing and outside the city of Delhi should be controlled to improve the air quality.

Of all 120 days of winter, about 15 days (at supersite) were in severe AQI category, mostly in the month of November, December and first half of January; it may be noted that mean AQI of entire Delhi will be in the severe category for 8-10 days. The very poor days were about 65. On a monthly AQI basis, the month of December (AQI; 352) was the worst and it was relatively better in February (AQI; 255). The mean AQI of the winter season was observed to be 326.

In winter season, the mean contribution of SIA from the sources within Delhi (up to 30 km radius from supersite) is 16% and the rest 84 % from outside Delhi. We have estimated the breakup of contributions at different levels of time resolutions (see below)

Summary of contribution to SIA

a. 24-hour basis (SIA 75 $\mu g/m^3$ (33% of $PM_{2.5}$), November 30, 2022). The contribution to SIA:

   outside of Delhi's emission: 79% with NH_4 (31%), SO_4 (20%) and NO_3 (28%).

   inside of Delhi's emission: 21% with NH_4 (10%), SO_4 (1%) and NO_3 (10%).

b. Monthly basis (SIA 72 $\mu g/m^3$ (33% of $PM_{2.5}$), December 2022). The contribution to SIA:

   outside of Delhi's emission: 83% with NH_4 (30%), SO_4 (25%) and NO_3 (28%).

   inside of Delhi's emission: 17% with NH_4 (9%), SO_4 (1%) and NO_3 (7%)

c. Winter season (SIA 55 $\mu g/m^3$ (29% of $PM_{2.5}$), November – February 2023). The Contribution to SIA:

   outside of Delhi's emission: 83% with NH_4 (33%), SO_4 (24%) and NO_3 (26%).

   inside of Delhi's emission: 17% with NH_4 (9%), SO_4 (1%) and NO_3 (7%)

It may be noted that the above break up is only for SIA. The contribution of sources other than SIA to $PM_{2.5}$ is expected to be mostly from emissions within Delhi except for the period of crop residue burning.

The measured speciation of $PM_{2.5}$ permits estimation of contribution crop residue (*parali*) to $PM_{2.5}$ in Delhi. The impact of crop residue burning is estimated during the period November 1 to 25, 2022. In this period mean contribution of parali burning was 22%, however, on certain days, it was very high and exceeded 35 percent.

The WRF-Chem (Weather Research and Forecasting model coupled with Chemistry) model and artificial and machine learning (AI-ML) models are used for simulations of air quality forecast. The levels of $PM_{2.5}$ were forecasted for three days in advance. The AI-ML model forecast was accurate for about 85 percent of time. The forecasted $PM_{2.5}$ levels were translated into AQI for three days in advance for the entire city of Delhi both in space and time on hourly basis.

Web Portal (raasman.com) for Real-Time Advanced Air Source Management Network (R-AASMAN) was developed as a real-time air quality analyzing and visualizing web application. It represents the air quality status based on real-time pollutant measurements and meteorological conditions. Furthermore, to improve air quality, the software analyzes the pollutant data and helps identify pollution sources using a source apportionment algorithm called CMB (Chemical Mass Balance). Additionally, the forecast estimates the air quality conditions and the pollution source contribution for the next few days. Finally, on the basis of analysis, a report is inferred, and a detailed action plan is suggested (see the table below).

Table: Control Action Plan for Delhi City

Source	Control Action	Time Frame
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.	Short Term
	Link Commercial license to clean fuel	Short Term
	Ash/residue from the tandoor and other activities should not be disposed of near the roadside. Requires ward-level surveillance.	Short Term
Domestic Sector	LPG to all including economic weaker and temporary labours.	Short Term
	New building complex or society with PNG supply distribution network	Short Term
	By 2030, the city may plan to shift to electric cooking (common in western countries) or PNG at the minimum	Long Term
Municipal Solid Waste (MSW) Burning	Any type of garbage burning should be strictly stopped.	Short Term
	Desilting and cleaning of municipal drains	
	Waste burning in Industrial areas should be stopped.	
	Daily, Monthly mass balance of MSW generation and disposal	
	Sensitize people and media through workshops and	

Source	Control Action	Time Frame
	literature distribution so as not to burn the waste.	
Construction and Demolition	Wet suppression	Short Term
	Wind speed reduction (for large construction sites)	
	Enforcement of C&D Waste Management Rules. The waste should be sent to a construction and demolition processing facility	Short Term
	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 should be covered by a fine screen.	
	No storage (no matter how small) of construction material near the roadside (up to 10 m from the edge of the road)	
	Sensitize construction workers and contract agencies through workshops.	
Road Dust	The silt load in Delhi varies from 2.0 to 12.5 g/m^2. The silt load on each road should be reduced to under 2 gm/m^2. Regular vacuum sweeping should be done on the road having a silt load above 2 gm/m^2.	Short Term
	Convert unpaved roads to paved roads. Maintain pothole-free roads.	
	Implementation of truck loading guidelines; use appropriate enclosures for haul trucks and gravel paving for all haul routes.	
	Increase green cover and plantation. Undertake the green of open areas, community places, schools, and housing societies.	
	vacuum-assisted sweeping is carried out four times a month on major roads with road washing.	
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 the BS-IV category as well)	Long Term
	Industries must be encouraged to use BS-VI or BS-IV (with DPF) vehicles for the transportation of raw and finished products	Short Term
	Introduction of cleaner fuels (CNG/ LPG) for all	Long Term

Source	Control Action	Time Frame
	vehicles (other than 2-W).	
	Check to overload: Expedited installation of weigh-in-motion bridges and machines at all entry points to Delhi.	Six-months
	Electric/Hybrid Vehicles should be encouraged; New residential and commercial buildings to have charging facilities. All new city buses should be electric.	Short Term
	Bus stop and their parking should be rationalized to ensure more efficient utilization. The depots should include well-equipped maintenance workshops. Adequate charging stations.	Short Term
	Enforcement of bus lanes and keeping them free from obstruction and encroachment.	Short Term
	Route rationalization: Improvement of availability by rationalizing routes and fleet enhancement with requisite modification.	Short Term
	IT systems in buses, bus stops, control centers, and passenger information systems for the reliability of bus services and monitoring.	Short Term
	Movement of materials (raw and product) within the city should be allowed between 10 PM to 5 AM.	Short Term
	Incentivise and aggressively implement e-mobility including required charging infrastructure. Strategic plan for EV charging infrastructure at each 3 km in urban areas, 25 km on highways (both sides) and 100 km for buses and trucks and swappable battery stations.	
	Adequate vehicle scrappage infrastructure should be developed in next three years. Extended Producer Responsibility (EPR) may be considered for vehicle manufactures, who will have to build required vehicle scrap plants.	
Industries and DG Sets	Ensuring emission standards in industries. Shifting of polluting industries.	Short Term
	Strict action to stop unscientific disposal of hazardous waste in the surrounding area	
	Industrial waste burning should be stopped immediately	Short Term
	Following best practices to minimize fugitive	Short Term

Source	Control Action	Time Frame
	emissions within the industry premises, all leakages within the industry should be controlled	
	Area and road in front of the industry should be the responsibility of the industry	
	Multi-cyclones should be replaced by baghouses. Ensure installation and operation of air pollution control devices in industries.	Long Term
	Diesel Generator Sets	
	Strengthening of grid power supply, uninterrupted power supply to the industries.	Long Term
	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.	Long Term
	Efficient recovery system for solvents in chemical industries: The technologies suggest 95% recovery of VOCs is feasible and same may be adopted	Short Term
Decongestion of Roads in 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.	Short Term
	Disciplined Public transport (designate one lane stop).	
	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.	
	Examine the existing framework for removing broken vehicles from roads and create a system for speedy removal and ensure minimal disruption to traffic.	
	Synchronize traffic movements or introduce intelligent traffic systems for lane-driving.	
	Mechanized multi-story parking at bus stands, and big commercial areas. Remove at least 50 percent of on-street parking in the city.	
	Identify traffic bottleneck intersections and develop a smooth traffic plan.	
	Parking policy in congestion areas (high parking cost, at city centers, only parking is limited for physically challenged people, etc).	

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Real-Time Source Apportionment and Forecasting for Advance Air Pollution Management in Delhi

1 Background

Industrialization and emissions from various sources are on the rise. It is desirable that for existing areas stressed under high ambient pollution levels, scientific and systematic identification of sources and their contributions to ambient air are established for effective air quality management.

Air pollution is an important environmental component and requires an action plan that should be based on cause-effect analysis. However, this is not simple. The problem becomes more complex due to the multiplicity and complexity of the air-polluting source mix, automobiles, electricity generators, domestic fuel burning, roadside dust, construction activities, etc., which co-exist with industries (Nagar et al., 2017).

Understanding the pollution sources is important to control and prevent $PM_{2.5}$ emissions. This requires the identification and contribution of the sources at breathing levels in space and time. In previous studies, typical ambient sampling devices collect several hours of integrated average samples and are of low temporal resolution, which are then sent off to be laboratory analysis in a time-consuming and labor-intensive way (Chang et al., 2018, Cooper et al., 2010).

There is a need for the hour that one should move from low temporal resolution source apportionment to high-resolution source apportionment studies i.e., real-time source apportionment. This enhancement will provide instant results and quick decision-making for the timely control of air pollution emissions.

Researchers usually use two types of techniques to assess the impact of pollution sources. (i) source-oriented models, and (ii) receptor-oriented models. Especially for airborne particulate matter (PM both PM_{10} (particles of 10 micrometer and smaller) and $PM_{2.5}$ (particles of 2.5 micrometer and smaller)), receptor models based on a chemical mass balance and statistical analysis of pollutant concentrations observed at a receptor are preferred in complex urban environment (Belis et al., 2013). Figure 1 schematically presents the working of two modeling approaches. We need to understand the source-to-receptor linkage from either of these techniques or the synergy of these two techniques for the City of Delhi and NCR. A forecasting approach based on dispersion modeling (WRF-CHEM/CMAQ) should also be developed to control the local and far-distant sources well advanced in time.

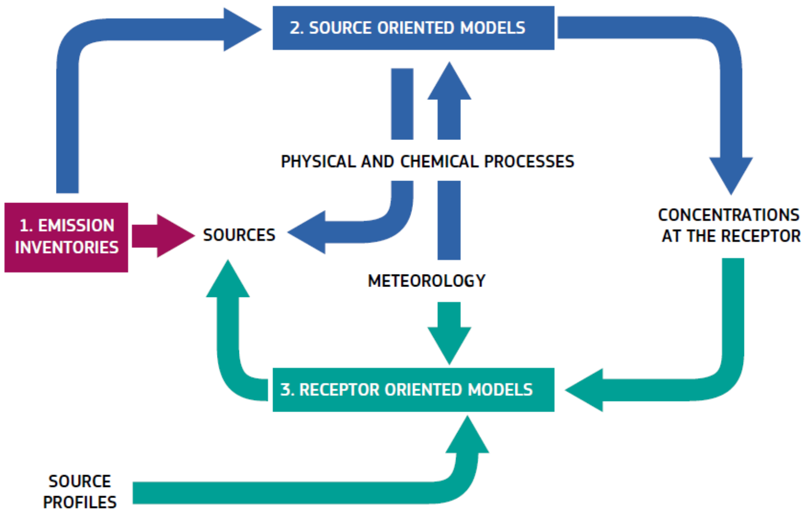


Figure 1: Methods for source identification (Belis et. al., 2014)

Delhi Pollution Control Committee (DPCC) signed the MoU with the IIT Kanpur lead consortium on October 22, 2021 to develop a state-of-the-art stationary air quality monitoring station i.e., supersite, conduct real-time source apportionment of sources deteriorating the air quality and interpretation of measurements for taking short and long-term actions. The supersite is in full operation from November 1, 2022 and it was formally launched by the Chief Minster of Delhi on January 30, 2023. This report presents the details of the supersite and results and findings from the winter sampling 2022-23.

A presentation was made on 31.03.2023 covering the operation of the supersite, source apportionment results and their interpretation and attainment of the objectives of the study. In this presentation, it was desired that another presentation covering detailed science and methodology shall be made. The second presentation was done on 06.04.2023 covering the detailed science and methodology. Based on this presentation, DPCC, through letter no. F (10)(13)/Env/2021/Part-II/1183, dated 10.05.2023, desired validation of models used in the study. A report covering the validation of model results was submitted to DPCC on 07.06.2023. Another detailed presentation was done on 09.08.2023, where officials from CPCB, Delhi, IMD, New Delhi and IITM, Pune were present. Based on this presentation, DPCC desired to (i) break down the measured species in $PM_{2.5}$ into receptor-model calculated species (within the source) and provide another level of validation with measured concentrations, (ii) break down the components of inorganic secondary $PM_{2.5}$ into sulphates, nitrates and ammonium, and (iii) these components be further divided into contribution from within Delhi and outside of Delhi. A report covering the above three points was submitted on 02.09.2023.

This is the revised report addressing the above issues including validation of results and break-up of secondary inorganic aerosols (NH_4, SO_4, NO_3) in terms of contribution from within Delhi and outside of Delhi, especially NCR (other than Delhi).

2 Objectives of the Study

The study had the following objectives:

2. Establish state-of-the-art *supersite* capable of monitoring $PM_{2.5}$, NO_2, NOx, CO, SO_2, Ozone, elemental carbon, organic carbon, PAHs, elements, ions, secondary inorganic and organic aerosols, molecular markers, and other organic compounds. This site will lead to the following levels of interpretation and decision-making:

    i. ***Forecasting***: air quality and air quality index (AQI) at multiple locations, identify and locate the potential contributing sources within and outside Delhi, and control of potential sources wherever feasible. This will be done using dispersion modeling and/or artificial neural network and the forecasting will be validated using the air quality data generated through supersite; finally, the best suitable technique will be adopted.

    ii. Daily interpretation of air quality, quantitative source apportionment and establish the reliability of forecasting versus observed source apportionment and improve/control actions.

    iii. Weekly interpretation of air quality, source apportionment, and further strengthen control actions within and outside Delhi.

    iv. Monthly and seasonal interpretation with trajectory and source apportionment analysis with additional knowledge of PAHs, molecular markers, and secondary organic and inorganic aerosols. Establish detailed and reliable source-receptor linkages and suggest a higher level of controls at major sources, for example, road dust, industrial emissions, and alternative fuels, household emissions decongestion of roads and vehicular movements, and other non-point sources.

    v. Annual interpretation of air quality, trajectory, and source apportionment analysis leading to long-term control actions for all sources within and outside Delhi.

vi. Support the above analysis (i. through v.) and interpretations with the dispersion model.

3. Develop state-of-the-art mobile air quality laboratory for source apportionment at multiple locations to daily and weekly interpretation of air quality, source apportionment, and further strengthen local and far distant sources.

4. Low cost unmanned spatial monitoring network for molecular markers and elements for hotspots and critical areas.

5. A detailed analysis of air quality data generated at the supersite and mobile laboratory to develop a short- and long-term comprehensive action for the city.

Assessment of improvement in ambient air quality and emission reduction with the implementation of actions derived from the study.

3 Development of the Supersite, Air Quality Measurements and Interpretation

A supersite at Sarvodaya Bal Vidyalaya, Rouse Avenue, New Delhi was developed which is capable of measurement of $PM_{2.5}$, NO_2, NO_x, CO, SO_2, Ozone, elemental carbon, organic carbon, PAHs, elements, ions, secondary inorganic and organic aerosols, molecular markers, and other organic compounds (Figure 2).

The following instruments (Table 1) are installed and are in operation at the supersite (Figure 3 to Figure 7).

Table 1: Analyzers and instruments

S.No.	Instrument
1.	Online Real-time Metal Analyzer
2.	$PM_{2.5}$ Online Measurement
3.	Ozone Analyzer
4.	SO_2 Analyzer
5.	NO-NOx Analyzer
6.	Carbon-monoxide Analyzer:
7.	Carbonaceous Aerosol Speciation System
8.	Aethalometer
9.	Online Ion-Chromatograph

10.	Secondary Organic Aerosol (offline)
11.	EDXRF Metal Analyzer (Offline)
12.	PM_{10}/$PM_{2.5}$ Sampler with PBL (offline)
13.	Wind and meteorological measurements
14.	5 Stations offline molecular marker network at five locations (suggested by the DPCC) - Anand Vihar, Mundaka, Dwarka, Vivek Vihar, Jahangir Puri)

All the instruments required for real-time source apportionment are installed, calibrated, and running at the supersite since November 2022.

The offline molecular marker network at five locations, Anand Vihar, Mundaka, Dwarka, Vivek Vihar, and Jahangir Puri are calibrated, installed, and are in operation (Figure 8).

A state-of-the-art mobile air quality van with instruments capable of real-time source apportionment is developed. The mobile van will be used for location specific air quality measurements and identification of sources at the hotspots to understand the contribution of sources to air pollution and take location specific air pollution control measures (Figure 9).

Figure 2: Operation of Super Site: Instruments and Air Quality Measurements

Figure 3: Gaseous Analyzer, Elemental Analyzer, and $PM_{10}/PM_{2.5}$ with PBL Analyzer

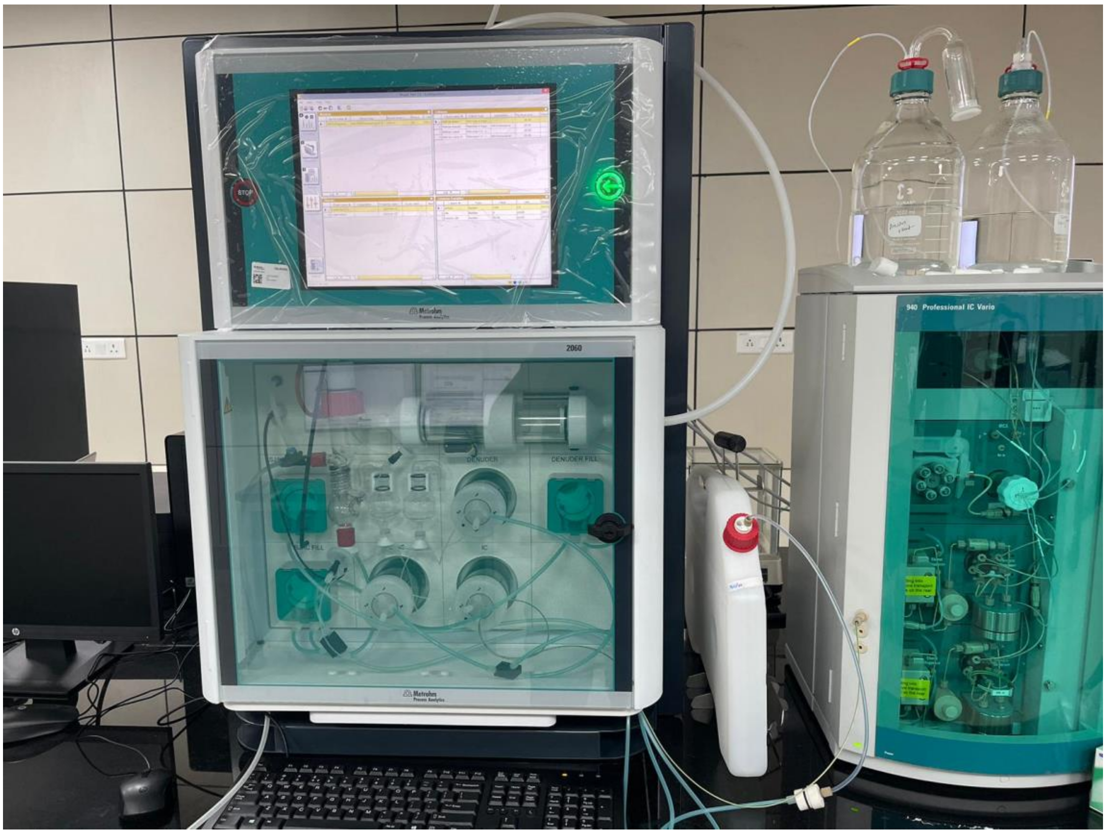


Figure 4: Ion-Chromatograph

Figure 5: ED-XRF for filter-based Metal Analysis

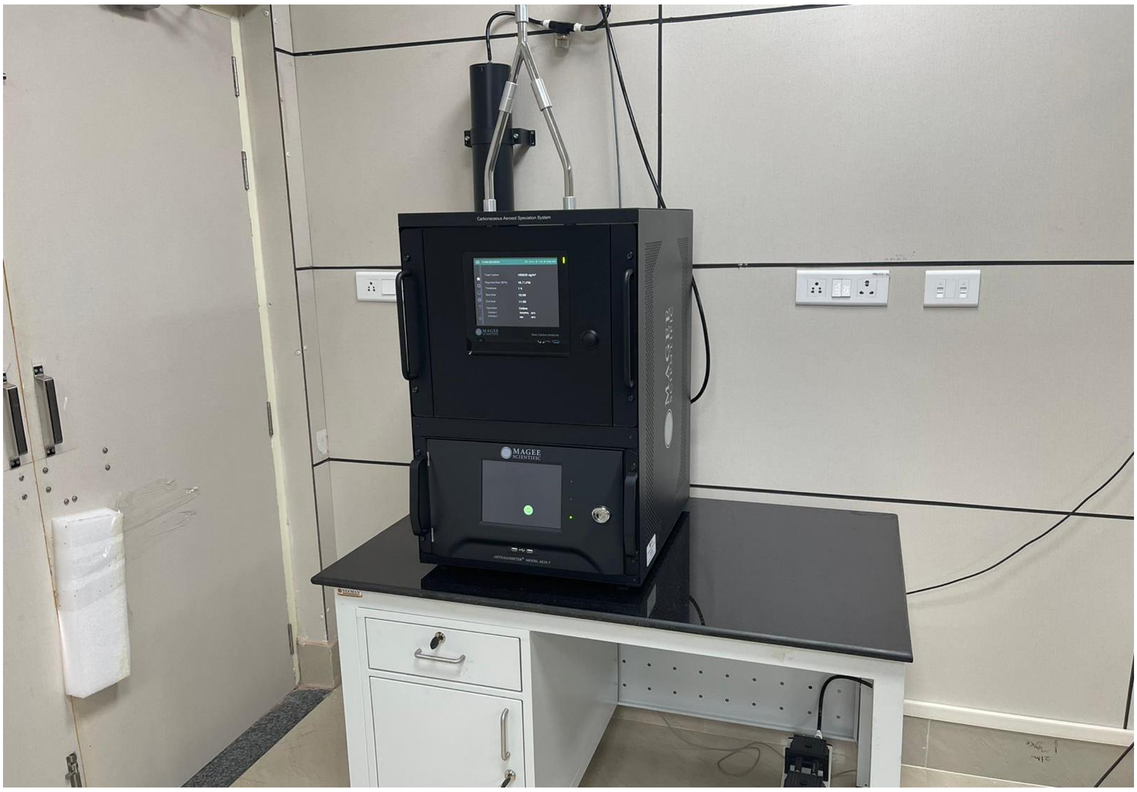


Figure 6: Carbonaceous Aerosol Speciation System and Aethalometer

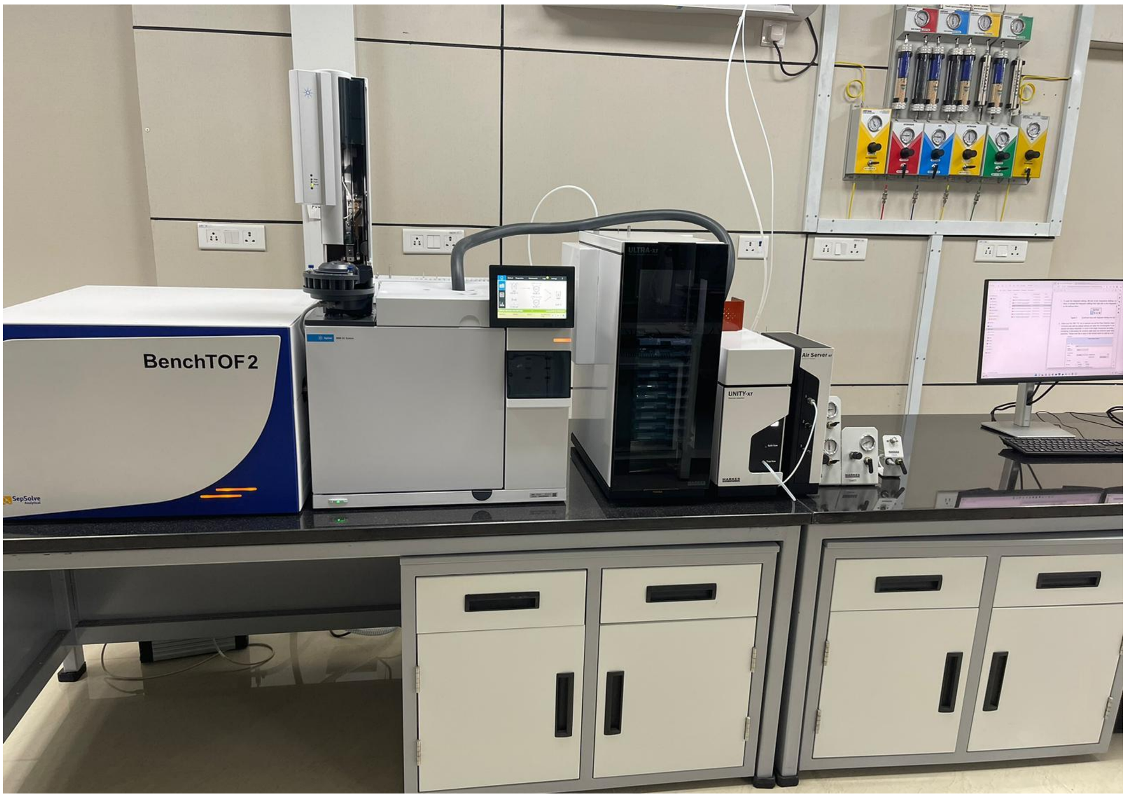


Figure 7: GCMS for VOCs and Secondary Organic Aerosols

Figure 8: Five Offline Stations for Molecular Marker

Figure 9: Mobile air quality stations and instruments

3.1 $PM_{2.5}$ Measurements at Supersite

$PM_{2.5}$ levels in Delhi are of paramount interest from health of citizens and visible pollution. At the supersite $PM_{2.5}$ levels are measured continuously on an hourly basis. Figure 9 shows the monthly mean and winter season's mean $PM_{2.5}$ concentration. The highest monthly average concentration was in January (217 µg/m^3) and the lowest level was in February (127 µg/m^3). The mean concentration of the winter season was observed at 192 µg/m^3.

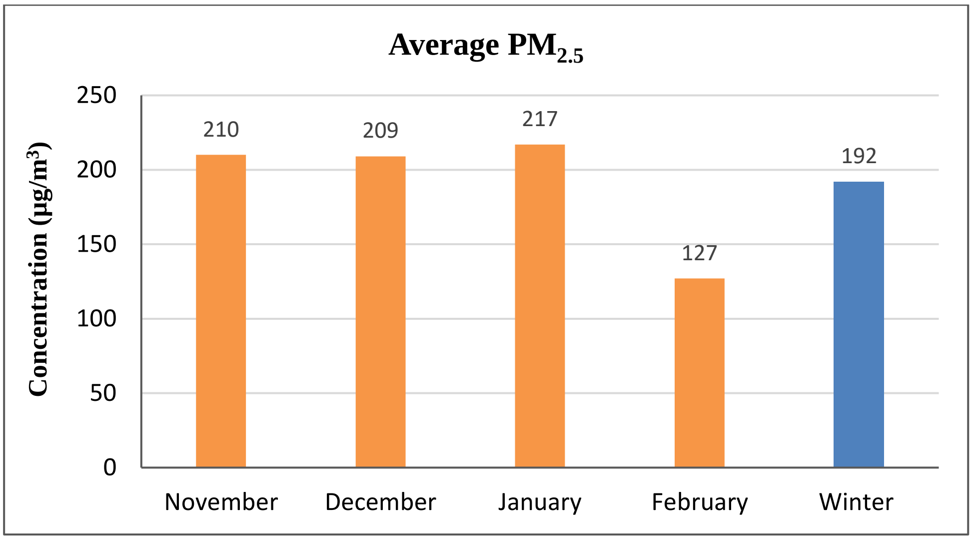


Figure 10: Average $PM_{2.5}$ Concentration during Winter Season

Winter is most critical season where levels exceed the national air quality standards (NAAQS) by a factor of five on some days. As an example, Figure 11 shows the hourly $PM_{2.5}$ concentration over the period Feb 12-18, 2023 wherein some concentrations have reached 340 ug/m^3. It can be seen that there are significant variations over the 24-hour cycle in hourly concentration and certain episodic periods can also be seen with high concentration during February 16-17, 2023. Therefore, for effective control of $PM_{2.5}$, it is important to identify sources of PM2.5 at a finer time resolution and their contributions to ambient air pollution.

For a summary representation, daily air quality over the period February 12-18 is shown with basic statistics (Figure 12). The first half of the month was windy, and strong breezes helped in improving the ventilation (product vertical mixing height and wind speed) inside the city and helping the dispersion of pollutants.

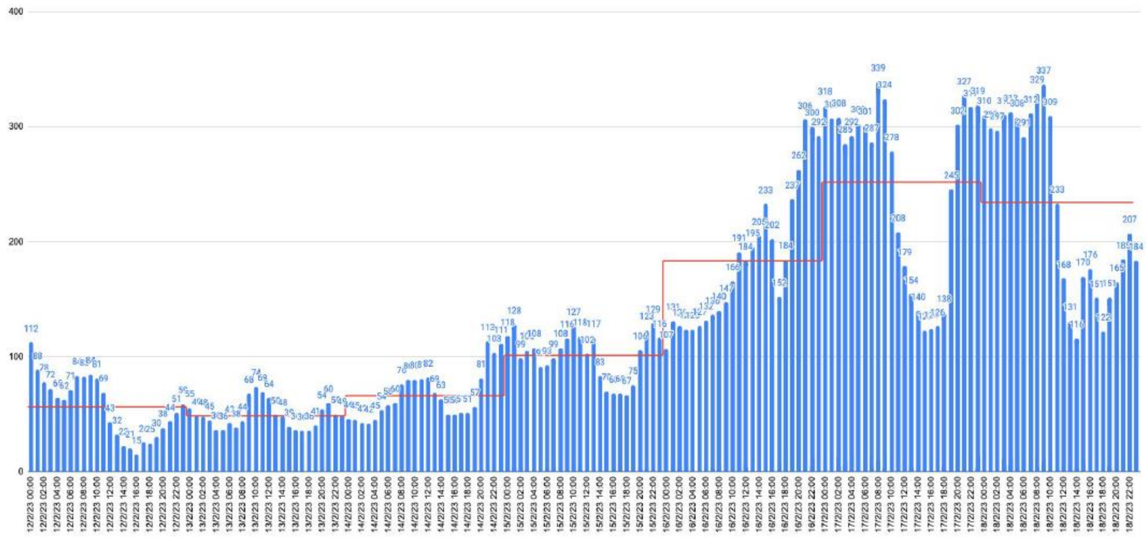


Figure 11: Hourly PM2.5 levels February 12-28, 2023 (μg/m³)

Synthesis of PM2.5 Concentration							
	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Date	12/02/2023	13/02/2023	14/02/2023	15/02/2023	16/02/2023	17/02/2023	18/02/2023
Mean PM2.5 (ug/m3)	57	49	66	101	183	252	234
Minimum (ug/m3)	15	36	42	67	107	123	116
Maximum (ug/m3)	112	74	113	129	306	339	337

Figure 12: 24-hourly concentration of PM2.5 during February 12-18, 2023

3.2 Real-Time Air Quality Index (AQI) at Supersite

AQI, a composite number of air quality in easy-to-understand term (Figure 13) is calculated using CPCB methodology on an hourly basis at the supersite. The Figure 14 shows the daily AQI over the winter season. The worst air quality was observed in November, December and January. Twenty-eight days were in severe category.

On a monthly AQI basis, the month of December (AQI; 352) was the worst and it was relatively better in February (AQI; 255). The mean AQI of the winter season was observed to be 326 (Figure 15).

AQI	Remark	Color Code	Possible Health Impacts
0-50	Good		Minimal impact
51-100	Satisfactory		Minor breathing discomfort to sensitive people
101-200	Moderate		Breathing discomfort to the people with lungs, asthma and heart diseases
201-300	Poor		Breathing discomfort to most people on prolonged exposure
301-400	Very Poor		Respiratory illness on prolonged exposure
401-500	Severe		Affects healthy people and seriously impacts those with existing diseases

Figure 13: AQI Colour Code and Health Impact

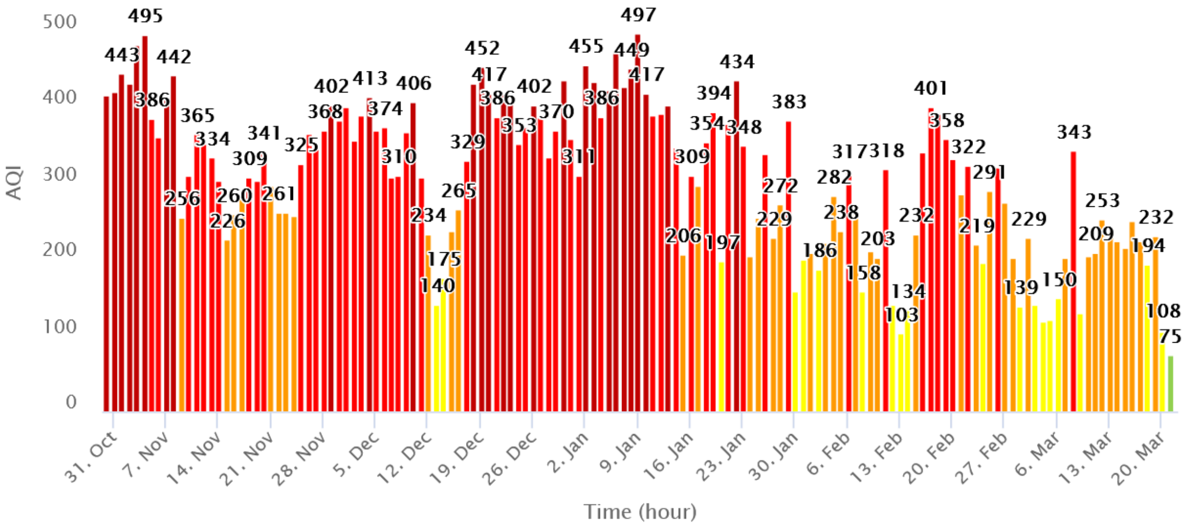


Figure 14: Daily AQI over the winter season at the Super site

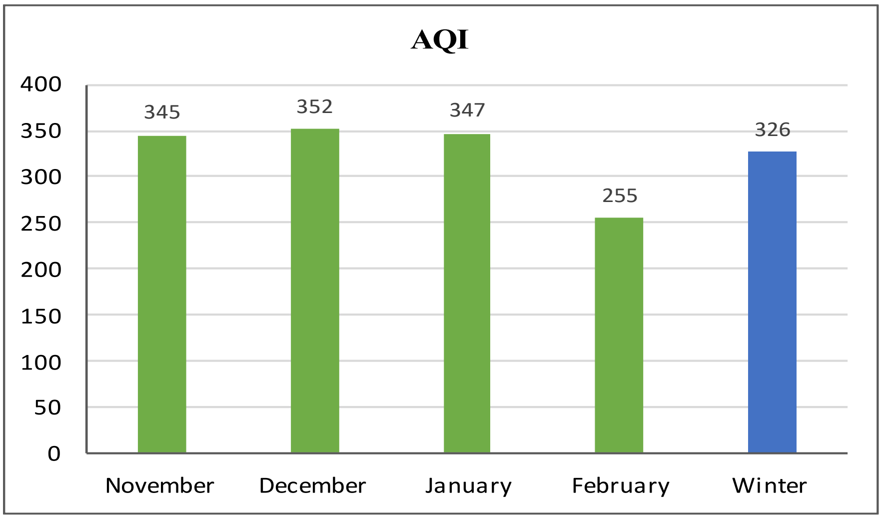


Figure 15: AQI during Winter Season

3.3 Real-Time Source Apportionment

The real-time source apportionment of $PM_{2.5}$, as an example for January 29, 2023, is shown in Figure 16. The results show secondary inorganic aerosols, which are mostly expected travel from far distances, contribution to be the highest (32%) followed by biomass burning (24%), vehicles (17%), and coal and fly ash (7%), the rest of all sources contribute less than 5% individually. On similar pattern of hourly source contribution, the daily source apportionment of sources is shown in Figure 17 and Figure 18, which is also showing a significant contribution of secondary inorganic aerosols (10 – 60 percent), biomass burning (5 – 50 percent), vehicle (10 - 35 percent) and other sources (10 – 25 percent).

The average of winter season's source apportionment is shown in Figure 19 for the period November 01 – March 2, 2023. For a broad policy levels, both SIA (32 percent) and biomass burning (24 percent; within and outside Delhi) contribute the most followed by vehicles at 17 percent.

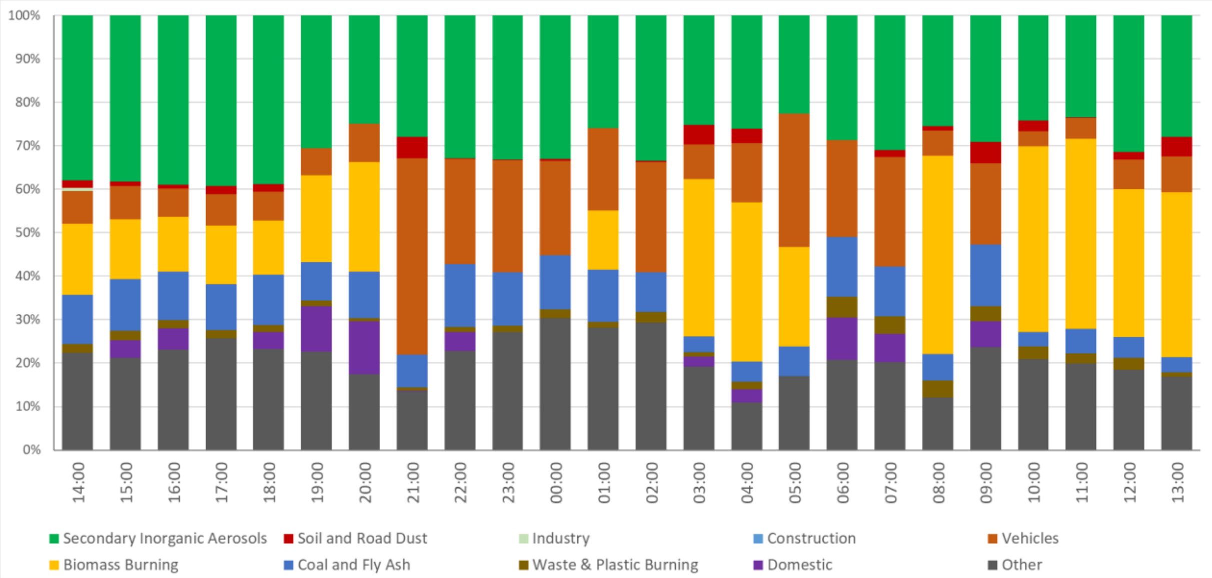


Figure 16: Hourly Source Apportionment for a day (i.e., Jan 29, 2023)

The types of particles present in each source category is discussed below.

- Secondary Inorganic Aerosols: Particles such as sulfate, nitrate, ammonium are formed in the atmosphere from the interaction of various gases. Potential Sources include powerplants, refineries, brick kilns, vehicles, agriculture, organic waste decomposition, and open drains.
- Soil and Road Dust: Air-borne dust from roads & shoulders, vehicle movement, dry soil, and tillage operations.
- Industry: Furnace, boiler, and metal casting & refining.
- Construction: Building construction & demolition, raw material storage, ready mix concrete plant, and loading & unloading operations at construction site.
- Vehicles: Off & on-road vehicles, petrol, diesel, CNG-powered vehicles, and diesel generator sets.
- Biomass Burning: Wood, dung, agriculture residue, and plant branches & leaves burning.
- Coal and Fly Ash: Combustion of coal, dry fly ash ponds, burning of heavy oils, tandoors, cement storage, distribution, loading & unloading, and construction activities.
- Waste and Plastic Burning: Municipal solid waste, plastic, paper boards, used tires and wire burning.
- Domestic: LPG uses.
- Others: Tire & brake wear and paints

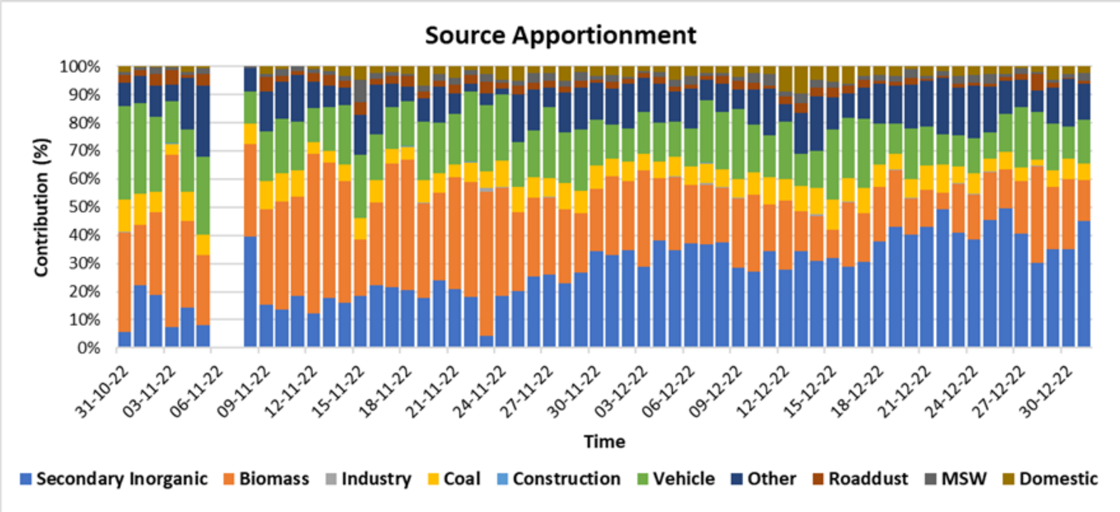


Figure 17: Daily Source Apportionment (Oct 31, 2022 – Dec 30, 2022)

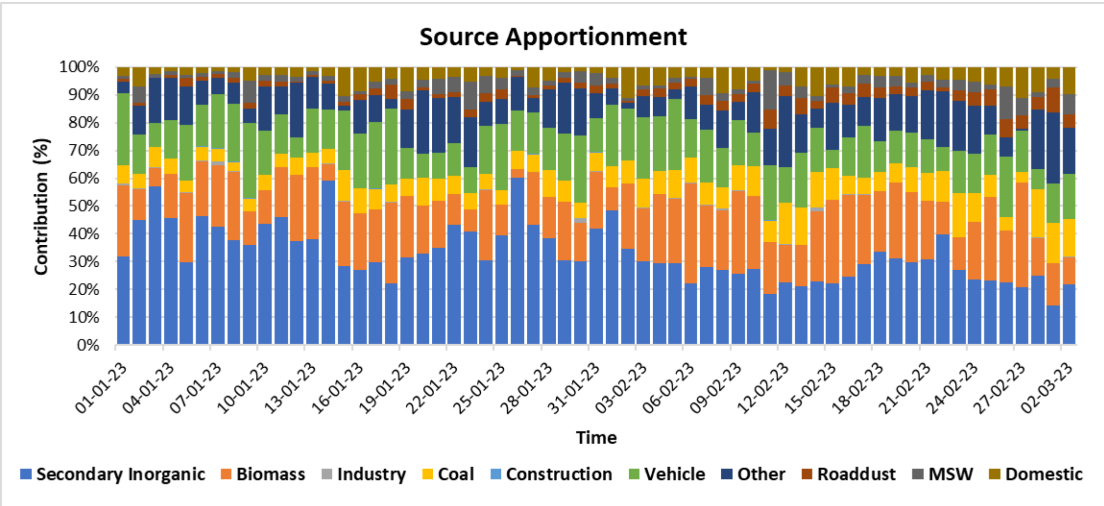


Figure 18: Daily Source Apportionment Nov 01 – March 2, 2023

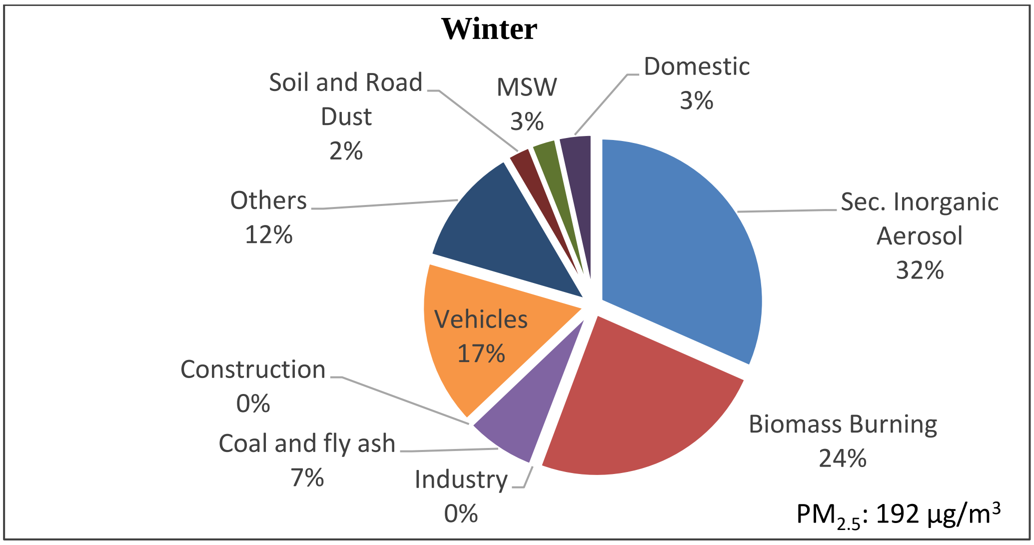
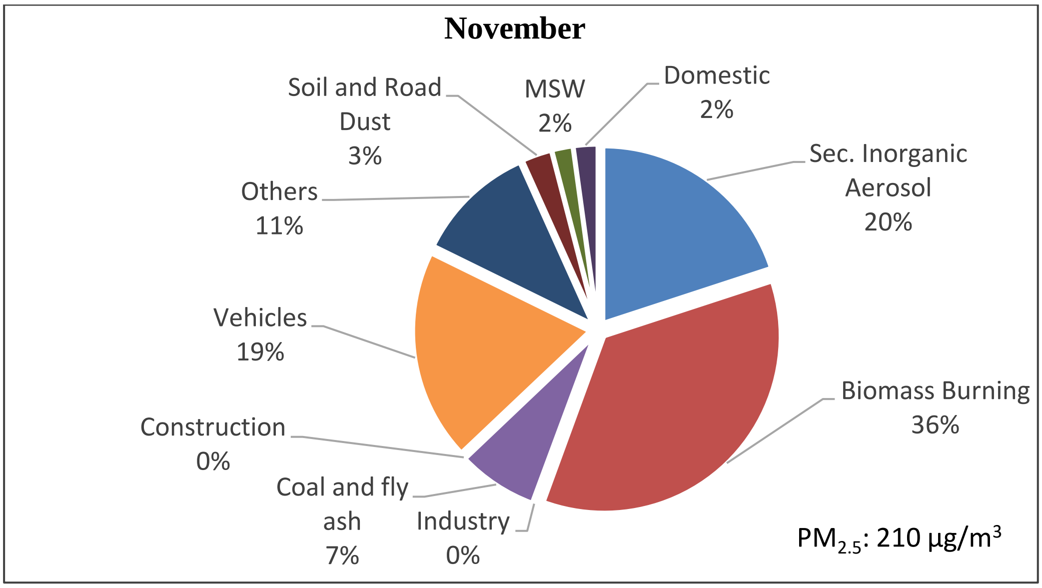
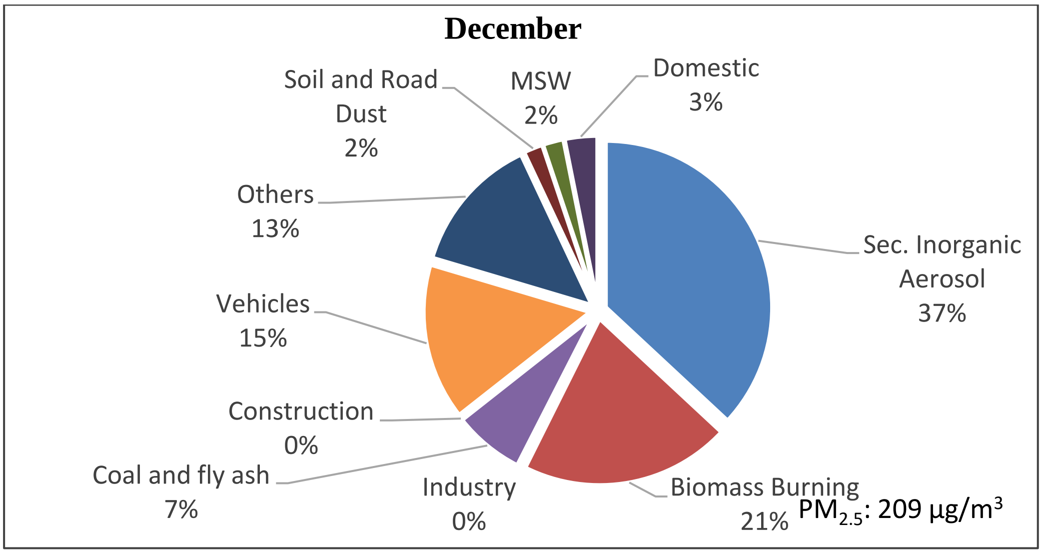
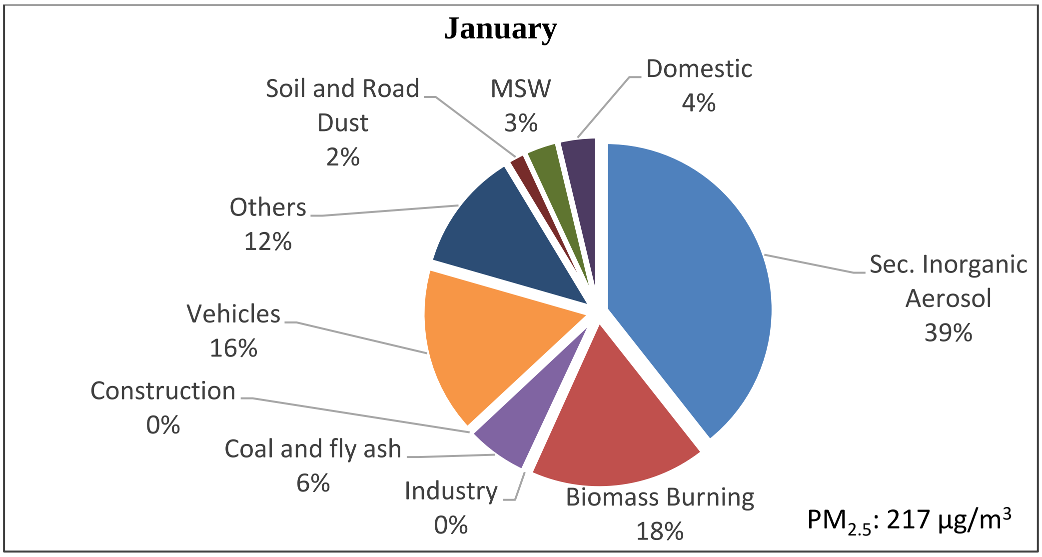


Figure 19: Source Apportionment of $PM_{2.5}$ during Winter Season

In terms of monthly analysis (Figure 20), the results show biomass burning contribution to be maximum in November (36%) and drop down to 18% in January and again increases to 24% in February. Secondary inorganic aerosol contribution is seen to be the highest (39%) in January. The vehicular contribution shows a uniform pattern and ranges from 15-19% in the season and is seen highest in November. The half-monthly mean levels are also shown in Figure 21.







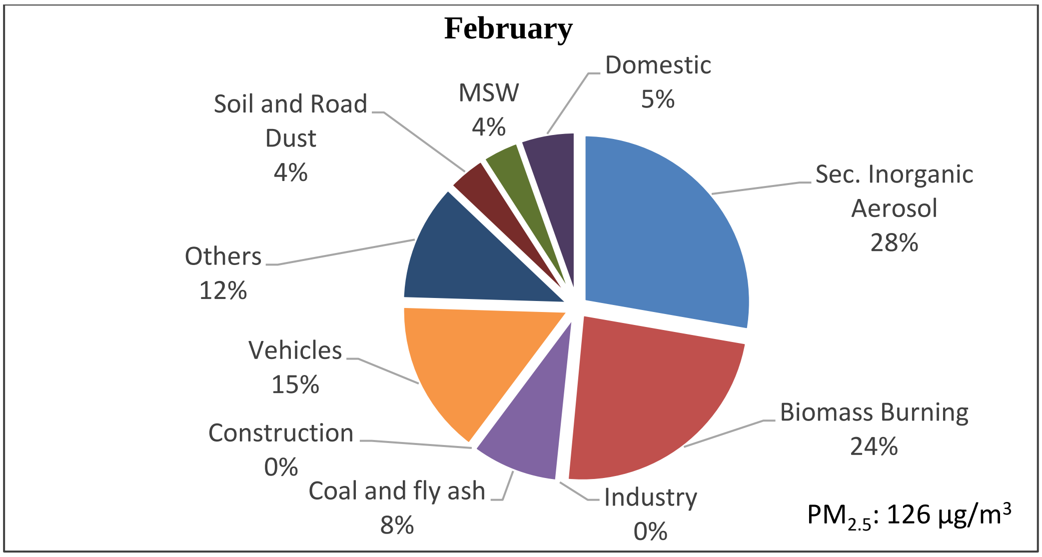


Figure 20: Monthly Source Apportionment

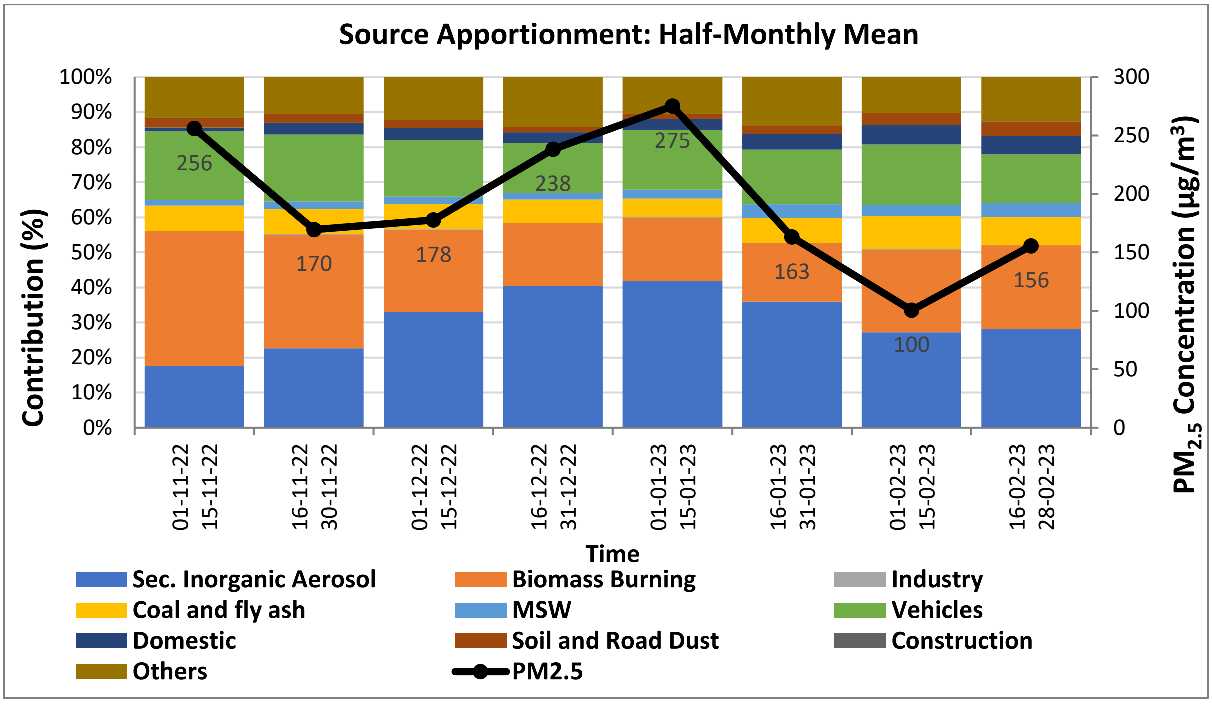


Figure 21: Half-Monthly Source Apportionment

3.3.1 Contribution of Delhi's and Outside Emissions to Secondary Inorganic Aerosols at Supersite

The secondary inorganic aerosols (SIA), comprised mostly of NO_3, SO_4 and NH_4, are measured continuously as $PM_{2.5}$ constituents at the supersite. The primary precursors of SIA are NH_3, SO_2 and NO_x gases which are transformed into SIA particles in the atmosphere through atmospheric chemistry. The overall SIA is the net contribution of primary emissions occurring in Delhi and those from outside Delhi.

A state-of-the-art WRF-Chem (Weather Research Forecasting with Chemistry) model has been applied to assess the contributions to NO_3, SO_4 and NH_4 from the primary emissions in Delhi and those from outside Delhi. The hourly metrological parameters were generated for winter months. Specifically, as the first step in the modelling exercise, emissions from Delhi were switched off and the contribution of outside sources at the supersite was estimated. In the second step, emissions were considered only from Delhi. It may be mentioned that performance of WRF-chem model was adjudged adequate against $PM_{2.5}$ levels measured at supersite, Mandir Marg and ITO Thus, this modelling exercise provides the mean hourly contribution of emissions within Delhi and those from outside of Delhi. The results have been utilized to break down the contribution of NO_3, SO_4 and NH_4 at supersite attributed to emissions from Delhi and outside.

In winter season, the mean contribution of SIA from the sources within Delhi (up to 30 km radius from supersite) is 16% and the rest 84 % from outside Delhi. We have estimated the breakup of contributions at different levels of time resolutions; (i) Hourly (Figures 22 - 23); (ii) Daily (Figure 24); (iii) Half-monthly (Figure 25), (iv) Monthly (Figure 26), and (v) Winter season (Figure 27). The half-monthly and monthly summary with seasonal statistics is given in Tables 2 – 3.

Summary of contribution to SIA

a. 24-hour basis (SIA 75 µg/m^3 (33% of $PM_{2.5}$), November 30, 2022). The contribution to SIA:

   outside of Delhi's emission: 79% with NH_4 (31%), SO_4 (20%) and NO_3 (28%).

   inside of Delhi's emission: 21% with NH_4 (10%), SO_4 (1%) and NO_3 (10%).

b. Monthly basis (SIA 72 µg/m^3 (33% of $PM_{2.5}$), December 2022). The contribution to SIA:

   outside of Delhi's emission: 83% with NH_4 (30%), SO_4 (25%) and NO_3 (28%).

   inside of Delhi's emission: 17% with NH_4 (9%), SO_4 (1%) and NO_3 (7%)

c. Winter season (SIA 55 µg/m^3 (29% of $PM_{2.5}$), November – February 2023). The Contribution to SIA:

   outside of Delhi's emission: 83% with NH_4 (33%), SO_4 (24%) and NO_3 (26%).

   inside of Delhi's emission: 17% with NH_4 (9%), SO_4 (1%) and NO_3 (7%)

For further details of the breakup of SIA, refer to Tables 2 and 3.

It may be noted that the above break up is only for SIA. The contribution of sources other than SIA to $PM_{2.5}$ is expected to be mostly from emissions within Delhi except for the period of crop residue burning.

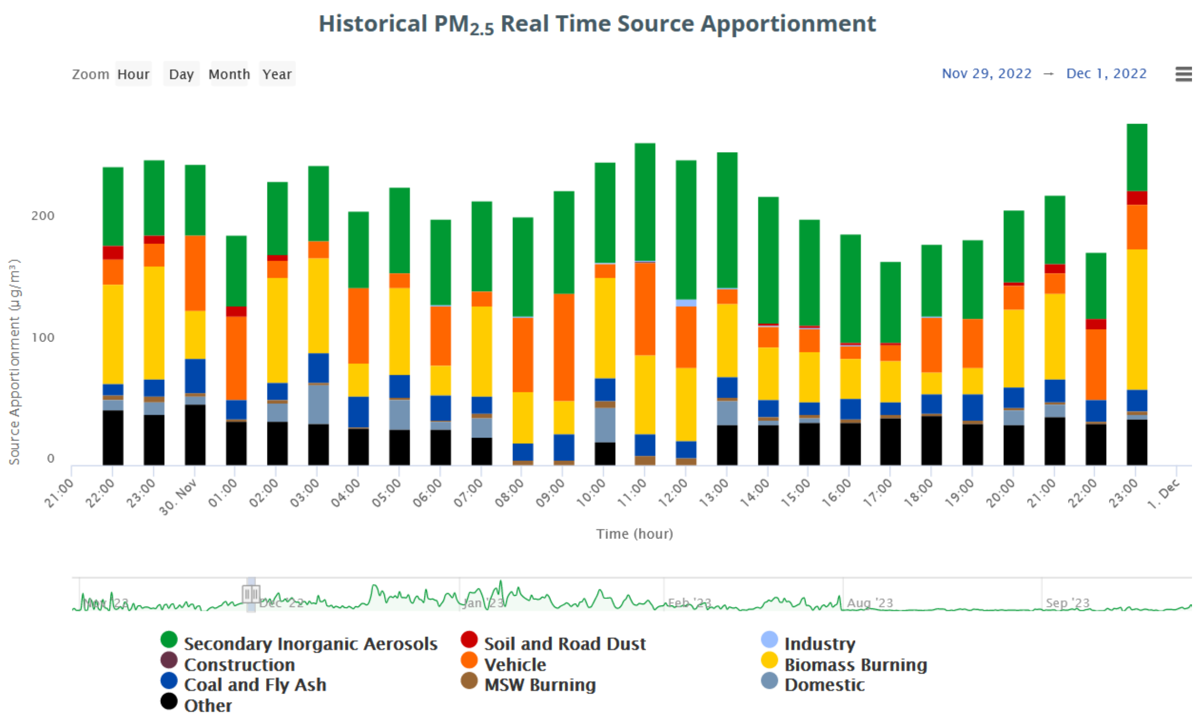


Figure 22: Hourly PM2.5 Real Time Source Apportionment (i.e., Nov 30, 2022)

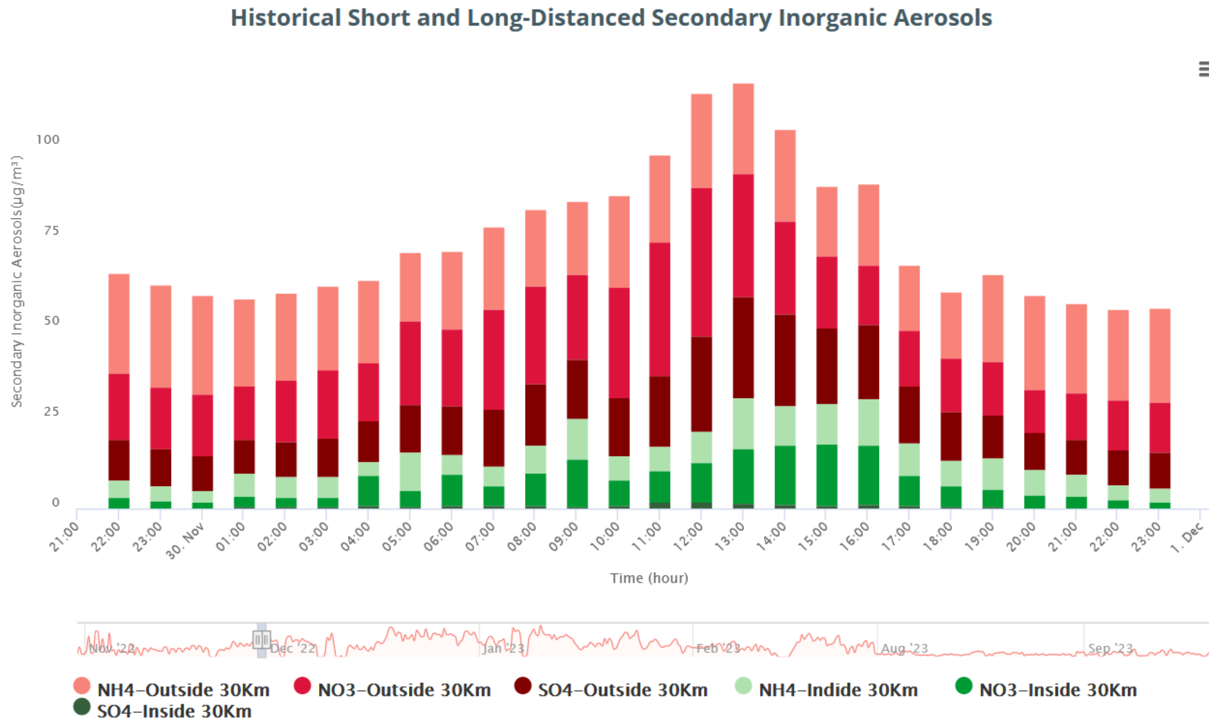


Figure 23: Breakup of Secondary Inorganic Aerosols (Delhi and outside emissions) in Hourly PM2.5

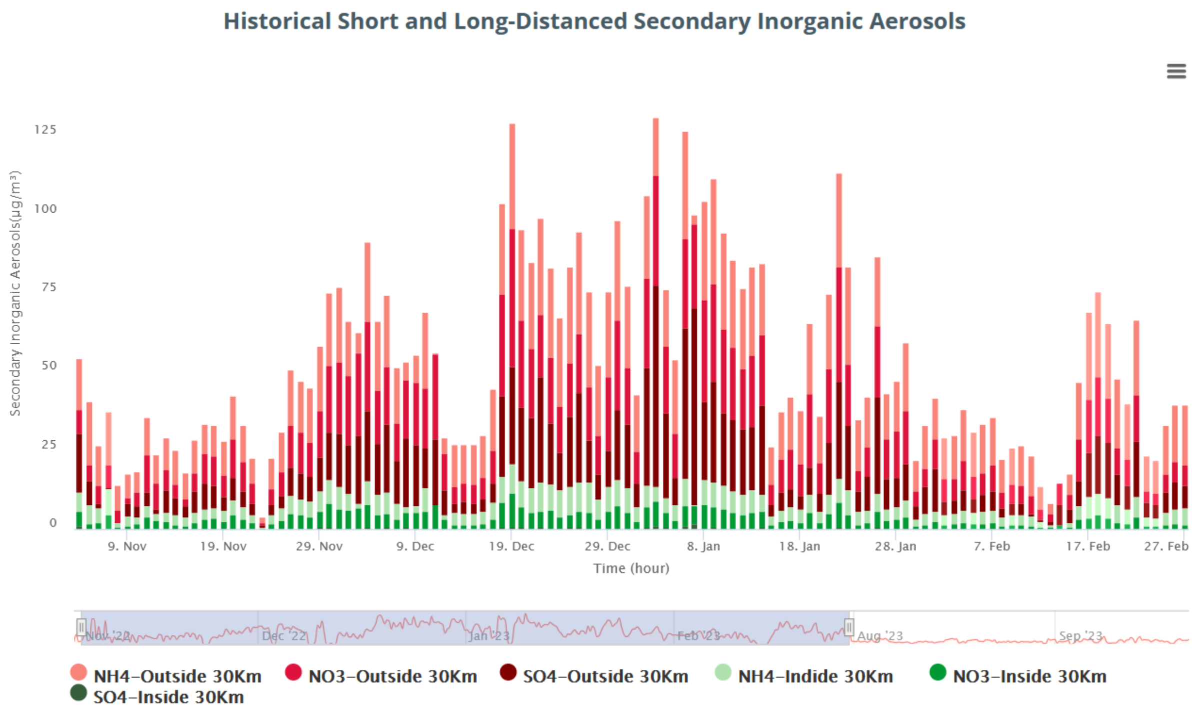


Figure 24: Breakup of Short and long-distanced Secondary Inorganic Aerosols in 24-Hourly $PM_{2.5}$

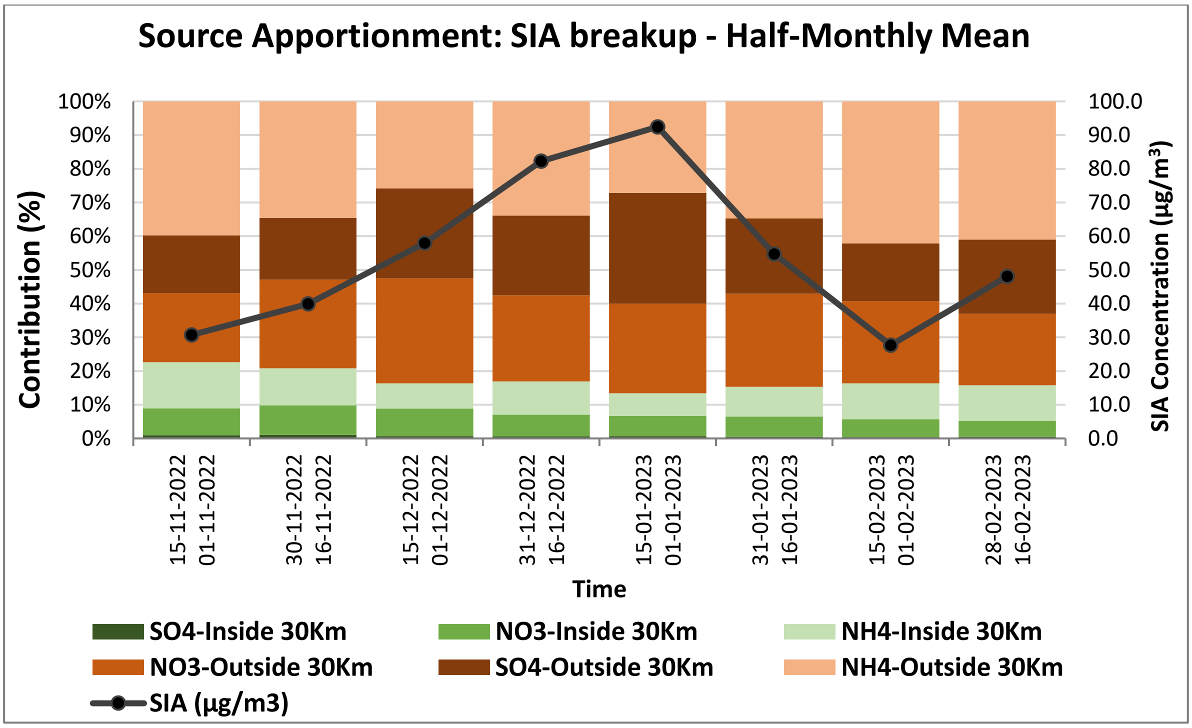
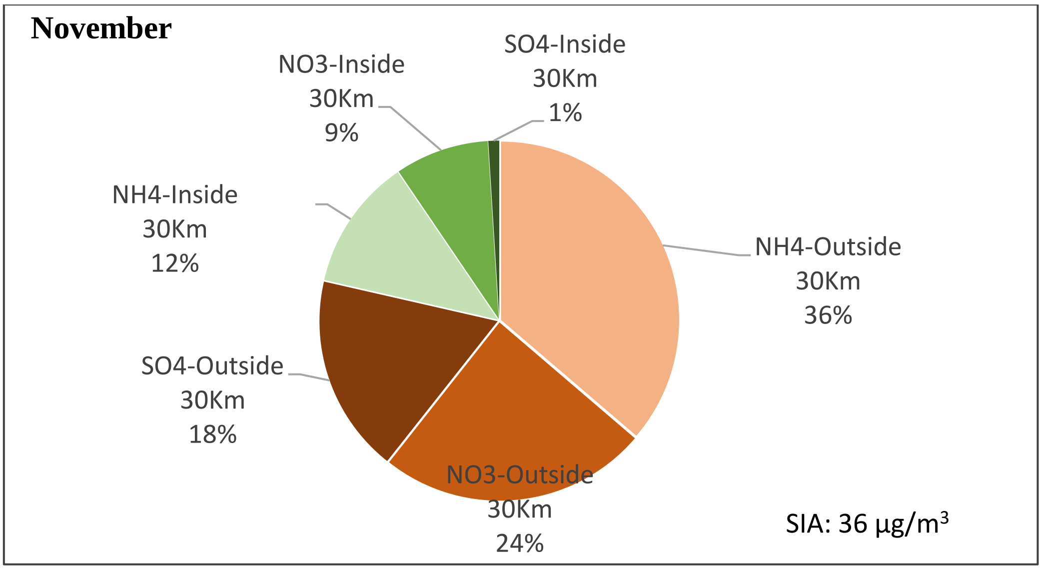
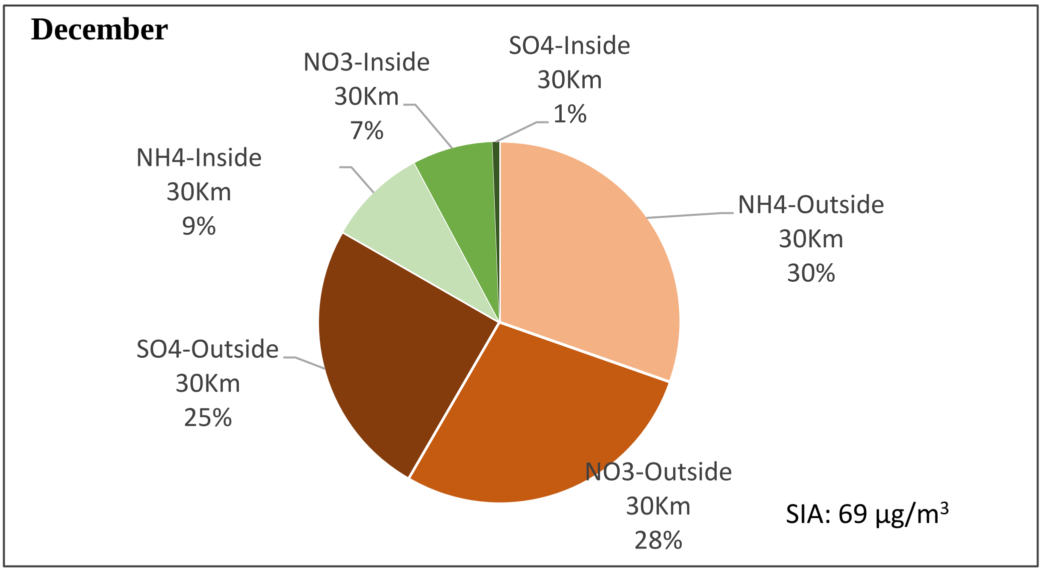
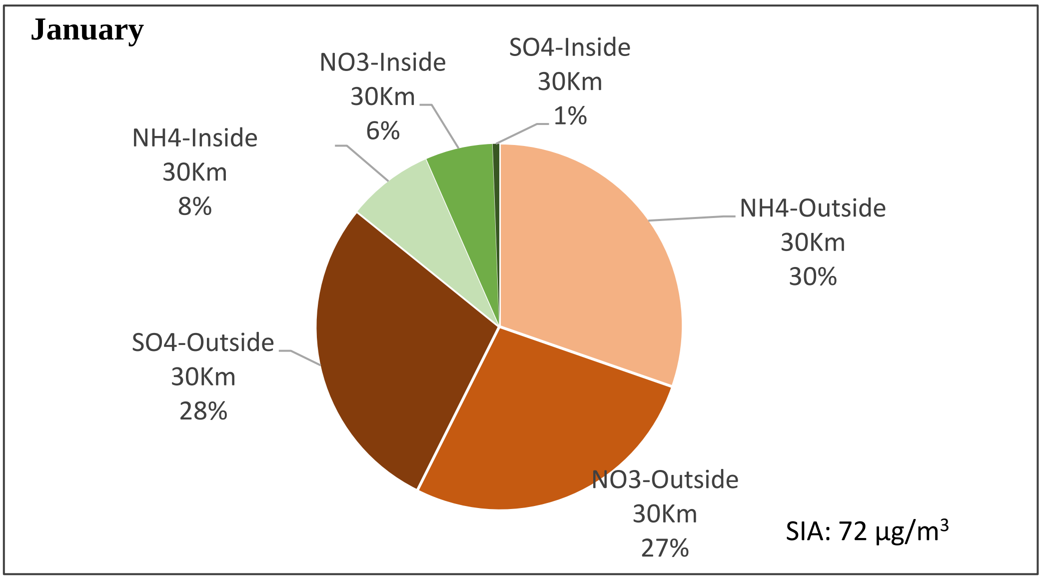


Figure 25: Half-Monthly Breakup of SIA at supersite during winter


November
NO3-Inside 30Km 9%
SO4-Inside 30Km 1%
NH4-Inside 30Km 12%
NH4-Outside 30Km 36%
SO4-Outside 30Km 18%
NO3-Outside 30Km 24%
SIA: 36 µg/m3


December
NO3-Inside 30Km 7%
SO4-Inside 30Km 1%
NH4-Inside 30Km 9%
NH4-Outside 30Km 30%
SO4-Outside 30Km 25%
NO3-Outside 30Km 28%
SIA: 69 µg/m3


January
NO3-Inside 30Km 6%
SO4-Inside 30Km 1%
NH4-Inside 30Km 8%
NH4-Outside 30Km 30%
SO4-Outside 30Km 28%
NO3-Outside 30Km 27%
SIA: 72 µg/m3

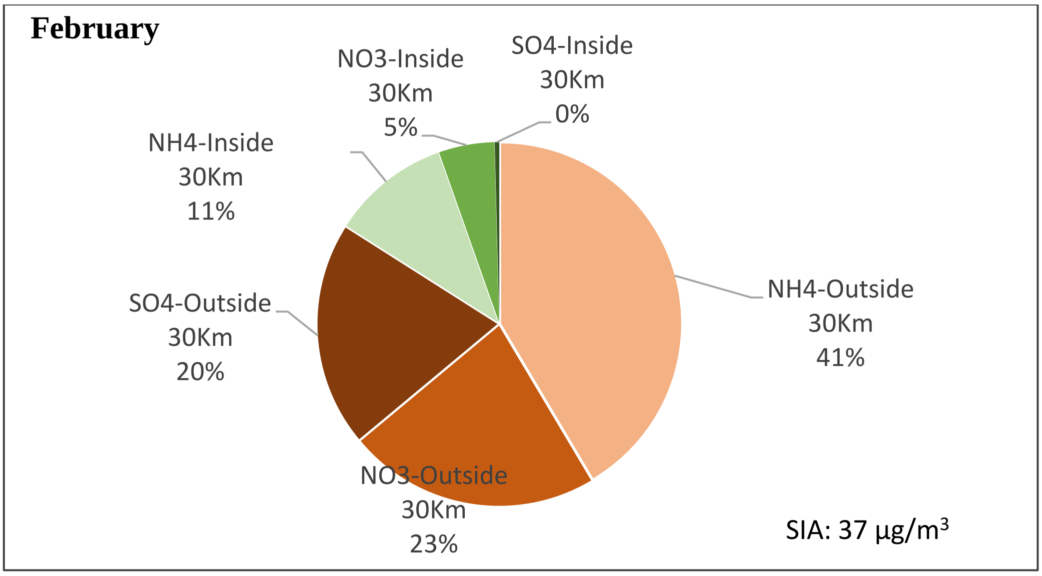


Figure 26: Monthly Breakup of Short and Long-term Breakup of SIA in Winter Season

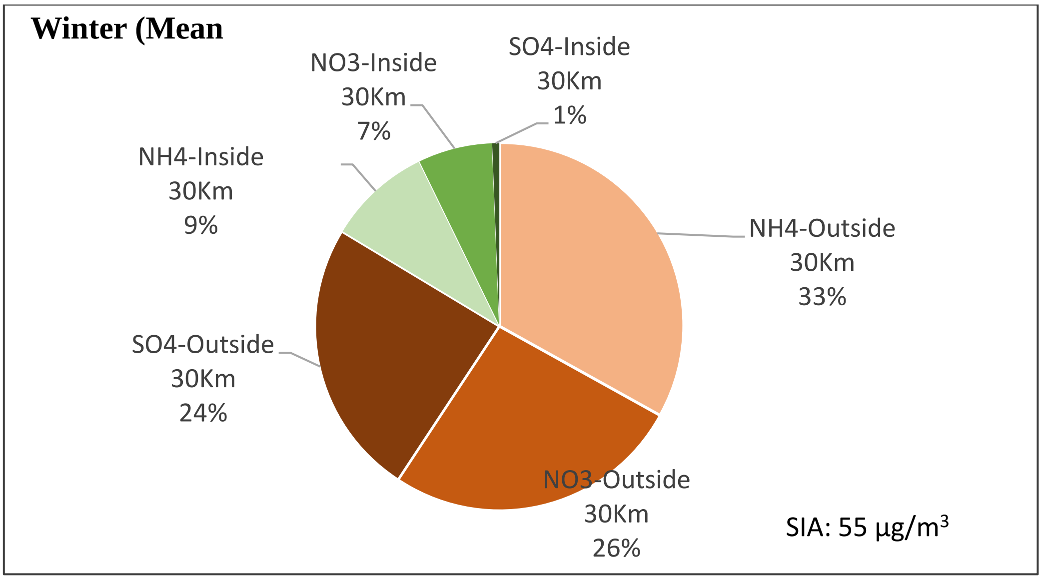


Figure 27: Average Breakup of Short and Long-term Breakup of SIA in Winter Season

Source Description of Secondary Inorganic Aerosols:

Particles such as sulfate, nitrate, ammonium are formed in the atmosphere from the interaction of various gases. Potential Sources include powerplants, refineries, brick kilns, vehicles, industry, agriculture, organic waste decomposition, and open drains. Here it is split in 6 parts 'NH_4-Outside 30 Km','NO_3-Outside 30 Km','SO_4-Outside 30 Km','NH_4-Inside 30 Km','NO_3-Inside 30 Km','SO_4-Inside 30 Km' (30 km signifies a tentative boundary dividing Delhi from outside domain

We have applied the modelling results and modified the demo website (not open to the public right now) to clearly show the breakup of SIA species (NO_3, SO_4 and NH_4) both for emissions from Delhi and outside (Figures 23 – 24). It may be noted that on the website the contribution is referred to as within 30 km (of supersite) and outside 30 km so as not to bring in administrative boundaries. Once *agreed upon*, the information as per the demo website can be produced and shown on the regular website for DPCC and public viewing.

Table 2: Half-Monthly summary of percent SIA breakup at Supersite, New Delhi

Start Date	End Date	$PM_{2.5}$ (µg/m³)	SIA (µg/m³)	Percent contribution in SIA								% SIA in PM2.5
				NH4-Outside 30Km	NO3-Outside 30Km	SO4-Outside 30Km	NH4-Inside 30Km	NO3-Inside 30Km	SO4-Inside 30Km	SIA-Outside 30 km	SIA-Inside 30 km	
01-11-2022	15-11-2022	273.3	30.7	39.7	20.6	17.1	13.7	8.0	0.9	77.4	22.6	11.2
16-11-2022	30-11-2022	169.1	39.9	34.5	26.3	18.3	11.1	8.8	1.0	79.1	20.9	23.6
01-12-2022	15-12-2022	179.1	57.9	25.8	31.1	26.7	7.6	8.1	0.7	83.6	16.4	32.3
16-12-2022	31-12-2022	238.3	82.2	33.9	25.6	23.6	9.9	6.5	0.6	83.0	17.0	34.5
01-01-2023	15-01-2023	264.6	92.4	27.2	26.6	32.8	6.8	5.9	0.7	86.6	13.4	34.9
16-01-2023	31-01-2023	165.5	54.7	34.8	27.7	22.3	8.8	6.0	0.4	84.7	15.3	33.1
01-02-2023	15-02-2023	102.1	27.7	42.1	24.4	17.1	10.7	5.3	0.4	83.7	16.3	27.1
16-02-2023	28-02-2023	163.3	48.1	41.0	21.2	22.1	10.5	4.8	0.5	84.2	15.8	29.4

Table 3: Monthly summary of percent SIA breakup at Supersite, New Delhi

Month	$PM_{2.5}$ (µg/m³)	SIA (µg/m³)	Percent contribution in SIA								% SIA in PM2.5
			NH4-Outside 30Km	NO3-Outside 30Km	SO4-Outside 30Km	NH4-Inside 30Km	NO3-Inside 30Km	SO4-Inside 30Km	SIA-Outside 30 km	SIA-Inside 30 km	
November	209.9	36.3	36.3	24.4	17.9	11.9	8.5	1.0	78.6	21.4	17.3
December	208.7	69.4	30.4	28.0	24.9	8.9	7.2	0.6	83.3	16.7	33.3
January	211.7	71.9	30.3	27.1	28.4	7.6	6.0	0.6	85.8	14.2	33.9
February	129.8	37.0	41.5	22.5	20.1	10.6	5.0	0.4	84.0	16.0	28.5
Mean (winter)	190.7	54.7	33.1	26.2	24.4	9.2	6.6	0.6	83.6	16.4	28.7
STD Dev.	94.7	30.3	10.13	6.39	9.19	3.05	1.99	0.33	3.30	3.30	8.85
Minimum	47.6	9.2	0.89	5.15	0.15	0.26	0.77	0.01	65.67	8.08	3.71
Maximum	719.0	132.5	67.26	47.64	62.25	21.73	12.95	1.79	91.92	34.33	51.06

3.4 Contribution of Crop Residue Burning CRB) during November 2022

The measured speciation of $PM_{2.5}$ permits estimating the contribution crop residue (*parali*) to $PM_{2.5}$ in Delhi using the tracer method. The potassium (K) levels are used as markers for biomass burning and CRB in several studies (Lim et al., 2012; Cheng et al., 2013; Rajput et al., 2014; Singh et al., 2014; Souza et al., 2014; Chen et al., 2017; Nagar et al., 2017).

At the supersite, the levels of K varied from 3 to 8 µg/m^3 during CRB (parali) period compared to normal levels of K (1 – 3 µg/m^3) in the post-CRB and winter periods. The increased levels help to estimate the contribution of *parali* burning.

The impact of crop residue burning is estimated during the period November 1 to 25, 2022. In this period mean contribution of *parali* was 22%. The contribution was very high on some occasions, where it exceeded 35% (Figure 28).

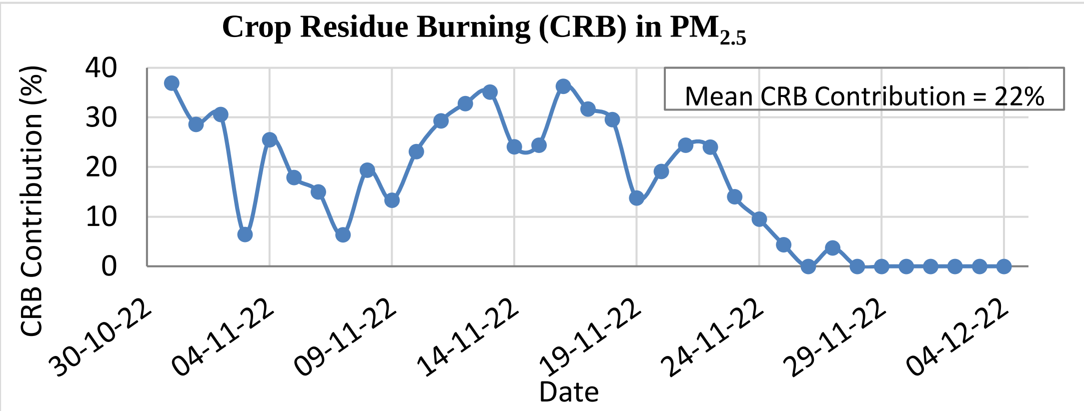


Figure 28: Crop Residue Burning

Validation

Mean *parali* contribution was 22% in $PM_{2.5}$ in November, estimated using measurements at the supersite was comparable with other studies showing the average contribution of CRB in Delhi as 25 – 30% (Nagar and Sharma 2022). Further, they have reported that normalized K levels dropped by 52% in the post-CRB period compared to the CRB period in Delhi.

Further evidence of a similar impact is available from Lan et al. (2022; *Nature Communication),* stating that "Due to a combination of relatively high downwind population density, agricultural output, and cultivation of residue-intensive crops, six districts in Punjab alone contribute to 40% of India-wide annual air quality impacts from residue burning."

Since world over K (potassium) is used as a tracer, the results obtained from the supersite are validated and acceptable for CRB contribution to Delhi's $PM_{2.5}$.

4 Model Validation

4.1 Methodology

WRF–Chem (Weather Research and Forecasting model coupled with Chemistry) model and artificial and machine learning (AI-ML) models are used for simulations of air quality forecast. The detailed flow chart of implemented methodology is given in Figure 29 and Figure 30.

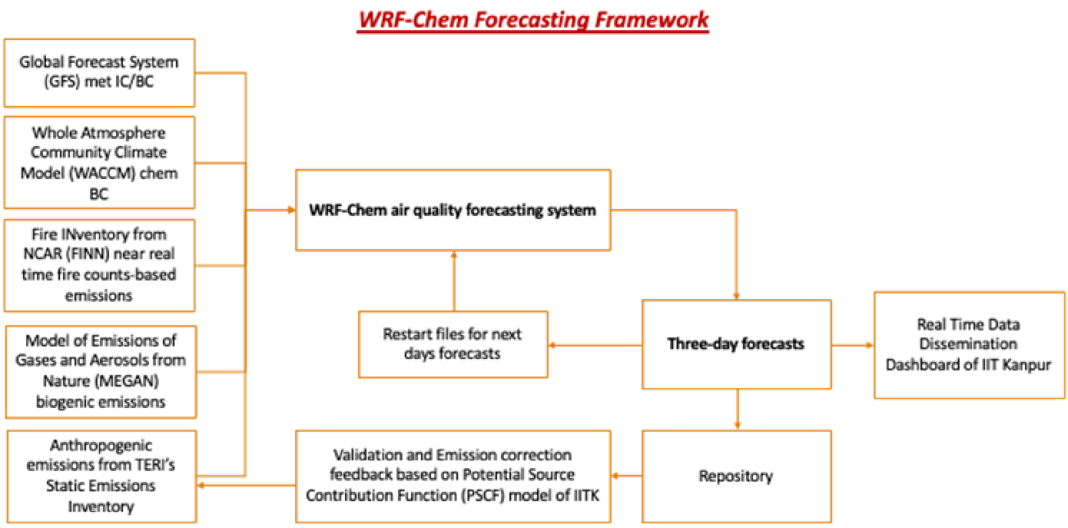


Figure 29: WRF-Chem based methodology adapted in this study

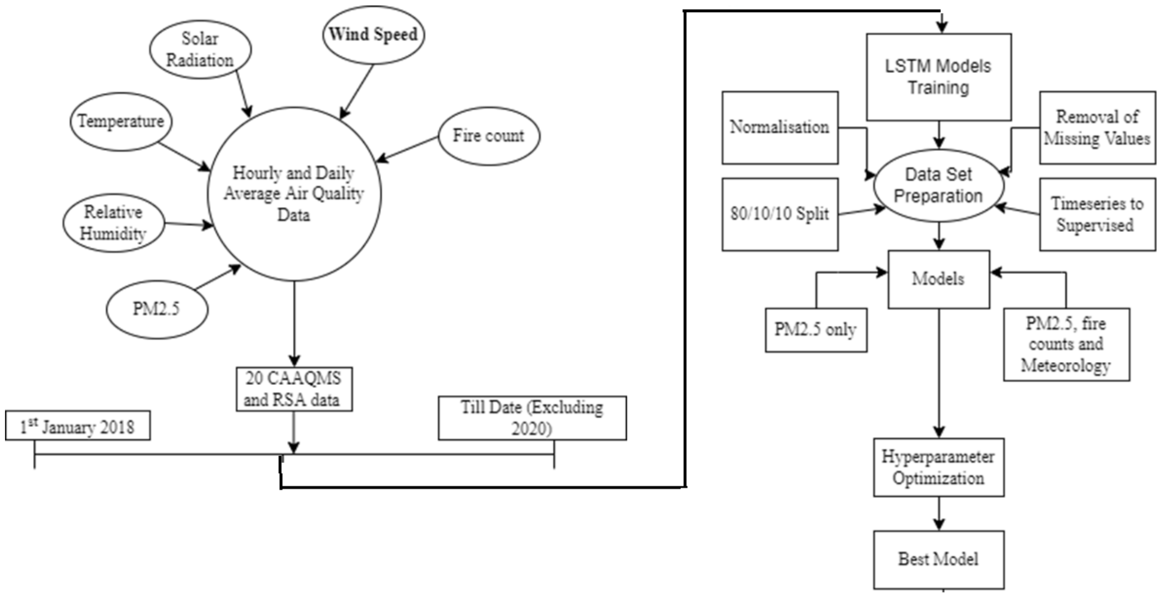


Figure 30: AI-ML based forecasting

Weather Research Forecasting model with chemistry (WRF-Chem): Advanced Research WRF (ARW) model with chemistry (WRF-Chem) has been applied to model the transport and transformation of CRB emission (i.e., $PM_{2.5}$, BC, OC, NO_x, SO_2, NH_3, CH_4, NMOC, NMHC, VOCs) in IGP and for the current validation exercise. WRF integrates the compressible, non-hydrostatic Euler equations for simulating meteorological/climatic conditions at local and regional levels. The model uses Runge-Kutta 2^{nd} and 3^{rd} order time integration schemes with smaller time steps for acoustic and gravity-wave modes and 2^{nd} to 6^{th} order advection schemes in horizontal and vertical directions for spatial discretization (Skamarock et al., 2008 and Nagar and Sharma, 2022).

The WRF-Chem simulates the emission (E), advection by 3-dimensional wind (u, v, w), diffusion (K), chemical reaction (R) and removal by dry deposition (D) of pollutants by solving the continuity equation for each chemical species (s) in a three-dimensional (x, y, z) grid system in the atmosphere. The simplified Eulerian continuity equation is stated mathematically that governs the time dependency of species concentration (Cs) within each grid as a sum of all the physical and chemical processes (Grell et al., 2005; Skamarock et al., 2008).

The WRF-Chem model has been applied for modelling of gaseous and particulate pollutants at the local and long-distance transport in the different regions in India and worldwide (Gupta and Mohan, 2015; Marrapu, 2012; Michael et al., 2014; Seethala et al., 2011; Nagar & Sharma, 2022; Azmi et al., 2023).

4.2 USEPA Chemical Mass Balance and IIT Kanpur's I2TK-RSA 1.0

USEPA's CMB8.2 (USEPA, 2004) is a receptor model (independent of WRF-Chem) for quantifying the contribution of the sources in the individual sample. CMB method apportions sources using extensive quantitative source emission profiles, and statistical approaches to infer source contribution without a prior need for 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. The CPCB guidelines approve this method for carrying out source apportionment studies, and many cities in the country have adopted this model.

The ambient $PM_{2.5}$ data with chemical composition is used for apportioning the contribution of various emitting sources to ambient air quality for Delhi. The model results were analyzed in terms of R-square (model fitting) and model-computed per cent mass (compared to the measured mass) (Nagar et al., 2017).

IIT Kanpur model, I^2TK-RSA1.0 is developed and validated against USEPA's CMB 8.2 for real-time source apportionment and integrated with the CMB method. The CMB8.2 model was run for each hour data set at the supersite to validate the I^2TK-RSA1.0 model, the two models provided identical results (Figure 31). It is seen that the receptor model developed by IIT Kanpur provides identical results as that of the USEPA CMB 8.2 Model.

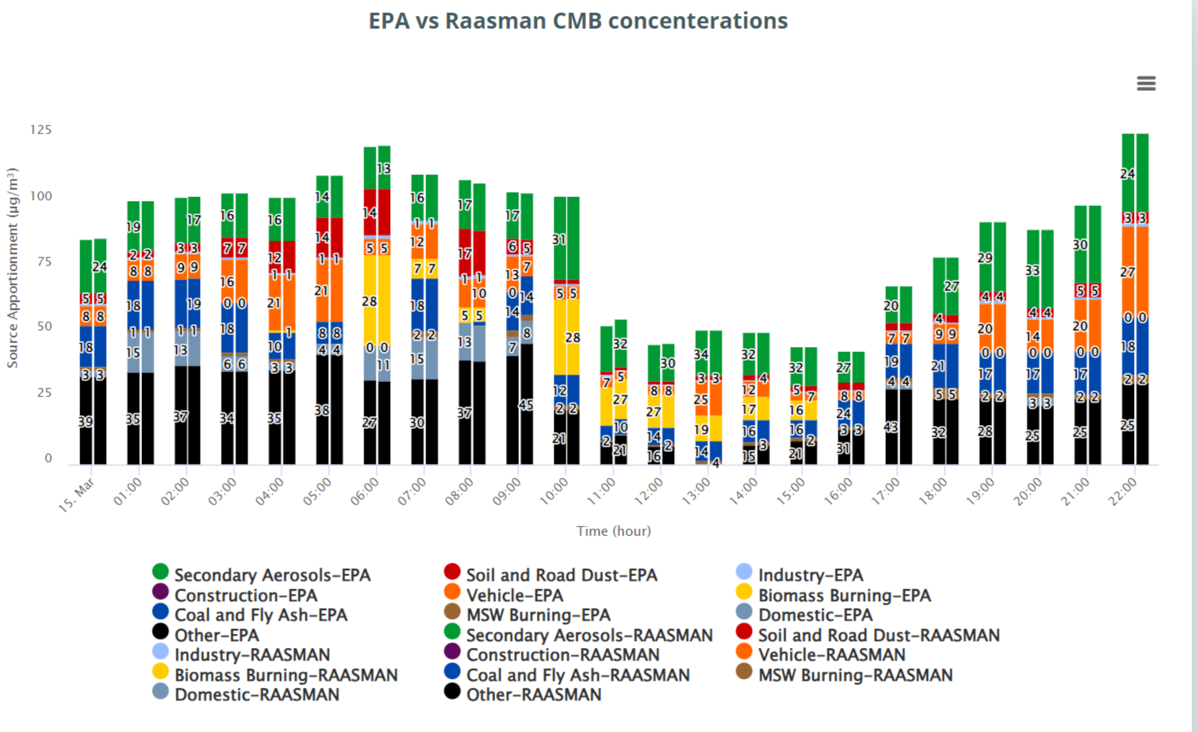


Figure 31: USEPA CMB 8.0 vs RAASMAN CMB (I^2TK-RSA1.0) COMPARISON

Validation: USEPA model CMB8.2 and I^2TK 1.0 model produce identical results.

4.3 Advanced Validation: Measured PM2.5 Species and Modelling Results

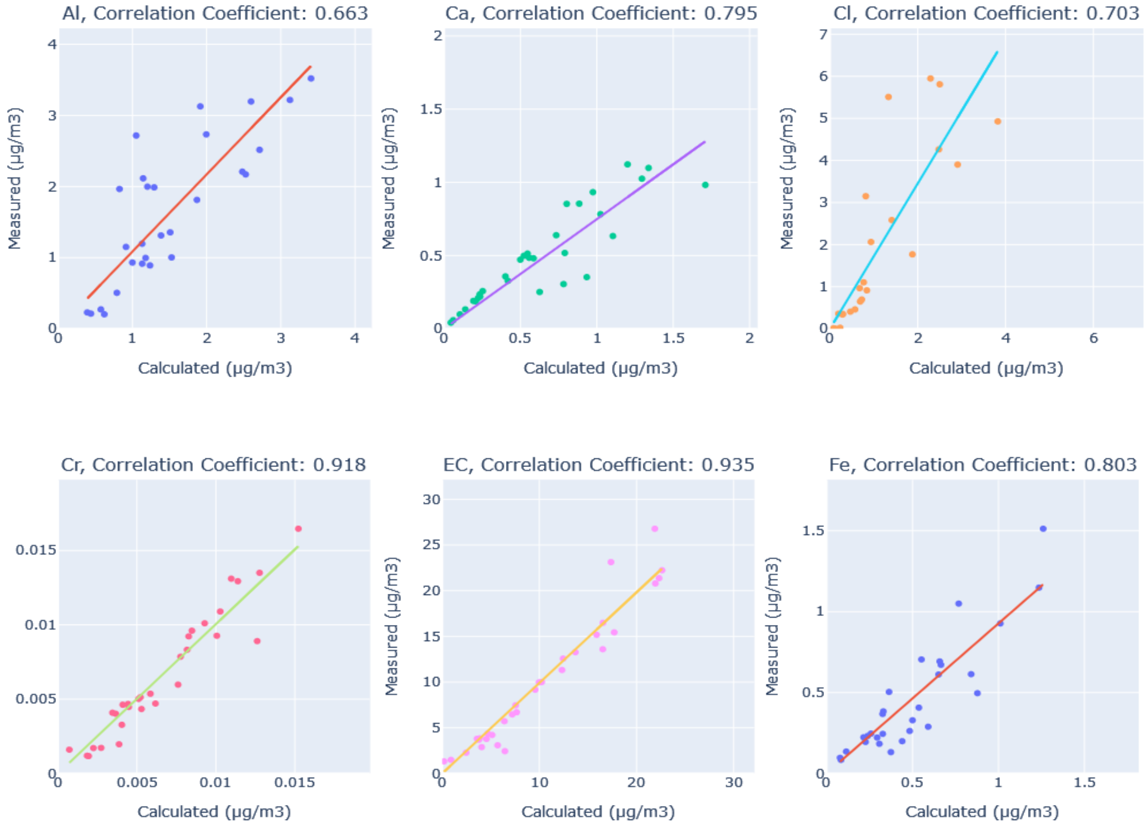
The following major species are measured in $PM_{2.5}$: Al, Si, K, Ca, Cr, Cl, Mn, Fe, Zn, Pb, EC, OC, SO_4, NO_3, NH_4.

Figure 32 shows the measured species concentration with the summation of species concentration computed by the IITK-developed receptor model. These two concentrations (i.e., measured and modelled) should be comparable for a good validation of the model. It is seen that for all 15 species model results are comparable and nearly identical with measured concentration for 32 - 35 hours.

Figure 32 also shows the coefficient of determination (R^2) which is a number between 0 and 1 that measures how well a statistical model predicts an outcome. One can interpret the R^2 as the proportion of variation in the dependent variable (i.e., measured concentration) that is predicted or explained by the model.

The R^2 varies between 0.7 and 0.99 which suggests that model-calculated levels are validated and explain the measured concentrations well. The coefficient of correlation between the model calculated and measured concentration ranges from 0.84 – 0.99 which suggests a significant linear relationship between measured and computed concentration.

Figure 33 shows the mass closure of measured $PM_{2.5}$ concentration by the receptor model. This independent validation suggests that the model performs extremely well.



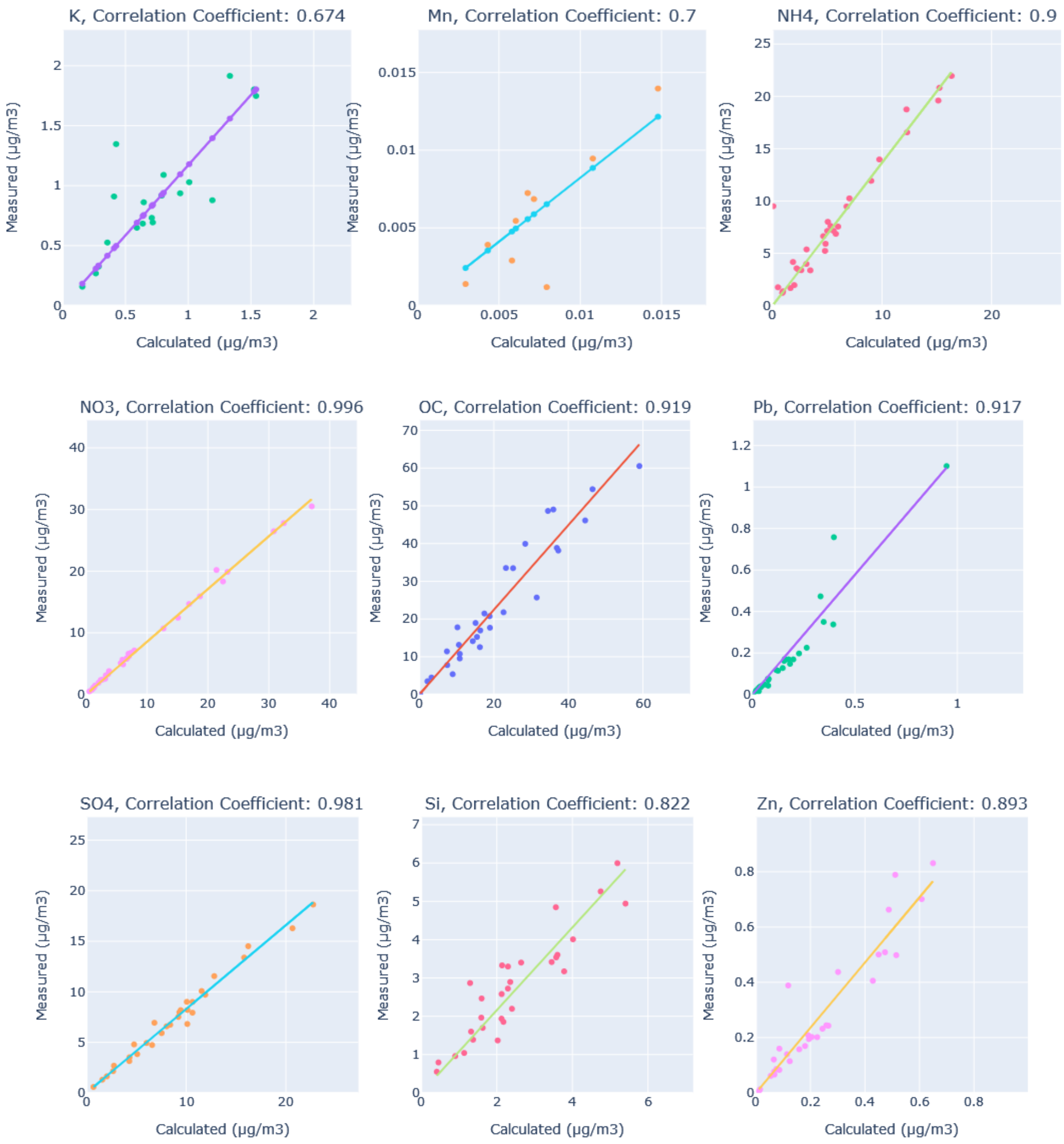


Figure 32: Measured PM2.5 Species and Modelling Results

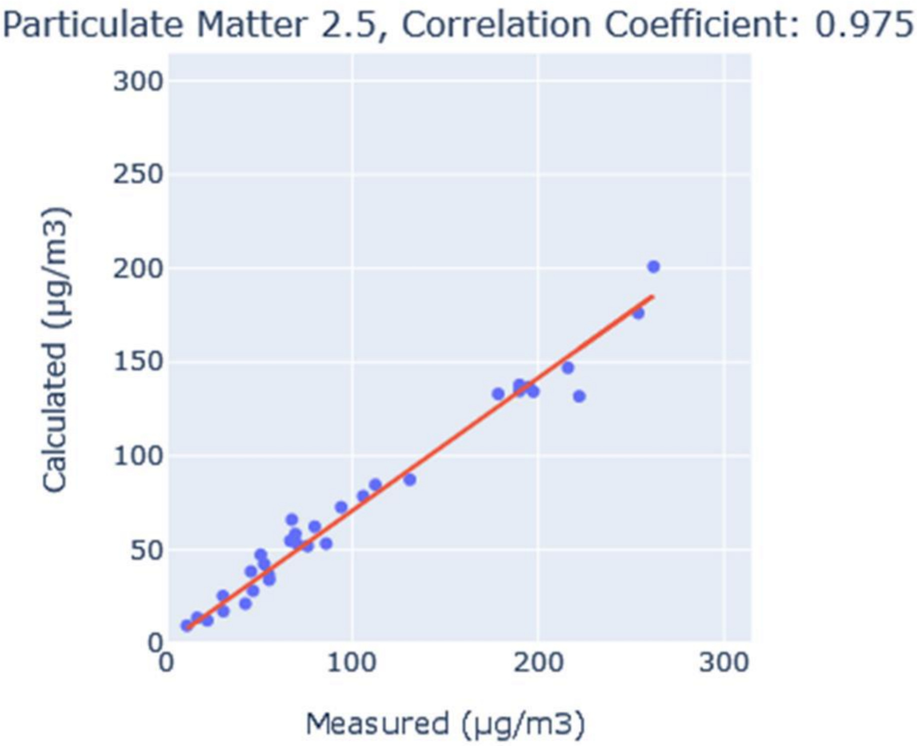
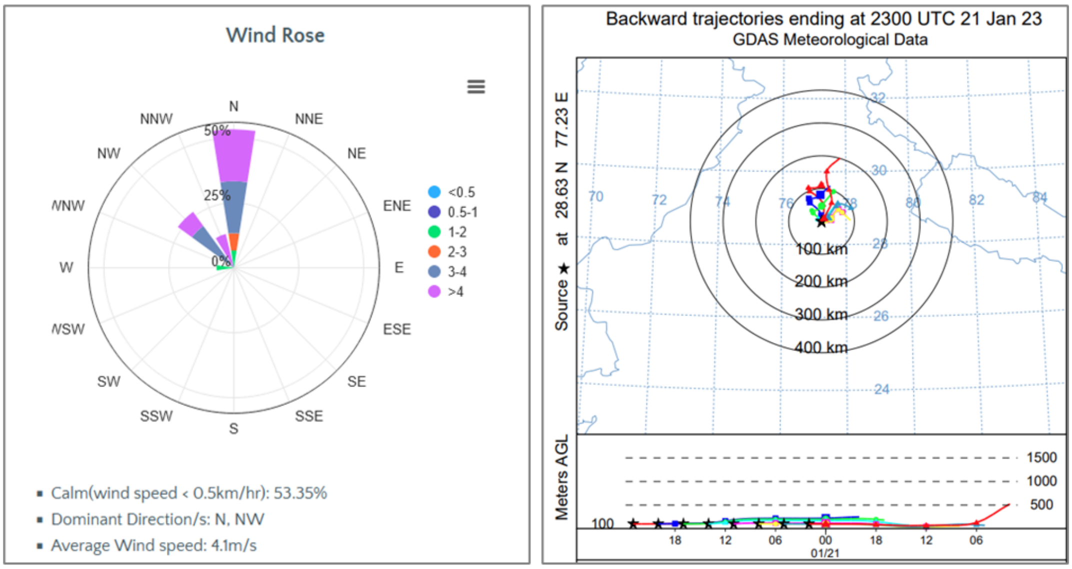


Figure 33: Measured $PM_{2.5}$ and Modelling Results

4.4 Meteorology validation

The WRF-Chem model outputs were validated against the observed meteorological parameters (temperature, RH, WS and WD) (Nagar and Sharma 2022). For example, see the measured wind direction and wind trajectory analysis (NOAA, 2013) of January 21, 2023 (Figure 34). The wind measurements and trajectory show the same wind direction as the north. This suggests that meteorological measurements at the supersite are validated by wind trajectory analysis obtained from National Oceanic and Atmospheric Administration (NOAA), USA.



(a) Measured wind (b) Modelled backward trajectories

Figure 34: measured wind and backward trajectory comparison at supersite

4.5 WRF-Chem Forecast vs Realtime Source Apportionment

The forecasted source apportionment is shown in Figure 35. The WRF-Chem forecast, and real time source apportionment data shows good agreement. However, there are some differences in between. Those might be due to the uncertainties involved in the emission inventory used in the WRF-Chem, domain of the area, grid size etc.

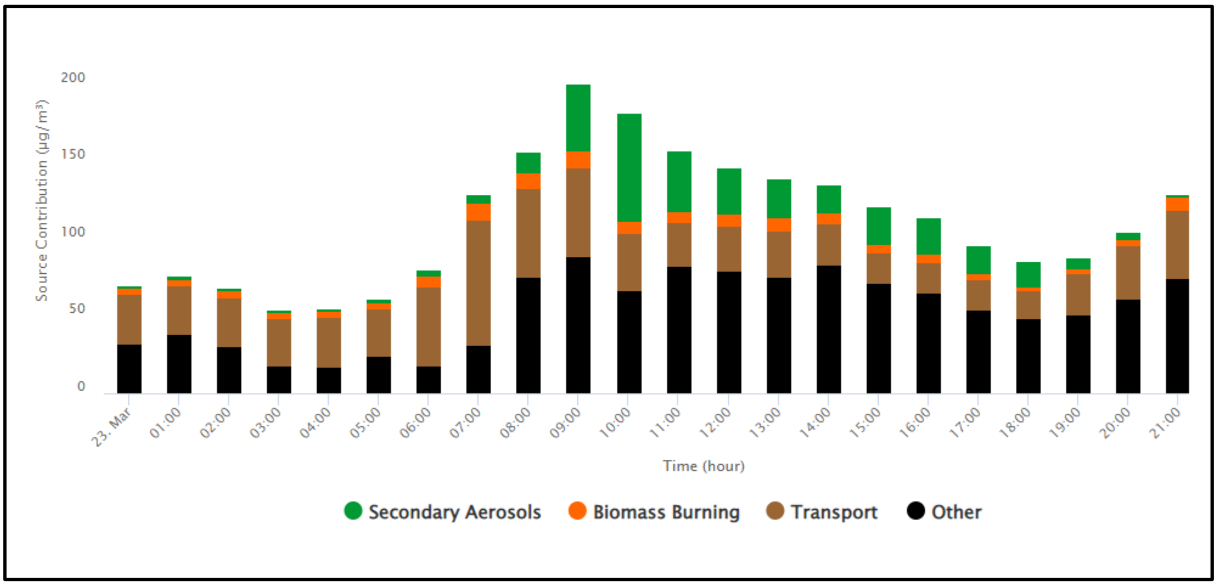


Figure 35: Real time sources over New Delhi

4.6 Observed and forecasted $PM_{2.5}$

Figure 36 shows the observed and forecasted $PM_{2.5}$ obtained from the model. They show good agreement in most of the cases. The few intense where the observed $PM_{2.5}$ is higher than the forecasted may be due to the incomplete information of chemical species used in the model.

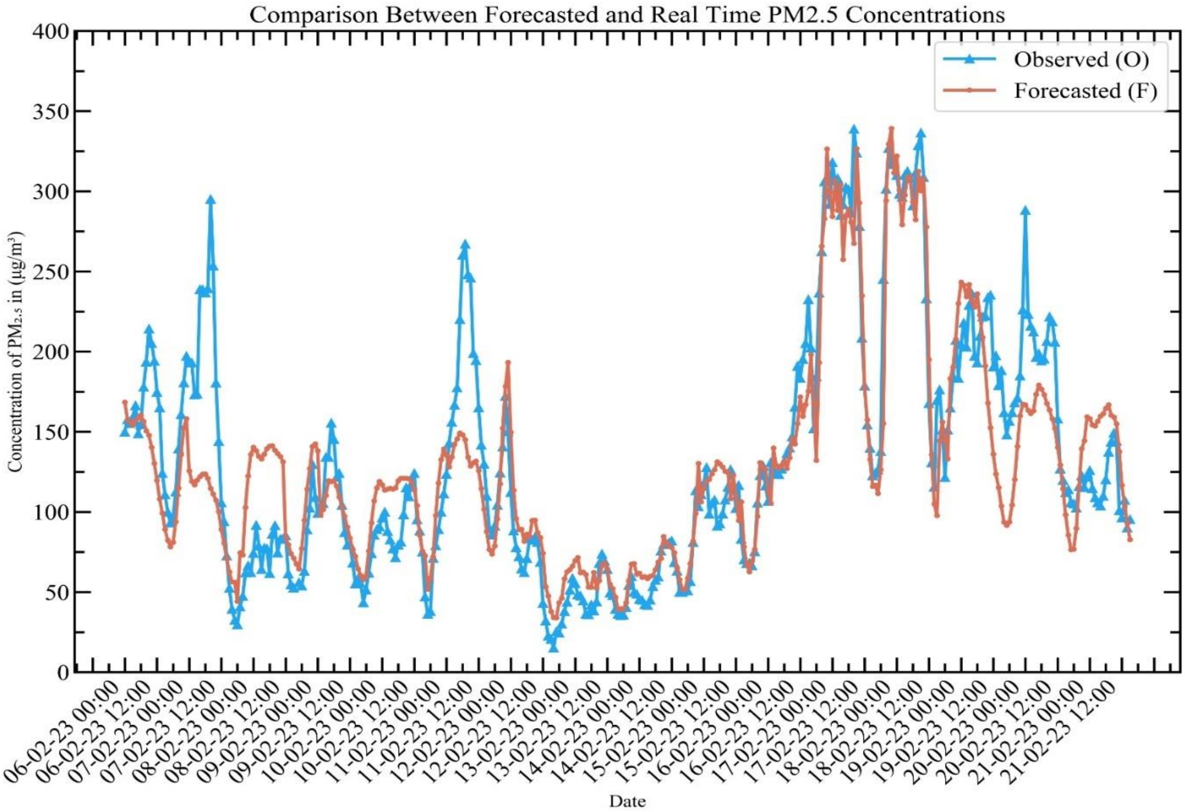


Figure 36: Forecast vs observations of $PM_{2.5}$

4.7 Brief discussion and way forward

Both WRF-Chem and AI-ML based forecasting has been carried out since November, 2022. While the AI-ML based forecast for total $PM_{2.5}$ has been reasonable, WRF-Chem based SA results aren't always in agreement with the Real time SA at supersite. One major reason for this could be the in-accuracy of yearly emission inventory used in this study. Further, some sources identified at the supersite, aren't available in the emission inventory. Thus, more work is needed to improve the emission inventory in future to improve the forecast of source contributions.

4.8 Forecasting the Air Quality Index (AQI)

The air quality index can be forecasted for the whole Delhi city on hourly basis 72-hour advance. This can be very useful information for common people who are advised to get less exposed in air pollution. In addition, strategic plans can be formulated well in advance. The AQI forecast can be observed on http://www.raasman.com/dashboard/forecast_aqi. Some of the AQI over Delhi city is given in Figure 37.

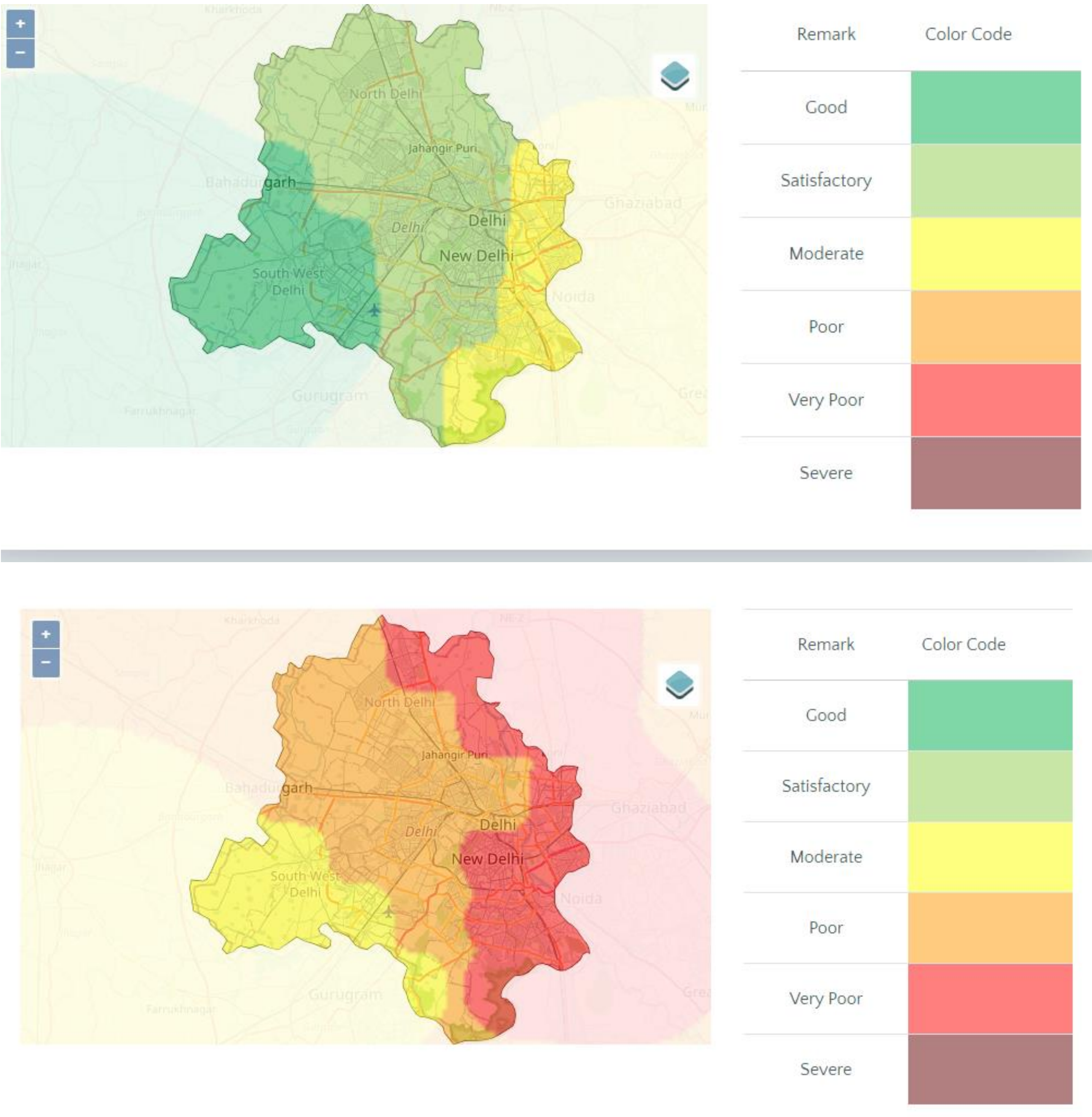
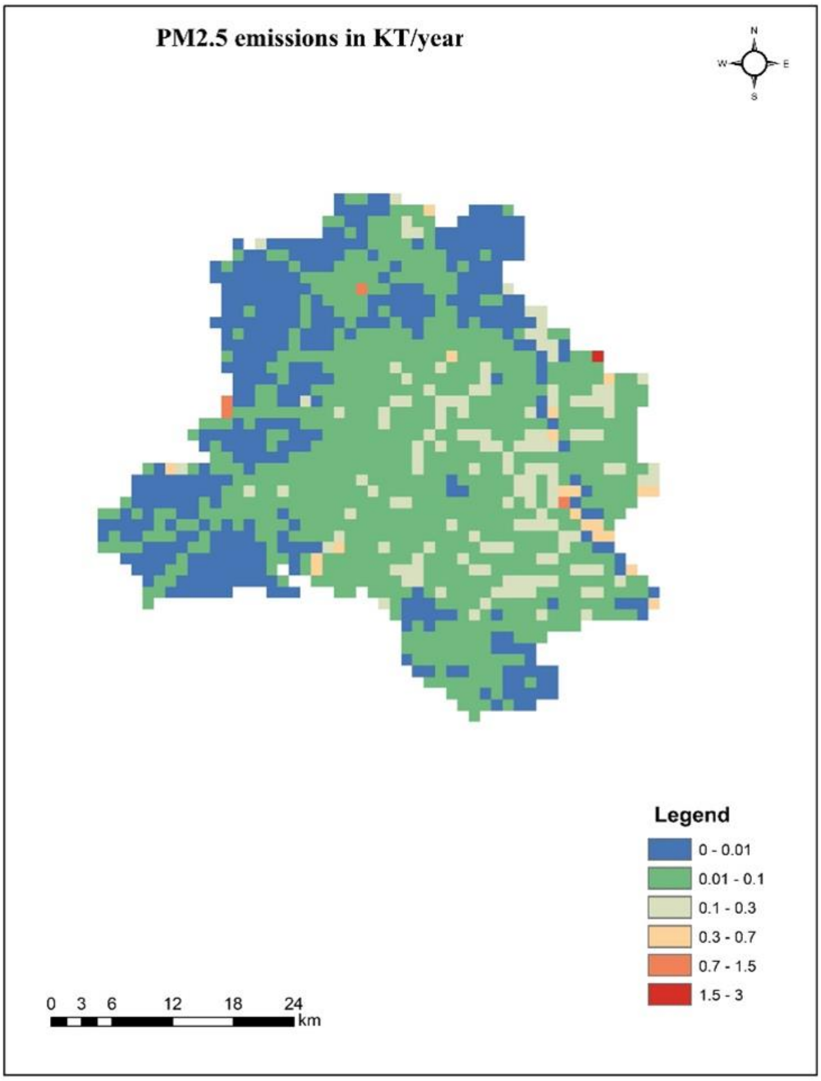


Figure 37: AQI forecast for Delhi

4.9 Emission of $PM_{2.5}$, SO_2 and NOx in Delhi per square kilometre

The emission of $PM_{2.5}$, SO_2 and NO_x in Delhi per square kilometer is given below in the table and spatially shown in Figure.

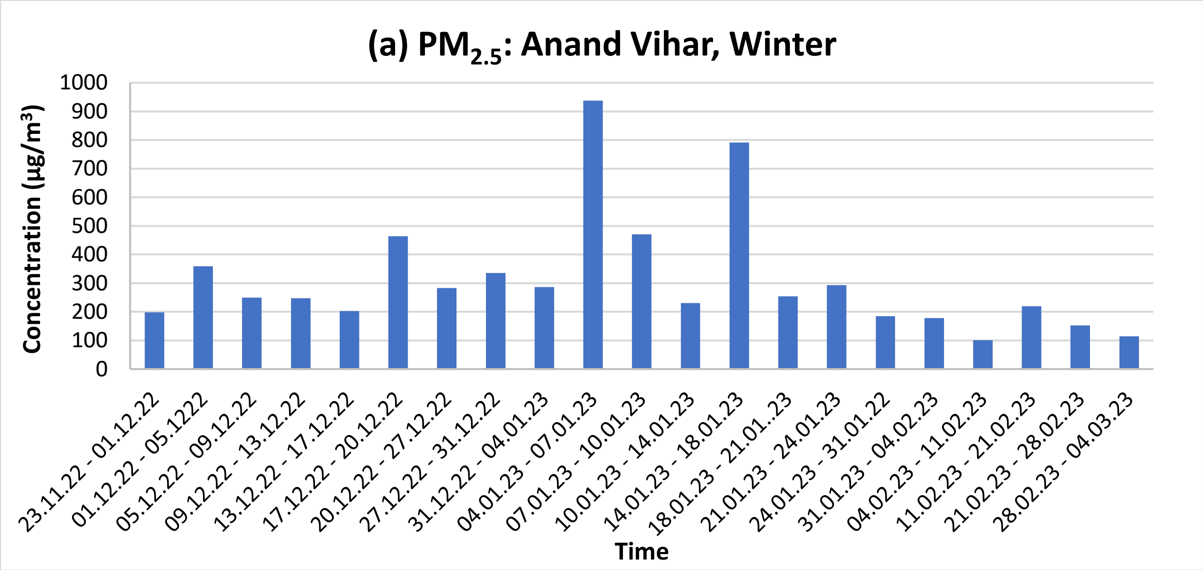
Pollutant	Delhi (tonnes/sq.km/year)
$PM_{2.5}$	29.3
SO_2	3.0
NO_x	62.8

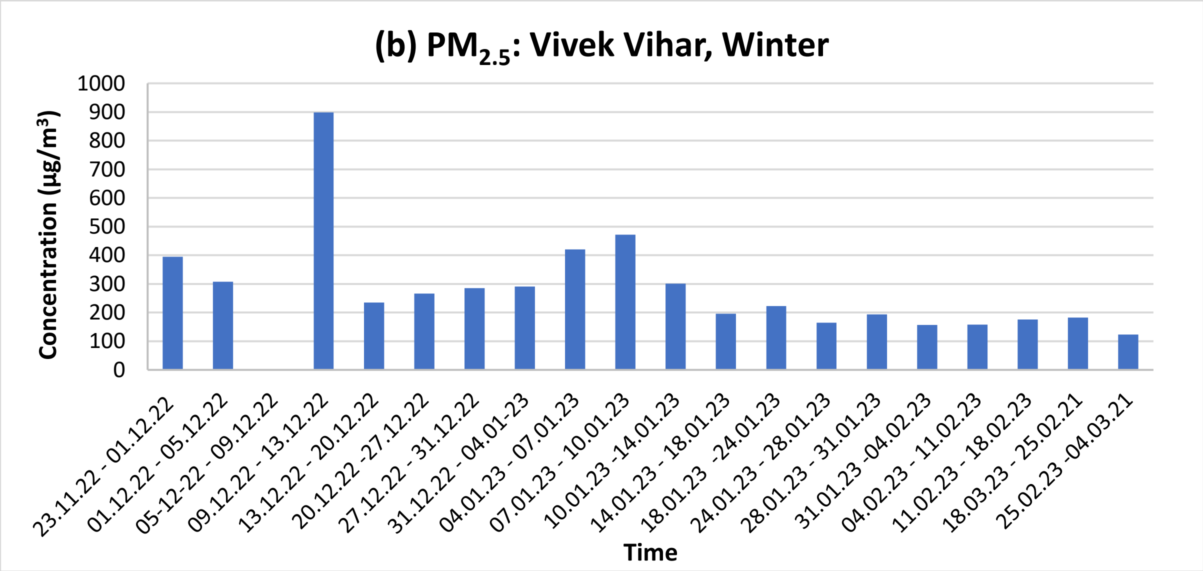


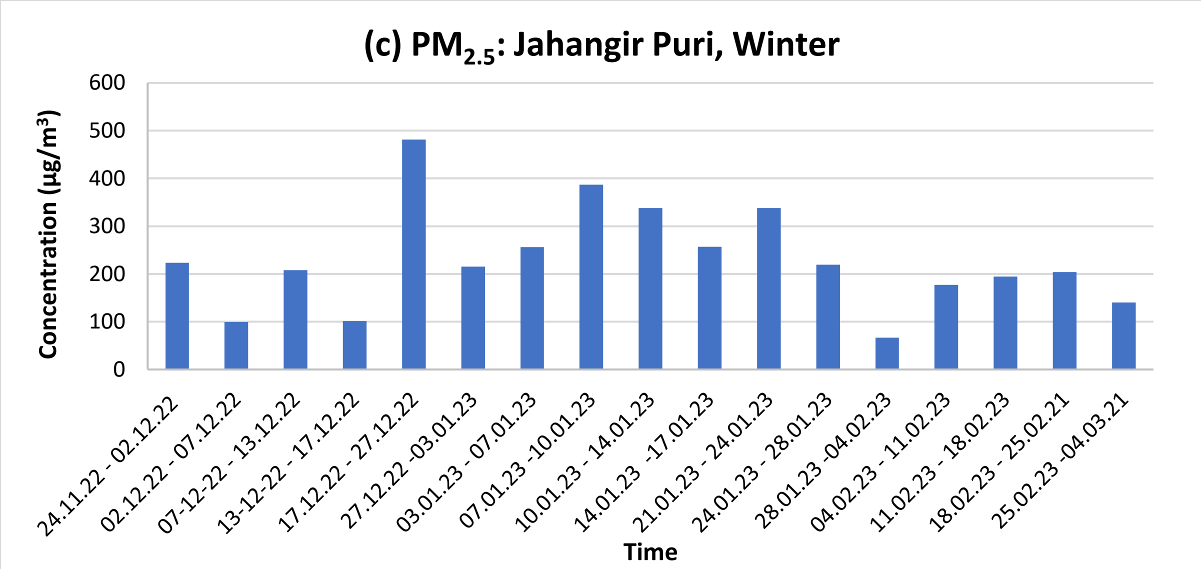
4.10 Monitoring at five offline hotspot stations

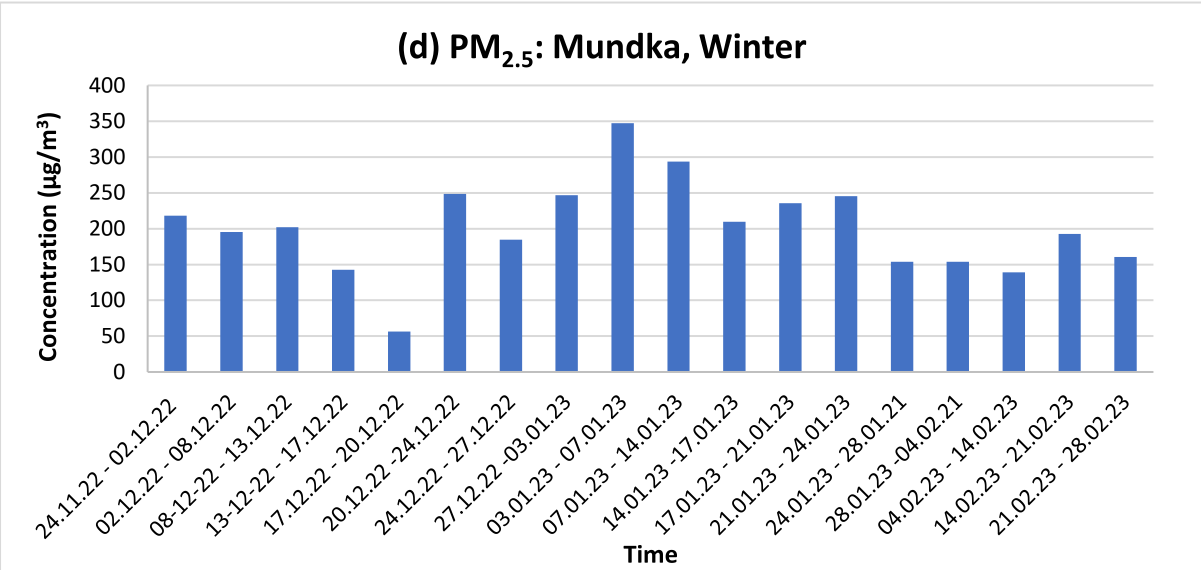
$PM_{2.5}$ Levels

The levels of $PM_{2.5}$ measured at five locations in Delhi using low-flow sampler are presented in Figure 38. The statistical summary is presented in Table 4. The mean levels are shown in Figure 39. The sampling period is about 6 – 7 days for each sample.









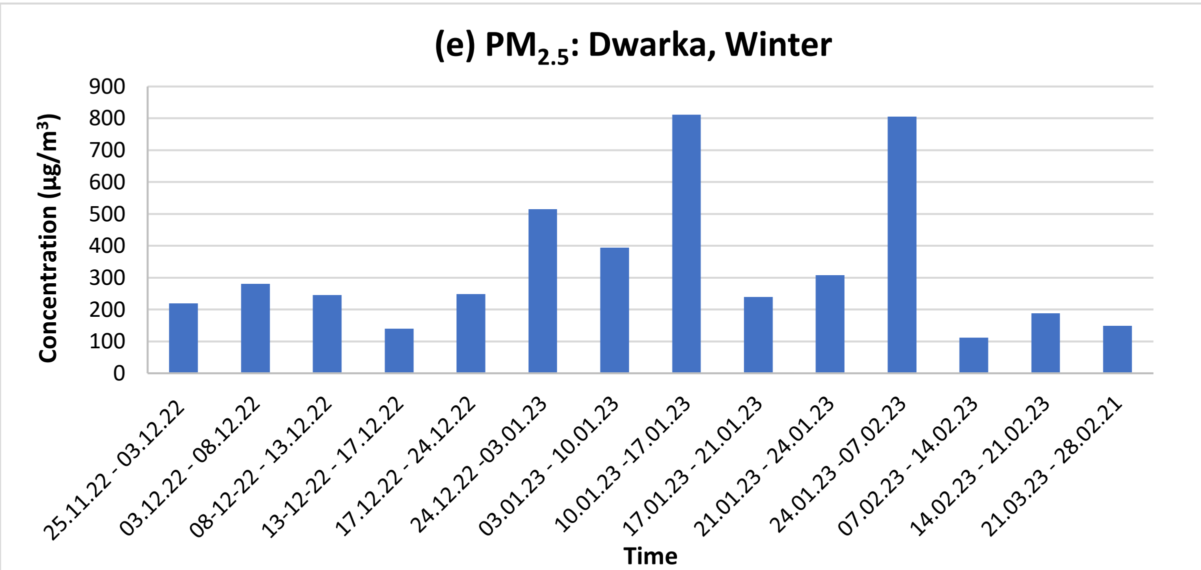


Figure 38: $PM_{2.5}$ levels at five offline hotspot sites

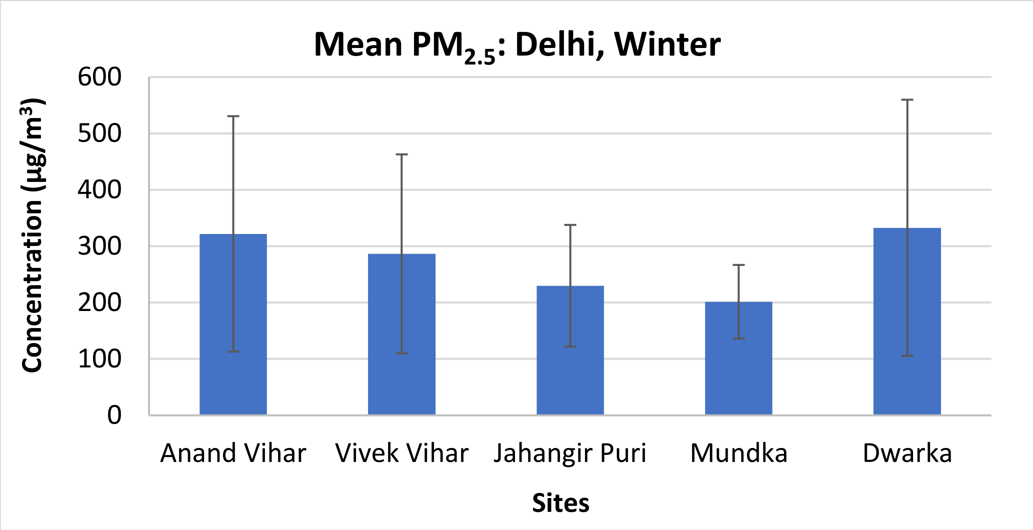


Figure 39: Mean $PM_{2.5}$ levels at five offline hotspot sites

Table 4: Statistical summary of $PM_{2.5}$ at hotspot sites

	$PM_{2.5}$ (µg/m^3)				
	Anand Vihar	**Vivek Vihar**	**Jahangir Puri**	**Mundka**	**Dwarka**
Mean	322	286	230	201	333
SD	209	176	108	65	227
Max	937	898	481	347	812
Min	101	124	66	56	111
CV	0.65	0.62	0.47	0.32	0.68

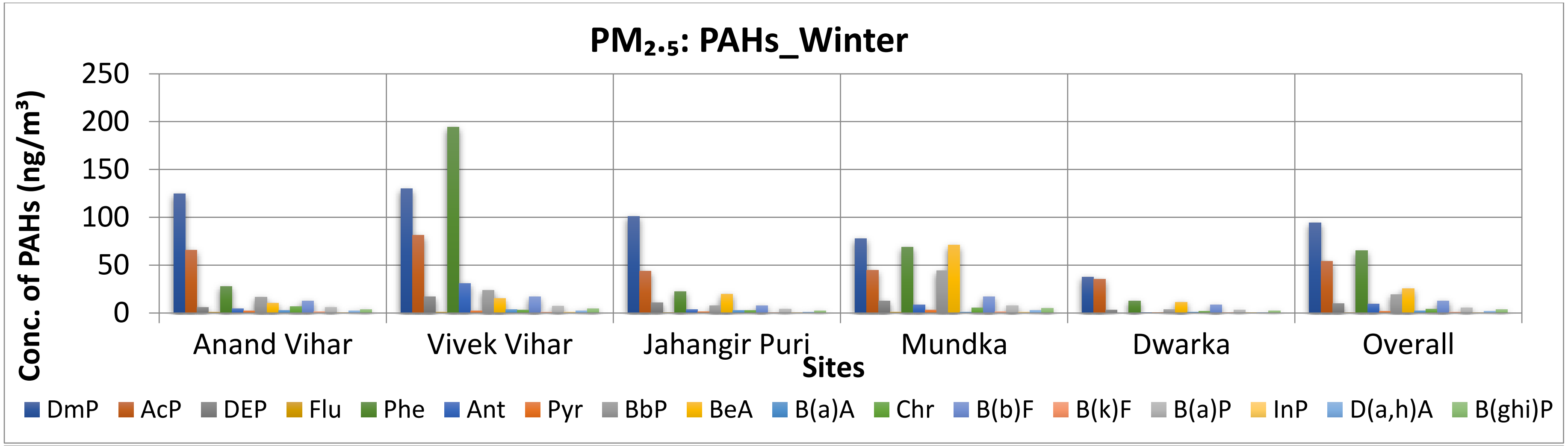
Organic Markers: PAHs and Hopanes

PAHs

The concentrations of PAHs (from the solid phase only) with some specific markers were analyzed. 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). A statistical summary of PAHs is presented in Table 5 for the winter season. Figure 40 shows the average measured concentration of PAHs at five sites for the winter season.

Table 5: Overall summary of average concentration (ng/m³) of PAHs in $PM_{2.5}$ for the winter season

Site Location		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
Anand Vihar	Mean	124.59	65.73	6.13	1.19	27.98	4.42	2.55	16.69	10.47	2.91	7.01	12.57	1.25	6.00	0.53	2.16	3.90	296.08
	SD	125.41	52.98	6.50	1.62	58.87	12.93	2.61	31.53	15.71	2.40	10.41	15.58	1.59	7.36	0.45	3.00	5.07	226.61
	Max	357.13	222.52	26.01	5.80	229.67	49.28	8.56	123.92	61.98	8.15	36.37	60.34	6.33	28.85	1.56	11.80	20.51	735.95
	Min	11.61	27.62	0.40	0.00	1.39	0.12	0.04	1.29	0.34	0.52	0.42	0.90	0.11	0.66	0.09	0.08	0.60	56.07
	CV	1.01	0.81	1.06	1.36	2.10	2.93	1.02	1.89	1.50	0.82	1.49	1.24	1.27	1.23	0.86	1.39	1.30	0.77
Vivek Vihar	Mean	130.15	81.21	17.19	0.92	194.36	31.10	2.32	23.92	15.41	3.55	3.30	17.17	1.17	7.26	0.93	2.36	4.76	537.09
	SD	48.69	30.27	16.98	0.50	155.18	30.08	3.03	60.78	10.51	3.07	8.52	14.47	1.20	6.10	0.43	1.86	4.13	182.32
	Max	220.14	126.02	57.53	1.88	492.55	90.41	10.53	196.74	36.40	9.69	27.53	46.72	3.88	18.21	1.49	5.46	12.91	865.31
	Min	67.44	45.53	3.46	0.32	9.64	1.20	0.29	1.20	3.21	0.62	0.32	3.47	0.28	1.62	0.28	0.31	1.11	260.10
	CV	0.37	0.37	0.99	0.54	0.80	0.97	1.31	2.54	0.68	0.86	2.58	0.84	1.03	0.84	0.46	0.79	0.87	0.34
Jahangir Puri	Mean	101.13	43.72	10.76	0.61	22.58	3.62	1.48	7.54	19.88	2.90	2.85	7.84	0.75	4.02	0.65	1.11	2.43	233.87
	SD	94.53	45.77	9.95	0.70	20.35	3.54	0.94	5.26	14.69	2.21	3.23	7.34	0.70	4.28	0.91	1.45	2.31	158.10
	Max	384.91	147.89	37.33	2.49	82.55	12.72	3.43	17.68	60.70	7.13	12.03	22.94	2.70	15.36	3.43	5.56	9.04	692.49
	Min	2.79	6.62	0.78	0.00	1.57	0.11	0.19	2.00	4.83	0.74	0.48	0.38	0.13	0.39	0.00	0.10	0.39	81.97
	CV	0.93	1.05	0.92	1.15	0.90	0.98	0.63	0.70	0.74	0.76	1.14	0.94	0.93	1.07	1.40	1.31	0.95	0.68
Mundka	Mean	77.74	44.98	12.74	0.98	68.82	8.62	3.30	44.20	71.23	1.00	5.54	17.01	1.43	7.66	0.95	2.63	5.04	373.88
	SD	52.09	22.71	1.44	0.02	86.60	10.87	3.10	46.81	24.36	0.62	6.51	11.73	1.17	3.65	0.41	1.50	2.51	72.18
	Max	114.57	61.04	13.75	1.00	130.06	16.31	5.49	77.30	88.45	1.44	10.15	25.30	2.26	10.24	1.24	3.69	6.81	424.92
	Min	40.91	28.93	11.72	0.97	7.59	0.93	1.12	11.10	54.01	0.56	0.94	8.71	0.61	5.08	0.66	1.57	3.27	322.85
	CV	0.67	0.50	0.11	0.02	1.26	1.26	0.94	1.06	0.34	0.62	1.17	0.69	0.81	0.48	0.43	0.57	0.50	0.19
Dwarka	Mean	37.71	35.41	3.36	0.15	12.82	0.37	0.45	3.78	11.48	0.80	1.95	8.66	0.54	3.25	0.39	0.62	2.19	123.93
	SD	35.55	21.40	1.38	0.17	20.36	0.20	0.11	3.09	10.83	0.34	0.81	5.02	0.17	1.52	0.30	0.48	0.91	52.26
	Max	78.95	78.69	5.91	0.46	53.79	0.53	0.59	9.75	29.67	1.43	3.47	16.61	0.84	5.34	0.97	1.39	3.78	193.80
	Min	1.48	22.96	2.26	0.00	0.20	0.08	0.32	1.65	1.83	0.50	1.01	2.67	0.33	1.27	0.14	0.10	1.20	62.32
	CV	0.94	0.60	0.41	1.14	1.59	0.54	0.23	0.82	0.94	0.43	0.42	0.58	0.33	0.47	0.77	0.77	0.41	0.42



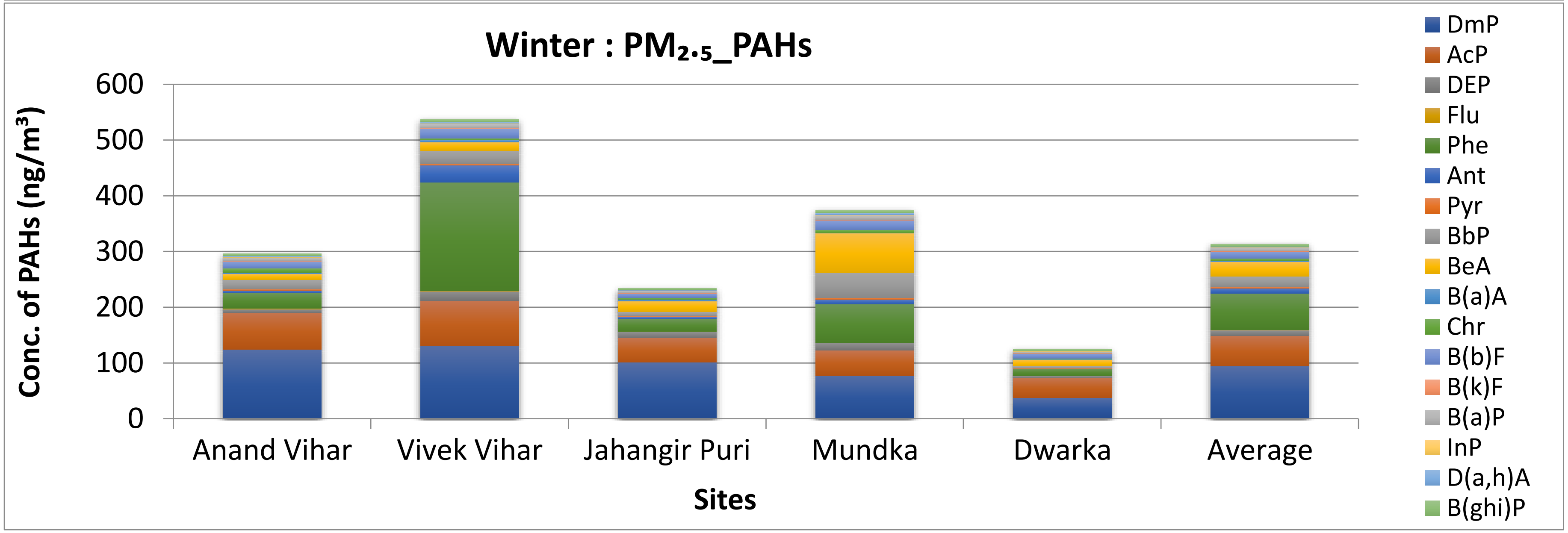


Figure 40: Mean levels of PAHs at offline hotspot sites

Hopanes

Total six molecular markers analyzed were: Tritriacontane, Hentriacontane, Pentriacontane, 17 β(H) 21 β(H)_hopane, 17 α(H) 21 α(H)_hopane, 17 α(H) - 22,29,30 - Trisnorhopane. The n-alkanes are generally emitted from all types of combustion sources and hopanes from the combustion of coal (C), gasoline (G) and diesel (D) (Zhang et al., 2009). Figure 41 shows the average measured concentration of hopanes at five sites for the winter season. A statistical summary of hopanes (molecular markers) are presented in Table 6 for the winter season.

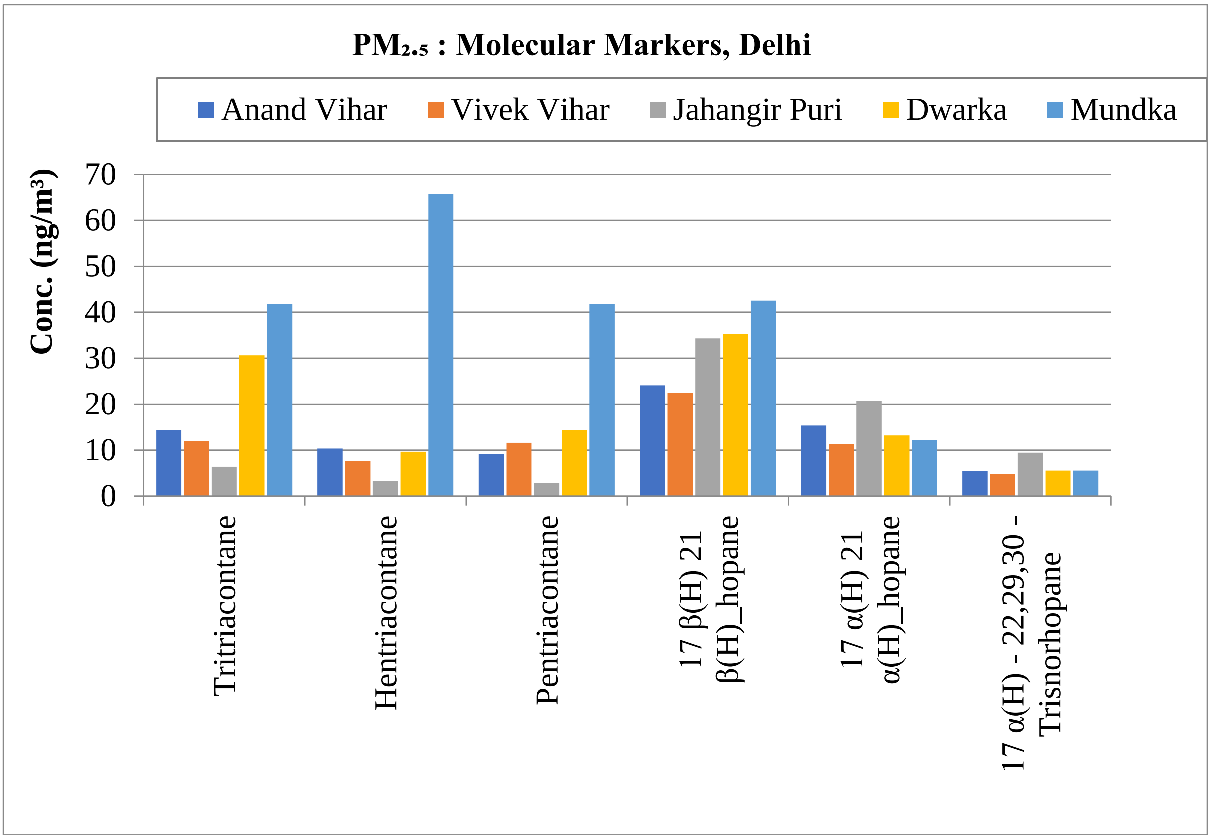


Figure 41: Molecular markers at offline sites in winter

Table 6: Overall summary of average concentration (ng/m^3) of hopanes in $PM_{2.5}$ for winter season

Site		Tritriacontane	Hentriacontane	Pentriacontane	17 β(H) 21 β(H)_hopane	17 α(H) 21 α(H)_hopane	17 α(H) - 22,29,30 - Trisnorhopane	Total
Anand Vihar	Mean	14.37	10.37	9.09	24.07	15.38	5.46	78.7
	SD	9.78	7.60	4.12	12.50	12.77	2.44	31.5
	Min	1.83	1.29	2.53	9.93	4.02	2.43	30.1
	Max	31.12	26.07	16.11	45.81	45.24	10.00	134.2
	CV	0.68	0.73	0.45	0.52	0.83	0.45	0.40
Vivek Vihar	Mean	12.04	7.67	11.61	22.44	11.37	4.84	70.0
	SD	9.77	3.54	7.49	9.35	4.63	2.48	17.0
	Min	4.71	3.40	3.46	11.70	6.35	2.48	44.6
	Max	28.86	13.06	22.42	37.11	17.72	8.28	85.8
	CV	0.81	0.46	0.64	0.42	0.41	0.51	0.24
Jahangir Puri	Mean	6.35	3.32	2.83	34.35	20.76	9.42	77.0
	SD	5.24	1.77	1.99	30.19	15.27	6.05	53.7
	Min	0.28	0.92	1.45	10.39	8.36	3.86	30.1
	Max	19.08	6.53	7.45	99.61	64.36	25.47	213.4
	CV	0.82	0.53	0.70	0.88	0.74	0.64	0.70
Dwarka	Mean	30.62	9.70	14.37	35.21	13.21	5.58	108.7
	SD	24.72	8.18	12.64	21.69	7.93	6.12	54.0
	Min	2.26	1.57	0.99	11.98	4.52	1.11	24.1
	Max	81.06	24.16	39.71	96.47	31.31	24.81	182.8
	CV	0.81	0.84	0.88	0.62	0.60	1.10	0.50
Mundka	Mean	41.78	65.76	41.75	42.54	12.19	5.58	209.6
	SD	25.52	99.12	42.91	16.87	7.25	2.91	137.2
	Min	10.61	2.93	2.59	24.19	4.72	2.77	67.9
	Max	88.41	297.04	135.31	81.59	22.61	10.31	452.5
	CV	0.61	1.51	1.03	0.40	0.60	0.52	0.65

Inorganic markers: Metals

A statistical summary of metals is presented in Table 7 for the winter season.

Table 7: Statistical summary of metals in $PM_{2.5}$ at five offline sites

(1) Anand Vihar (in µg/m³)													
Winter	**PM2.5**	**Al**	**As**	**Ba**	**Br**	**Ca**	**Cd**	**Cl**	**Co**	**Cr**	**Cs**	**Cu**	**Fe**
Mean	321.9	1.11	0.03	0.03	0.11	1.55	0.05	10.66	0.00	0.01	0.01	0.31	1.24
SD	208.8	1.10	0.02	0.02	0.12	1.38	0.03	7.34	0.00	0.00	0.01	0.47	0.92
Max	937.39	4.80	0.10	0.07	0.57	5.45	0.15	30.14	0.01	0.02	0.03	2.22	4.22
Min	100.95	0.15	0.01	0.01	0.03	0.29	0.01	2.99	0.00	0.00	0.00	0.05	0.33
CV	0.65	0.99	0.83	0.49	1.09	0.89	0.71	0.69	0.61	0.38	1.05	1.53	0.74
Winter	**K**	**Mn**	**Na**	**Ni**	**P**	**Pb**	**Rb**	**S**	**Si**	**Sr**	**Ti**	**V**	**Zn**
Mean	3.17	0.05	1.28	0.00	0.09	0.56	0.00	5.88	3.31	0.01	0.09	0.00	0.89
SD	1.33	0.02	0.78	0.00	0.05	0.52	0.00	4.70	2.82	0.01	0.08	0.00	0.57
Max	6.88	0.10	3.25	0.01	0.25	2.41	0.01	23.70	12.25	0.03	0.33	0.02	2.83
Min	1.39	0.02	0.35	0.00	0.02	0.15	0.00	1.24	0.75	0.00	0.02	0.00	0.22
CV	0.42	0.40	0.61	0.51	0.59	0.93	0.76	0.80	0.85	0.72	0.88	0.90	0.64

(2) Vivek Vihar (in µg/m³)													
Winter	**PM2.5**	**Al**	**As**	**Ba**	**Br**	**Ca**	**Cd**	**Cl**	**Co**	**Cr**	**Cs**	**Cu**	**Fe**
Mean	286.5	0.49	0.03	0.02	0.12	0.61	0.11	8.47	0.00	0.01	0.01	0.59	0.62
SD	176.4	0.21	0.01	0.01	0.09	0.25	0.04	3.51	0.00	0.00	0.01	0.35	0.16
Max	897.96	0.93	0.06	0.04	0.41	1.22	0.17	16.98	0.01	0.02	0.02	1.59	0.92
Min	123.77	0.00	0.01	0.01	0.04	0.19	0.03	0.89	0.00	0.01	0.00	0.15	0.38
CV	0.62	0.44	0.47	0.32	0.73	0.40	0.36	0.41	0.25	0.30	1.13	0.59	0.27
Winter	**K**	**Mn**	**Na**	**Ni**	**P**	**Pb**	**Rb**	**S**	**Si**	**Sr**	**Ti**	**V**	**Zn**
Mean	2.53	0.04	1.04	0.00	0.06	0.81	0.00	4.76	1.53	0.01	0.04	0.00	1.24
SD	0.72	0.01	0.44	0.00	0.03	0.53	0.00	2.31	0.54	0.00	0.01	0.00	0.41
Max	4.01	0.06	2.00	0.01	0.10	1.89	0.00	10.21	2.55	0.01	0.07	0.00	2.25
Min	0.93	0.02	0.16	0.00	0.00	0.26	0.00	0.28	0.11	0.00	0.02	0.00	0.74
CV	0.28	0.28	0.42	0.35	0.47	0.66	0.63	0.48	0.35	0.27	0.33	0.28	0.33

(3) Jahangir Puri (in µg/m³)												
Winter	**PM2.5**	**Al**	**As**	**Ba**	**Br**	**Ca**	**Cd**	**Cl**	**Co**	**Cr**	**Cs**	**Cu**	**Fe**
Mean	229.8	0.39	0.02	0.02	0.07	0.57	0.04	8.63	0.00	0.01	0.00	0.17	0.70
SD	108.0	0.24	0.01	0.02	0.04	0.26	0.02	3.85	0.00	0.00	0.00	0.11	0.62
Max	481.25	0.82	0.04	0.08	0.18	0.97	0.09	16.40	0.01	0.02	0.01	0.40	2.88
Min	66.28	0.09	0.00	0.01	0.01	0.21	0.01	1.85	0.00	0.00	0.00	0.02	0.21
CV	0.47	0.61	0.62	0.80	0.61	0.46	0.57	0.45	0.61	0.43	1.28	0.65	0.89
Winter	**K**	**Mn**	**Na**	**Ni**	**P**	**Pb**	**Rb**	**S**	**Si**	**Sr**	**Ti**	**V**	**Zn**
Mean	2.22	0.06	1.02	0.00	0.06	0.35	0.00	4.09	1.48	0.00	0.04	0.00	0.80
SD	0.89	0.08	0.47	0.00	0.03	0.21	0.00	1.92	0.70	0.00	0.02	0.00	0.45
Max	3.91	0.34	1.94	0.01	0.13	0.80	0.01	7.32	2.48	0.01	0.09	0.00	1.71
Min	0.59	0.00	0.26	0.00	0.02	0.06	0.00	1.12	0.46	0.00	0.02	0.00	0.15
CV	0.40	1.31	0.46	0.68	0.48	0.59	0.60	0.47	0.47	0.44	0.53	0.42	0.56

(4) Mundka (in µg/m³)													
Winter	**PM2.5**	**Al**	**As**	**Ba**	**Br**	**Ca**	**Cd**	**Cl**	**Co**	**Cr**	**Cs**	**Cu**	**Fe**
Mean	201.5	0.66	0.02	0.02	0.05	1.09	0.02	8.06	0.00	0.01	0.00	0.08	1.04
SD	65.3	0.36	0.01	0.01	0.01	0.57	0.01	2.28	0.00	0.00	0.01	0.04	0.49
Max	347.44	1.33	0.04	0.04	0.07	2.27	0.05	11.35	0.00	0.02	0.02	0.17	2.07
Min	56.42	0.21	0.00	0.00	0.03	0.37	0.01	2.75	0.00	0.00	0.00	0.01	0.39
CV	0.32	0.55	0.49	0.51	0.24	0.53	0.43	0.28	0.29	0.38	1.24	0.57	0.48
Winter	**K**	**Mn**	**Na**	**Ni**	**P**	**Pb**	**Rb**	**S**	**Si**	**Sr**	**Ti**	**V**	**Zn**
Mean	2.29	0.07	0.93	0.00	0.04	0.47	0.00	3.80	2.07	0.01	0.05	0.00	0.45
SD	0.60	0.05	0.28	0.00	0.02	0.34	0.00	1.51	0.93	0.00	0.02	0.00	0.21
Max	3.07	0.22	1.35	0.01	0.09	1.51	0.00	6.34	3.79	0.02	0.09	0.00	0.89
Min	0.65	0.02	0.40	0.00	0.00	0.05	0.00	0.58	0.67	0.00	0.02	0.00	0.07
CV	0.26	0.72	0.30	0.50	0.47	0.73	0.42	0.40	0.45	0.45	0.44	0.35	0.47

(5) Dwarka (in µg/m³)

Winter	PM2.5	Al	As	Ba	Br	Ca	Cd	Cl	Co	Cr	Cs	Cu	Fe
Mean	332.67	0.94	0.02	0.02	0.05	1.44	0.03	8.42	0.00	0.01	0.00	0.06	1.13
SD	227.1	0.85	0.02	0.01	0.03	1.49	0.02	6.30	0.00	0.01	0.00	0.04	0.78
Max	811.95	3.72	0.09	0.07	0.11	6.39	0.08	21.64	0.01	0.03	0.01	0.16	3.63
Min	111.42	0.25	0.00	0.01	0.02	0.45	0.01	2.30	0.00	0.00	0.00	0.02	0.62
CV	0.683	0.903	1.110	0.630	0.551	1.039	0.695	0.748	0.772	0.831	1.765	0.638	0.690
Winter	**K**	**Mn**	**Na**	**Ni**	**P**	**Pb**	**Rb**	**S**	**Si**	**Sr**	**Ti**	**V**	**Zn**
Mean	3.27	0.07	0.92	0.00	0.08	0.44	0.00	6.02	2.92	0.01	0.08	0.00	0.48
SD	1.83	0.03	0.56	0.00	0.04	0.62	0.00	4.77	2.50	0.01	0.07	0.00	0.23
Max	7.81	0.13	2.06	0.01	0.19	2.52	0.01	17.88	11.03	0.04	0.31	0.01	0.95
Min	1.56	0.03	0.32	0.00	0.03	0.04	0.00	1.81	1.18	0.00	0.03	0.00	0.11
CV	0.560	0.482	0.609	0.822	0.552	1.418	0.575	0.792	0.855	0.893	0.944	0.915	0.480

$PM_{2.5}$ and its constituents (metals, ions and carbon) at supersite

The weekly mean levels of $PM_{2.5}$ and its constituents are presented in Table 8. The monthly mean levels (with standard deviation) of $PM_{2.5}$ and its constituents are presented in Table 9.

Table 8: Weekly mean levels of $PM_{2.5}$ and its constituents (metals, ions and carbon) at supersite

Weekly Mean			Metals (µg/m³)													
Date-Start	Date-end	$PM_{2.5}$	Al	Si	S	K	Ca	P	Ti	V	Cr	Mn	Fe	Co	Ni	Cu
01-11-22	07-11-22	329	4.09	4.89	22.08	4.65	1.02	0.073	0.031	0.020	0.012	0.044	0.905	0.054	0.004	0.062
08-11-22	14-11-22	194	2.73	3.37	14.75	2.96	0.71	0.051	0.018	0.011	0.008	0.028	0.573	0.034	0.003	0.081
15-11-22	21-11-22	148	2.18	3.05	8.57	2.22	0.62	0.041	0.014	0.008	0.007	0.026	0.492	0.030	0.003	0.087
22-11-22	28-11-22	161	2.28	3.80	9.41	2.10	0.74	0.046	0.021	0.011	0.010	0.036	0.699	0.041	0.004	0.061
29-11-22	05-12-22	234	2.69	4.17	19.26	2.38	0.79	0.063	0.027	0.015	0.010	0.045	0.899	0.053	0.004	0.067
06-12-22	12-12-22	177	2.41	3.70	15.24	2.06	0.68	0.056	0.021	0.011	0.010	0.040	0.646	0.039	0.004	0.073
13-12-22	19-12-22	174	2.37	3.81	12.88	1.75	0.67	0.054	0.020	0.011	0.009	0.035	0.610	0.037	0.003	0.065
20-12-22	26-12-22	246	3.09	3.57	28.03	2.04	0.58	0.085	0.016	0.010	0.010	0.037	0.469	0.029	0.005	0.091
27-12-22	02-01-23	233	2.82	3.09	20.29	2.11	0.55	0.067	0.014	0.009	0.008	0.026	0.439	0.027	0.003	0.110
03-01-23	09-01-23	340	3.60	3.50	36.19	2.18	0.52	0.099	0.015	0.011	0.009	0.032	0.402	0.026	0.005	0.287
10-01-23	16-01-23	202	2.36	2.93	19.16	1.59	0.47	0.058	0.011	0.008	0.007	0.023	0.358	0.022	0.003	0.042
17-01-23	23-01-23	207	2.97	4.23	15.54	2.23	0.78	0.070	0.021	0.012	0.010	0.038	0.605	0.037	0.004	0.206
24-01-23	30-01-23	131	1.83	2.43	14.98	1.33	0.42	0.046	0.010	0.007	0.007	0.026	0.397	0.024	0.003	0.084
31-01-23	06-02-23	110	1.66	3.15	10.80	1.30	0.48	0.036	0.014	0.008	0.006	0.022	0.484	0.028	0.002	0.029
07-02-23	13-02-23	94	1.62	3.49	9.14	1.18	0.50	0.035	0.014	0.008	0.006	0.023	0.483	0.029	0.003	0.103
14-02-23	20-02-23	169	2.49	4.97	17.50	2.17	0.78	0.059	0.026	0.013	0.009	0.039	0.802	0.048	0.003	0.087
21-02-23	27-02-23	131	2.23	4.70	15.52	1.87	0.74	0.052	0.023	0.011	0.008	0.032	0.664	0.040	0.004	0.174
28-02-23	06-03-23	73	1.60	3.94	8.62	1.15	0.58	0.034	0.015	0.008	0.006	0.022	0.484	0.029	0.002	0.057

Weekly Mean		Metal (µg/m³)									Ions (µg/m³)				Carbon (µg/m³)	
Date-Start	Date-end	Zn	As	Sr	Cd	Sb	Ba	La	Hg	Pb	Cl	NO3	SO4	NH4	OC	EC
01-11-22	07-11-22	0.673	0.042	0.046	0.088	0.134	0.037	0.055	0.007	0.207	6.3	13.5	9.9	16.3	94.1	20.0
08-11-22	14-11-22	0.533	0.042	0.025	0.054	0.078	0.007	0.032	0.005	0.229	5.8	14.8	14.4	13.6	55.2	15.6
15-11-22	21-11-22	0.450	0.038	0.023	0.052	0.063	0.003	0.025	0.004	0.217	7.4	13.7	8.5	10.0	46.0	12.1
22-11-22	28-11-22	0.535	0.045	0.024	0.048	0.065	0.004	0.038	0.005	0.250	7.5	17.0	8.7	9.8	48.9	15.2
29-11-22	05-12-22	0.697	0.037	0.031	0.062	0.088	0.009	0.048	0.006	0.191	8.2	30.4	19.0	22.2	55.4	25.7
06-12-22	12-12-22	0.586	0.039	0.028	0.059	0.077	0.004	0.037	0.005	0.221	8.3	20.8	16.3	21.0	42.9	17.9
13-12-22	19-12-22	0.553	0.027	0.026	0.055	0.075	0.005	0.035	0.005	0.158	9.5	24.3	13.7	19.3	42.5	17.0
20-12-22	26-12-22	0.814	0.038	0.030	0.072	0.085	0.000	0.028	0.006	0.211	12.0	29.3	28.0	32.5	47.0	19.4
27-12-22	02-01-23	0.572	0.050	0.031	0.069	0.104	0.006	0.026	0.006	0.269	12.0	29.6	20.5	28.7	54.5	18.7
03-01-23	09-01-23	0.673	0.080	0.039	0.096	0.122	0.000	0.028	0.009	0.529	14.8	36.4	38.5	36.5	67.1	27.4
10-01-23	16-01-23	0.535	0.031	0.029	0.058	0.083	0.000	0.021	0.005	0.170	12.7	26.2	20.3	23.9	46.1	15.5
17-01-23	23-01-23	0.920	0.070	0.031	0.079	0.110	0.001	0.037	0.007	0.406	16.4	27.7	15.8	21.3	49.1	19.9
24-01-23	30-01-23	0.492	0.034	0.022	0.050	0.084	0.000	0.018	0.005	0.183	8.2	18.4	14.7	15.0	29.9	11.9
31-01-23	06-02-23	0.245	0.015	0.018	0.033	0.048	0.001	0.025	0.003	0.111	6.3	13.6	9.8	11.1	30.1	10.9
07-02-23	13-02-23	0.470	0.045	0.017	0.043	0.054	0.001	0.025	0.004	0.263	5.0	10.3	5.7	8.3	25.0	9.1
14-02-23	20-02-23	0.640	0.048	0.024	0.058	0.071	0.002	0.046	0.005	0.256	5.9	20.6	16.3	13.3	43.2	17.9
21-02-23	27-02-23	0.659	0.070	0.021	0.067	0.071	0.003	0.040	0.006	0.393	5.3	13.7	13.8	11.2	33.6	14.2
28-02-23	06-03-23	0.476	0.026	0.015	0.038	0.041	0.003	0.027	0.003	0.149	7.9	4.3	5.6	6.4	20.4	7.7

Table 9: Monthly mean levels with standard deviation (mean±SD) of $PM_{2.5}$ and its constituents (metals, ions and carbon) at supersite

Monthly Mean			Metals (µg/m³)													
Date-Start	Date-End	PM2.5	Al	Si	S	K	Ca	P	Ti	V	Cr	Mn	Fe	Co	Ni	Cu
01-11-22	30-11-22	210 ± 102	2.82 ± 1.25	3.84 ± 1.16	13.90 ± 6.36	2.95 ± 1.52	0.79 ± 0.30	0.05 ± 3.93	0.022 ± 0.019	0.013 ± 0.026	0.009 ± 0.021	0.035 ± 0.005	0.691 ± 0.016	0.041 ± 0.326	0.004 ± 0.019	0.075 ± 0.002
01-12-22	31-12-22	209 ± 67	2.64 ± 0.65	3.64 ± 0.72	18.94 ± 8.38	2.04 ± 0.53	0.64 ± 0.15	0.06 ± 2.94	0.019 ± 0.020	0.011 ± 0.008	0.009 ± 0.004	0.036 ± 0.003	0.600 ± 0.015	0.036 ± 0.245	0.004 ± 0.014	0.067 ± 0.002
01-01-23	31-01-23	217 ± 104	2.67 ± 0.93	3.21 ± 0.97	21.41 ± 11.78	1.82 ± 0.63	0.54 ± 0.20	0.07 ± 4.19	0.014 ± 0.027	0.009 ± 0.007	0.008 ± 0.003	0.029 ± 0.003	0.433 ± 0.011	0.027 ± 0.167	0.004 ± 0.010	0.160 ± 0.002
01-02-23	28-02-23	126 ± 51	2.01 ± 0.66	4.19 ± 1.14	13.09 ± 6.32	1.64 ± 0.68	0.64 ± 0.20	0.05 ± 1.13	0.020 ± 0.018	0.010 ± 0.009	0.007 ± 0.004	0.029 ± 0.003	0.623 ± 0.013	0.037 ± 0.249	0.003 ± 0.015	0.098 ± 0.001

Monthly Mean		Metal (µg/m³)									Ions (µg/m³)				Carbon (µg/m³)	
Date-Start	Date-end	Zn	As	Sr	Cd	Sb	Ba	La	Hg	Pb	Cl	NO3	SO4	NH4	OC	EC
01-11-22	30-11-22	0.562 ± 0.060	0.042 ± 0.250	0.030 ± 0.027	0.061 ± 0.015	0.086 ± 0.024	0.013 ± 0.044	0.039 ± 0.150	0.005 ± 0.043	0.226 ± 0.002	7.07 ± 3.46	15.98 ± 8.27	10.75 ± 7.63	12.76 ± 7.81	61.21 ± 30.91	16.63 ± 6.56
01-12-22	31-12-22	0.638 ± 0.032	0.035 ± 0.316	0.029 ± 0.016	0.061 ± 0.005	0.081 ± 0.018	0.003 ± 0.018	0.034 ± 0.005	0.006 ± 0.014	0.197 ± 0.001	9.81 ± 3.63	26.71 ± 10.34	19.34 ± 9.42	24.88 ± 9.17	47.23 ± 13.66	19.10 ± 6.78
01-01-23	31-01-23	0.646 ± 0.286	0.054 ± 0.373	0.030 ± 0.062	0.071 ± 0.008	0.101 ± 0.035	0.002 ± 0.043	0.026 ± 0.007	0.006 ± 0.012	0.321 ± 0.004	12.80 ± 5.24	26.59 ± 10.55	22.15 ± 13.17	23.90 ± 11.24	47.26 ± 21.35	18.38 ± 9.49
01-02-23	28-02-23	0.504 ± 0.155	0.045 ± 0.339	0.020 ± 0.041	0.050 ± 0.005	0.061 ± 0.028	0.002 ± 0.027	0.035 ± 0.002	0.005 ± 0.015	0.258 ± 0.003	6.47 ± 4.82	14.26 ± 7.52	11.27 ± 6.40	11.03 ± 4.46	33.48 ± 11.93	13.26 ± 6.63

4.11 Control Action Plan

Short-term and Long-term control plan has been developed and is presented in Table 10:

Table 10: Control Action Plan

Source	Control Action	Time Frame
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.	Short Term
	Link Commercial license to clean fuel	Short Term
	Ash/residue from the tandoor and other activities should not be disposed of near the roadside. Requires ward-level surveillance.	Short Term
Domestic Sector	LPG to all including economic weaker and temporary labours.	Short Term
	New building complex or society with PNG supply distribution network	Short Term
	By 2030, the city may plan to shift to electric cooking (common in western countries) or PNG at the minimum	Long Term
Municipal Solid Waste (MSW) Burning	Any type of garbage burning should be strictly stopped.	Short Term
	Desilting and cleaning of municipal drains	
	Waste burning in Industrial areas should be stopped.	
	Daily, Monthly mass balance of MSW generation and disposal	
	Sensitize people and media through workshops and literature distribution so as not to burn the waste.	
Construction and Demolition	Wet suppression	Short Term
	Wind speed reduction (for large construction sites)	
	Enforcement of C&D Waste Management Rules. The waste should be sent to a construction and demolition processing facility	Short Term

Source	Control Action	Time Frame
	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 should be covered by a fine screen.	
	No storage (no matter how small) of construction material near the roadside (up to 10 m from the edge of the road)	
	Sensitize construction workers and contract agencies through workshops.	
Road Dust	The silt load in Delhi varies from 2.0 to 12.5 g/m^2. The silt load on each road should be reduced to under 2 gm/m^2. Regular vacuum sweeping should be done on the road having a silt load above 2 gm/m^2.	Short Term
	Convert unpaved roads to paved roads. Maintain pothole-free roads.	
	Implementation of truck loading guidelines; use appropriate enclosures for haul trucks and gravel paving for all haul routes.	
	Increase green cover and plantation. Undertake the green of open areas, community places, schools, and housing societies.	
	vacuum-assisted sweeping is carried out four times a month on major roads with road washing.	
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 the BS-IV category as well)	Long Term
	Industries must be encouraged to use BS-VI or BS-	Short Term

Source	Control Action	Time Frame
	IV (with DPF) vehicles for the transportation of raw and finished products	
	Introduction of cleaner fuels (CNG/ LPG) for all vehicles (other than 2-W).	Long Term
	Check to overload: Expedited installation of weigh-in-motion bridges and machines at all entry points to Delhi.	Six-months
	Electric/Hybrid Vehicles should be encouraged; New residential and commercial buildings to have charging facilities. All new city buses should be electric.	Short Term
	Bus stop and their parking should be rationalized to ensure more efficient utilization. The depots should include well-equipped maintenance workshops. Adequate charging stations.	Short Term
	Enforcement of bus lanes and keeping them free from obstruction and encroachment.	Short Term
	Route rationalization: Improvement of availability by rationalizing routes and fleet enhancement with requisite modification.	Short Term
	IT systems in buses, bus stops, control centers, and passenger information systems for the reliability of bus services and monitoring.	Short Term
	Movement of materials (raw and product) within the city should be allowed between 10 PM to 5 AM.	Short Term
	Incentivise and aggressively implement e-mobility including required charging infrastructure. Strategic plan for EV charging infrastructure at each 3 km in urban areas, 25 km on highways (both sides) and 100 km for buses and trucks and swappable battery stations.	

Source	Control Action	Time Frame
	Adequate vehicle scrappage infrastructure should be developed in next three years. Extended Producer Responsibility (EPR) may be considered for vehicle manufactures, who will have to build required vehicle scrap plants.	
Industries and DG Sets	Ensuring emission standards in industries. Shifting of polluting industries.	Short Term
	Strict action to stop unscientific disposal of hazardous waste in the surrounding area	
	Industrial waste burning should be stopped immediately	Short Term
	Following best practices to minimize fugitive emissions within the industry premises, all leakages within the industry should be controlled	Short Term
	Area and road in front of the industry should be the responsibility of the industry	
	Multi-cyclones should be replaced by baghouses. Ensure installation and operation of air pollution control devices in industries.	Long Term
	Diesel Generator Sets	
	Strengthening of grid power supply, uninterrupted power supply to the industries.	Long Term
	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.	Long Term
	Efficient recovery system for solvents in chemical industries: The technologies suggest 95% recovery of VOCs is feasible and same may be adopted	Short Term
Decongestion of Roads in 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.	Short Term
	Disciplined Public transport (designate one lane	

Source	Control Action	Time Frame
	stop).	
	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.	
	Examine the existing framework for removing broken vehicles from roads and create a system for speedy removal and ensure minimal disruption to traffic.	
	Synchronize traffic movements or introduce intelligent traffic systems for lane-driving.	
	Mechanized multi-story parking at bus stands, and big commercial areas. Remove at least 50 percent of on-street parking in the city.	
	Identify traffic bottleneck intersections and develop a smooth traffic plan.	
	Parking policy in congestion areas (high parking cost, at city centers, only parking is limited for physically challenged people, etc).	

5 Web Portal for Real-Time Advanced Air Source Management Network (R-AASMAN)

R-AASMAN is a real-time air quality analyzing and visualizing web application. Currently, it's used to assess Delhi's air quality status. It briefly represents the air quality status based on real-time pollutant measurements and meteorological conditions. Furthermore, to improve air quality, the software analyzes the pollutant data and helps identify pollution sources using a source apportionment algorithm called CMB (Chemical Mass Balance). Additionally, the forecast estimates the air quality conditions and the pollution source contribution for the next few days. Finally, on the basis of analysis, a report is inferred, and a detailed action plan is provided to the user.

Most of these modules have limited access which is managed by a multi-user system (i.e., an authentication system for three different types of users like Admin, Staff, and normal user). All these modules are discussed in detail as follows.

5.1 About R-AASMAN

The Home page of the website gives access to all modules and describes it briefly. The about page gives detailed information of the website. The Figures 42 to 43 show home page and about page. Table 11 describes the different information available under different sub-category.

Figure 42: Home page of web portal

ntrol Committee

HOME Real Time AQ AQ

About R-AASMAN

Air Pollution System AQ Management

Air is the prime resource for the sustenance of life on earth. The very existence of life on the earth is because there exists an atmosphere. All types of vegetation and creatures including human beings thrive in the atmosphere in one form or another. For example, human beings need a continuous supply of air almost at the rate of 10-20 cubic meters per day. It can easily be conceived that air not suitable for breathing can make people sick.

The air pollution problem can be depicted as a system consisting of three basic components:

(i) emission sources;

(ii) Transport through atmospheric processes

(iii) receptors.

Receptors receive the harmful impacts of air pollution. The impact on receptors (living entities of the physical environment) can be from short-term to life-threatening and economic losses.

The ultimate aim of air quality officials is to provide an answer to the question: what are the optimum ways to prevent/minimize the impact of air pollution on the receptor? This can be accomplished by air quality modelling and management.

In the simplest term, air quality modelling is a systematic approach that attempts to link the source emission strength (i.e., emission rate) through atmospheric processes to assess the extent of the impact on the receptors.

The air pollution problem is complex due to the multiplicity of the air-polluting source mix, automobiles, generators, domestic fuel burning, roadside dust, construction activities, etc., which co-exist with industries. Understanding the pollution sources requires the identification and contribution of the sources at breathing levels in space and time.

Complexity: Multiple Co-existing Sourses, Pollutants, Transformation Processes

Complexity: Decoding the Sources

1 Daily filter samole

Biomass burning + Diesel Exhaust + Cement factory + Dust + Sea salts + ... (residuals)

To identify and apportion the source contributions, air quality sampling devices collect several hours of integrated average samples and sent them off to the laboratory for analysis which is a time-consuming and labour-intensive way and takes a long time.

The new state-of-the-art techniques can provide the chemical composition of PM2.5 almost instantly and render the contribution of sources and help in quick decision-making for the timely control of air pollutant emissions.

DPCC signed MoU with the IIT Kanpur-lead consortium on October 20, 2021, to develop a state-of-the-art stationary air quality monitoring station i.e., supersite with the objective of real-time source apportionment and establish a reliable air quality forecasting system with source apportionment for next few days for public dissemination and improvements in air quality.

The supersite will provide weekly, monthly and seasonal interpretation of air quality and sources with trajectory and source apportionment analysis and suggest a higher level of control at major sources. The other component of the project is to develop a state-of-the-art mobile air quality laboratory for source apportionment at multiple locations for the weekly interpretation of air quality, and source apportionment, and further strengthen actions at local and far distant sources.

All the instruments required for real-time source apportionment are installed, calibrated, and running at supersite. The offline instruments are also calibrated and running.

Contact Us

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Links

Home
About
Services
Deparments
Contact

Address

Figure 43: Description on home page about R-AASMAN

Table 11: Sections of web portals

S.No.	Section	Description
1.	AQ Measurements	Collecting AQ data for $PM_{2,5}$, ions, metals, EC, OC, BC, SO_2, NO, NO_2, O_3, CO and $PM_{2.5}$, SO_2, NO_2, O_3, CO, NH_3 displayed on website for authorized personnel only.
2.	Real-time Source Apportionment at Rouse Avenue (Supersite)	Successfully data dissemination for the following: a. Daily Real Time Source Apportionment (3 Days) b. Hourly Real Time $PM_{2.5}$ Source Apportionment c. Historical $PM_{2.5}$ Source Apportionment
3.	Real Time Air Quality Index at Rouse Avenue (Supersite)	Successfully data dissemination for the following: a. Hourly Air Quality Index b. Historical Air Quality Index
4.	Source Apportionment Forecast	Successfully data dissemination for the following: a. Hourly $PM_{2.5}$ Source Apportionment Forecast for Next 3 Days b. Historical $PM_{2.5}$ Source Apportionment Forecast c. Hourly $PM_{2.5}$ Concentration Forecast for Next 3 Days
5.	Air Quality Reports	Daily, Weekly, Monthly and Yearly will be available. All reports are being validated starting 21st November 2022.

5.2 Air Quality Measurements

To assess the air quality status, we measure the air pollutant concentrations and meteorological conditions. All these parameters are measured in real-time using many machines, situated near about center of Delhi (Sarvodaya Bal Vidyalaya, Rouse Avenue, Delhi). These parameters are collected and displayed on an hourly basis in real time, on the website. The image below (Figure 44) shows the graphical representation of these measured parameters.

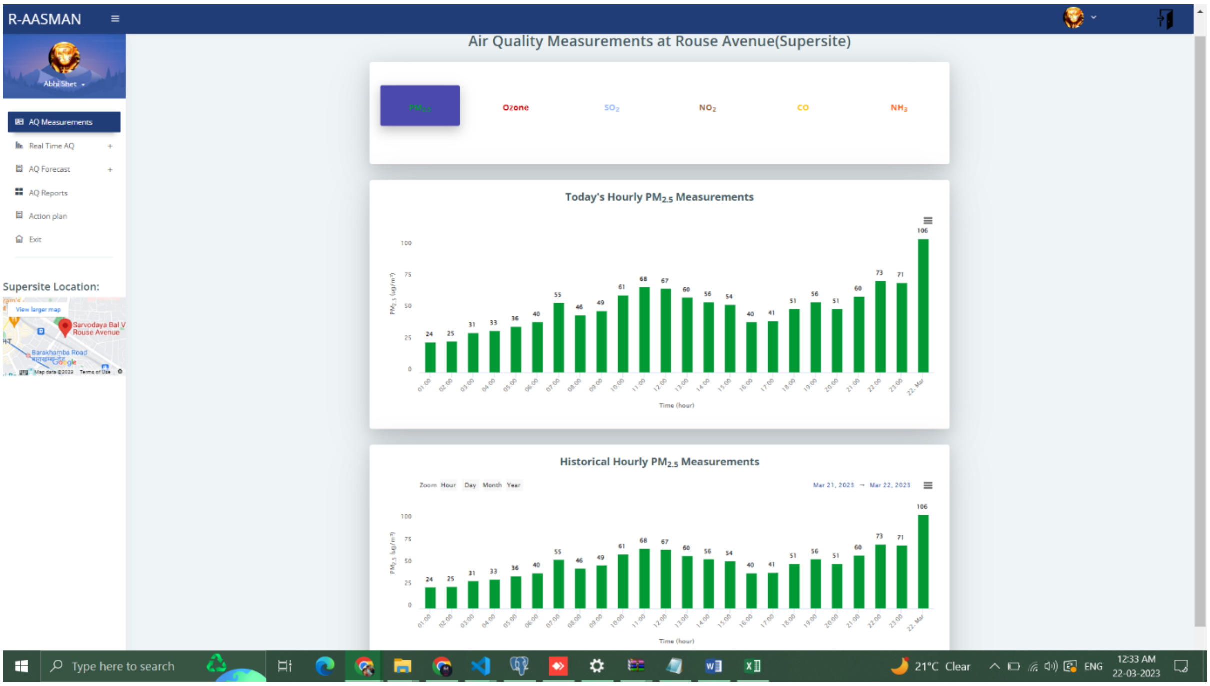

Figure 44: Display of real-time and historical measurement of AQ data

The measured parameters are as follows:

1. Air Pollutants: O_3 (µg/m^3), $PM_{2.5}$ (µg/m^3), SO_2 (µg/m^3), NO_2 (µg/m^3), CO, NH_3 (µg/m^3)
2. Meteorological Parameters: Temperature (^{o}C), Relative Humidity (%), Pressure (kPa), Wind Speed (km/hr), Wind Direction (^{o})

This module is restricted to staff users only. Here, in first graph we show last 24 hours data, second graph displays all historical data

5.3 Real Time Air Quality

Based on the measured values, some analysis is derived and it is displayed to the user in a user-friendly way. The first main aim of the software i.e., to identify the air pollution sources is attained in this module. Along with it, the real-time air quality Index is calculated and is displayed to the user. These parameters are discussed briefly below.

5.3.1 Real-time Source Apportionment

To identify the polluting sources, we have used an algorithm called Chemical Mass Balance (CMB). Abstractly, CMB takes the different pollutant fractions of $PM_{2.5}$ as input such as CO, NH_3, Metals, Carbon, etc., and processes these inputs to predict the different sources that have polluted the region like Industry, Construction, Domestic, etc. The image below gives an example of a visual representation of these apportioned sources shown in Figure 45.

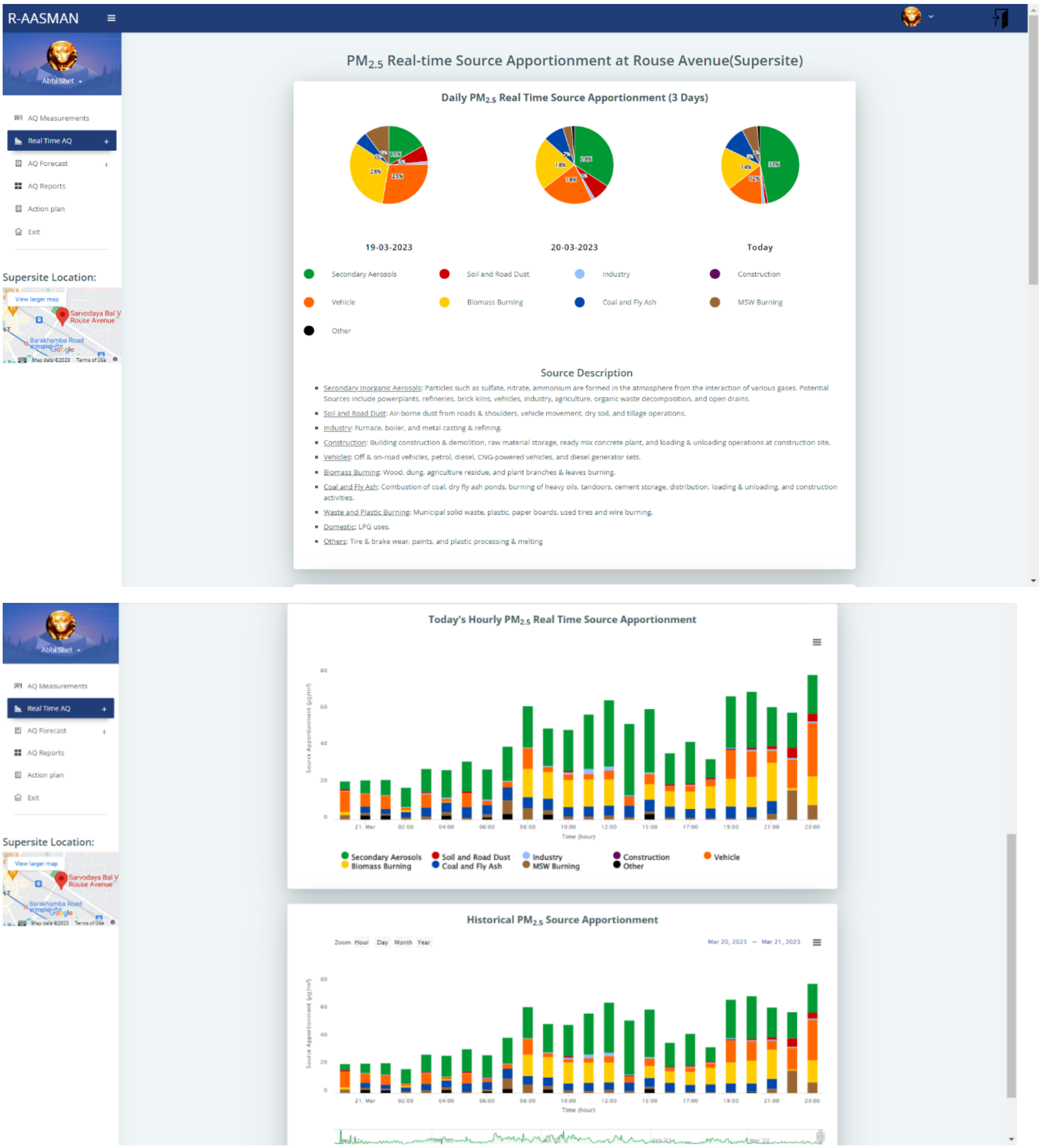

Figure 45: Display of Real time Source apportionment

The three-pie chart at the top gives the daily average percentage of all source contributions for three days (today, yesterday, day before yesterday), along with the source description of each source. Next are two hourly graphs giving the hourly source contribution of the last 24 hours and all historical data respectively.

Working of CMB

1. Take the different pollutant contributions of PM$_ {2.5} $ as input
   Concentrations(C) = {OC, EC, F, Cl, NO_3, SO_4, NH_4, Be, B, Na, Mg, Al, Si, P, K, Ca, Cr, V, Mn, Fe, Co, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Cd, Cs, Ba, Pb}
2. For each value calculate uncertainty using the following formula

$$Uncertainity(\sigma) = \forall C_i \begin{Bmatrix} \frac{5}{6} MDL_i, & if\ C_i \leq MDL_i \\ \sqrt{(0.1\backslash C_i)^2 + (MDL_i)^2} & else \end{Bmatrix}, \ i = 0,1,2,..I$$

3. Take the source profile which gives the relation between pollution sources and the PM\${2.5}\$ pollutants. It basically gives the fraction of different pollutants produced by different known sources. But some sources are collinear (affects the matrix inversion) and also there are different source profiles for the same source. For such conditions, form different sets of source profiles with each element consisting of non-collinear and unique source profiles. For all these elements find best fitting source contribution solution

$$SF = \{F^0_{\{IJ_0\}}, F^1_{\{IJ_1\}}, F^2_{\{IJ_2\}}, \dots . F^L_{\{IJ_L\}}\}$$

4. From this step to step 7 is the actual algorithm functioning. While these steps consider $F_{IJ} = F^l_{IJl}$ Set the initial estimate of the source contributions equal to zero.

$$S\_\{j\}\text{^}\{k = 0\} = 0, \qquad j = 0,1,2,..J$$

5. Calculate the diagonal components of the effective variance matrix, V_e. All off-diagonal components of this matrix are equal to zero.

$$V^k_{e_{ij}} = \sigma^2_{C_i} + \sum_{j=0}^{J} \left(S^k_j\right)^2 \cdot \left(\sigma_{F_{ij}}\right)^2$$

6. Calculate the k+1 value of S_j

$$S^{k+1} = (F^T \cdot (V_e)^{-1} \cdot F)^{(-1)F^T} \cdot (V_e)^{-1} C$$

7. Test the (k+1)th iteration against the kth iteration. If any S_{k+1}^j is negative eliminate the source with the smallest concentration, else check for convergence. This helps in eliminating negative contributions. If S_{k+1}^j differs by more than 1\% i.e. the

weights are not converged, then perform the next iteration. If all differ by less than 1\% i.e. the weights are converged, then terminate the algorithm.

$$if \min\left(S_j^{\{k+1\}}\right) < 0 \ then \ remove \min\left(S_j^{k+1}\right) and \ goto \ step \ 5$$

$$if \ \left|\frac{S_j^{\{k+1\}} - S_j^k}{S_j^k}\right| > 0.01 \ then \ goto \ step \ 5$$

$$if \ \left|\frac{S_j^{\{k+1\}} - S_j^k}{S_j^k}\right| < 0.01 \ then \ goto \ step \ 8$$

8. Following the above steps, we get a set of optimal source contributions for different source profile combinations.

$$SS = \{S_1, S_2, S_3, \ldots\ldots\ldots\ldots S_L\}$$

9. We can get optimal weight out of this set by comparing its FM(Fit Measure) score. The FM score is special score defined for cmb evaluation.

$$FM = \frac{1}{\chi^2} + R^2 + \frac{\%mass}{100} + FracEst, \quad \%mass \leq 100$$

$$FM = \frac{1}{\chi^2} + R^2 + \frac{\%mass}{100} + FracEst, \quad \%mass < 100$$

$$where, \chi^2 = \frac{1}{I - J}\left[\frac{\left(C_i - \sum_{j=1}^{J} F_{ij} S_j\right)^2}{V_e}\right]$$

$$\%mass = 100\left(\sum_{j=1}^{J} S_j\right) / C_i$$

$$R^2 = 1 - \frac{[I - J]\chi^2}{\sum_{i=0}^{I} \frac{C_i}{V_{e_{ij}}}}$$

$$FracEst = \frac{Number\ of\ Source\ Profiles}{Number\ of\ Sources\ predicted}$$

10. By comparing the FM score for all predicted sources, we pick the one with max FM score as final output.

5.3.2 Real-time Air Quality Index

The Air Quality Index is used to compare the air quality with its possible health effects on a person. The national standard formula is used to define AQI on the website. The AQI is based on 6 main pollutants $PM_{2.5}$, SO_2, NO_2, CO, O_3, NH_3. The AQI for each pollutant is calculated and compared to get the pollutant with worst AQI as final AQI. The Figure 46 shows an example of graphical representation of hourly AQI.

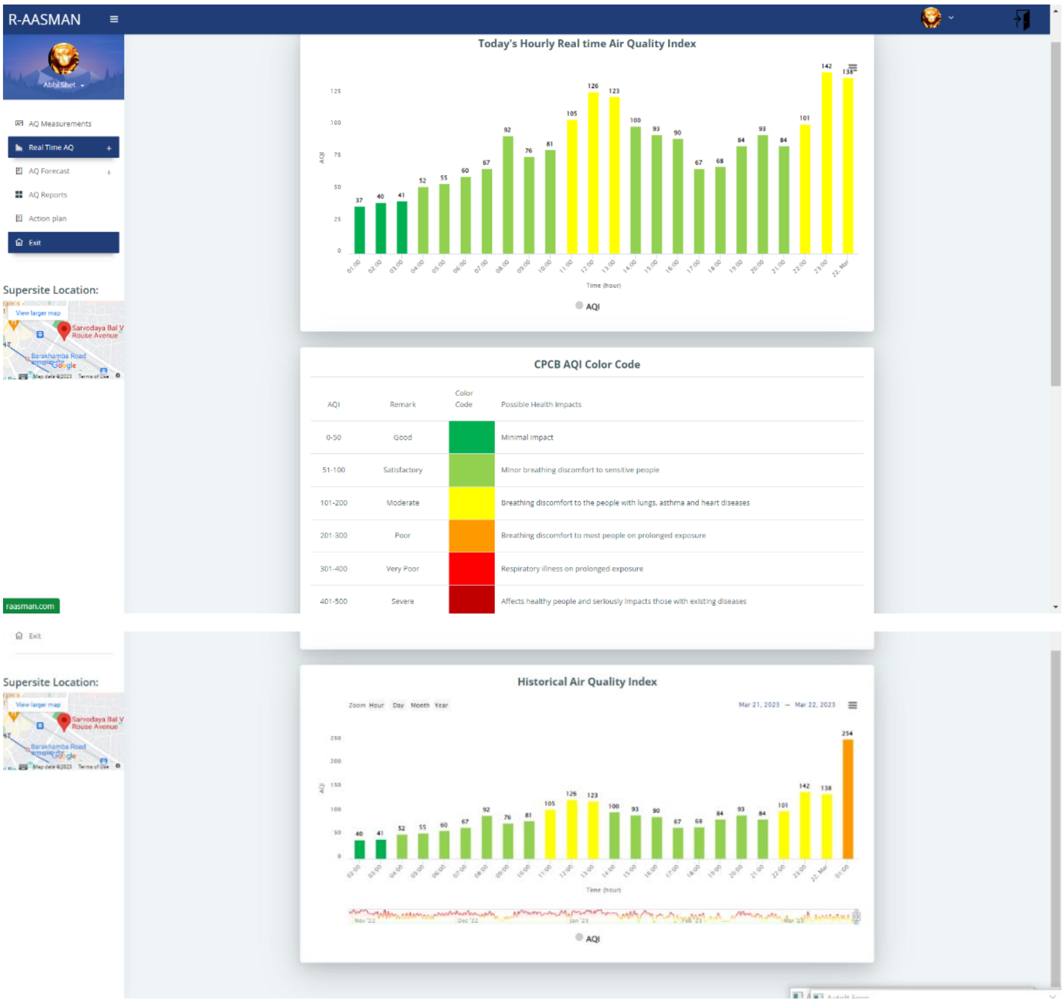

Figure 46: Display of AQI

There are two graphs with hourly AQI, one is for last 24 hours and other with all records till now (Figure 31). The whole records graph can only be accessed by staff users.

5.4 Air Quality Forecast

The air quality forecast estimates the future air quality conditions using different parameters. For the air quality forecast the used parameters are real-time meteorological conditions and emission inventory of Delhi. The different forecasted parameters are as follows.

5.4.1 Source Apportionment Forecast

The pollution source contribution is forecasted using real-time meteorological conditions and emission inventory of Delhi as input. The neural network algorithm is used to forecast/predict the source contributions. Figure 47 shows hourly source contribution forecast.

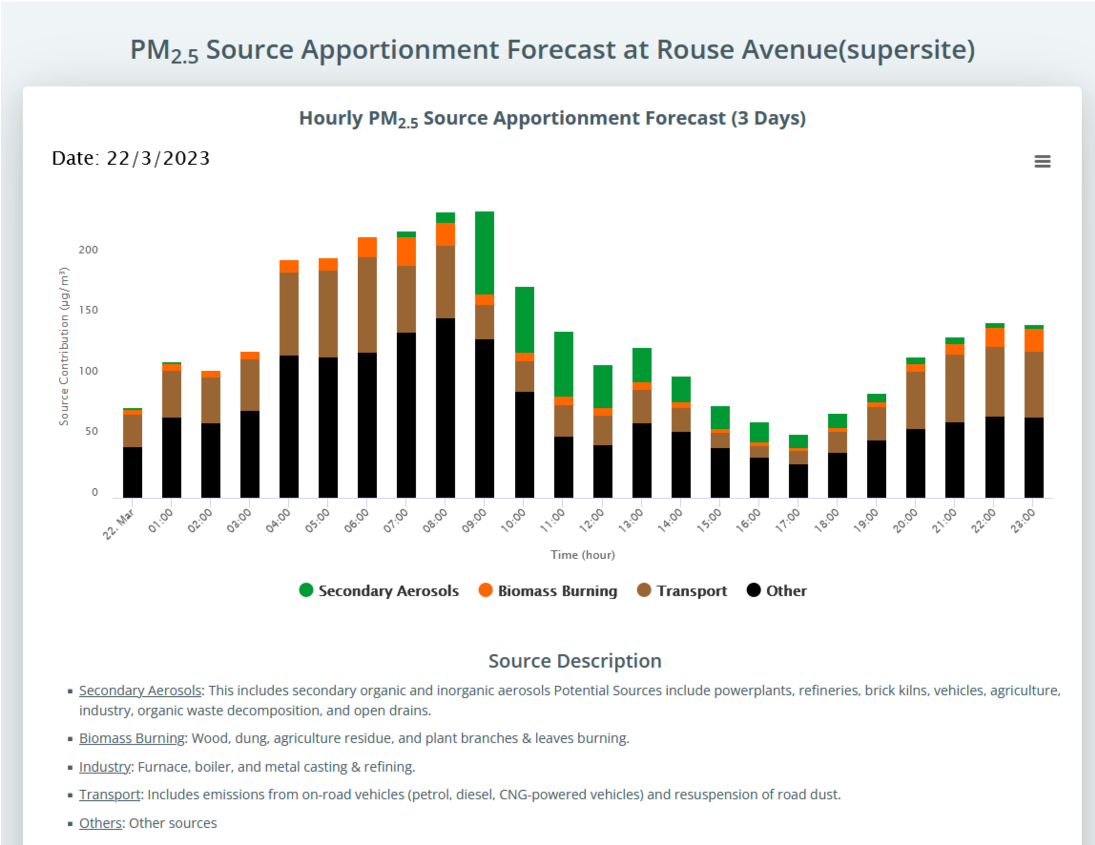

Figure 47: Display of source apportionment forecast for next three days

The figure shows two different sections one with 3 days hourly forecast and one with all previous forecast records (staff only).

5.4.2 Air Quality Index Forecast

For air quality Index pollutants are forecasted in similar way as source contribution. And based on these pollutants AQI is calculated using standard formula. The AQI is predicted spatially all over Delhi in hourly format. As shown in figure below the map displays the spatial AQI all over Delhi for a certain hour. The map is based on open layers google map. Hence, we can focus and distinguish the boundaries easily. Also, you can increase and decrease the opacity of map overlays to your own comfort to have a clear view. With a proper legend to identify air quality. The forecast for next 3 days can be seen.

5.4.3 PM2.5 Forecast

$PM_{2.5}$ is forecasted in a similar manner. Figure 48 shows two sections, one with 3 days hourly forecast and one with all previous records of $PM_{2.5}$ hourly forecast.

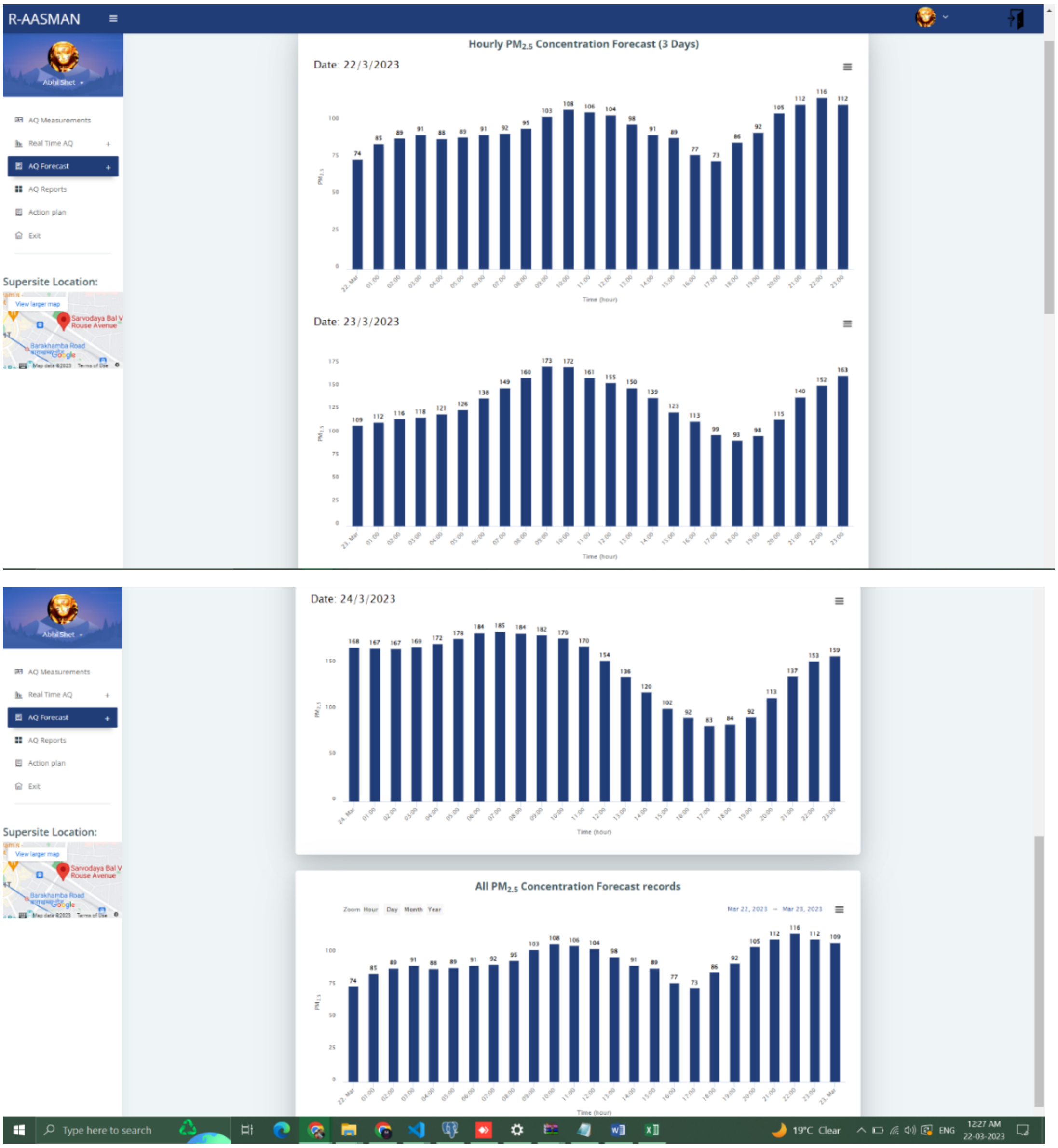

Figure 48: Display of $PM_{2.5}$ forecast

5.5 Air Quality Report

The air quality report contains overall summary of all parameters shown on the website. We can get daily, weekly, monthly and annually reports each report summarizes the respective period of time in the report. The report mainly consists of graphs and tables consisting of information of maxima, minima and mean of different values shown in graphs (Figure 49). The figure below gives a proper picture of how report looks like. It also has option to print pdf and get csv data. The module access is restricted to staff users.

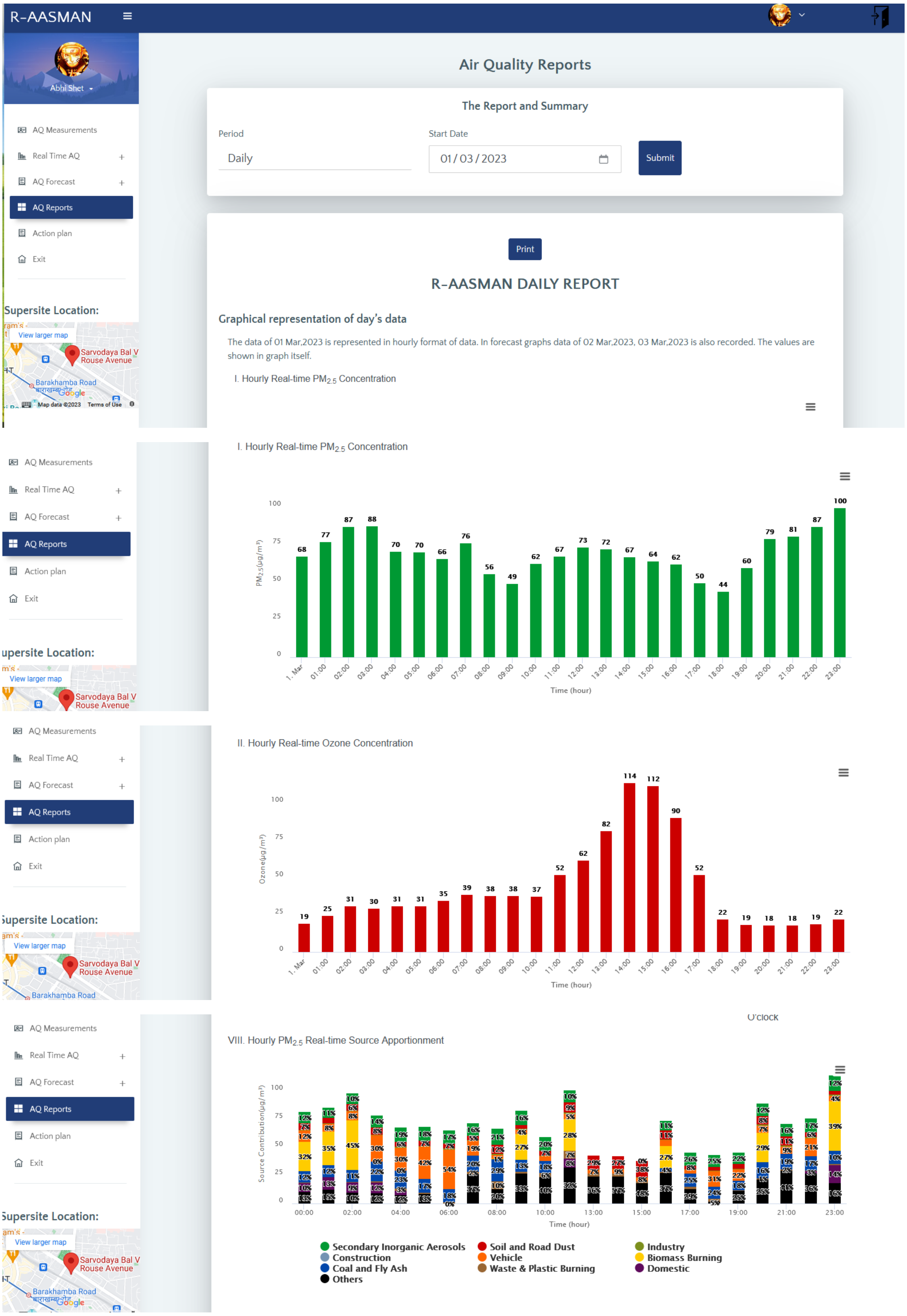

Figure 49: Display of report (Daily, Weekly, Monthly and Annual)

5.6 Sector-wise Action Plan

We give a proper sector-wise action plan for major polluting sectors in this module. To determine the major polluting sectors the main factor used is wind direction. The evaluation is done on daily basis. As shown in figure below, first we see a wind rose which is based on wind speed and wind direction. The 24 hours wind data is used to plot that day's wind rose. The calm wind duration, dominant directions and average wind speed is also defined below the rose. The calm wind is when wind speed is below 0.5%, which is when we cannot be certain of wind direction. The next is pollution rose based on hourly $PM_{2.5}$ measurements. Dominant directions and average $PM_{2.5}$ are also displayed. The directions having wind duration more than 10% of a day are considered as dominant directions, if no direction has more than one 10% wind duration then the directions with top 2 wind duration is considered as dominant direction. For all these major sectors. Below it is map pointing the major polluting sectors for the day. These sectors are determined based on pollution rose dominant directions. For all these sectors the pollution source contributions are displayed in table (Figure 50). The module access is restricted to staff users

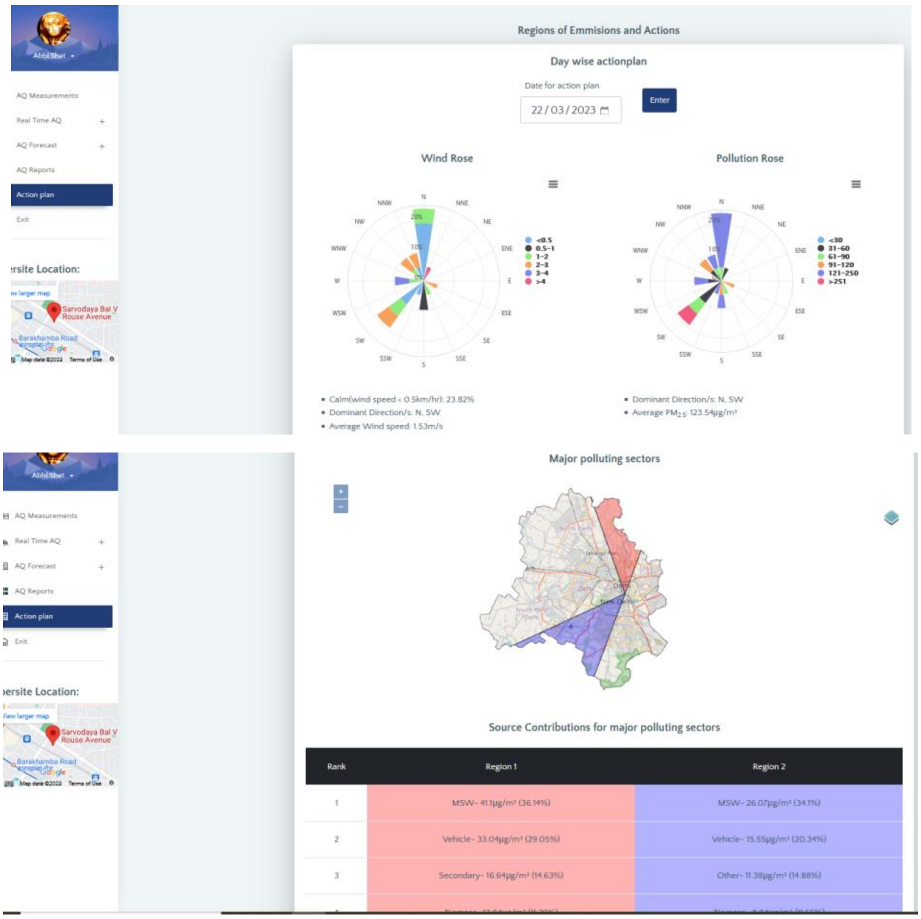

Figure 50: Display of region of implementing action plan

5.7 Login System for authorized personnels

The login system is provided so that access can be granted to the content limited to user (Figure 51). There are three different user's admin, staff, and a common user. The admin has a special access to grant and revoke the staff privileges to users. The staff users have 100% access to the website and special privileges to download data from the website. The common user has limited access to the website. In the first image we can see sign up page. Here the website takes name, email id, user type, password as input and create the user. Next is sign in page where website takes users email id and password to get the user details and provide respective access. Following to it is forgot password page where you can change password using emailed OTP.

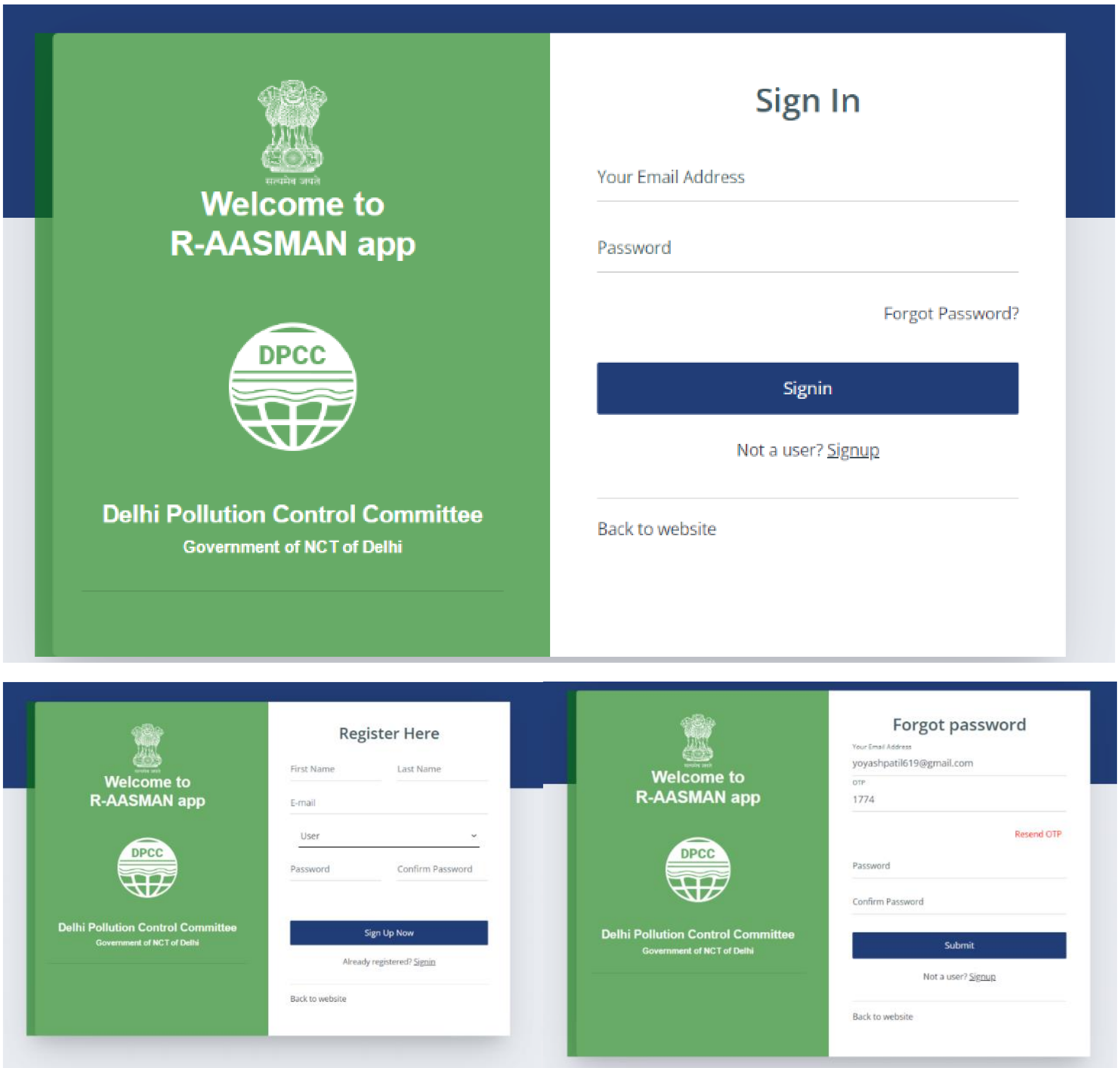

Figure 51: Login page of portal for authorized personnel

6 References

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