

SOURCE APPORTIONMENT OF AMBIENT PARTICULATE MATTER DURING WINTER SEASON IN DELHI

Sponsored by

**DELHI POLLUTION CONTROL COMMITTEE
(DPCC)**

Government of National Capital Region, New Delhi



Prepared By
Department of Civil Engineering
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Executive summary

Air quality management in India is being studied rigorously due to recent air pollution episodes. The country has also advanced in its understanding of particulate matter (PM_{10} and $PM_{2.5}$) trends, but the amount of information available on PM sources and its chemical characteristics is scanty. A comprehensive study on chemical analysis of PM delivers data useful in identifying sources of pollution, potential health effects, and environmental implications. The PM concentrations in the Indian cities especially Delhi city is showing an increasing trend despite the several control measures being implemented. Therefore, an effective control strategy requires a comprehensive analysis of chemical and morphological characteristics of PM at different elevations to differentiate local and regional PM emission sources.

In the present research project, the historical PM_{10} , $PM_{2.5}$, SO_2 , NO_2 data (2012 to 2016) measured at DPCC stations namely Anand Vihar, Mandir Marg, Punjabi Bagh, RK Puram in Delhi city were analyzed to characterize the air quality trends in Delhi city. The historical data analysis showed that PM_{10} concentrations at four DPCC monitoring locations were ranged between 37.9 to $937.17\mu g/m^3$, while, $PM_{2.5}$ concentrations were ranged between 24.09 to $466.45\mu g/m^3$. The ambient NO_2 concentration was found to be in range of 5.41 to $91.79\mu g/m^3$ and SO_2 concentration in the range between 10.03 to $81.01\mu g/m^3$. The exceedance factor was calculated using the five year historical data and indicated that the $PM_{2.5}$ and PM_{10} concentrations were exceeding national ambient air quality standards (NAAQS). Results indicated that more than 75% of the PM_{10} and $PM_{2.5}$ concentrations were exceeded the NAAQS ($PM_{10}=100$ and $PM_{2.5}=60\mu g/m^3$) in all four monitoring stations. The 15% of the NO_2 and SO_2 concentrations were also exceeded the NAAQS limit values ($SO_2=80$ and $NO_2=80\mu g/m^3$) at all four locations.

As a part of the present research work, PM_{10} and $PM_{2.5}$ concentrations were measured at different elevations in selected locations representing urban background, city center, upwind and downwind of the Delhi city to identify the PM emission sources. The air quality monitoring campaign at different elevation was carried during January to May 2017 at seven locations namely Okhla, IIT Delhi, Murthal, Delhi college of Engineering (DCE), Shri Balwant Institute of Technology (SBIT), Anand Vihar and Punjabi Bagh. The measured PM_{10} concentrations at different elevation were found to be in range of 29.4 to 527.78 and 28.7 to $398.74\mu g/m^3$ in lower elevations (LE = 4 to 12 m) and higher elevations (HE = 10-30 m), respectively. Similarly, the $PM_{2.5}$ concentrations were in the range of 23.67 to 217.6 and 28.7 to $398.74\mu g/m^3$ in lower elevations and higher elevations, respectively. It

was observed that both PM₁₀ and PM_{2.5} concentrations were exceeding NAAQS limits at all seven monitoring locations.

The collected PM samples were analyzed for elements, ions, elemental and organic carbon, and morphological characteristics. The concentration of elements such as S, Si, Al, Ca, Na, Mg and K were found to be higher in PM_{2.5} samples, representing contribution from mineral dust and fuel oil combustion. The ionic composition of PM_{2.5} indicated the dominance of Cl⁻, SO₄²⁻, Na⁺ and NO₃⁻, these are generally representing emissions from the open waste burning and secondary pollutant formation. The elemental composition of PM₁₀ samples showed the higher concentration of Si, Na, Al with minor amounts of S, K, Ca, Mg, Ti and Ba. These elements are the signatures for mineral dust and traffic emissions. The concentration of ionic species such as Cl⁻, SO₄²⁻, NO₃⁻, NH₄⁺, K⁺ in PM₁₀, are indicators of secondary particulate formation and biomass burning.

Positive matrix factorization (PMF) and Chemical mass balance (CMB) model were used to identify the sources contributing to PM mass. The results of CMB and PMF approaches revealed that vehicular emission (LE: 21% to 48%; HE: 23% to 51%), fuel oil combustion i.e. industrial and domestic combustion (LE: 20% to 37 %; HE: 24% to 40 %) were the two major contributors to PM concentration in Delhi city during winter season. Mineral dust (LE: 4% to 33 %; HE: 4% to 24%), biomass burning (LE: 4% to 14%; HE: 6% to 15%), solid waste burning (LE: 1 % to 10 %; HE: 2% to 10%), construction activities (LE and HE: 2%), coal burning (LE: 1% to 9 %; HE: 4 % to 11%) secondary aerosols (LE: 5% to 16%; HE: 3% to 20%) were also contributed to PM mass at the study areas. Emissions from fuel oil combustion indicated as a major contributor to PM_{2.5} at higher elevation on the other hand traffic emission was a major contributor at lower elevation. The source apportionment of PM₁₀ showed that vehicular emission, fuel oil combustion and mineral dust/ re-suspended, biomass burning and solid waste burning were the key contributors to PM₁₀ mass. Secondary aerosols were also identified as significant contributor to PM mass in few study locations. The present study suggests the control of vehicular exhaust emissions, fuel-oil combustion, re-suspended dust, coal burning, biomass and solid waste combustion activities will significantly improve the air quality of Delhi city during winter season.

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ABBREVIATIONS

CNG	Compressed Natural Gas
CPCB	Central Pollution Control Board
CMB	Chemical Mass Balance
DPCC	Delhi Pollution Control Committee
EPA	Environmental Protection Agency
HE	Higher Elevation
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
LE	Lower Elevation
LOD	Limit of Detection
LOQ	Limit of Quantification
MSW	Municipal Solid Waste
NAAQS	National Ambient Air Quality Standards
PCA	Principal Component Analysis
PM	Particulate Matter
PMF	Positive Matrix Factorization
PTFE	Poly Tetra Fluoro Ethylene
SEM	Scanning Electron Microscope
SPSS	Statistical Package for the Social Sciences
WHO	World Health Organization

ACRONYMS

$(\text{NH}_4)_2\text{SO}_4$	Ammonium sulfate
Al	Aluminium
As	Arsenic
Ba	Barium
C	Carbon
Ca^{2+}	Calcium
Cd	Cadmium
Cl^-	Chloride
CO	Carbon monoxide
CO_2	Carbon dioxide
Cr	Chromium
Cu	Copper
EC	Elemental carbon
F^-	Fluoride
H_2SO_4	Sulfuric acid
HCl	Hydrochloric acid
HNO_3	Nitric acid
K^+	Potassium
Mg^{2+}	Magnesium
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na^+	Sodium

NH ₄ ⁺	Ammonia
NH ₄ NO ₃	Ammonium nitrate
Ni	Nickel
NO ₃ ⁻	Nitrate
NO _x	Nitrogen oxides
OC	Organic carbon
Pb	Lead
S	Sulphur
Sb	Antimony
Se	Selenium
Sn	Tin
SO ₂	Sulphur oxide
SO ₄ ²⁻	Sulphate
Sr	Strontium
Ti	Titanium
V	Vanadium
Zn	Zinc

NOTATIONS

%	Percent
°C	Degree Celsius
m /s	Meter per second
µg/m ³	Microgram per cubic meter
ppm	Parts per million
RH	Relative humidity
T	Temperature
WS	Wind speed
LE	Lower elevation
HE	Higher elevation

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CHAPTER 1

INTRODUCTION

Urban air pollution poses a significant threat to the environment and public health throughout the world. Air pollution in megacities is getting worse due to fast urbanization and industrialization. Delhi's air quality reported being dropping from moderate to very poor during the winter season of the year, characterized by very low wind speed $< 1\text{m/s}$. Critical pollutants responsible for degradation of air quality in urban areas are particulate matter (PM), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and ozone (O_3). Any combustion activities would produce any of these or all pollutants except O_3 which is produced due to the interaction of precursor pollutants. Out of these pollutants, the PM size under 2.5-micron meter diameter is the most known harmful pollutant. The $\text{PM}_{2.5}$ consists of sulfate (SO_4^{2-}) aerosol, nitrate (NO_3^-) aerosols, secondary organic aerosols (SOA).

Urban air pollution causes approximately 10,500 premature deaths annually in Delhi (Khillare and Sarkar, 2012). In particular for Delhi city, increasing concentrations of PM cause thousands of premature deaths and six million asthma attacks each year (Guttikunda and Goel, 2013). The recent study in Delhi reported that the outdoor exercisers at locations with high $\text{PM}_{2.5}$ ($\leq 2.5\text{ }\mu\text{m}$ in aerodynamic diameter) concentrations are at risk of lung function impairment due to PM deposition in the smaller and larger airways (Kesavachandran et al., 2015). Delhi and its National Capital Region (NCR) have a population of 25.8 million that is 7.6% of India's urban population (Kumar et al., 2011). This drastic growth in population has resulted in extensive consumption of energy resource to meet their transportation and other demands. Past studies are consistently showing high PM_{10} and $\text{PM}_{2.5}$ concentrations in the ambient air of Delhi, irrespective of locations (Pant et al., 2015; Tiwari et al., 2014). The adverse health impacts of high urban air pollution need to be managed to improve living standards, but recent studies have ranked Delhi as the "worst" polluted city based on an environmental performance index (Hsu and Zomer, 2014).

The transport sector is one of the major sources of air pollution in urban areas (Sharma et al., 2005; Gupta et al., 2012). The rapidly growing vehicle fleets, distance traveled by each vehicle, and change in land use pattern are some of the primary causes of vehicular air pollution in urban areas (Srimuruganandam and Nagendra, 2011; Gulia et al., 2015). The increase in motorized road transport has resulted both in heavy traffic congestion and reduction in vehicular speed on the



roads of Delhi, besides leading to increased emissions of pollutants such as $PM_{2.5}$, PM_{10} , and NO_x (CPCB, 2010; DPCC, 2016). The Delhi traffic fleet is heterogeneous in terms of fuels, engine capacity, technologies, vintage and mixed usage patterns which make pollution emission inventory estimation a challenging task. More than one-third of PM_{10} emissions in Delhi is generated by road-suspension (Guttikunda and Goel, 2013). Vehicle exhaust emissions are a major source of $PM_{2.5}$, contributing up to 45% of total $PM_{2.5}$ emissions in the Delhi NCR during 2010.

At the outset, Delhi has many sources for its current bad air quality especially in winter, which can be categorized into local and non-local, point versus diffused sources. Coal-fired thermal power plants (20 – 30 km outside Delhi), brick kilns are examples for non-local point sources. Crop residue burning from Haryana and Punjab is contributing to Delhi's air pollution through long-range transport (LRT) is again a non-local area source. The vehicle exhaust (biggest one), road dust re-suspension, open waste burning, diesel generator sets are local emissions getting diffused and eventually degrading Delhi's air quality. The source apportionment study of six Indian cities (e.g., Delhi, Chennai, Kanpur, Mumbai, Bangalore, and Pune) carried out by the Central Pollution Control Board (CPCB, 2010) has reported that PM_{10} (particle having the aerodynamic diameter below $10\mu m$) concentrations in the ambient air are significantly high, irrespective of the type of locations. The concentrations of PM_{10} are relatively higher at kerbside/roadside monitoring locations. The PM pollution level has been found severe, and NO_2 is an emerging pollutant in all these six cities. Recent studies have explained that along with the PM mass concentration, the chemical composition of PM is also important for health risk assessment. Thus, proper identification and quantification of PM sources are important for prioritizing air pollution mitigation requirements (Khillare and Sarkar, 2012). The origins of PM, its chemical nature and generation mechanism makes PM a very complex matrix thus identifying its sources becomes a tedious and challenging task (Perrino et al., 2011).

The dust load in Delhi is heterogeneous, and some of the factors have been identified as SSW windblown dust transported from the Thar Desert during summer season (Yadav et al., 2016). PM concentrations are high during winter due to temperature inversion and lower mixing height. Summer months experience higher mixing height and thus comparatively lower concentrations of PM (Kothai et al., 2008; Kumar et al., 2014). Non-uniform dispersion and the fallout of fugitive dust also lead to high PM concentration in urban areas due to variation in meteorological parameters and the presence of a variety of sources (Balakrishna and Pervez, 2009). The previous



study carried out in Delhi showed that PM₁₀ consisted of more soil components in summer and higher concentrations of secondary pollutants and organics in winter (Perrino et al., 2011). Fine PM remains suspended in the air for a longer period and is also transported over long distances by wind. Hence, it is important to study the chemical characteristics of the finer fraction of PM to identify their sources which would further help in controlling the PM at the sources; before it reaches to the receptors (Chakraborty and Gupta, 2009).

A study carried out by Sharma et al. (2016) in Delhi during 2013-2014, reported the presence of Na, Mg, Al, P, S, Cl, K, Ca, Si, Cr, Ti, As, Br, Pb, Fe, Zn and Mn which accounted for 18.5% ($48.1 \pm 3.4 \mu\text{g}/\text{m}^3$) of PM₁₀ mass. OC ($25.6 \pm 12.4 \mu\text{g}/\text{m}^3$) and EC ($12.1 \pm 6.8 \mu\text{g}/\text{m}^3$) constituted 10% and 5% of PM₁₀ mass, respectively. A linear correlation between EC and OC concentrations of PM₁₀ indicated their common sources as traffic emission, biomass burning. The water-soluble inorganic ionic species (WSIC) (sum of the concentrations of cations and anions) accounted for 30% of PM₁₀ mass. The major sources of PM₁₀ identified by using Positive Matrix Factorization (PMF) were soil dust (22.7%), secondary aerosols (20.5%), vehicle emissions (17%), fossil fuel burning (15.5%), biomass burning (12.2%), industrial emissions (7.3%) and sea salts (4.8%) (Sharma et al., 2016). The mass concentration of PM₁₀ and its chemical composition showed higher concentrations in winter season as compared to other seasons, while the lowest concentrations were observed in the monsoon season. In another study carried out in Delhi over four years, it was observed that wind-assisted transport and re-suspension of surface dust contributed to 56% of PM₁₀ load. The other contributions to PM₁₀ load were from industrial and vehicular emission (23%), coarse (9%) and fine (12%) grain crustal material (Yadav et al., 2016). The chemical characterization of PM₁₀ samples collected by 8-stage cascade impactor showed the presence of heavy metals such as As, Pb, Zn, Cd, Ni, and Fe. The average concentration of coarse PM₁₀ (2.1-10 μm) was observed to be $68.3 \pm 17 \mu\text{g}/\text{m}^3$ while that of PM_{2.5} (fine PM (<2.5 μm)) concentration was $71.3 \pm 15 \mu\text{g}/\text{m}^3$ during the monitoring period (February-May 1998). Fine fraction of PM was observed to have a higher metal concentration (except Fe) as compared to the coarse fraction of PM (Balachandran et al., 2000).

Deserts, urban and industrial areas are located close to each other in Asian countries thus anthropogenic aerosols, and Asian dust often co-exists (Sugimoto et al., 2016). Aluminosilicates (K-feldspars, plagioclases, muscovite), calcites, dolomites were observed in the PM₁₀ samples of Delhi. Such minerals are associated with Aravalli and Delhi Supergroup of rocks and also wind



transported loose sediments (quartz, feldspars, mica) from the Thar Desert and Indo-Gangetic Plain (IGP). The elements observed in such samples are Ca and Mg. High concentration of Na was transported as saline deposits from windblown dust from Thar and Kutch desert region. It was also studied that dust storms in summer carry fine PM from Thar desert to Delhi in large quantities (500-800 tonnes/miles²) (Singh et al., 2008; Yadav et al., 2016). Potential Source Contribution Function (PSCF) and Hysplit model (used to construct backward trajectories) results at the sampling site showed that air mass trajectories and PM₁₀ are mainly contributed from the Indo Gangetic Plain (IGP) region (Uttar Pradesh, Haryana, and Punjab), Afghanistan, Pakistan and surrounding areas (Xu and Akhtar., 2010; Sharma et al., 2016). Another major source of PM identified in past studies is soil tillage, fugitive dust and wind erosion from agricultural fields. The major processes that contribute to fine PM are direct entrainment of loose particles from surface soils of agricultural fields by wind, and breakage (wear and tear) of mobile saltation and aggregates and large-sized particles into fine suspended PM (Li et al., 2015). The major sources of PM₁₀ in Delhi (Fine and Coarse Fraction) identified using Principal Component Analysis (PCA) were vehicular emissions, industrial emission, and soil resuspension (Balachandran et al., 2000). Much of the air quality modeling has been carried out on deterministic models which have taken into consideration of emissions, meteorology, atmospheric physics, and chemistry to estimate the air quality at spatial and temporal scales. Most of the models require considerable computational capabilities and input data. However, there are limitations in models to provide accurate representations of pollutant reactions and concentrations in the atmosphere. Chemical Mass Balance (CMB) model is used for source apportionment of primary pollutants. Positive Matrix Factorization (PMF) is a widely used receptor model for apportionment of PM. Back trajectory models are analogous models of atmospheric transport that help in calculating the position of air sampled in a backward direction from the receptor (Hopke, 2016).

Several control measures were made in Delhi after smog episode in 2016 like the closure of construction activities, vacuum cleaning of roads to take out dust, water sprinkling on roads, ban on diesel generator (DG) sets, and ban on selling firecrackers, odd-even policy for a short period. However, there is a great need for a detailed systematic study to develop better and sustainable engineering solutions for long term air quality of the city. Thus the present research of source apportionment has taken up with the aim of analyzing ambient air at two different



Source apportionment of ambient particulate matter during winter season in Delhi

elevations, identifying chemical markers and statistically matching to its sources and quantification.



CHAPTER 2

SCOPE AND OBJECTIVES

Scope: The scope of the present research project is to identify the sources contributing particulate matter concentration in different elevations at selected locations namely urban background, city center, upwind and downwind of the city center in Delhi city and NCR region through chemical characterization and source-receptor modeling.

The objectives of the study are

1. Measurement of particulate matter (PM_{10} and $PM_{2.5}$) concentrations at selected locations, i.e., urban baseline, city center, upwind and downwind of the city center in Delhi city during the winter season.
2. Chemical characterization of 24-hr average PM_{10} and $PM_{2.5}$ mass collected at different elevations of selected locations in Delhi city.
3. Morphological (shape and size) characteristics of PM_{10} and $PM_{2.5}$ at different elevations of selected locations in Delhi city.
4. Identification of PM_{10} and $PM_{2.5}$ source contributions at different elevations of selected locations in Delhi city using source-receptor modeling.



CHAPTER 3

METHODOLOGY

3.1 Description of the study areas

Currently, the Delhi Pollution Control Committee has continuous monitoring stations in Anand Vihar, Mandir Marg, Punjabi Bhag and RK Puram (Figure 3.1).



Figure 3.1. Ambient air quality monitoring locations run by DPCC in Delhi city.

For the present work, study areas were identified in consultation with the officials from the Delhi Pollution Control Committee (DPCC). Air quality monitoring was carried out at Anand Vihar, Punjabi Bhag, Murthal, DTU, Okhla and IIT Delhi (Figure 3.2). Table 3.1 provides the latitude and longitude of the study sites and Table 3.2 provides possible primary emission sources.

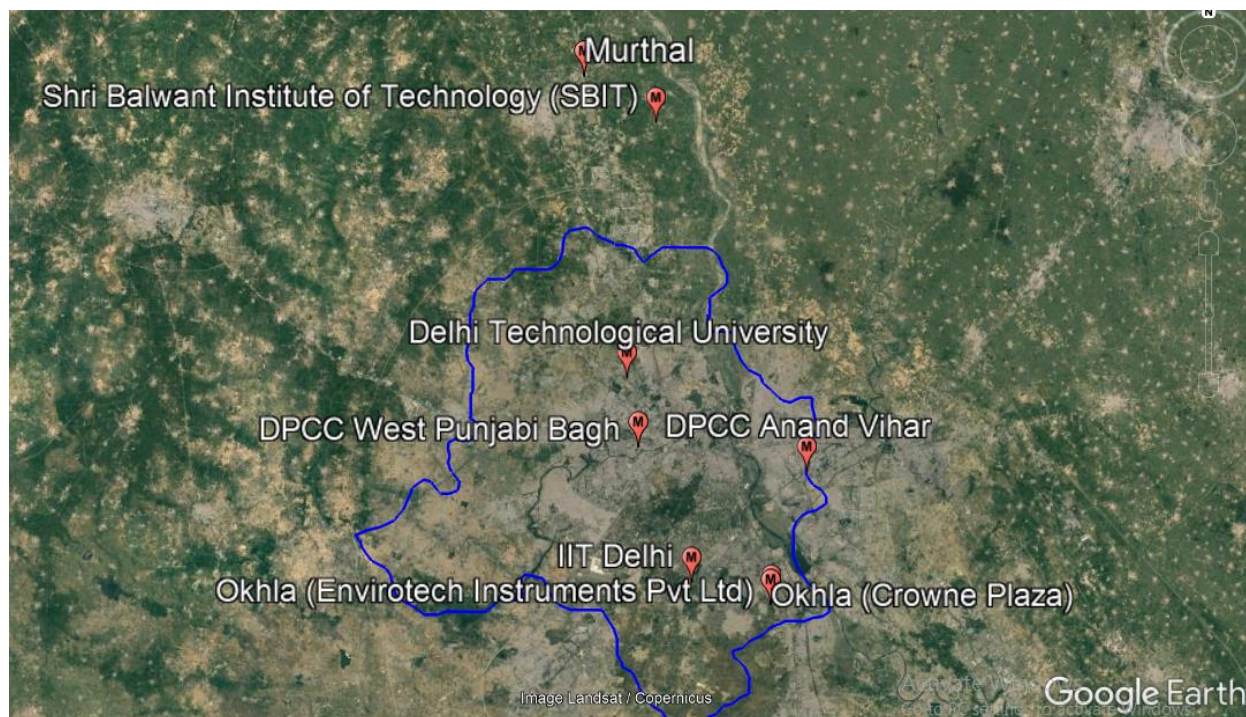


Figure 3.2. Present study monitoring locations.

Table 3.1: Latitude and longitude of the DPCC monitoring sites.

Monitoring Station	Latitude	Longitude
IIT Delhi	28°32'41.84"N	77°11'33.48"E
Sree Balwant Institute of Technology (Near Sonapat)	28°59'24.00"N	77° 9'3.56"E
Delhi Technological University	28°44'59.84"N	77° 7'5.85"E
Okhla	28°31'43.60"N	77°16'20.36"E
DPCC West Punjabi Bagh	28°40'11.63"N	77° 7'52.23"E
DPCC Anand Vihar	28°38'49.55"N	77°18'57.36"E
Murthal	28° 55' 43.58" N	77° 5' 28.60" E



Table 3.2: Description and sources of each study site.

Sl. No.	Sampling location	Description of site	Type of sources
1	IIT Delhi	Residential	Road dust, vehicular emission, construction, and demolition,
2	Delhi College of Engineering	Residential & industrial	Industries, domestic cooking, DG sets, vehicles, road dust, garbage burning
3	Okhla (Envirotech and Crowne Plaza)	Industrial & commercial	Industries, DG sets, vehicles, road dust
4	SBIT, Sonapat	Residential, agricultural	Road dust, vehicular emission, agricultural burning
5	Punjabi Bagh	Residential	Road dust, vehicles, domestic cooking
6	Anand Vihar	Major traffic intersection	Vehicles, road dust, construction activities
7	Murthal	Residential, agricultural	Soil dust, vehicular emission, agricultural burning

IIT DELHI: The Indian Institute of Technology Delhi (abbreviated IIT Delhi or IITD) is a premier engineering institution located in Delhi. IIT Delhi is located in Hauz Khas, South Delhi. The IIT Delhi campus has 325 acres (132 ha) surrounded by Hauz Khas area and monuments such as the Qutub Minar and Lotus Temple. The campus is also close to other educational institutions such as the Jawaharlal Nehru University (JNU), Indian Institute of Foreign Trade (IIFT), All India Institute of Medical Sciences (AIIMS), National Institute of Fashion Technology (NIFT), National Council of Educational Research and Training (NCERT) and Indian Statistical Institute (ISI). The surrounding area of IIT Delhi is densely populated and has a large number of commercial establishments. The Aurobindo Marg is a major arterial road near IIT Delhi which caters to both



inter-city and intra-city traffic. Gurgaon is connected to Delhi via Aurobindo Marg road, and this road also passes through dense residential areas (Goel et al., 2015).

Two locations inside the IIT Delhi campus were selected for monitoring. The lower elevation was selected at the rooftop of the Civil Engineering Department (4th floor, ~20m) the higher elevation was selected at the rooftop of Bell Tower (9th floor, ~36m).

OKHLA: Okhla (Old Canal Housing & Land Authority) is a Suburban colony in South Delhi district located at Delhi-UP border. It is more commonly known as Okhla Industrial Area (OIA) or Okhla Industrial Estate, an industrial suburb of South Delhi which is mainly divided into three Phases. Okhla has lent its name to the nearby planned township of NOIDA (New Okhla Industrial Development Area). The lower elevation for monitoring was selected at the rooftop (2nd storey, 6m) of Envirotech Instruments Pvt. Ltd while the higher elevation was selected at the rooftop of Hotel Crowne Plaza (9th storey, 30m).

DTU (Delhi Technical University): Delhi Technological University (DTU), formerly known as Delhi College of Engineering is an engineering university located in New Delhi, India. It is one of the oldest engineering colleges in India and Delhi's first engineering college. It was established in 1941 as Delhi Polytechnic and was under the control of the Government of India. The college has been under the government of the National Capital Territory of Delhi since 1963 and was affiliated with the University of Delhi from 1952 to 2009. In 2009, the college was given state university status, thus changing its name to Delhi Technological University. Two locations were selected inside the campus for monitoring. The lower elevation was selected at the rooftop of the guesthouse (~5m) while the higher elevation was selected at the rooftop of the Civil Engineering building (~15m)

SBIT, SONEPAT: Sonapat district lies between 28-48' south to 29-17'-30" north latitude and 76-27' west to 77-19' east longitude on national highway number 1. The district has been divided into three regions, namely Khadar, Upland and sandy. The *Khadar region* a narrow area (2-4 miles in width) and formed by the River Yamuna along its course. Thus it is a flood-prone zone. The crops commonly grown in this area are rice, wheat, sugarcane, banana, papaya, vegetable, and other fruit and flower crops. The *Upland plain* consists of Sonapat tehsil (West of Khadar) and is a highly productive region. Along with the availability of good irrigation facilities this region is extensively cultivated. The *Sandy region* is a small part in the Eastern area of the district and comprises of sandy loam soil.



Shri Balwant Institute of Technology is a technical institute based in Palra, Haryana and near to Sonapat district. It was founded in 2006 by Chanderwati Educational and Charitable Trust. SBIT is the part of SB Group of Institutions. The campus of the Institute occupies over 20 acres in Delhi NCR. It is about 15 min drive from the Delhi-Haryana border and located adjacent to the proposed Rajiv Gandhi Education City. It is adjacent to Meerut Road from where UP-Haryana border is 10 km, Delhi-Haryana border is 18 km and 6.5 km from National Highway 1. The monitoring was carried out at two elevations inside the campus. One was at the rooftop of a building which was at the elevation of 4m, and another was at the roof of the lecture hall building at the elevation of 10m.

MURTHAL: Murthal is a big village in Sonipat district of Haryana. It is located 13 km north of Sonipat, 50 kilometers from the national capital New Delhi. It is one of the fastest growing villages in the sonipat region. Farming is the major activity in this locality. Monitoring was carried out at two elevations at Deenbandhu Chhotu Ram University of Science and Technology. Monitoring at a lower elevation and higher elevation was carried at 5m and 20m respectively.

3.2 Data collection

DPCC provided the meteorological and air quality data for the last five years (2012-2016) for four stations (Anand Vihar, Punjabi Bagh, Mandir Marg, and RK Puram).

3.3 Air Quality Monitoring Campaign

Measurement of Particulate Matter (PM): The PM₁₀ mass concentrations were monitored using high volume sampler, APM 460 NL (Envirotech Instruments Pvt. Ltd. India) with average flow rate of 1.1 m³/min and PM_{2.5} mass concentration was measured by APN 550 (Envirotech Instruments Pvt. Ltd. India) with average flow rate of 16.7 L/min. PM_{2.5} samples were collected in 46.2 mm diameter PTFE filters with polypropylene support ring of pore size 0.2 µm (Whatman International Limited, USA) and PM₁₀ samples were collected on glass microfiber filters of size 20.3 x 25.4 cm (Whatman International Limited, USA). The 24-hours average concentrations of PM₁₀ and PM_{2.5} were monitored at two different heights (3-12 m and 20-36 m building height) for 45 days at urban baseline, upwind and downwind of the city center in Delhi city and NCR region (upwind). In addition to this, PM₁₀ and PM_{2.5} were also monitored at 2 DPCC locations (Punjabi Bagh and Anand Vihar) in East-West direction for 5-7 days. Table 3.3 provides the details of monitoring parameters.

Gravimetric analysis: Filters will be weighted twice before and after sampling by a microbalance (make: Model MC5, Sartorius AG, Goettingen, Germany) with a sensitivity of ±1 µg in the 0-250



mg range. Before weighing, the samples were equilibrated in a desiccator at room temperature at a relative humidity of 30-40% for 24 hours. Field blank filters were collected to reduce gravimetric bias due to contamination of filter handling during and after sampling.

Table 3.3: Methods of monitoring air quality parameters.

Particular	PM ₁₀	PM _{2.5}
Sampling instrument	High Volume Sampler	High Volume Sampler
Sampling principle	Filtration of aerodynamic sizes with a size cut by impaction	Filtration of aerodynamic sizes with a size cut by impaction
Flow rate	0.8-1.2 m ³ /min	16.7LPM
Analytical Instrument	Electronic Balance	Electronic Micro Balance
Analytical method	Gravimetric	Gravimetric

3.4 Chemical characterization of PM samples

The collected PM samples were analyzed for cations, anions, trace elements, and morphological characteristics.

Analysis of water-soluble ionic species: Water-soluble cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+} and NH_4^+) and anions (Cl^- , NO_3^- and SO_4^{2-}) were extracted and analyzed as per standard operating procedure (CPCB, 2006). The filter samples were impregnated with isopropyl alcohol for 15 mins. Later these impregnated samples were extracted with deionized water ($18.2 \text{ M}\Omega \text{ cm}^{-3}$, Millipore, Milli-Q) in an ultrasonic bath and kept overnight. Nylon membrane syringe filters (13 mm dia, pore size $0.45 \mu\text{m}$, Acrodisc®, Sigma Aldrich) were used to filter the extracts. The samples were then exposed to ultrasonic energy by placing them into an ultrasonic bath for 60 mins at 60°C . The analysis of anions and cations were carried out by using IonPac™ AS18, SCS16 column in Dionex™ Integriion™ HPIC™ System (Thermo Fisher Scientific Inc.) (Fig. 4.6a) respectively, with 23mM NaOH as eluent for anions and 40mM methane sulphonic acid as eluent for cations. Isocratic elution at 1 mL min^{-1} was adopted for the determination of anions and cations. The same procedure was repeated for field blanks and laboratory blanks.



Analysis of PM- bound elements: After gravimetric analysis, filter papers were used for elemental analysis using ED-XRF analysis. The PTFE and quartz filter samples collected from each location for two elevations were analyzed semiquantitatively for elements using energy dispersive X-ray fluorescence (ED-XRF) (PANalytical Epsilon 5). The instrument features an integrated X-Y sample changer that can analyze up to 133 samples in an automated way. X-rays irradiated the filter samples from a Gd tube under vacuum, equipped with a Ge X-ray detector. The primary beam from the X-ray tube first irradiates a polarizing target before striking the sample placed at 90°. The sample spectrum is recorded by a detector positioned at 90° to the sample in a third plane, thus eliminating the effect of scattered X-ray tube radiation by polarization and considerably reducing the spectral background level. The instrument features a polarized (Cartesian geometry) path with secondary targets as Al, Ti, Ge, Zr, and Al₂O₃. This method is nondestructive, requires little sample preparation and gives reliable results. The system's software (Epsilon 5 software) automatically analyzed the sample spectrum and determined the net intensities of the element peaks as soon as the measurement was completed. The blank filter was also analyzed for quality control purpose.

EC-OC analysis: A 0.5 cm² area was punched from the quartz filters containing the PM_{2.5} sample for the estimation of elemental and organic carbon (EC-OC). The organic carbon (OC), elemental carbon (EC) and total carbon (TC) contents of PM_{2.5} filter samples collected were analyzed using thermal/optical carbon analyzer (DRI Model 2015, Atmos-lytic, Inc., Calabasas, CA, USA). The analysis was performed on a 0.5 cm² area punched from the filters using IMPROVE_A protocol (Interagency Monitoring of Protected Visual Environments_A): Thermal/ Optical Reflectance and Thermal/Optical Transmittance based measurements. The filters laden with PM_{2.5} were heated in pure helium (He) atmosphere in the absence of oxygen at 140, 280, 480, and 580°C, respectively to quantify OC fractions (OC1, OC2, OC3, and OC4). The EC fractions (EC1, EC2, and EC3) was estimated in an oxidizing atmosphere (2% O₂ and 98% He) at 580, 780, and 880°C respectively. Morphological characteristics of PM: Many studies have been carried out in the field of air pollution and aerosol research using electron microprobe X-ray analysis or Scanning Electron Microscope (SEM) analysis to identify different types of particles and link them to possible sources (Xie et al., 2005; Linak et al., 2007; Rajamma et al., 2009; Rajamma et al., 2015).

.In the present work, the morphological characteristics of PM_{2.5} were analyzed using the High-Resolution Scanning Electron Microscope (FEI Quanta FEG 200). Approximately 1cm² of the



PTFE filter is cut from the filter paper used for the analysis. A very thin film of gold (Au) coating for each sample is done by using a vacuum coating unit called Gold Sputter Coater. The fine coating of gold makes the samples to achieve electrical conductivity. The gold sputtered samples is introduced into a vacuum chamber for obtaining morphologies of individual particles. The working conditions are set at an accelerating voltage of 20 kV, a beam current of 40–50 μA and a Si (Li) detector placed 10mm away from the samples to be analyzed.

Table 3.4. PM_{10} and $\text{PM}_{2.5}$ samples monitoring campaign in Delhi city during January –May 2017

Sl. No.	Location	Elevation	Start date	Last date	No. of days monitored
1	Okhla	Lower (6 m)	30.1.17	24.03.17	36
		Upper (30 m)	30.1.17	24.03.17	49
2	IIT Delhi	Lower (12 m)	30.1.17	19.04.17	38
		Upper (36 m)	07.02.17	19.04.17	34
3	DCE	Lower (5 m)	07.2.17	11.04.17	35
		Upper (15 m)	07.2.17	11.04.17	35
4	Murthal	Lower (5 m)	08.02.17	08.03.17	15
		Upper (20 m)	08.02.17	08.03.17	15
5	SBIT	Lower (4 m)	03.05.17	13.05.17	12
		Upper (10 m)	02.05.17	13.05.17	12
6	Punjabi Bhag	Lower	04.04.17	11.04.17	6
7	Anand Vihar	Lower	12.05.17	18.05.17	2
Total					283

3.5 Source apportionment of PM

Receptor models represent mathematical methods for quantifying and qualifying the contribution from sources to ambient PM, based on the structure or fingerprints of the sources. The structure of the source is identified by using analytical approaches for the media and fundamental species, or consolidation of species is needed to separate the influences. A composition data set can be shown as a data matrix 'X' of 'i' by 'j' dimensions, in which 'I' is the



number of samples and ‘j’ represents a number of chemical species that were measured, with uncertainties ‘u’. The receptor model aims to resolve chemical mass balance (CMB) between measured source profiles and species concentration. The sources profiles are described with a number of factors ‘p’, the species profile ‘f’ of each source, and the amount of mass g which is created by the influence of each factor to each sample. The CMB equation can be resolved with many models including 3 models that EPA has developed. In this work, EPA Positive Matrix Factorization (version 5) & EPA chemical mass Balance have been used.

3.5.1 Positive Matrix Factorization

PMF represents a multivariate factor analysis program that decomposes a matrix of identified data set into two matrices, factor contributions (G) and factor profiles (F). These factor profiles need to be studied by the user to allocate the source types that may be influenced by the same cluster, by using quantified source profile information and emissions of discharge registers. PMF assumes that linear combinations of different source emissions support concentrations at a receptor site. Thus, measured mass concentrations of selected species can be mostly expressed as (Paatero et al., 2014)

$$X_{ij} = \sum_{k=1}^p g_{ik} f_{kj} + e_{ij} \quad (\text{Eq.3.1})$$

Where ‘ X_{ij} ’ is the measured concentration of the j^{th} species in the i^{th} sample, f_{kj} is the profile of j^{th} chemical species emitted by the k^{th} source, g_{ik} is the amount of mass contributed by k^{th} source to the i^{th} sample, and e_{ij} is the residual for each sample or species. The matrices of g and f are determined by minimizing an objective function (Paatero et al., 2014).

Results are created using the boundary condition that no sample can have significantly negative source influence. PMF combines both user-identified uncertainties correlated to the sample data to weight individual points and sample concentration. This characteristic permits the analyst to include confidence in the measurement process. PMF model obliges several repetitions of the fundamental Multi-linear Engine (ME) with an aim to categorize the most optimal factor contributions and profiles. ME is created to resolve the PMF problem by aggregating two steps. Firstly, the analyst creates a table which specifies the PMF model. After that, a programmed secondary model reads the previously created parameter table and computes the solution. The best practice is to iterate the model approximately 20 times for the development of a solution and 100



times for the creation of the final solution, however different starting point should be used every time.

Variability due to chemical transformation or method fluctuations can influence considerably by causing significant differences in factor profiles among PMF runs. The analyst needs to identify all the error estimates in PMF to comprehend the strength of the model outcomes. Lastly, PMF needs a data set containing some parameters which are measured across various samples. Usually, PMF is used on diverse PM datasets containing from 10 to 20 species over 30 samples. An uncertainty value that is assigned to each species and sample should be estimated by using the additional uncertainty data set. This data set is designed using propagated uncertainties or other available information such as collocated sampling precision (EPA Positive Matrix Factorization (PMF) 5.0. Fundamentals and User Guide).

PMF requires two types of input data: first, sample species concentration values and second, sample species uncertainty values or parameters of calculating uncertainty. Samples species uncertainty are calculated using equation 3.2 (Adam Reff and Shelly I. Eberly, 2007)

$$\text{Uncertainty} = 0.05 X_{ij} + DL_{ij} \quad (\text{Eq.3.2})$$

Where ‘ X_{ij} ’ is the measured concentration and ‘ DL_{ij} ’ is the method detection limit for energy dispersive x-ray fluorescence (EDXRF) and ion chromatography. Method detection limit for EDXRF is shown in Table 3.5. Method detection limit for common ions (Cl^- , SO_4^{2-} , NO_3^- , NH_4^+ , K^+) in ion chromatography was estimated as 6.3 ng.



Table 3.5: Method detection limit for EDXRF.

Species	MDL in ng
Na	253
Mg	924
Al	1298
Si	11607
S	192
Cl	127
K	135
Ca	335
Ti	19
V	55
Cr	48
Mn	18
Fe	875
Ga	89
Ni	6
Cu	117
Zn	450
As	172
Br	23
Sr	64
Cd	439
Sn	274
Sb	499
Ba	502
Pb	41

Data Processing

The data set contains samples from both the levels were analysed for the PM10 mass (133, 24h concentration samples), ionic species Cl^- , SO_4^{2-} , NO_3^- , NH_4^+ , K^+ , Ca^{2+} and trace elements Na, Mg, Si, K, Fe, Cu, Zn, Pb, Ga, Sn, Sr, Cd, Al, Sb, As, Ca, Ti, V, Mn, Ni, Cr, Br were detected.

In the data set, some samples did not contain all measurements for some species. Taking into account that PMF model cannot be run if some data is missing, a certain amount of species and samples needed to be excluded in the present study; thus, the original data set was reduced to create a data set that will contain records for all days and species present. i.e., from the original data set, mainly trace elements which were missing the most of the measurements were excluded.



The goal of Positive Matrix Factorization (PMF) is to identify the number of factors p , the species profile f of each source, and the amount of mass g contributed by each factor to each sample. It is very important for the data analyst to know what types of sources are present in the study area. In the present study, source profiles were selected considering the information of the study area.

3.5.2 Chemical Mass Balance model

CMB analysis is a well-established form of receptor-oriented air quality modeling (Watson et al., 1990). The CMB was first proposed by Winchester and Nifong (1971), Hidy and Friedlander (1972) and Kneip et al. (1972) for estimating the contributions from different emission sources. The CMB model expresses concentrations of different chemical properties measured at a monitoring site (or “receptor”) as a linear sum of products of source profile abundances and source contribution estimates.

The CMB modeling tool includes an “effective variance least squares” solution that propagates measurement precision for both ambient data and source profiles, giving quantitative uncertainty estimates for source contribution estimates. This solution also gives less weight to chemical or physical properties in the ambient concentrations/source profiles that have higher uncertainties or source variability and larger influence to those source characteristics that are precise and constant. The solution yields large source contribution uncertainties when source profiles are too similar, or “collinear,” to be distinguished from each other. Other mathematical tests and performance measures are included to evaluate the goodness of fit, colinearity, and sensitivity to the model parameters.

The CMB model uses the chemical composition of airborne particulate matter samples to estimate the contributions of different source types to the measured concentrations at the receptor site using previously estimated source fingerprints. The chemical composition of each source type’s emission (commonly known as source profile or source fingerprints) may be obtained from the United States Environmental Protection Agency (USEPA) library (SPECIATE). This model quantifies contributions from chemically distinct source-types rather than contributions from individual pollution emitters. This model cannot separate the sources that have very similar chemical compositions. It does estimate the source contributions for each sample. The particle composition may differ from one sample to the next owing to differences in emission rates, wind directions, wind speed, and changes in emission compositions. However, the variations in the source compositions are not taken into account in these analyses.



The assumptions made in the CMB model are: (i) compositions of source emissions are constant over the period of ambient and source sampling; (ii) chemical species do not react with each other; (iii) all sources with a potential for contributing to the receptor have been identified, and their emissions characterized; (iv) the number of sources or source categories is less than or equal to the number of species; (v) the source profiles are linearly independent of each other; and (vi) measurement uncertainties are random, uncorrelated, and normally distributed.

The model consists of the following equations

$$C_i = F_{i1}S_1 + F_{i2}S_2 + \dots + F_{ij}S_i + \dots + F_{ij}S_j \quad \text{————(Eq.3.3)}$$

Where

C_i = Concentration of species i measured at a receptor site

F_{ij} = Fraction of species i emissions from source j

S = Estimate of the contribution of source j

i = Number of chemical species

These equations have a unique solution only when the number of species is equal to or greater than the number of sources. It has been generally found that the greater the number of species, the more precise the apportionment. The method also requires precision estimates for the C_i and F_{ij} values as model input. These precision estimates result in realistic uncertainties associated with the source contribution estimate, S_j that are calculated by the model.

The CMB model diagnostics for PM are in the acceptable limits as prescribed in the CMB user guidelines (Watson et al., 1990). For each of the PM samples,

- The fraction of variance in measured concentrations, explained by the variation in calculated concentrations (r^2) more than 0.8, Weighted sum of squares of the difference between calculated and measured fitting species concentration (Ψ^2) less than 4,
- The degree of freedom (DF) greater than 5,
- Percent of aerosol mass explained by sources between 80-120,
- The ratio of calculated to measured concentration (C/M ratio) between 0.5 – 2, and the absolute value of ratio of residual to uncertainty (R/U) less than 4.



Source apportionment of ambient particulate matter during winter season in Delhi

While running the CMB model the following important steps to be followed are (i) identification and selection of the contributing sources and chemical species; (ii) estimation of the fraction of each of the chemical species which is contained in each source type (source profiles); (iii) estimation of the uncertainty in both ambient concentrations and source profiles; and (iv) solution of the CMB equations.



CHAPTER 4

RESULTS AND DISCUSSION

4.1. Analysis of 5-year historical wind rose, and pollution rose data for various locations in Delhi city

The year wise wind rose, and pollution rose diagrams were plotted to understand the trend of air quality in Delhi city. The wind direction and velocity has a significant role in transport and dispersion of air pollutants in the atmosphere. The plotted wind rose diagram for 2012 to 2016 at Mandir Marg, Anand Vihar, Punjabi Bagh, and R K Puram are shown in Figure. 4.1, 4.3, 4.5 and 4.7, respectively. These figures described the variation in wind speed and wind direction from 2012 to 2016. The results indicated that at Mandir Marg the wind was approaching from the NNE, NE, and ENE direction. At Anand Vihar, wind direction fluctuated between W, ENE, and E. At Punjabi Bagh, prevailing wind direction fluctuated between NW and NNE. At R K Puram, the earlier dominant wind direction was from East in 2012 which slowly shifted to NW in 2016. The pollution rose diagram of 2012 to 2016 at Mandir Marg, Anand Vihar, Punjabi Bagh, and R K Puram are shown in Figure. 4.2, 4.4, 4.6 and 4.8, respectively.

Figure.4.2 shows that PM_{10} concentration was found to be between $100-200 \mu g/m^3$ and $200-300 \mu g/m^3$ at Mandir Marg during predominant winds blew from NE, ENE, and E.

The PM_{10} concentration observed between $400-500 \mu g/m^3$ and $500-600 \mu g/m^3$ at Anand Vihar during the predominant winds were from ENE and E (Figure.4.4). The PM_{10} concentration at Punjabi Bagh was found to be between $100-200 \mu g/m^3$ and $200-300 \mu g/m^3$ when prevailing winds from NE, ENE, and E (Figure.4.6). Figure.4.8 shows that PM_{10} concentration in the range between $100-200 \mu g/m^3$ and $200-300 \mu g/m^3$ at RK Puram during predominant winds were from WNW, W, ENE, and E.



Source apportionment of ambient particulate matter during winter season in Delhi

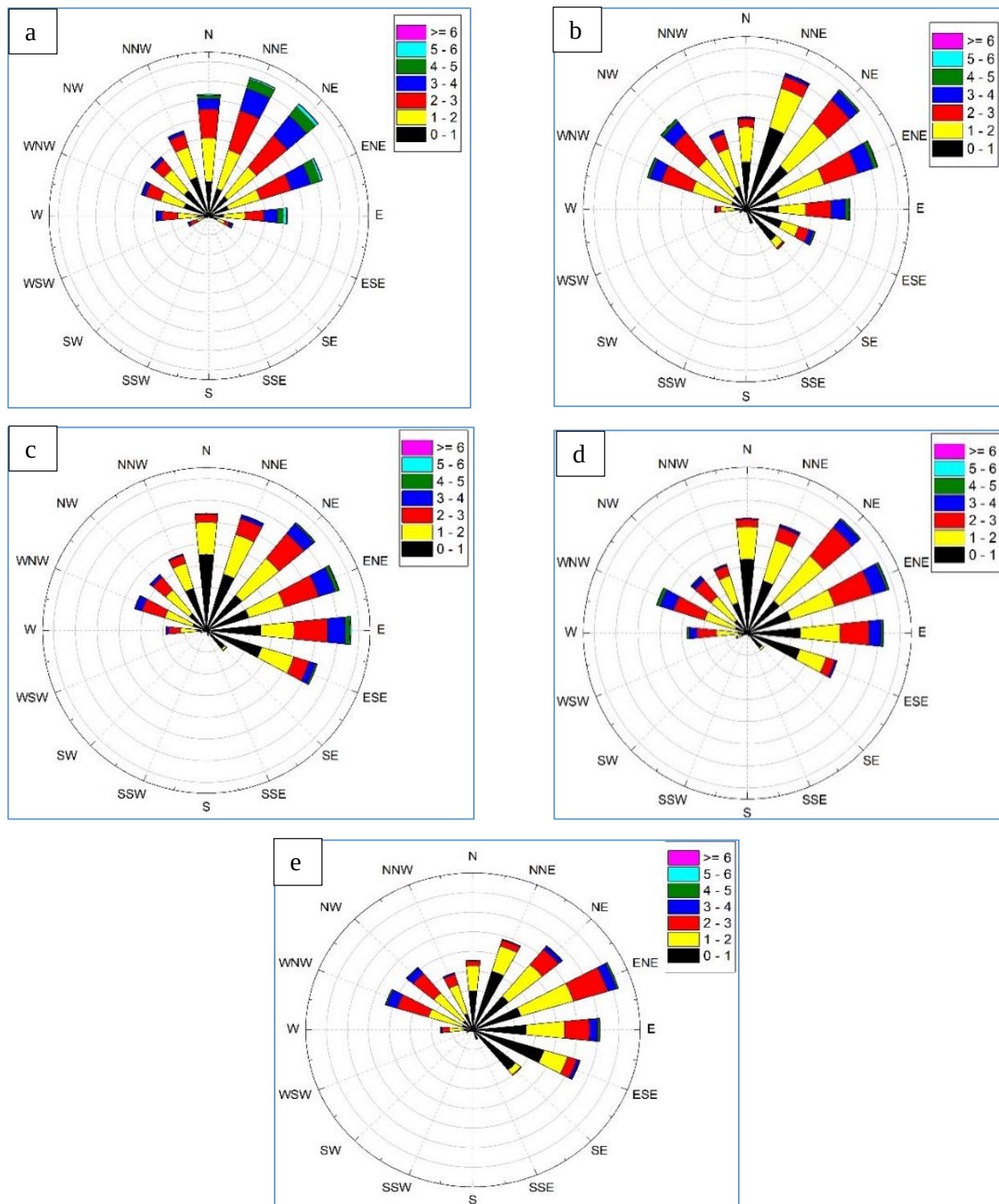


Figure 4.1. Wind rose diagram at Mandir Marg for the year (a) 2012 (b) 2013 (c) 2014 (d) 2015 and (e) 2016.



Source apportionment of ambient particulate matter during winter season in Delhi

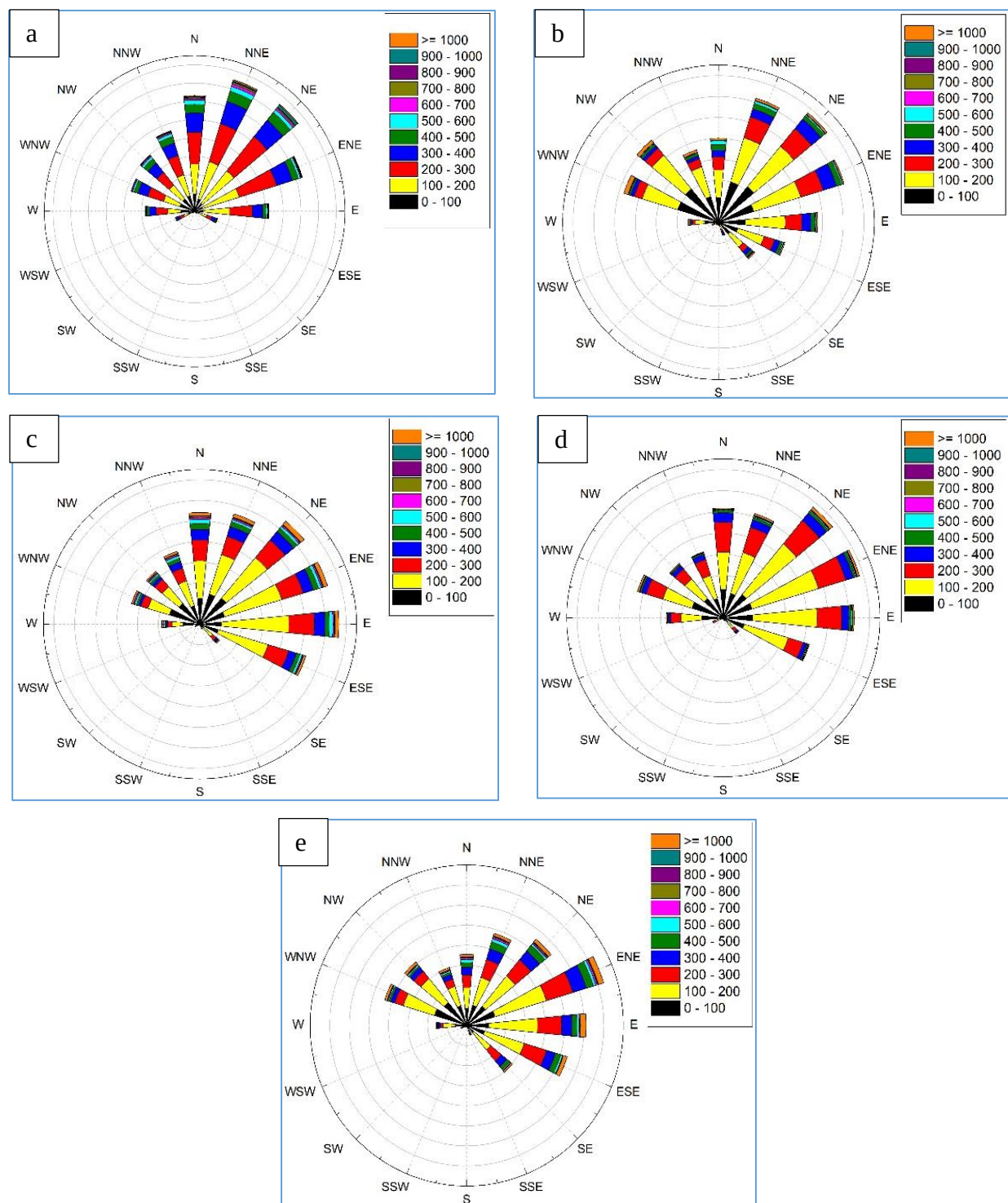


Figure 4.2. Pollution rose diagram of PM₁₀ at Mandir Marg for the year (a) 2012 (b) 2013 (c) 2014 (d) 2015 and (e) 2016.



Source apportionment of ambient particulate matter during winter season in Delhi

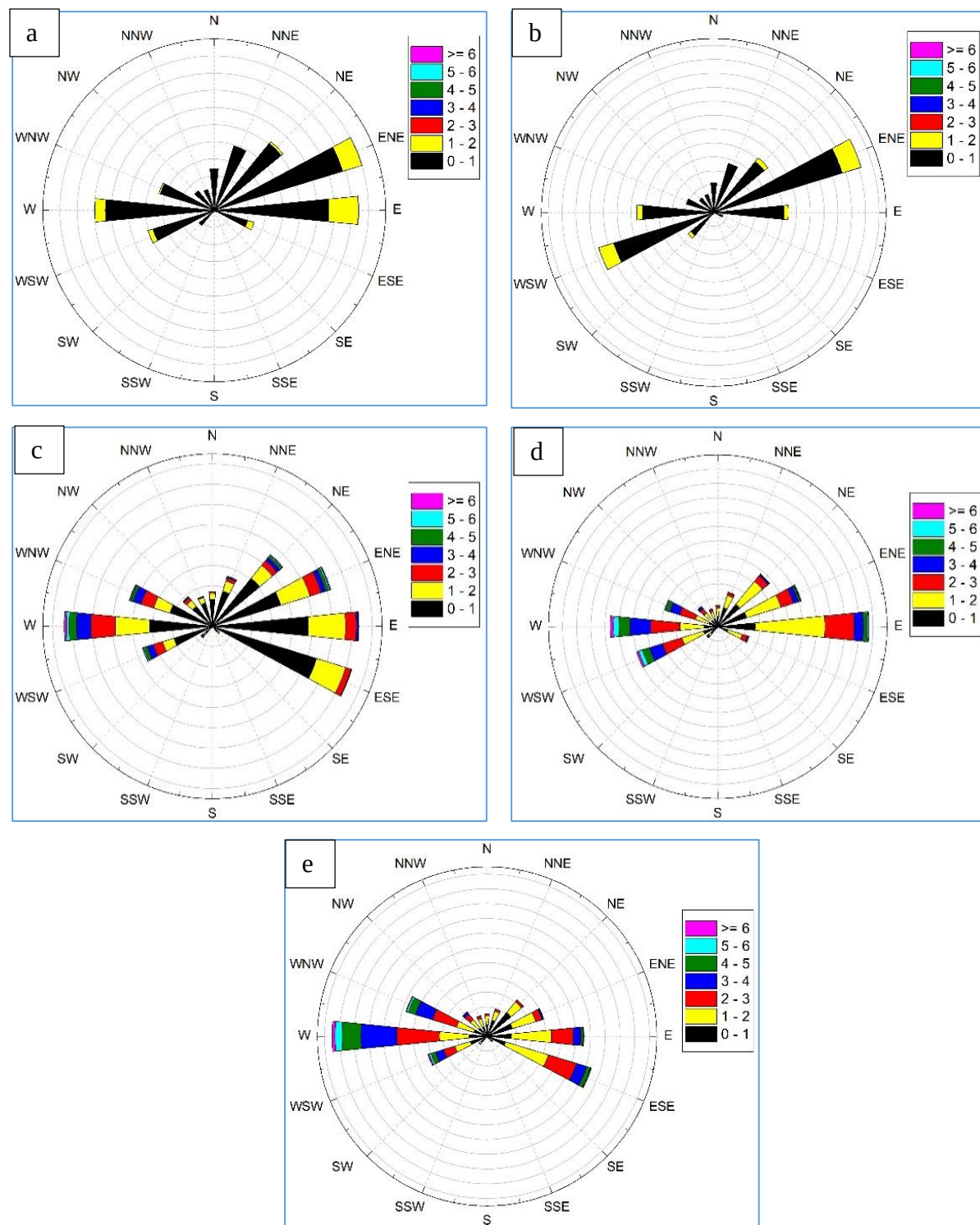


Figure 4.3. Wind rose diagram of Anand Vihar for the year (a) 2012 (b) 2013 (c) 2014 (d) 2015 and (e) 2016.

Source apportionment of ambient particulate matter during winter season in Delhi

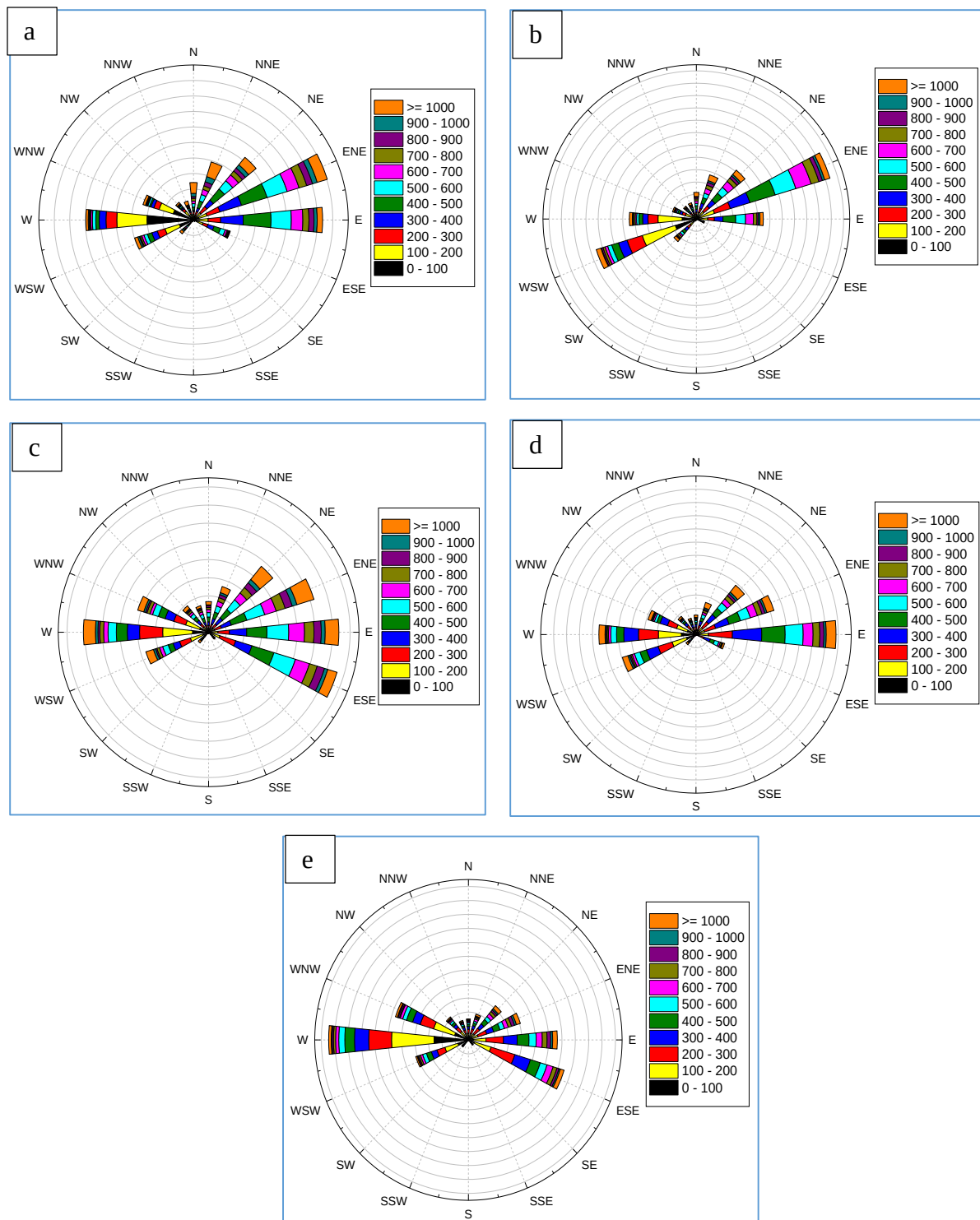


Figure 4.4. Pollution rose diagram of PM₁₀ Anand Vihar for the year (a) 2012 (b) 2013 (c) 2014 (d) 2015 and (e) 2016.



Source apportionment of ambient particulate matter during winter season in Delhi

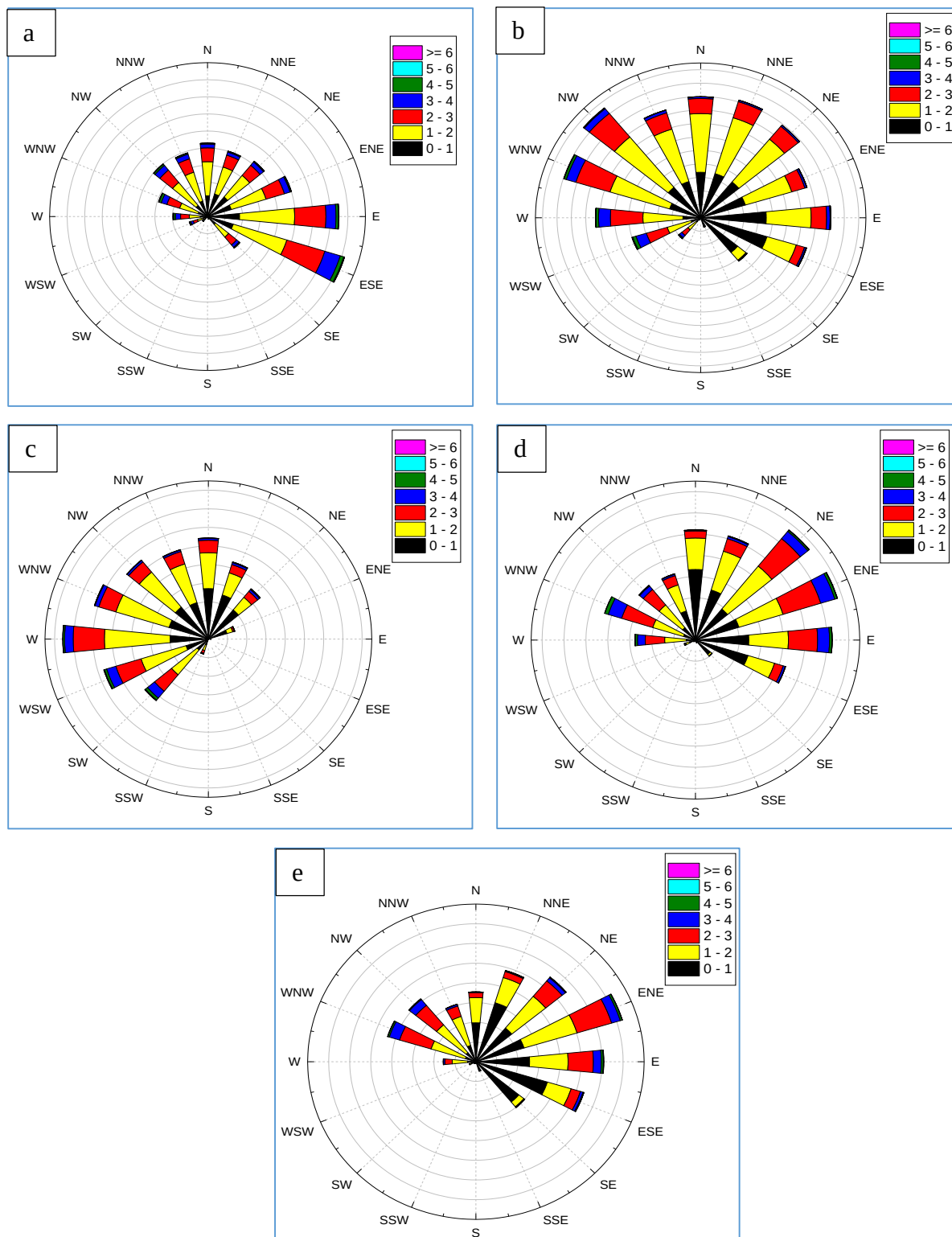


Figure 4.5. Wind rose diagram at Punjabi Bagh for the year (a) 2012 (b) 2013(c) 2014 (d) 2015 and (e) 2016.



Source apportionment of ambient particulate matter during winter season in Delhi

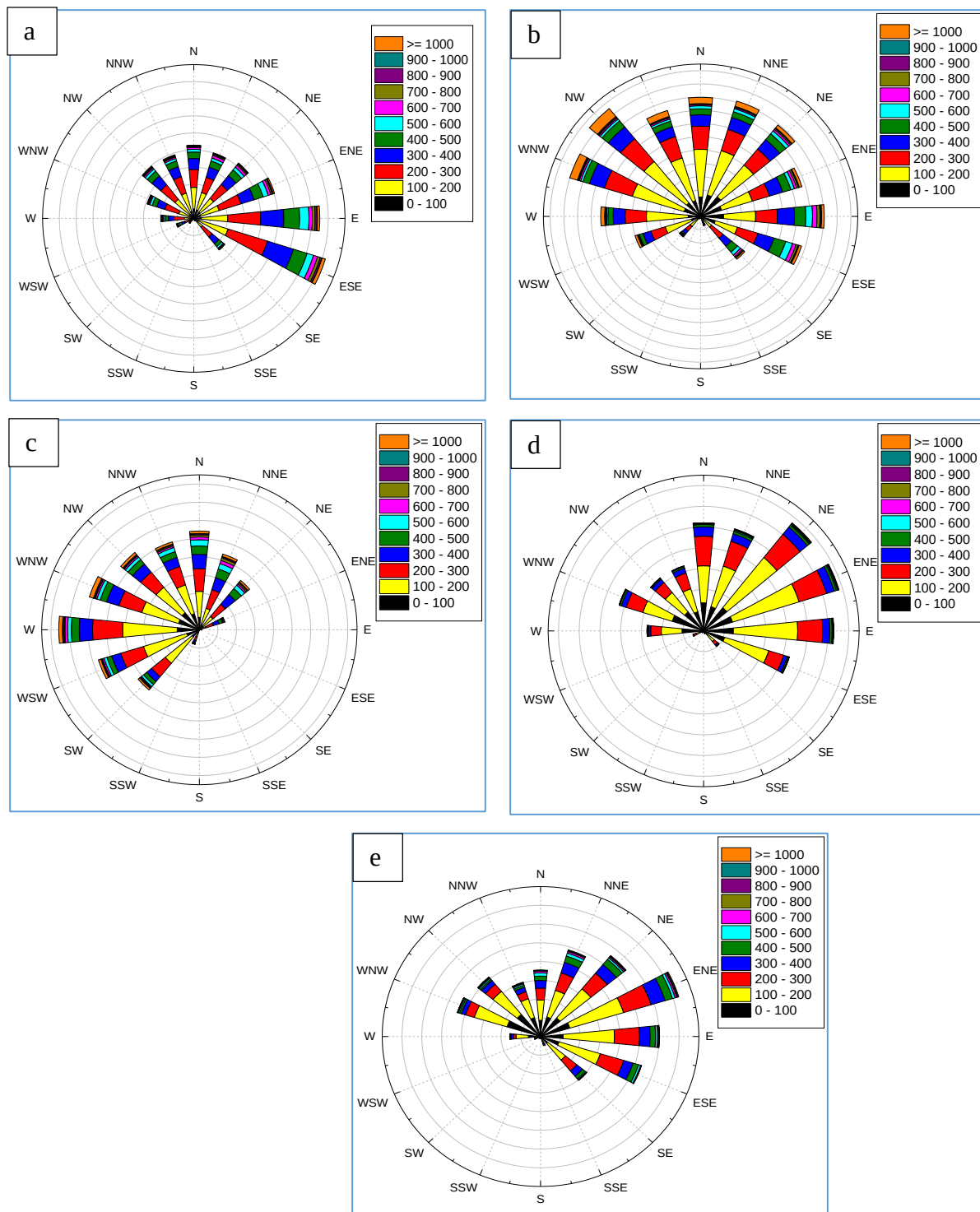


Figure 4.6. Pollution rose diagram of PM₁₀ at Punjabi Bagh for the year (a) 2012 (b) 2013 (c) 2014 (d) 2015 and (e) 2016.



Source apportionment of ambient particulate matter during winter season in Delhi

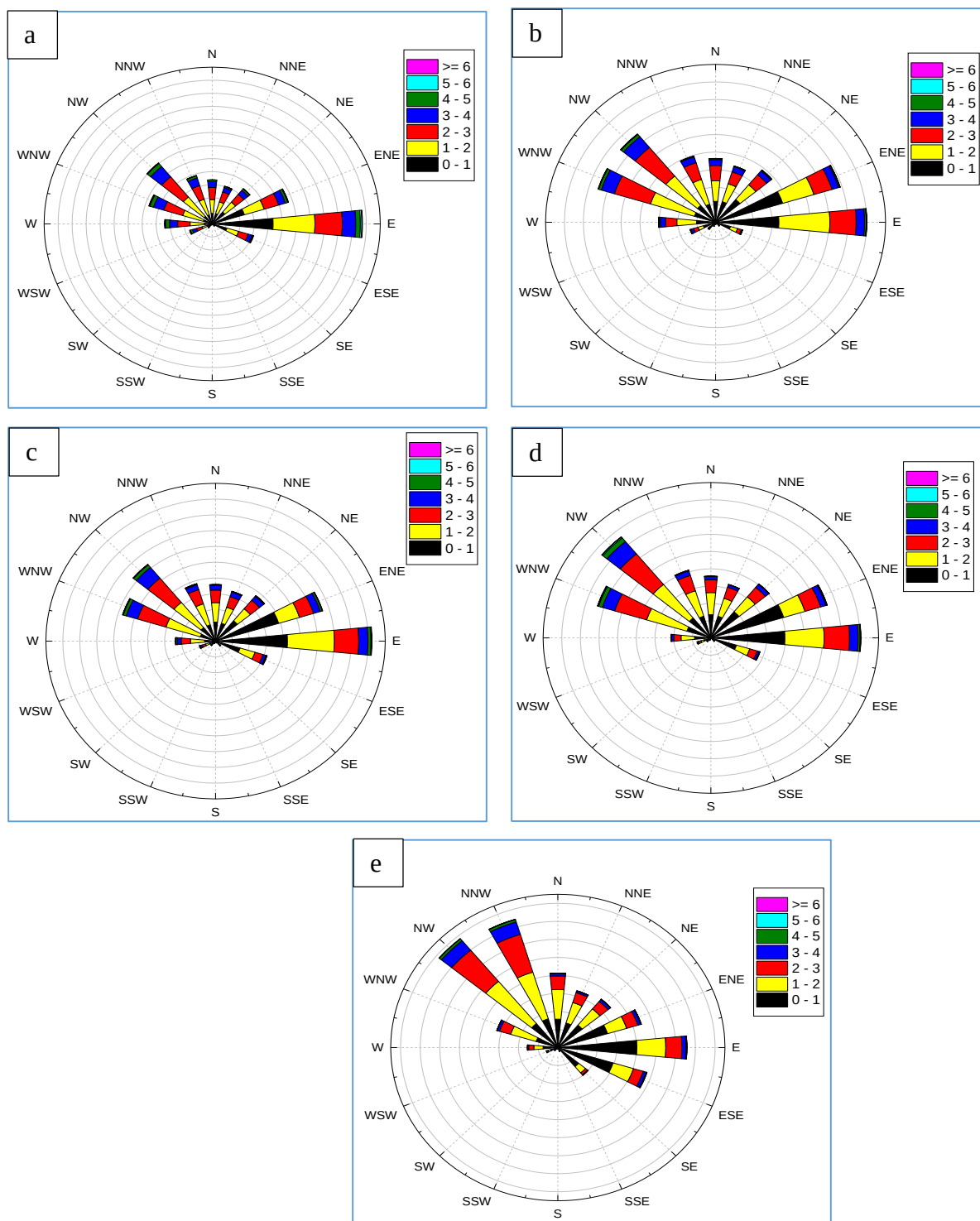


Figure 4.7. Wind rose diagram at R K Puram for the year (a) 2012 (b) 2013 (c) 2014 (d) 2015 and (e) 2016.

Source apportionment of ambient particulate matter during winter season in Delhi

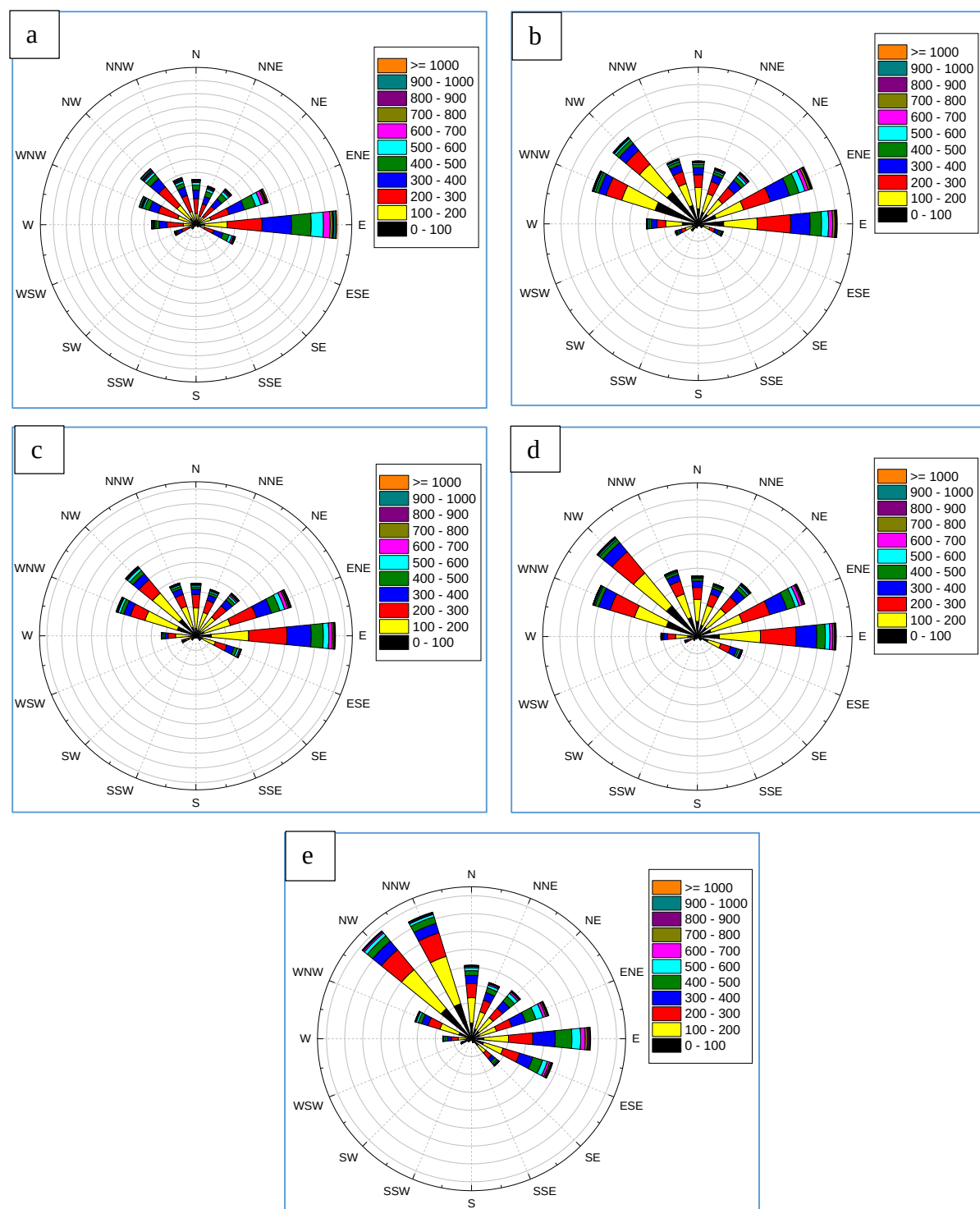


Figure 4.8. Pollution rose diagram of PM_{10} at R K Puram for the year (a) 2012 (b) 2013 (c) 2014 (d) 2015 and (e) 2016.



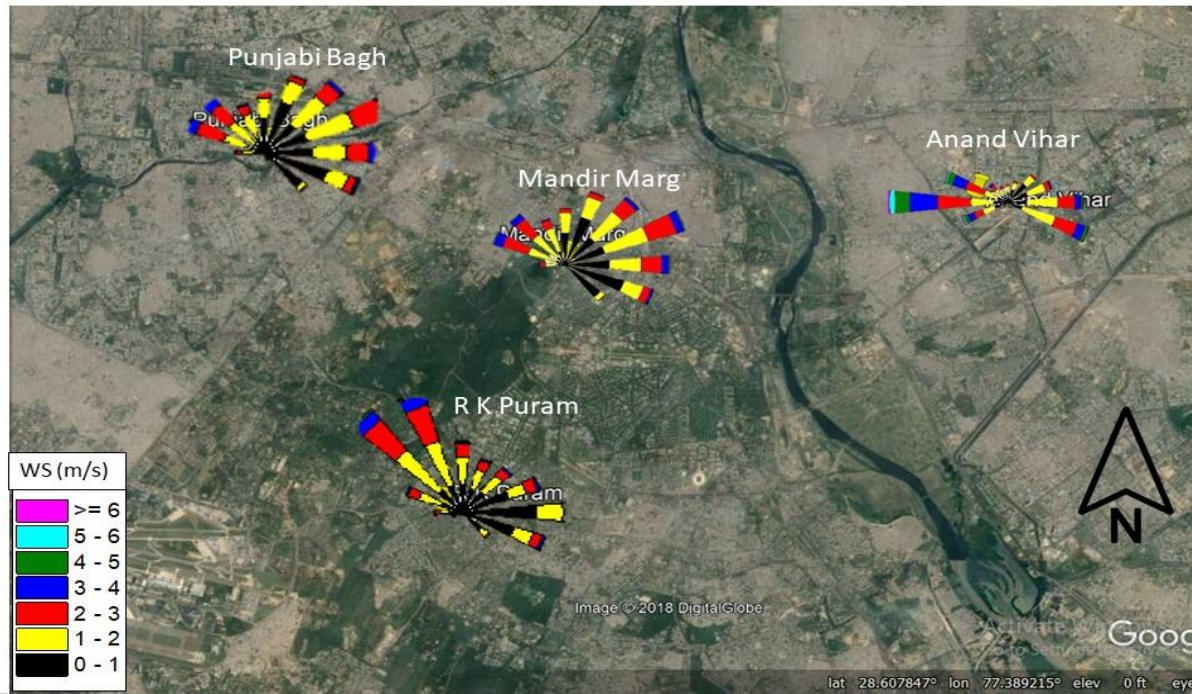


Figure 4.9. Summary of the wind rose at different locations in Delhi city for the year 2016.

4.2 Time series of historical air quality data in Delhi city (2012-2016)

4.2.1 Air Quality data at Anand Vihar

Anand Vihar is situated in the eastern part of Delhi between 28.65°N , and 77.30°E . This location has one of the largest railway station terminal (ANVT), spread over 42 acres connecting all eastbound trains from Delhi. This is also one of the major Traffic Intersection of the city. Located near the border of Delhi and Uttar Pradesh state, Anand Vihar contains inter-State bus terminus, the Ghazipur sanitary landfill, and the NH-24 and hence, Anand Vihar has the characteristics of commercial, industrial and residential area.

Figures 4.10 (a-e) present the time series of 24-hour average $\text{PM}_{2.5}$ concentration monitored at Anand Vihar, Delhi for the year 2012 to 2016. The 24-hour average $\text{PM}_{2.5}$ concentrations were found to be between 22.6 and $458 \mu\text{g}/\text{m}^3$. The results indicated that the 24-hour average $\text{PM}_{2.5}$ concentration exceeded National Ambient Air Quality Standards ($\text{NAAQS} = 60 \mu\text{g}/\text{m}^3$) for 81.6% of the monitoring period (2012-2016).

Figures 4.10 (f-j) show the time series analysis of 24-hour average PM₁₀ concentrations monitored at Anand Vihar, Delhi for the year 2012 to 2016. The 24-hour average PM₁₀ concentrations were found to be in the range of 52.9 to 963.1 µg/m³. The assessment of 24-hour average concentration of PM₁₀ at this location indicated 92.5% violations of NAAQS (100 µg/m³) from 2012 to 2016.

Figures 4.11 (a-e) show the time series analysis of the 24-hour average concentration of nitrogen dioxide (NO₂), monitored at Anand Vihar, Delhi for the year 2012 to 2016. The 24-hour average NO₂ concentrations were found to be in the range of 5.01 (minimum) to 98.6 µg/m³ (maximum). The assessment of 24-hour average concentration of NO₂ indicated 17.5% violations of NAAQS (80 µg/m³) from 2012 to 2016.

Figure 4.12(a-e) display the time series analysis of the 24-hour average concentration of sulfur dioxide (SO₂), monitored at Anand Vihar, Delhi for the year 2012 to 2016. The 24-hour average SO₂ concentrations were found to be in the range of 10.03 to 79.2 µg/m³. The assessment of 24-hour average concentration of SO₂ indicated that SO₂ concentration was within the limit (80 µg/m³) from 2012 to 2016.

Source apportionment of ambient particulate matter during winter season in Delhi

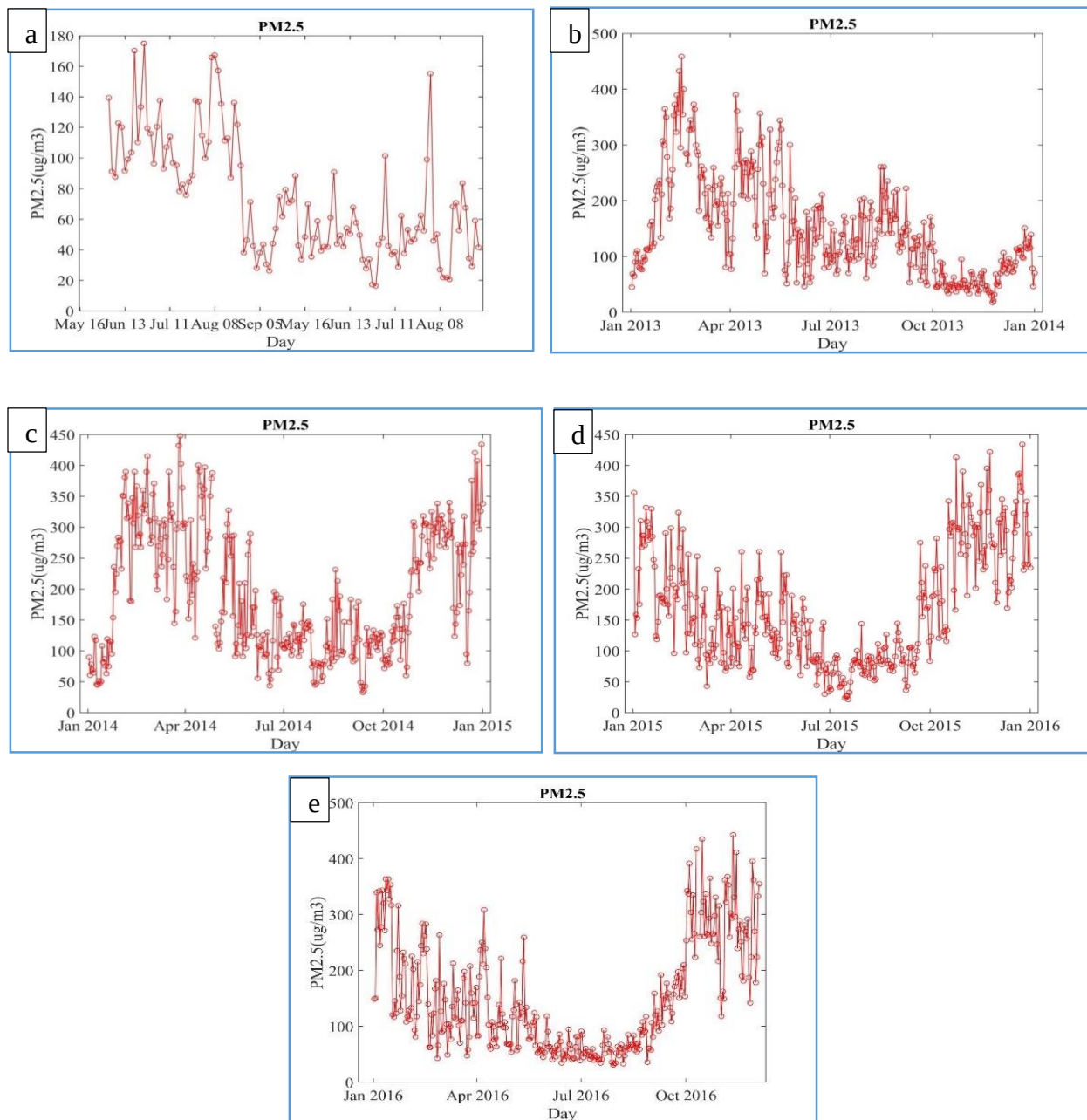


Figure 4.10. Time series of $PM_{2.5}$ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Anand Vihar



Source apportionment of ambient particulate matter during winter season in Delhi

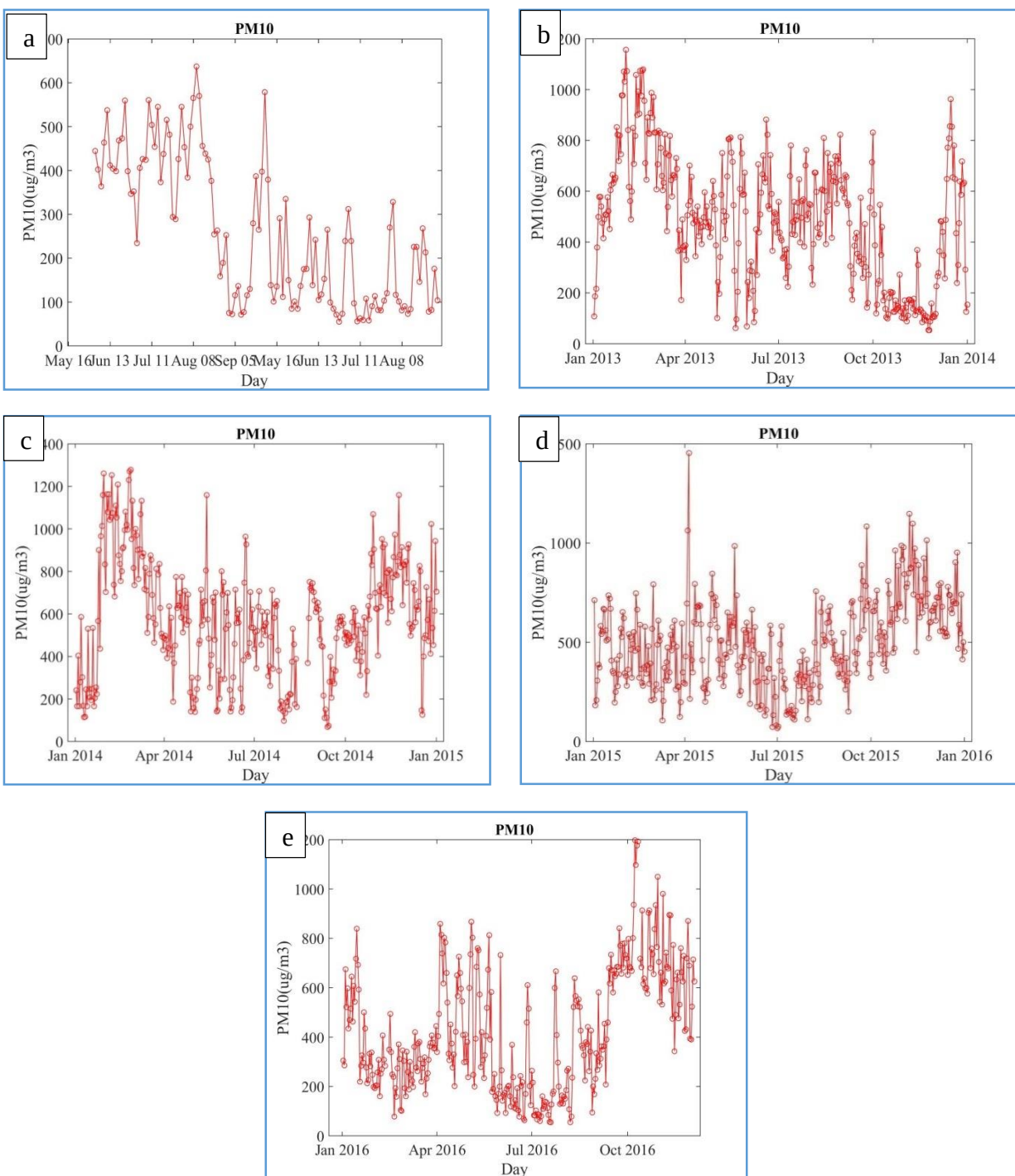


Figure 4.10. Time series of PM_{10} for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Anand Vihar



Source apportionment of ambient particulate matter during winter season in Delhi

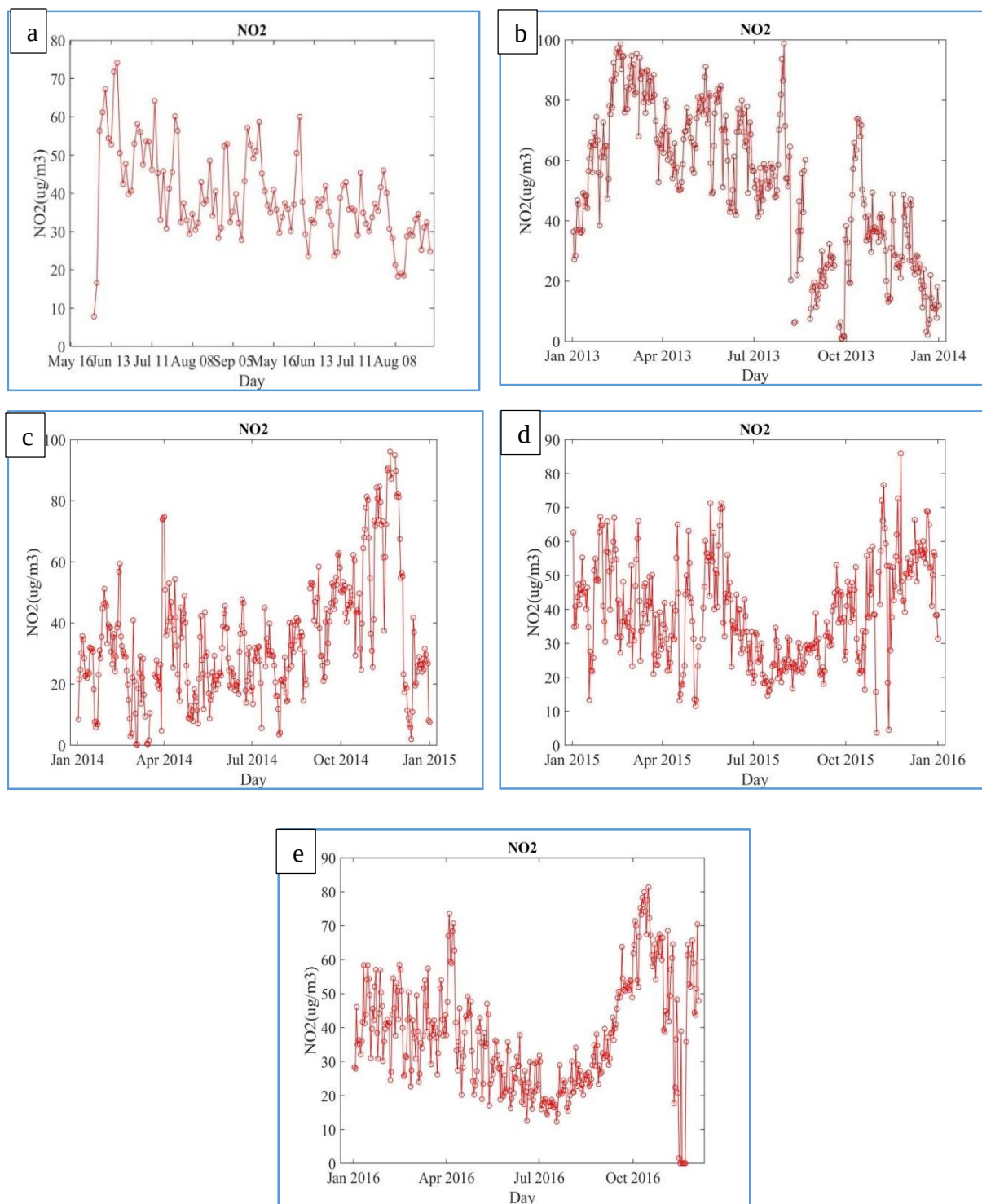


Figure 4.11. Time series of NO_2 for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Anand Vihar.



Source apportionment of ambient particulate matter during winter season in Delhi

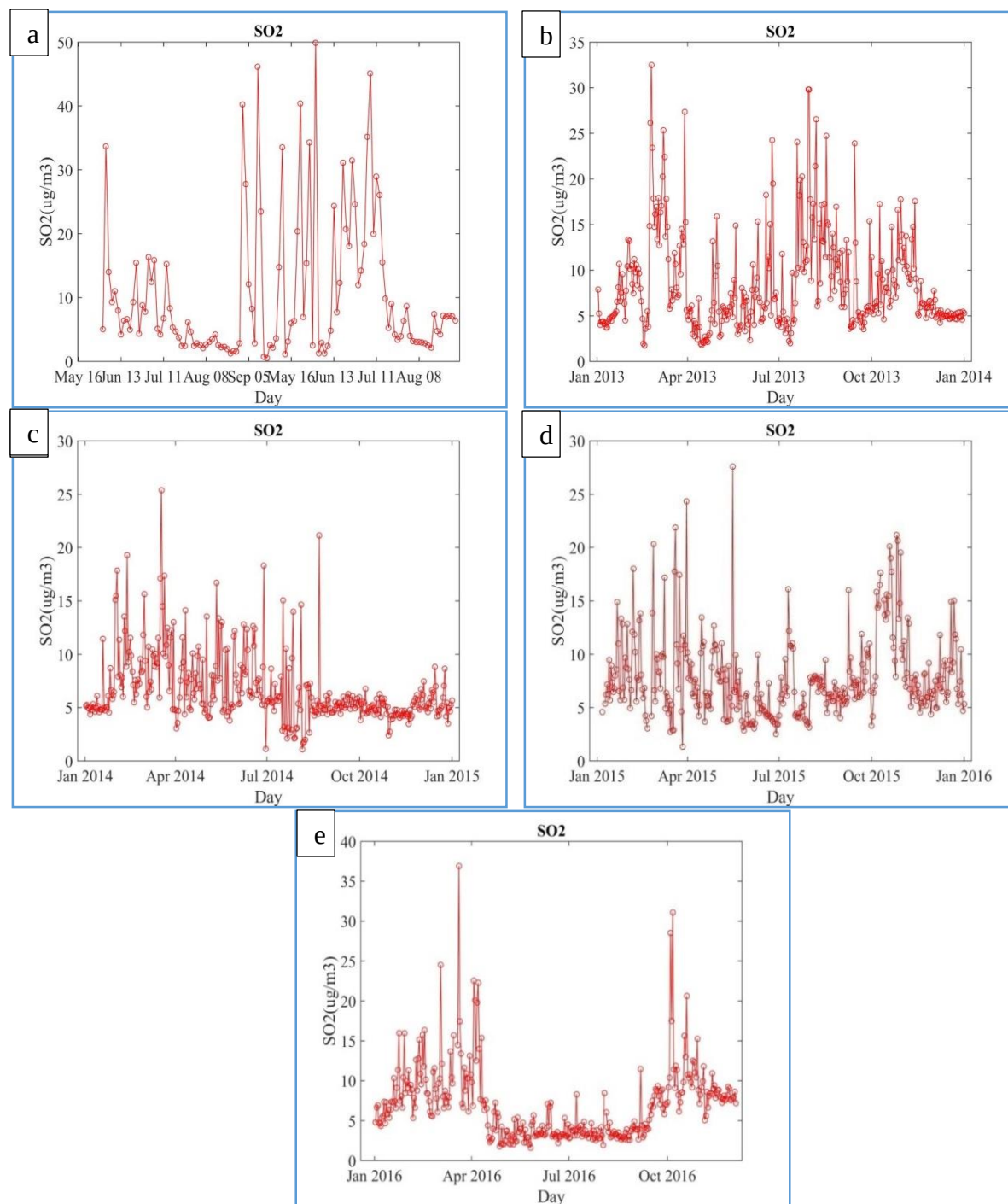


Figure 4.12. Time series of SO_2 for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Anand Vihar.



4.2.2 Air Quality data at Mandir Marg

The continuous ambient monitoring stations (CAQMS) at Mandir Marg is located in Central Delhi near N P Boys Senior Secondary School. Situated towards the west of National ridge forest with Gole Market and Connaught place towards east. The area is classified as a business cum Traffic intersection area.

Figures 4.13 (a-e) illustrates the time series of 24-hour average $PM_{2.5}$ concentrations monitored at Mandir Marg, Delhi for the year 2012 to 2016. The 24-hour average $PM_{2.5}$ concentrations were found to be in the range of 22.7 to 447 $\mu g/m^3$. The results indicated that 75% of the 24-hour average $PM_{2.5}$ concentrations were exceeded the NAAQS (60 $\mu g/m^3$).

Figures 4.13 (f-j) present the time series analysis of 24-hour average PM_{10} concentration monitored at Mandir Marg, Delhi for the year 2012 to 2016. The 24-hour average PM_{10} concentrations were found to be in range of 30 to 889 $\mu g/m^3$. The analysis of the result indicated that 82% of the 24-hour average concentration of PM_{10} exceeded the NAAQS (100 $\mu g/m^3$).

Figures 4.14 (a-e) presents the time series analysis of the 24-hour average concentration of NO_2 , monitored at Mandir Marg, Delhi for the year 2012 to 2016. The 24-hour average NO_2 concentrations ranged between 5.3 and 97.2 $\mu g/m^3$.

Figures 4.15 (a-e) show the time series analysis of the 24-hour average concentration of sulfur dioxide, monitored at Mandir Marg, Delhi for the year 2012 to 2016. The 24-hour average SO_2 concentrations were found to be in the range of 10.1 to 98.9 $\mu g/m^3$. The assessment of 24-hour average concentration of SO_2 shows that 6% of the average concentrations exceeded the NAAQS (80 $\mu g/m^3$).



Source apportionment of ambient particulate matter during winter season in Delhi

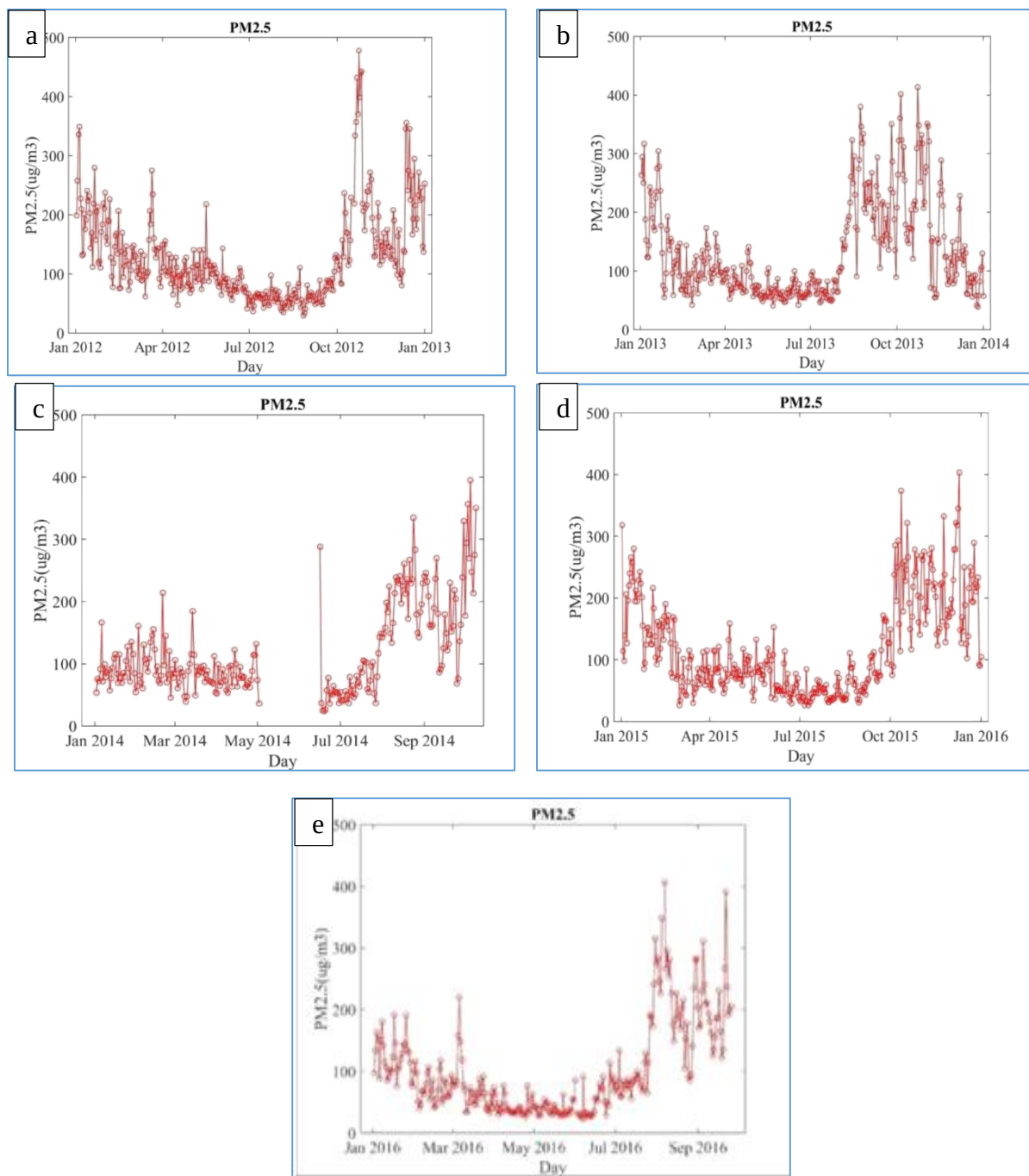


Figure 4.13. Time series of $PM_{2.5}$ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Mandir Marg.



Source apportionment of ambient particulate matter during winter season in Delhi

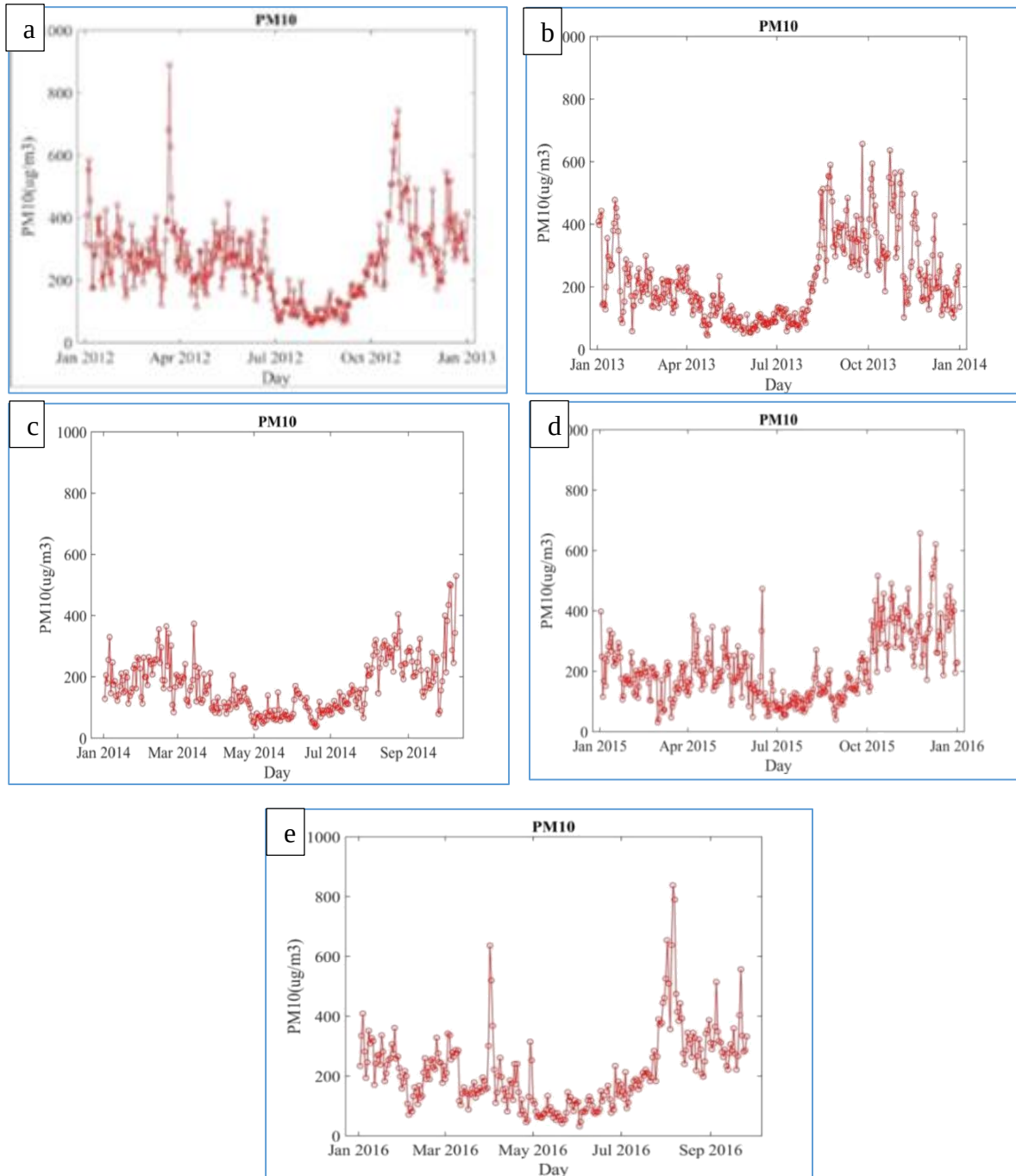


Figure 4.13. Time series of PM₁₀ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Mandir Marg.



Source apportionment of ambient particulate matter during winter season in Delhi

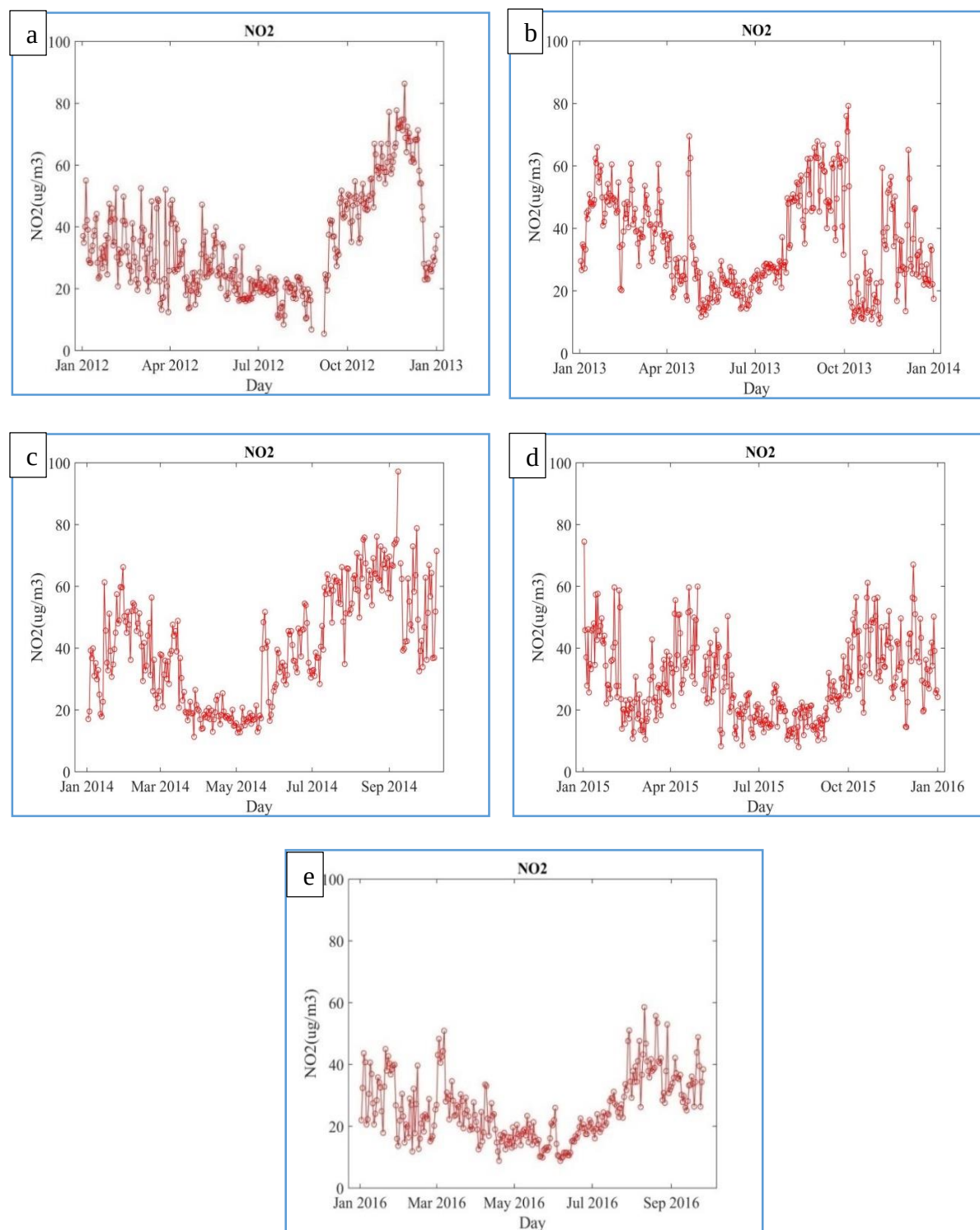


Figure 4.14. Time series of NO₂ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Mandir Marg.



Source apportionment of ambient particulate matter during winter season in Delhi

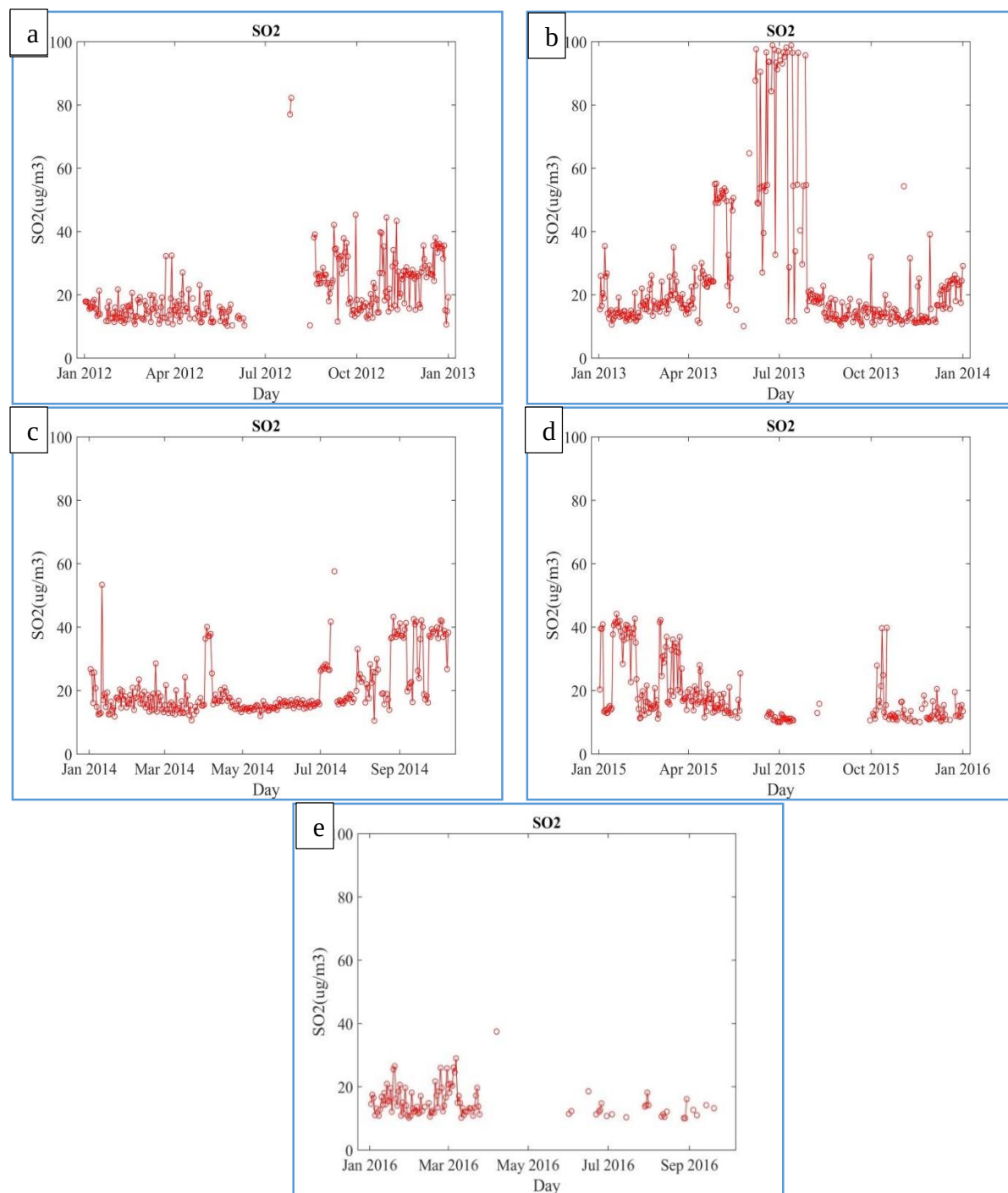


Figure 4.15. Time series of SO₂ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Mandir Marg.



4.2.3 Air Quality data at Punjabi Bagh

Punjabi Bagh, located about 30 m away from West Delhi, is famous for large bungalows and commercial establishments. This residential area is divided into 2 zones, East and West by the Ring Road. It is well connected to various parts of the city through bus road as well as Delhi metro. The area can be characterized as a residential and commercial area for air quality monitoring. Punjabi Bagh is sandwiched between Rohtak Road from one end and Ring Road from the other end. Thousands of trucks are diverted via Rohtak Road to the Ring Road which further contributes to the high pollution concentration. Industries in Mayapuri and Mangolpuri are also nearby of Punjabi Bagh contributing to the air pollution.

Figures 4.16 (a-e) present the time series analysis of the 24-hour average concentration of $PM_{2.5}$, monitored at Punjabi Bagh, for the year 2012 to 2016. The 24-hour average $PM_{2.5}$ concentrations were found to be in the range of 26.8 to 493 $\mu g/m^3$. The analysis of 24-hour average $PM_{2.5}$ concentration indicated that 82.3% of the concentrations had exceeded the NAAQS (60 $\mu g/m^3$).

Figures 4.16 (f-j) show the time series analysis of the 24-hour average concentration of PM_{10} , monitored at Punjabi Bagh, Delhi for the year 2012 to 2016. The 24 hour average PM_{10} , concentrations were found to be in the range of 37.6 to 911.6 $\mu g/m^3$. The assessment of 24-hour average PM_{10} concentration showed that 91% of the PM_{10} concentrations were exceeded NAAQS (100 $\mu g/m^3$).

Figures 4.17 (a-e) show the time series analysis of the 24-hour average concentration of NO_2 , monitored at Punjabi Bagh, Delhi for the year 2012 to 2016. The 24-hour average NO_2 concentrations were found to be in the range of 6.2 to 99.15 $\mu g/m^3$. The assessment of 24-hour average concentration of Nitrogen dioxide showed that 3.6% of the Nitrogen dioxide concentrations had exceeded NAAQS (80 $\mu g/m^3$).

Figures 4.18 (a-e) present the time series analysis of the 24-hour average concentration of SO_2 , monitored at Punjabi Bagh, Delhi for the year 2012 to 2016. The 24-hour average SO_2 concentrations were found to be in the range of 10 to 84.1 $\mu g/m^3$. The analysis shows that 7% of the SO_2 concentrations have exceeded the NAAQS (80 $\mu g/m^3$).



Source apportionment of ambient particulate matter during winter season in Delhi

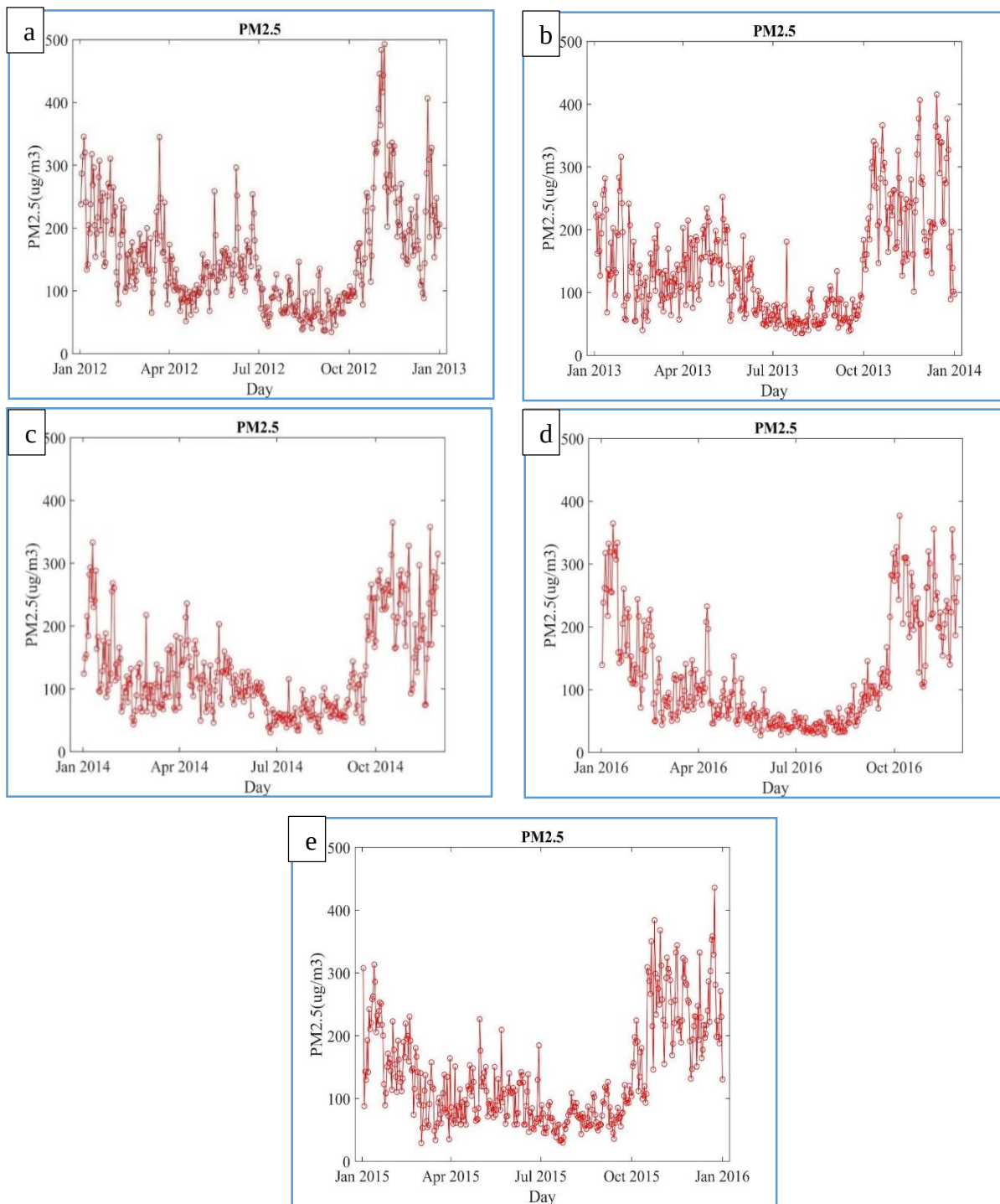


Figure 4.16. Time series of $PM_{2.5}$ for the year (a) 2012 (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Punjabi Bagh.



Source apportionment of ambient particulate matter during winter season in Delhi

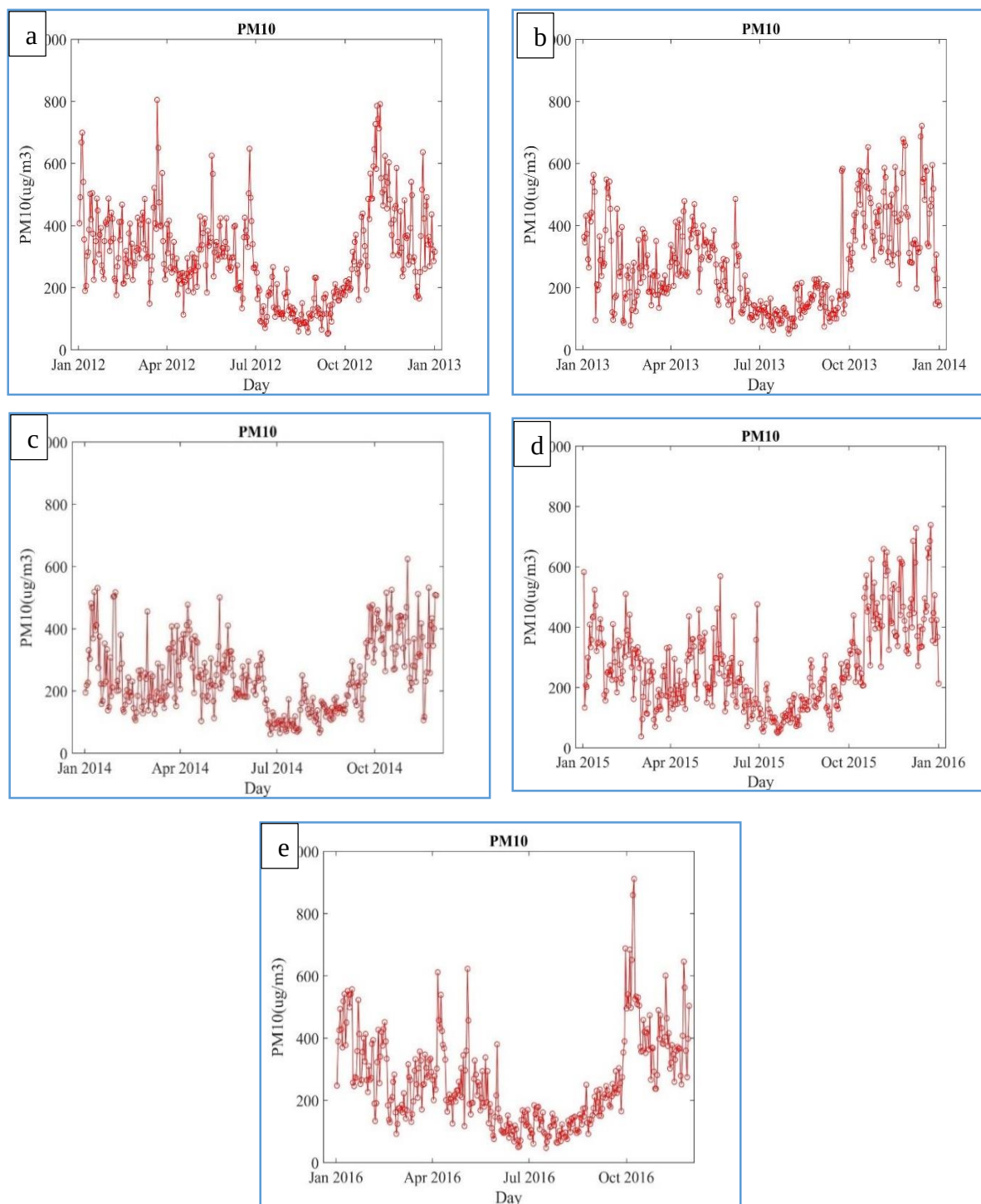


Figure 4.16. Time series of PM₁₀ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (j) 2016 at Punjabi Bagh.



Source apportionment of ambient particulate matter during winter season in Delhi

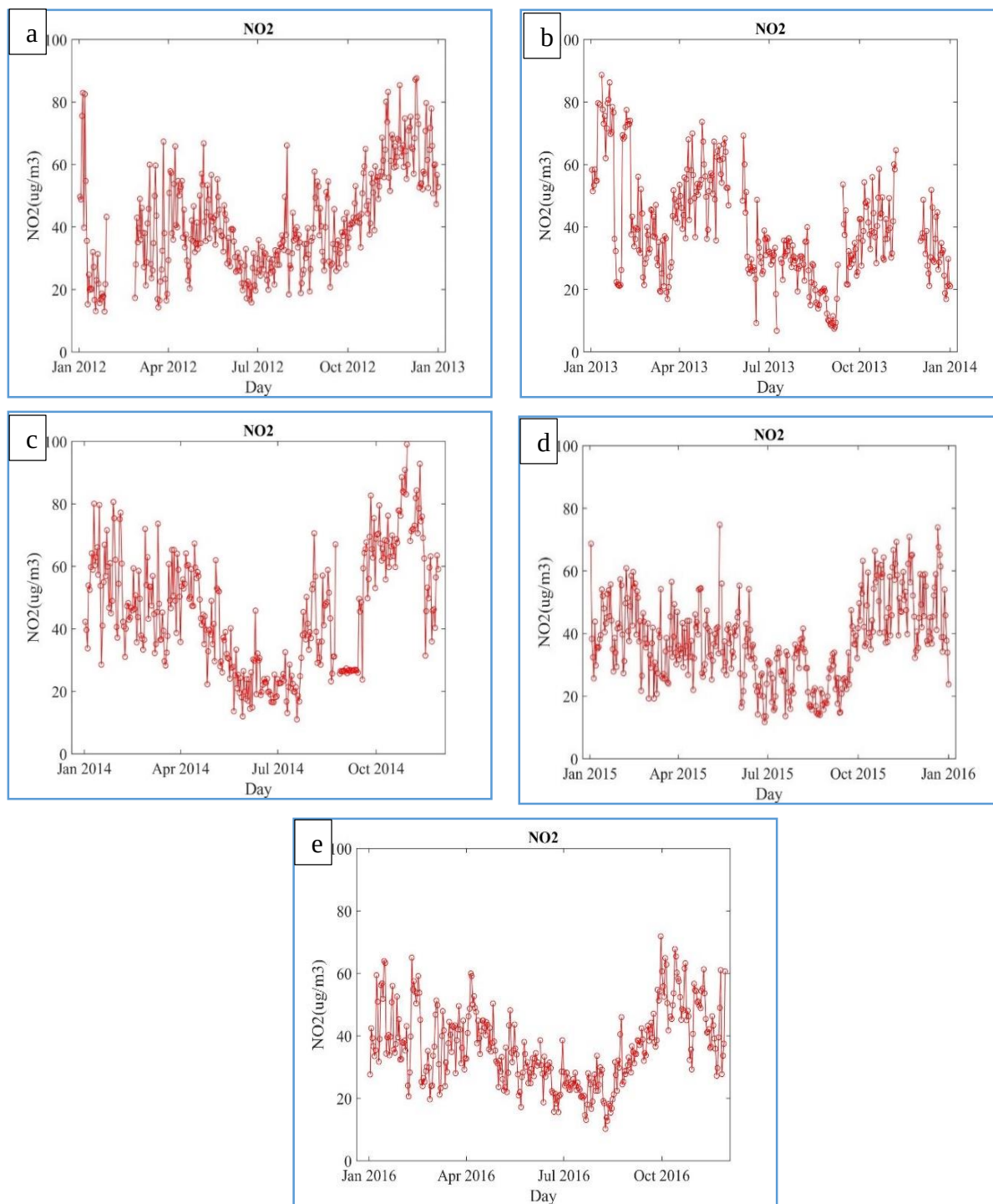


Figure 4.17. Time series of NO₂ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Punjabi Bagh.



Source apportionment of ambient particulate matter during winter season in Delhi

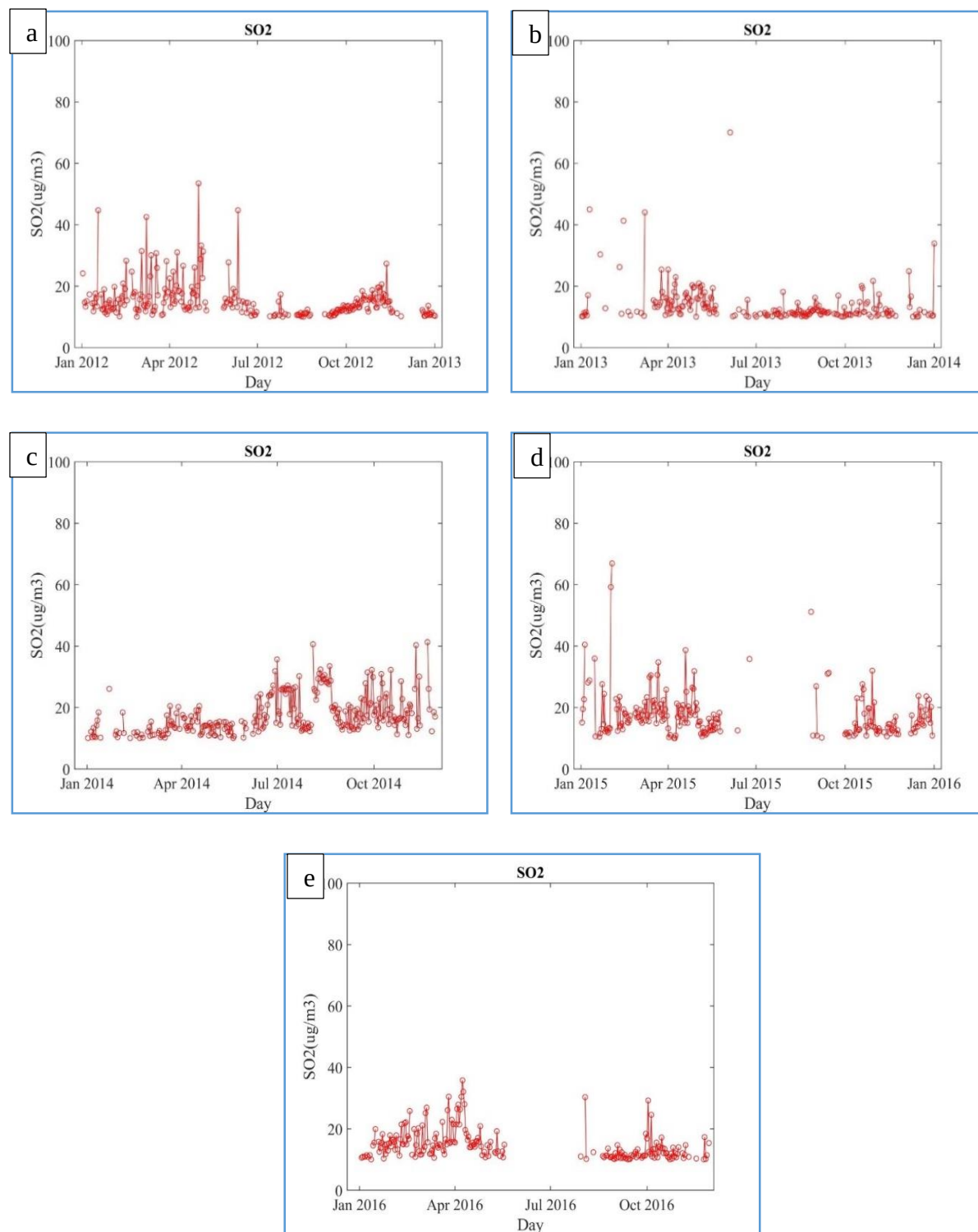


Figure 4.18. Time series of SO₂ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at Punjabi Bagh.



4.2.4 Air Quality data at RK Puram

The R K Puram CAQMS monitoring station is located near Kendriya Vidyalaya Sector 2, RK Puram. The location is classified as a residential area; the nearest road is Africa Avenue crowded by buses and private automobiles. R K Puram is sandwiched between two ring roads and ongoing metro and flyover construction work. It encompasses 12 sectors, sandwiched between Ring Road and Outer Ring Road. Thousands of diesel trucks and other commercial vehicles pass through the Ring Road and Outer Ring Road.

Figures 4.19 (a-e) presents the time series of the 24-hour average concentration of PM_{2.5} monitored at RK Puram, Delhi for the year 2012 to 2016. The 24-hour average PM_{2.5} concentrations were found to be in the range of 24.25 to 467.8 µg/m³. The analysis of the result indicated that 83.6% of the 24-hour average concentrations of PM_{2.5} exceeded the NAAQS (60 µg/m³).

Figures 4.19 (f-j) show the time series of the 24-hour average concentration of PM₁₀ monitored at RK Puram, Delhi for the year 2012 to 2016. The 24-hour average PM₁₀ concentrations were found to be in the range of 31.1 to 985 µg/m³. The assessment of 24-hour average concentration of PM₁₀ indicated that 87.5% of the concentrations exceeded the NAAQS (100 µg/m³).

Figures 4.20 (a-e) show the time series analysis of the 24-hour average concentration of NO₂, monitored at RK Puram, Delhi for the year 2012 to 2016. The 24-hour average NO₂ concentrations were found to be in the range of 5.14 µg/m³ (minimum) to 82.2 µg/m³ (maximum). The analysis shows that 2% of the concentrations have exceeded the NAAQS (80 µg/m³).

Figures 4.21 (a-e) show the time series analysis of the 24-hour average concentration of SO₂, monitored at RK Puram, Delhi for the year 2012 to 2016. The 24-hour average SO₂ concentrations were found to be in the range of 10 µg/m³ (minimum) to 85.9 µg/m³ (maximum). The assessment of 24-hour average concentration of SO₂ indicated that 2% of the concentrations exceeded the NAAQS (100 µg/m³).



Source apportionment of ambient particulate matter during winter season in Delhi

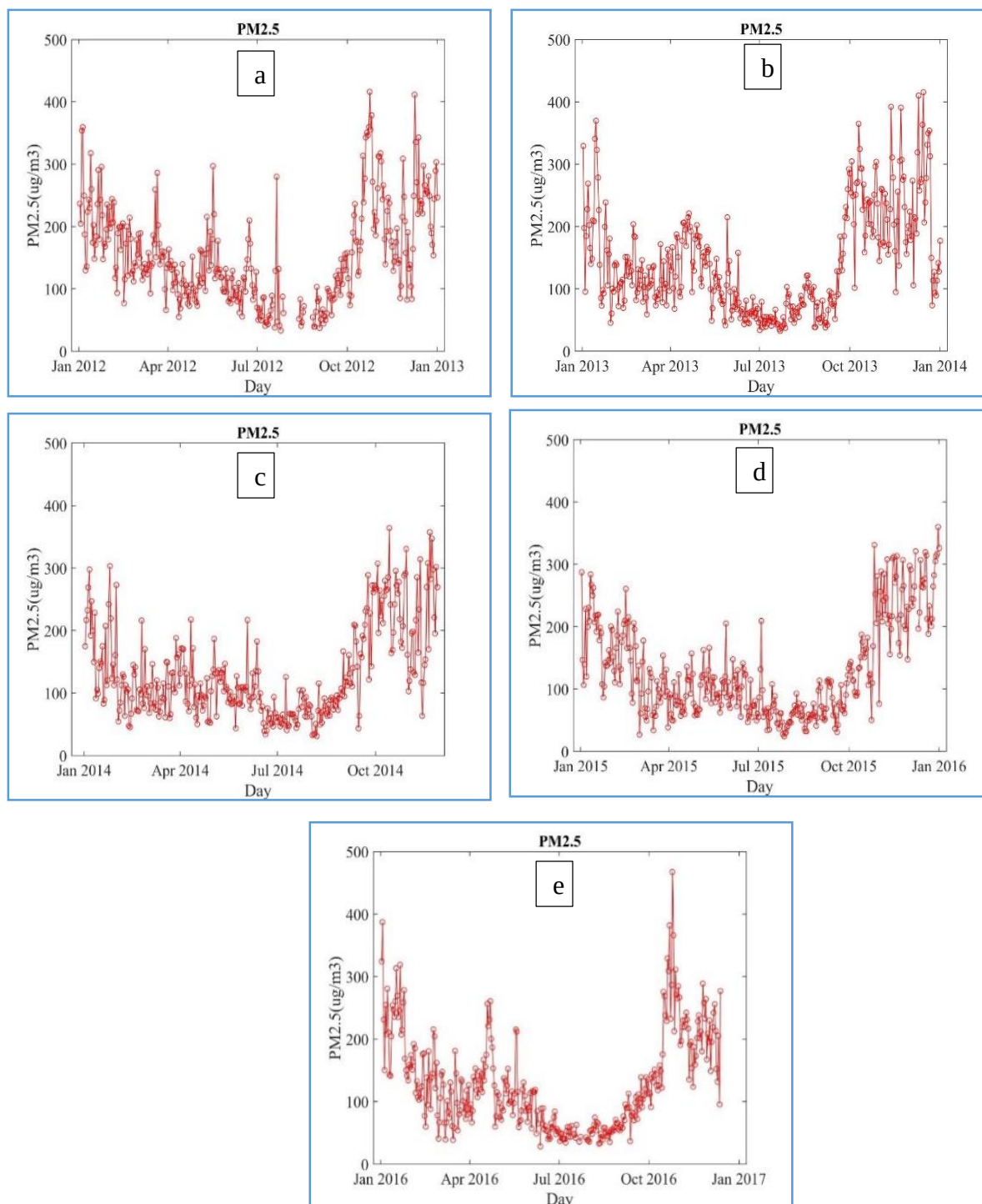


Figure 4.19. Time series of $PM_{2.5}$ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at RK Puram.

Source apportionment of ambient particulate matter during winter season in Delhi

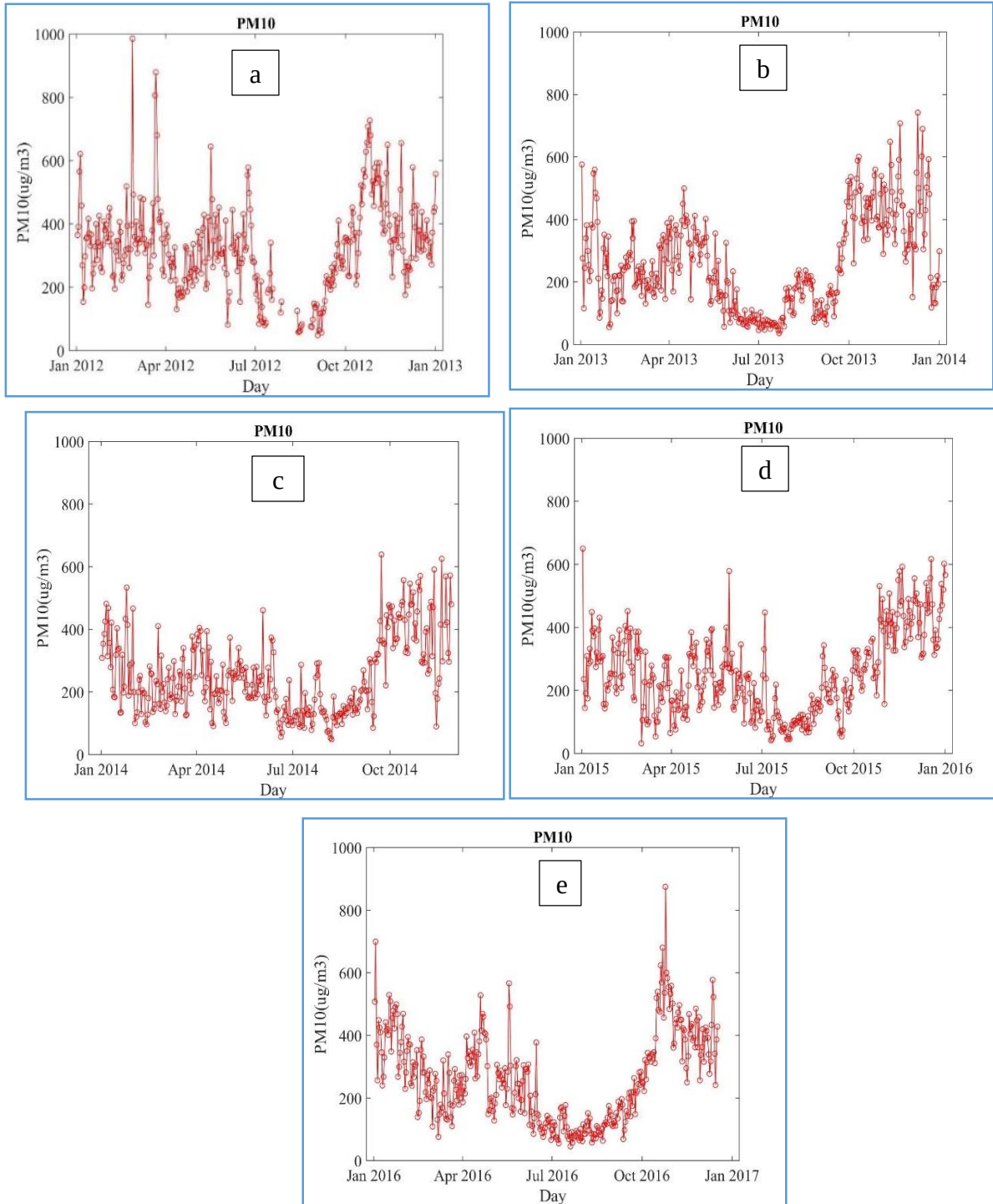


Figure 4.19. Time series of PM₁₀ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at R K Puram



Source apportionment of ambient particulate matter during winter season in Delhi

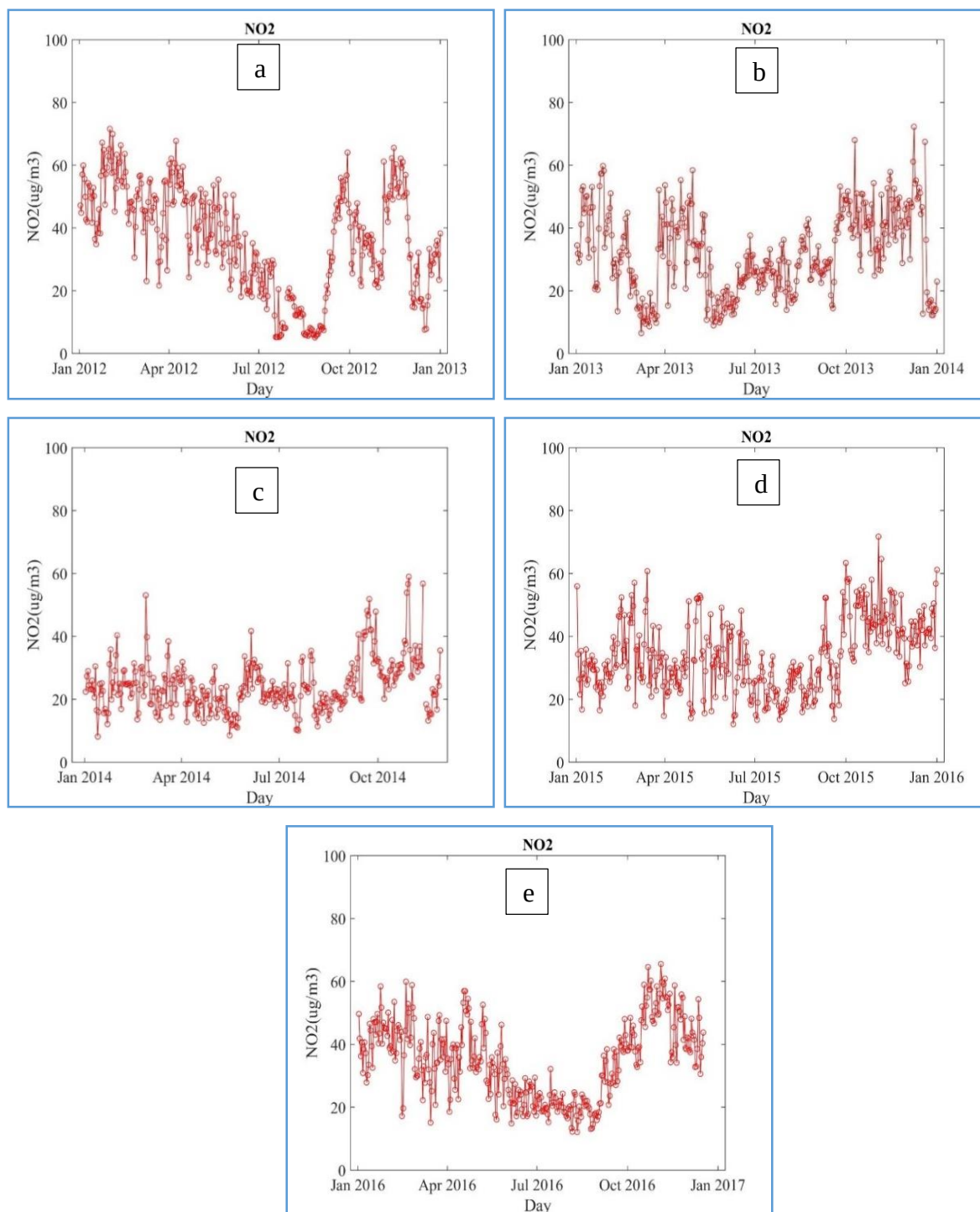


Figure 4.20. Time series of NO₂ for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at R K Puram



Source apportionment of ambient particulate matter during winter season in Delhi

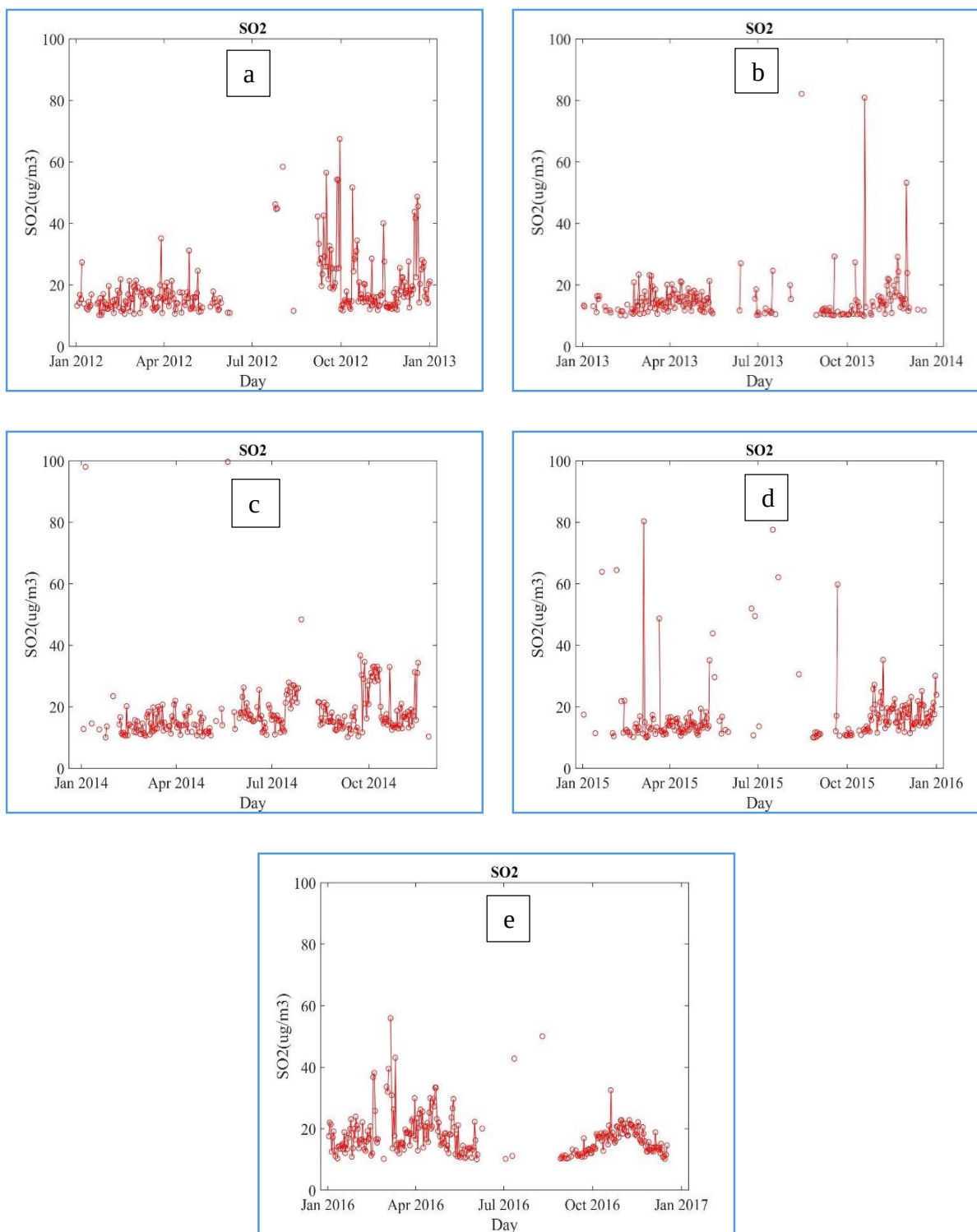


Figure 4.21. Time series of SO_2 for the year (a) 2012, (b) 2013, (c) 2014, (d) 2015, (e) 2016 at R K Puram



Table 4.1: Summary of DPCC CAAQMS locations.

Location	Type	PM concentration ($\mu\text{g}/\text{m}^3$)	Possible sources	Predominant wind direction
Anand Vihar	Traffic	$\text{PM}_{10} = 412.1 \pm 93.8$ $\text{PM}_{2.5} = 148.3 \pm 44.4$	Vehicles, landfill, industries	ENE and E
Mandir Marg	Residential	$\text{PM}_{10} = 216.8 \pm 31.7$ $\text{PM}_{2.5} = 120.6 \pm 12.5$	Vehicles	NE, NNE and ENE
Punjabi Bagh	Residential	$\text{PM}_{10} = 271.8 \pm 19.7$ $\text{PM}_{2.5} = 137.1 \pm 13.01$	Diesel vehicles, industries	NW and NNE
R K Puram	Commercial and residential	$\text{PM}_{10} = 271.7 \pm 32.2$ $\text{PM}_{2.5} = 138.1 \pm 10.5$	Vehicles, construction	E and NW

4.2.5 $\text{PM}_{2.5}$ and PM_{10} concentrations exceedances

Time series of $\text{PM}_{2.5}$ and PM_{10} concentrations showed that 70% of the $\text{PM}_{2.5}$ and PM_{10} concentrations had exceeded the NAAQS. A slight decrease in the exceedance was observed for $\text{PM}_{2.5}$ in the year 2016 as compared to other years. The PM_{10} exceedance reduction was not that significant in the year 2016 as compared to $\text{PM}_{2.5}$.



The exceedance percentage for various pollutants for the Delhi city is as given in table 4.2.

Table 4.2: Number of days per year exceeding the NAAQS standards.

Location	Year	NO ₂ (80 µg/m ³)	SO ₂ (80 µg/m ³)	PM _{2.5} (60 µg/m ³)	PM ₁₀ (80 µg/m ³)
Anand vihar	2012	0	0	125	177
	2013	49	0	313	354
	2014	12	0	265	272
	2015	1	0	341	359
	2016	1	0	291	338
RK Puram	2012	1	0	314	317
	2013	1	2	309	301
	2014	2	2	323	340
	2015	1	1	301	320
	2016	1	0	280	320
Punjabi Bagh	2012	7	1	338	344
	2013	3	2	301	340
	2014	13	0	304	335
	2015	0	3	312	333
	2016	0	0	247	326
Mandir Marg	2012	0	1	314	323
	2013	0	19	268	255
	2014	0	0	256	270
	2015	0	0	264	307
	2016	0	0	200	264

4.3 Air quality monitoring at different elevations in Delhi city

The ambient air monitoring campaign was carried out at different study areas within Delhi city for the winter season to understand the variation of PM concentration at different elevations. High volume samplers were used to measure the PM₁₀ and PM_{2.5} at two different elevations of the study area represented by HE- higher elevation and LE- lower elevation.

4.3.1 Variation of PM₁₀ concentration at two different elevations

Figure 4.22 presents the variation of 24-hours PM₁₀ concentration in two different elevations at various locations in Delhi city.



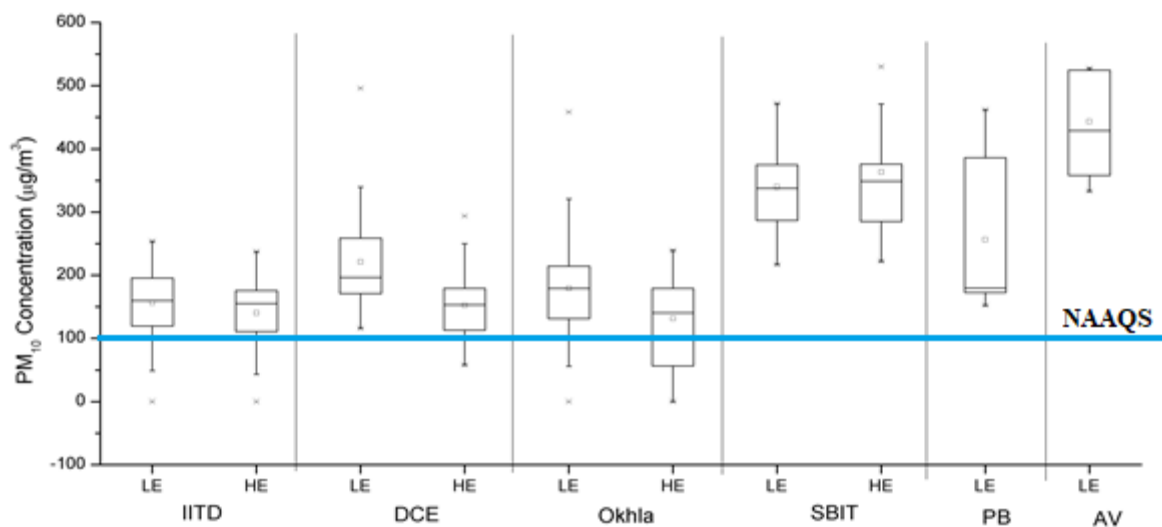


Figure 4.22. PM₁₀ concentration variation in two different elevations at various locations in Delhi city.

Table 4.3: PM₁₀ concentration ratio between higher and lower elevation for different locations

Location	HE (PM ₁₀)/ LE (PM ₁₀) ratio
IITD	0.9
DCE	0.7
Okhla	0.7
SBIT	1.1

PM₁₀ is the coarser particles and are generally contributed by resuspended dust. The retention time of PM₁₀ is less as it gets settled fast due to its higher size. Hence it is expected that the PM₁₀ concentration is higher at a lower elevation as compared to a higher elevation. This trend is seen in all the locations except SBIT. The HE/LE PM₁₀ ratio is given in table 4.3. It is observed that the ratio is above 1 in the case of SBIT. In other locations, it is less than 1 or almost equal to 1. The concentration of PM₁₀ at a lower elevation at IITD varied from 29.4 to 242.10 µg/m³ and for the higher elevation; it ranged from 43.1 to 253.37 µg/m³. The construction activities and cleaning of the roads using mechanized vacuum cleaner which contributes to high PM₁₀.



At Delhi College of Engineering (DCE), the concentration of PM₁₀ at lower elevation has varied from 75.98 to 496.13 µg/m³ and for the higher elevation; it ranged from 57.70 to 398.74 µg/m³. The average concentration of PM₁₀ for lower elevation was 214.68 µg/m³ which is higher than the NAAQS value. For higher elevation, the average concentration was 170.10 µg/m³ which is 70% higher than the National Ambient Air Quality Standards value.

At Okhla, the concentration of PM₁₀ at lower elevation has varied from 54.3 to 458.47 µg/m³ and for the higher elevation; it ranged from 28.7 to 239.46 µg/m³. The lower elevation site was at the rooftop of Envirotech Pvt. Ltd which is situated next to a minor road with very few vehicles. On the other hand, the higher elevation instruments were placed on the rooftop of a 10-story hotel. It is situated next to a major road.

At Shri Balwant Institute of Technology (SBIT), the concentration of PM₁₀ at lower elevation has varied from 271.19 to 471.90 µg/m³ and for the higher elevation; it has varied from 221.97 to 530.15 µg/m³. The range of mass concentration of PM₁₀ at the two elevations does not differ much. The higher elevation captures PM₁₀ from local sources.

At Punjabi Bagh, the instruments were set up at the top of the cabin. The data at Punjabi Bagh was collected from April 3, 2017, to April 11, 2017. The average concentration at Punjabi Bagh was 256.29 µg/m³ which is 156% higher than the NAAQS value. The concentration of PM₁₀ varied from 152.25 to 462.19 µg/m³.

At Anand Vihar, the presence of a bus stop, metro location and a flyover within a distance of 50m from the sampling location contributed to high PM₁₀ as compared to other locations. A large number of commuters movement causes dust resuspension. Since the height of the instruments was about 10ft (3m), most of the re-suspended dust is captured by the instruments. No precipitation was observed during this monitoring period which must have further contributed to the high dust concentration. Even by visual observation, substantial dust clouds were observed on all the monitoring days. Also, the location is primarily considered as a residential area, the recent developments in Delhi resulting in more construction of roads and metro railway, the concentrations are always higher in these locations.



Table 4.4: Descriptive statistics of PM₁₀ observed at different monitoring locations (all values in µg/m³).

Location	Max	Quarter3	Median	Quarter1	Min	SD
DCE LE	496.13	257.33	196.15	170.74	75.98	76.73
DCE HE	398.74	187.14	164.57	126.5	57.7	71.42
IITD LE	242.1	188.45	150.74	116.62	29.4	56.9
IITD HE	253.37	176.6	156.75	107.14	43.1	60.36
Okhla LE	458.47	210.12	171.07	119.36	54.3	81.85
Okhla HE	239.46	193.3	150.85	65.79	28.7	66.68
Anand Vihar	527.78	515.49	458.67	375.88	333.12	84.09
Punjabi Bagh	462.19	335.8	182.13	174.54	152.25	132.72

4.3.2 Variation of PM_{2.5} concentration in two different elevation

The variation of PM_{2.5} concentration in two different elevations at various locations in Delhi city is as given in figure 4.23.

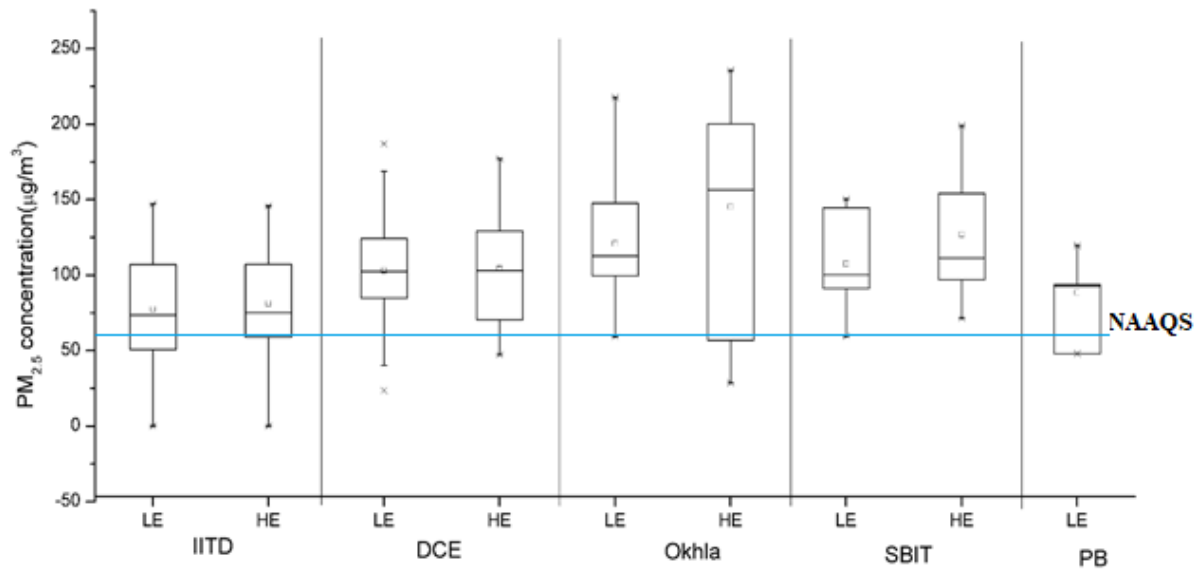


Figure 4.23. PM_{2.5} concentration variation across two different elevations at various sites in Delhi city.



Table 4.5: PM_{2.5} concentration ratio between higher and lower elevation for different locations

Location	HE (PM _{2.5}) / LE (PM _{2.5}) ratio
IITD	1.1
DCE	1.1
Okhla	1.5
SBIT	1.1

In contrast to PM₁₀ concentrations, PM_{2.5} concentrations showed a different trend with higher concentration in the higher elevations. In all the locations, the HE/LE ratio was 1.1 which shows a slightly higher concentration in the HE (Table 4.5). At Okhla, the ratio was comparatively higher, i.e., 1.5. Okhla, being an industrial area, the emissions of fine particulates from industries might be the reason for higher concentrations in HE. Also, there is a dump yard nearby which might also be resulting in higher concentrations in this area.

The concentration of PM_{2.5} in IITD at lower elevation has varied from 26.4 to 147.10 µg/m³ and for the higher elevation; it varied from 31.8 to 145.67 µg/m³. The average concentration of PM_{2.5} for the entire three months for lower elevation was 77.38 µg/m³ which is 0.03% higher than the NAAQS value. For higher elevation, the average concentration was 81.27 µg/m³ which is 0.02% higher than the NAAQS value. PM₁₀, PM_{2.5} and PM₁ concentrations measured by Grimm Aerosol Spectrometer (Model 1.108) for LE were observed to be 144.3 ± 38, 57.7 ± 32 and 42.6 ± 27, respectively (Figure A31). However, for HE, 134±58, 62.3±41 and 46.2±34 were PM₁₀, PM_{2.5}, and PM₁ concentrations, respectively (Figure A32). It was evident that PM₁₀ concentrations in LE were greater than the HE, majorly due to coarse particles from re-suspended dust. While, fine particles, i.e., PM_{2.5} and PM₁ were higher in HE compared to LE contributed from traffic emissions and combustions activities.

Further, PM_{2.5}/PM₁₀ and PM₁/PM₁₀ ratios were found to be 0.39, 0.28 and 0.46, 0.33 at LE and HE, respectively. These results also comprehend that HE has finer particles compared to LE. The diurnal pattern results indicated two peaks i.e., morning and evening for both LE and HE corresponding to morning and evening traffic emissions. The construction activities also contribute to fine particles which remain suspended in the atmosphere. Apart from this, IIT Delhi campus is



situated on a major road of Delhi, and a large number of vehicles plying both outside the campus and inside the campus contributes to fine PM. The roads of the campus are cleaned twice using mechanized vehicular vacuum cleaner which also adds to the fine particles.

At DCE, the $PM_{2.5}$ concentration varied from 40.3 to 186.9 $\mu\text{g}/\text{m}^3$ at a lower elevation, and for the higher elevation, it varied from 47.3 to 177.2 $\mu\text{g}/\text{m}^3$. The average concentration of $PM_{2.5}$ for the two months for lower elevation was 104.1 $\mu\text{g}/\text{m}^3$ and 103.4 $\mu\text{g}/\text{m}^3$ for higher elevation which were exceeding the NAAQS. The $PM_{2.5}$ concentration at both the elevation was almost the same indicating that the sources for both were same. The LE and HE concentration trend were similar at IIT and DCE, maybe because both have similar environments, i.e., academic campus.

At Okhla, the concentration of $PM_{2.5}$ at lower elevation has varied from 47.9 to 217.60 $\mu\text{g}/\text{m}^3$ and for the higher elevation; it varied from 28.7 to 239.46 $\mu\text{g}/\text{m}^3$. The average $PM_{2.5}$ concentration of the two months for lower elevation was 101.09 $\mu\text{g}/\text{m}^3$ which is 26% higher than the NAAQS value. For higher elevation, the average concentration was 137 $\mu\text{g}/\text{m}^3$ which is 71% higher than the NAAQS value. Okhla is an industrial area; thus fine PM from industries and also from vehicular emissions caused an increase in $PM_{2.5}$ mass concentrations.

At SBIT it was observed that the average value of $PM_{2.5}$ was 107.49 $\mu\text{g}/\text{m}^3$ for lower elevation and 127.05 $\mu\text{g}/\text{m}^3$ for higher elevation. The concentration of $PM_{2.5}$ at lower elevation has varied from 59.41 to 150.33 $\mu\text{g}/\text{m}^3$ and for the higher elevation; it has varied from 71.44 to 198.83 $\mu\text{g}/\text{m}^3$. The higher concentration at higher elevation is due to fine particles remaining suspended in the atmosphere. However, the mass concentrations in lower elevation are comparable to a higher elevation. It may be due to several reasons, such as the presence of a mechanical workshop and cattle shed about 50m away from the sampling location. The presence of exhaust fans and workshop activities and the cattle feeding activities produce fine particles which may not quickly move due to hindrances from trees and bushes.

The average concentration at Punjabi Bagh was 88.55 $\mu\text{g}/\text{m}^3$ which is 10% higher than the NAAQS value. The concentration of $PM_{2.5}$ varied from 47.95 $\mu\text{g}/\text{m}^3$ - 119.63 $\mu\text{g}/\text{m}^3$. The monitoring site is located inside a school which is in a residential area. The vehicles passing from the road also contributed to $PM_{2.5}$ mass concentration.



Table 4.6: $PM_{2.5}/PM_{10}$ ratio at LE and HE at various locations in Delhi city.

Location	PM _{2.5} /PM ₁₀ ratio	
	LE	HE
IITD	0.7	0.7
DCE	0.56	0.7
Okhla	0.7	0.97
SBIT	0.32	0.35

The $PM_{2.5}/PM_{10}$ ratio was calculated separately for lower elevation and higher elevation as given in table 4.6. At Okhla, there was a significant variation among the ratios for HE and LE as compared to other locations. This indicates that the additional fine particle emission source contribution to higher elevation fine PM concentration. This may be the proximity of HE monitoring site to a major road which contributes to fine PM as well as other sources like industrial emissions and dumps yard emissions. At SBIT, the ratio is a smaller value, which indicates that most of the particle concentration is comprised of particles of sizes greater than 2.5 microns. As mentioned earlier, the presence of a mechanical workshop and cattle shed about 50m away from the sampling location might have resulted in this type of particle characteristics. Table 4.7 presents the summary of monitoring results at LE and HE. Table 4.8 present an overview of PM concentrations reported in the earlier studies for Delhi city.



Table 4.7: Descriptive statistics of PM_{2.5} observed at different monitoring locations (all values in µg/m³).

Location	Max	Quarter3	Median	Quarter1	Min	SD
SBIT LE	150.33	137.28	102.81	92	59.41	31.95
SBIT HE	198.83	156.89	114.19	103.86	71.44	40.68
DCE LE	186.96	124.26	102.42	84.8	23.67	38
DCE HE	177.16	130.1	106.02	95.63	47.26	36.05
IITD LE	147.1	106.8	74.07	50.92	26.4	34.71
IITD HE	145.67	106.31	77.32	59.48	31.8	31.96
Okhla LE	217.6	120.06	101.57	72.55	47.9	41.16
Okhla HE	209.26	194.05	148.88	63.53	22.4	66.92
Punjabi Bagh	119.63	100.34	93.31	81.52	47.95	29.77

Table 4.8: PM concentrations observed from previous studies.

Parameters	Concentrations (µg/m ³)	Location	Reference
PM ₁₀	249.7±103.9 (Jan 2013-June 2014)	Central Delhi	Sharma et al., 2016
PM ₁₀	164±124 (Jan 2006-Dec 2009)	South Delhi (JNU)	Yadav et al., 2016
PM ₁₀	166.5±54.7 Rajghat (central Delhi) 175.5±67.6 Mayur Vihar (~600 m from Noida Link road) 192.3±63.4 Mithapur (sub-urban residential area) (Dec 2008-Nov 2009)	3 sites in Delhi (Overall mean= 178.2±62.7 µg/m ³) Weekdays mean=186.4 ±41.8 µg/m ³ Weekends mean= 160.9 ±70.2 µg/m ³	Khillare and Sarkar., 2012
PM _{2.5}	150	Delhi (2012-2014)- Punjabi Bagh, Mandir Marg, RK Puram	

4.4 Meteorology of Delhi City

The measurements at different locations were correlated with the corresponding meteorological factors. Table 4.9 gives the descriptive statistics of the meteorological parameters during the monitoring period.



Table 4.9: Descriptive statistics of temperature and relative humidity data collected during the monitoring period (data collected from [www. wunderground.com](http://www.wunderground.com)).

Parameter	Month	Average $\pm$ SD	Maximum	Minimum
Temperature	February	18.64 $\pm$ 2.39	24	15
	March	23.10 $\pm$ 4.44	31	17
	April	30.40 $\pm$ 2.42	34	24
	May	32.68 $\pm$ 2.51	37	26
Relative Humidity	February	64.18 $\pm$ 9.95	79	40
	March	48.06 $\pm$ 8.97	69	35
	April	31.03 $\pm$ 6.59	46	16
	May	38.10 $\pm$ 12.33	73	23

4.4.1 Temperature and Relative Humidity

The daily average, maximum and minimum temperatures and relative humidity (RH) for different months were showed in Table 4.9. The temperature increased steadily from February to May while the RH decreased from February to April while it increased in May due to rainfall. A number of zero precipitation days in February. There were four precipitation days in March (8/3/17-11/3/17) accompanied by a thunderstorm. The maximum precipitation was observed on the 9th March (2.03mm) while the average rainfall seen over those three days (and overall month) was 0.10 $\pm$ 0.39 mm. Rain and thunderstorm were found on five days in April with average rainfall being 0.89 $\pm$ 4.36mm, and the maximum rainfall was observed on 4th April (23.88mm). May experienced nine days of rainfall and thunderstorm with the average rainfall being 1.04 $\pm$ 3.67 mm, and maximum rainfall was observed on 21st May (17.02mm). Meteorological variables play an important role in air pollutants concentrations. Although the correlation is non-linear but according to previous studies air pollution has been observed to be high in the winter season due to inversion conditions. High wind speed may carry dust storm while calm conditions may avoid dilution of pollutant.

On the other hand, rainfall washes away the PM. In the present study, very high PM concentrations were observed on a few days which drastically reduced soon after rainfall. High RH may coagulate PM_{2.5} and make it into bigger particles which may settle easily.



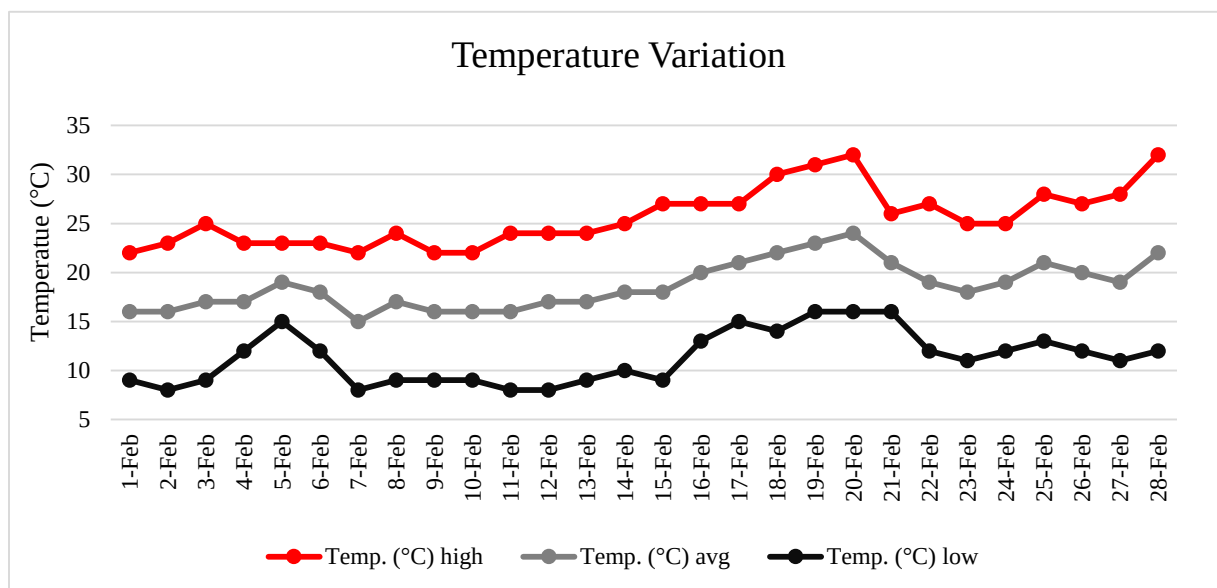


Figure 4.24. Daily temperature variation observed in February in New Delhi.

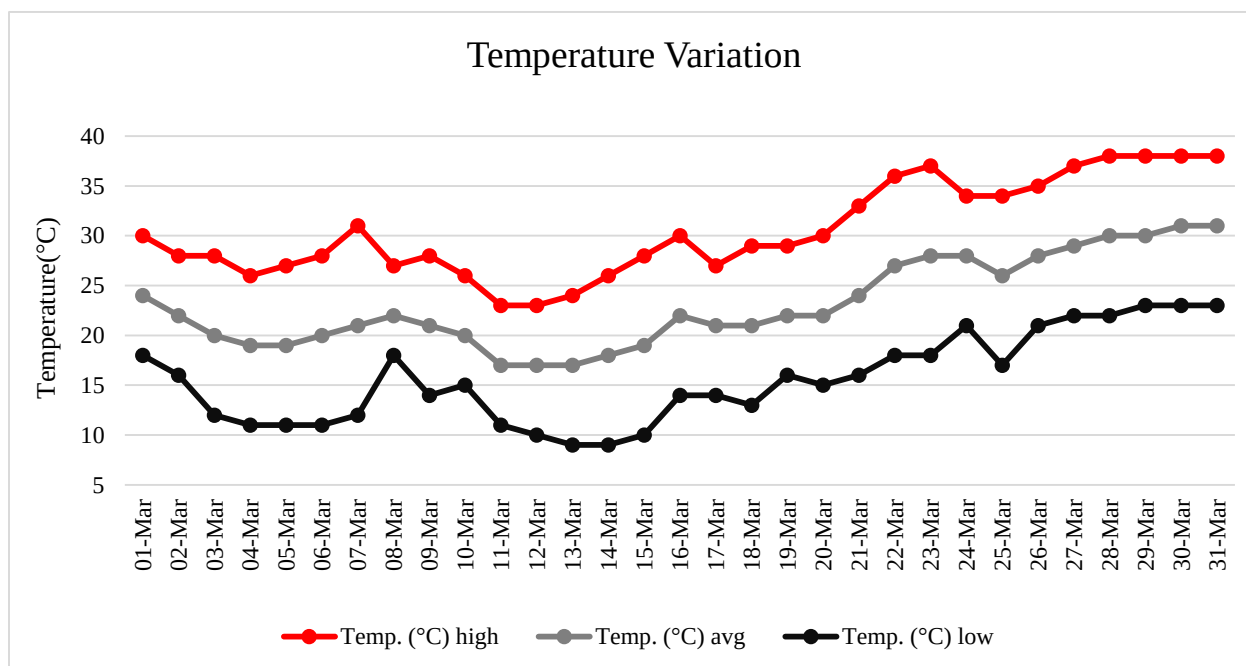


Figure 4.25. Daily temperature variation observed in March in New Delhi.



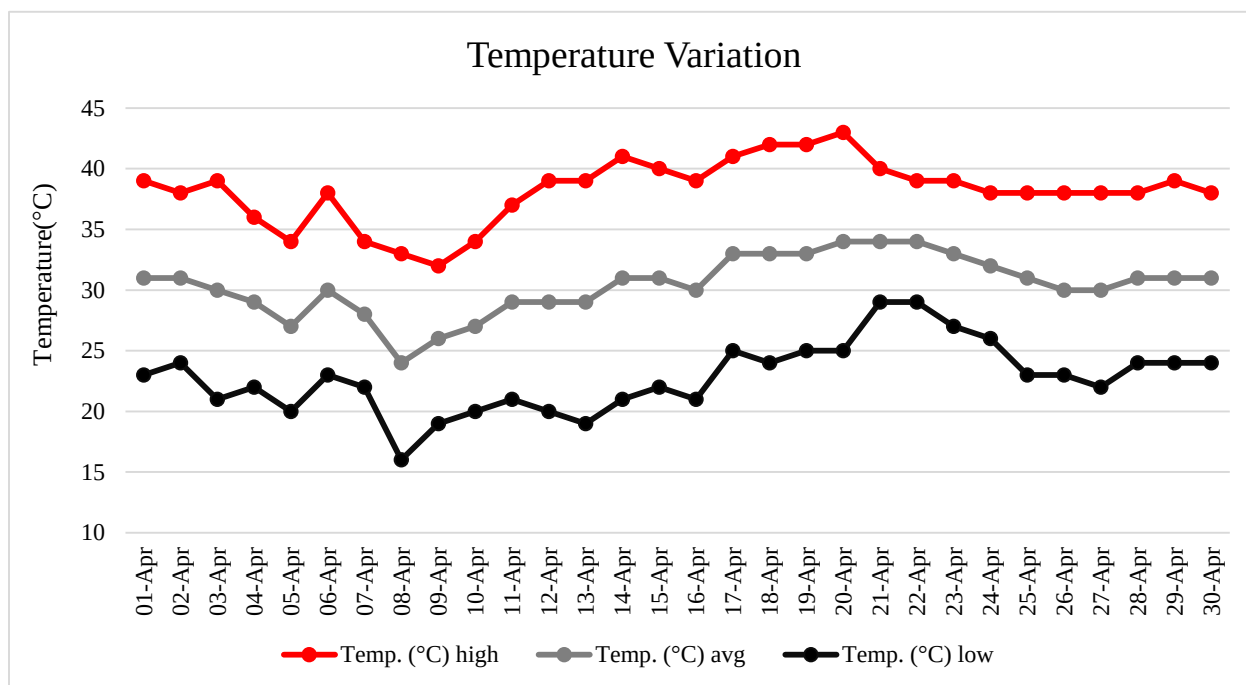


Figure 4.26. Daily temperature variation observed in April in New Delhi.

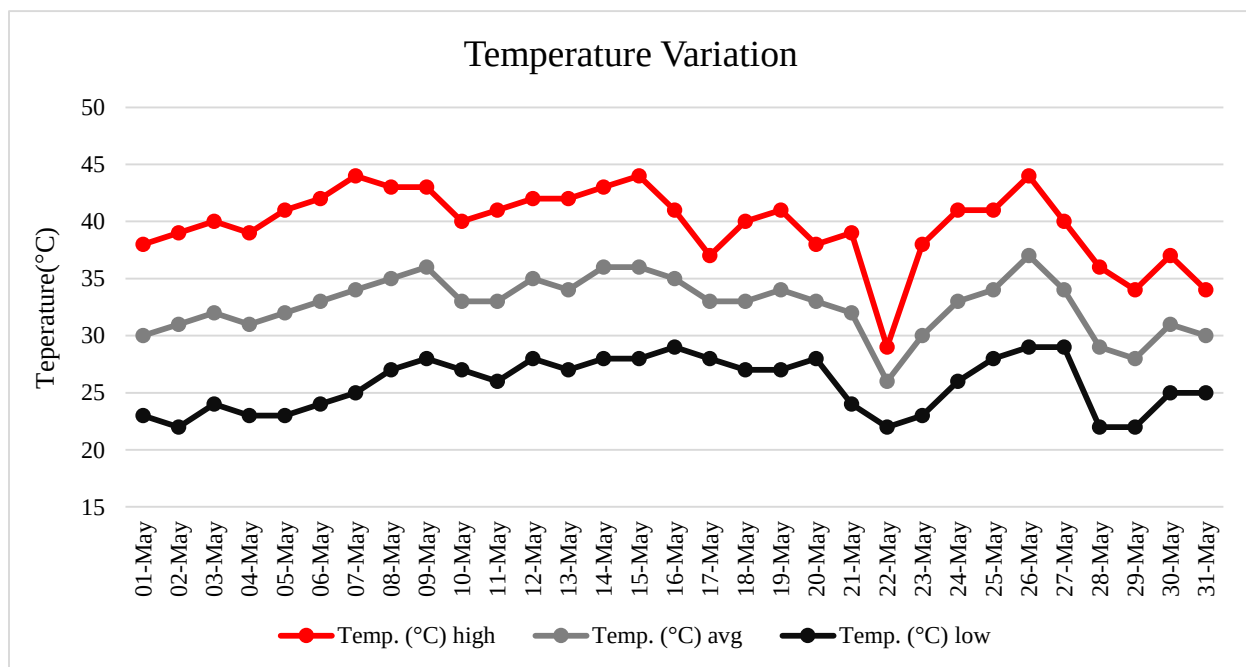


Figure 4.27. Daily temperature variation observed in May in New Delhi.



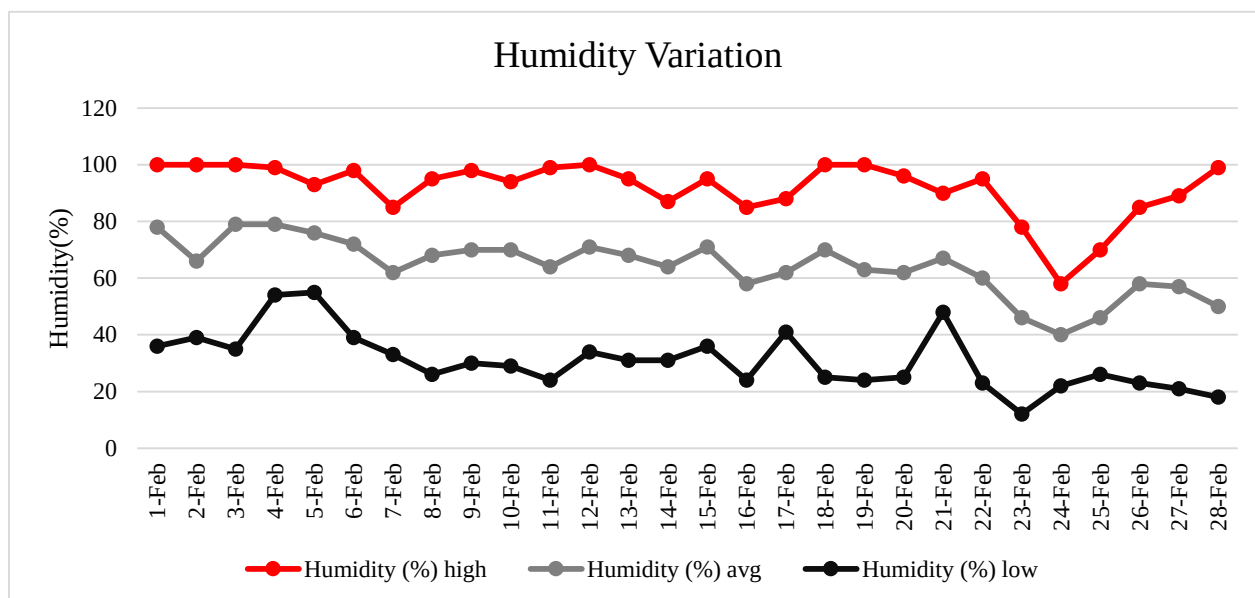


Figure 4.28. Daily relative humidity variation observed in February in New Delhi.

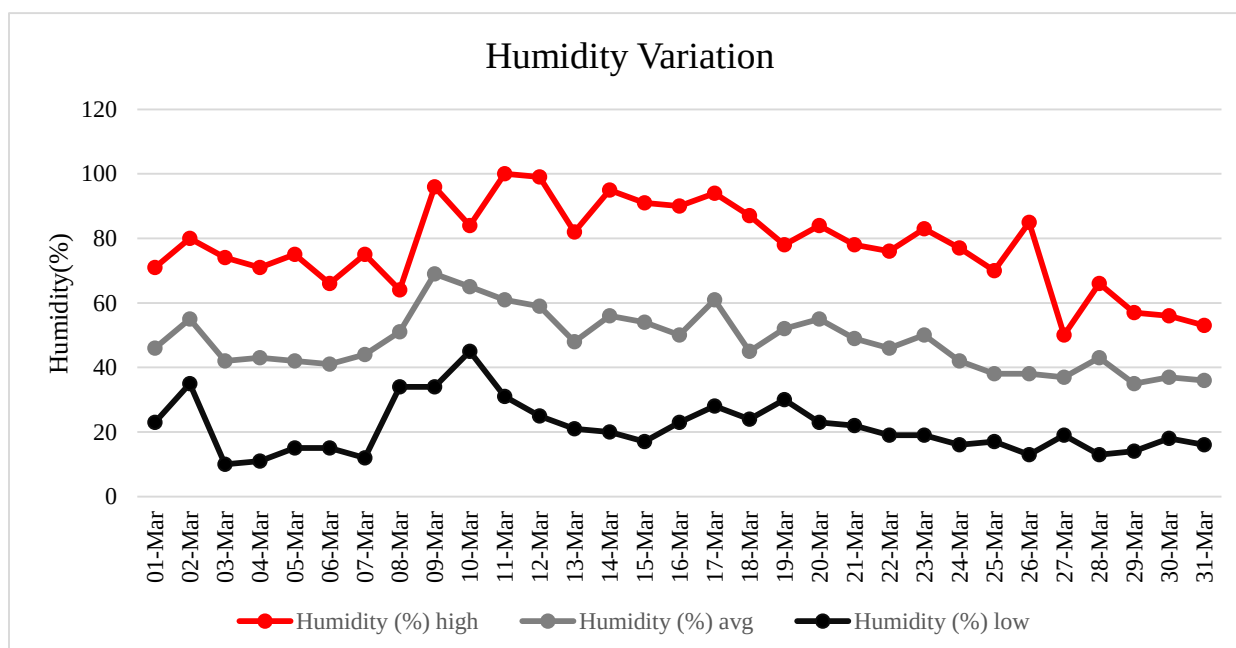


Figure 4.29. Daily relative humidity variation observed in March in New Delhi.



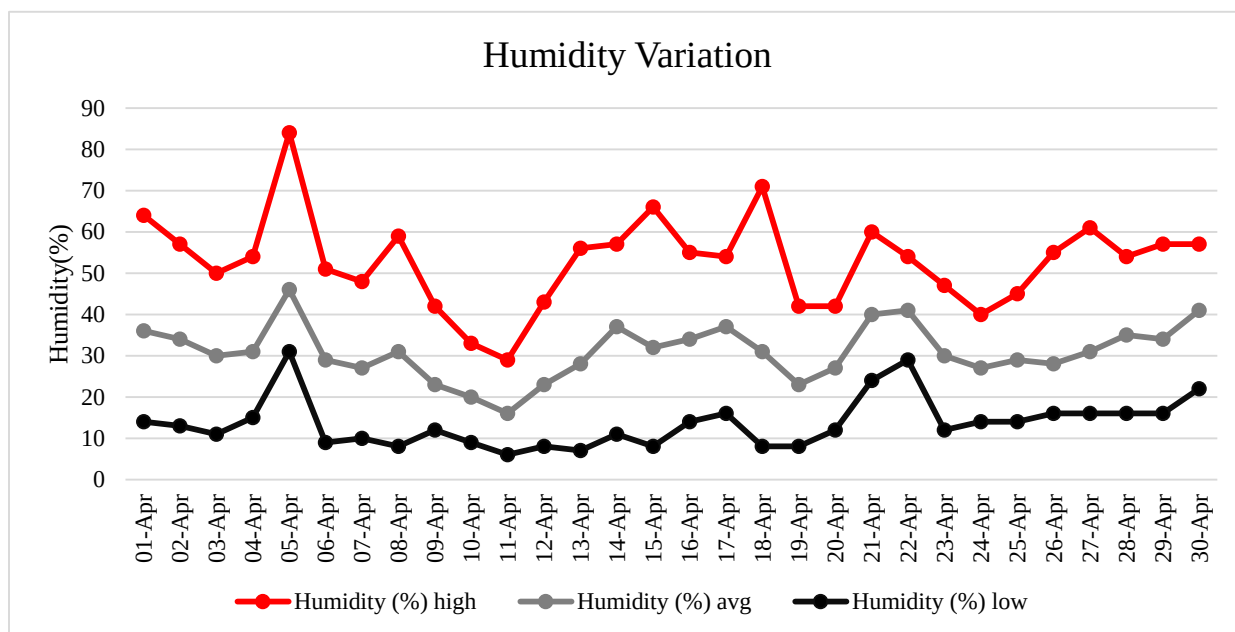


Figure 4.30. Daily relative humidity variation observed in April in New Delhi.

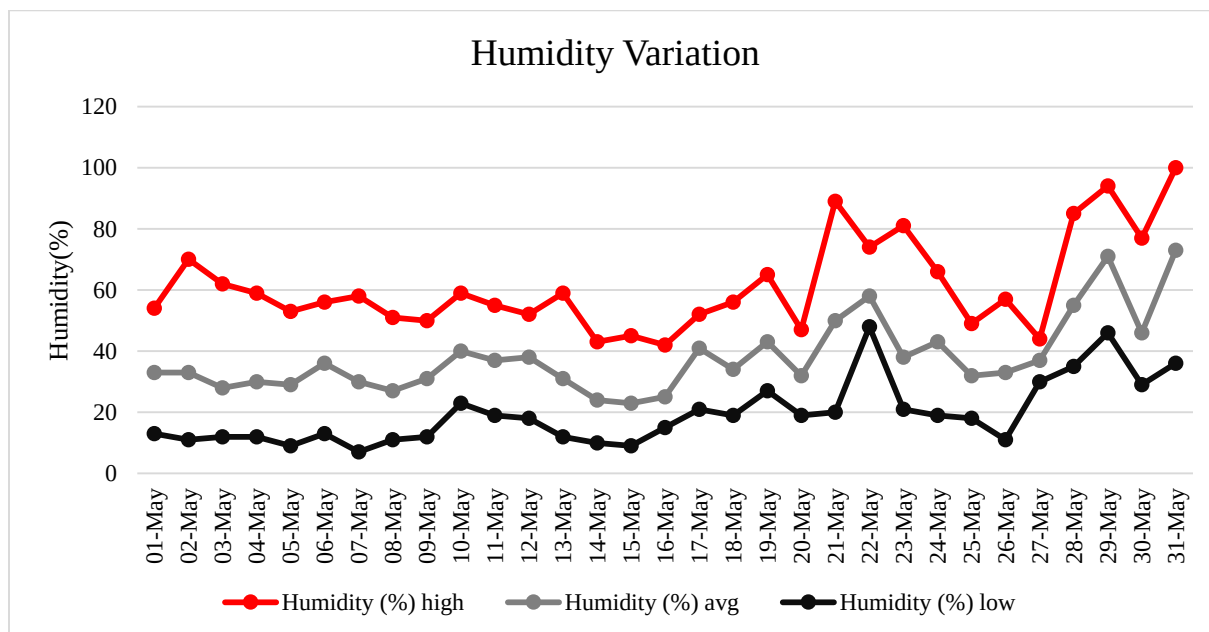
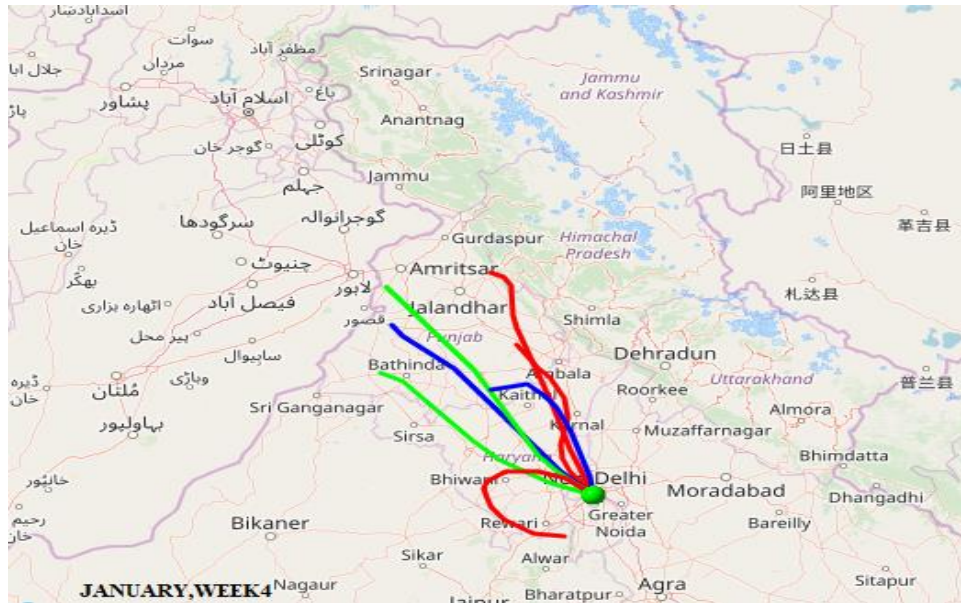
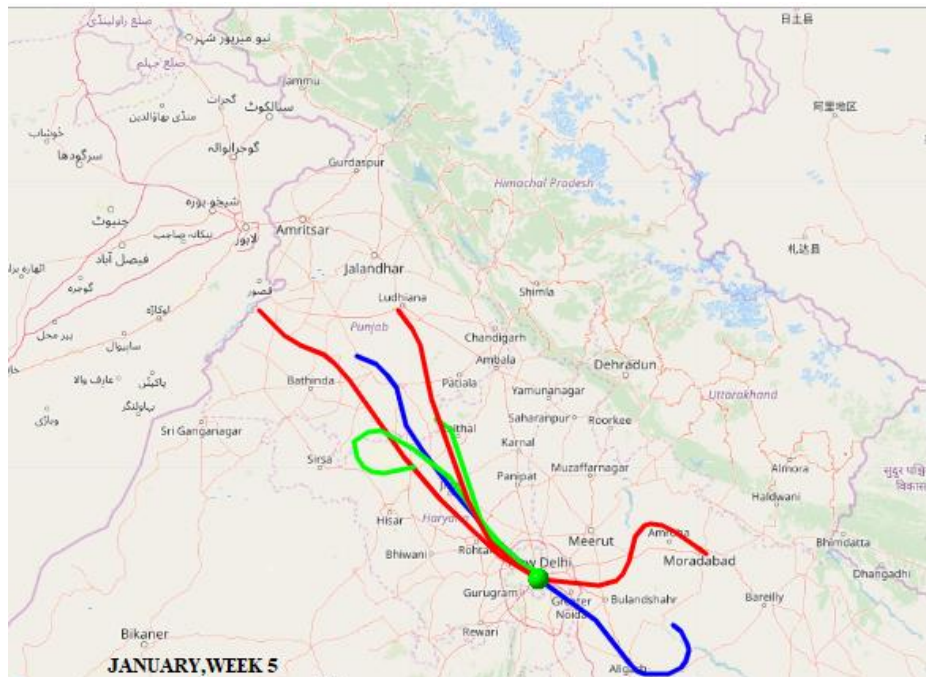


Figure 4.31. Daily relative humidity variation observed in May in New Delhi.

Hysplit Back Trajectory Model



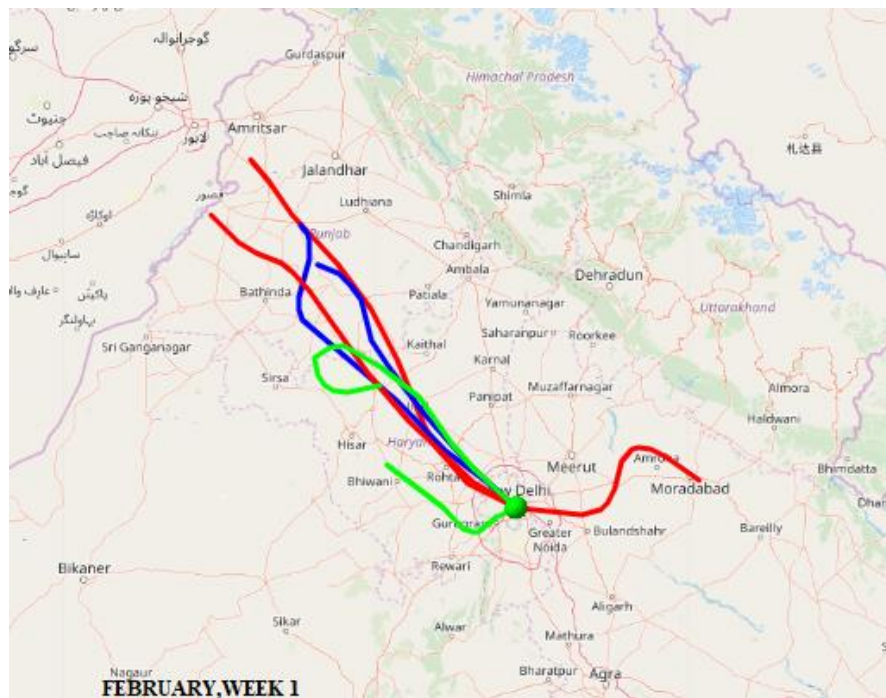
(a)



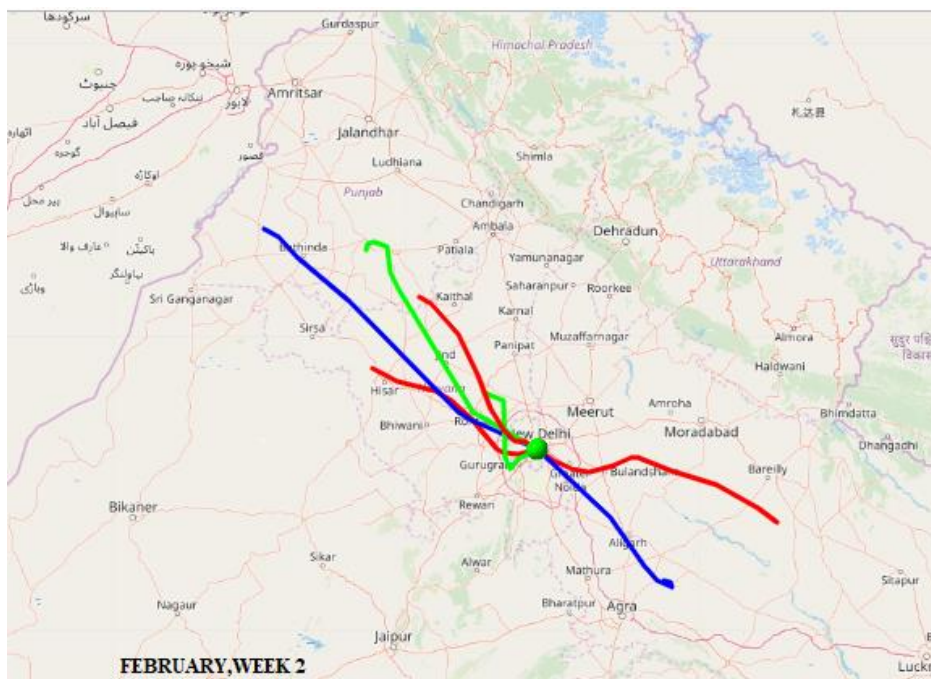
(b)

Figure.4.32. Back trajectory of wind for January for (a) week 4 and (b) week 5.

Source apportionment of ambient particulate matter during winter season in Delhi



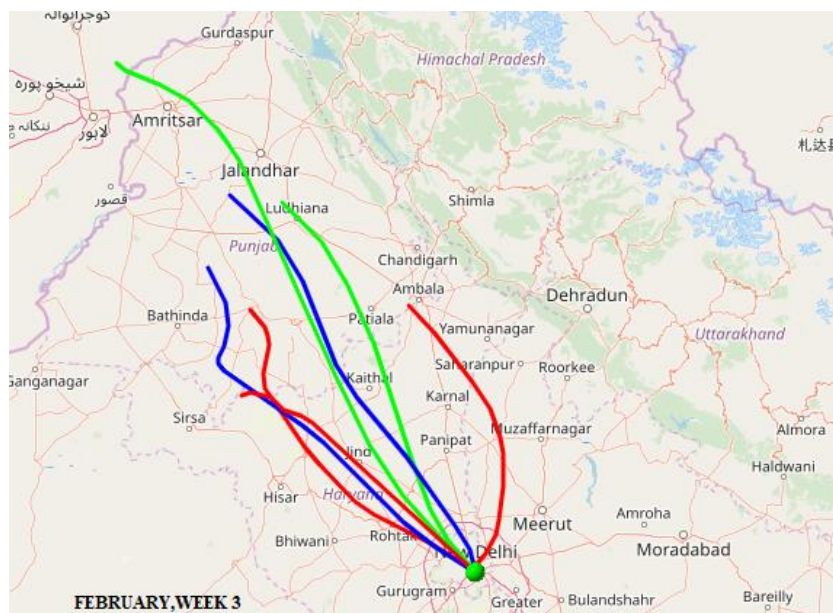
(a)



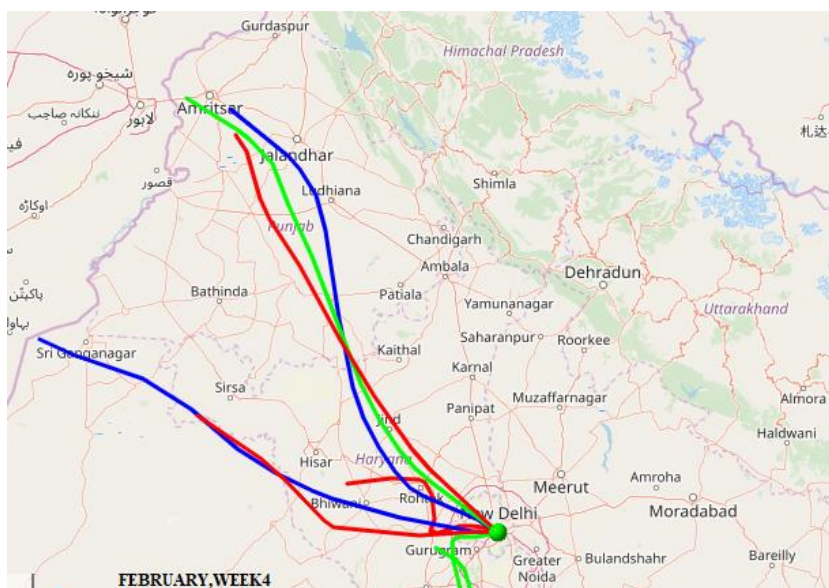
(b)

Figure.4.33. Back trajectory of wind for February for (a) week 1 and (b) week 2

Source apportionment of ambient particulate matter during winter season in Delhi



(c)

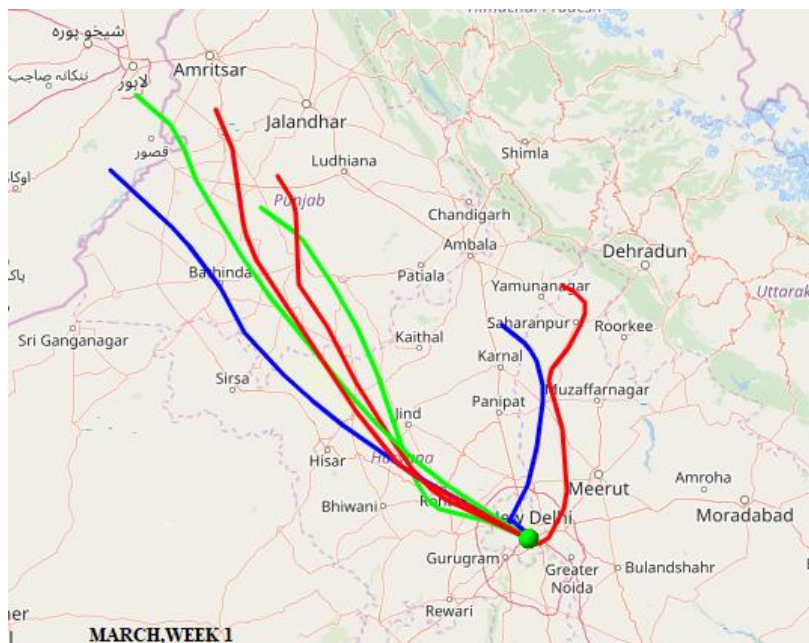


(d)

Figure.4.33. Back trajectory of wind for February for (c) week 3 and (d) week 4.



Source apportionment of ambient particulate matter during winter season in Delhi



(a)

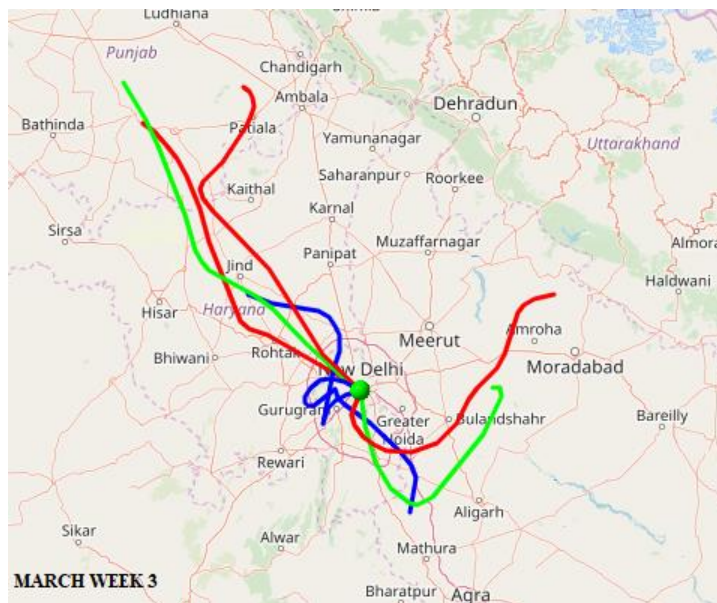


(b)

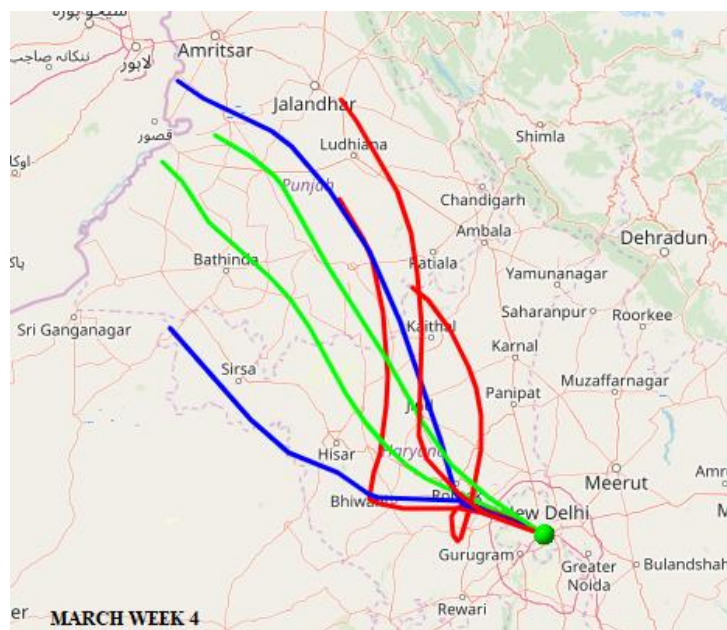
Figure.4.34. Back trajectory of wind for March for (a) week 1 and (b) week 2.



Source apportionment of ambient particulate matter during winter season in Delhi



(c)

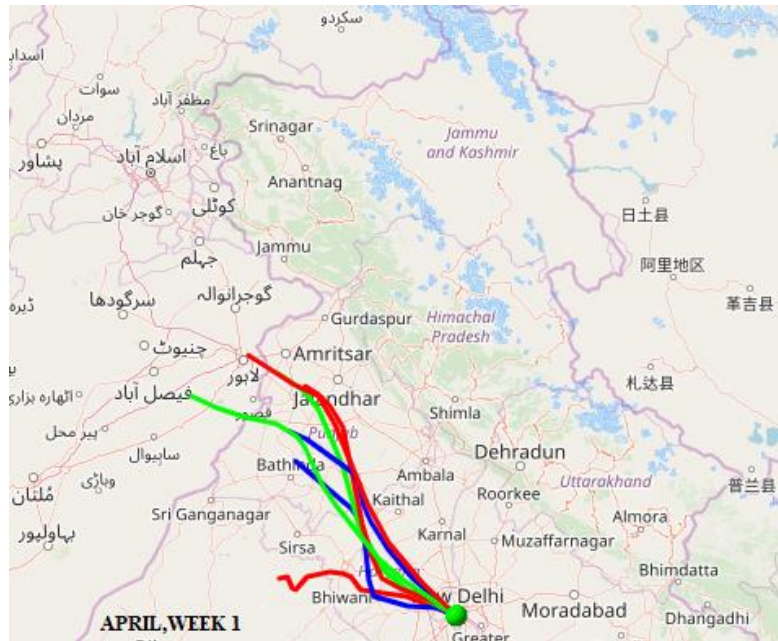


(d)

Figure 4.34. Back trajectory of wind for March for (c) week 3 and (d) week 4.



Source apportionment of ambient particulate matter during winter season in Delhi



(a)



(b)

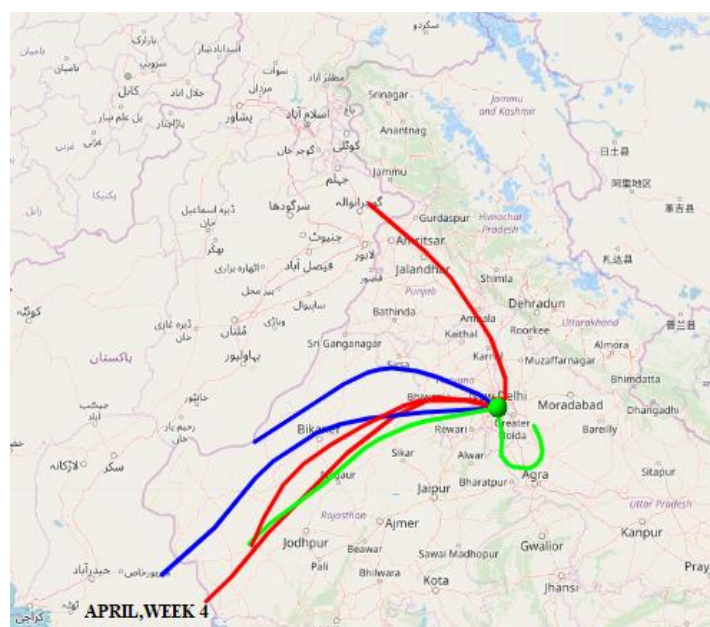
Figure 4.35. Back trajectory of wind for April for (a) week 1 and (b) week 2.



Source apportionment of ambient particulate matter during winter season in Delhi



(c)



(d)

Figure 4.36. Back trajectory of wind for April (c) week 3 and (d) week 4.



HYSPLIT back trajectory model was run for the whole monitoring period (January 4th week to April 4th week) for Delhi city as shown in figures 4.32 to 4.35. The back trajectories indicated predominant winds are blowing from NW and W direction. As wind parcel travels from Punjab, Haryana, and Rajasthan to Delhi, it picks up pollutants, along with the wind parcel.

Despite the ban on biomass burning in Delhi city, the emissions from crop residue burning which is common incidents in the states of Punjab and Haryana during summer months carry away pollutants to Delhi by long-range transport phenomena. However, few cases have also been reported in newspaper articles that biomass burning is carried out by people from lower strata from different locations in the city, especially during winter to prevent themselves from the biting cold.

4.4.2 Correlation among PM₁₀, PM_{2.5}, and meteorological variables

The meteorological parameters were correlated with the PM measurements to understand the influence of meteorology on air pollution at the study areas. The temperature was observed to have a negative correlation with PM except for Punjabi Bagh. This is because the monitoring in Punjabi Bagh was conducted during summer, where the monitoring was done at other locations mainly in winter months. The precipitation events were also found to be affecting reducing PM concentrations. Relative humidity also plays an important role in PM concentration. A negative correlation was observed between concentration and relative humidity. It was found that a lower concentration of PM concentration was observed at high relative humidity and vice versa. The correlation between PM and meteorological parameters are as given in figure 4.36 to 4.50 and table 4.10.



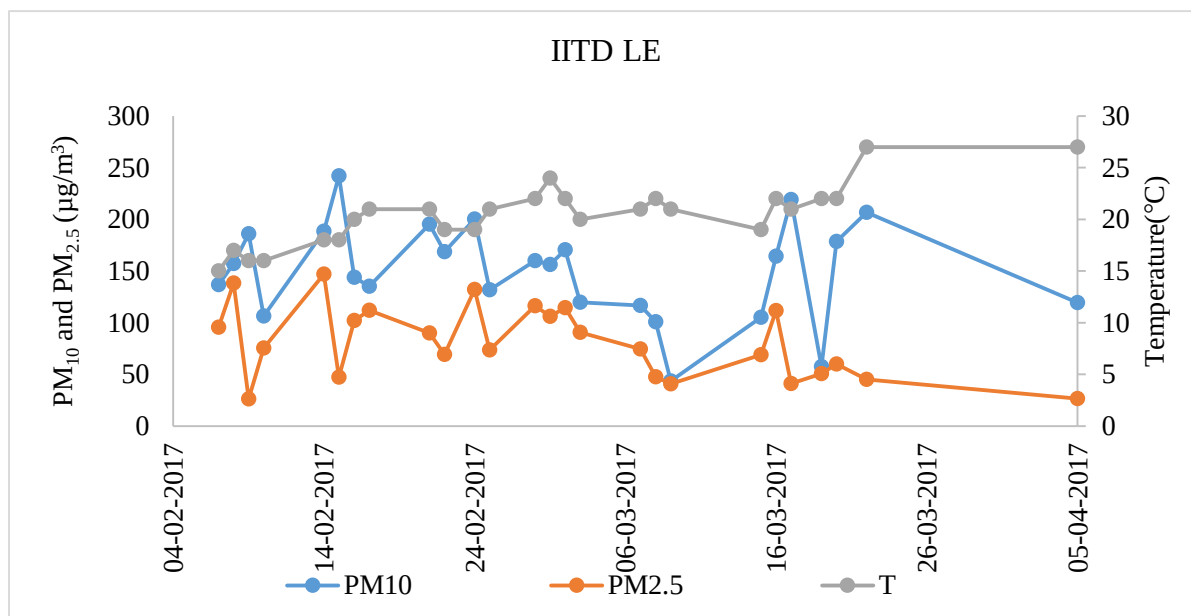
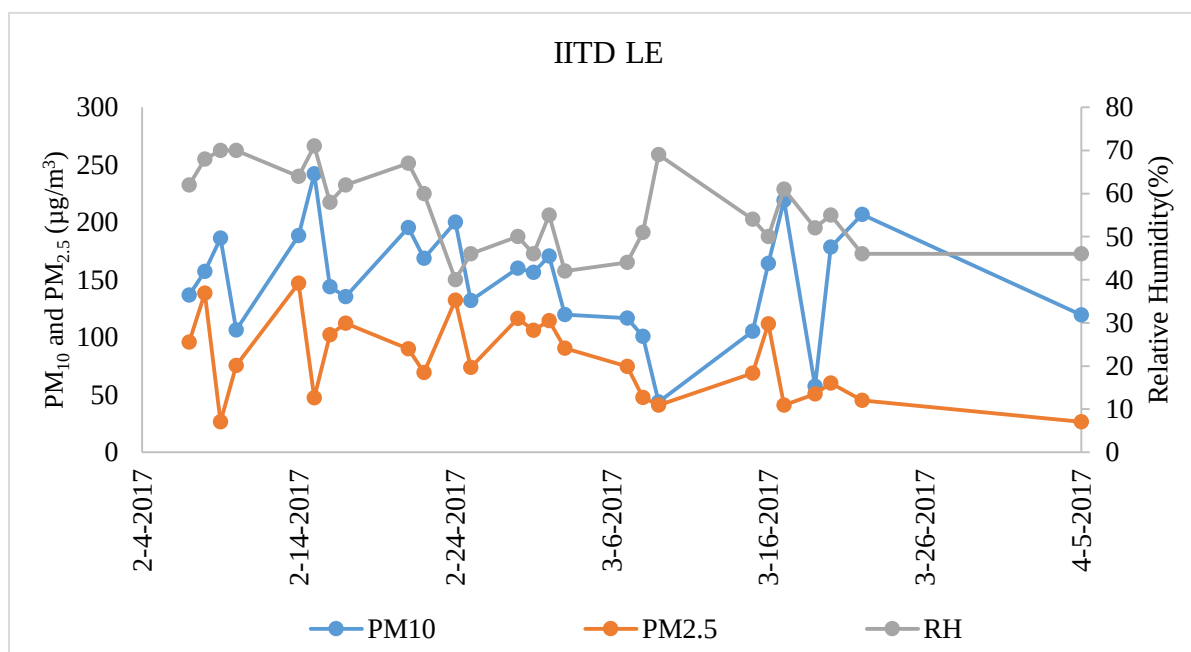


Figure 4.37. Correlation of PM₁₀, PM_{2.5} and Temperature at IIT LE.



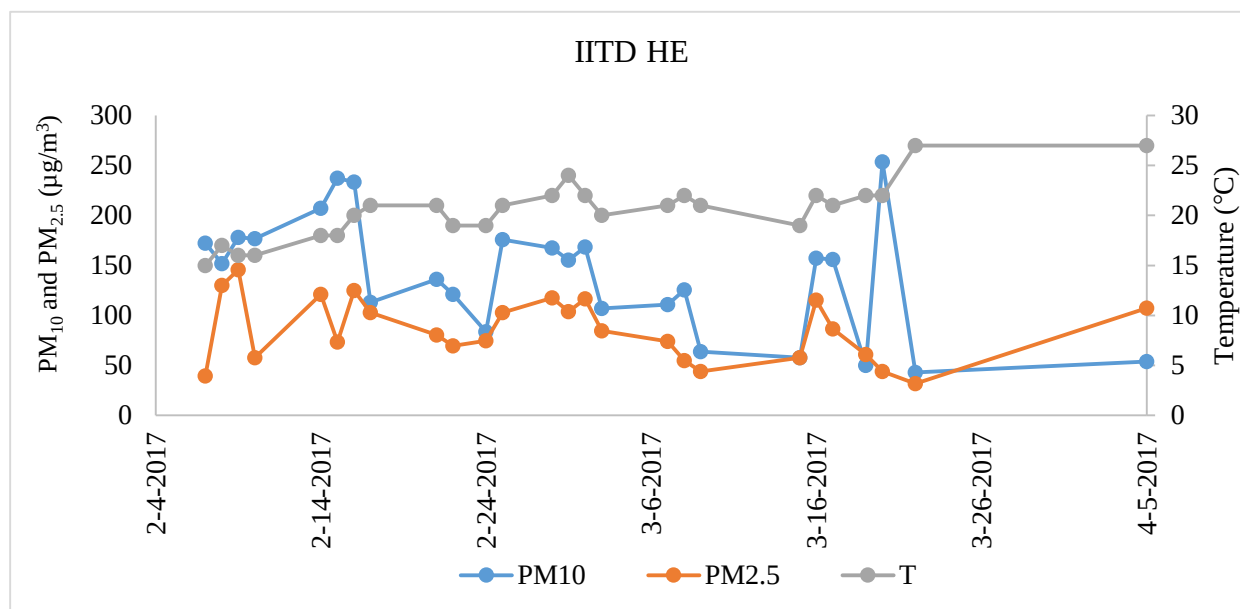


Figure 4.39. Correlation of PM₁₀, PM_{2.5} and Temperature at IIT HE.

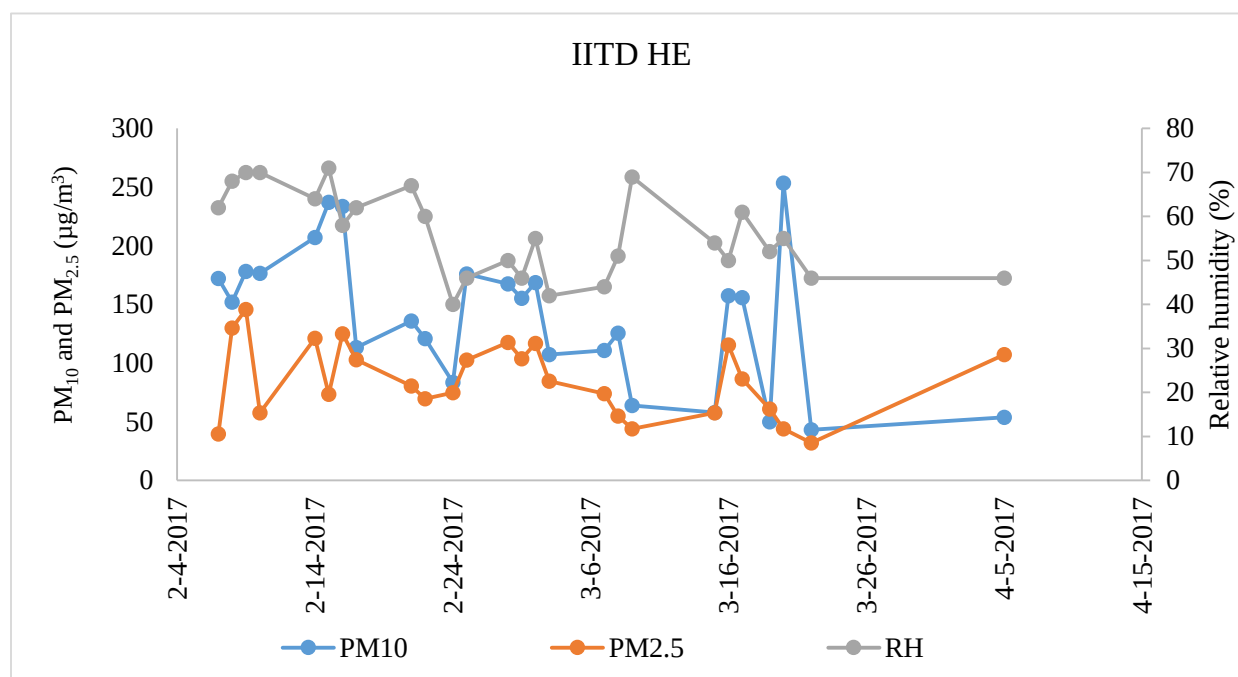


Figure 4.40. Correlation of PM₁₀, PM_{2.5} and Relative Humidity at IIT HE.



Source apportionment of ambient particulate matter during winter season in Delhi

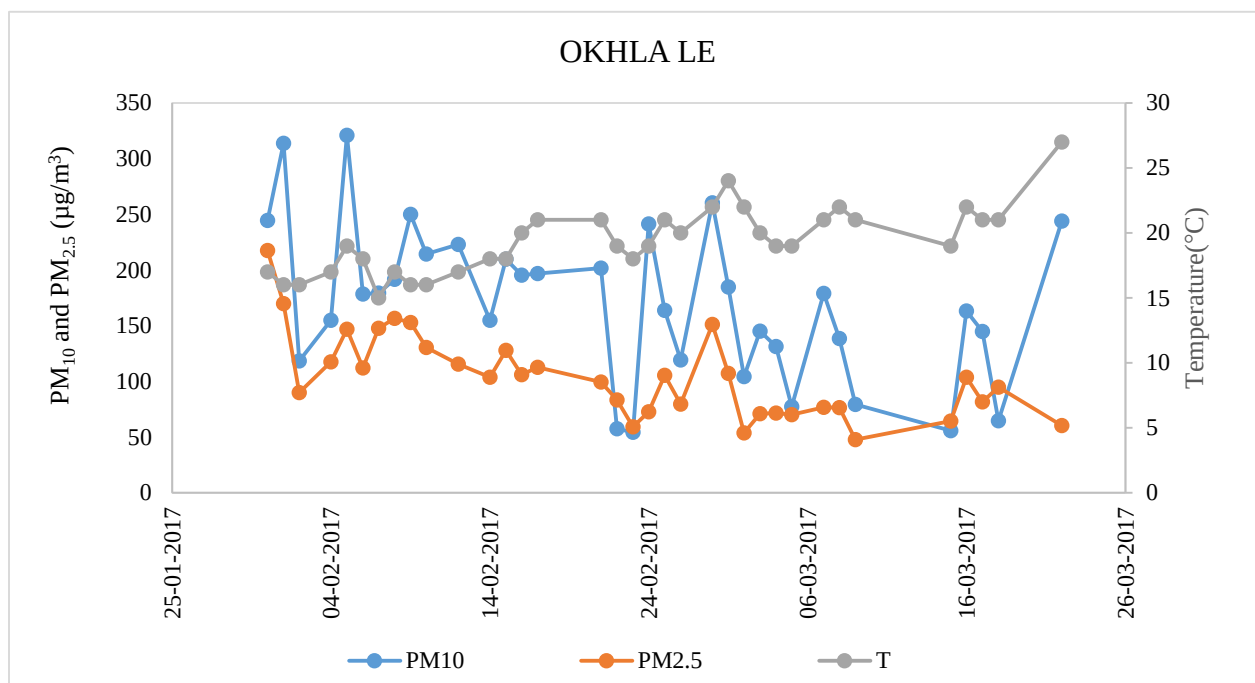


Figure 4.41. Correlation of PM₁₀, PM_{2.5} and Temperature at Okhla LE.

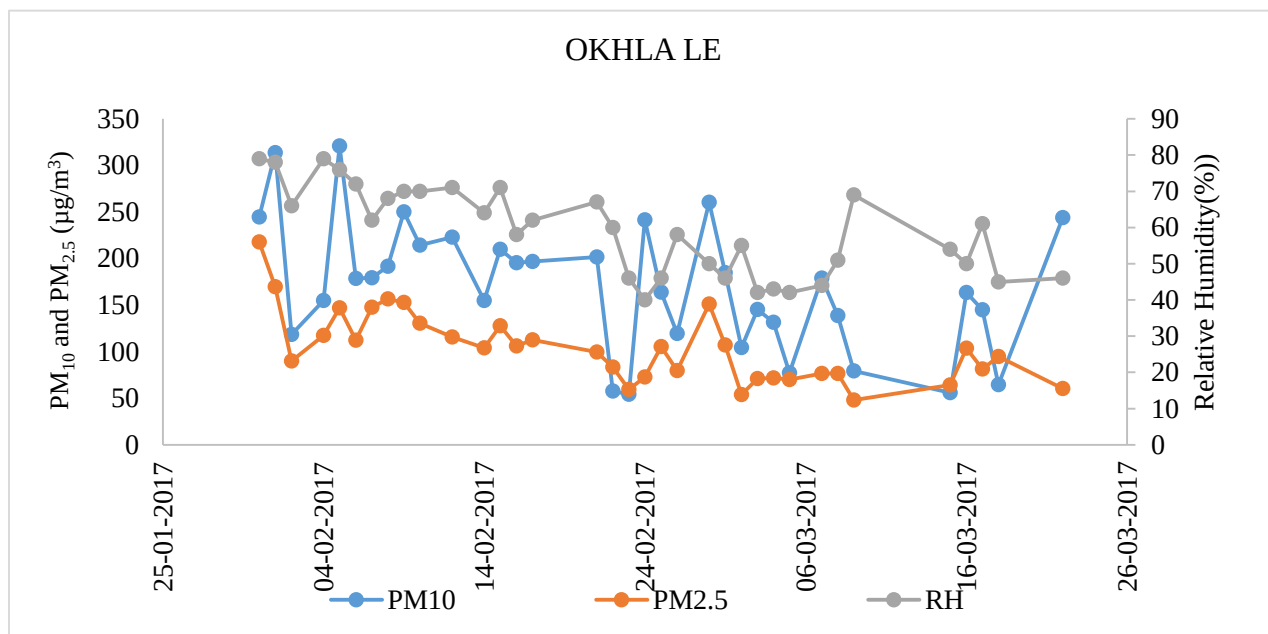


Figure 4.42. Correlation of PM₁₀, PM_{2.5} and Relative Humidity at Okhla LE.



Source apportionment of ambient particulate matter during winter season in Delhi

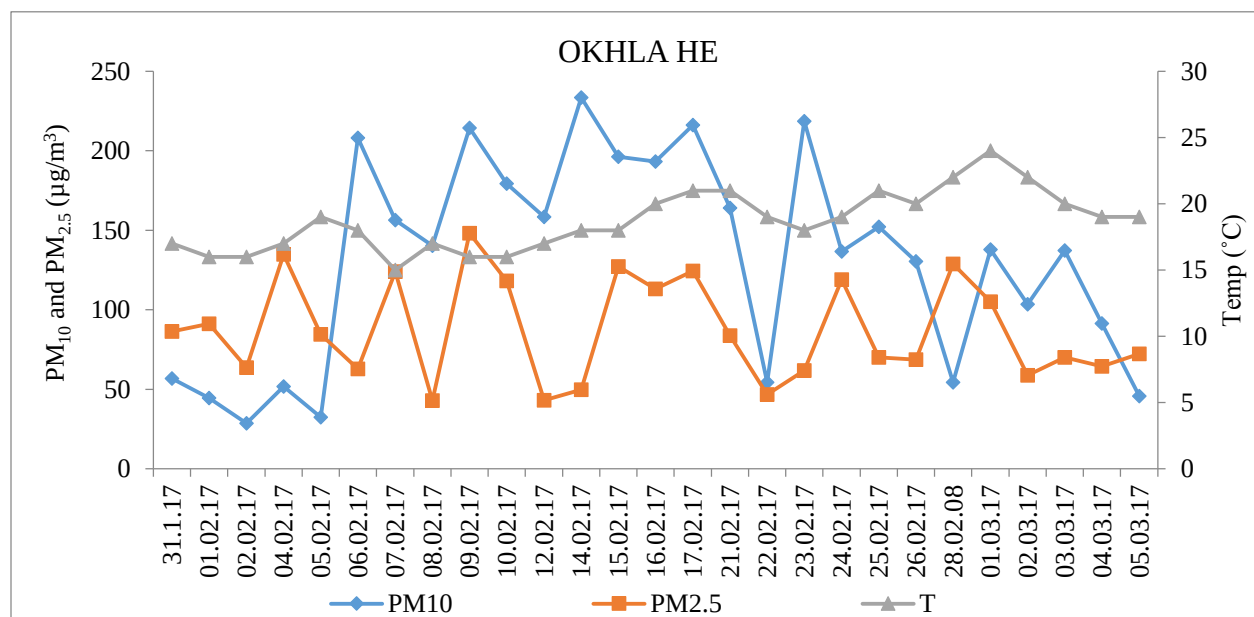


Figure 4.43. Correlation of PM₁₀, PM_{2.5} and Temperature at Okhla HE.

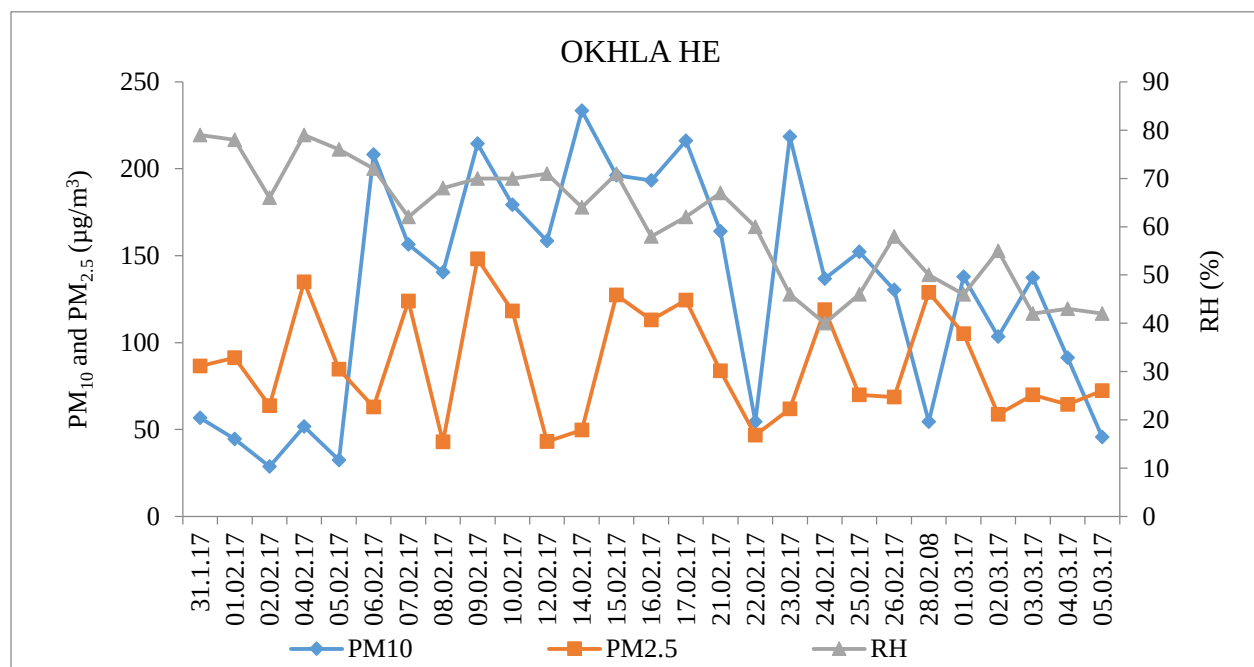


Figure 4.44. Correlation of PM₁₀, PM_{2.5} and Relative Humidity at Okhla HE.



Source apportionment of ambient particulate matter during winter season in Delhi

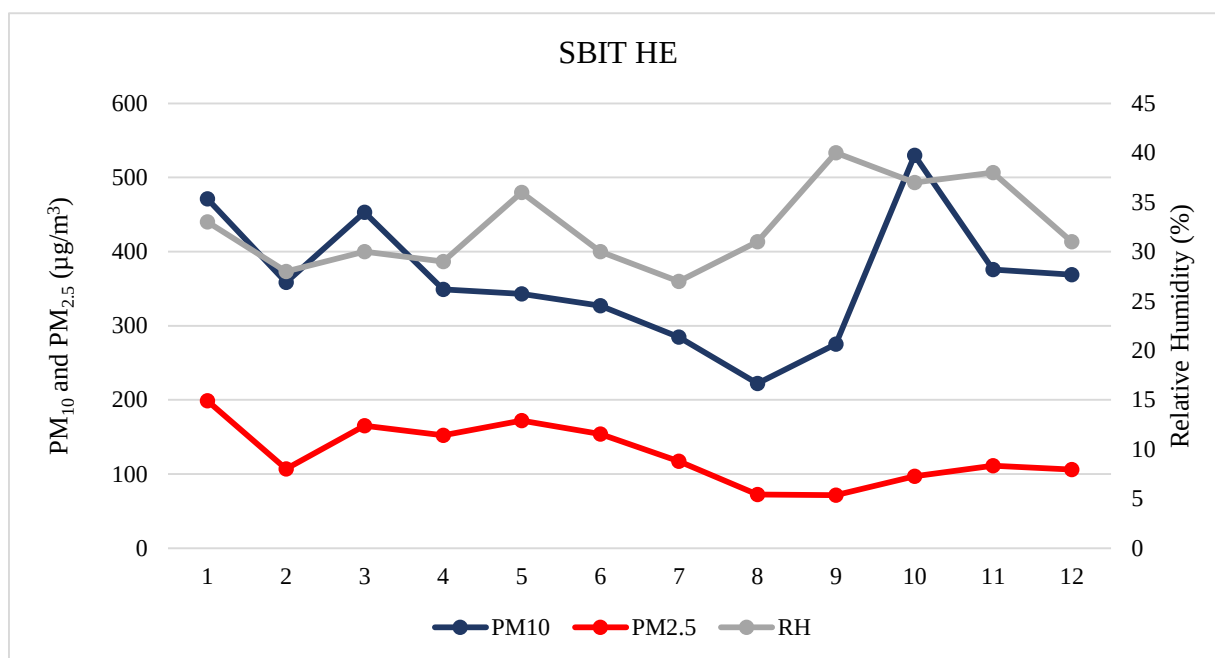


Figure 4.45. Correlation of PM₁₀, PM_{2.5} and Relative humidity at SBIT HE.

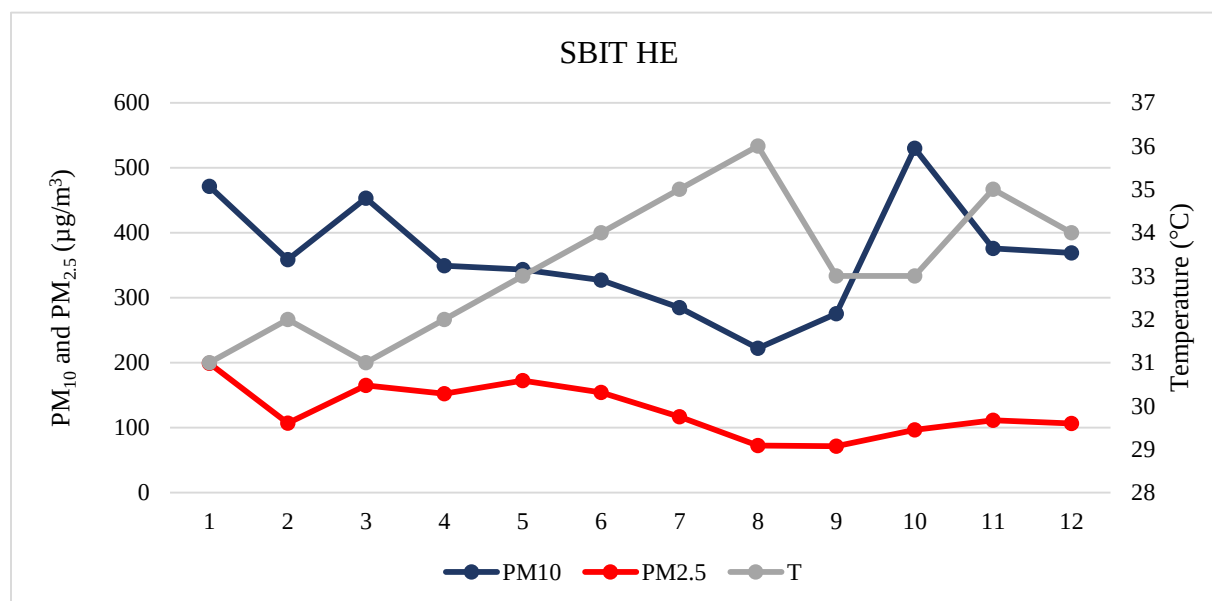


Figure 4.46. Correlation of PM₁₀, PM_{2.5} and temperature at SBIT HE.



Source apportionment of ambient particulate matter during winter season in Delhi

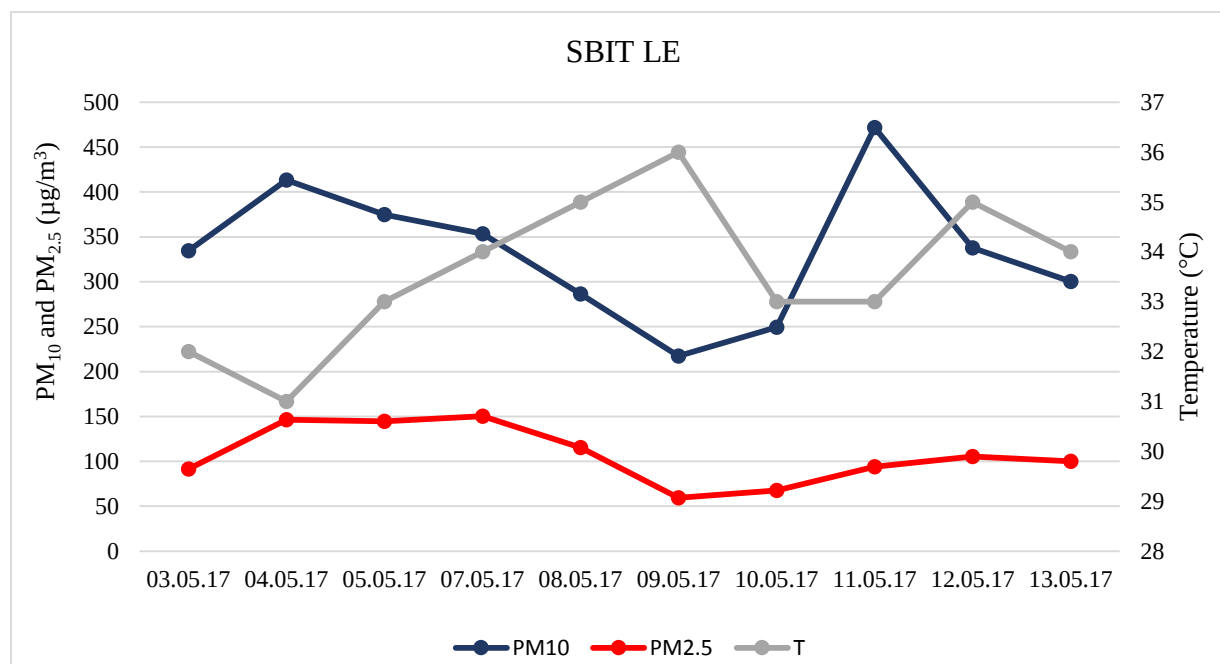


Figure 4.47. Correlation of PM₁₀, PM_{2.5} and Temperature at SBIT LE.

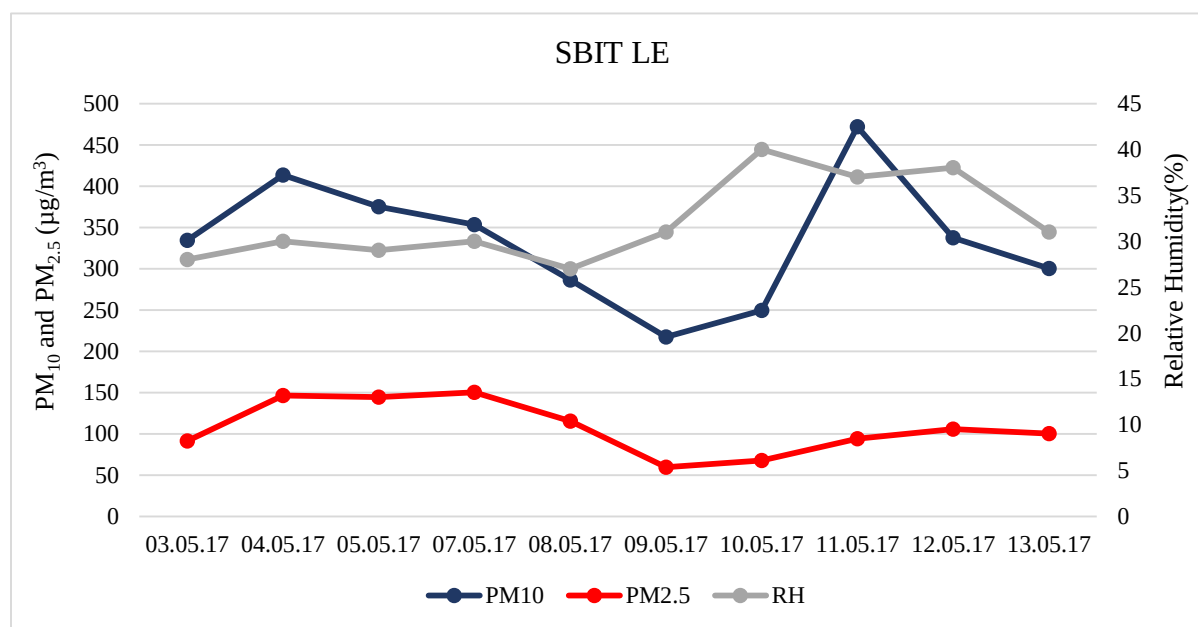


Figure 4.48. Correlation of PM₁₀, PM_{2.5} and Relative Humidity at SBIT LE.



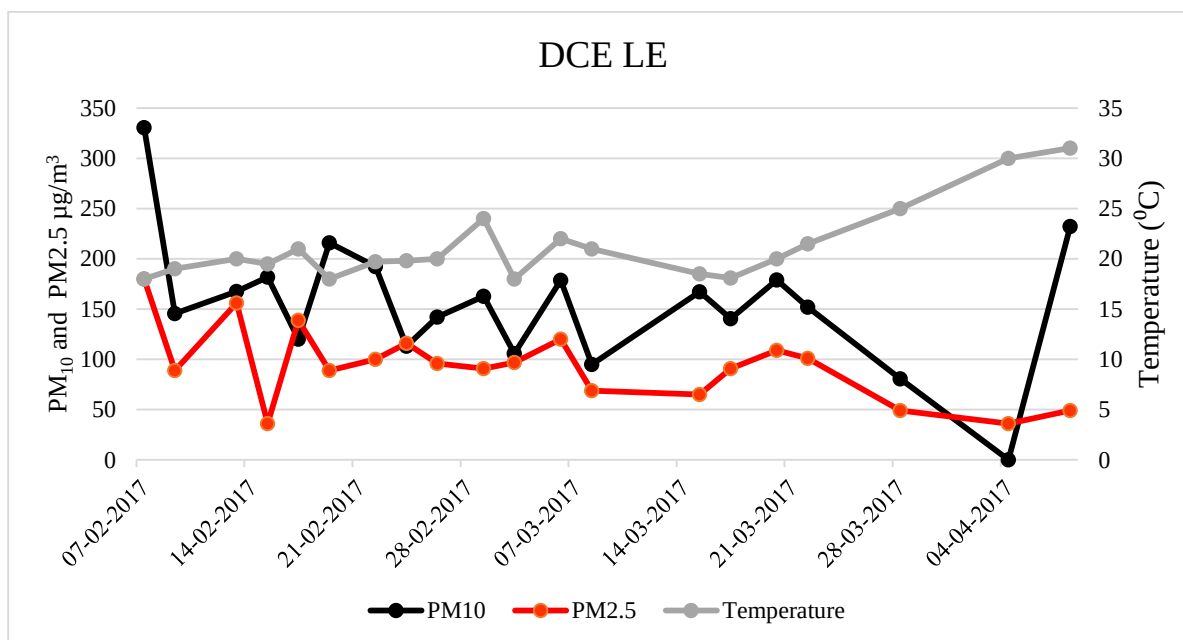


Figure 4.49. Correlation of PM₁₀, PM_{2.5} and Temperature at DCE LE.

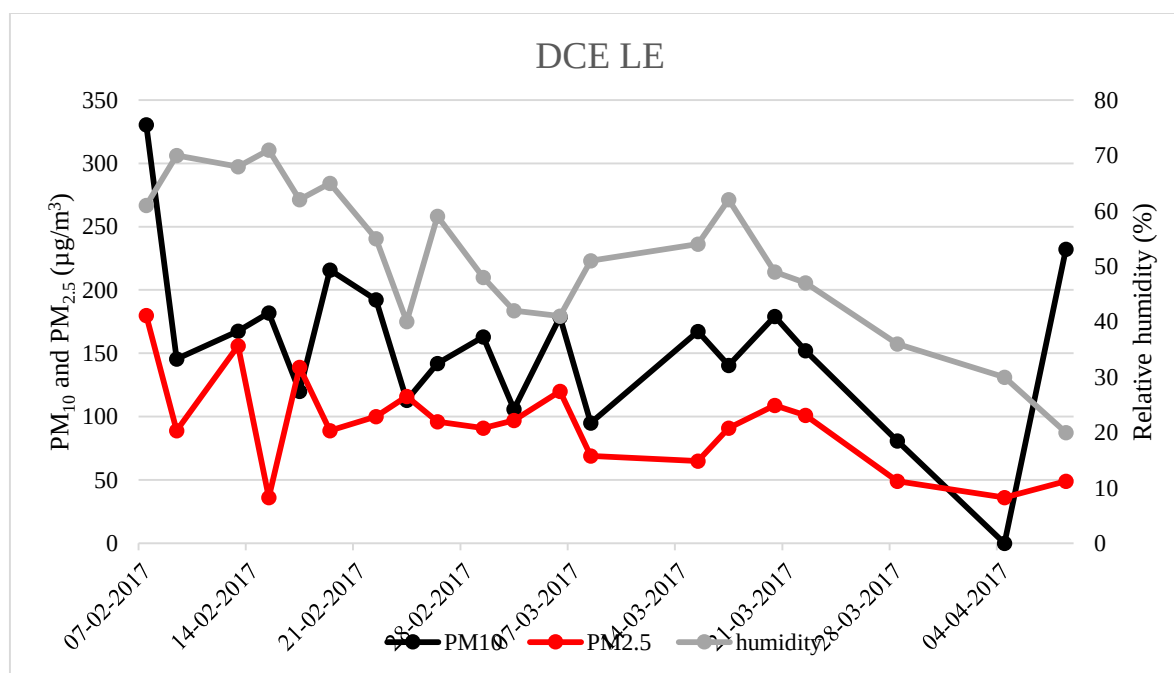


Figure 4.50. Correlation of PM₁₀, PM_{2.5} and Relative Humidity at DCE LE.



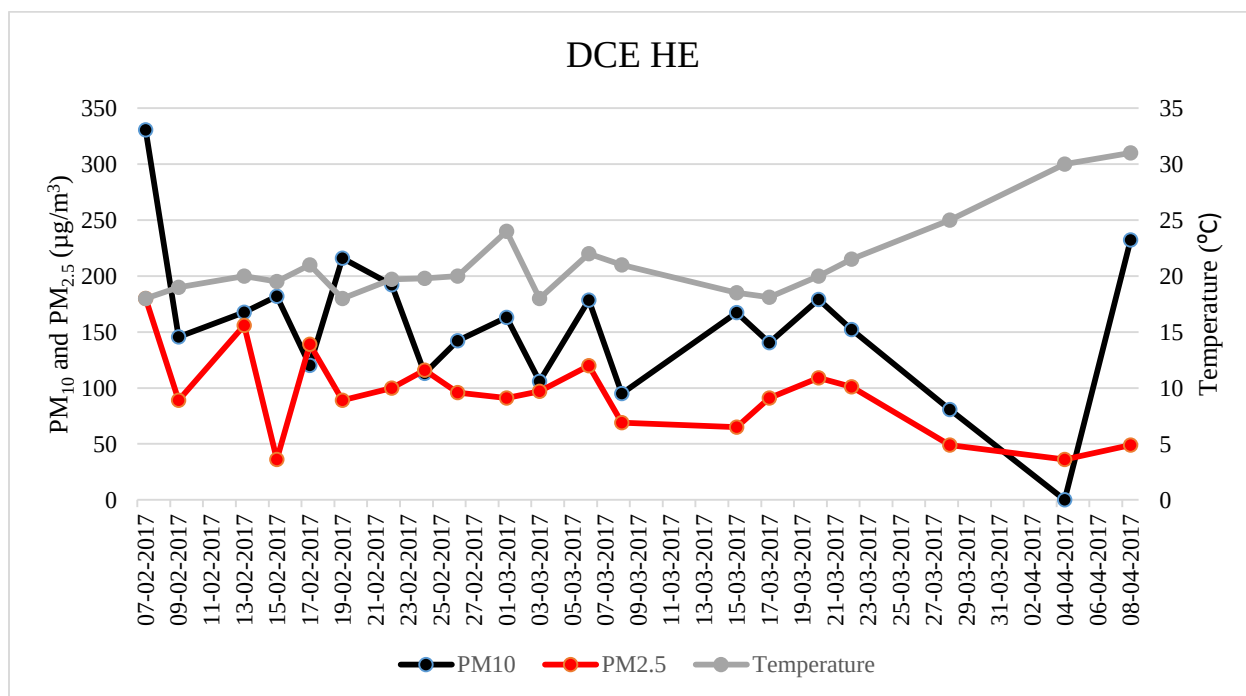


Figure 4.51. Correlation of PM₁₀, PM_{2.5} and Temperature at DCE HE.

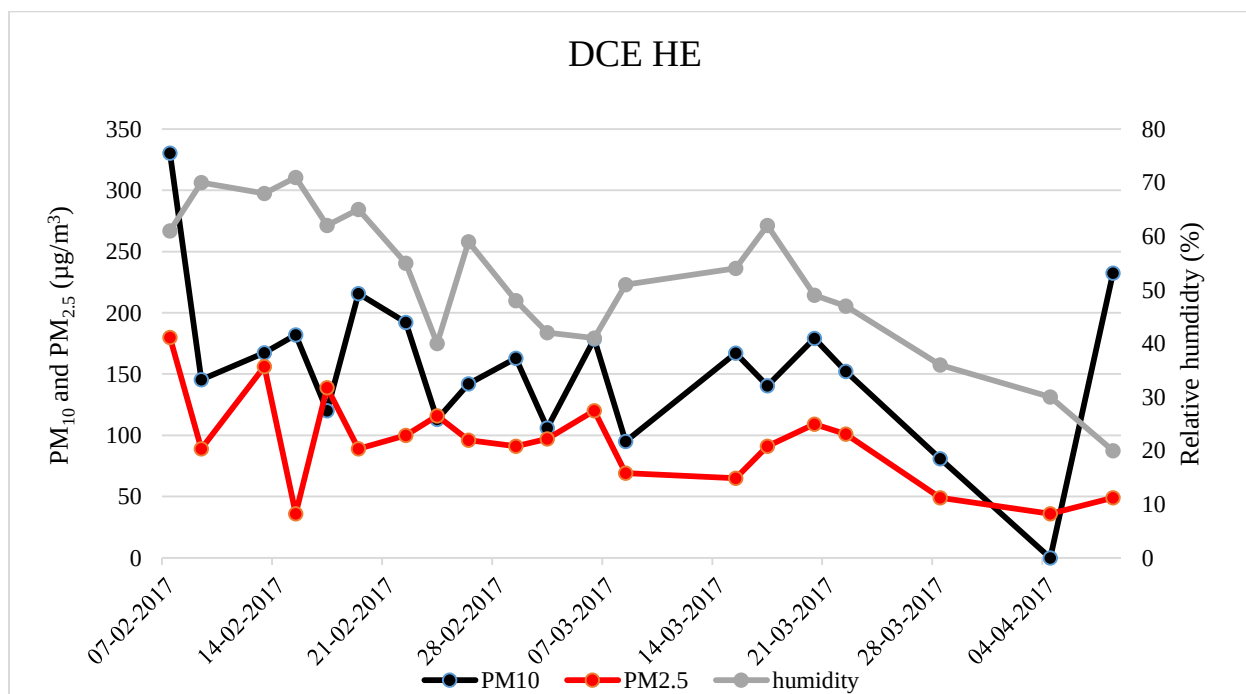


Figure 4.52. Correlation of PM₁₀, PM_{2.5} and Relative Humidity at DCE HE.



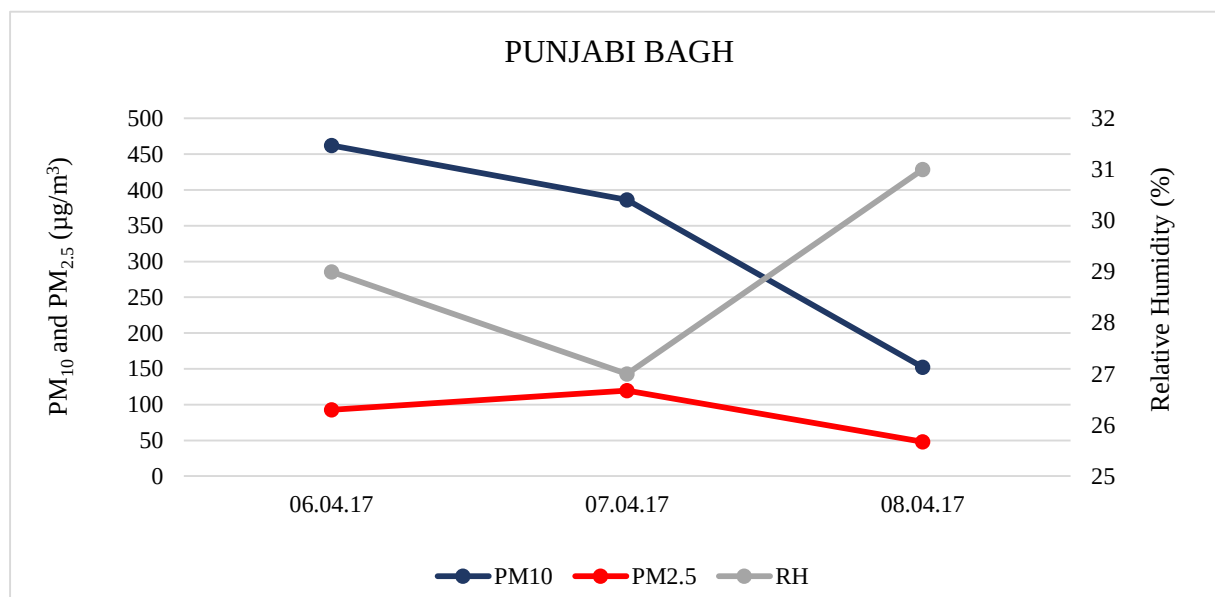


Figure 4.53. Correlation of PM₁₀, PM_{2.5} and Temperature at Punjabi Bagh.

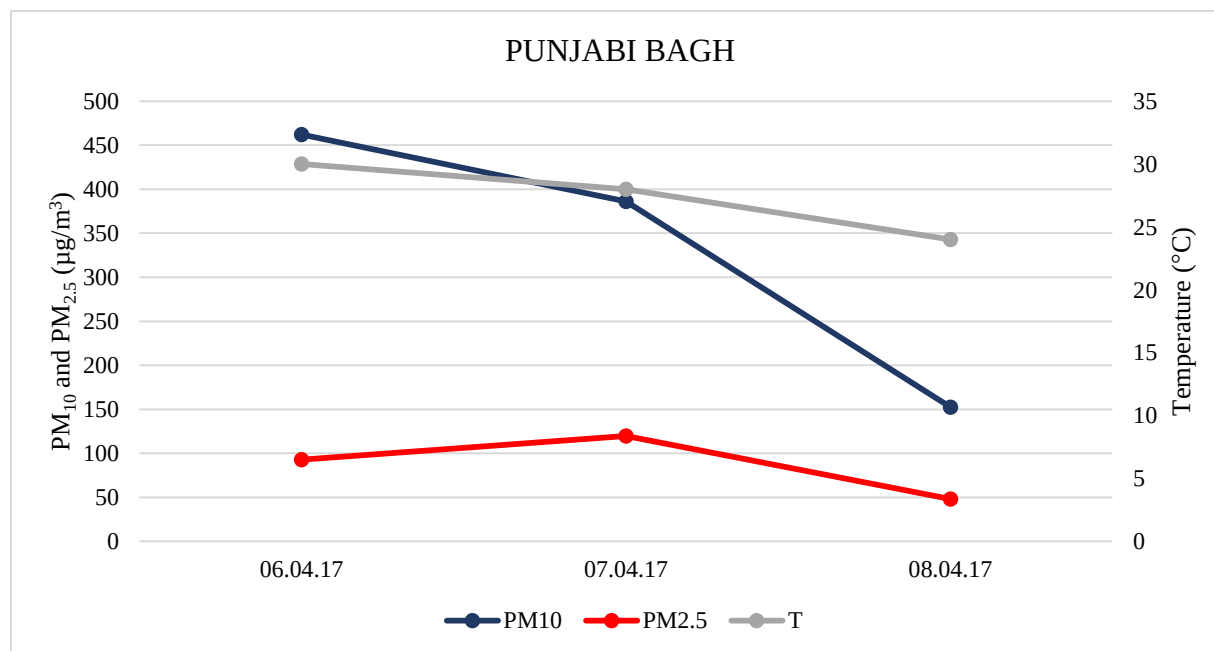


Figure 4.54. Correlation of PM₁₀, PM_{2.5} and Relative humidity at Punjabi Bagh.



Table 4.10: Correlation coefficients of different variables for different monitoring locations.

Variables	IIT LE	IIT HE	OKHLA LE	OKHLA HE	ANVT	DCE LE	DCE HE	SBIT LE	SBIT HE	PB
PM ₁₀ , PM _{2.5}	0.34	0.53	0.73	0.120	NA	0.02	0.15	0.57	0.44	0.81
PM ₁₀ ,T	-0.05	-0.11	-0.11	0.01	0.75	0.26	-0.02	-0.59	-0.63	0.99
PM ₁₀ ,RH	0.035	0.09	0.33	-0.06	-0.72	-0.26	-0.08	0.033	0.17	-0.72
PM ₁₀ ,WS	-0.07	-0.21	-0.15	0.35	-0.07	-0.14	-0.07	-0.17	-0.21	0.68
PM ₁₀ , Rain	-0.56	-0.46	-0.330	No rainfall	No rainfall	-0.06	-0.26	-0.140	-0.13	No Rainfall
PM _{2.5} ,T	-0.12	-0.11	-0.46	-0.04	NA	-0.51	-0.2	-0.367	-0.61	0.76
PM _{2.5} ,RH	-0.20	-0.02	0.53	0.13	NA	0.34	0.19	-0.454	-0.23	-0.99
PM _{2.5} ,WS	-0.21	-0.39	-0.37	0.17	NA	0.03	-0.19	-0.020	-0.28	0.14
PM _{2.5} , Rain	-0.41	-0.45	-0.37	No rainfall	NA	-0.03	-0.22	-0.332	-0.31	No Rainfall

4.5 Chemical characterization of PM_{2.5} samples

The elemental, ionic and EC-OC analysis were carried out for the PM_{2.5} filter papers, and the results are discussed in the following sections.

4.5.1 Elemental analysis of PM_{2.5} samples

The PM samples collected at different locations of two elevations were analyzed semiquantitatively for elements using energy dispersive X-ray fluorescence (ED-XRF) (PANalytical Epsilon 5). The results are as shown in the following figures (Figures 4.52 to 4.56). All the results are blank corrected.



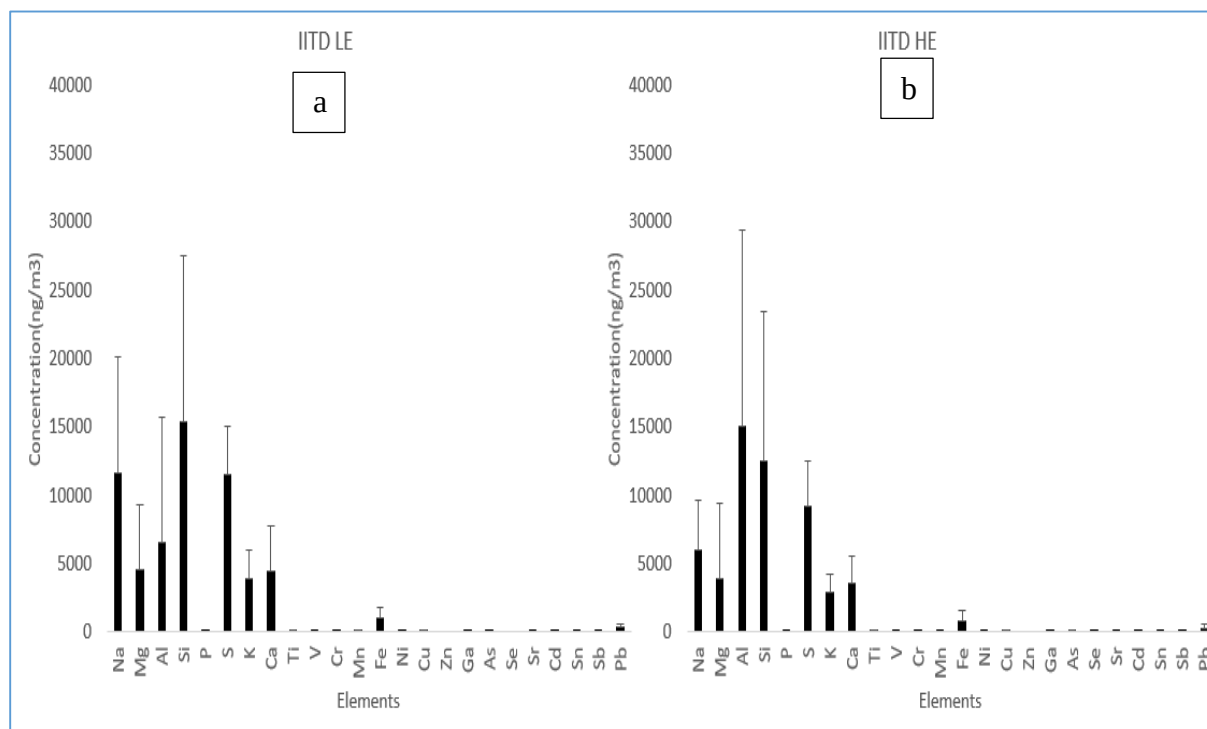


Figure 4.55. Elemental concentrations in the $PM_{2.5}$ collected at (a) lower elevation (b) higher elevation at IIT Delhi.

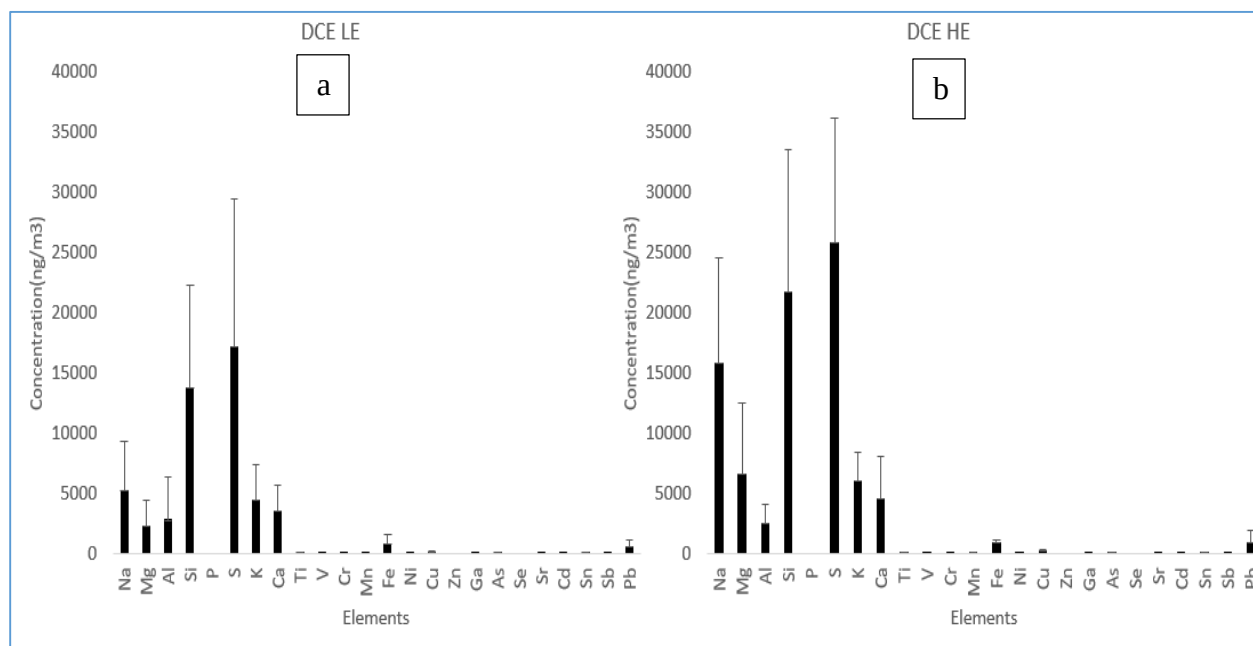


Figure 4.56. Elemental concentrations in the $PM_{2.5}$ collected at (a) lower elevation (b) higher elevation at DCE.



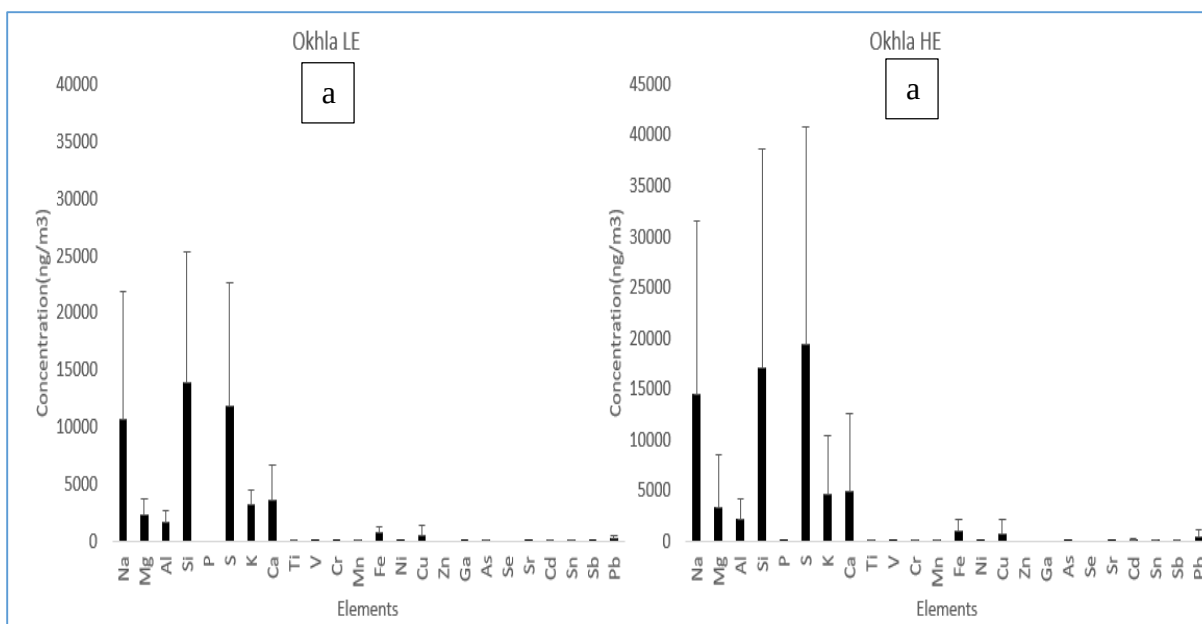


Figure 4.57. Elemental concentrations in the PM_{2.5} collected at (a) lower elevation (b) higher elevation at Okhla.

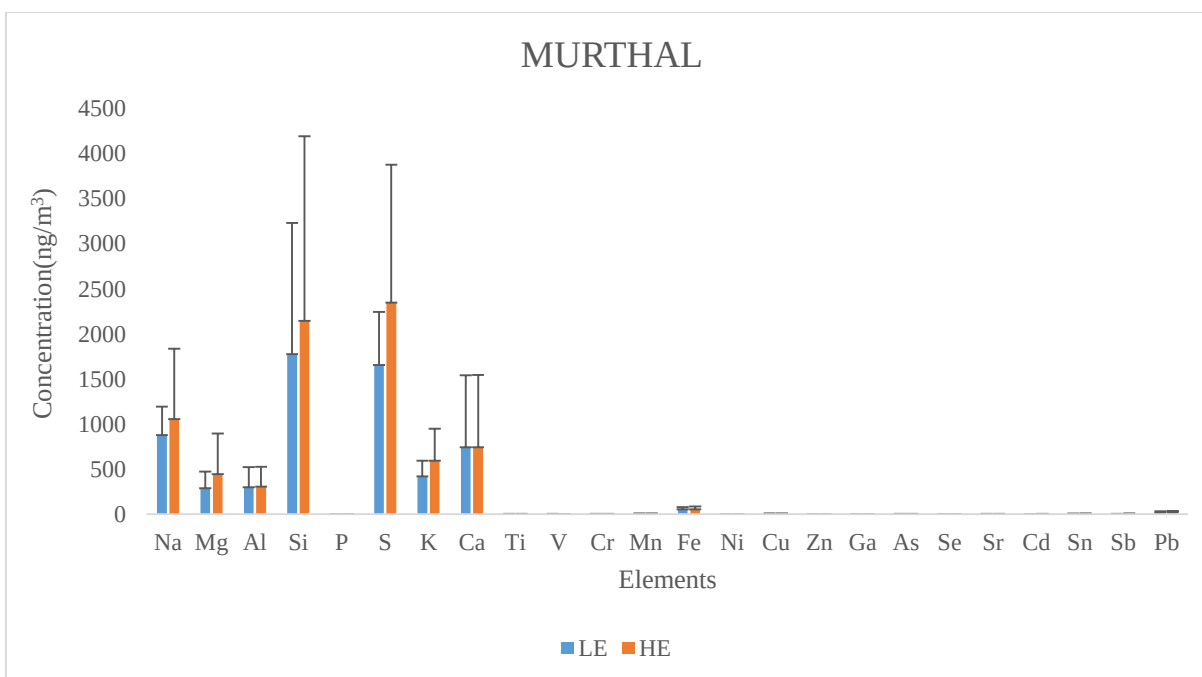


Figure 4.58. Elemental concentrations in the PM_{2.5} collected at elevation wise at Murthal.

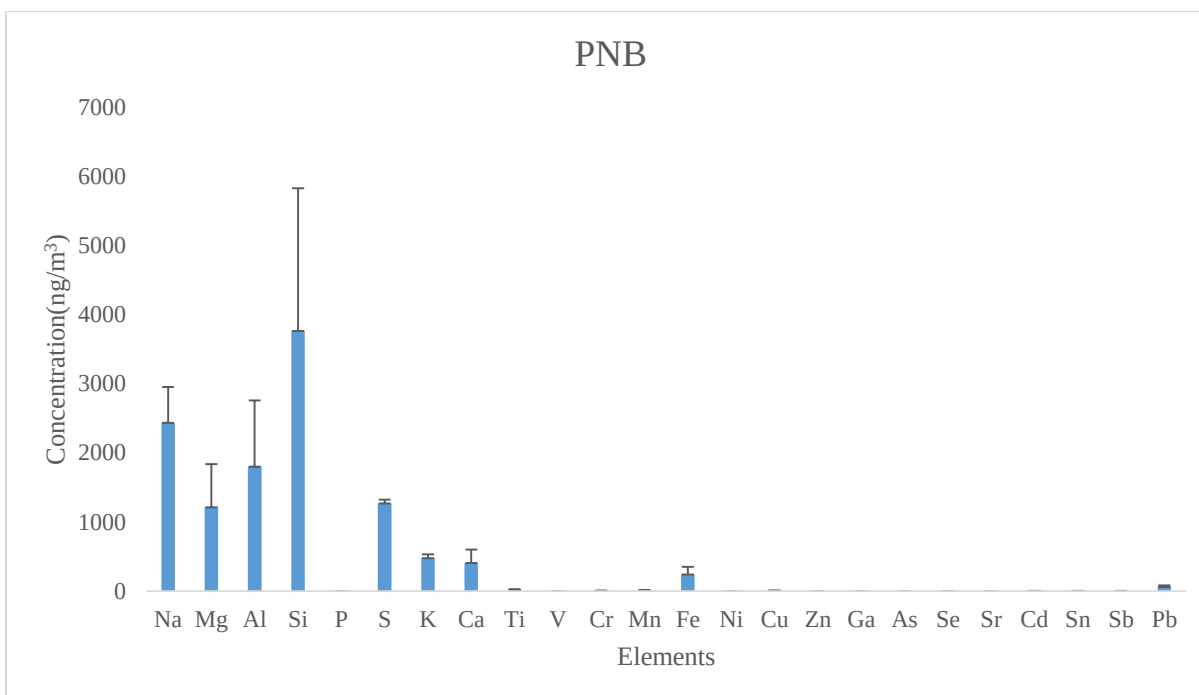


Figure 4.59. Elemental concentrations in the PM_{2.5} collected at elevation wise at PNB.

Na, Mg, S, Si, and Al in PM_{2.5} were found to be the most abundant elements in all the locations. The concentrations of the most of the elements except few elements like Mg were higher in lower elevation as compared to higher elevation. This indicates the contribution of re-suspended dust to the elemental concentration. The presence of several toxic elements including Pb and Fe were also observed. Previous studies were also reported that the elements Si, Ca, S etc., which are generally associated with soil/mineral dust and Fe, Pb and Br with diesel vehicles. Several elements are used as markers for various sources such as Pb and K for biomass burning (Cheng et al., 2013). Al, Si, Ca, Ti, Mn and Fe for crustal dust/soil (Cass, 1998; Chow et al., 2004; Viana et al., 2008; Pant and Harrison, 2012; Tiwari et al., 2013), As and Pb to be emitted from waste burning (Watson et al., 2008). V and Ni are associated with industrial emissions as well as oil combustion (Viana et al., 2008). Pb, Fe, Zn and K have also been associated with industrial emissions (Sahu et al., 2011; Moreno et al., 2013; Patil et al., 2013;). K and Br have also been reported from wood smoke (Kleeman et al., 1999; Fine et al., 2001) while Zn has been associated with incineration (Harrison et al., 1997; Moreno et al., 2013) and industrial burning (Duvall et al., 2012). Pb and Mg are also reported to be emitted from kerosene combustion (Patil et al., 2013). Elements such as Cu, Ba, Sb, and Sn have been associated with brake wear (Pant and Harrison, 2013).



4.5.2 Ionic analysis of PM_{2.5} samples

In Delhi city, Cl⁻ and SO₄²⁻ were found to be the most abundant ions (figure 4.57). The abundance of Cl⁻ might be an indication of solid waste burning or open burning (Patil et al., 2013). Earlier studies have reported higher Cl⁻ ion concentration in Delhi city especially during the winter season (Sudheer et al., 2014; Tiwari et al., 2013). The Cl⁻ concentration is found to be higher in lower elevation. Thus it can be inferred that the open burning might be contributing to the Cl⁻ concentration. The SO₄²⁻ and NO₃⁻ ions indicates the presence of secondary aerosols in the study site. K⁺ is found to be in trace quantity in PM_{2.5}.

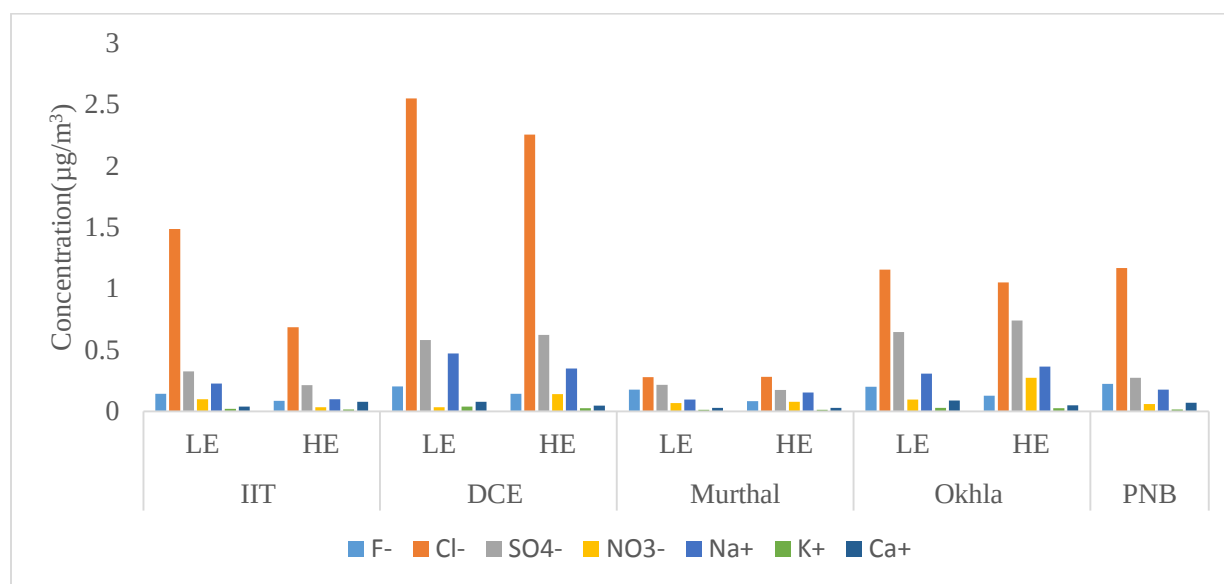


Figure 4.60. Concentration of PM_{2.5}-bound ions at elevation wise at different locations in Delhi city.

4.6 Chemical characterization of PM₁₀ samples

The elemental, ionic analysis was carried out for the PM₁₀ filter papers, and the results are discussed in the following sections.

4.6.1 Elemental analysis of PM₁₀ samples

The Glass fiber filter samples collected from each location for two elevations were analyzed semi quantitatively for elements using energy dispersive X-ray fluorescence (ED-XRF) (PANalytical Epsilon 5). The results are as shown in the following figures (Fig 4.58 to 4.6). All the results are blank corrected.



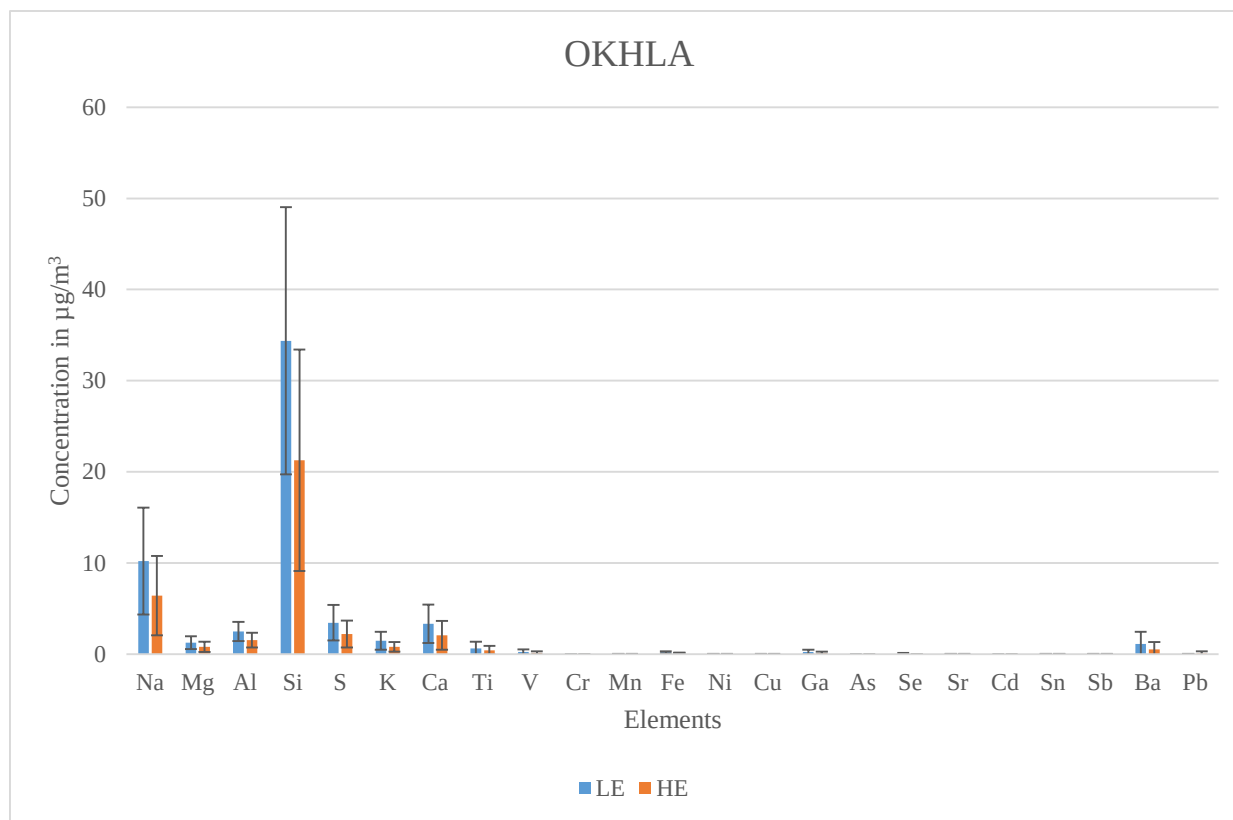


Figure 4.61. Elemental concentrations in the PM₁₀ collected at elevation wise at Okhla.

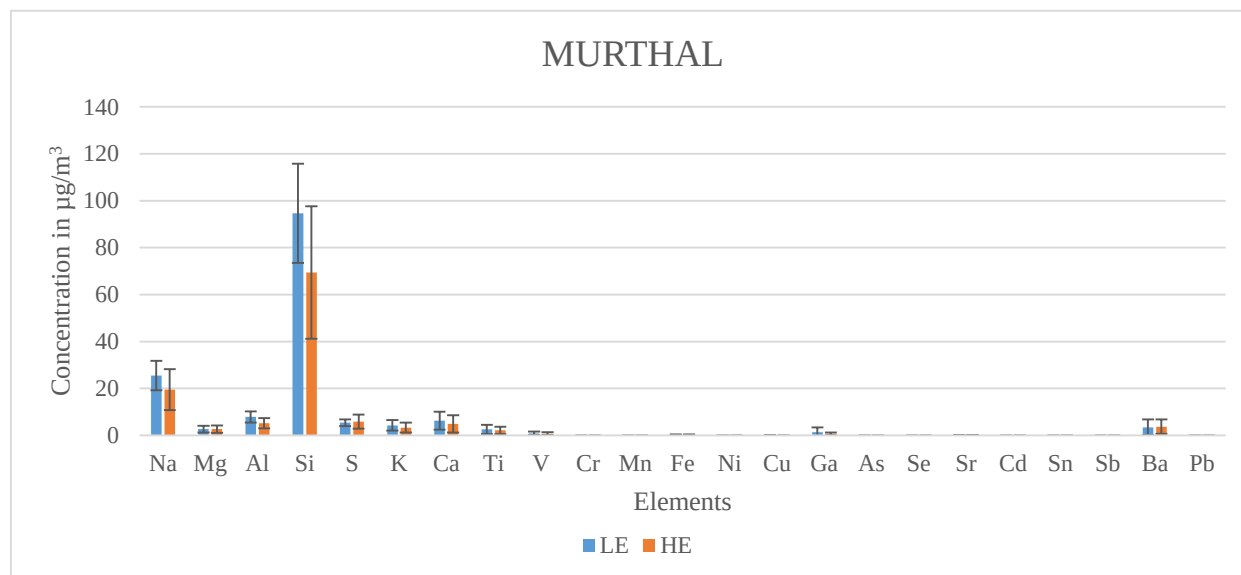


Figure 4.62. Elemental concentrations in the PM₁₀ collected at elevation wise at Murthal.



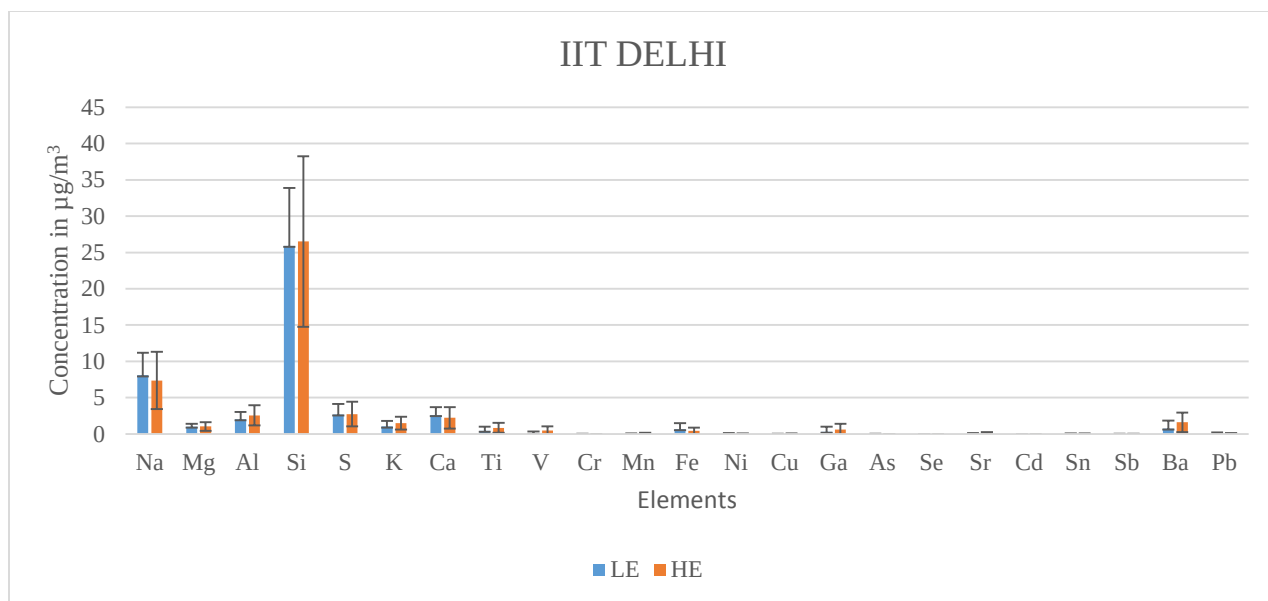


Figure 4.63. Elemental concentrations in the PM_{10} collected at elevation wise at IIT Delhi.

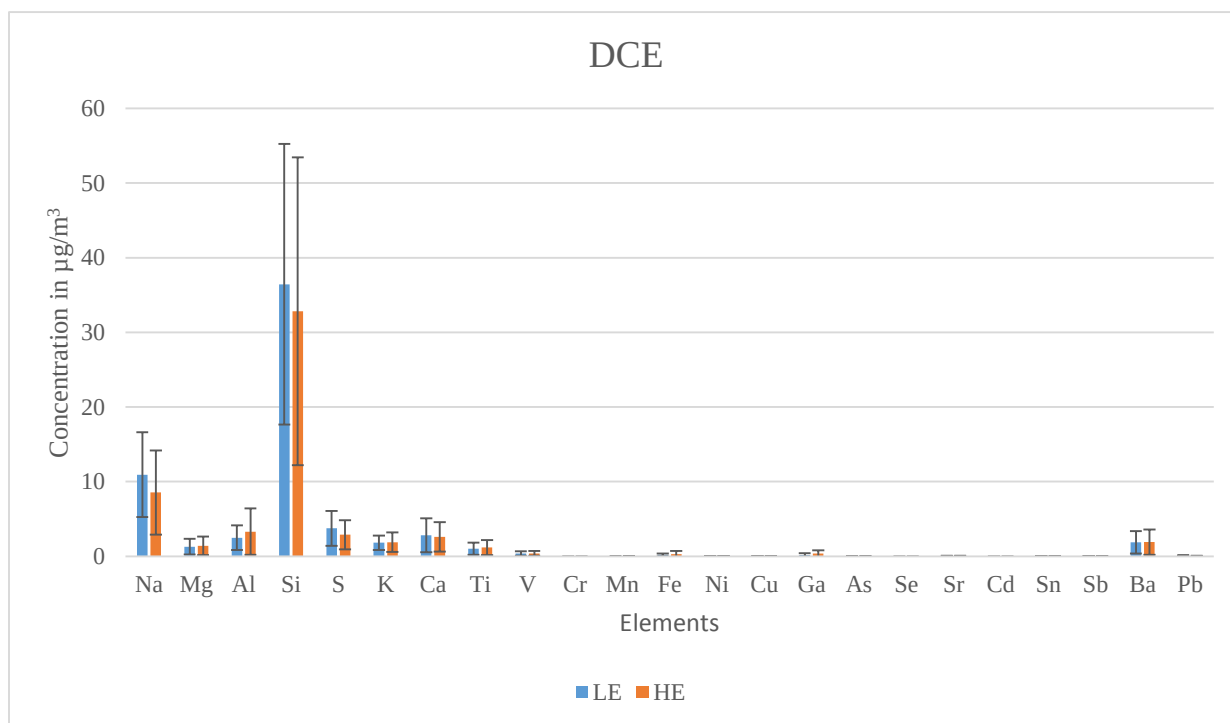


Figure 4.64. Elemental concentrations in the PM_{10} collected at elevation wise at DCE.



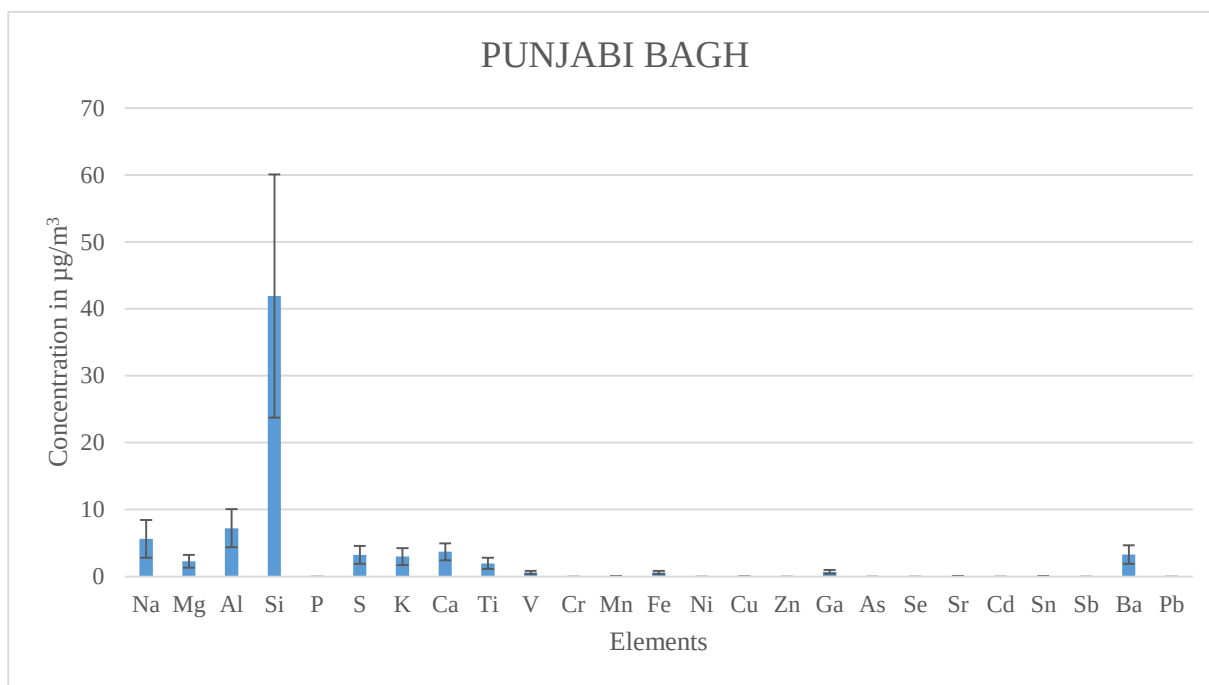


Figure 4.65. Elemental concentrations in the PM₁₀ collected at elevation wise at Punjabi Bagh.

Na, Mg, S, Si, and Al, Ti, V, Fe, Ba were found to be the most abundant elements in PM₁₀ at all the study locations. The concentrations of Ti, V were found to be higher in lower elevation. This indicates that a major contribution from fuel oil combustion. The concentrations of Si, Mg, Al in PM₁₀ were found to be higher than the concentration of these species in PM_{2.5}. This indicated the contribution of mineral dust to the elemental concentration. The presence of several toxic elements including Sb and Se Sn, As was also observed and indicated the contribution from coal combustion. Previous studies have reported that the elements Si, Ca, Al, are generally associated with soil/mineral dust and Fe, Pb and Ba with diesel vehicles.



4.6.2 Ionic analysis of PM₁₀ samples

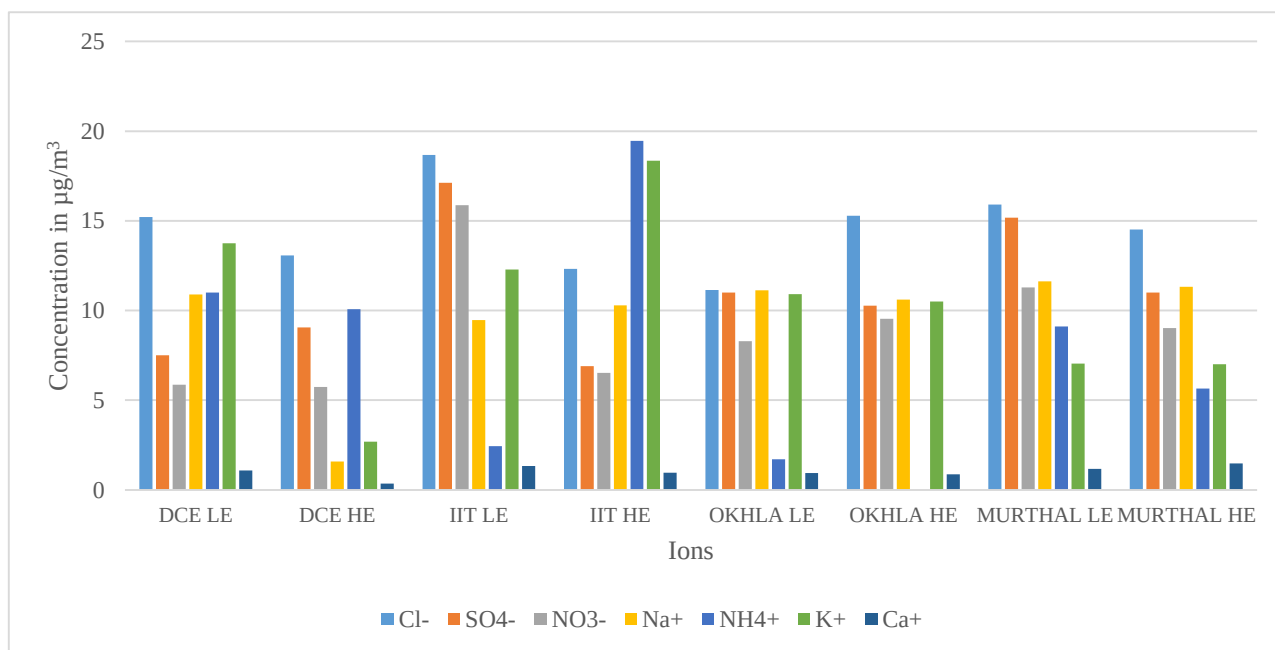


Figure 4.66. Concentration of PM₁₀-bound ions at elevation wise at different locations in Delhi city.

The Cl⁻, SO₄²⁻, NO₃⁻, NH₄⁺ were found to be the most abundant ions (figure 4.66). The abundance of Cl⁻ might be an indication of solid waste burning or open burning (Patil et al., 2013). Earlier studies have reported higher Cl⁻ ion concentration in Delhi city especially during the winter season (Sudheer et al., 2014; Tiwari et al., 2013). The Cl⁻ concentration is found to be higher in lower elevation. Thus it can be inferred that the waste burning and open burning might be contributing to the Cl⁻ concentration. The presence of SO₄²⁻, NO₃⁻ and NH₄⁺ was found to be an indicator for secondary aerosols. Presence of high levels of SO₄²⁻ and NH₄⁺ may be due to the presence of [NH₄]₂SO₄, NH₄HSO₄ and Na₂SO₄ which are the most likely sulfate compounds in PM. Presence of higher concentration of K⁺ indicates there is a significant burning activity in Delhi.



Table 4.11: Signatures for sources based on ionic species

Ions	Sources	Location	Reference
F ⁻	Sea salt	Kanpur	Chakraborty and Gupta., 2009
Cl ⁻	Sea salt, wood burning, open burning	Delhi	Sharma et al., 2016, Patil et al., 2013
SO ₄ ²⁻	Coal combustion, metal production, secondary aerosols, biomass and vegetative burning, fossil fuel combustion, fertilizer industries, etc.	Delhi	Sharma et al., 2016
NO ₃ ⁻	Vehicular emission, secondary aerosols,	Delhi	Sharma et al., 2016
NH ₄ ⁺	Biomass burning, secondary aerosols	Delhi	Sharma et al., 2016
Cl ⁻	fossil fuel combustion	Delhi	Sharma et al., 2016
K ⁺	Biomass and vegetative burning	Delhi	Sharma et al., 2016



Table 4.12: Signatures for sources based on elemental species

Elements	Sources	
Ca	Resuspension of soil	Chakraborty and Gupta., 2009 Kothai et al.,2008 Srivastava et al., 2016
Mg	Railway lines, Resuspension of soil	
Fe	Brake lining, automobile rust, motor car exhaust, soil resuspension, Railway lines(maximum)	
Cu	Earth's crust (natural source), vehicular emission, brake linings of the vehicle, industries (wood production, iron, and steel production, non-ferrous metal production, non-ferrous metal mining, phosphate fertilizer manufacture), Railway lines	
Ba	Brake wear	Srivastava et al., 2016
Ni	Coal combustion, metal production, fertilizer industries, vehicle exhaust (additive in fuel), tire dust, Railway lines, etc.	Chakraborty and Gupta., 2009 Kothai et al.,2008 Srivastava et al., 2016 Sharma et al., 2016 Yadav et al.,2016
Si	Resuspension of soil	
Pb	Vehicular emission, leaded petrol (added as antiknock agent), Coal combustion, metal production, fertilizer industries, fugitive emission from industries, etc.	
Cr	Coal combustion, metal production, fertilizer industries, chrome plating, and steel production industries, residential fuel combustion (natural gas, oil, coal), Railway lines, etc.	
Na	Sea spray, Railway lines, salt lakes in the desert	
K	Sea spray	



Zn	Vehicular emission, exhaust (additive in lubricating oil), galvanized materials, tire wear (used in rubber production), fossil fuel combustion	
V	Vehicular emission	
Se	Oil fired power plants and coal combustion	
Mn	Brake linings, tire wear, road dust, Railway lines	Srivastava et al., 2016
Cd	Non- ferrous metal mining and refining, phosphate fertilizers, waste incineration and disposal, coating and plating, smelting operations	Srivastava et al., 2016

4.6.3 EC-OC analysis of PM_{2.5} samples

The quartz PM_{2.5} filter papers were used for the EC/OC analysis, and the result was shown in figure 4.67.

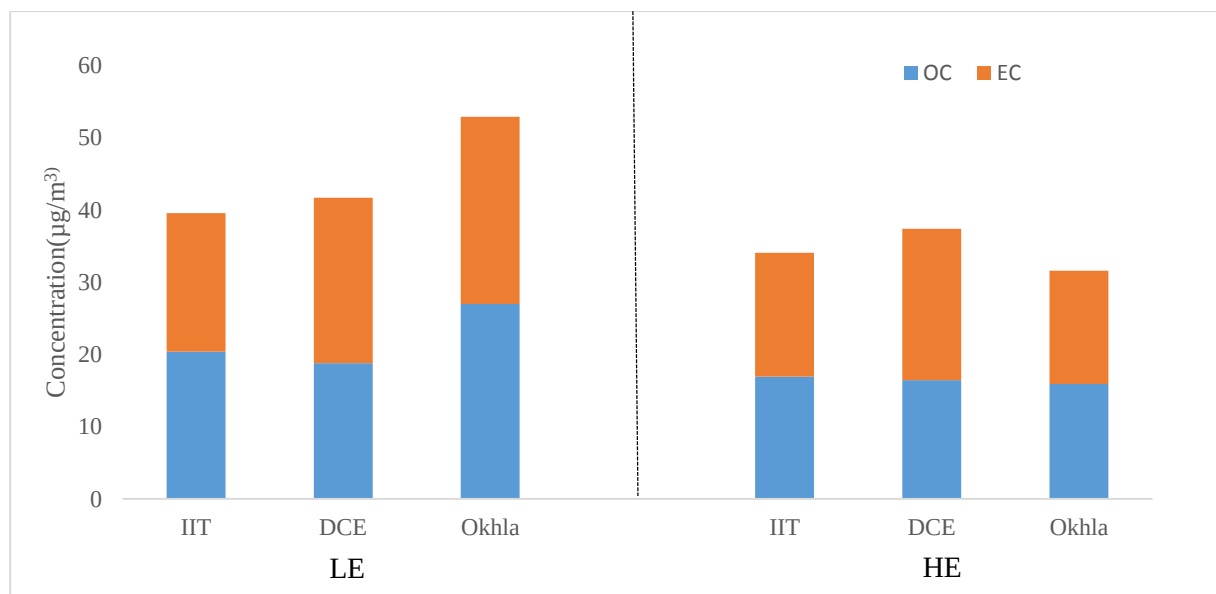


Figure 4.67. EC-OC concentrations level wise at various locations in Delhi city.



EC/OC concentrations were found to be higher at lower elevation in Okhla as compared to other locations. EC/OC concentrations were found to be in similar range at a higher elevation at all the three locations. The OC/EC ratio was calculated to understand the source contributions to EC/OC. An OC/EC ratio for all the LE and HE at all locations indicated that the EC and OC have similar source contributions. However, a lower ratio at DCE as compared to other locations indicated that the formation of secondary organic aerosols (SOA) is less as compared to other sites. As most of the measurements were taken when the temperature was comparatively lower; therefore, the chance of photochemical oxidation and SOA formation is expected to be less. The earlier studies also indicated that the maximum variation in the OC/EC ratio is observed during summer as compared to winter (Kumar and Attri, 2016). A similar observation is evident in the present study, as the ratio is comparatively higher in PNB, where the measurements were taken in April when the temperature was higher.

Table 4.13: OC/EC ratio elevation wise at various locations in Delhi city.

Location	OC/EC	
	LE	HE
IIT Delhi	1.06	0.99
DCE	0.82	0.79
Okhla	1.08	1.02
PNB	1.97	-

A strong correlation between OC and EC at both the elevations as shown in figure 4.64 and 4.65, ($R^2 = 0.8$) suggested the emissions were from common sources, where EC emitted from primary combustion sources, which implies that a major proportion of OC also originated from combustion.



Source apportionment of ambient particulate matter during winter season in Delhi

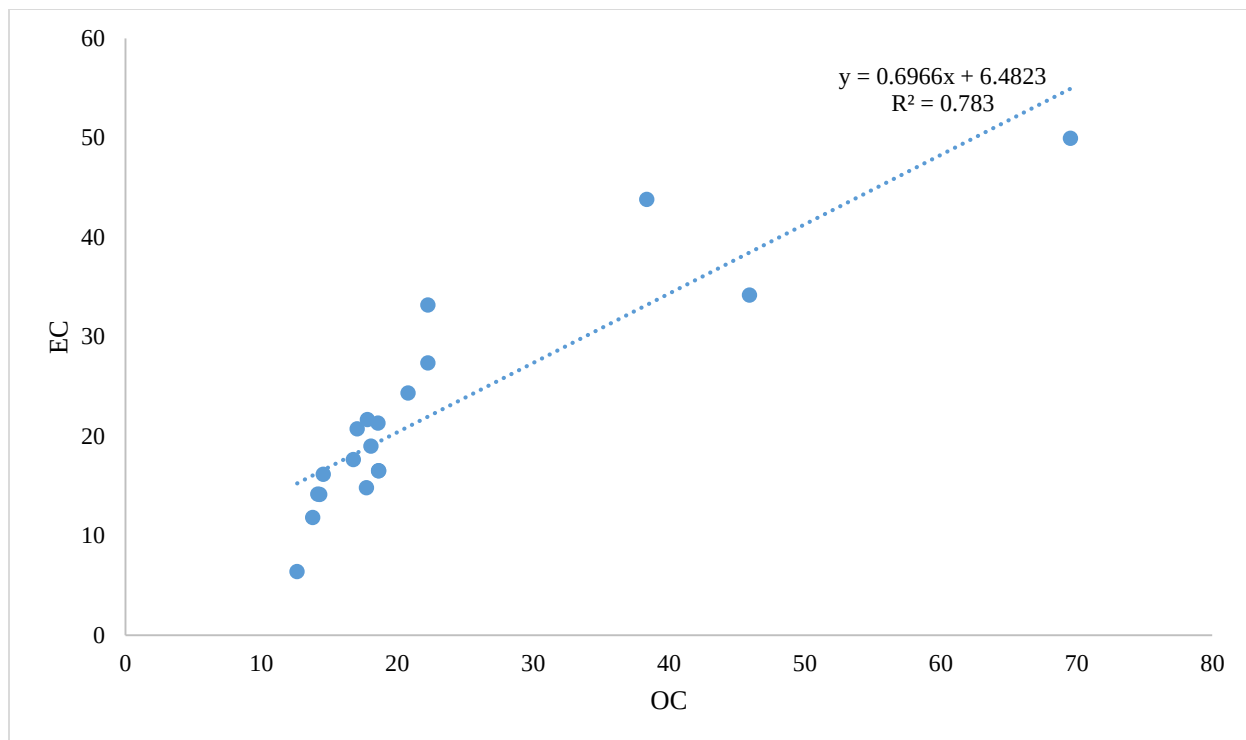


Figure 4.68. Correlation between EC and OC in PM_{2.5} samples collected at lower elevations

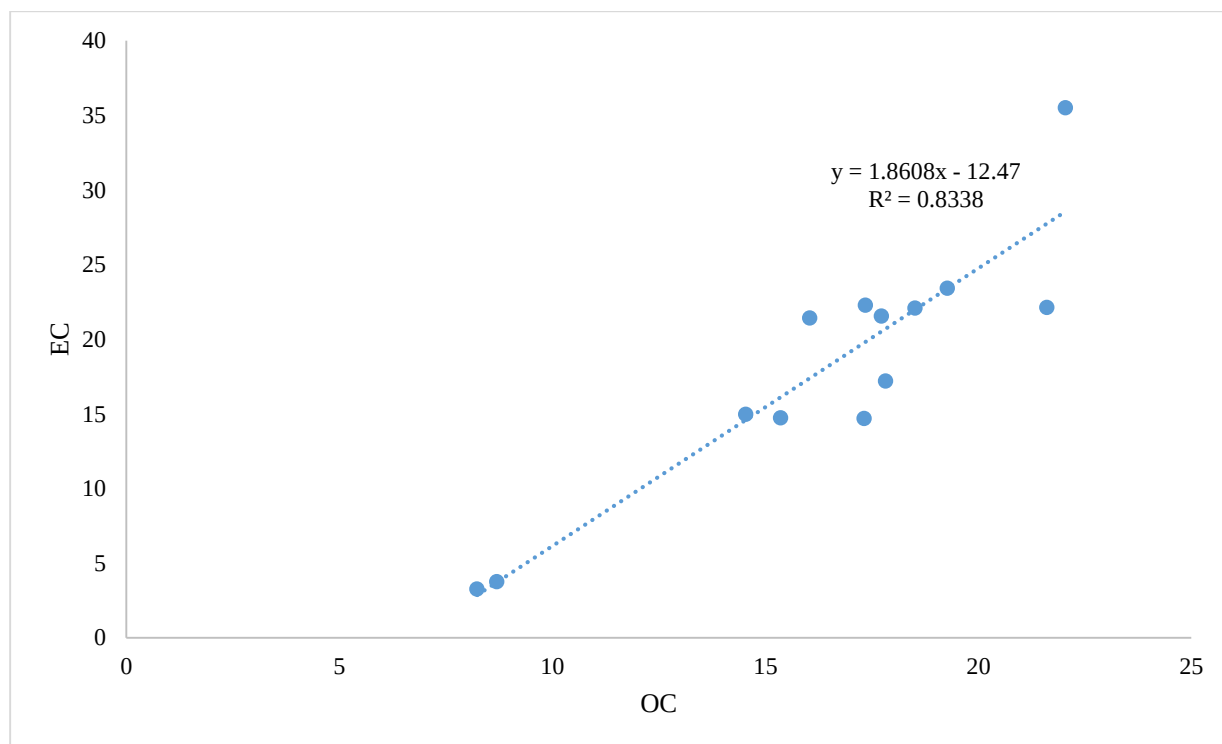


Figure 4.69. Correlation between EC and OC in PM_{2.5} samples collected at higher elevations.



4.6.4 POC and SOC concentrations in PM

The relative amounts of primary OC (POC) and secondary OC (SOC) can be estimated using EC tracer method, which involves the use of EC as a tracer for POC, allowing SOC to be estimated (Castro et al., 1999; Pio et al., 2011). Minimum ratios of OC/EC are taken as representative of primary OC (Pio et al., 2011), and OC above that ratio is taken to be SOC. The method outlined by Castro et al. (1999) was used, and estimates of SOC were calculated as follows.

$$\text{Secondary OC} = \text{TOC} - (\text{EC} \times [\text{OC/EC}]_{\min})$$

The contribution of SOC to the total OC was calculated to be 67% and 69% at LE and HE respectively.

4.6.5 Morphological Characteristics

SEM was carried out for four magnifications. 200X, 1.5KX, 5KX, 10KX. The results are given in the following figures.

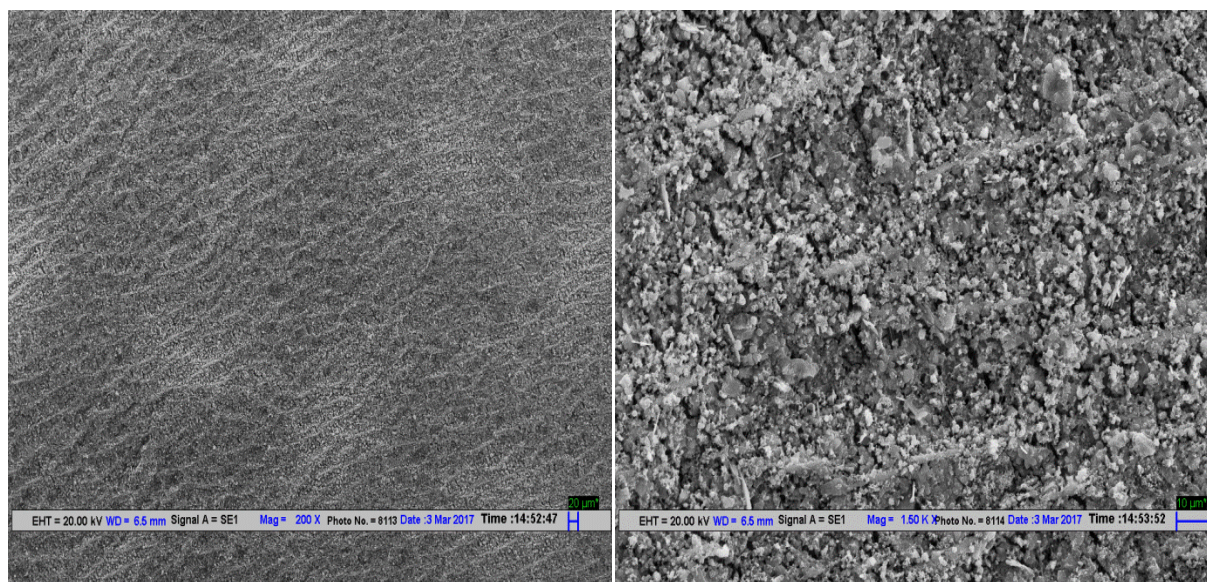


Figure 4.70. SEM of PM_{2.5} collected at DCE LE.

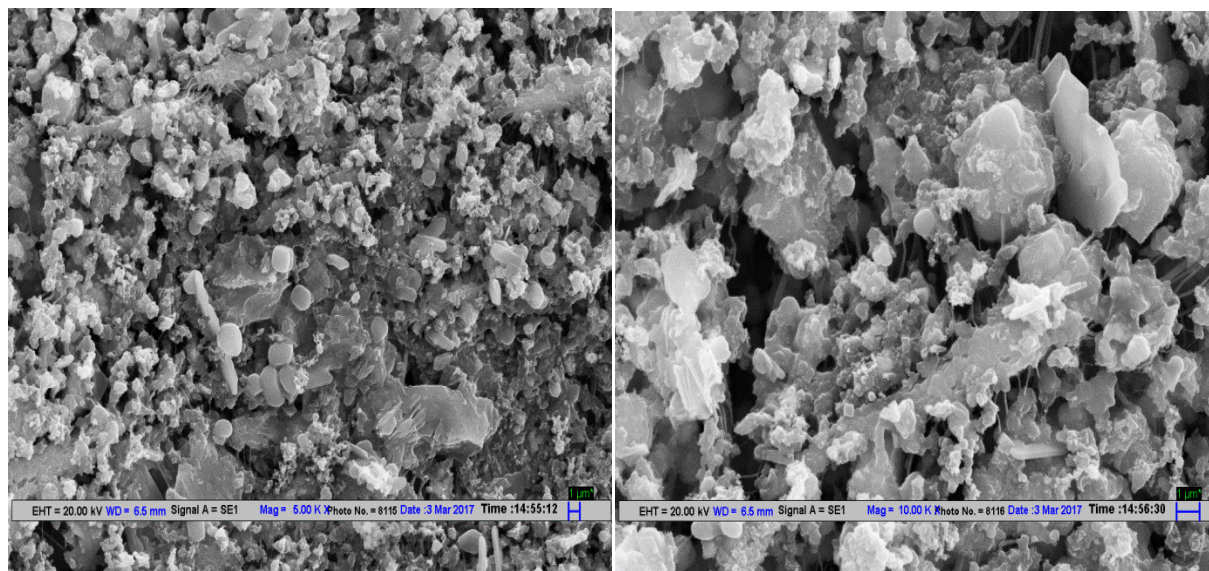


Figure 4.71. SEM of PM_{2.5} collected at DCE LE.

Figure 4.67 shows the microscopic image of the PM_{2.5} collected at DCE Guest House (lower elevation). At low resolution the particles look uniform, high magnification SEM image shows the distinct shapes of particles. Most of the particles are forming platelets. The round shaped particles are fly ash.

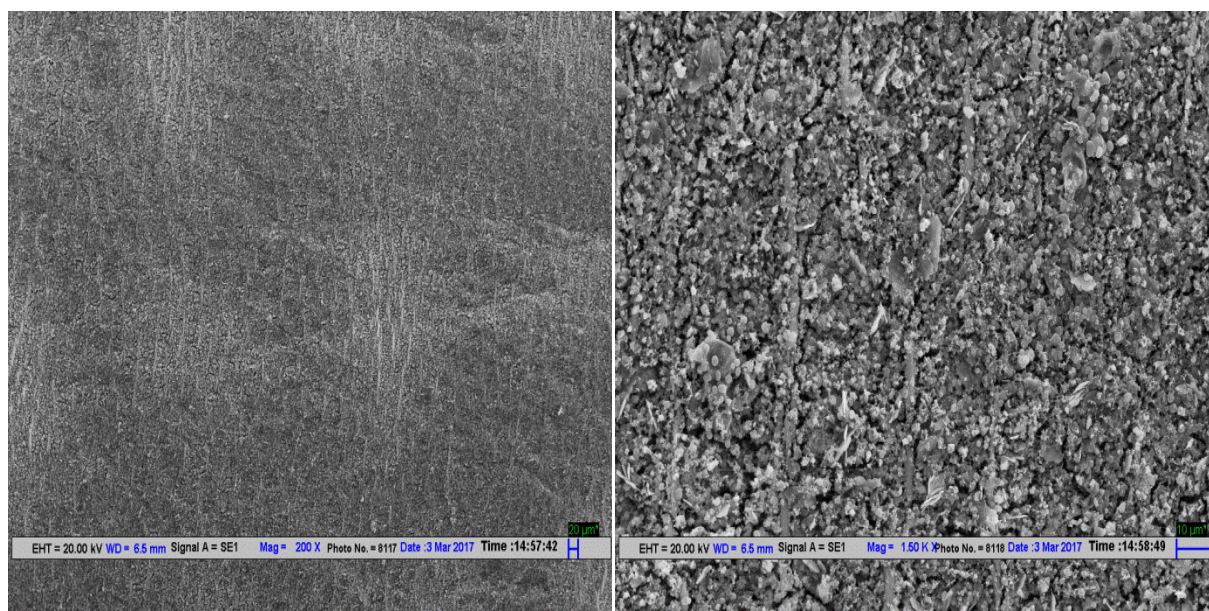


Figure 4.72. SEM of PM_{2.5} collected at DCE HE.

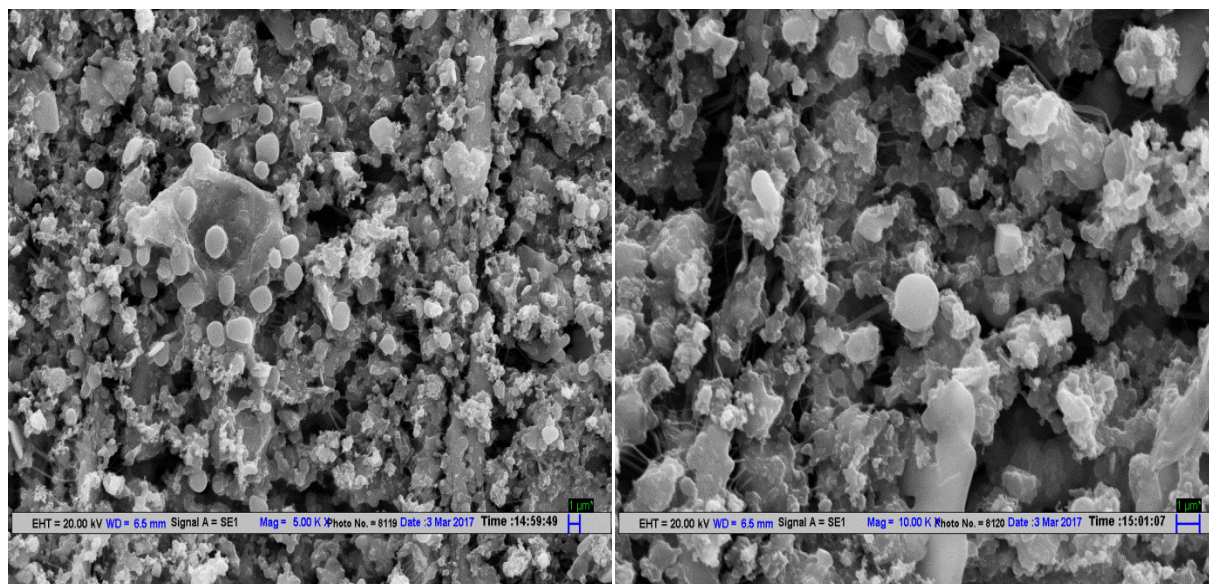


Figure 4.73. SEM of PM_{2.5} collected at DCE HE.

Figure 4.68 shows the microscopic image of the PM_{2.5} collected at the IIT Delhi. At low resolution the particles look uniform, high magnification SEM image shows the variety of shapes of particles. Spherical and platelets are the most common form of particles present in the collected dust system. The spherical shaped particles are fly ash.

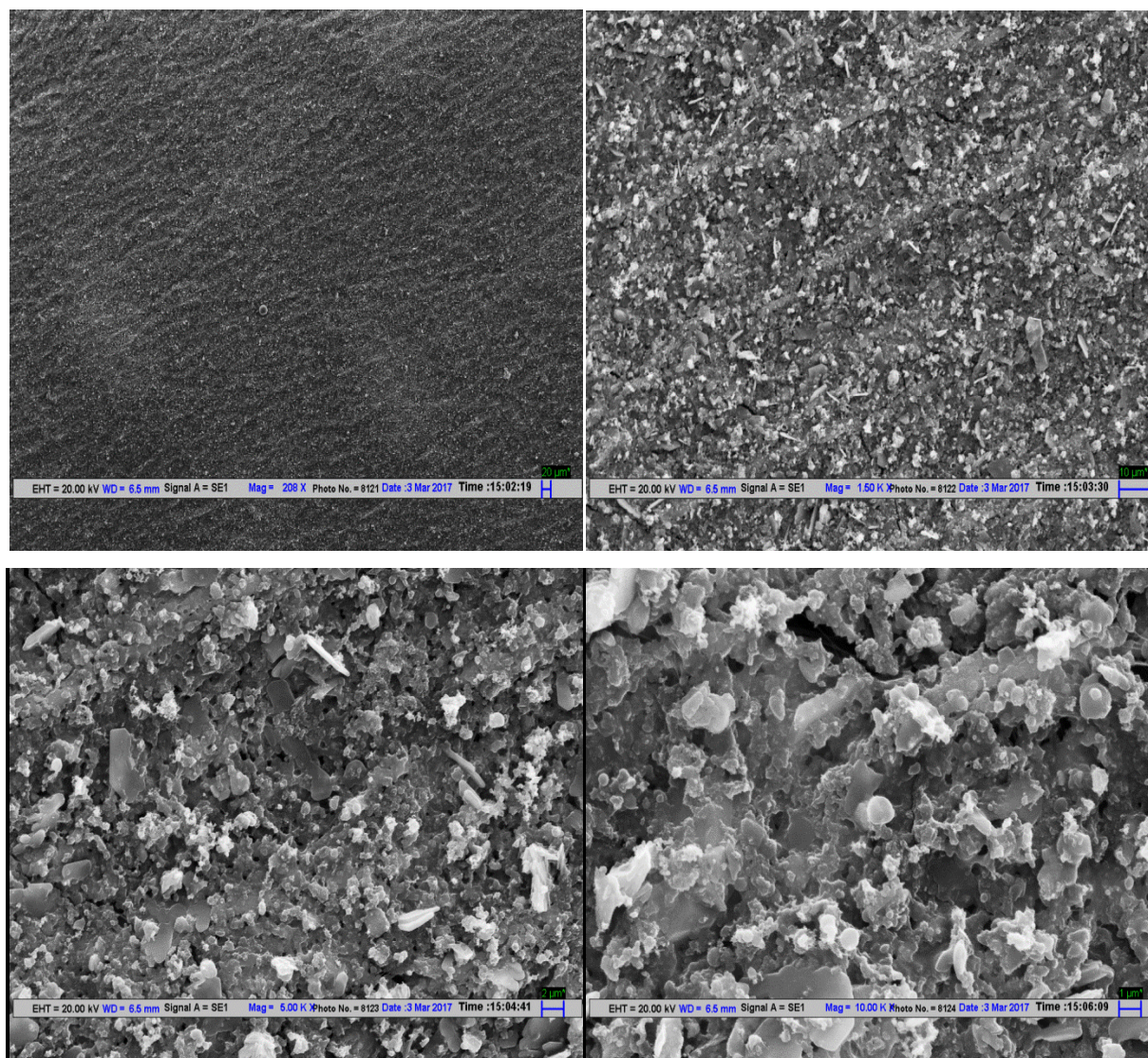


Figure 4.74. SEM of PM_{2.5} collected at IIT Delhi.

The PM_{2.5} collected at IIT Delhi was analyzed using SEM. Figure 4.69 shows the SEM image for PM_{2.5}. The dust here is mostly in the form of platelets with size in few microns to tens of microns. Also, there are few small spherical particles in the collected samples. The irregularly shaped particles are aluminosilicates which are mainly present in windblown dust.

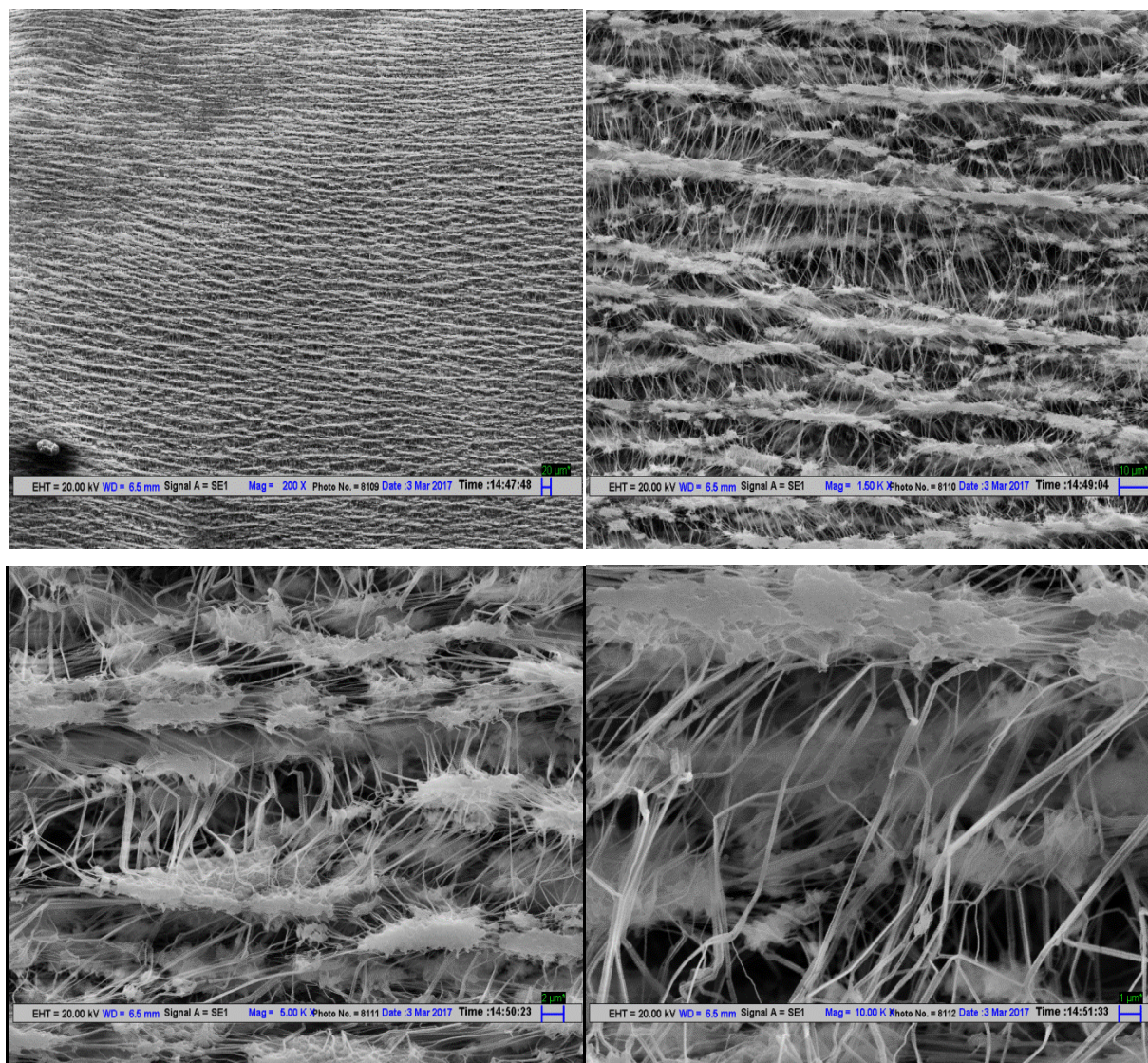


Figure 4.75. SEM of PM_{2.5} collected at Lab Blank.

Figure 4.70 shows the SEM for PM_{2.5} collected at the lab blank. The low magnification SEM shows highly connected fibrous structure. Studying the fibers at higher magnification reveals the fibers are highly interconnected with some areas of very high density.

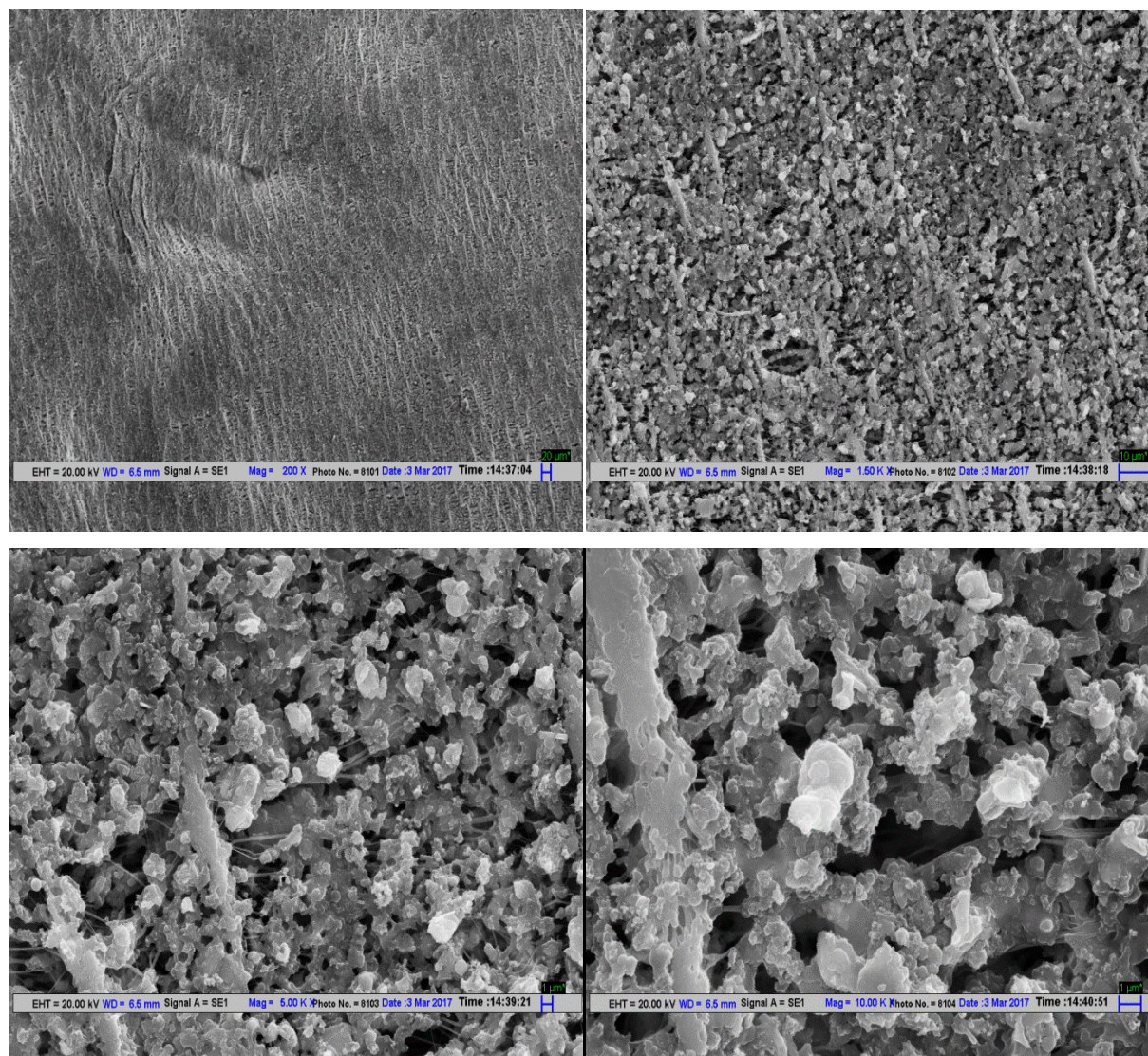


Figure 4.76. SEM of PM_{2.5} collected at LE, Okhla.

Figure 4.71 shows the SEM for the PM_{2.5} particle collected at a lower elevation of Okhla. The particles are ranging from few hundred nanometers and tens of microns. The particles are mostly dust aggregates and irregular shaped.

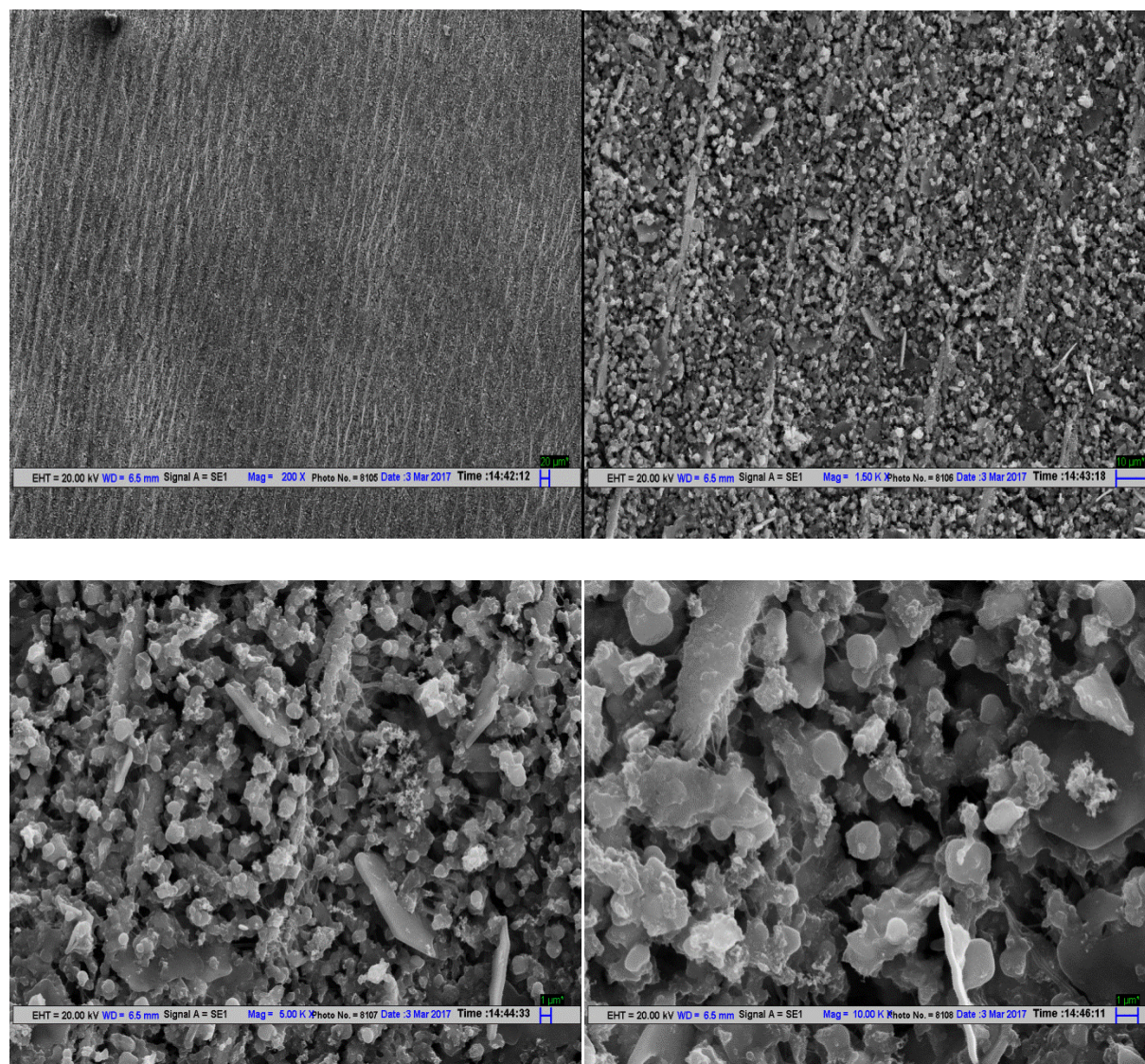


Figure 4.77. SEM of PM_{2.5} collected at HE Okhla.

Figure 4.72 shows the SEM for the PM_{2.5} particle collected at a higher elevation of Okhla; the particles are ranging from a few hundred nanometers and tens of microns. Most particles thus formed are making platelets or rod shape. Table 4.14 gives the composition characteristics of different types of particles and Table 4.15 gives the details of PM_{2.5} morphology obtained at different monitoring sites.

Table 4.14: Composition and Characteristics of different types of particles.

Type	Characteristics	Composition
Flyash (1-30 μ m- coal flyash) (15-82-oil flyash)	Heterogeneous in morphology, Mineral-rich spheres (coal-fired power plants), condensates on the outer surface of spheres, spherical aluminosilicates (minor amounts of Fe, Ca)	As, Se, V, Ni, Hg, Cu, Sb, Zn, Cl, Ta, Co (oil and coal fly ash)
Carbonaceous particles, soot (combustion-generated)	Mostly in PM ₁₀ , graphite-like structure, Heterogeneous in morphology (depends on fuel-type and composition), as aggregates	C
Sulfates (0.5-10 μ m)	Non-volatile fraction only analyzed since it is sublimed during analysis, heterogeneous morphology	S
Marine aerosol (<0.5 μ m)	Crystalline and diatoms fragments observed, Na and Cl only (cubic structure)	Found as NaCl, H ₂ SO ₄ , (NH ₄) ₂ SO ₄ , mixed [NaCl, (NH ₄) ₂ SO ₄], CaSO ₄ , MgSO ₄ , KCl.
Cu-bearing particles	Spheres in pure oxide form; high-temperature process	May also have Pb, Zn, Cl
Fe and Mn-bearing particles	Spheres in pure oxide form; high temperature or smelting process	Cr, Si, Fe may also be observed, P and S (from tailpipe emissions)(when MMT is an additive in gasoline)
Tire wear debris	Elongated, elliptical or cigar-shaped	Fe, Si, Al, Ti

Source: USEPA (2002); Xie et al., 2005



Table 4.15: Details of PM_{2.5} morphology obtained at different monitoring sites.

Season		Location/ Date/Day	Morphology	Location / Date/Day	Morphology	Location/ Date/Day	Morphology
WINTER	Higher elevation	IIT (HE) (26.2.17, SUN)	Flyash , Fe-p, SiMn	IIT (HE) (28.2.17, TUE)	Syngenite, aluminosilicates	IIT (HE) (9.2.17, THURS)	Syngenite, Gypsum
		Okhla (HE) (25.2.17, SAT)	Flyash, Fe-p, SiMn	Okhla (HE) (6.2.17, MON)	Flyash, Fe-p, SiMn, dolomite, illite, quartz, coal, hydrated lime, gypsum	Okhla (HE) (16.2.17, THURS)	Flyash, Fe- p, SiMn
		Okhla (HE) (26.2.17, SUN)	Soil dust, aluminosilicates				
		DCE (HE) (26.2.17, SUN)	Flyash, aluminosilicates	DCE (HE) (14.2.17, TUE)	Syngenite, illite gypsum, dolomite,	DCE (HE) (23.2.17,T HURS)	Flyash , Fe-p, SiMn
	Lower elevation	IIT (LE) (26.2.17, SUN)	Aluminosilicates				
		Okhla (LE) (26.2.17, SUN)	Coal, fly ash, soil dust	Okhla (LE) (6.2.17, MON)	Quartz, coal, hydrated lime		



Source apportionment of ambient particulate matter during winter season in Delhi

		DCE (LE) (26.2.17, SUN)	Flyash, aluminosilicates				
SUMMER	Higher elevation	IIT (HE) (5.3.17, SUN)	Combustion products, aluminosilicates	IIT (HE) (10.4.17, MON)	Aluminosilic ates, fibrous structures	IIT (HE) (16.3.17, THURS)	gypsum, aluminosili cates
		Okhla (HE) (17, SAT)	Aluminosilicates	Okhla (HE)	Aluminosilic ates	Okhla (HE) (9.3.17, THURS)	Illite, dolomite, aluminosili cate
		DCE (HE) (5.3.17,S UN)	Soot, slag, kaolinite	DCE (HE) (20.3.17, MON)	Illite, gypsum, dolomite, hydrated lime, syngenite	DCE (HE) (6.4.17,TH URS)	Illite, dolomite, hydrated lime
		SBIT (HE) (7.5.17, SUN)	Flyash, SiMn, Fe-p, gypsum, <i>unknown</i>	SBIT (HE) (8.5.17, MON)	Soot, dolomite, hydrated lime, <i>unknown</i>	SBIT (HE) (4.5.17, THURS)	Syngenite, aluminosili cates
	Lower elevation	IIT (LE) (19.3.17, SUN)	Gypsum, aluminosilicates	IIT (LE) (3.4.17, MON)	Illite, auminosilicat e		
		Okhla (LE)	Aluminosiicates				



Source apportionment of ambient particulate matter during winter season in Delhi

		(5.3.17, SUN)					
		DCE (LE) (5.3.17,S UN)	Fibrous (unknown), aluminosilicates	DCE (LE) (3.4.17, MON)	Fibrous (unknown), aluminosilicates		
		SBIT (LE) (13.5.17, SAT)	Flyash, soot	SBIT(LE) (8.5.17, MON)	Soot, <i>Unknown</i>		
	DPCC stations	PNB	NA			PNB (6.4.17, Thurs)	Illite, dolomite, hydrated lime, soot
		AV (14.5.17, SUN)	Illite, dolomite, hydrated lime, soot	AV (15.5.17, MON)	Illite, dolomite, hydrated lime, soot	NA	
Blank	Laboratory Blank	Fibers of filter paper No particles observed					
	Field Blank						

Note: HE (higher elevation), LE(lower elevation), Fe-p (Fe particle), SiMn (Silicomanganese), PNB (Punjabi Bagh), AV (Anand Vihar), IIT(Indian Institute of Technology Delhi), SBIT (Sri Balwant Institute of Technology, Sonapat), DCE (Delhi College of Engineering), NA(not applicable)



4.7 PM Source Apportionment

The major sources of PM considered at the study area namely, IIT Delhi, Delhi College of Engineering (DCE), Okhla and Murthal, are fuel oil combustion, emission from vehicular exhaust, biomass burning, solid waste burning, construction activities, and other unidentified sources.

4.7.1 Positive Matrix Factorization

PMF modeling resolved a six-factor solution for PM₁₀. Overall, the PMF resolved factors explained about 96% of the total PM₁₀ mass measured at the study site. In order to identify the source type, the resolved source profiles from PMF analysis were compared with the key indicator species reported worldwide from the source apportionment studies (Lee et al., 1999; Chueinta et al., 2000; Ramadan et al., 2000; Song et al., 2001; Watson et al., 2001; Qin et al., 2002; Kim et al., 2003, 2004; Chow et al., 2004; U.S.EPA, 2004; Almeida et al., 2005; He et al., 2006; Yuan et al., 2006; Gildemeister et al., 2007; Bullock et al., 2008; Yarkin and Bayram, 2008; Callén et al., 2009). Preliminary data analysis was conducted as a part of the characterization and trend analysis to understand the trends and relationships among species that would impact PMF analysis.

If the factor is characterized by highest loading of Ca, Ba, Cr, Cd, Mg, Fe, Al, Cu, Na, these indicator species were commonly found and correlated with motor vehicle emissions (Chueinta et al., 2000). Since the study sites are surrounded by a large number of road networks, the motor vehicles emission were expected to be the major contributor in PM mass.

Presence of Ba, Fe, Cu, Zn is an indicator for non-exhaust vehicular emission (brake and tire wear) Tire wear is a complex process driven by the interaction between the tire and the pavement. It results in wear products from both the pavement and tire. The wear products from tires include rubber, carbon black, and other organic constituents along with some metals (Zn, Cu, and Ba). Zn (used in rubber production as galvanized materials in the form of zinc oxide as 1.5–2% of rubber) is contributed mainly from tire wear (Adachi and Tainosho, 2004). The presence of Zn, Cu, and Ba in PM₁₀ indicates the frequent application of brakes. Ba was also used as a smoke suppressant additive to diesel fuel. The brake wear may due to the brake pads or due to the brake linings. The brake linings that were subject to wear composed of several metallic, inorganic and organic materials. The composition is dependent on the manufacturer and lining type, but metals that have been linked with brake wear were Fe and Cu that can be present in significant amounts, as well as Ca, Na and Zn (Luhana et al., 2004). Cu in PM were also emitted from diesel engines.



Species like Cr, Cd emits from the catalytic converter in the tile pipe. Presence of Ni, V, S, Sb, Sn, Mn in the factor profile are indicators of fuel oil combustion. As residual fuel combustion effluent from residential and commercial buildings is enriched with fine particle Ni (relative to V), it is suggested that the observed Ni is mainly a result of residual fuel combustion in such buildings.

Many of the contaminants associated with crude oil are more likely to be found in lower concentrations in lighter fuel oil distillation products (e.g., nos. 1, 2, and three fuel oils). In contrast, the residual oil fractions (e.g., nos. 5 and six fuel oils) contain significantly more of the contaminants that were in the crude oil and can include substantial amounts of trace metals like Sb, Sn, Ni, V, and S.

Factor profile with Chemical species NH_4^+ , SO_4^{2-} , NO_3^- represents secondary aerosols. Presence of SO_4^{2-} and NH_4^+ indicates the involvement of the secondary PM formations and photochemical reaction (Cheng et al., 2000). Particulate sulfate is a product of gas-to-particle phase reactions involving SO_2 emitted from both natural and anthropogenic (coal, diesel, and oil combustion processes) sources. H_2SO_4 can react via gas and aqueous phase processes, and the most common pathway with respect to gas-phase processes is with the hydroxyl ($\text{OH}^\cdot$) radical. At typical atmospheric levels of $\text{OH}^\cdot$ the lifetime of SO_2 is about one week and can result in a maximum sulfate production rate of 2% per hour at midday (Seinfeld and Pandis, 1998). Aqueous-phase reactions are another important pathway for SO_2 oxidation. The majority of aqueous-phase reactions with SO_2 occur in cloud-water, and once dissolved, SO_2 can oxidize via several pathways. Dissolved SO_2 , can oxidize into sulfate, by reacting with dissolved ozone, hydrogen, and organic peroxides, hydroxyl radicals and various oxides of nitrogen. High levels of SO_4^{2-} may be due to the presence of $[\text{NH}_4]_2\text{SO}_4$, NH_4HSO_4 and Na_2SO_4 which are the most likely sulfate compounds in PM. The H_2SO_4 usually exists in very acidic atmospheres. If available, ammonia readily reacts with H_2SO_4 to become a more neutralized $[\text{NH}_4]_2\text{SO}_4$ complex. If enough ammonia is present, the sulfate will be found as $[\text{NH}_4]_2\text{SO}_4$. NH_4^+ in PM_{10} may be formed due to the intense gas phase reactions with NH_3 gas, enriched on sulfate and soil particle when excess NH_3 gas was available. NH_4 in $\text{PM}_{2.5}$ may originate by the reaction of NH_3 vapors with acidic gases such as H_2SO_4 , HNO_3 , and HCl or NH_3 vapor may react or condense on an acidic particle surface of anthropogenic origin. The stability of the products NH_4NO_3 , $(\text{NH}_4)_2\text{SO}_4$ and NH_4Cl are different and depend on temperature and relative humidity. $(\text{NH}_4)_2\text{SO}_4$ is most stable while NH_4Cl is most volatile; hence NH_3 prefers to react with H_2SO_4 (Chandra Mouli et al., 2003).



NO_3 in PM_{10} may be soil derived as well as formed in the atmosphere during the day as well as night. During the day, it is formed due to the reaction between atmospheric HNO_3 and airborne soil (Wolf et al., 1986). Whereas, in the night NO_3 is formed directly on the soil particles by the reactions $[\text{NO}_3 + \text{NO}_2 + \text{M} \rightarrow \text{N}_2\text{O}_5 + \text{M}, \text{ and } \text{N}_2\text{O}_5 + \text{H}_2\text{O}_{\text{soil}} \rightarrow \text{HNO}_3]$. NO_3 in $\text{PM}_{2.5}$ may be formed by the homogeneous gas-phase transformation of NO_x to HNO_3 , followed by the reaction with NH_3 to form NH_4NO_3 , which is highly volatile and can remain stable in the particulate phase (Seinfeld, 1986; Chandra Mouli et al., 2003). NH_4NO_3 in the atmosphere may exist in reversible phase equilibrium with gaseous HNO_3 . The phase change corresponds to the transfer of nitrate between the fine particle and gas phase. If atmosphere thermodynamic equilibrium is realized, nitrate may be distributed either as aerosol or gas depending on the respective dissociation equilibrium.

Mineral dust profile will have a higher contribution from Si, Al, Ca, Fe, which is indicating the influence of Mineral dust. This may come from road wear of asphalt pavement (in general it is composed of 95% mineral grains containing mainly Ca, Al, Si, Na, K, and 5% filler and binding material). The sources of Cr include road dust contaminated by emissions of Cr based catalytic converter. Presence of K indicated that local soil is strongly contaminated by the biological materials.

Presence of EC, OC, K^+ , K indicates that they are emitted from burning of biomass. Biomass burning is a primary source of K^+ mainly in the form of KCl, K_2SO_4 and KNO_3 (Li et al., 2003) and Carbonaceous material EC and OC, a significant fraction of particle-phase emission from fires (Brito et al., 2014; Kondo et al., 2011). While OC is directly emitted to the atmosphere or formed from the oxidation and condensation of organic vapors, EC is primary and emitted from combustion sources (Cabada et al., 2004).

Coal combustion factor profile contains species like As, Se. Although As and Se are also emitted by metals operations and smelters, respectively, their simultaneous loading on this factor, and the fact that coal emissions are highly enriched in, and major sources of both of these elements (Helble, 2000) uniquely identifies this factor as related to the combustion of coal, some 94% of which is presently burned in coal-fired electric power plants (U.S.EPA, 2010).



PM Source apportionment at Okhla

At Okhla, PMF has resolved five factors and four factors at a lower elevation and higher elevation respectively. Mineral dust and traffic emission are resolved as a single factor due to the presence of chemical species from both the sources in the source profile and their together contribution was about 53% of the PM₁₀ mass at a lower elevation, which is slightly higher than the higher elevation (49%). Fuel oil combustion has been resolved by the model at both the elevation and their contribution at lower elevation was about 25% and was found to increase with elevation, hence contribution at a higher elevation was about 40%. Fuel oil combustion accounts for both industrial and domestic combustion. Model resolved solid waste burning and biomass burning only at a lower elevation and their contributions are 10% and 5% respectively. Secondary aerosols contribute to trace quantities and are about 7% and 2% in lower and higher elevation respectively. It is found that secondary aerosols decrease with elevation due to the rapid formation of secondary aerosols take place in the ground level. Factor 3 in higher elevation was found unidentified sources.

Source apportionment at Okhla LE

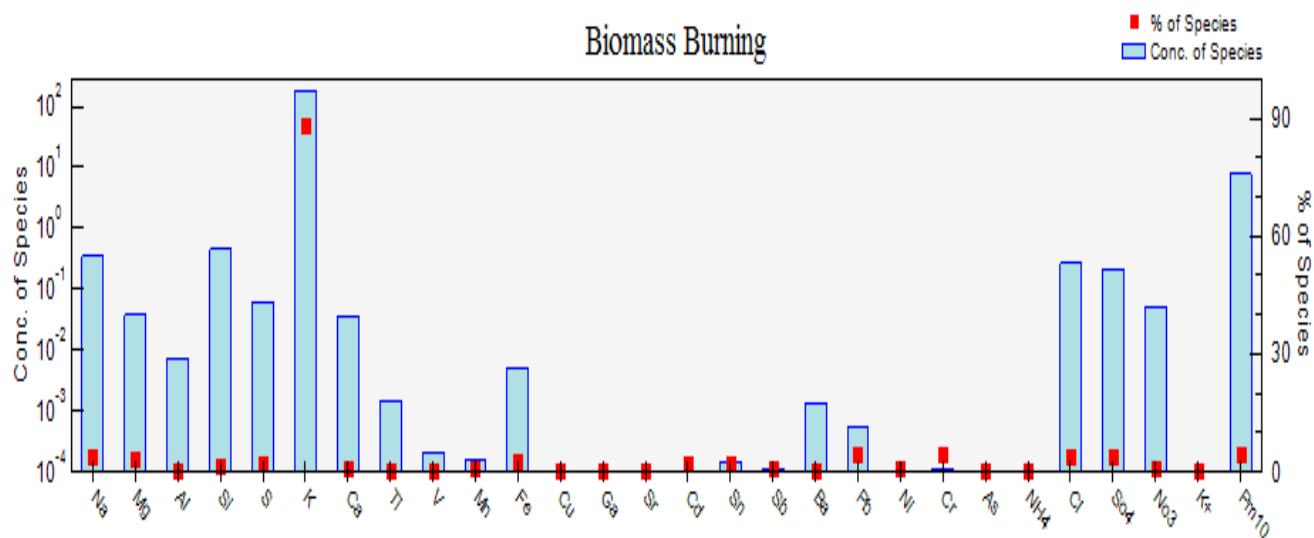


Figure.4.78. Source profile for Factor 1 at Okhla LE.



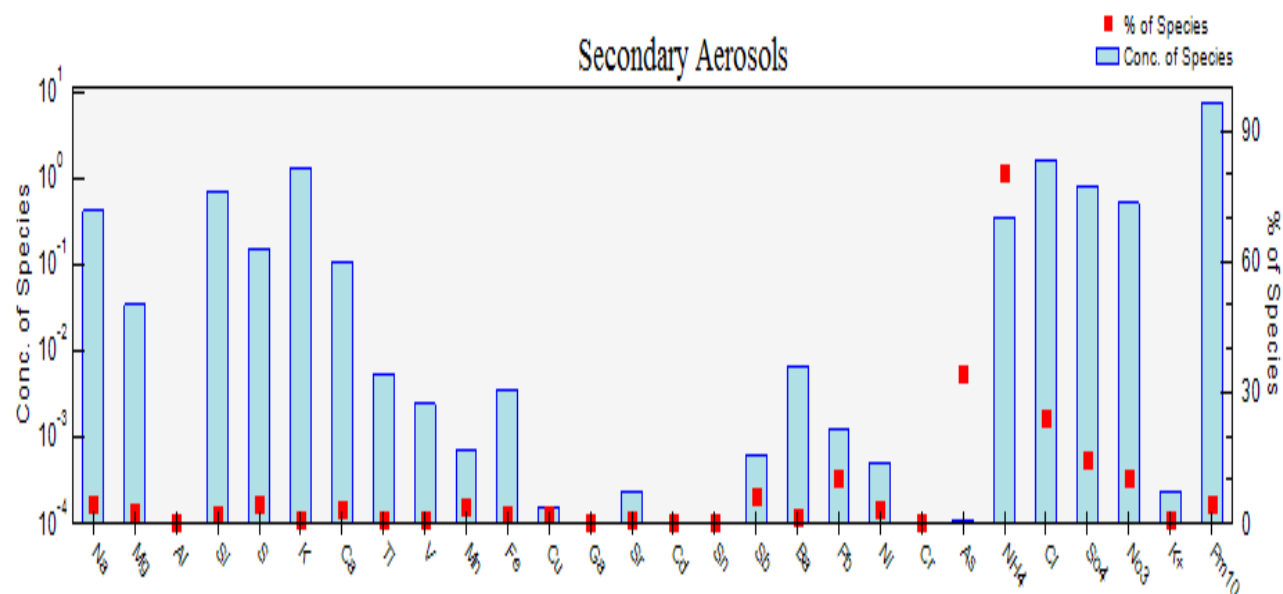


Figure 4.79. Source profile for Factor 2 at Okhla LE.

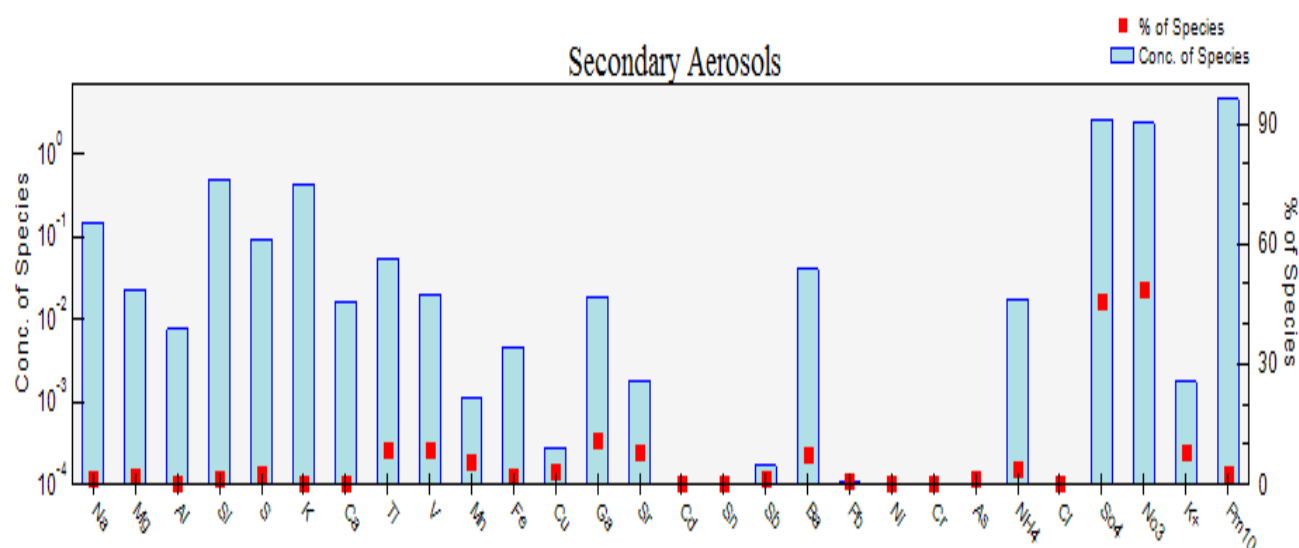


Figure 4.80. Source profile for Factor 3 at Okhla LE.



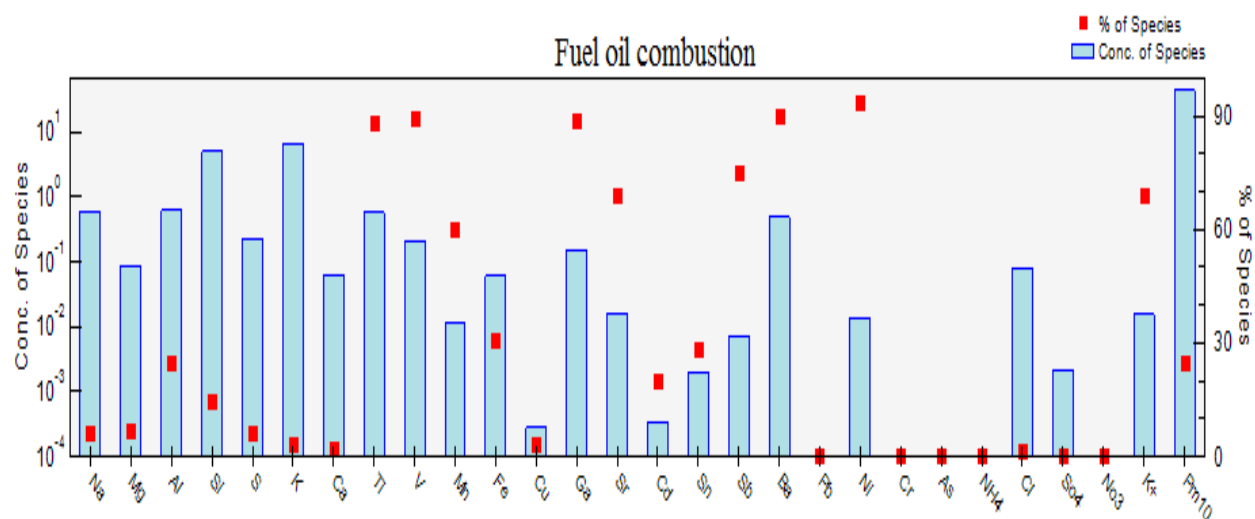


Figure 4.81. Source profile for Factor 4 at Okhla LE.

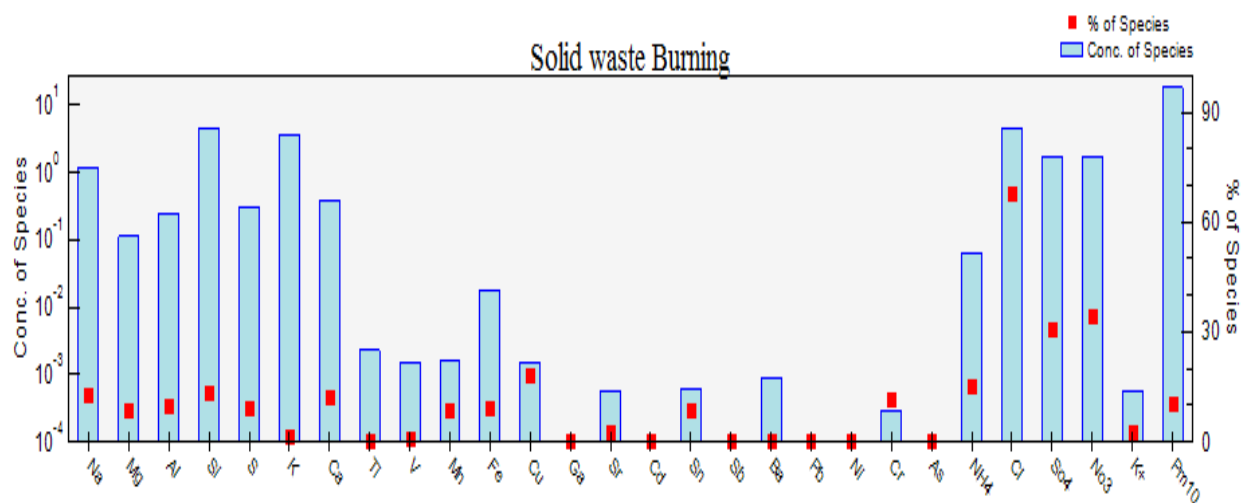


Figure 4.82. Source profile for Factor 5 at Okhla LE.



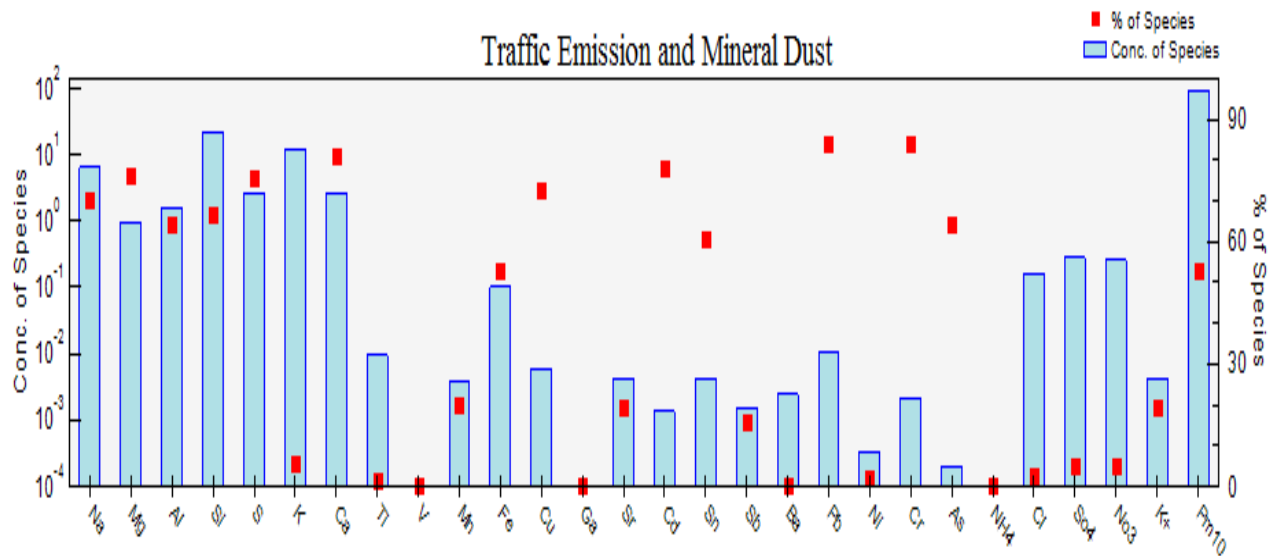


Figure 4.83. Source profile for Factor 6 at Okhla LE.



Source apportionment of ambient particulate matter during winter season in Delhi

The sources represented by the profiles and main average contributors to their presence in PM₁₀ samples are listed in Table 4.16:

Table 4.16: Source profile of PM₁₀-bound elements and ions measured at Okhla. LE.

Location and Elevation	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Okhla Lower elevation	K (90%)	NH ₄ ⁺ (80%), Cl ⁻ (25%), SO ₄ ²⁻ (21%), NO ₃ ⁻ (10%)	SO ₄ ²⁻ (47%), NO ₃ ⁻ (49%)	Ti (84%), V (86%), Mn (60%), Ga (90%), Ni (89%), Ba (88%), Sb (74%), Sr (74%)	Si (70%), Al (69%), Na (78%), Ca (83%), Cd (70%), Cr (74%), Pb (73%)	Cl ⁻ (65%)
Sources	Biomass burning	Secondary aerosols	Secondary aerosols	Fuel oil combustion (both industrial & domestic)	Traffic emission & mineral dust	Open burning

Note: Percentage shown in the bracket represents the percentage fraction of the chemical species in the PM mass.



Source apportionment of ambient particulate matter during winter season in Delhi

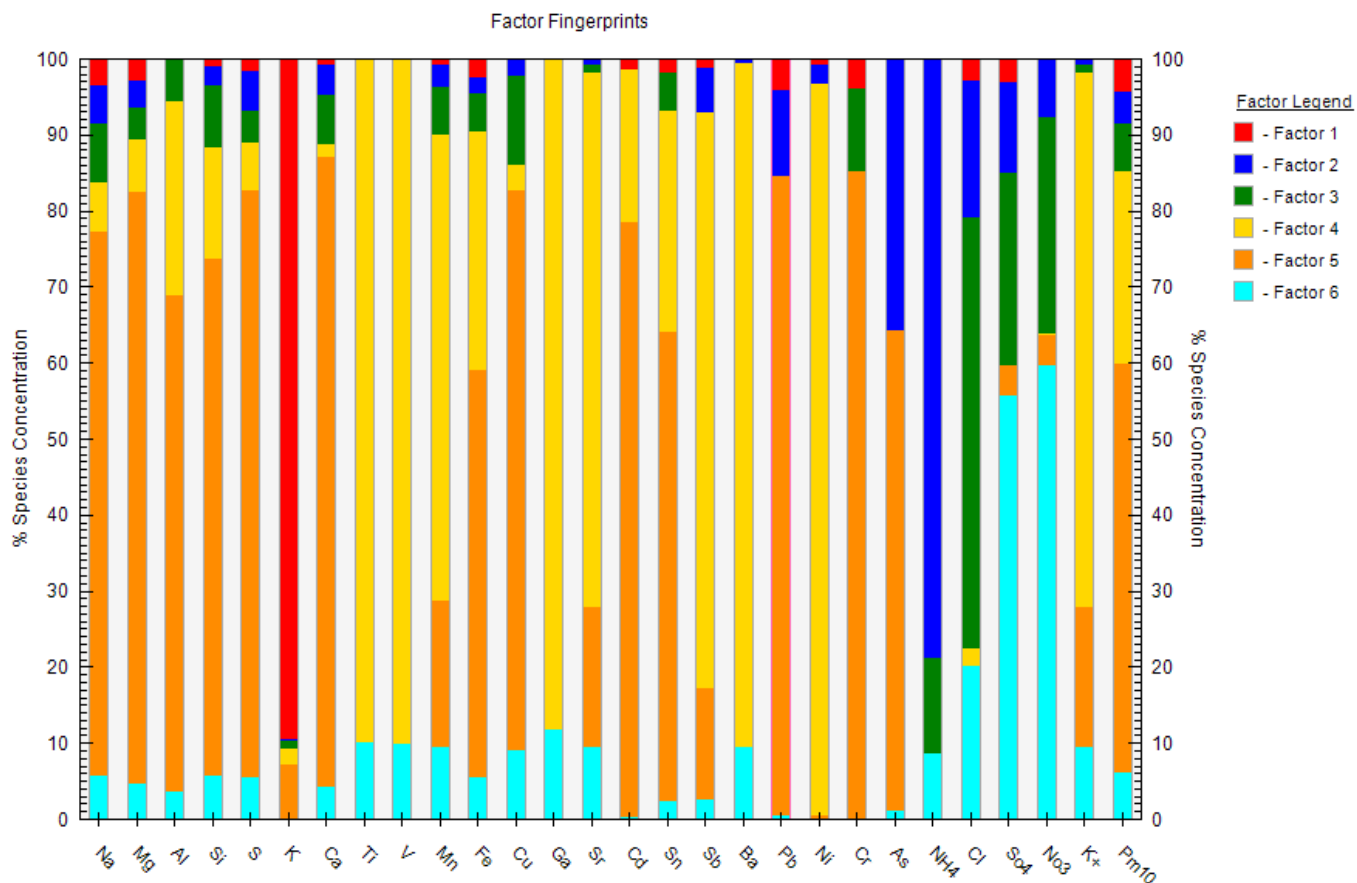


Figure 4.84. Factors contribution to Chemical species at Okhla LE.

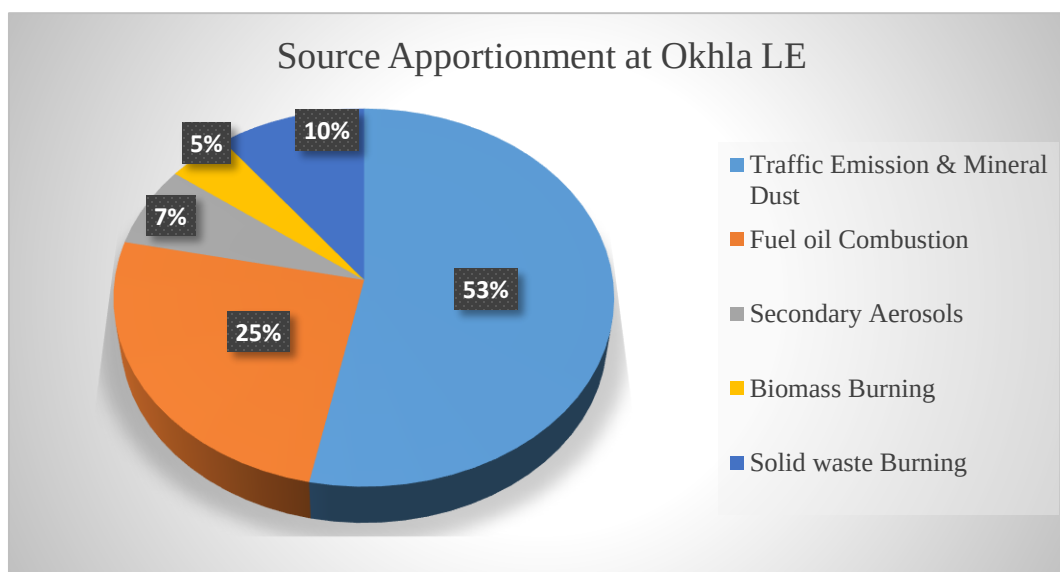


Figure 4.85. Source apportionment of PM₁₀ at Okhla LE.



Source apportionment at Okhla HE

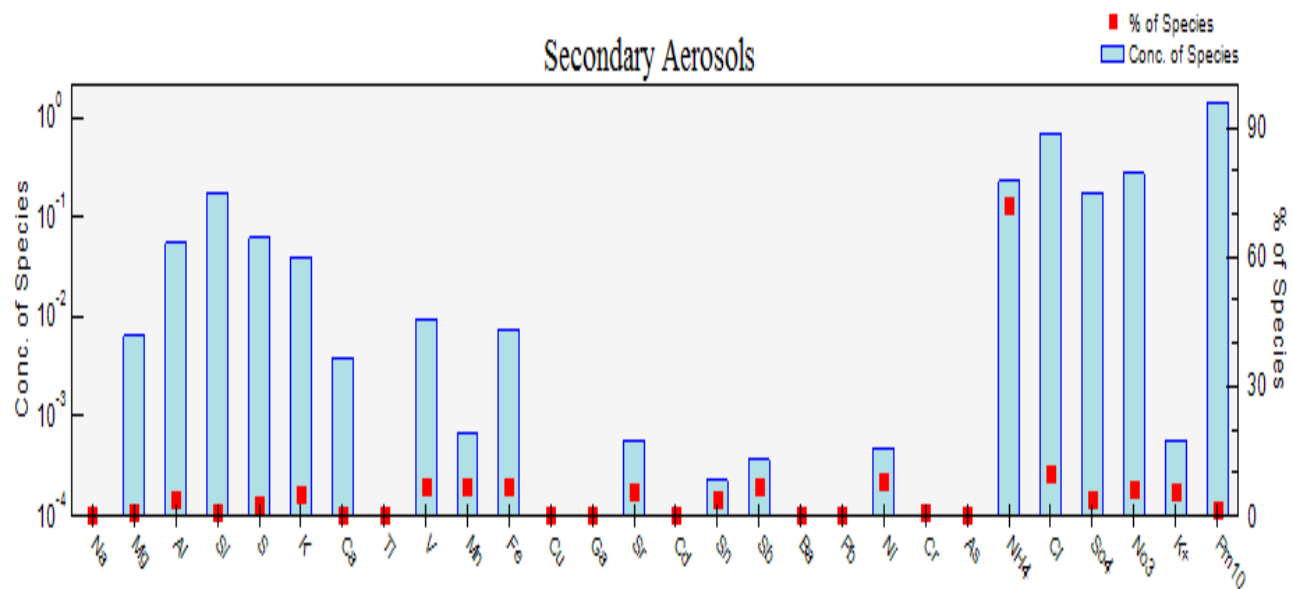


Figure 4.86. Source profile for Factor 1 at Okhla HE.

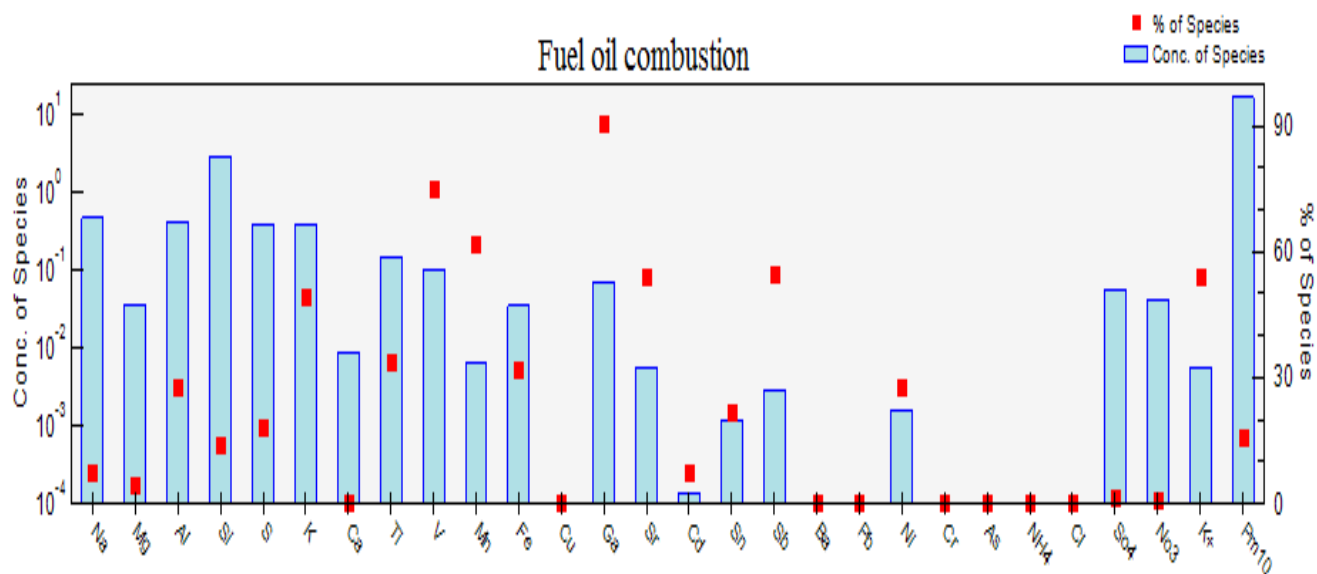


Figure 4.87. Source profile for Factor 2 at Okhla HE.



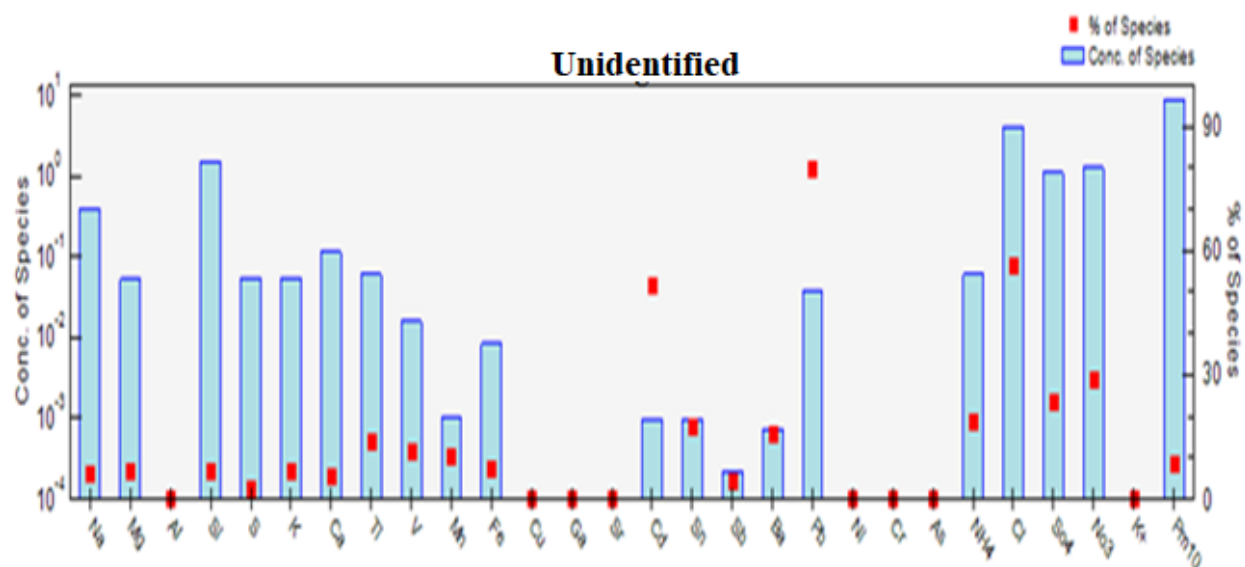


Figure 4.88. Source profile for Factor 3 at Okhla HE.

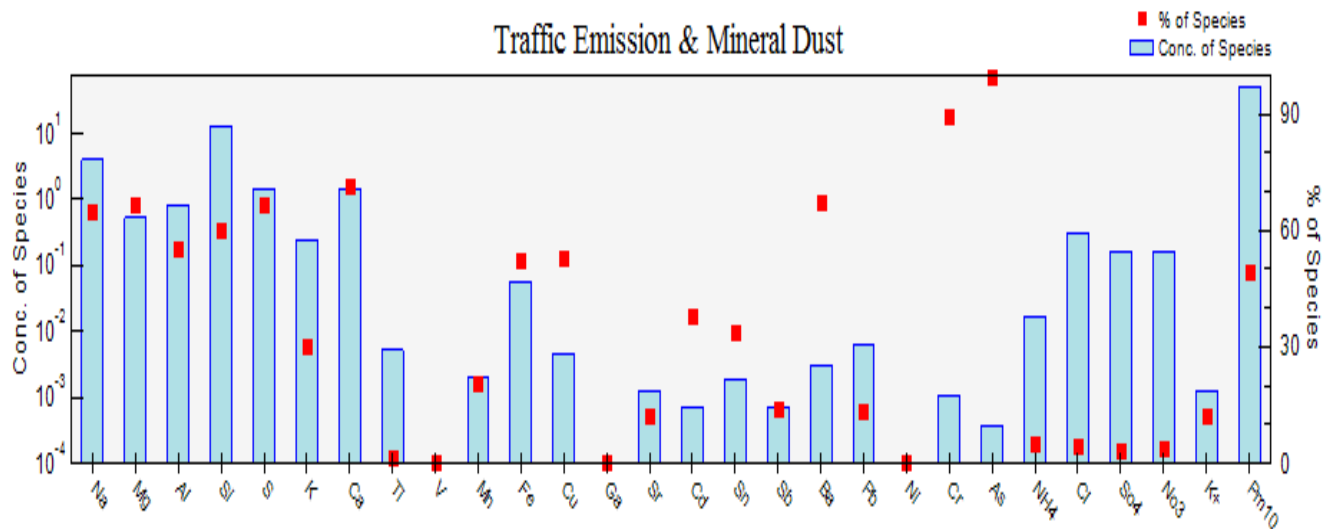


Figure 4.89. Source profile for Factor 4 at Okhla HE.

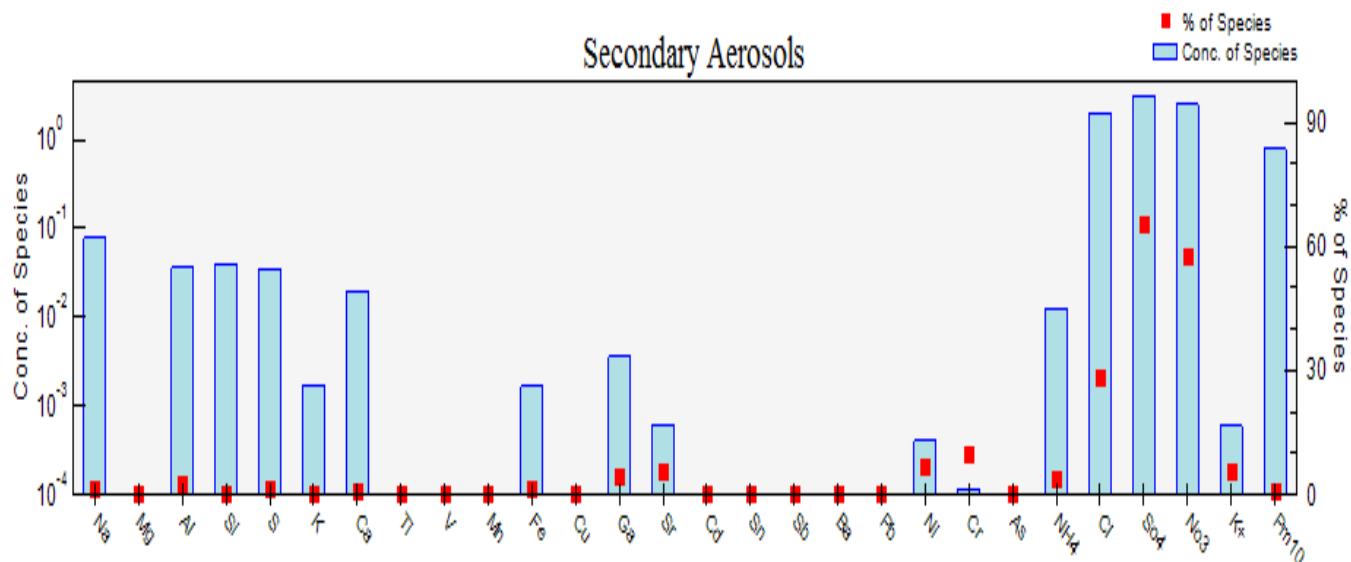


Figure 4.90. Source profile for Factor 5 at Okhla HE.

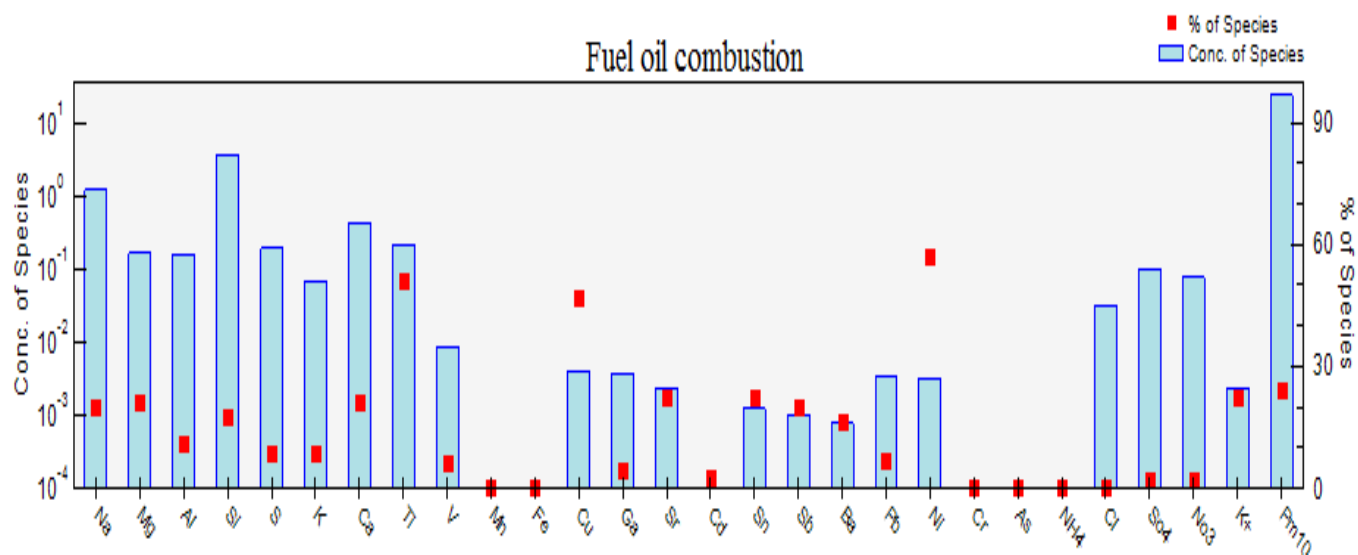


Figure 4.91. Source profile for Factor 6 at Okhla HE.



Source apportionment of ambient particulate matter during winter season in Delhi

The sources represented by the profiles and main average contributors to their presence in PM₁₀ samples are identified as:

Table 4.17: Source profile of PM₁₀-bound elements and ions measured at Okhla level 2.

Location and Elevation	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
OKHLA Higher elevation	NH ₄ ⁺ (74%)	Ti (50%), V (70%), Mn (63%), Ga (87%), Ni (30%), Sb (57%), Sr (57%)	Cd (50%), Pb (75%), Cl ⁻ (59%)	Si (57%), Al (56%), Na (68%), Mg (69%), Ca (83%), Fe (58%), Cr (84%), As (100%)	SO ₄ ²⁻ (62%), NO ₃ ⁻ (58%)	Ti (60%), Cu (50%), Ni (60%)
Sources	Secondary aerosols	Fuel oil combustion (both Industrial & domestic)	Unidentified	Traffic emission & mineral dust	Secondary aerosols	Fuel oil combustion (both Industrial & domestic)

Note: Percentage shown in the bracket represents the percentage fraction of the chemical species in the PM mass.



Source apportionment of ambient particulate matter during winter season in Delhi

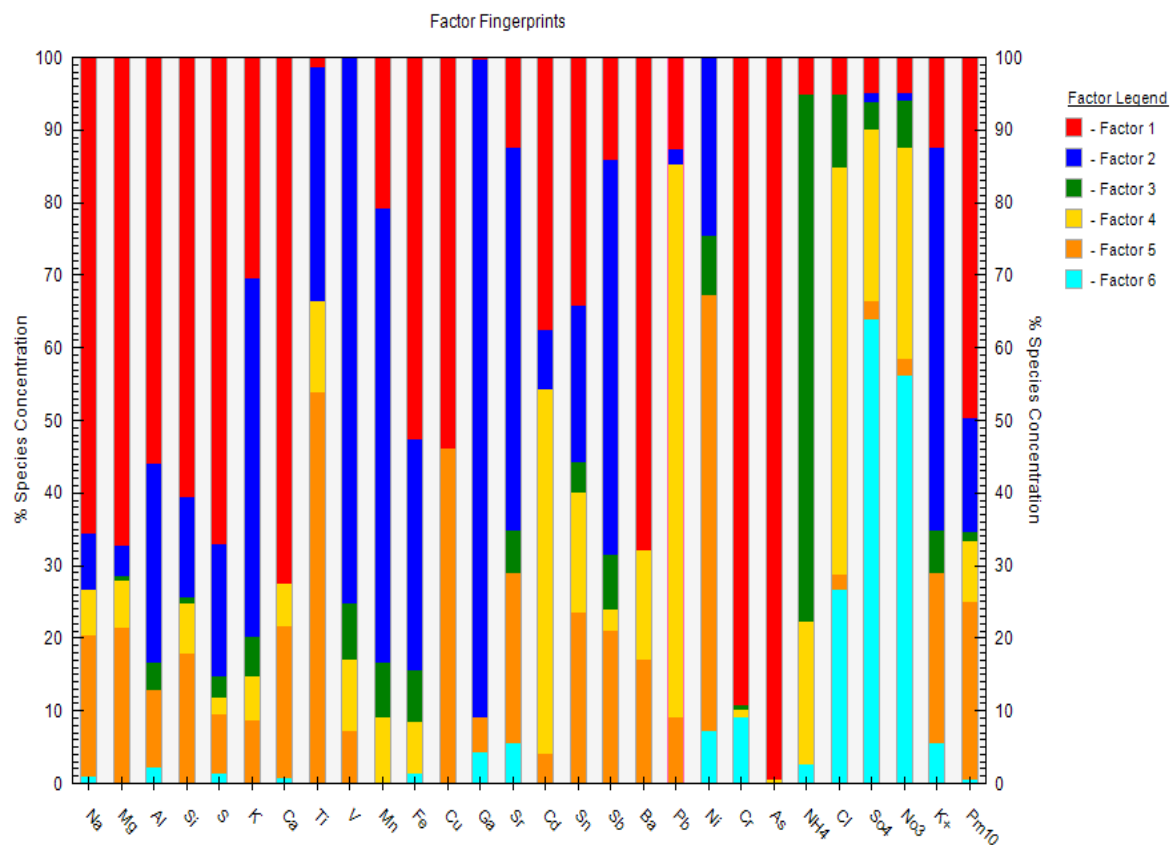


Figure 4.92. Factors contribution to Chemical Species at Okhla HE.

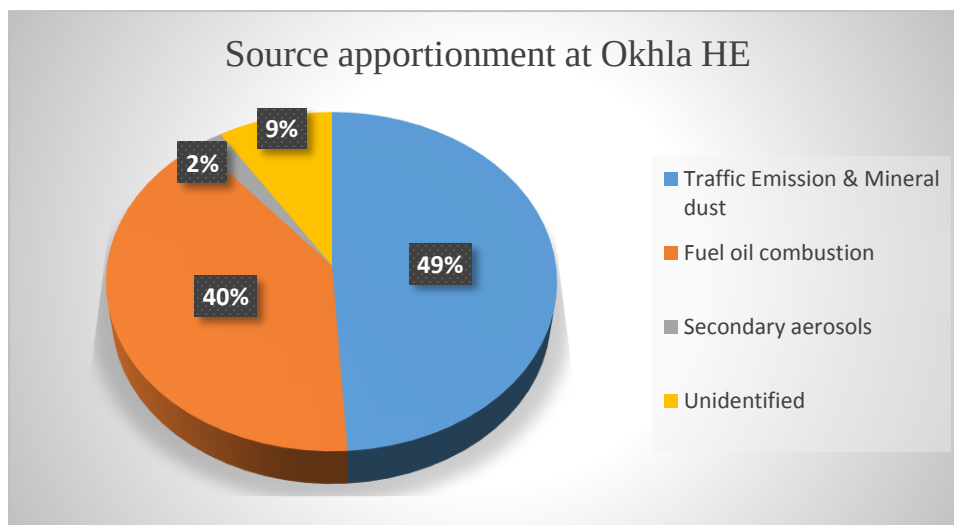


Figure 4.93. Source apportionment of PM₁₀ at Okhla HE.



PM Source apportionment at IIT Delhi

PMF model has resolved five factors and four factors at a lower elevation and higher elevation, respectively at IIT Delhi. Mineral dust and traffic emission are the predominant sources at this study site, and their contribution was about 45% and 14% respectively at a lower elevation. At higher elevation model has resolved mineral dust and traffic emission as a single factor and their together contribution was about 43% of the PM₁₀ mass at a higher elevation, which is lesser than lower elevation when both sources were added at a lower elevation. This is due to a decrease in mineral dust in higher elevation. Fuel oil combustion has been resolved by the model at both the elevation and their contribution at lower elevation was about 23% and was found to increase with elevation, hence contribution at a higher elevation was about 49%. Fuel oil combustion accounts for both industrial and domestic combustion. Coal burning was identified at this site, and their contribution was in trace quantities 2% and 4% in lower and higher elevations respectively. Secondary aerosols were the third major contributor at this site, and their contribution was about 16% and 14% at a lower elevation and higher elevation respectively.

Source apportionment at IIT Delhi LE

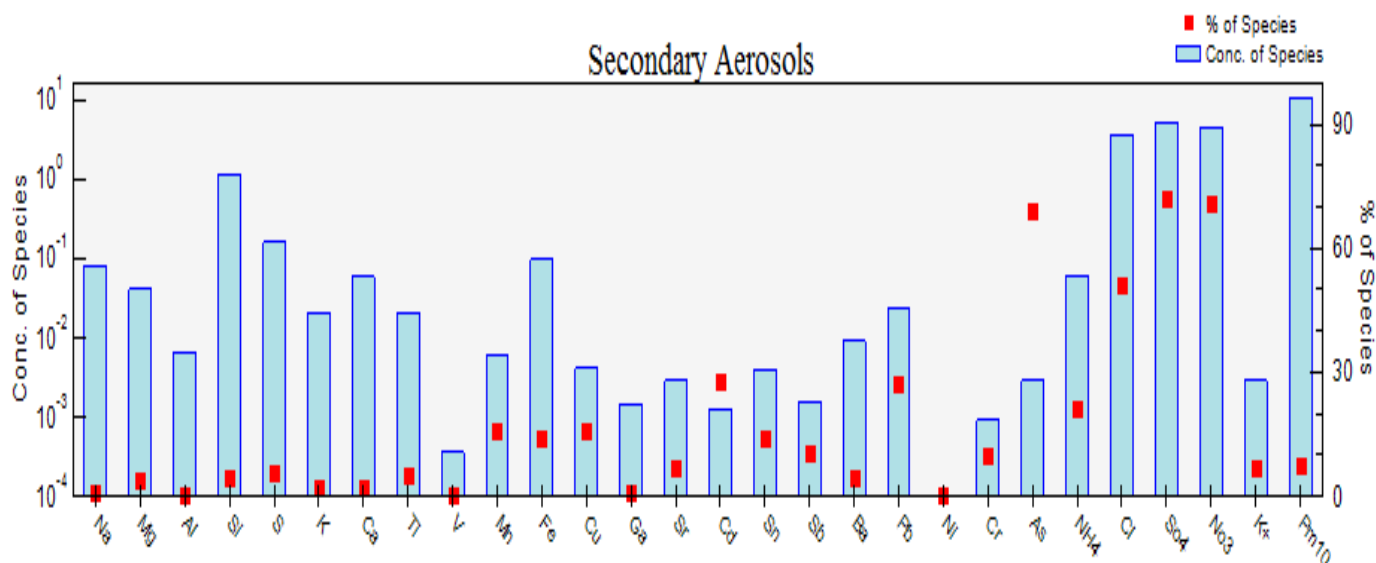


Figure 4.94. Source profile for Factor 1 at IIT Delhi LE.



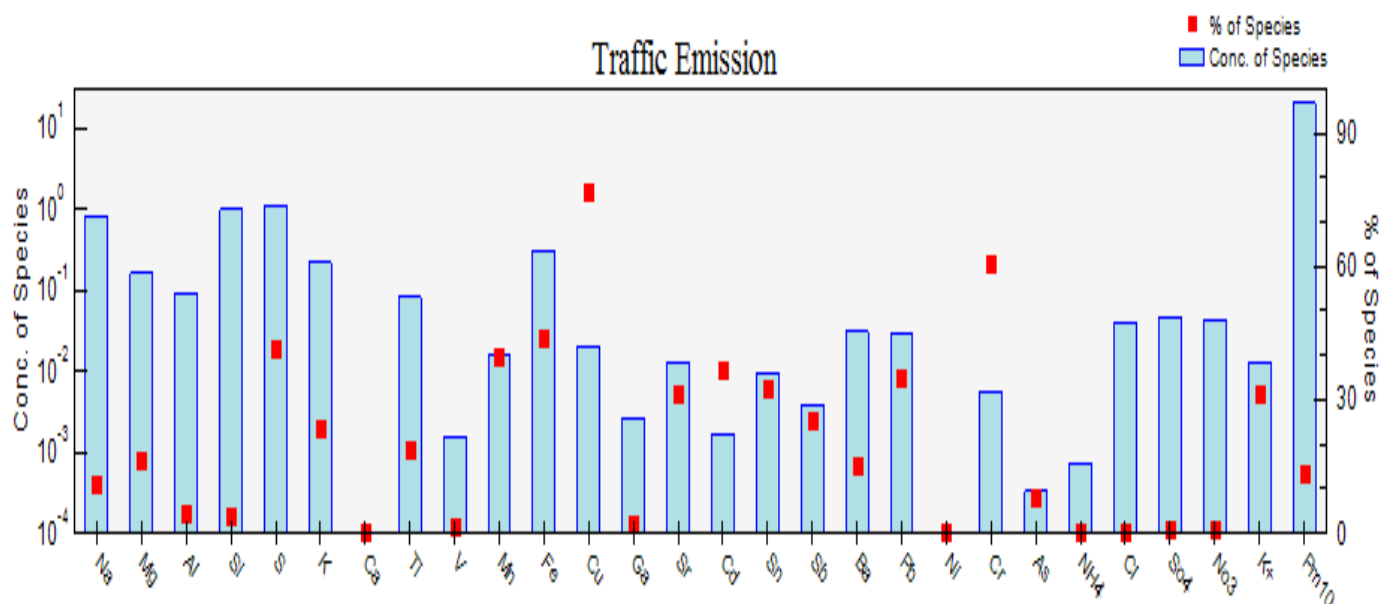


Figure 4.95. Source profile for Factor 2 at IIT Delhi LE.

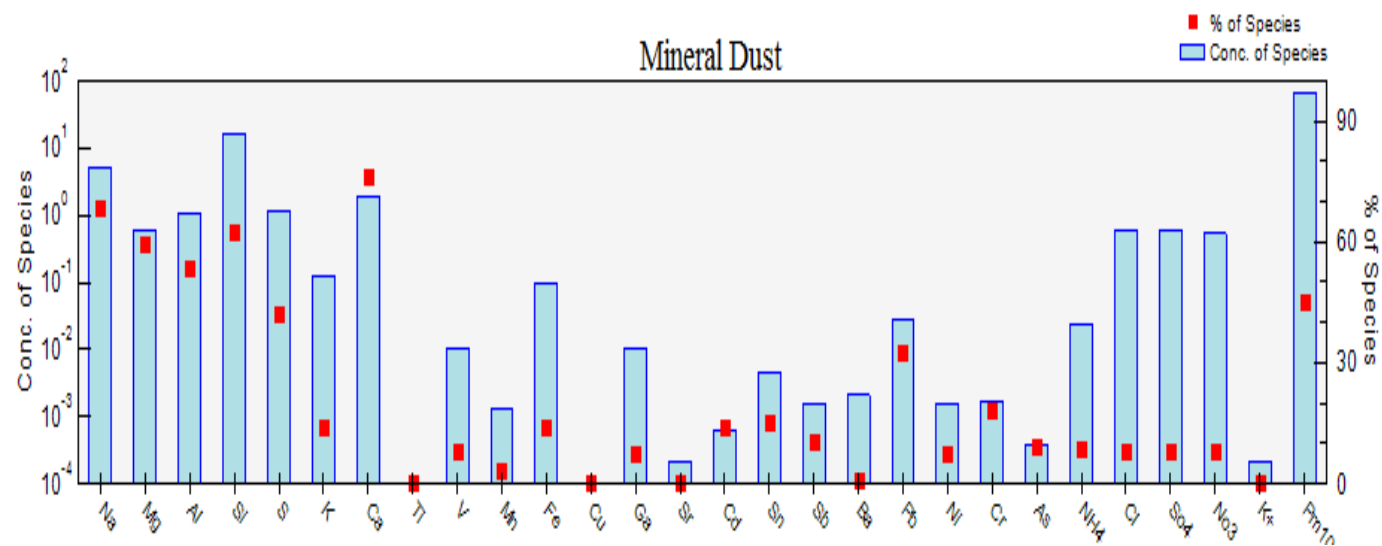


Figure 4.96. Source profile for Factor 3 at IIT Delhi LE.



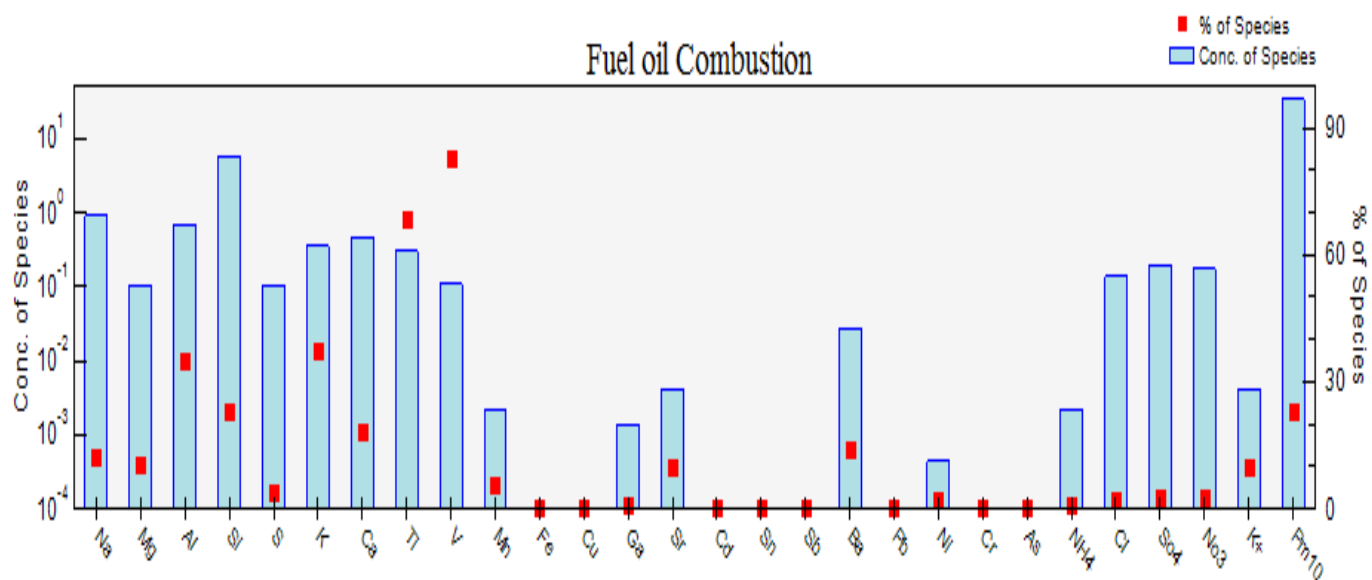


Figure 4.97. Source profile for Factor 4 at IIT Delhi LE.

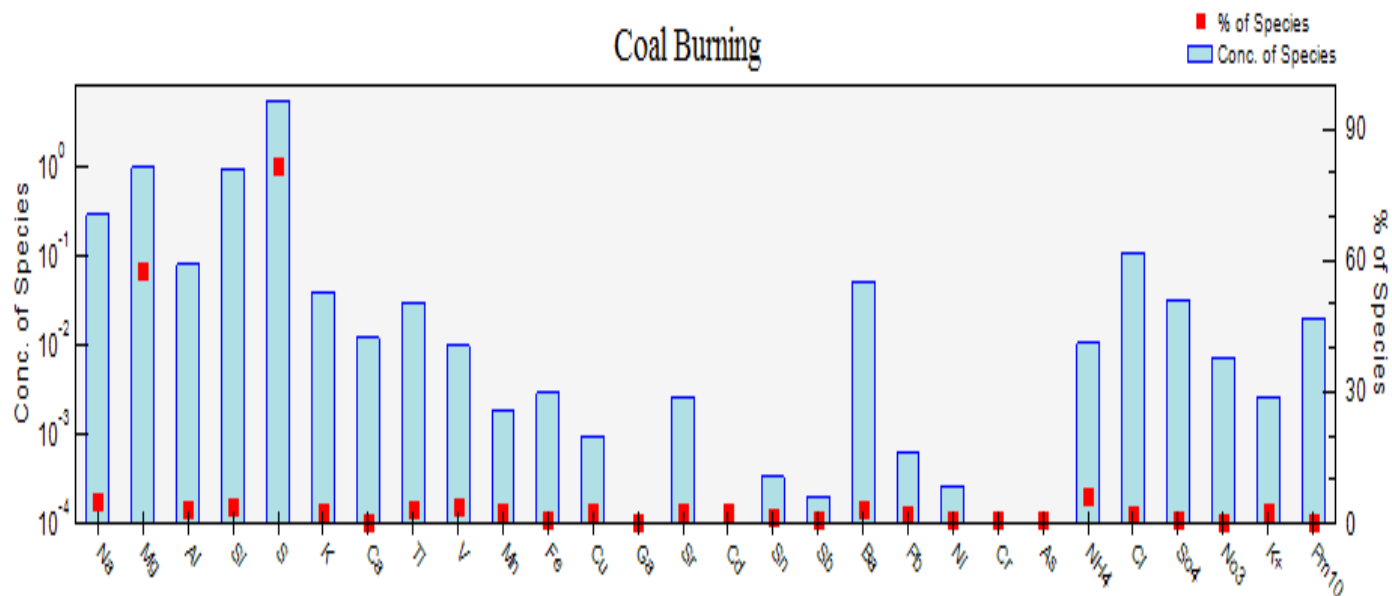


Figure 4.98. Source profile for Factor 5 at IIT Delhi LE.



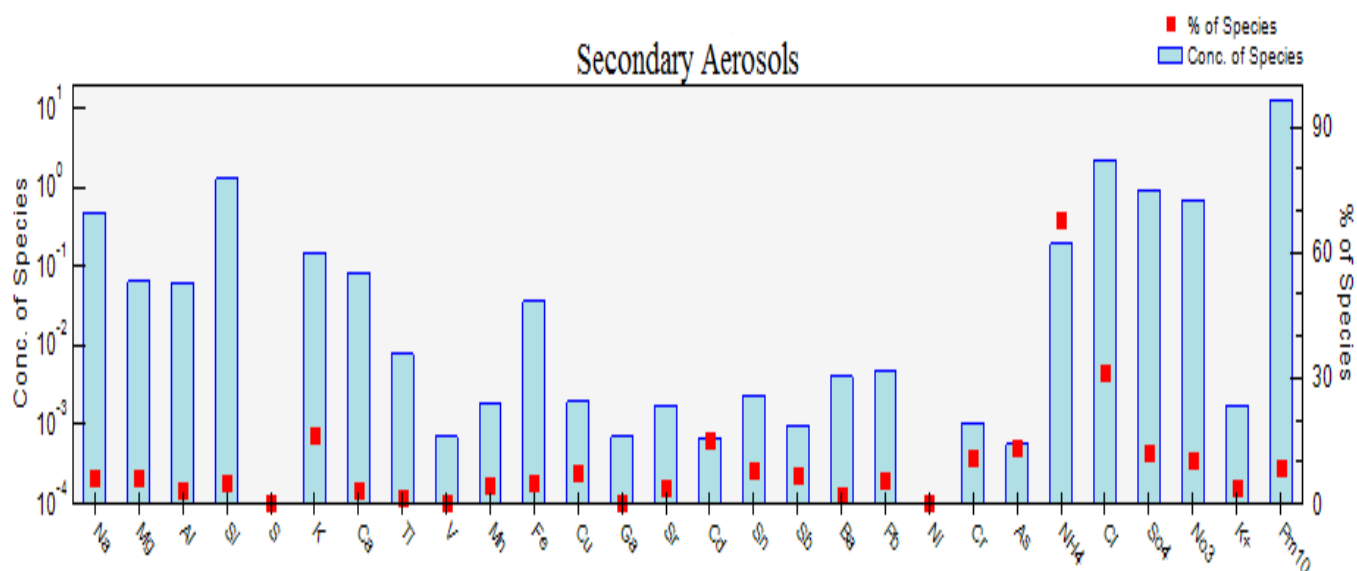


Figure 4.99. Source profile for Factor 6 at IIT Delhi LE.

The sources represented by the profiles and main average contributors to their presence in PM₁₀ samples are identified listed in Table 4.18:

Table 4.18: Source profile of IIT Delhi lower elevation for PM₁₀-bound elements and ions.

Location and Elevation	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
IIT Delhi Lower elevation	NH ₄ ⁺ (26%), SO ₄ ²⁻ (70%), NO ₃ ⁻ (68%)	Si (67%), Al (60%), Na (70%), Mg (62%), Ca (65%),	Fe (53%), Cr (62%), Cu (80%), Mn (50%)	Ti (65%), V (80%), K (40%)	S (80%), Mg (62%)	NH ₄ ⁺ (62%)
	Secondary aerosols	Mineral dust	Traffic emission	Fuel oil combustion	Coal combustion	secondary aerosols

Note: Percentage shown in the bracket represents the percentage fraction of the chemical species in the PM mass.



Source apportionment of ambient particulate matter during winter season in Delhi

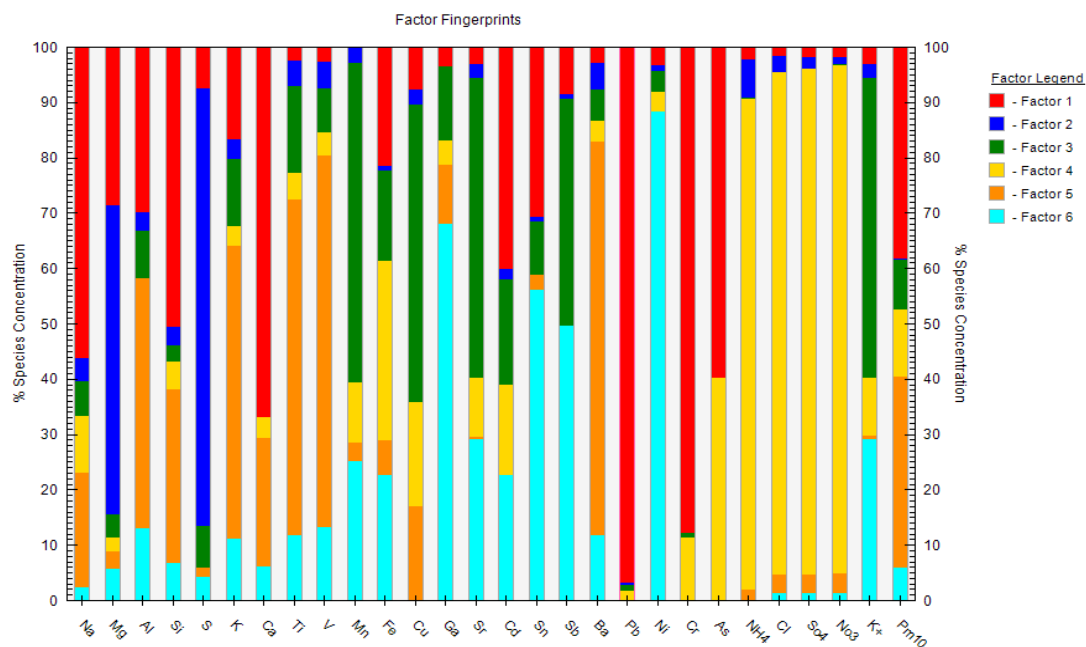


Figure 4.100. Factors contribution to Chemical species at IIT Delhi LE.

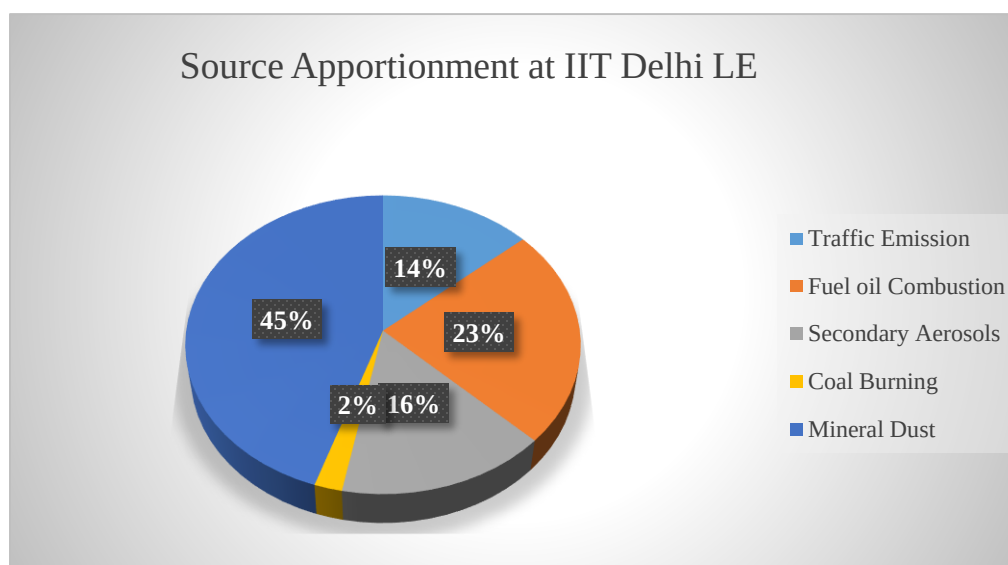


Figure 4.101. Source apportionment of PM₁₀ at IIT Delhi LE

Source apportionment at IIT Delhi HE

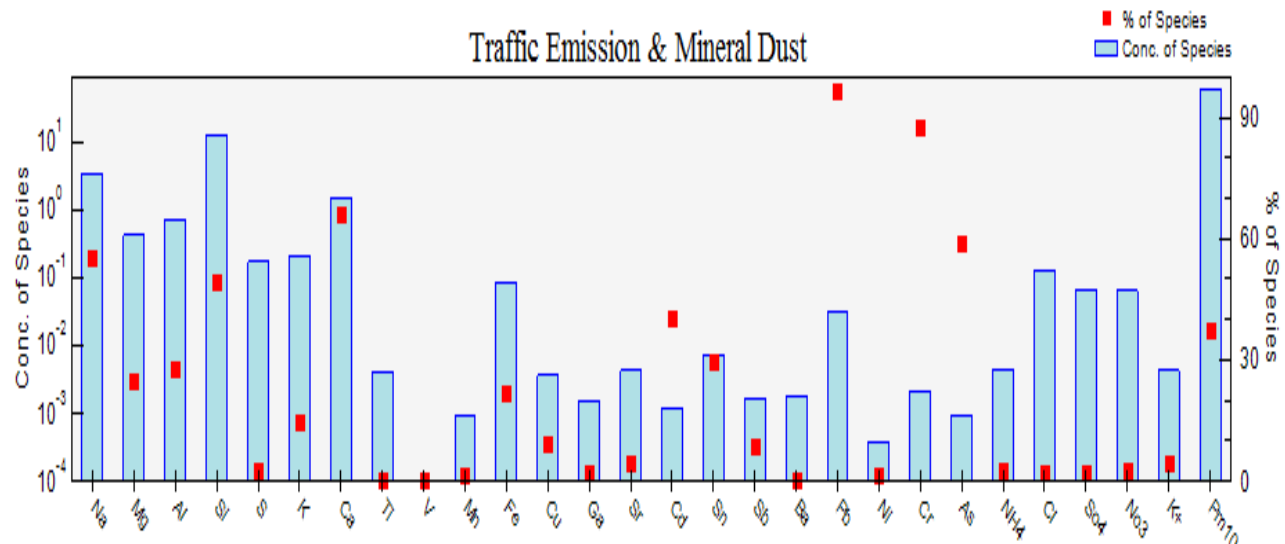


Figure 4.102. Source profile for Factor 1 at IIT Delhi HE.

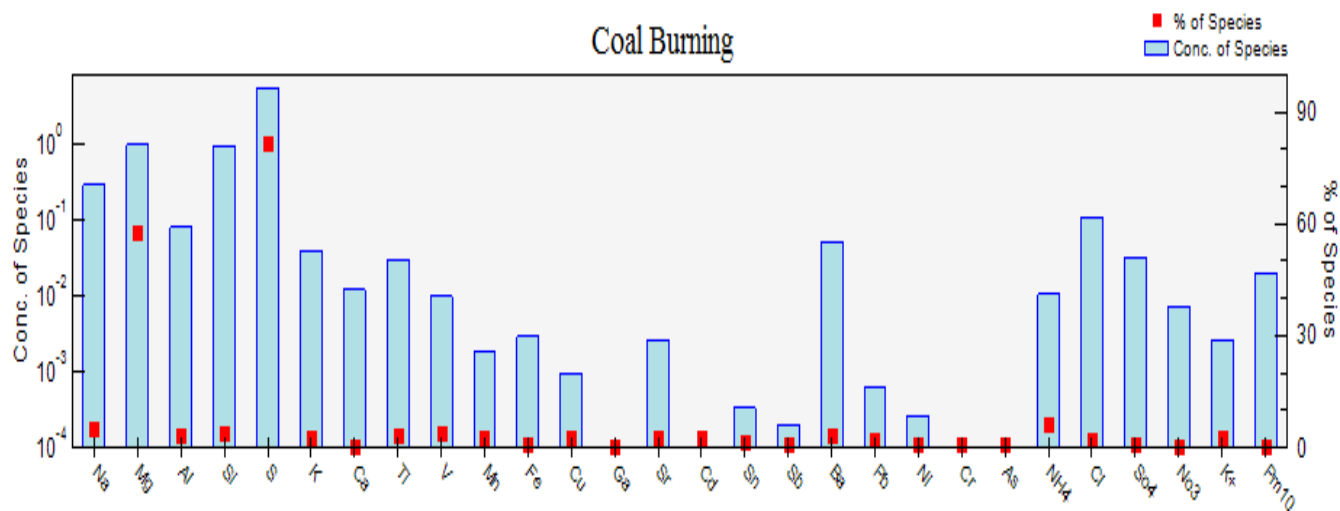


Figure 4.103. Source profile for Factor 2 at IIT Delhi HE.



Secondary Aerosols

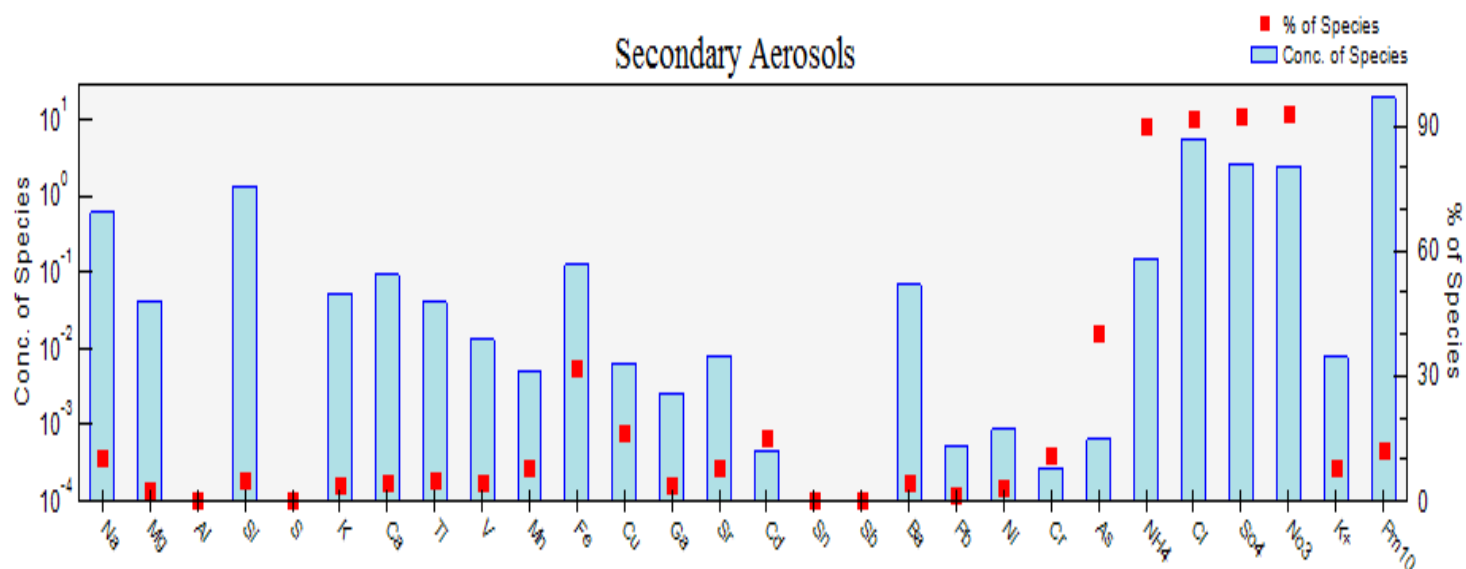


Figure 4.104. Source profile for Factor 3 at IIT Delhi HE.

Traffic emission

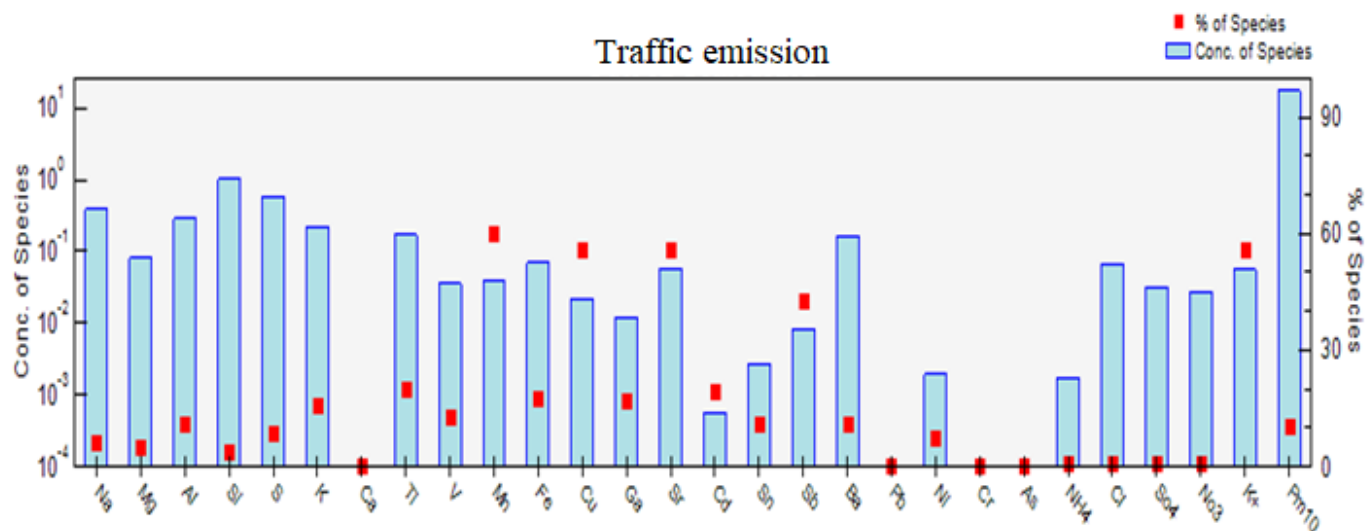


Figure 4.105. Source profile for Factor 4 at IIT Delhi HE.



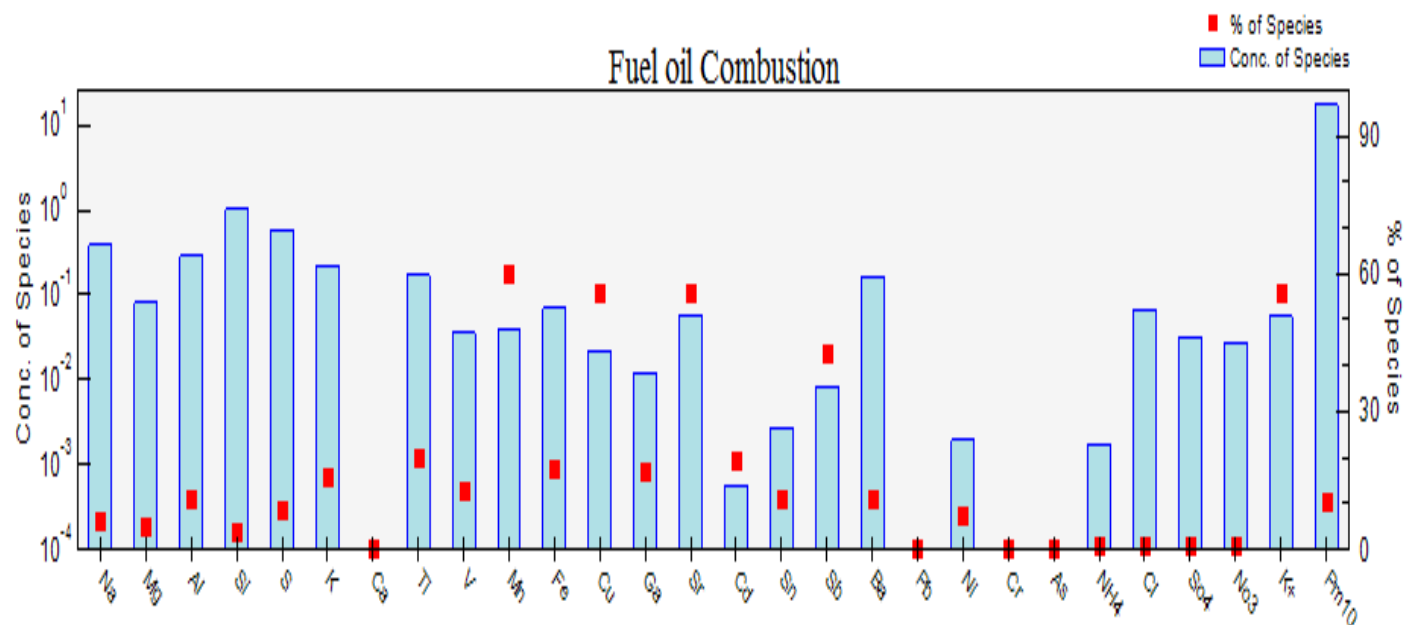


Figure 4.106. Source profile for Factor 5 at IIT Delhi HE.

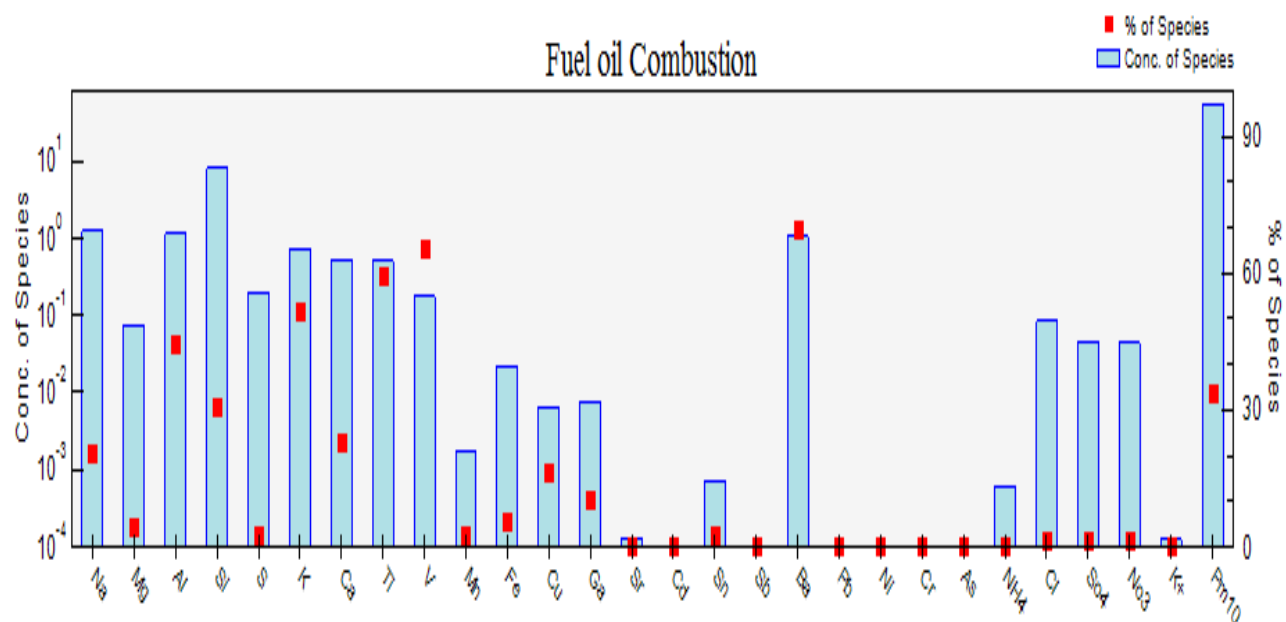


Figure 4.107. Source profile for Factor 6 at IIT Delhi HE.



Source apportionment of ambient particulate matter during winter season in Delhi

The sources represented by the profiles and main average contributors to their presence in PM₁₀ are listed in table 4.19:

Table 4.19: Source profile of PM₁₀-bound elements and ions measured at IIT Delhi HE.

Location and Elevation	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
IIT Delhi Higher elevation	Si (60%), Al (30%), Na (62%), Mg (25%), Ca (70%), Fe (25%), Cr (85%), As (60%)	S (80%), Mg (62%)	NH ₄ ⁺ (87%), SO ₄ ²⁻ (89%), NO ₃ ⁻ (90%), Cl ⁻ (90%)	Mn (60%), Cu (59%), Sr (62%)	Ti (70%), V (80%), K (35%)	Mn (30%), Ga (65%), Ni (85%), Sb (50%), Sr (40%), Sn (60%)
Sources	Traffic emission and mineral dust	Coal combustion	Secondary Aerosols	Traffic emission	Fuel oil combustion	Fuel oil combustion

Note: Percentage shown in the bracket represents the percentage fraction of the chemical species in the PM mass



Source apportionment of ambient particulate matter during winter season in Delhi

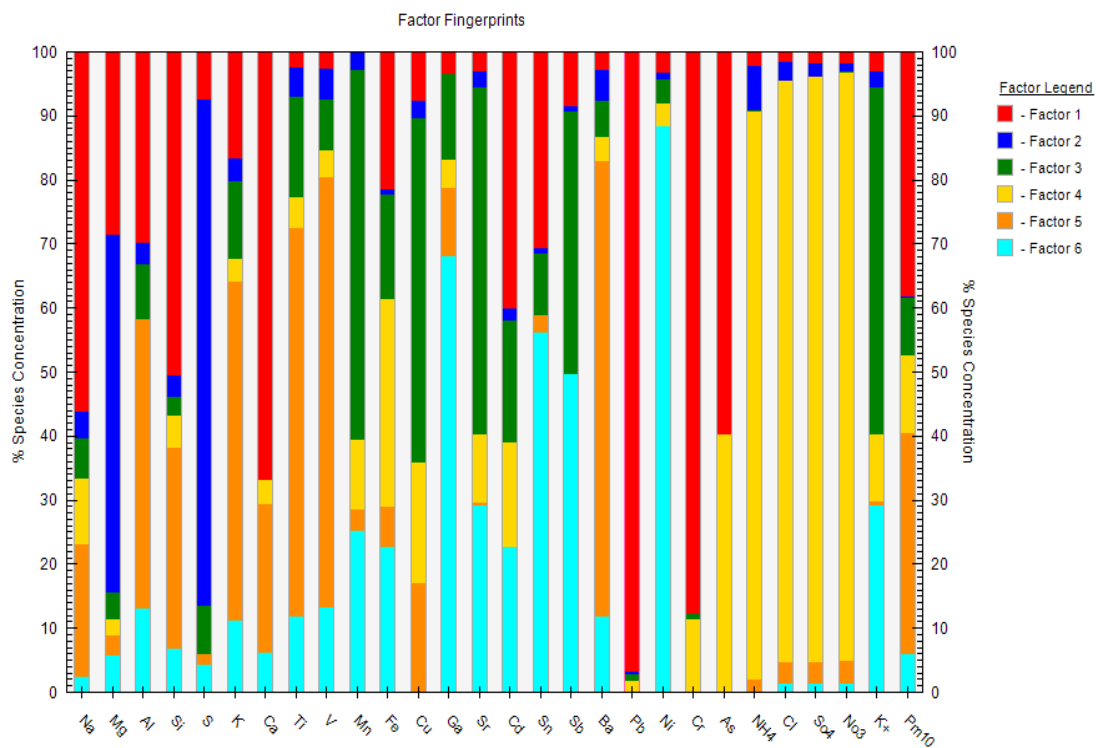


Figure 4.108. Factors contribution to chemical species at IIT Delhi HE.



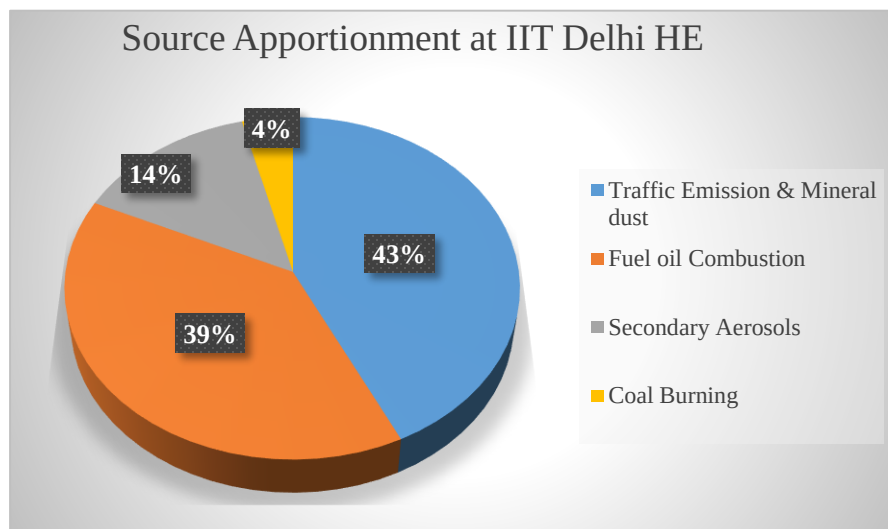


Figure 4.109. Source apportionment of PM₁₀ at IIT Delhi HE.

PM Source apportionment at DCE LE

At DCE, the model has resolved four factors and five factors at a lower elevation and higher elevation respectively. Fuel oil combustion was the predominant source at this study site, and their contribution at both the elevation was higher and found to be 32% and 39% at a lower elevation and higher elevation respectively. Mineral dust & traffic emission are resolved as a single factor due to the presence of chemical species from both the sources in the source profile and their together contribution was about 47% of the PM₁₀ mass at a lower elevation, and their contributions in higher elevation were about 18% and 28% respectively. Secondary aerosols were the major contributor at lower elevation (20%), and its contribution was in trace quantities (1%) in higher elevation. Coal burning was identified at a lower elevation, and its concentration was about 1%. Factor 4 in higher elevation was found to be unidentified sources.



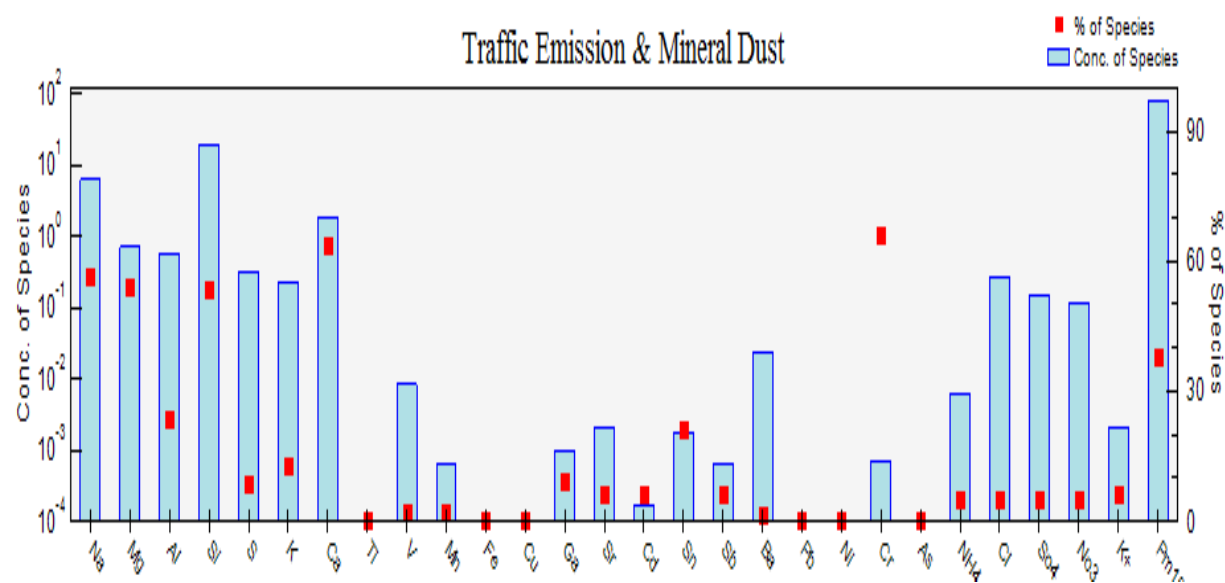


Figure 4.110. Source profile for Factor1 at DCE LE.

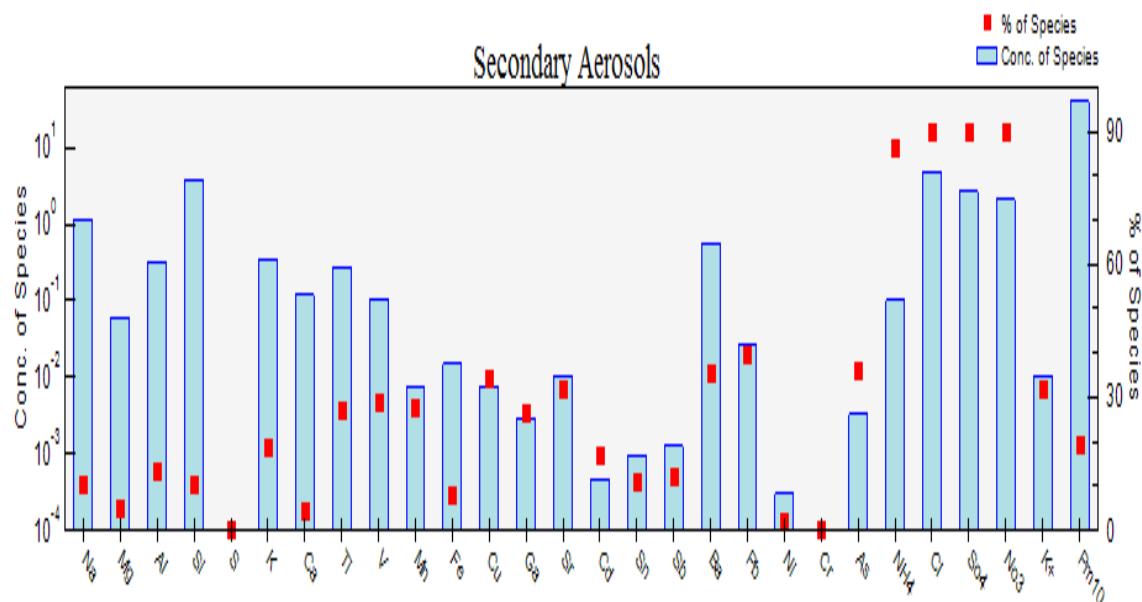


Figure 4.111. Source profile for Factor 2 at DCE LE.



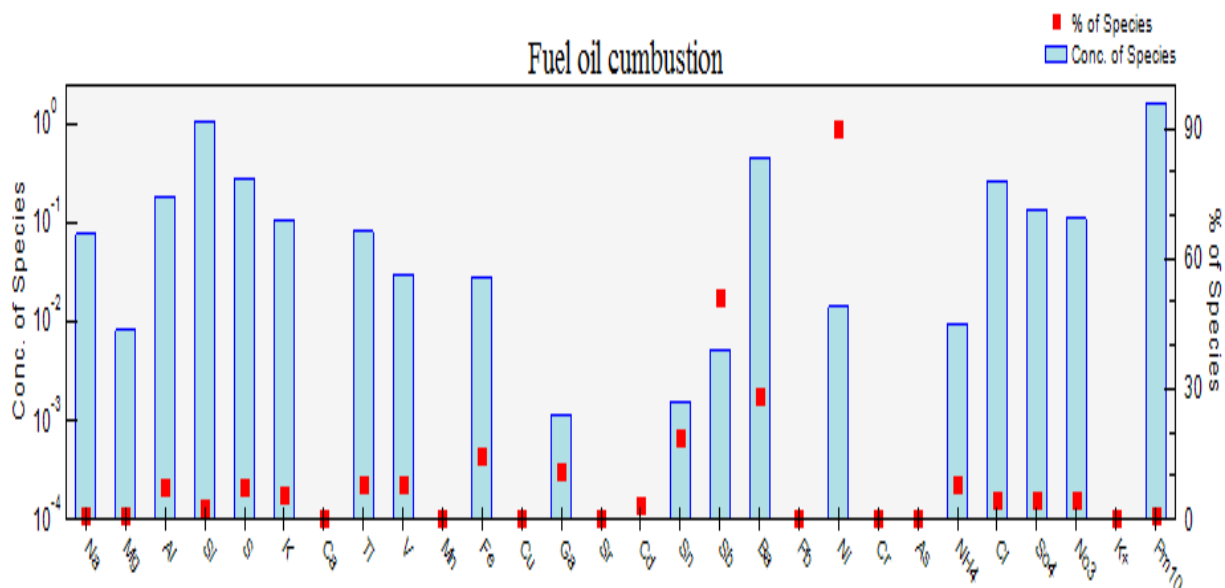


Figure 4.112. Source profile for Factor 3 at DCE LE.

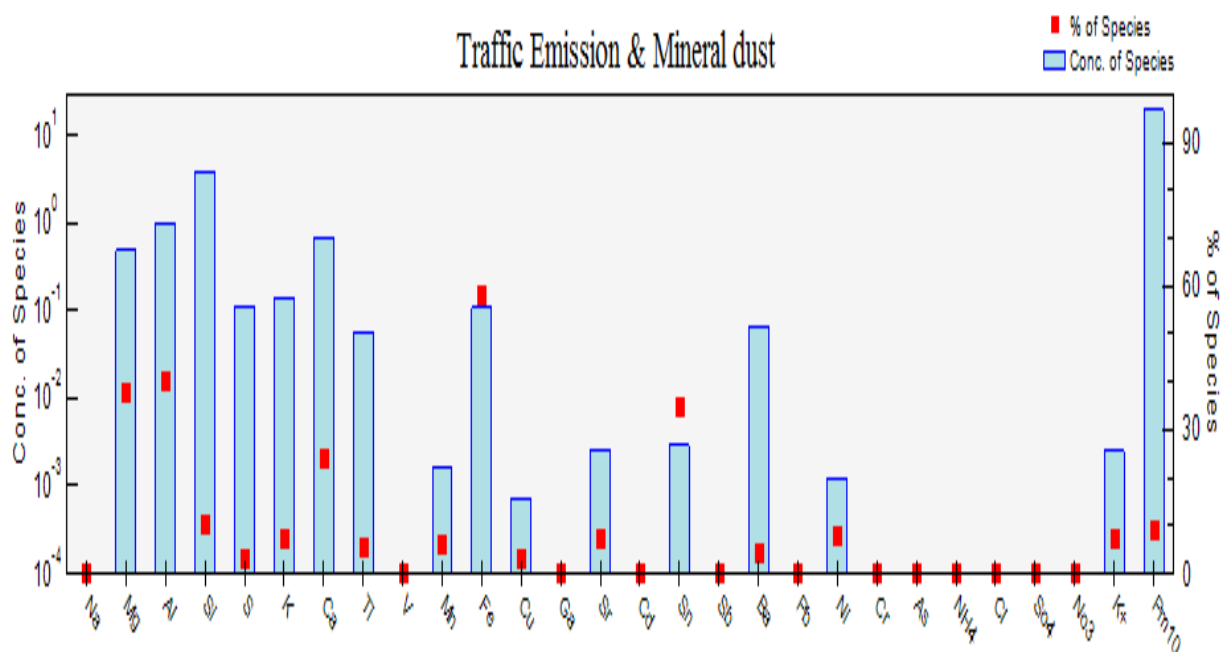


Figure 4.113. Source profile for Factor 4 at DCE LE.



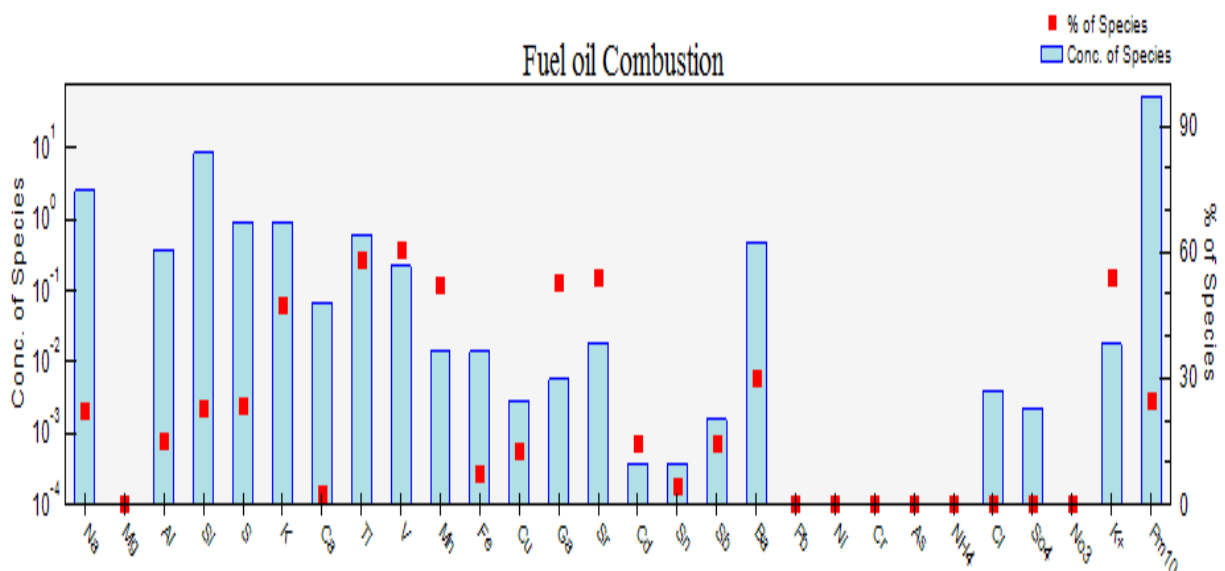


Figure. 4.114. Source profile for Factor 5 at DCE LE.

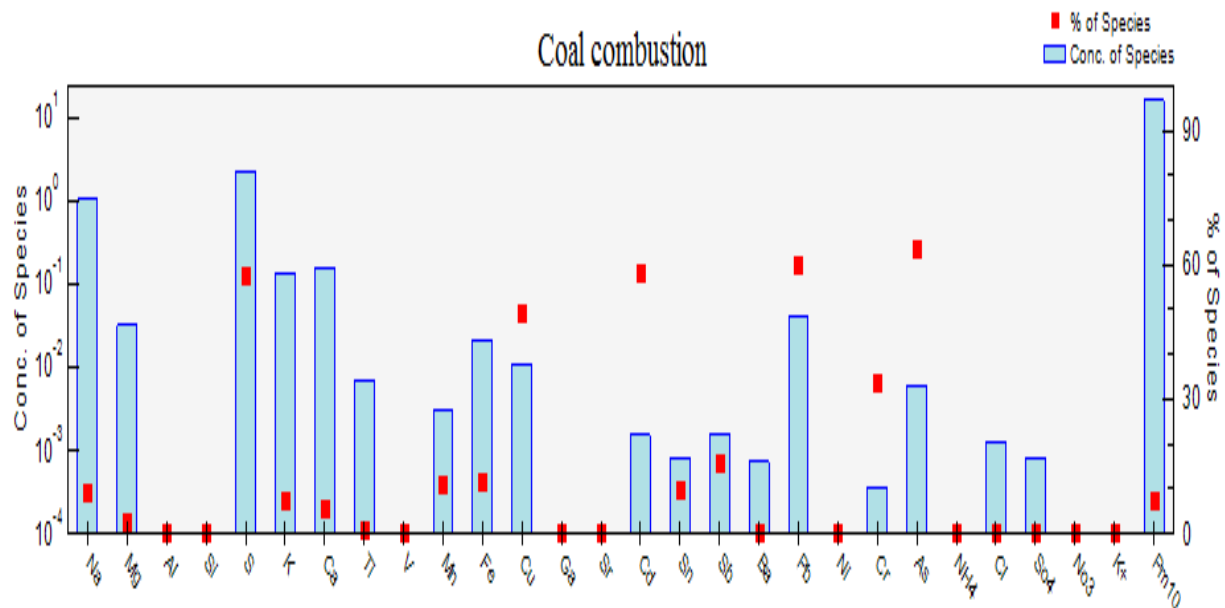


Figure 4.115. Source profile for Factor 6 at DCE LE.

Source apportionment of ambient particulate matter during winter season in Delhi

The sources represented by the profiles and main average contributors to their presence in PM₁₀ are listed in table 4.20:

Table.4.20. Source profile of PM₁₀-bound elements and ions measured at DCE LE.

Location and Elevation	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
DCE Lower elevation	Si (60%), Al (25%), Na (62%), Mg (60%), Ca (75%), Cr (65%)	NH ₄ ⁺ (89%), SO ₄ ²⁻ (89%), NO ₃ ⁻ (90%), Cl ⁻ (90%)	Al (50%), Mg (48%), Ca (28%), Fe (60%)	Ni (90%), Ba (32%), Sb (50%), Sn (20%)	Ti (60%), V (62%), K (55%), Ga (58%), Sr (58%)	S (61%), Pb (62%), As (62%), Cd (60%), Cu (58%)
	Traffic emission and mineral dust	Secondary aerosols	Traffic emission and mineral dust	Fuel oil combustion	Fuel oil combustion	Coal combustion

Note: Percentage shown in the bracket represents the percentage fraction of the chemical species in the PM mass.



Source apportionment of ambient particulate matter during winter season in Delhi

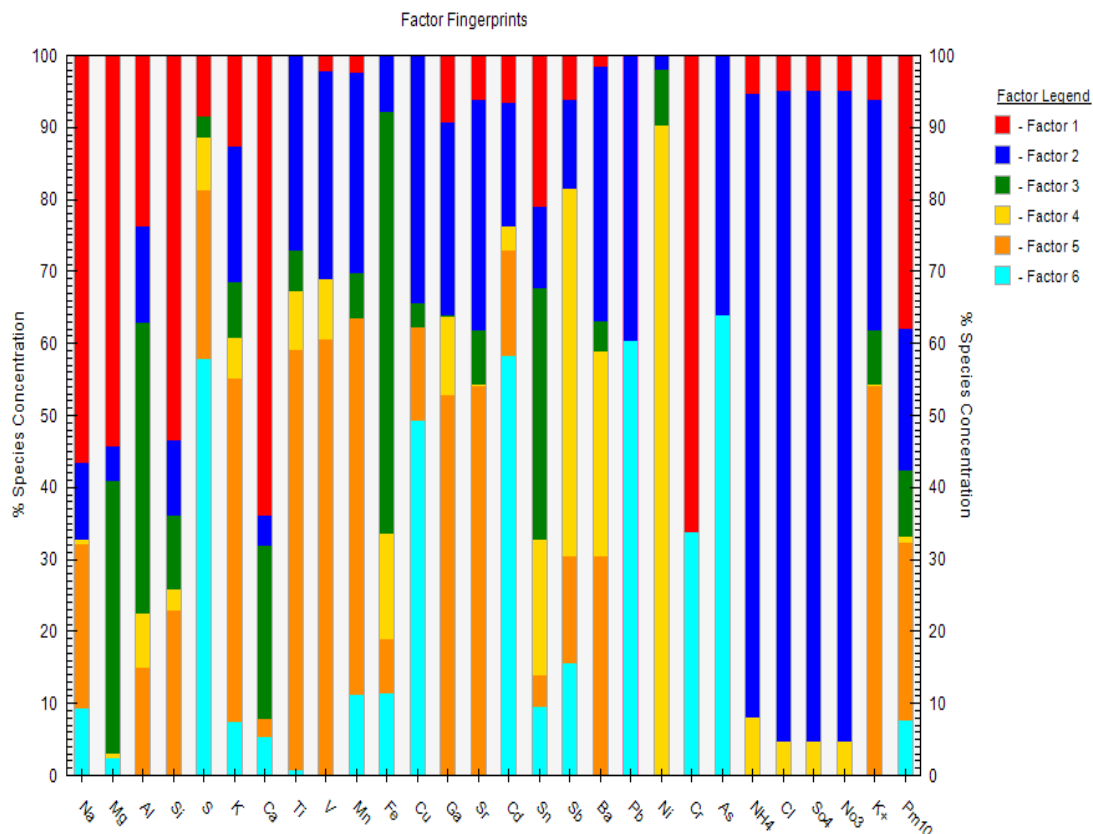


Figure 4.116. Factors contribution to Chemical species at DCE LE

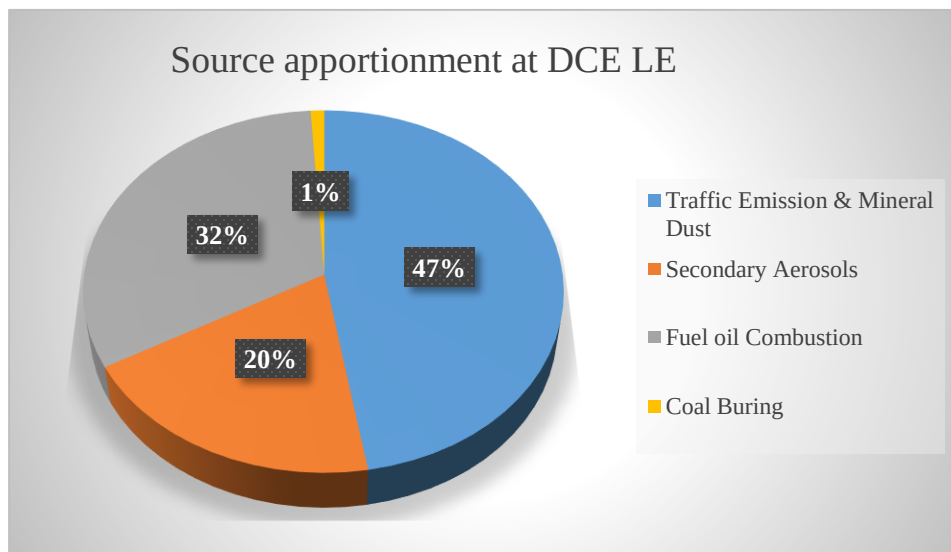


Figure.4.117. Source apportionment of PM₁₀ at DCE LE



PM Source apportionment at DCE at HE

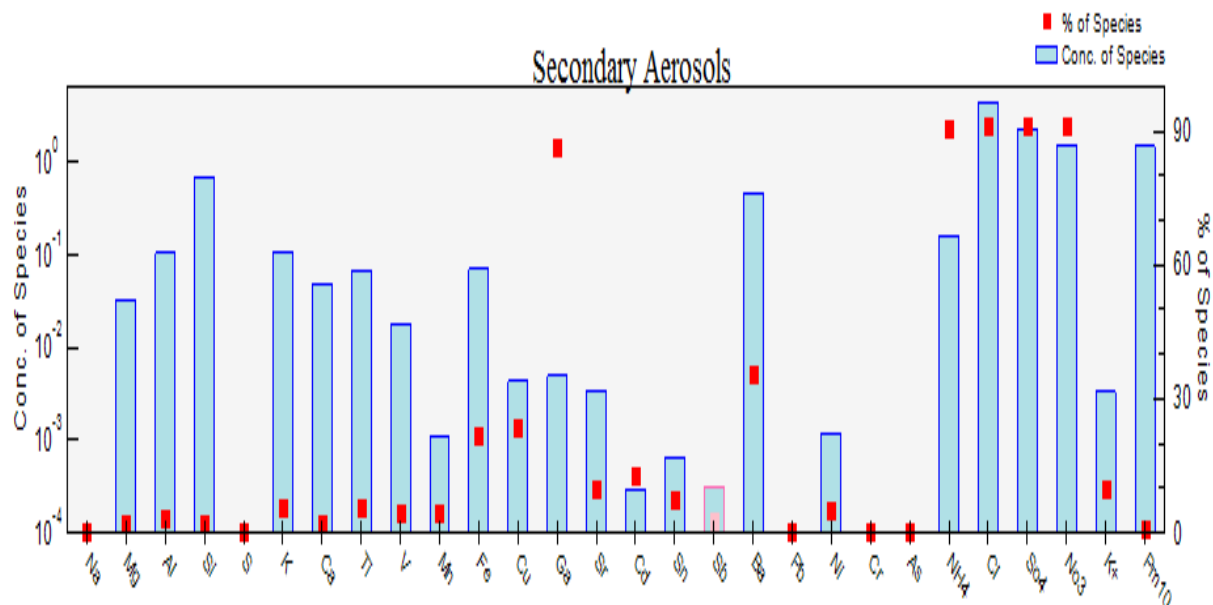


Figure 4.118. Source profile for Factor 1 at DCE HE.

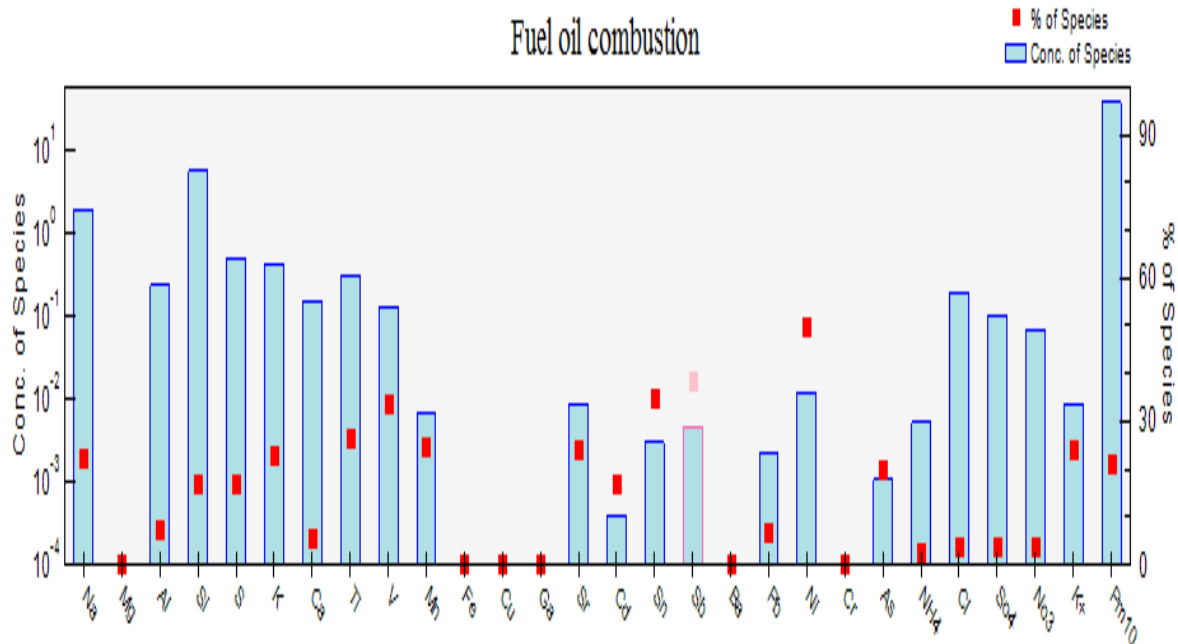


Figure.4.119. Source profile for Factor 2 at DCE HE.



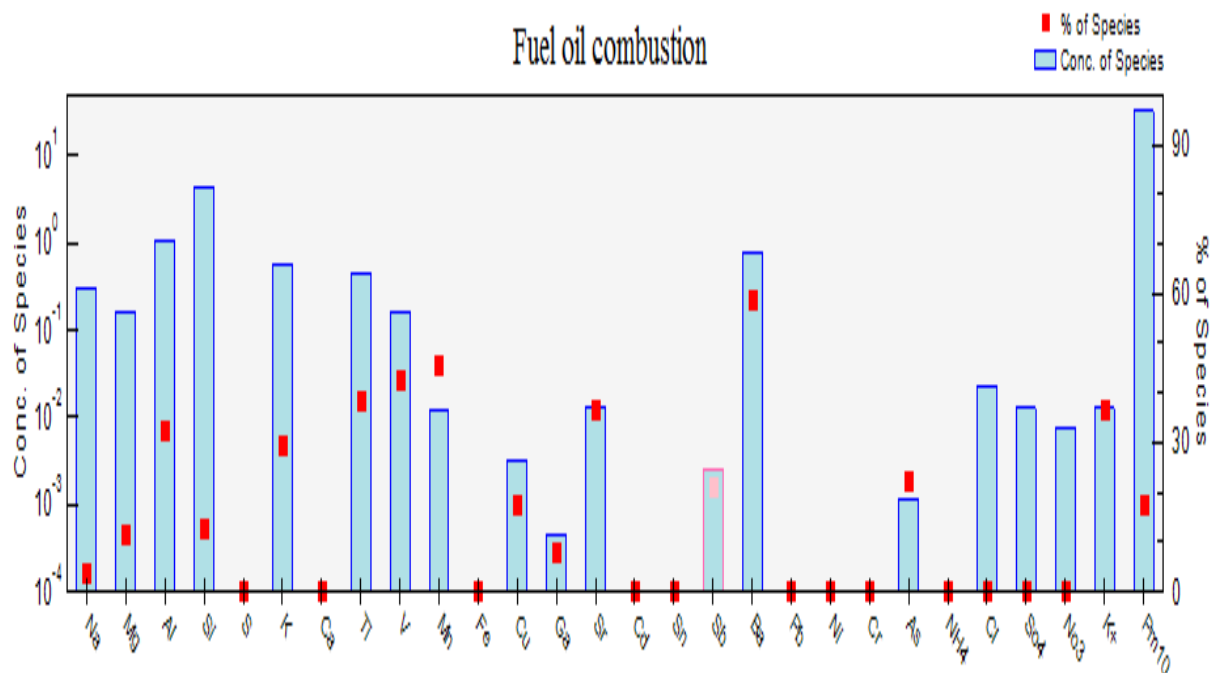


Figure 4.120. Source profile for Factor 3 at DCE HE.

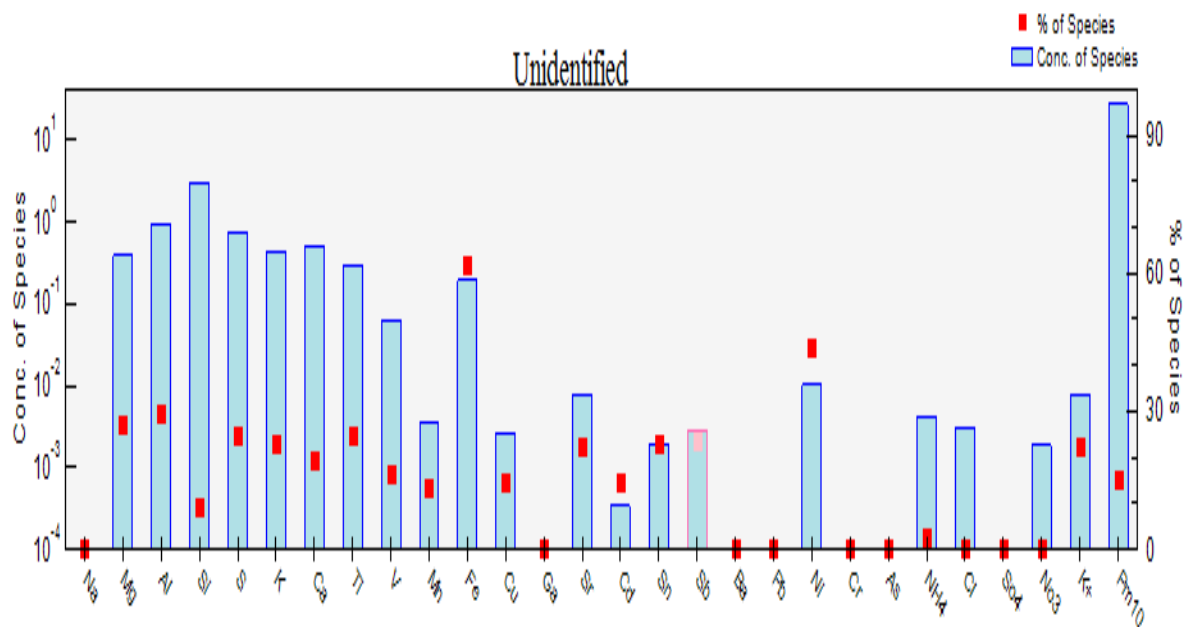


Figure 4.121. Source profile for Factor 4 at DCE HE.



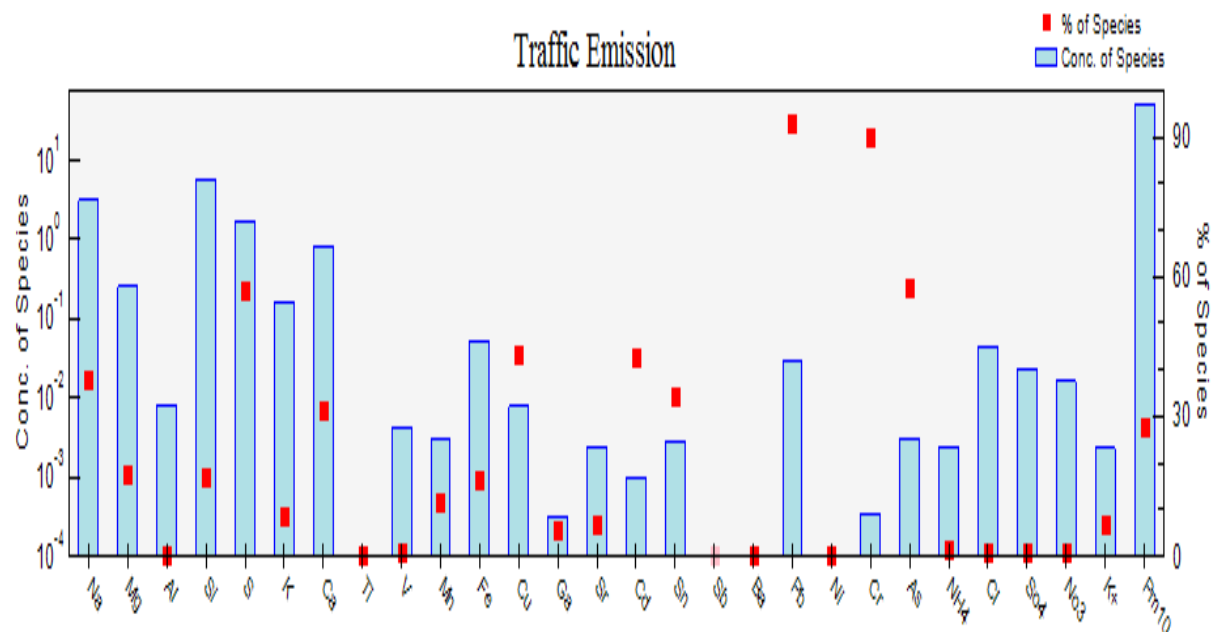


Figure 4.122. Source profile for Factor 5 at DCE HE.

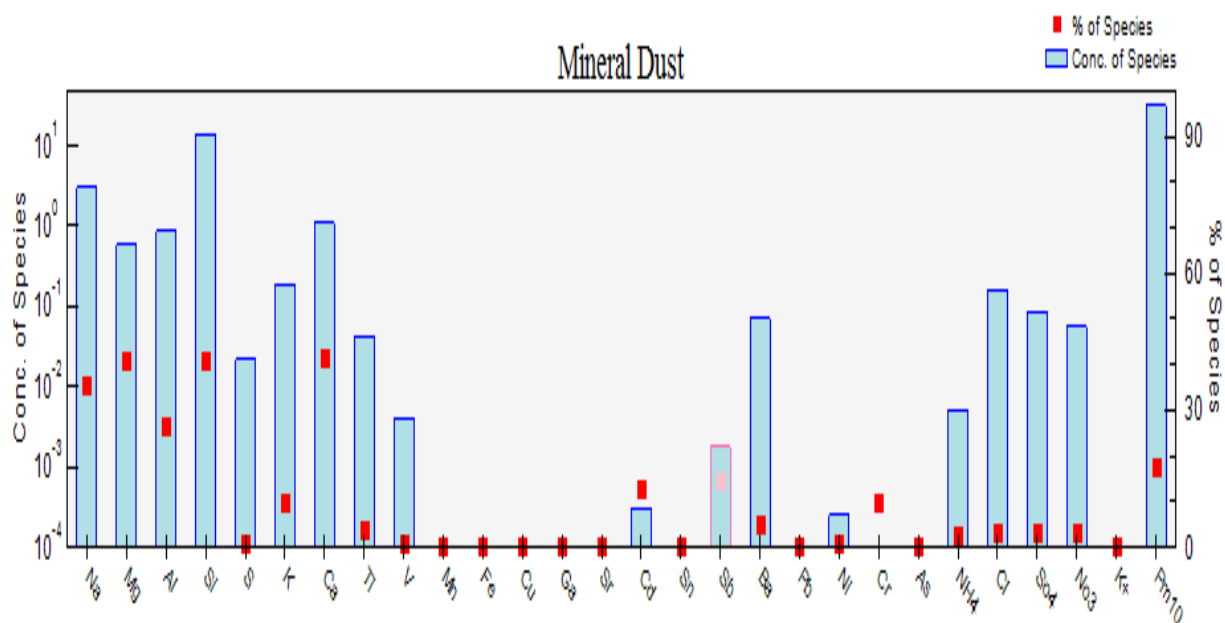


Figure 4.123. Source profile for Factor 6 at DCE HE.



Source apportionment of ambient particulate matter during winter season in Delhi

The sources represented by the profiles and main average contributors to their presence in PM₁₀ are listed in Table 4.21:

Table.4.21. Source profile of PM₁₀-bound elements and ions measured at DCE HE.

Location and Elevation	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
DCE Higher elevation	NH ₄ ⁺ (89%), SO ₄ ²⁻ (89%), NO ₃ ⁻ (90%), Cl ⁻ (90%)	Ti (60%), V (62%), Mn (55%), Ni (55%), Sn (40%), Sb (43%)	Ti (50%), V (55%), Mn (58%), Ba (60%)	Fe (60%), Ni (51%)	Cr (90%), Pb (90%), Cd (50%), Cu (50%)	Na (43%), Mg (47%), Al (30%), Si (47%), Ca (59%)
	Secondary aerosols	Fuel oil combustion	Fuel oil combustion	Unidentified	Traffic emission	Mineral dust

Note: Percentage shown in the bracket represents the percentage fraction of the chemical species in the PM mass.



Source apportionment of ambient particulate matter during winter season in Delhi

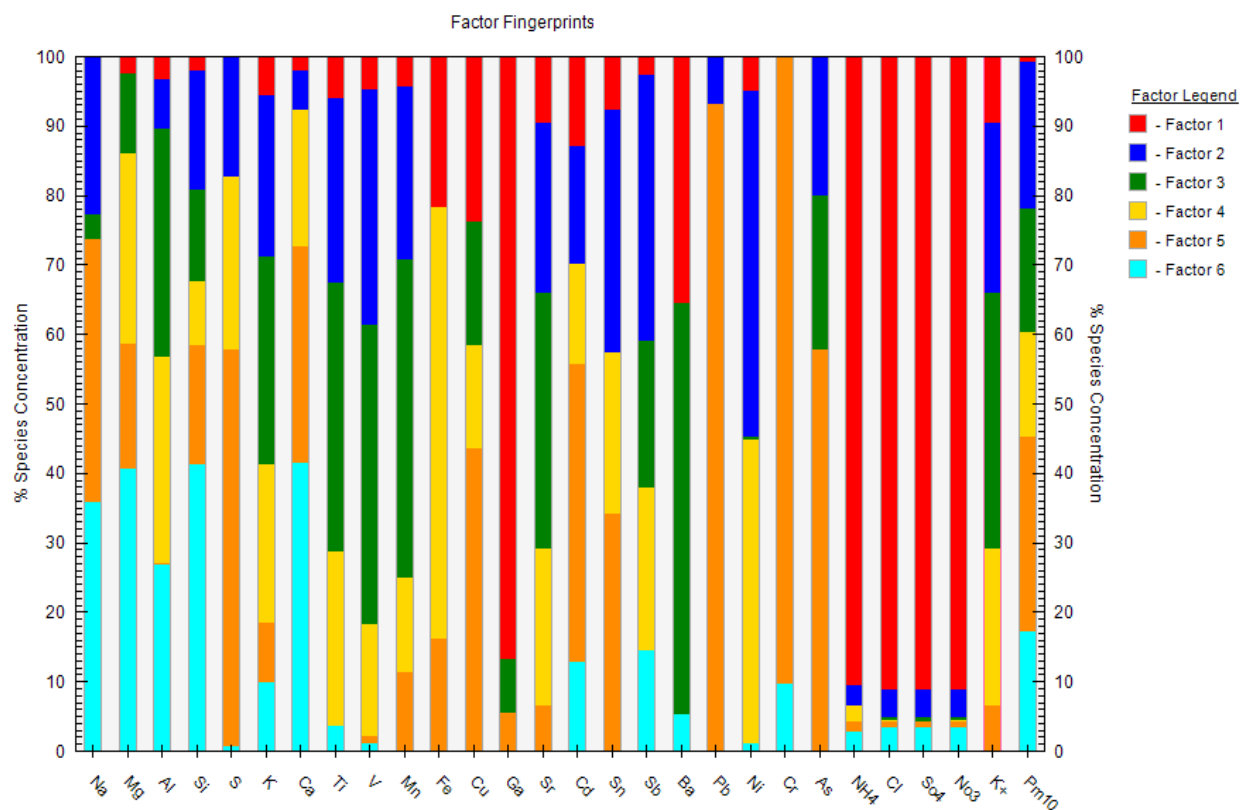


Figure 4.124. Factors contribution to Chemical species at DCE HE.

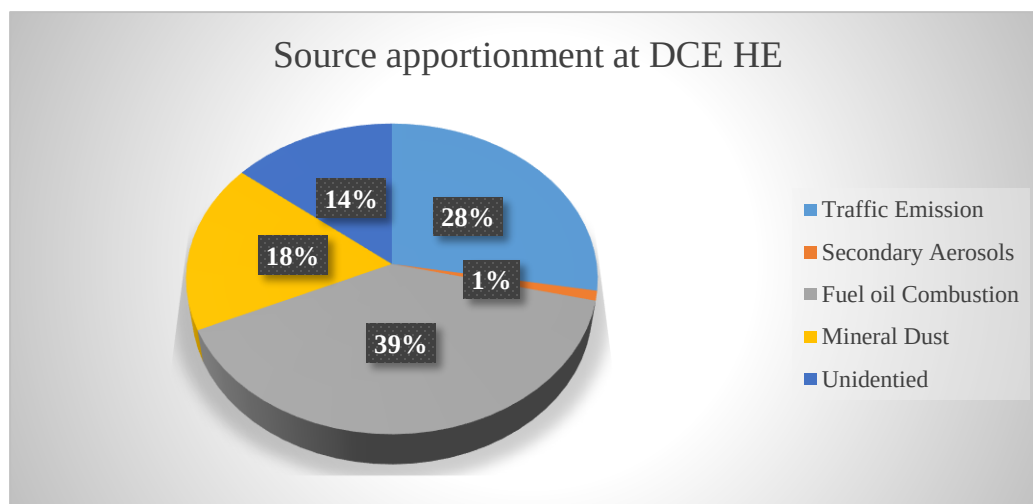


Figure 4.125. Source apportionment of PM₁₀ at DCE HE.



PM Source apportionment at Murthal

At Murthal, the model has resolved four factors and five factors at a lower elevation and higher elevation, respectively. Mineral dust and fuel oil combustion are the predominant sources at this study site, their contribution was similar about 32% at a lower elevation, and the contribution of fuel oil combustion was about 28% in higher elevation. Fuel oil combustion includes both domestic and industrial combustion. Murthal is a rural site. Hence soil dust is a predominant at this site. At both elevations, the model has resolved mineral dust and traffic emission as a single factor, and their together contribution was about 16% and 22% of the PM₁₀ mass at a lower elevation and higher elevation, respectively. Secondary aerosols are the major contributor at lower elevation (20%), and its contribution was in trace quantities (3%) in higher elevation. Mineral dust and fuel oil combustion were resolved as a single factor due to the presence of chemical species from both the sources in the source profile. Both these sources contribute about 43% of the PM₁₀ mass at a higher elevation. Solid waste burning was found to be in trace quantity (about 4%).

PM Source apportionment at Murthal LE

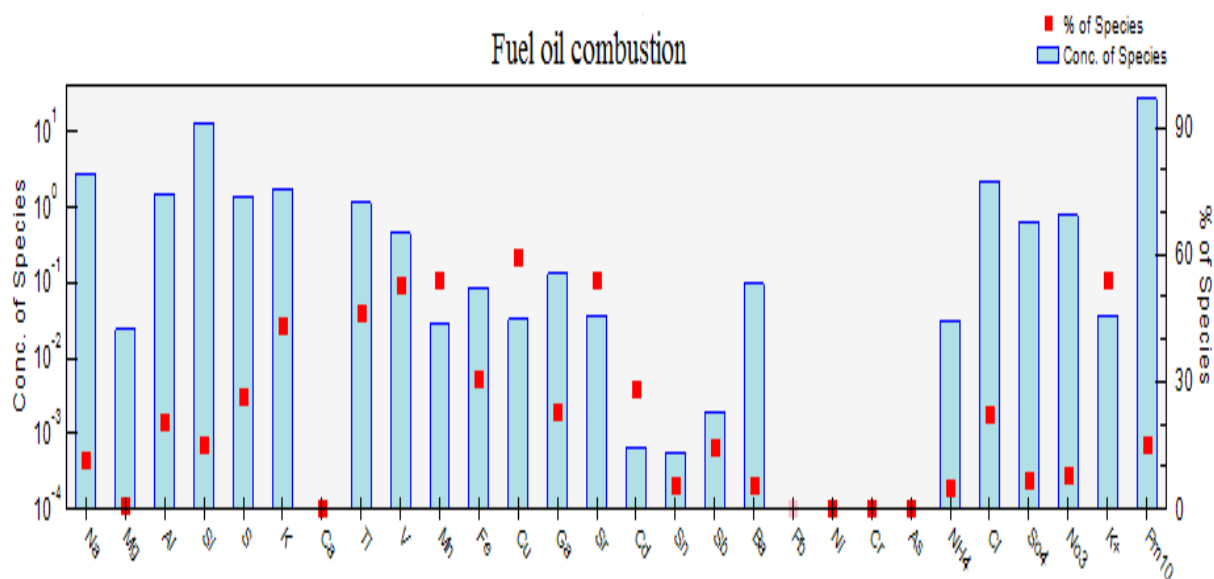


Figure 4.126. Source profile for Factor 1 at Murthal LE.



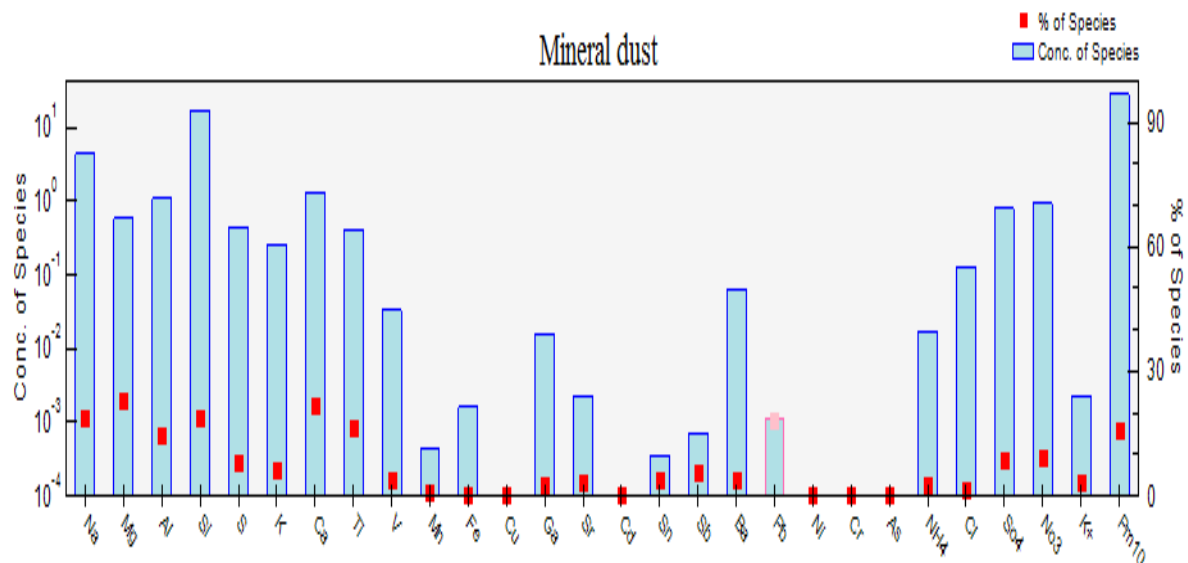


Figure 4.127. Source profile for Factor 2 at Murthal LE.

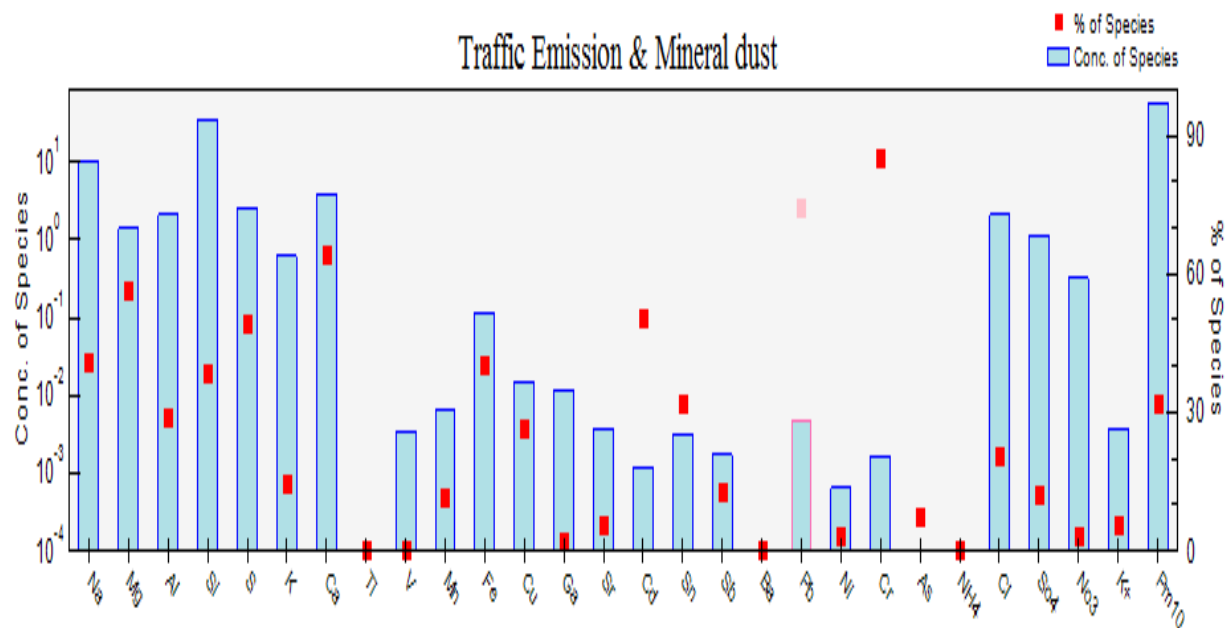


Figure 4.128. Source profile for Factor 3 at Murthal LE.

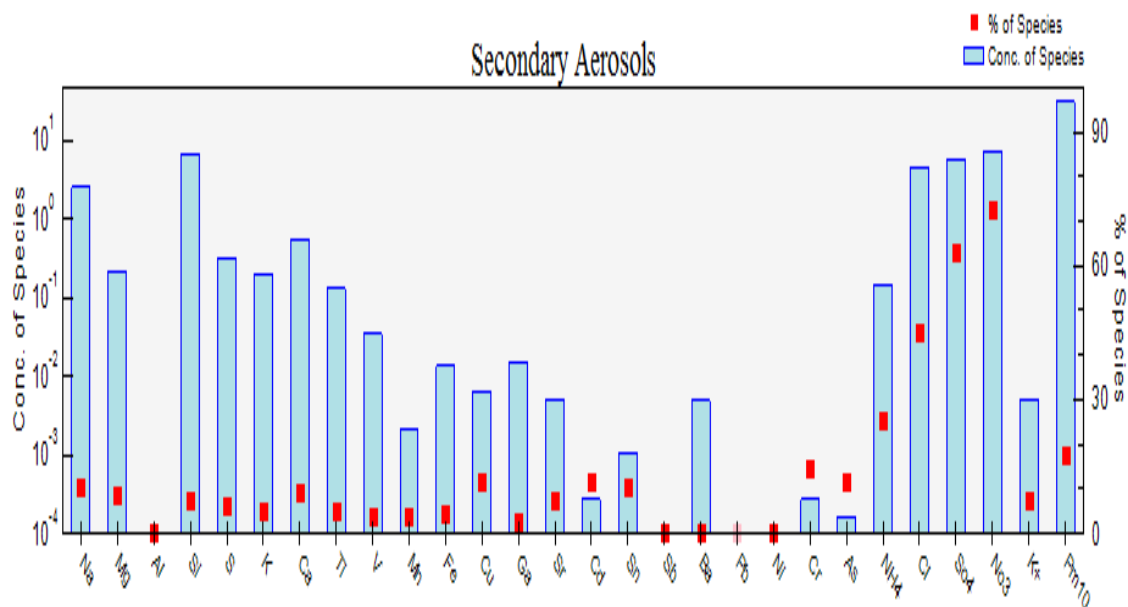


Figure 4.129. Source profile for Factor 4 at Murthal LE.

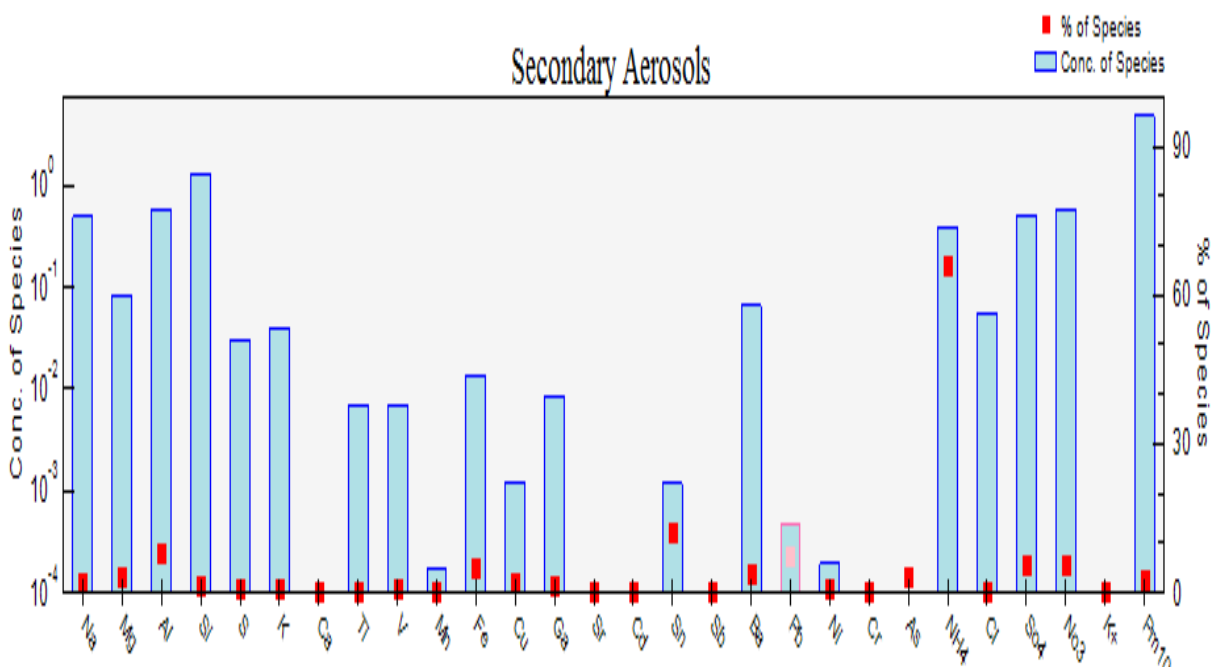


Figure 4.130. Source profile for Factor 5 at Murthal LE.



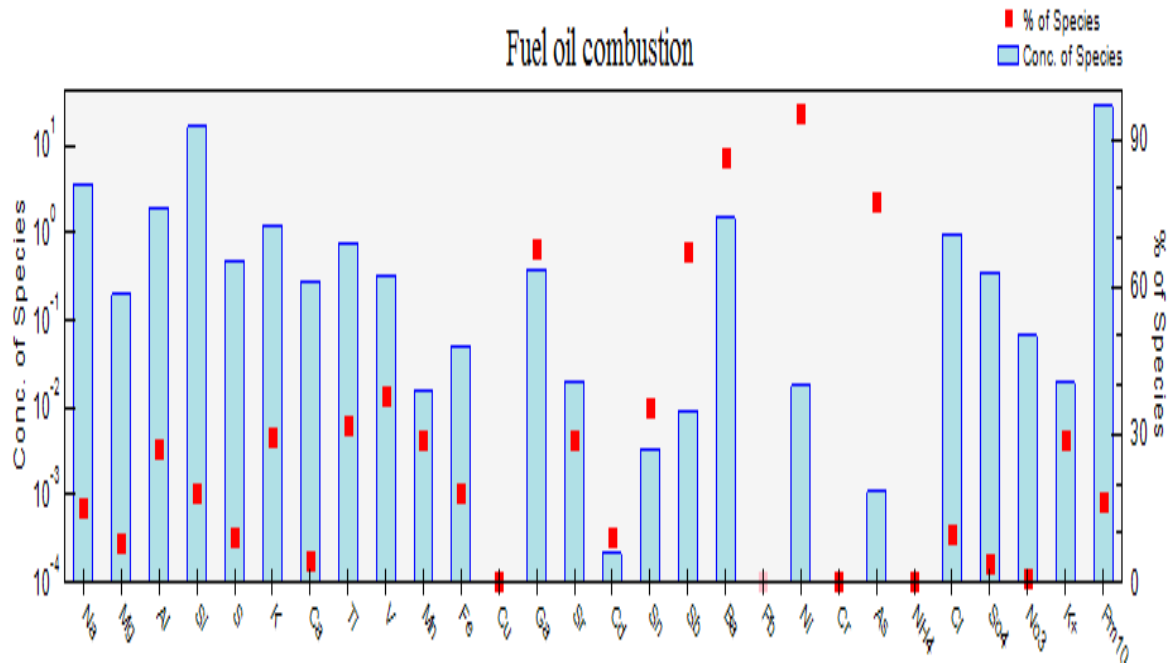


Figure 4.131. Source profile for Factor 6 at Murthal LE.



Source apportionment of ambient particulate matter during winter season in Delhi

The sources represented by the profiles and main average contributors to their presence in PM₁₀ are listed in Table 4.22:

Table.4.22. Source profile of PM₁₀-bound elements and ions measured at Murthal LE.

Location and Elevation	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Murthal Lower elevation	Ti (60%), Cu (60%), Sr (58%), Mn (60%)	Si (28%), Na (28%), Mg (30%), Ca (28%)	Al (50%), Fe (50%), Si (28%), Na (45%), Mg (60%), Ca (70%), Cr (80%), Cd (50%)	SO ₄ ²⁻ (60%), NO ₃ ⁻ (65%), NH ₄ ⁺ (28%)	NH ₄ ⁺ (63%)	Ga (61%), Sb (62%), Ba (85%), Ni (90%), As (85%).
	Fuel oil combustion	Mineral dust	Traffic emission and mineral dust	Secondary aerosols	Secondary aerosols	Fuel oil combustion

Note: Percentage shown in the bracket represents the percentage fraction of the chemical species in the PM mass.



Source apportionment of ambient particulate matter during winter season in Delhi

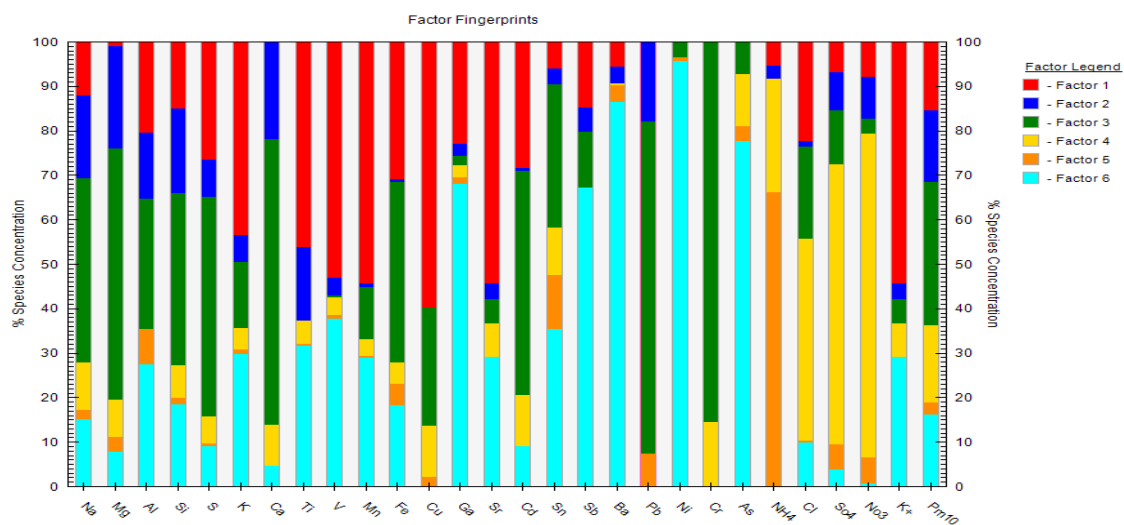


Figure 4.132. Factors contribution to chemical species at Murthal LE.

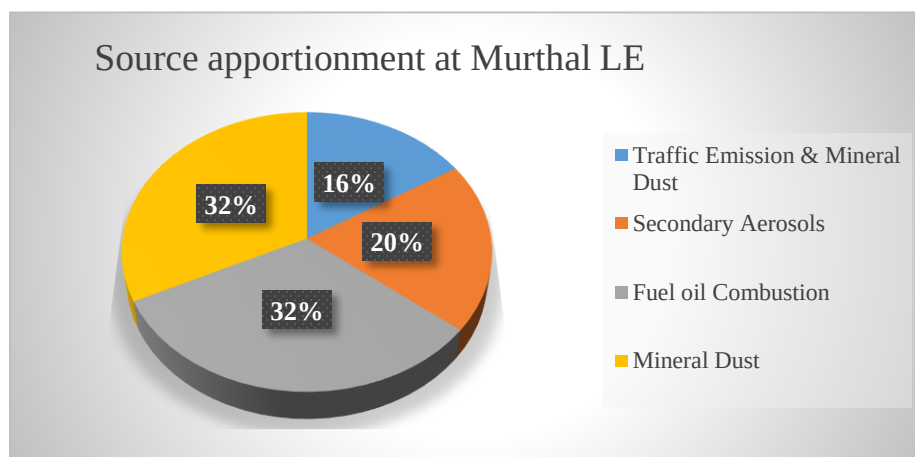


Figure 4.133. Source apportionment of PM₁₀ at Murthal LE.



Source apportionment at Murthal HE

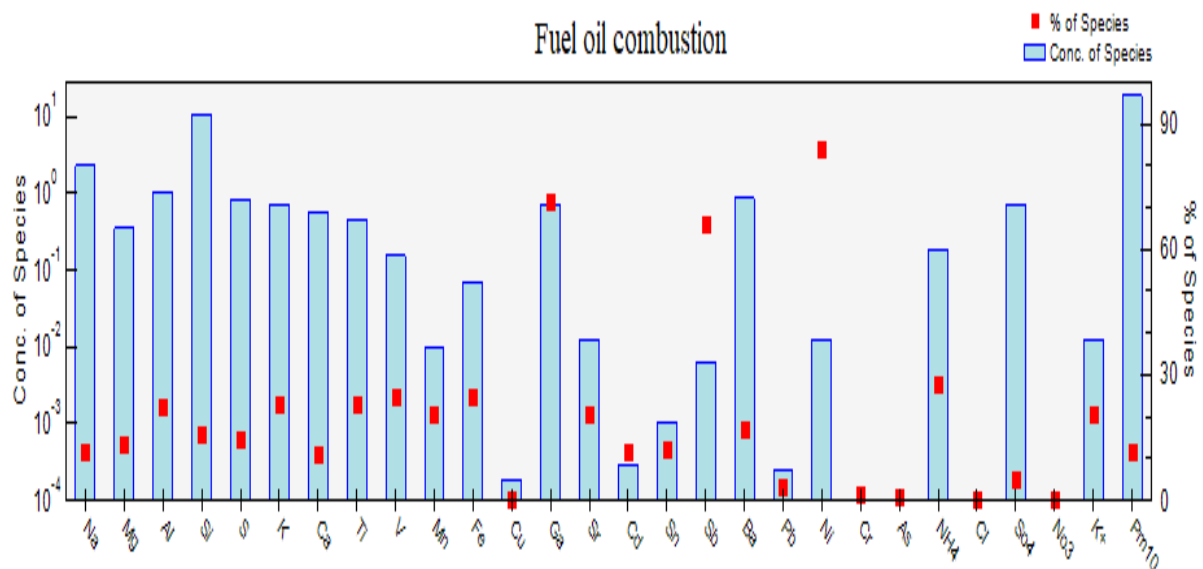


Figure 4.134. Source profile for Factor 1 at Murthal HE.

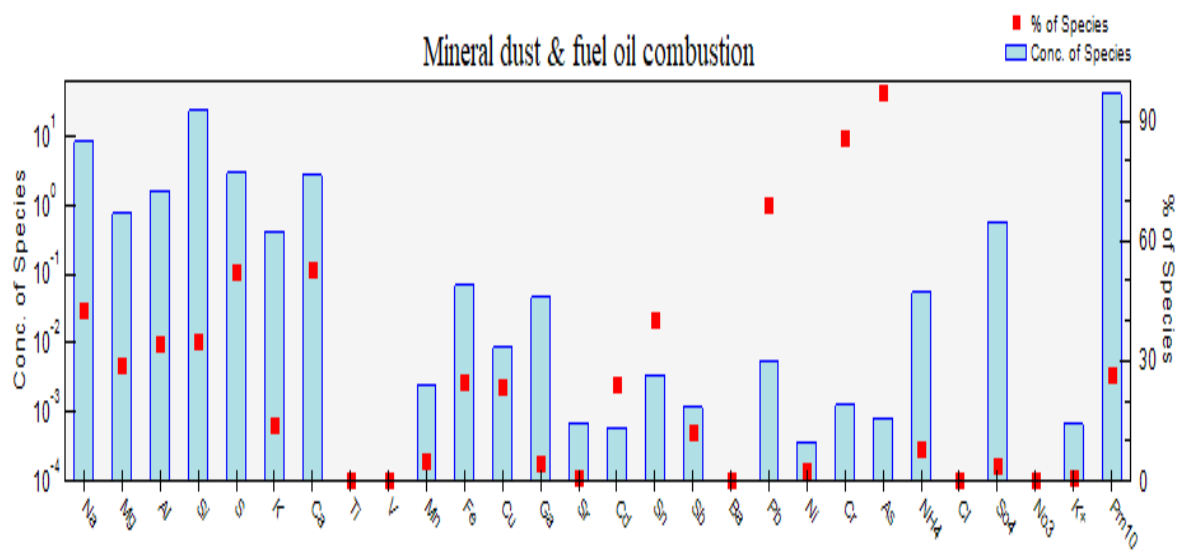


Figure 4.135. Source profile for Factor 2 at Murthal HE.



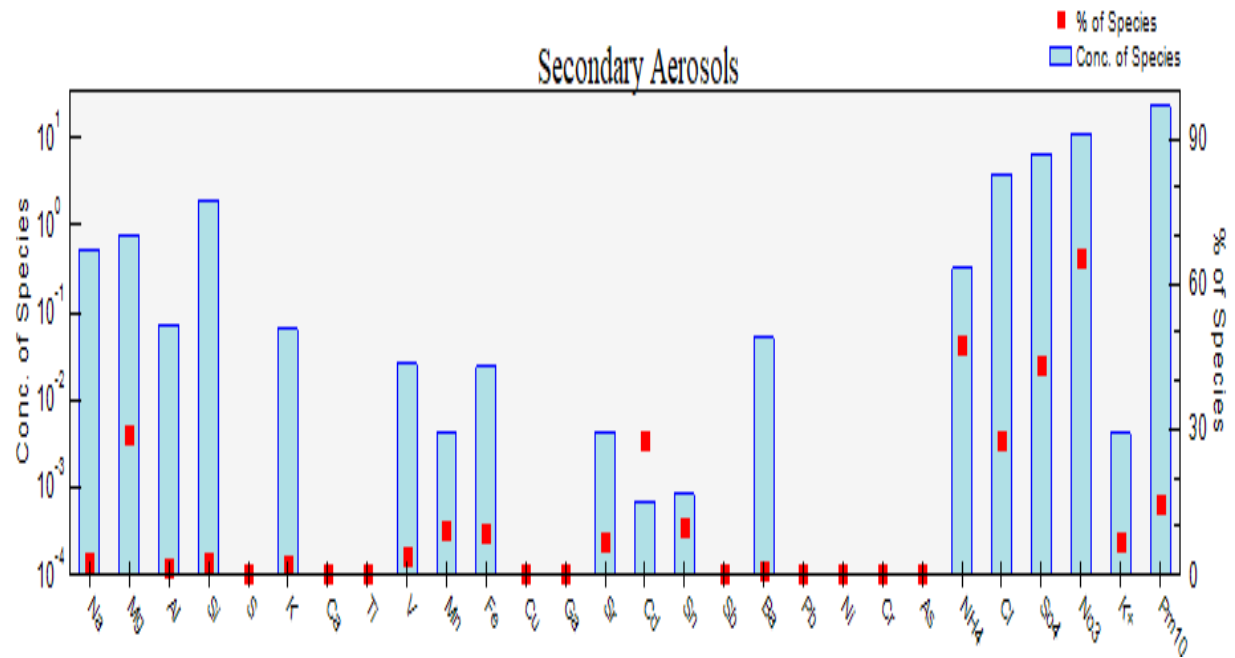


Figure 4.136. Source profile for Factor 3 at Murthal HE.

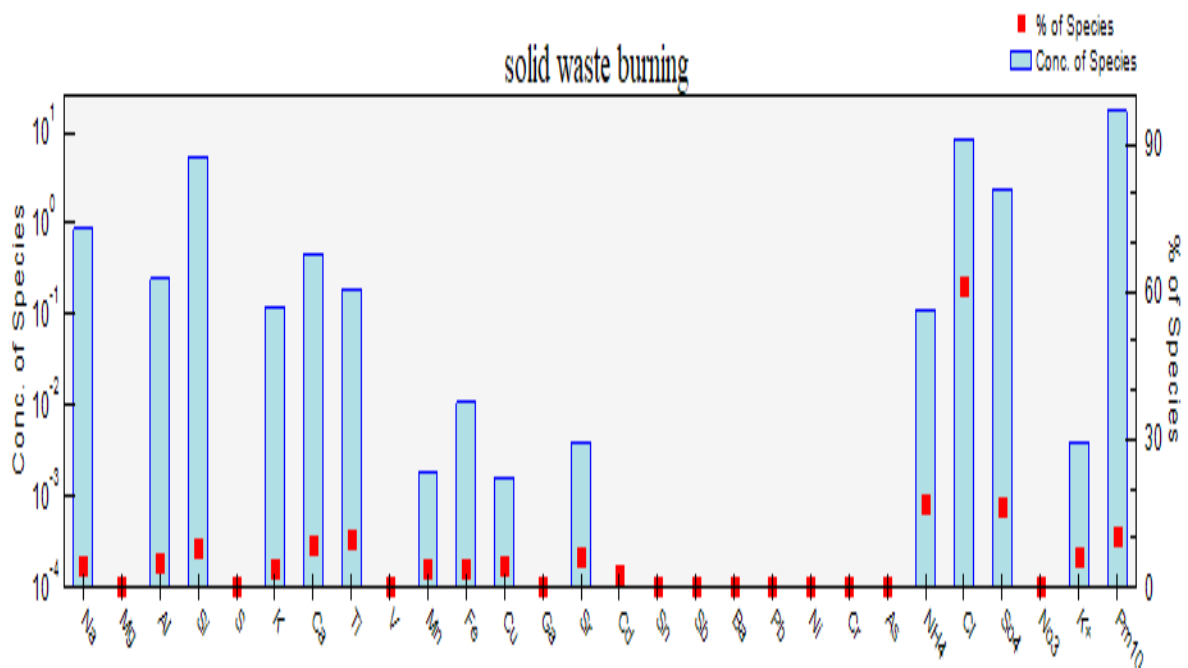


Figure 4.137. Source profile for Factor 4 at Murthal HE.

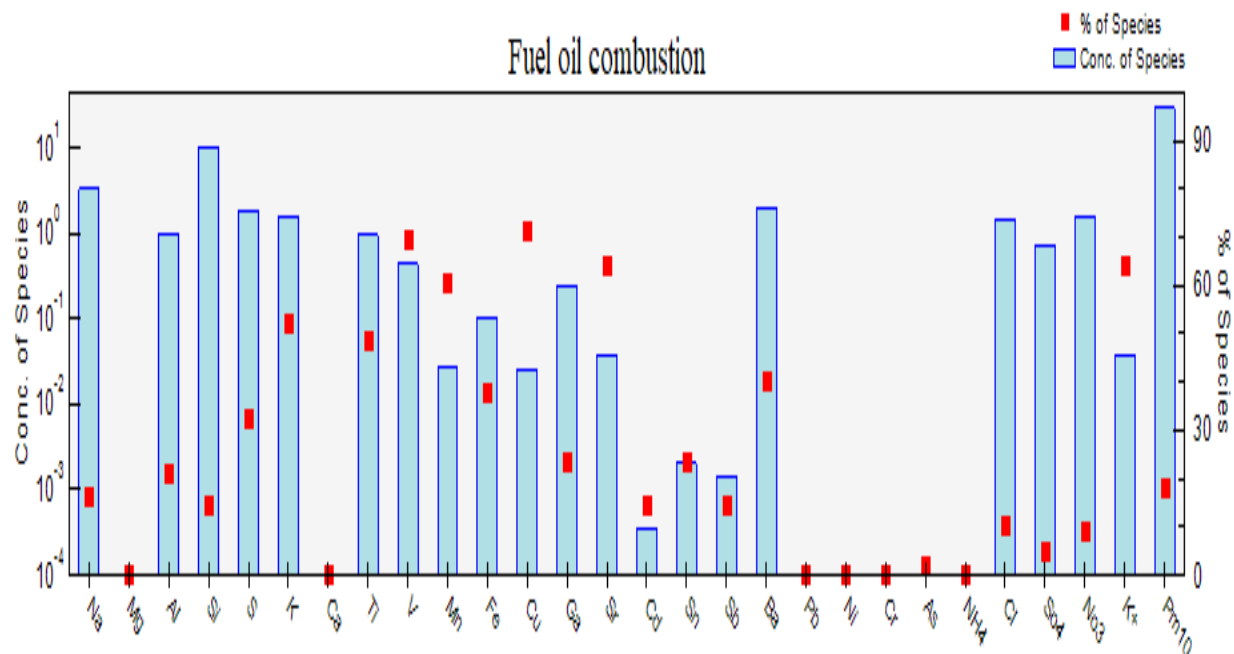


Figure 4.138. Source profile for Factor 5 at Murthal HE.

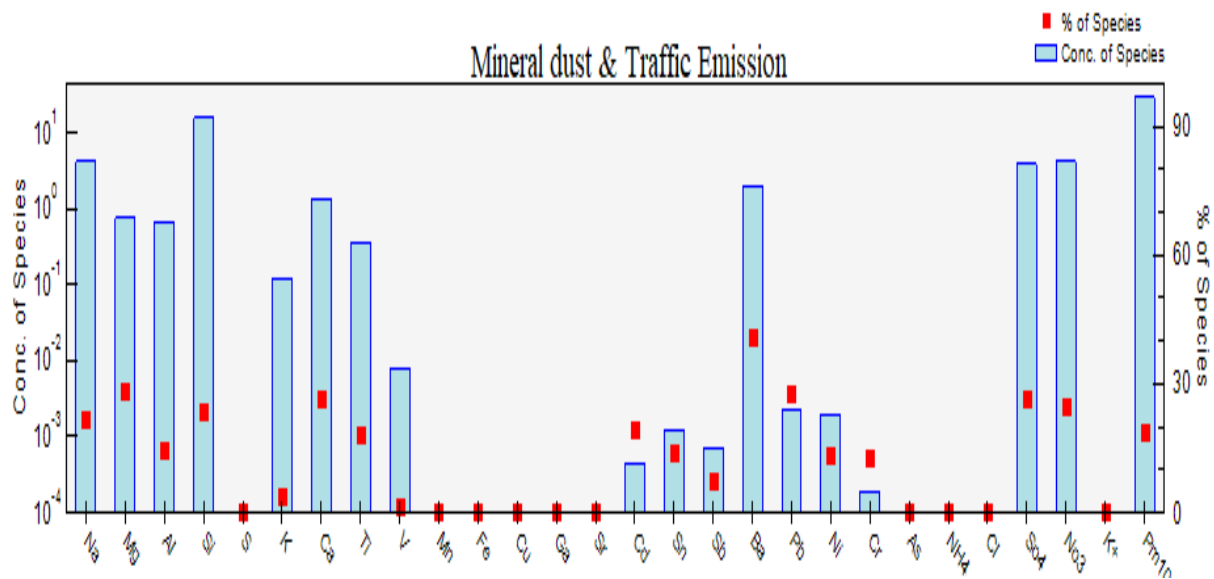


Figure 4.139. Source profile for Factor 6 at Murthal HE.



Source apportionment of ambient particulate matter during winter season in Delhi

The sources represented by the profiles and main average contributors to their presence in PM₁₀ are listed in Table 4.23:

Table 4.23: Source profile of PM₁₀-bound elements and ions measured at Murthal HE.

Location and Elevation	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Murthal Higher elevation	Ga (70%) Sb (68%) Ni (85%)	As (100%) Cr (78%) Pb (70%) Ca (60%) S (60%) Si (48%) Al (50%)	NH ₄ ⁺ (60%) SO ₄ ²⁻ (58%) NO ₃ ⁻ (62%)	Cl ⁻ (62%)	K (58%) Ti (58%) V (62%) Sr (59%) Ba (46%)	Si (30%) Mg (30%) Ca (30%) Ti (25%) Ba (45%)
	Fuel oil combustion	Mineral dust & fuel oil combustion	Secondary aerosols	Solid waste burning	Fuel oil combustion	Mineral dust & traffic emission

Note: Percentage shown in the bracket represents the percentage fraction of the chemical species in the PM mass.



Source apportionment of ambient particulate matter during winter season in Delhi

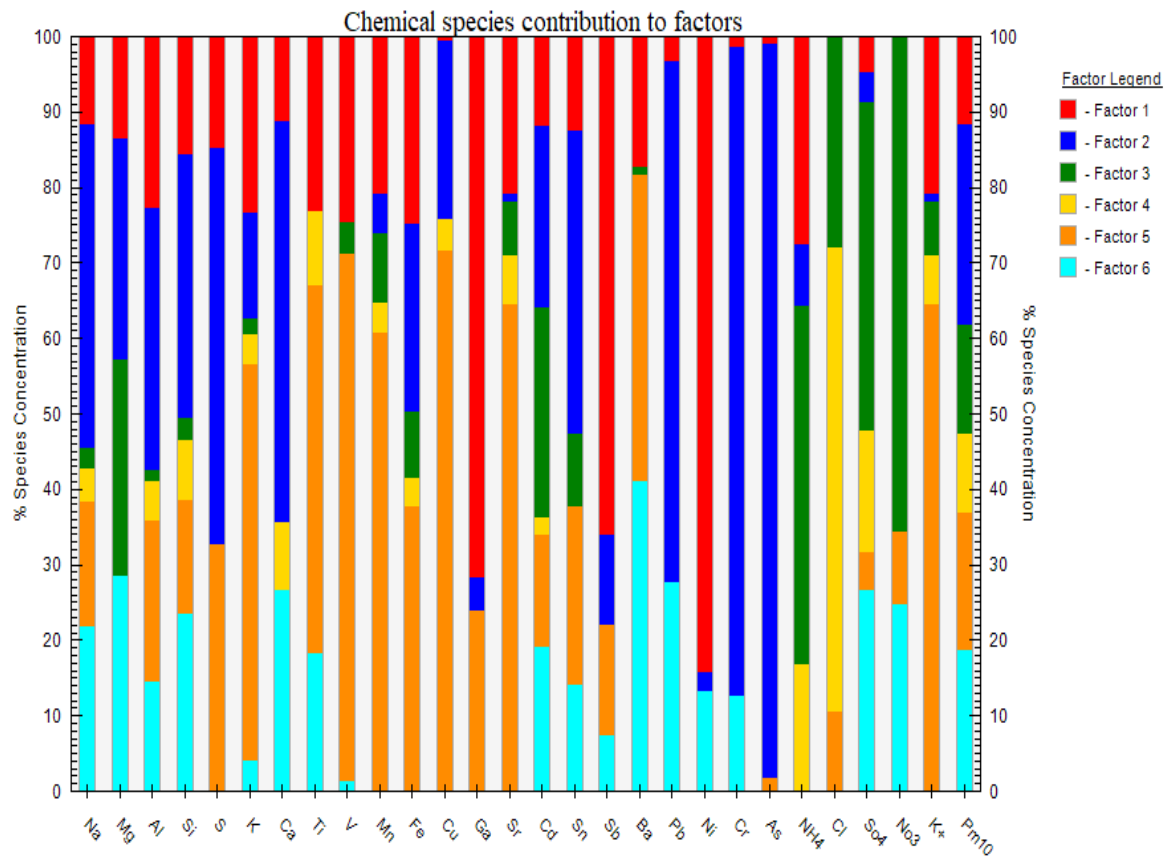


Figure 4.140. Factors contribution to chemical species at Murthal HE.

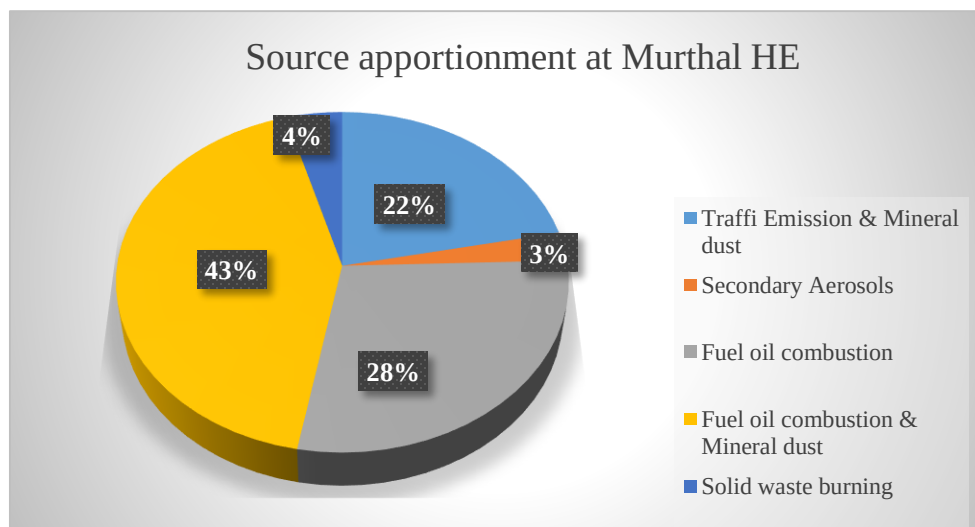


Figure.4.141 Source apportionment of PM₁₀ at Murthal HE.



4.7.2 Chemical Mass Balance Model

Ambient concentration of the species and its uncertainty are used as input to the CMB model. The values below the detection limit are replaced by 1/2 of the minimum reported value. The standard uncertainty values of sampled air volume of PM samplers, microbalance, pipette and repeatability of ED-XRF and IC for analyzed elements and ions respectively, are used for the uncertainty calculations.

Preliminary data analysis was conducted to understand the trends and relationships among species that would impact CMB analysis. Further, the fractional amount in each source-type emission (source profiles) and its uncertainty estimates were used as a second input to the CMB model. For the present work, source profiles were obtained from the U.S. EPA Speciate 4.2 database (U.S. EPA, 2009). The PM₁₀ and PM_{2.5} source profiles (expressed by weight percent by mass) used in this study are shown in Figs — 4.142 and 4.149, respectively.

Eight source profiles listed in the U.S. EPA Speciate 4.2 databases were tested in the CMB model. Among the Eight source profiles, seven were estimated by the model. Vehicular emission, Mineral dust, coal combustion, fuel oil combustion, secondary aerosols, solid waste burning, and biomass burning were among the seven-estimated source. Figure.4.137 to figure.4.144 shows speciate source profile for eight sources.

Presence of higher fraction of EC, OC, K⁺ in the speciate one as shown in the figure.4.137 indicates that they are emitted from burning of biomass. Biomass burning is a primary source of K⁺ mainly in the form of KCl, K₂SO₄ and KNO₃ (Li et al., 2003) and Carbonaceous material EC and OC, a significant fraction of particle-phase emission from fires (Brito et al., 2014; Kondo et al., 2011). While OC is directly emitted to the atmosphere or formed from the oxidation and condensation of organic vapors, EC is emitted from combustion sources (Cabada et al., 2004).

Second, speciate in figure.4.138 have a higher mass fraction of Al, Si, Ca, Fe, which are the signature for construction activities. Construction activities have contributed significantly to elevate dust concentration that is mainly characterized by high calcite CaCO₃, calcareous material SiO₂, bauxite Al₂O₃ and iron Fe₂O₃ (Hanadi et al., 2018).

Presence of higher weight fraction of Ca, Al, Fe, EC, OC, SO₄²⁻ in the speciate three as shown in the figure.4.139, represents the sign of traffic emission. Presence of Al is contributed from wear of pistons (Kimura et al., 2006), while Fe is from the doping of diesel with ferrocene



$((C_5H_5)_2Fe)$ (Braun et al., 2006). In the combustion chamber, $((C_5H_5)_2Fe)$ is decomposed into $Fe_2(OH)_2(g)$, and then to $Fe_2(SO_4)_3(s)$ in the exhaust system (Du et al., 1998). Fe was also released from metal wear in the exhaust system walls as flakes of iron (Vuk et al., 1976). Metal sulfates such as $CaSO_4$ (SO_4^{2-}) is formed due to flue gas desulphurization (Li et al., 2006). In this reaction the $CaCO_3$ decomposes to CaO , and then CaO reacts with SO_2 to form $CaSO_4(s)$. The other forms of metallic sulfates are $BaSO_4$ and $ZnSO_4$.

Fourth speciate have higher contribution from Si, Al, Ca, Fe as shown in the figure.4.140, which is indicating the influence of Mineral dust. This may come from road wear of asphalt pavement (in general it is composed of 95% mineral grains containing mainly Ca, Al, Si, Na, K, and 5% filler and binding material). The sources of Cr include road dust contaminated by emissions of Cr based catalytic converter. Presence of K indicated that local soil is strongly contaminated by the biological materials.

Presence of higher contribution of Ni, V, S, EC, OC in the speciate five as shown in figure.4.141 are indicators of fuel oil combustion. As residual fuel combustion from residential and commercial buildings is enriched with fine particle Ni (relative to V), it is suggested that the observed Ni is mainly a result of residual fuel combustion in such buildings.

Many of the contaminants associated with crude oil are more likely to be found in lower concentrations in lighter fuel oil distillation products (e.g., nos. 1, 2, and three fuel oils). In contrast, the residual oil fractions (e.g., nos. 5 and six fuel oils) contain significantly more of the contaminants that were in the crude oil and can include substantial amounts of trace metals like Ni, V, and S. EC, and OC are primarily emitted from any combustion process.

Coal combustion speciates six shown in figure 4.142 contains higher weight fraction species like As, Se. Although As and se are also emitted by metals operations and smelters, respectively, their simultaneous loading on this factor, and the fact that coal emissions are highly enriched in and major sources of both of these elements (Helble, 2000) and identifies this factor as related to the combustion of coal (U.S.EIA, 2010). Speciate profile 7 with high chemical species NH_4^+ , SO_4^{2-} , NO_3^- represents secondary aerosols as shown in figure.4.143.

Presence of SO_4^{2-} and NH_4^+ proves the involvement of the secondary PM formations and photochemical reaction (Cheng et al., 2000). Particulate sulfate is a product of gas-to-particle phase



reactions involving SO_2 emitted from both natural and anthropogenic (coal, diesel, and oil combustion processes) sources.

NH_4^+ in PM_{10} may be formed due to the intense gas phase reactions with NH_3 gas, enriched on sulfate and soil particle when excess NH_3 gas was available. NH_4 in $\text{PM}_{2.5}$ may originate by the reaction of NH_3 vapors with acidic gases such as H_2SO_4 , HNO_3 , and HCl or NH_3 vapor may react or condense on an acidic particle surface of anthropogenic origin. NO_3 in PM_{10} may be soil derived as well as formed in the atmosphere during the day as well as night. During the day, it is formed due to the reaction between atmospheric HNO_3 and airborne soil (Wolf et al., 1986). Whereas, in the night NO_3 is formed directly on the soil particles by the reactions [$\text{NO}_3 + \text{NO}_2 + \text{M} \rightarrow \text{N}_2\text{O}_5 + \text{M}$, and $\text{N}_2\text{O}_5 + \text{H}_2\text{O}_{\text{soil}} \rightarrow \text{HNO}_3$]. NO_3 in $\text{PM}_{2.5}$ may be formed by the homogeneous gas-phase transformation of NO_x to HNO_3 , followed by the reaction with NH_3 to form NH_4NO_3 , which is highly volatile and can remain stable in the particulate phase (Seinfeld, 1986; Chandra Mouli et al., 2003).

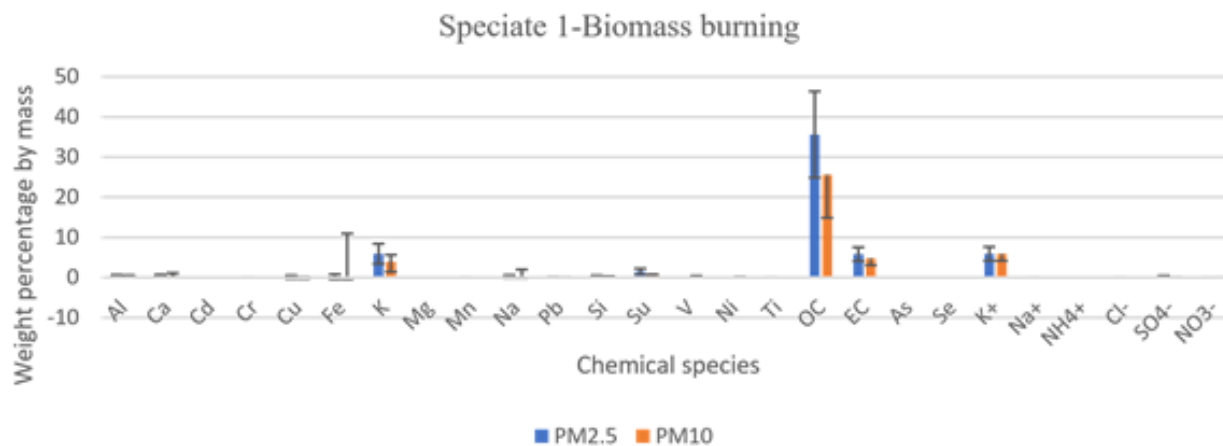


Figure.4.142. Speciate profile for Biomass burning



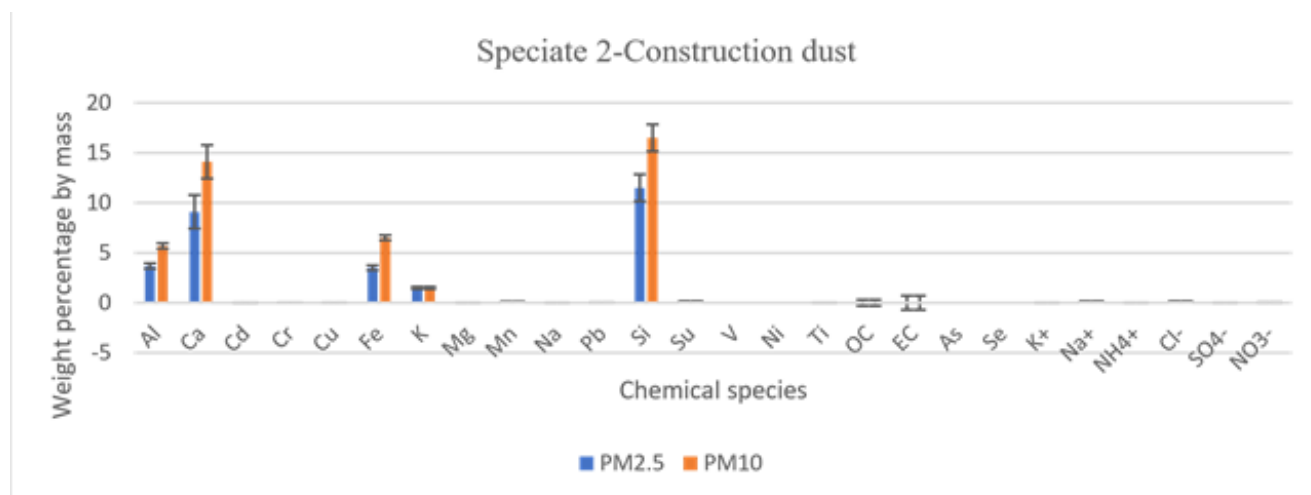


Figure.4.143.Speciate profile for Construction dust

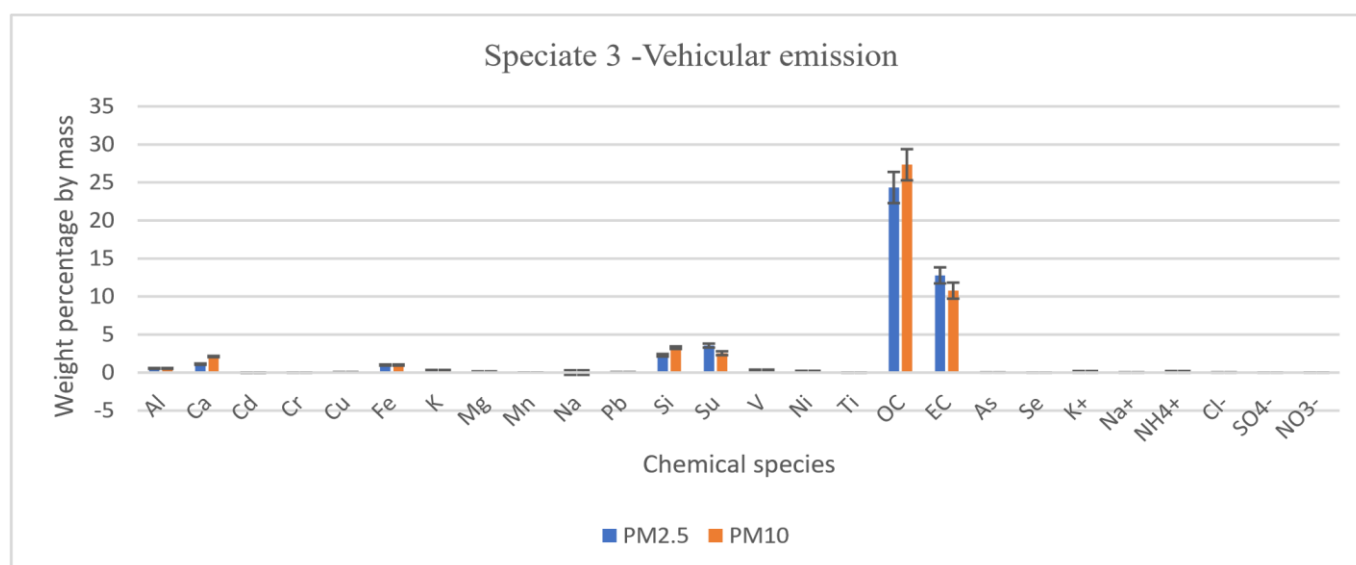


Figure.4.144 Speciate profile for vehicular emission



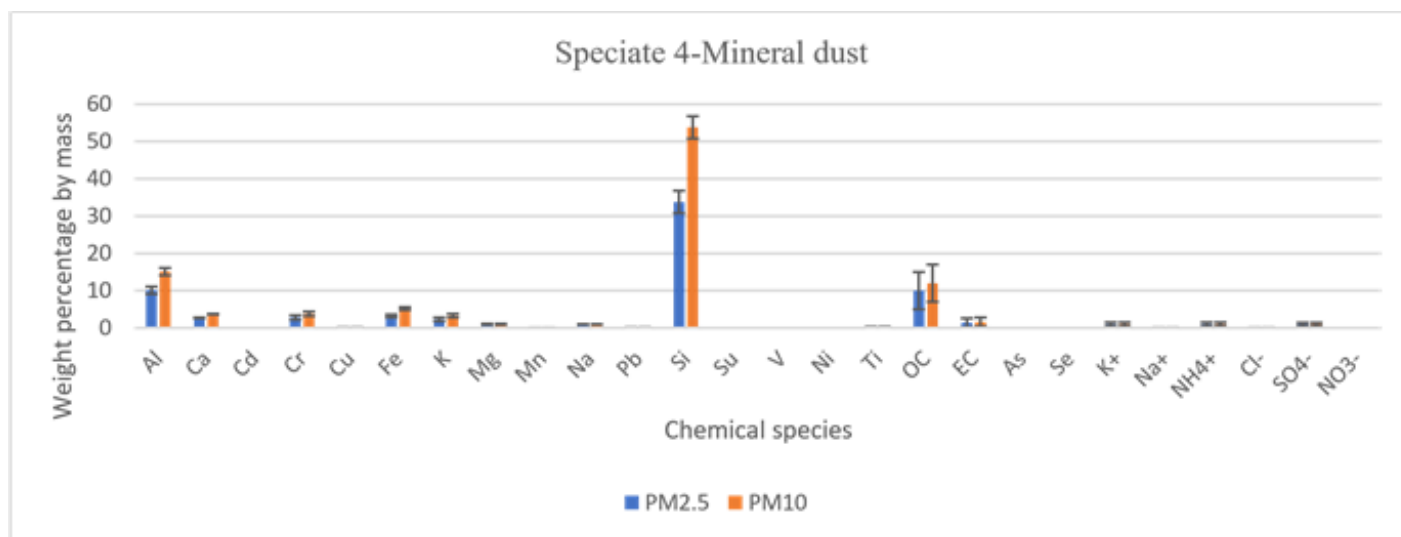


Figure.4.145 Speciate profile for Mineral dust

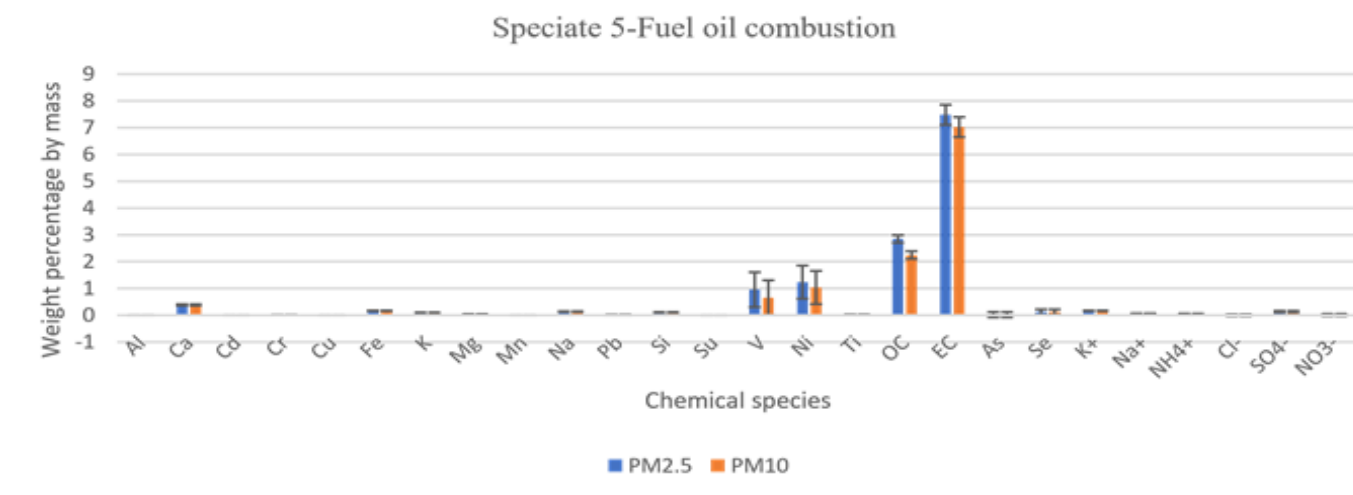


Figure.4.146 Speciate profile for fuel oil combustion



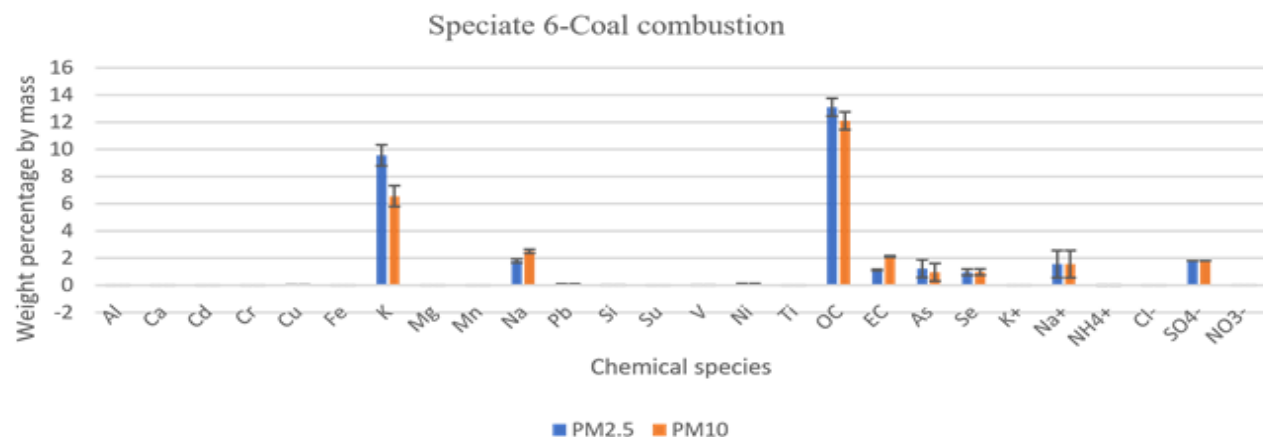


Figure.4.147 Speciate profile for coal combustion

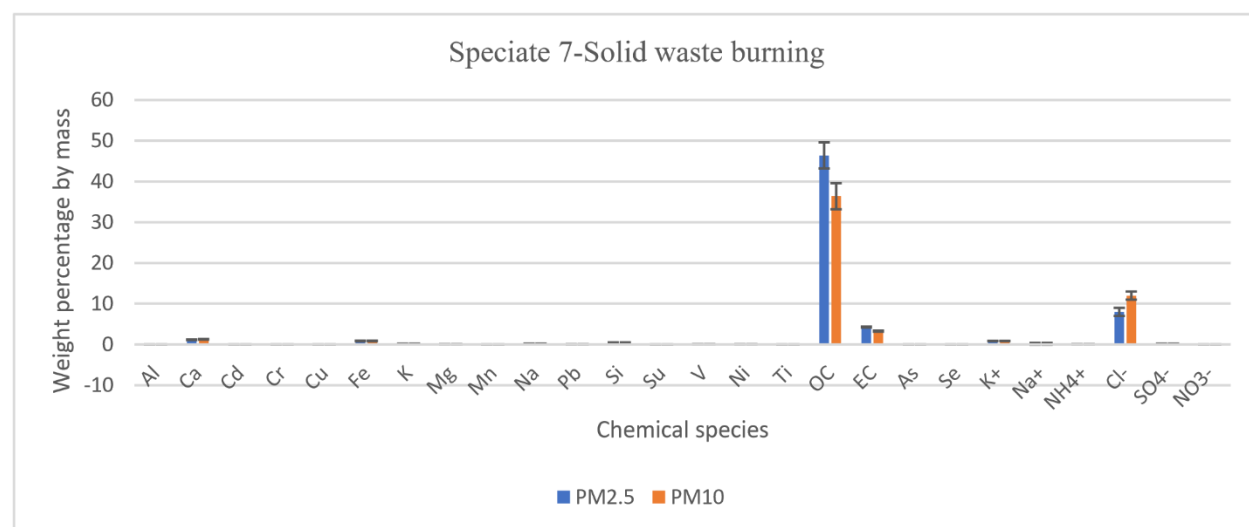


Figure.4.148 Speciate profile for solid waste burning

Source apportionment of ambient particulate matter during winter season in Delhi

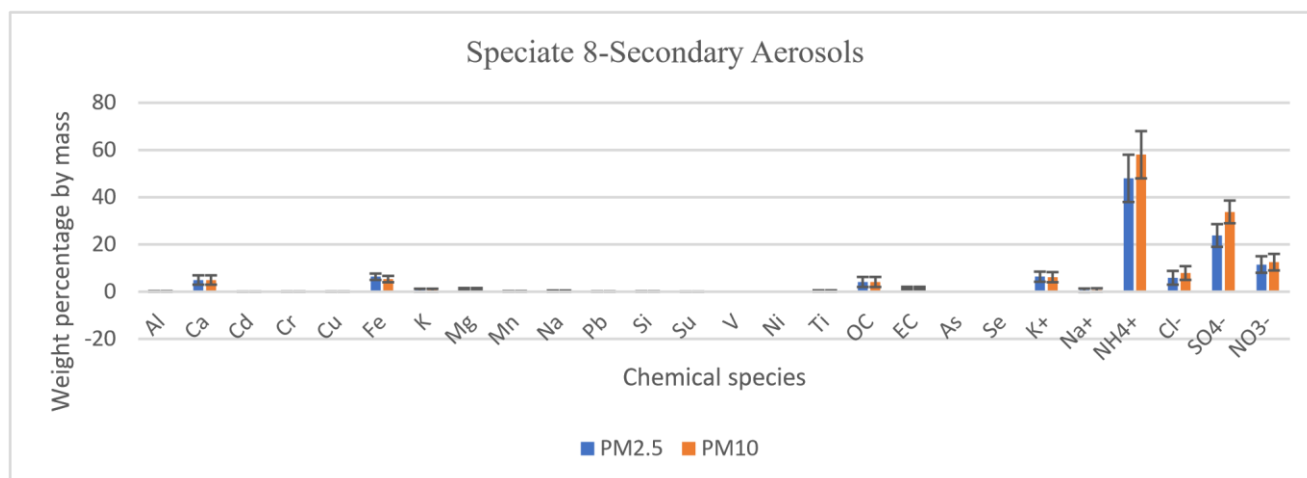


Figure.4.149 Speciate profile for secondary aerosols

Table.4.24. CMB model performance statistics of PM₁₀

Study site	Elevation	R ²	χ^2	% Mass	Fit measures	Degree of freedom
Okhla	LE	0.72	0.54	85.1	1.07	12
	HE	0.73	1.2	86.1	0.89	11
IIT Delhi	LE	0.69	0.6	69.3	1.2	9
	HE	0.91	0.87	56.2	0.96	8
DCE	LE	0.56	3.2	82.1	0.91	5
	HE	0.86	3.6	66.2	0.87	15
Murthal	LE	0.84	1.3	79.3	0.73	12
	HE	0.81	0.89	46.2	0.79	17



Table.4.25. CMB model performance statistics of PM_{2.5} source apportionment

Study site	Elevation	R ²	χ^2	% Mass	Fit measures	Degree of freedom
Okhla	LE	0.69	1.47	96.7	1.02	3
	HE	0.59	3.3	85.6	0.87	9
IIT Delhi	LE	0.79	2.7	81.3	1.36	11
	HE	0.81	0.62	78.6	0.72	16
DCE	LE	0.93	0.95	76.7	0.89	32
	HE	0.83	0.63	88.6	0.69	19
Murthal	LE	0.81	1.98	63.3	1.4	6
	HE	0.82	1.56	90.6	1.62	4

Source apportionment of PM_{2.5} and PM₁₀ at Okhla

Okhla LE

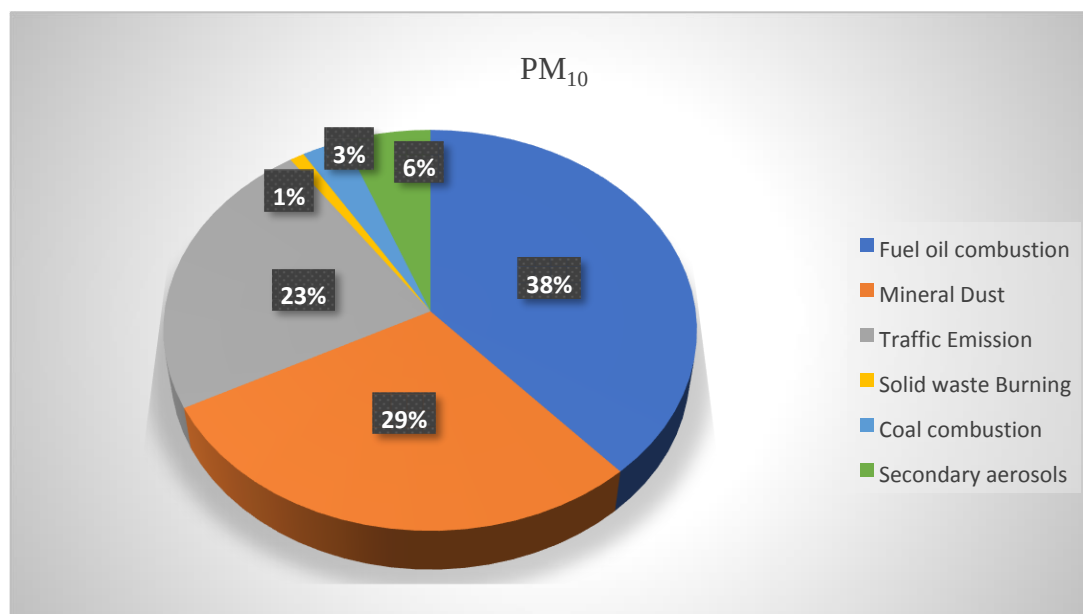


Figure.4.150 Source apportionment of PM₁₀ at Okhla LE

Source apportionment of ambient particulate matter during winter season in Delhi

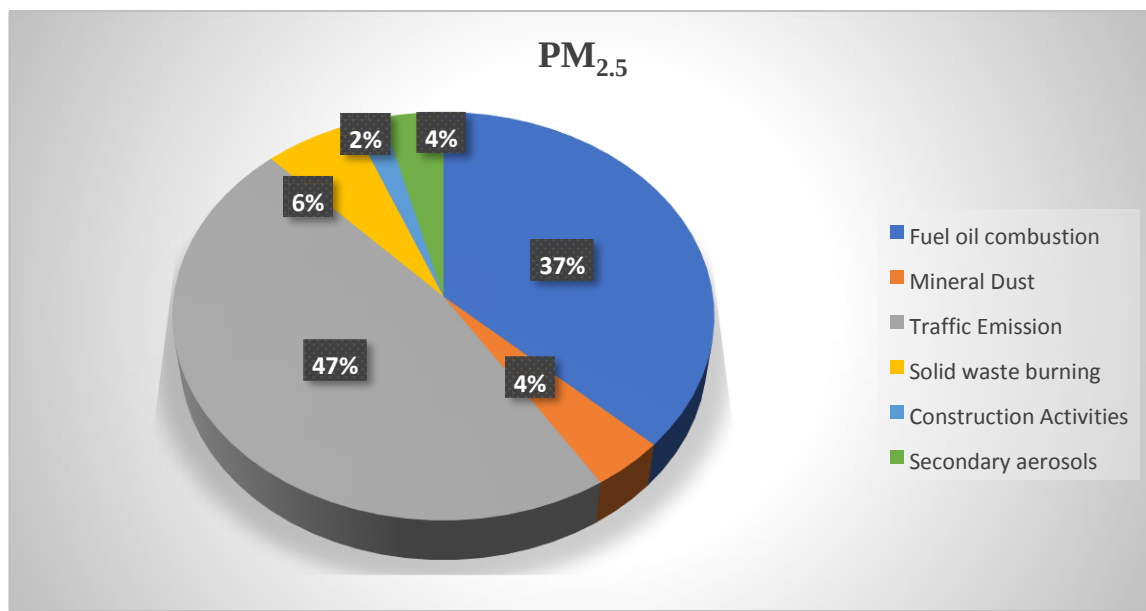


Figure.4.151 Source apportionment of PM_{2.5} at Okhla LE

Okhla HE

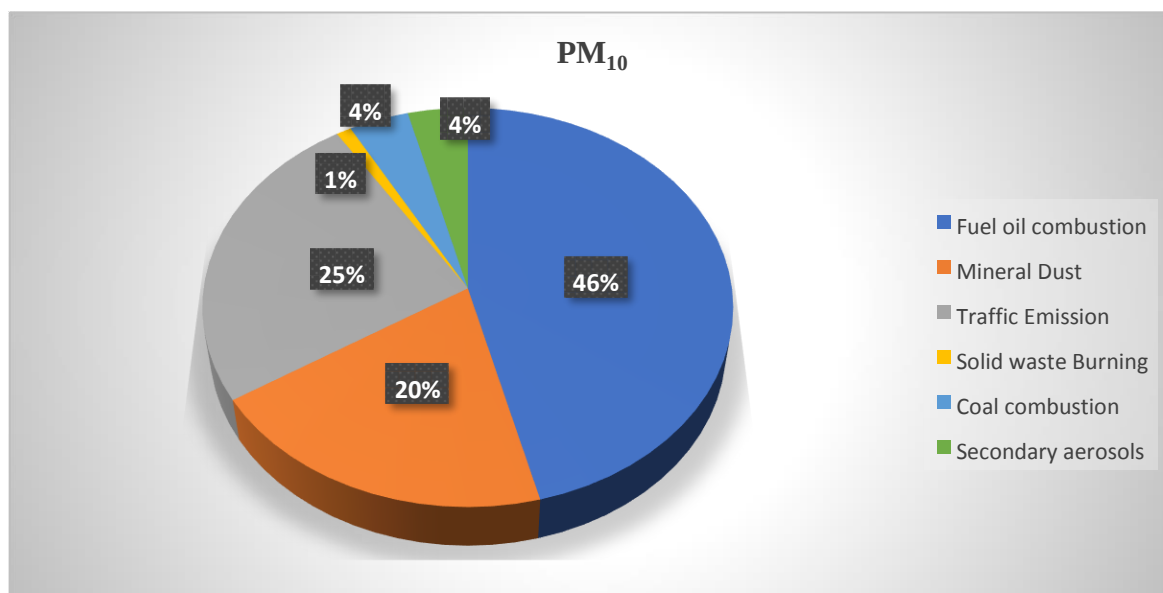


Figure.4.152 Source apportionment of PM₁₀ at Okhla HE



Source apportionment of ambient particulate matter during winter season in Delhi

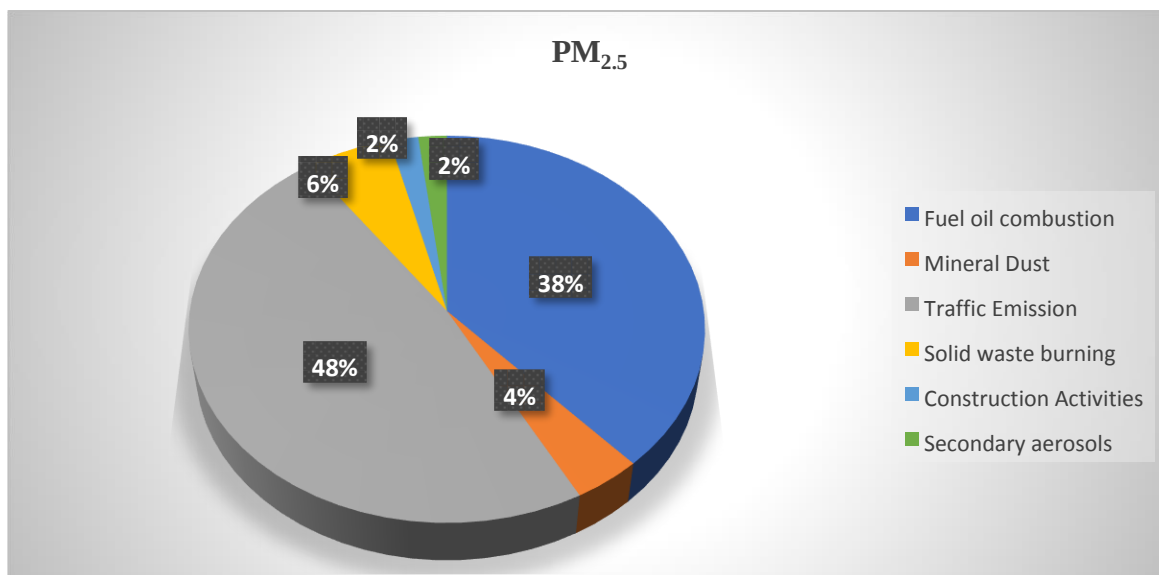


Figure.4.153 Source apportionment of PM₁₀ at Okhla HE

Source apportionment of PM_{2.5} and PM₁₀ at IIT Delhi

IIT Delhi LE

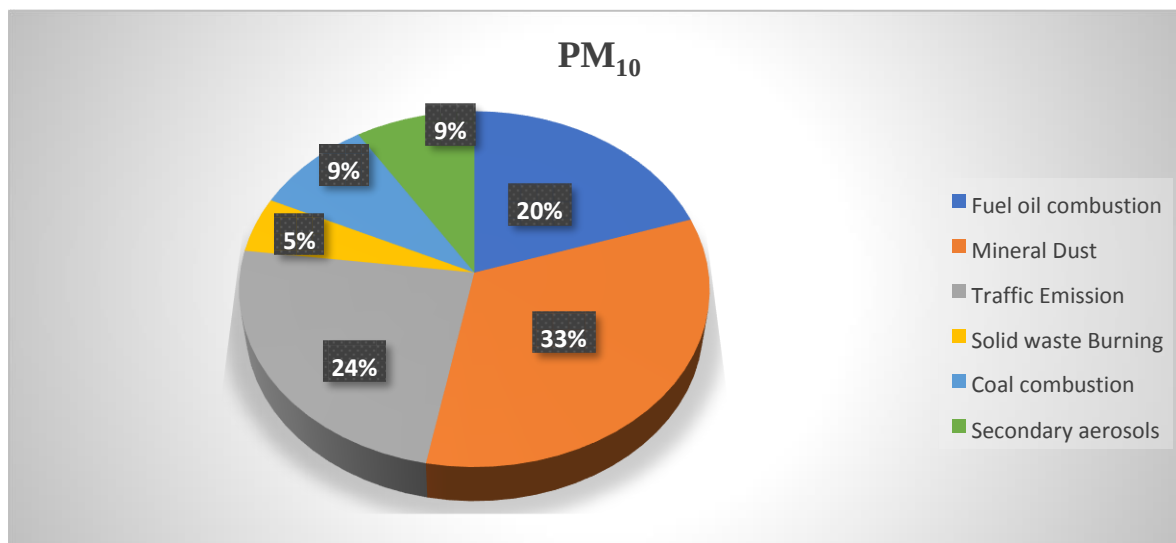


Figure.4.154 Source apportionment of PM₁₀ at IIT Delhi LE



Source apportionment of ambient particulate matter during winter season in Delhi

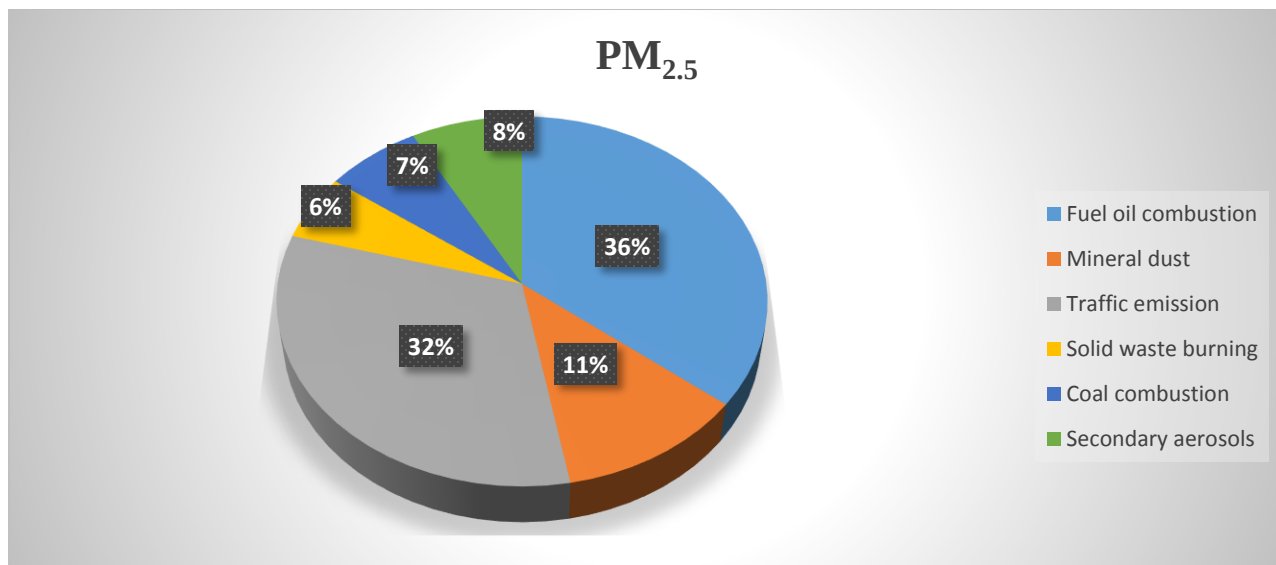


Figure.4.155 Source apportionment of PM_{2.5} at IIT Delhi LE

IIT Delhi HE

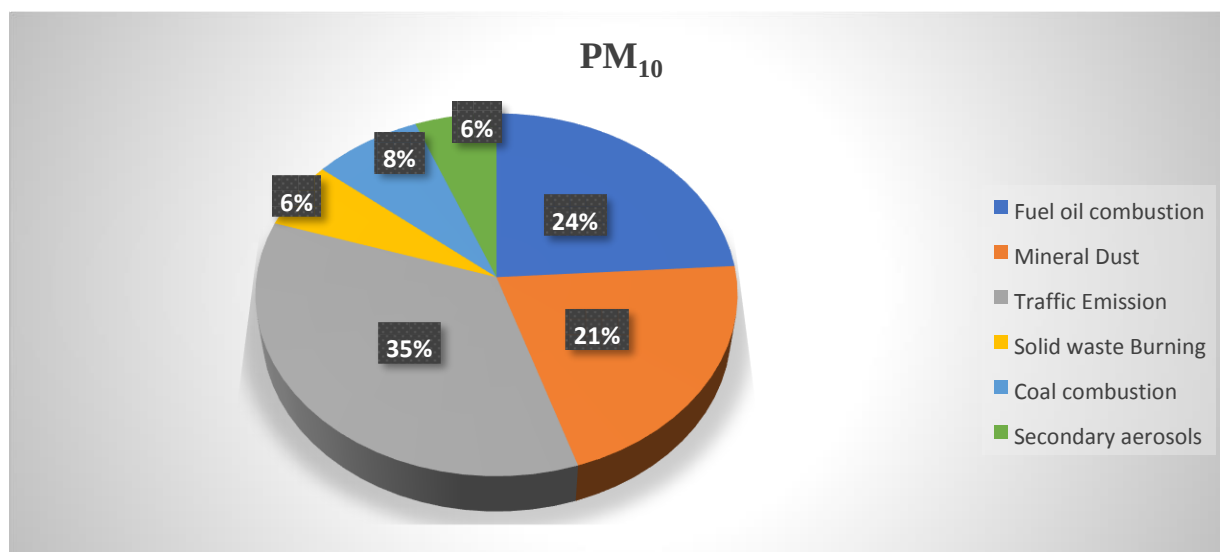


Figure.4.156 Source apportionment of PM₁₀ at IIT Delhi HE



Source apportionment of ambient particulate matter during winter season in Delhi

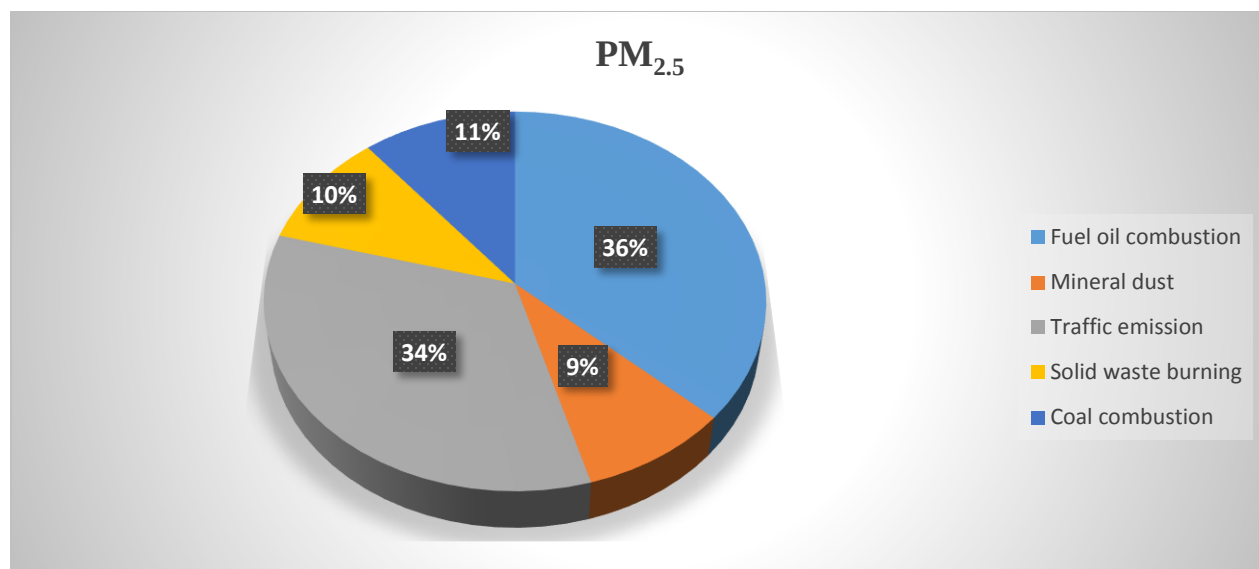


Figure.4.157 Source apportionment of PM_{2.5} at IIT Delhi HE

Source apportionment of PM_{2.5} and PM₁₀ at DCE

DCE LE

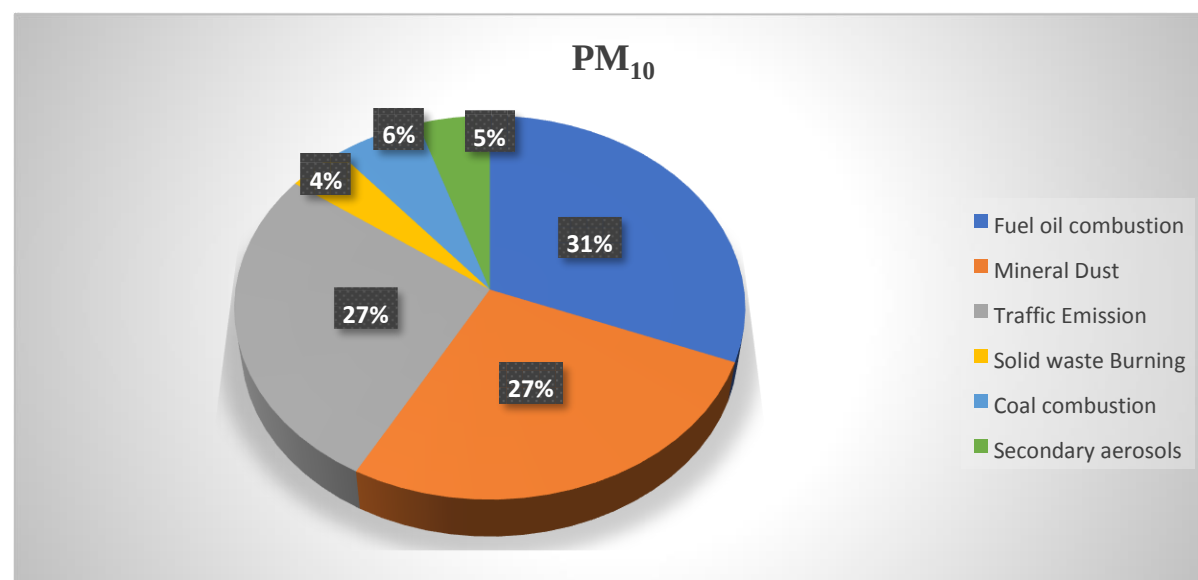


Figure.4.158 Source apportionment of PM₁₀ at DCE LE



Source apportionment of ambient particulate matter during winter season in Delhi

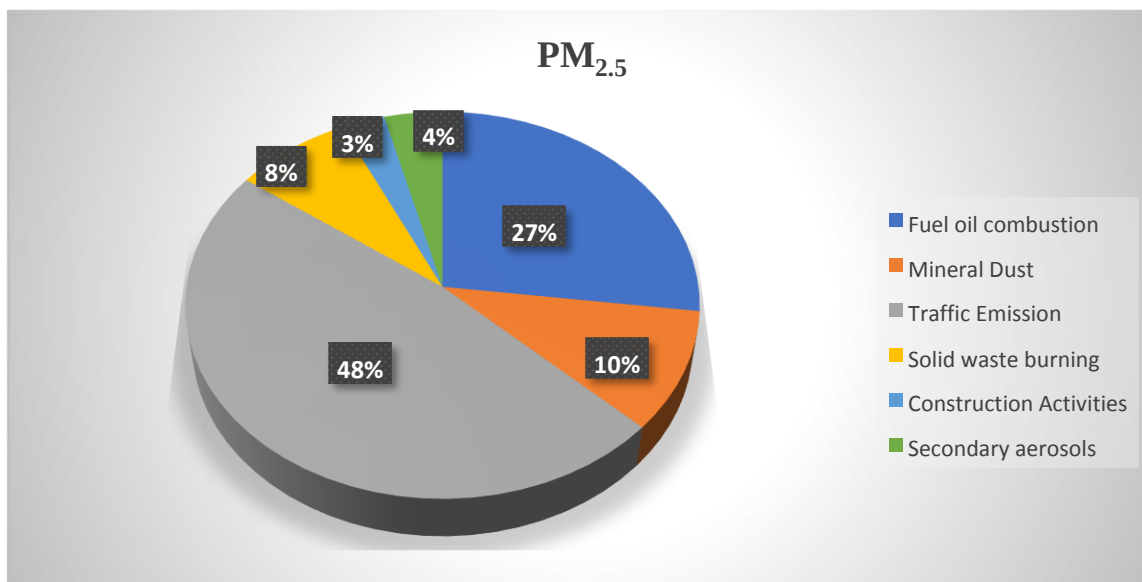


Figure.4.159 Source apportionment of PM_{2.5} at DCE LE

DCE HE

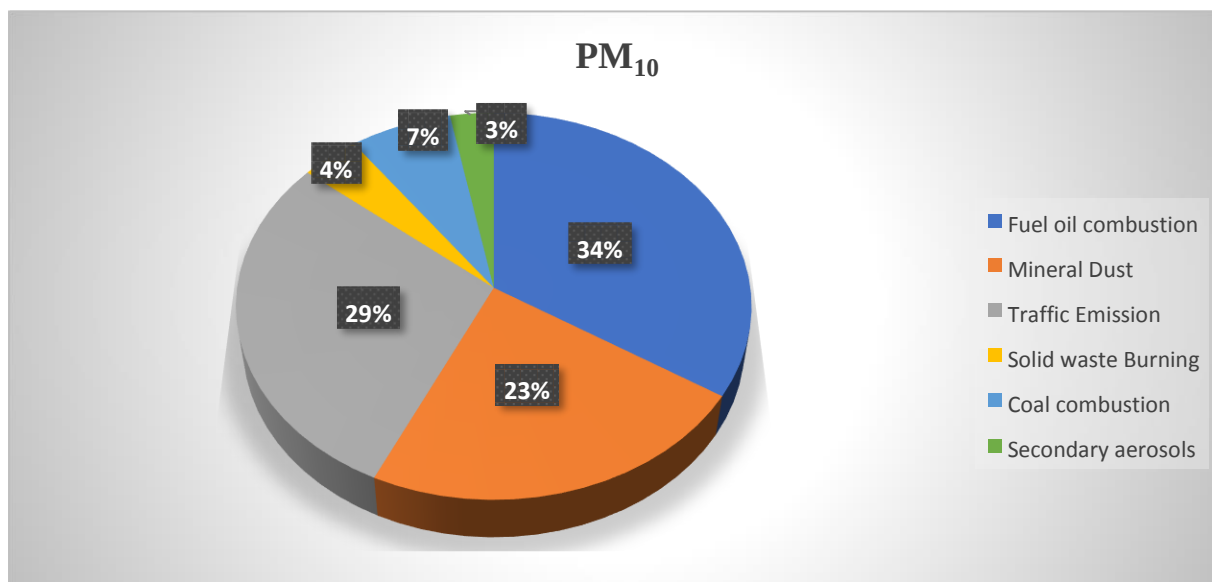


Figure.4.160 Source apportionment of PM₁₀ at DCE HE



Source apportionment of ambient particulate matter during winter season in Delhi

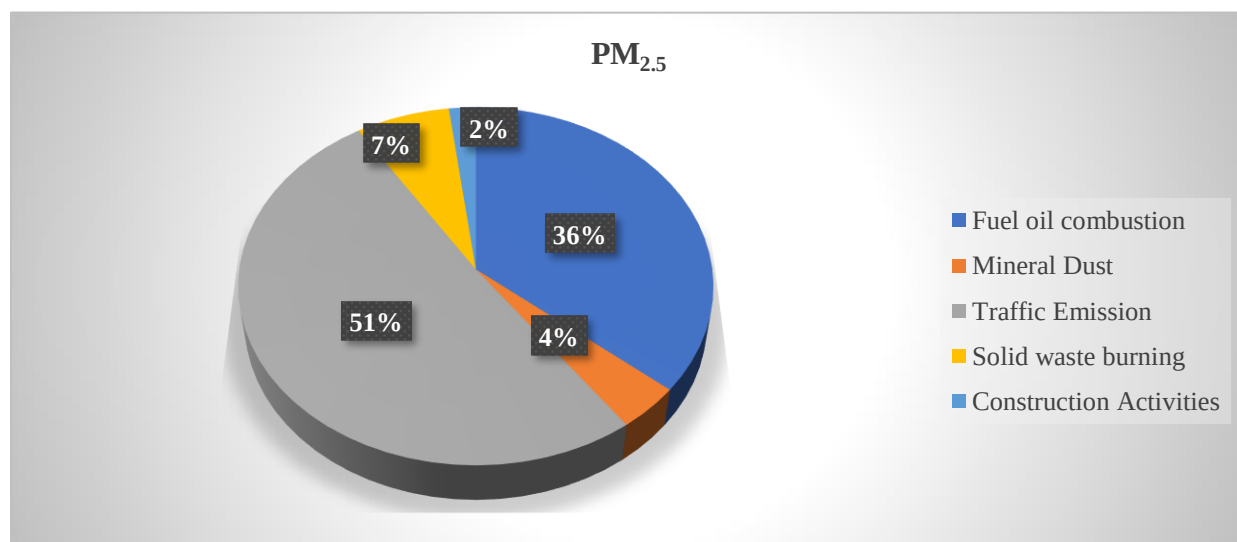


Figure.4.161 Source apportionment of PM_{2.5} at DCE HE

Source apportionment of PM_{2.5} and PM₁₀ at Murthal

Murthal LE

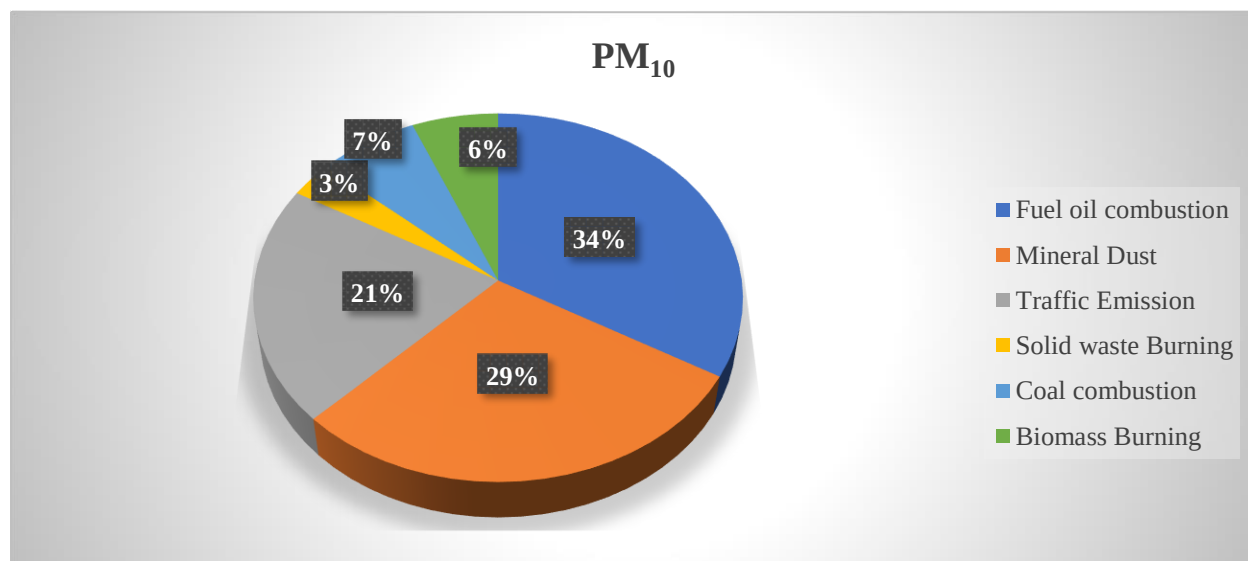


Figure.4.162 Source apportionment of PM₁₀ at Murthal LE



Source apportionment of ambient particulate matter during winter season in Delhi

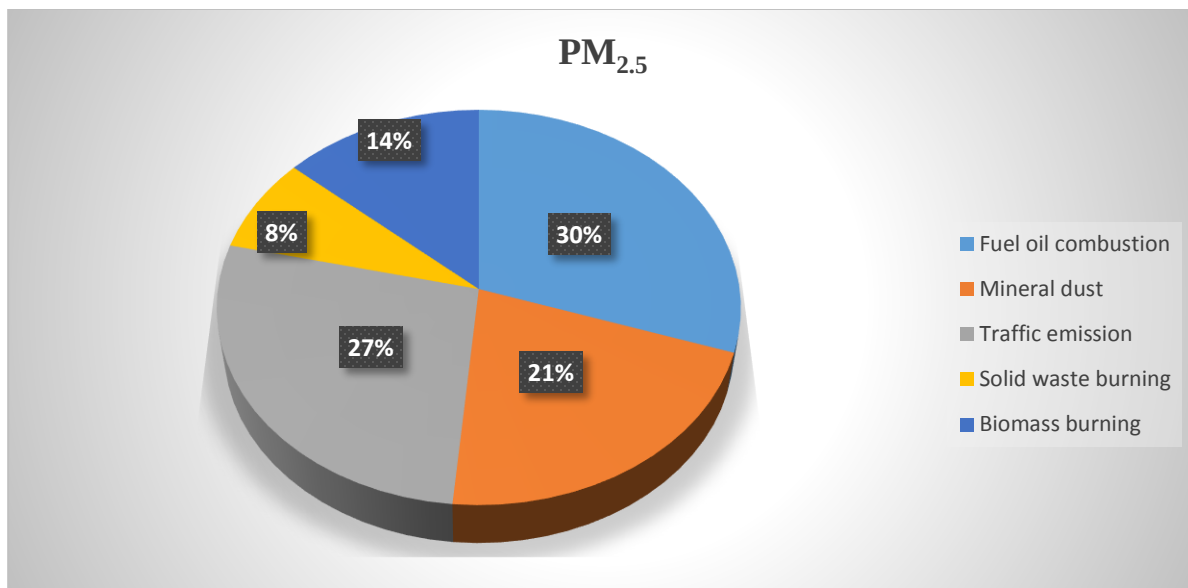


Figure.4.163 Source apportionment of PM_{2.5} at Murthal LE

Murthal HE

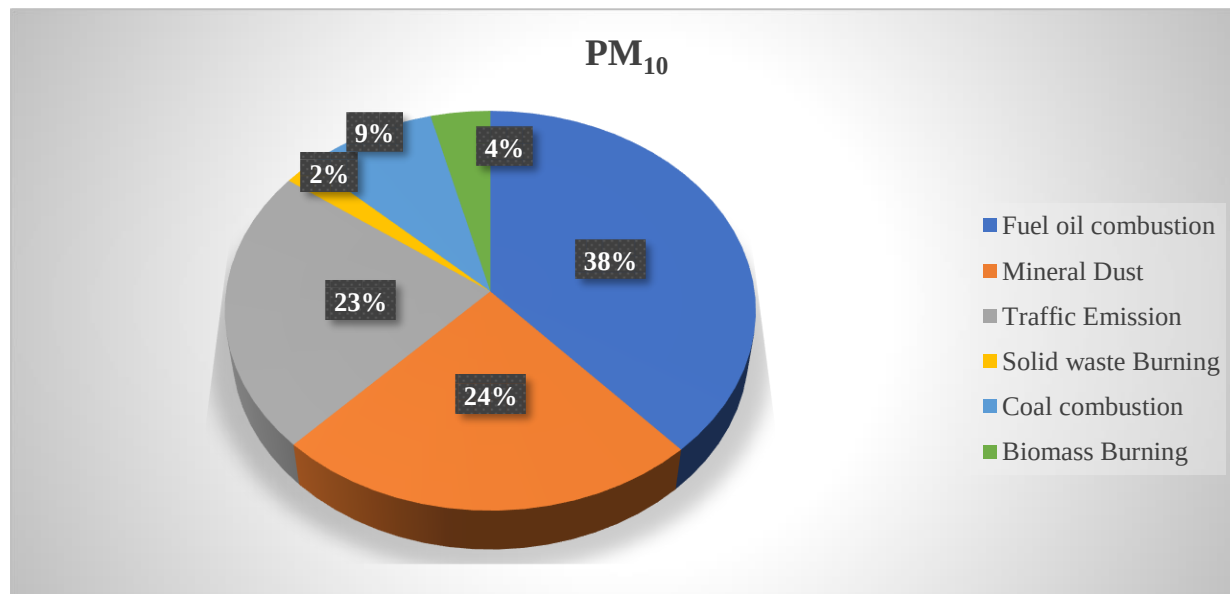


Figure.4.164 Source apportionment of PM_{2.5} at Murthal HE



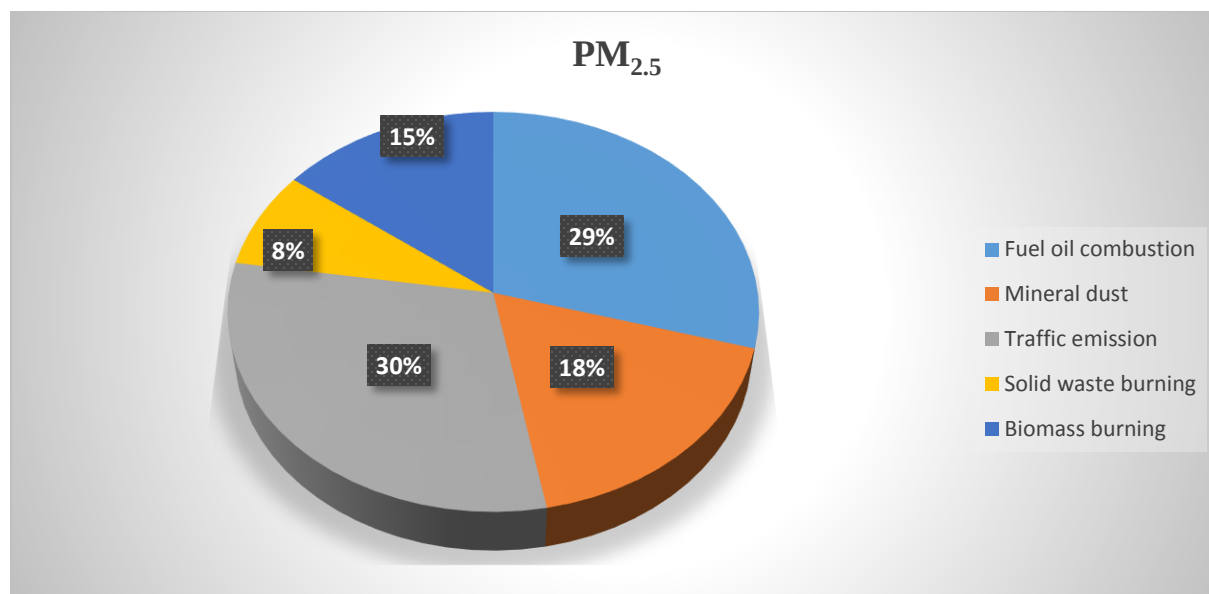


Figure.4.165 Source apportionment of PM_{2.5} at Murthal HE

It can be seen that both vehicular emission and fuel oil combustion increases with elevation at the study site. Vehicular emission contribution was in the range of 21% -27% for PM₁₀, and 24%- 51% for PM_{2.5} in lower elevation and 23% -47% PM₁₀, and 36%- 51% for PM_{2.5} in higher elevation and contribution from fuel oil combustion is in the range PM₁₀~ (20%-38%), PM_{2.5}~ (27%-37%) in lower elevation and PM₁₀~ (24-46%), PM_{2.5}~ (24%-38%) in higher elevation. Fuel oil combustion and vehicular emission have a higher fraction of smaller size particles, the percentage contribution of both these sources have found to be higher in PM_{2.5} than PM₁₀. Fuel oil combustion is the major contributor at Okhla due to its industrial presence, and vehicular emission is the major contributor at DCE.

The emission from mineral dust in PM₁₀ mass was higher relative to PM_{2.5} mass and also the predominant source at study site. Their contribution was in the range of 26%-33% for PM₁₀, and 4%-24% for PM_{2.5} in lower elevation and 20%-24% for PM₁₀, 4%-21% for PM_{2.5} in higher elevation. Mineral dust has predominantly higher size fraction, hence their contribution in PM_{2.5} is insignificant, and also contribution decreases with elevation. Mineral dust is the major contributor at Murthal. Soil dust from agricultural field contributes significantly to the PM mass at this rural site.



Solid waste burning was also the predominant factor estimated by the model but their contribution is low is in range of 1%-5% for PM_{10} , 3%-8% for $PM_{2.5}$ in the lower elevation and 1%-6% for PM_{10} , 2%-10% for $PM_{2.5}$ in the higher elevation. The contribution of this in $PM_{2.5}$ mass is found to be higher than PM_{10} . Input of this source is found similar at Okhla, DCE, and IIT Delhi. The model does not estimate this source at Murthal.

Murthal is the only study site where biomass burning was estimated by the model. Agricultural burning takes place at the midst of winter at this rural site. Hence high concentration of K^+ was recorded in this site. Their contribution is in the range of 14% for $PM_{2.5}$ at a lower elevation and 4% for PM_{10} , 15% for $PM_{2.5}$ in higher elevation.

Secondary aerosols were also the predominant factor in all the study site except Murthal. It is seen that secondary aerosols contribution was found to be higher in a lower elevation than higher elevation. This is due to the formation of NH_4NO_3 , i.e. reaction of soil enriched with air and NO_3 , hence this reactions takes place predominantly at a lower elevation and gradually reduces with elevation. Secondary aerosols contribution was in the range of 4%-9% for PM_{10} , 2%-6% for $PM_{2.5}$ in lower elevation and 4%-6% for PM_{10} , 2%-6% for $PM_{2.5}$ in higher elevation.

Coal burning was also a major contributor at all sites. Delhi has three coal-burning thermal power plants at its outskirts. Hence their traces are found in all study site. Their contribution was in the range of 3%-9% for PM_{10} , 7% for $PM_{2.5}$ in the lower elevation and 6%-8% for PM_{10} , 11% for $PM_{2.5}$ in the higher elevation. Presence of construction dusts PM_{10} and $PM_{2.5}$ were found to be in trace quantities. Their contribution was in the range 2% $PM_{2.5}$ in lower elevation and 2%-3% for $PM_{2.5}$ in higher elevation.



Table 4.26: Summary of earlier source apportionment studies for Delhi city.

Pollutant	Approach	Result (%)	Reference
PM _{2.5} (winter)	CMB	Diesel (10) Gasoline (9) Road Dust (11) Coal (14) Biomass (20) Sulfate (8) Nitrate (7)	Chowdhury et al. (2007)
SPM	CMB	Diesel vehicles Industries paved road dust gasoline vehicles solid waste soil and crustal dust	Srivastava and Jain (2007)
PM _{2.5}	CMB	Vehicles (7-40) Industry (10-19) Construction (16-41) Resuspended dust (17-56)	CPCB (2010)
PM ₁₀	PCA	Crustal (49-65) Vehicular (27-35) Industrial (4 - 21)	Khillare and Sarkar (2012)
TSP (winter)	Mass balance	Crustal material (48) Organic matter (23) Sulfate (4.9) Nitrate (4.5) Ammonium (2.7) Other (7.2)	Li et al. (2014).
PM _{2.5} (winter)	Pragmatic mass closure	Woodsmoke (23.3) Traffic (16.2) Dust (3.9) Sulfate (10.6) Nitrate (12.4) Chloride (12.3) Other OM (21.4)	Pant et al.,2015



Table 4.27: Summary of source contribution estimations of PM₁₀ through PMF analysis

Summary of source contribution estimations of PM ₁₀ through PMF analysis at lower elevation (LE) and higher elevation (HE) of different locations in Delhi city								
Description	Okhla		IIT Delhi		DCE		Murthal	
	LE	HE	LE	HE	LE	HE	LE	HE
Fuel oil combustion (%)	25	40	23	39	32	39	32	28
Mineral dust & Traffic emission (%)	53	49	-	43	47	-	16	22
Traffic emission (%)	-	-	14	-	-	28	-	-
Mineral dust (%)	-	-	45	-	-	18	32	-
Solid waste burning (%)	10	-	6	6	-	-	-	4
Biomass burning (%)	5	-	-	-	-	-	-	-
Coal burning (%)	-	-	2	4	1	-	-	-
Secondary aerosols (%)	7	2	16	14	20	1	20	3
Mineral dust & fuel oil combustion (%)	-	-	-	-	-	-	-	43
Unidentified (%)	-	9	-	-	-	14	-	-



Table 4.28: Summary of source contribution estimations of PM₁₀ and PM_{2.5} through CMB

Summary of source contribution estimations through CMB analysis at lower elevation (LE) and higher elevation (HE) of different locations in Delhi city								
Description	Okhla				IIT Delhi			
	PM ₁₀		PM _{2.5}		PM ₁₀		PM _{2.5}	
	LE	HE	LE	HE	LE	HE	LE	HE
Fuel oil combustion (%)	38	46	37	38	20	24	36	36
Mineral dust (%)	26	20	4	4	33	21	11	9
Traffic emission (%)	23	25	47	48	24	35	32	34
Solid waste burning (%)	1	1	6	6	5	6	6	10
Biomass burning (%)	-	-	-	-	-	-	-	-
Coal burning (%)	3	4	-	-	9	8	7	11
Construction activities (%)	-	-	2	2	-	-	-	-
Secondary aerosols (%)	6	4	4	2	9	6	8	-



CHAPTER 5

SUMMARY

The summary of the results for the present study is as given below.

5.1 Analysis of DPCC- CAAQMS data

The analysis of CAAQMS data indicated that PM_{10} and $PM_{2.5}$ concentrations were well above the NAAQS limit ($PM_{10} = 100$ and $PM_{2.5} = 60 \mu g/m^3$) during the winter season at all four locations in Delhi city. On an average, PM_{10} values were exceeded more than 300, 320, 336 and 284 for Anand Vihar, R K Puram, Punjabi Bagh, and Mandir Marg respectively. Similarly, the values of $PM_{2.5}$ were exceeded 267, 305, 300 and 260 days for Anand Vihar, R K Puram, Punjabi Bagh, and Mandir Marg, respectively. In the year 2016, the number of $PM_{2.5}$ exceedance was marginally decreased.

5.2 PM concentration at different elevations in Delhi city

The results of the PM_{10} and $PM_{2.5}$ samples collected at two different elevations of selected locations in Delhi city were summarized below:

At IIT Delhi study area: The concentration of PM_{10} has varied between 29.4 to 242.1 and 43.1 to 253.37 $\mu g/m^3$ for the lower elevations and higher elevations, respectively. Similarly, the concentration of $PM_{2.5}$ was varied between 26.4 to 147.1 and 31.8 to 145.67 $\mu g/m^3$ for the lower elevations and higher elevations, respectively.

At DCE study area: The concentration of PM_{10} was varied between 75.98 to 496.13 and 57.70 to 398.74 $\mu g/m^3$ at lower elevations and higher elevations, respectively. Similarly, the concentration of $PM_{2.5}$ was varied between 40.3 to 186.9 and 47.3 to 177.2 $\mu g/m^3$ for the lower elevations and higher elevations, respectively.

At Okhla study area: The concentration of PM_{10} was in the range between 54.3 to 458.4 and 28.7 to 239.46 $\mu g/m^3$ at lower elevations and higher elevations, respectively. Similarly, the concentration of $PM_{2.5}$ was varied between 47.9 to 217.6 and 22.4 to 209.26 $\mu g/m^3$ for the lower elevations and higher elevations, respectively.



At Anand Vihar study area: The concentration of PM₁₀ at lower elevation was in the range between 333.12 to 527.28 µg/m³. The present study result indicated that Anand Vihar is the most polluted place in the Delhi city.

At Punjabi Bagh study area: The PM₁₀ concentration at lower elevation was found to be in the range between 152.25 to 462.19 µg/m³. Similarly, the concentration of PM_{2.5} at lower elevation was varied between 81.52 to 119.63 µg/m³.

5.3 Chemical and morphological characterization of PM at different elevations in Delhi city

- Na, Mg, S, Si, and Al were found to be the most abundant elements at all the study locations. Most of the elemental concentrations were higher in the lower elevations as compared to higher elevations.
- The correlation analysis of elements indicated that the vehicular emissions and re-suspended dust were the major contributors to PM pollution in most of the sites. In Okhla, fuel oil combustion was found to be the major PM source contribution.
- A strong correlation between OC and EC at both the elevations, ($R^2 = 0.8$) suggested that the emissions from common sources are significantly contributed to PM masses.
- Morphological characteristics showed varying morphology with respect to location and elevation. The result also indicated flyash contribution in higher elevation and alumino-silicates contribution in lower elevation were significant.

5.4 PM₁₀ and PM_{2.5} source apportionment at different elevations in Delhi city

The PM_{2.5} source apportionment results of CMB approach showed that at lower elevations vehicular emission (27 % at Murthal to 48 % at DCE), fuel oil combustion, i.e. Industrial and domestic combustion (27 % at DCE to 37 % at Okhla) were the two major contributors to PM_{2.5} concentration in Delhi city during winter season. Mineral dust (4 % at Okhla to 21% at Murthal), biomass burning (14% at Murthal), solid waste burning (6% at Okhla to 8 % at Murthal), coal burning (7% at IIT Delhi), construction activities (2 % at Okhla), secondary aerosols (8% at IIT Delhi) were also contributed to the PM_{2.5} mass at study areas.



The PM_{2.5} source apportionment results of CMB approach showed that at higher elevations vehicular emission (30 % at Murthal to 51 % at DCE), fuel oil combustion, i.e. Industrial and domestic combustion (29 % at Murthal to 38 % at Okhla) were the two major contributors to PM_{2.5} concentration in Delhi city during winter season. Mineral dust (4 % at Okhla to 18 % at Murthal), Biomass burning (15 % Murthal), solid waste burning (6 % at Okhla to 10 % Murthal), coal burning (11 % at IIT Delhi), construction activities (2% at Okhla), secondary aerosols (4 % at Okhla to 8 % at IIT Delhi) were also contributed to PM_{2.5} mass at study areas.

The PM₁₀ source apportionment results of CMB and PMF approaches showed that at lower elevations vehicular emission (CMB: 21 % at Murthal to 27 % at DCE), fuel oil combustion i.e. Industrial and domestic combustion (CMB:20% at IIT Delhi to 30 % at Okhla; PMF: 23 % at IIT Delhi to 32% at Murthal) were the two major contributors to PM₁₀ concentration in Delhi city during winter season. Mineral dust (CMB: 26 % at Okhla to 33 % at IIT Delhi), Biomass burning (CMB:4 % at Murthal; PMF:5% at Okhla), solid waste burning (CMB: 1% at Okhla to 5% at IIT Delhi; PMF: 6% at IIT Delhi to 10 % at Okhla), coal burning (CMB:4% at Murthal; PMF:5% at Okhla), secondary aerosols (CMB: 5% at DCE to 9 % at IIT Delhi; PMF: 7% at Okhla to 16 % at IIT Delhi) were also contributed to PM₁₀ mass at study locations.

The PM₁₀ source apportionment results of CMB approach showed that at higher elevations vehicular emission (CMB: 33% at Murthal to 35 % at IIT Delhi), fuel oil combustion i.e. Industrial and domestic combustion (CMB: 24 % at IIT Delhi to 46 % at Okhla; PMF: 28% at Murthal to 40 % at Okhla) were the two major contributors to PM₁₀ concentration in Delhi city during winter season. Mineral dust (CMB:20% at Okhla to 24% at Murthal), biomass burning (CMB: 5% at Okhla), solid waste burning (CMB: 2% at Murthal to 6 % at IIT Delhi; PMF: 4 % at Murthal to 6 % at IIT Delhi), coal burning (CMB: 4% at Okhla to 8 % at IIT Delhi; PMF: 4% at IIT Delhi), secondary aerosols (CMB: 3% at DCE to 6% at IIT Delhi; PMF: 3% Murthal to 20 % at DCE) were also contributed to PM₁₀ mass at study areas.

The summary of PM₁₀ and PM_{2.5} source apportionment results are provided in Table 5.1



Table 5.1. Summary of the PM₁₀ and PM_{2.5} source apportionment results

Summary of source contribution estimations of PM _{2.5} and PM ₁₀ through CMB and PMF analysis at lower elevation (LE) and higher elevation (HE) in Delhi city						
Description	CMB				PMF	
	PM _{2.5}		PM ₁₀		PM ₁₀	
	LE	HE	LE	HE	LE	HE
Fuel oil combustion	27% (DCE) to 37% (Okhla)	29% (Murthal) to 38 % (Okhla)	20%(IIT Delhi) to 38%(Okhla)	24%(IIT Delhi) to 46% (Okhla)	23%(IIT Delhi) to 32%(Murthal)	28%(Murthal) to 40% (Okhla)
Mineral dust	4% (Okhla) to 21% (Murthal)	4 % (Okhla) to 18%(Murthal)	26% (Okhla) to 33% (IIT Delhi)	20%(Okhla) to 24%(Murthal)	47%(DCE) to 53% (Okhla)	43%(IIT Delhi) to 49%(Okhla)
Traffic Emission	27%(Murthal) to 48%(DCE)	30% (Murthal) to 51% (DCE)	21% (Murthal) to 27% (DCE)	23% (Murthal) to 35% (IIT Delhi)		
Solid waste burning	6%(Okhla) to 8%(Murthal)	6%(Okhla) to 10% (Murthal)	1%(Okhla) to 5% IIT Delhi	2% (Murthal) to 6%(IIT Delhi)	6%(IIT Delhi) to 10%(Okhla)	4%(Murthal) to 6%(IIT Delhi)
Biomass burning	14% (Murthal)	15% (Murthal)	4% (Murthal)	6%(Murthal)	5% (Okhla)	-
Coal Burning	7% (IIT Delhi)	11% (IIT Delhi)	3% (Okhla) to 9%(IIT Delhi)	4%(Okhla) to 8% (IIT Delhi)	1%(DCE) to 2%(IIT Delhi)	4% (IIT Delhi)
Construction activities	2% (Okhla)	2% (Okhla)	-	-	-	-
Secondary aerosols	8% (IIT Delhi)	4%(Okhla) to 8% (IIT Delhi)	5%(DCE) to 9%(IIT Delhi)	3% (DCE) to 6(IIT Delhi)	7%(Okhla) to 16% (IIT Delhi)	3%(Murthal) to 20% (DCE)



REFERENCES

- Balachandran, S., Meena, B. R., & Khillare, P. S. (2000). Particle Size Distribution And Its Elemental Composition In The Ambient Air Of Delhi. *Environment International*, 26(1), 49-54.
- Balakrishna, G., & Pervez, S. (2009). Source apportionment of atmospheric dust fallout in an urban-industrial environment in India. *Aerosol and Air Quality Research*, 9(3), 359-367.
- Beig, G., Chate, D. M., Ghude, S. D., Mahajan, A. S., Srinivas, R., Ali, K., ... & Trimbake, H. R. (2013). Quantifying the effect of air quality control measures during the 2010 Commonwealth Games at Delhi, India. *Atmospheric environment*, 80, 455-463.
- Belviso, C., Pascucci, S., Cavalcante, F., Palombo, A., Pignatti, S., Simoniello, T., & Fiore, S. (2011). Multi-Technique Application for Waste Material Detection and Soil Remediation Strategies: The Red Mud Dust and Fly Ash Case Studies. In *Soil Contamination. InTech*.
- Cass, G.R., (1998). Organic molecular tracers for particulate air pollution sources. *Trends Anal. Chem.* 17, 356-366.
- Castro, L.M., Pio, C.A., Harrison, R.M., Smith, D.J.T., (1999). Carbonaceous aerosol in urban and rural European atmospheres: estimation of secondary organic carbon concentrations. *Atmos. Environ.* 33, 2771e2781.
- Chakraborty, A., & Gupta, T. (2009). Chemical characterization of submicron aerosol in Kanpur region: a source apportionment study. *Int. J. Env. Ac. Eng*, 1, 19-27.
- Cheng, H., Deng, Z., Chakraborty, P., Liu, D., Zhang, R., Xu, Y., Luo, C., Zhang, G., Li, J., (2013). A comparison study of atmospheric polycyclic aromatic hydrocarbons in three Indian cities using PUF disk passive air samplers. *Atmos. Environ.* 73,16-21.
- Chow, J.C., Watson, J.G., Kuhns, H., Etyemezian, V., Lowenthal, D.H., Crow, D., Kohl, S.D., Engelbrecht, J.P., Green, M.C., (2004). Source profiles for industrial mobile and area sources in the big bend regional aerosol visibility and observational study. *Chemosphere* 54, 185-208.
- Chowdhury, Z., Zheng, M., Schauer, J.J., Sheesley, R.J., Salmon, L.G., Cass, G.R., Russell, A.G., 2007. Speciation of fine organic carbon particles and source apportionment of PM_{2.5} in Indian cities. *J. Geophys. Res.* 112, D15303. [http:// dx.doi.org/10.1029/2007JD008386](http://dx.doi.org/10.1029/2007JD008386).



- CPCB, 2010. Air Quality Monitoring, Emission Inventory and Source Apportionment Study for Indian Cities. Central Pollution Control Board, February 2010. Available at: http://www.cpcb.nic.in/Source_Apportionment_Studies.php (accessed 28.07.18.).
- Dholakia, H. H., Purohit, P., Rao, S., & Garg, A. (2013). Impact of current policies on future air quality and health outcomes in Delhi, India. *Atmospheric environment*, 75, 241-248.
- Duvall, R.M., Norris, G.A., Burke, J.M., Olson, D.A., Vedantham, R., Williams, R., (2012). Determining spatial variability in PM_{2.5} source impacts across Detroit, MI. *Atmos. Environ.* 47, 491-498.
- Fine, P.M., Cass, G.R., Simoneit, B.R.T., (2001). Chemical characterization of fine particle emissions from fireplace combustion of woods grown in the northeastern United States. *Environ. Sci. Technol.* 35, 2665-2675.
- Goel, R., Gani, S., Guttikunda, S. K., Wilson, D., & Tiwari, G. (2015). On-road PM 2.5 pollution exposure in multiple transport microenvironments in Delhi. *Atmospheric Environment*, 123, 129-138.
- Gulia, S., Nagendra, S. S., Khare, M., & Khanna, I. (2015). Urban air quality management- A review. *Atmospheric Pollution Research*, 6(2), 286-304.
- <http://censusindia.gov.in/> (Visited on 24/6/2017)
- http://cpcb.nic.in/National_Ambient_Air_Quality_Standards.php (Visited on 13/5/17).
- Khillare, P. S., & Sarkar, S. (2012). Airborne inhalable metals in residential areas of Delhi, India: distribution, source apportionment and health risks. *Atmospheric pollution research*, 3(1), 46-54.
- Kleeman, M.J., Schauer, J.J., Cass, G.R., (1999). Size and composition distribution of fine particulate matter emitted from wood burning, meat charboiling, and cigarettes. *Environ. Sci. Technol.* 33, 3516-3523.
- Kothai, P., Saradhi, I. V., Prathibha, P., Hopke, P. K., Pandit, G. G., & Puranik, V. D. (2008). Source apportionment of coarse and fine particulate matter at Navi Mumbai, India. *Aerosol and Air Quality Research*, 8(4), 423-436.



- Kumar, A., Srivastava, D., Agrawal, M., & Goel, A. (2014). Snapshot of PM loads evaluated at major road and railway intersections in an urban locality. *International Journal of Environmental Protection*, 4(1), 23.
- Li, J., Wang, G., Aggarwal, S.G., Huang, Y., Ren, Y., Zhou, B., Singh, K., Gupta, P.K., Cao, J., Zhang, R., 2014. Comparison of abundances, compositions and sources of elements, inorganic ions and organic compounds in atmospheric aerosols from Xi'an and New Delhi, two megacities in China and India. *Sci. Total Environ.* 476e477, 485e495.
- Li, H., Tatarko, J., Kucharski, M., & Dong, Z. (2015). PM_{2.5} and PM₁₀ emissions from agricultural soils by wind erosion. *Aeolian Research*, 19, 171-182.
- Linak, W. P., Yoo, J. I., Wasson, S. J., Zhu, W., Wendt, J. O., Huggins, F. E., ... & Gilmour, M. I. (2007). Ultrafine ash aerosols from coal combustion: Characterization and health effects. *Proceedings of the Combustion Institute*, 31(2), 1929-1937.
- Moreno, T., Karanasiou, A., Amato, F., Lucarelli, F., Nava, S., Calzolari, G., Chiari, M., Coz, E., Artinano, B., Lumberras, J., Borge, R., Boldo, E., Linares, C., Alastuey, A., Querol, X., Gibbons, W., (2013). Daily and hourly sourcing of metallic and mineral dust in urban air contaminated by traffic and coal-burning emissions. *Atmos. Environ.* 68, 33.
- MoRTH, The Ministry of Road Transport and Highways.(2010). Annual report 2010-2011, <http://morth.nic.in/showfile.asp?lid=414>.
- Pant, P., Harrison, R.M.,(2012). Critical review of receptor modelling for particulate matter: a case study of India,. *Atmos. Environ.* 49, 1-12.
- Pant, P., Harrison, R.M., (2013). Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: a review. *Atmos. Environ.* 77, 78-97.
- Pant, P., Shukla, A., Kohl, S. D., Chow, J. C., Watson, J. G., & Harrison, R. M. (2015). Characterization of ambient PM_{2.5} at a pollution hotspot in New Delhi, India and inference of sources. *Atmospheric Environment*, 109, 178-189.
- Patil, R.S., Kumar, R., Menon, R., Shah, M.K., Sethi, V., (2013). Development of particulate matter speciation profiles for major sources in six cities in India. *Atmos. Res.* 132e133, 1-11.



- Perrino, C., Tiwari, S., Catrambone, M., Dalla Torre, S., Rantica, E., & Canepari, S. (2011). Chemical characterization of atmospheric PM in Delhi, India, during different periods of the year including Diwali festival. *Atmospheric Pollution Research*, 2(4), 418-427.
- Pio, C., Cerqueira, M., Harrison, R.M., Nunes, T., Mirante, F., Alves, C., Oliveira, C., Sanchez de la Campa, A., Artinano, B., Matos, M., 2011. OC/EC ratio observations in Europe: re-thinking the approach for apportionment between primary and secondary organic carbon. *Atmos. Environ.* 45, 6121-6132.
- Rajamma, R., Senff, L., Ribeiro, M. J., Labrincha, J. A., Ball, R. J., Allen, G. C., & Ferreira, V. M. (2015). Biomass fly ash effect on fresh and hardened state properties of cement based materials. *Composites Part B: Engineering*, 77, 1-9.
- Sahu, M., Hu, S., Ryan, P.H., Le Masters, G., Grinshpun, S.A., Chow, J.C., Biswas, P., (2011). Chemical compositions and source identification of PM_{2.5} aerosols for estimation of a diesel source surrogate. *Sci. Total Environ.* 409, 2642-2651.
- Seames, W. S. (2003). An initial study of the fine fragmentation fly ash particle mode generated during pulverized coal combustion. *Fuel Processing Technology*, 81(2), 109-125.
- Sharma, S. K., Sharma, A., Saxena, M., Choudhary, N., Masiwal, R., Mandal, T. K., & Sharma, C. (2016). Chemical characterization and source apportionment of aerosol at an urban area of Central Delhi, India. *Atmospheric Pollution Research*, 7(1), 110-121.
- Somerset, V. S., Petrik, L. F., White, R. A., Klink, M. J., Key, D., & Iwuoha, E. (2004). The use of X-ray fluorescence (XRF) analysis in predicting the alkaline hydrothermal conversion of fly ash precipitates into zeolites. *Talanta*, 64(1), 109-114.
- Source apportionment of ambient particulate matter during winter season in Delhi (2017). Interim report Volume I (DPCC, IIT Madras, IIT Delhi), 1-61.
- Srimuruganandam, B., & Nagendra, S. S. (2011). Characteristics of particulate matter and heterogeneous traffic in the urban area of India. *Atmospheric environment*, 45(18), 3091-3102.
- Srivastava, D., Goel, A., & Agrawal, M. (2016). Particle Bound Metals at Major Intersections in an Urban Location and Source Identification Through Use of Metal



Markers. Proceedings of the National Academy of Sciences, India Section A: Physical Sciences, 86(2), 209-220.

- Sugimoto, N., Shimizu, A., Matsui, I., & Nishikawa, M. (2016). A method for estimating the fraction of mineral dust in particulate matter using PM 2.5-to-PM 10 ratios. *Particuology*, 28, 114-120.
- Tiwari, S., Pervez, S., Perrino, C., Bisht, D.S., Srivastava, A.K., Chate, D., (2013). Chemical characterization of atmospheric particulate matter in Delhi, India, Part II: source apportionment studies using PMF 3.0. *Atmos. Res.* 145-146, 45-56.
- Viana, M., Kuhlbusch, T.A.J., Querol, X., Alastuey, A., Harrison, R.M., Hopke, P.K., Winiwarter, W., Vallius, M., et al., (2008). Source apportionment of particulate matter in Europe: a review of methods and results. *J. Aerosol Sci.* 39, 827-849.
- Watson, J.G., Chen, L.-W.A., Chow, J.C., Doraiswamy, P., Lowenthal, D.H., (2008). Source apportionment: findings from the U.S. Supersites Program. *J. Air Waste Manag. Assoc.* 58, 265-288.
- Willis, R. D., Blanchard, F. T., & Conner, T. L. (2002). Guidelines for the application of SEM/EDX analytical techniques to particulate matter samples. EPA. Washington, US.
- Willis, R. D., Blanchard, F. T., & Conner, T. L. (2002). Guidelines for the application of SEM/EDX analytical techniques to particulate matter samples. EPA. Washington, US.
- Xie, R. K., Seip, H. M., Leinum, J. R., Winje, T., & Xiao, J. S. (2005). Chemical characterization of individual particles (PM 10) from ambient air in Guiyang City, China. *Science of the Total Environment*, 343(1), 261-272.
- Xie, R. K., Seip, H. M., Leinum, J. R., Winje, T., & Xiao, J. S. (2005). Chemical characterization of individual particles (PM 10) from ambient air in Guiyang City, China. *Science of the Total Environment*, 343(1), 261-272.
- Xu, X., & Akhtar, U. S. (2010). Identification of potential regional sources of atmospheric total gaseous mercury in Windsor, Ontario, Canada using hybrid receptor modeling. *Atmospheric Chemistry and Physics*, 10(15), 7073-7083.
- Yadav, S., Tandon, A., Tripathi, J. K., Yadav, S., & Attri, A. K. (2016). Statistical assessment of respirable and coarser size ambient aerosol sources and their timeline trend



Source apportionment of ambient particulate matter during winter season in Delhi

profile determination: a four year study from Delhi. Atmospheric Pollution Research, 7(1), 190-200.



APPENDIX

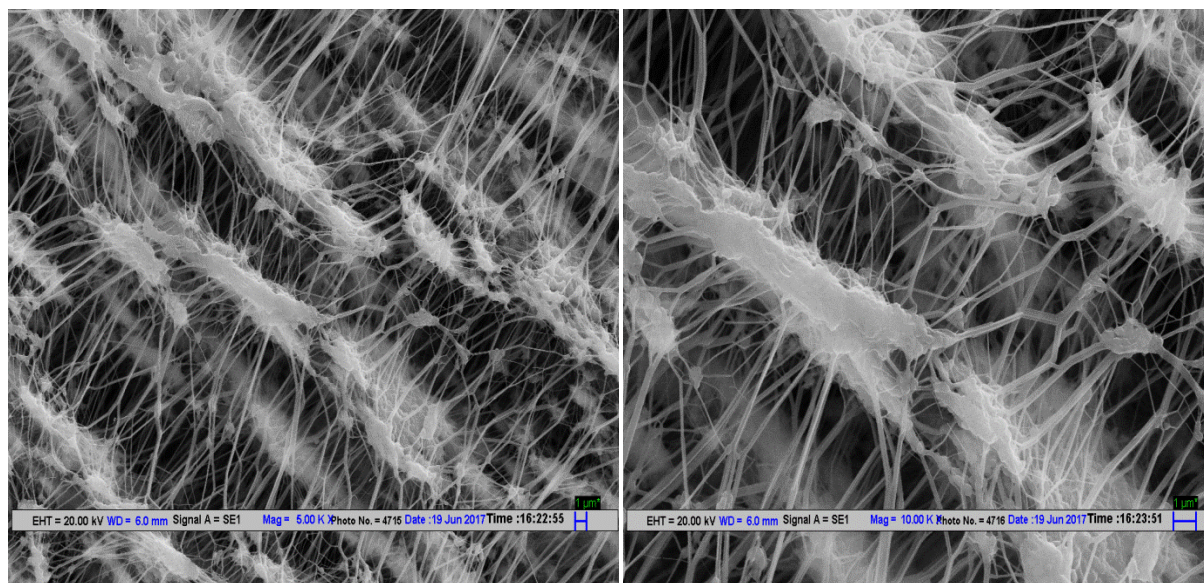


Figure A1: Field Blank

Winter (January –February)

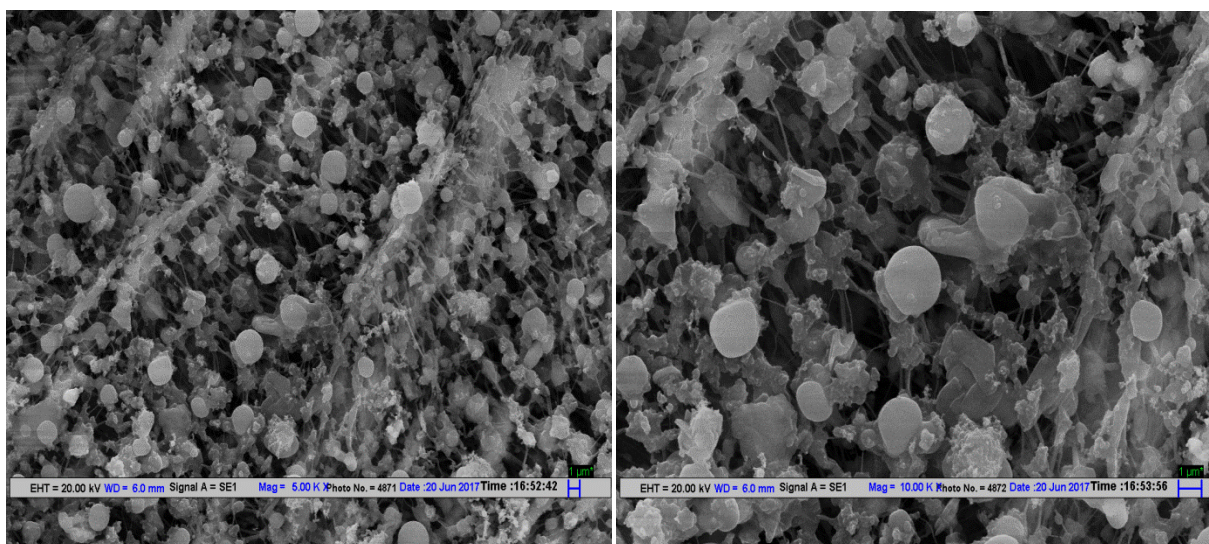


Figure A2: IIT (HE) during winter

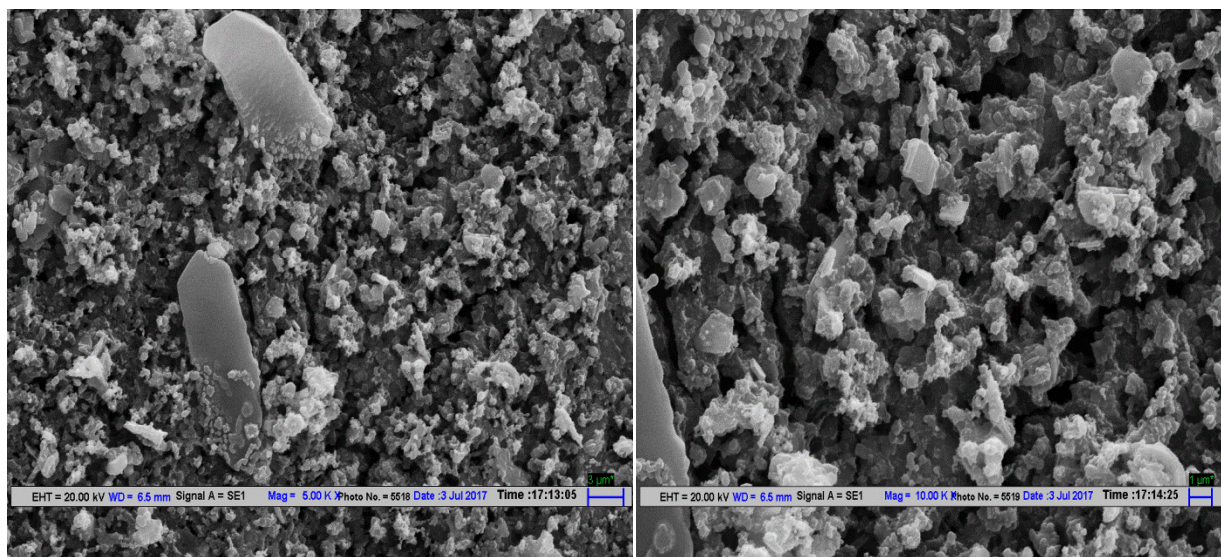


Figure A3: IIT (HE) (Tuesday) (28.2.17)

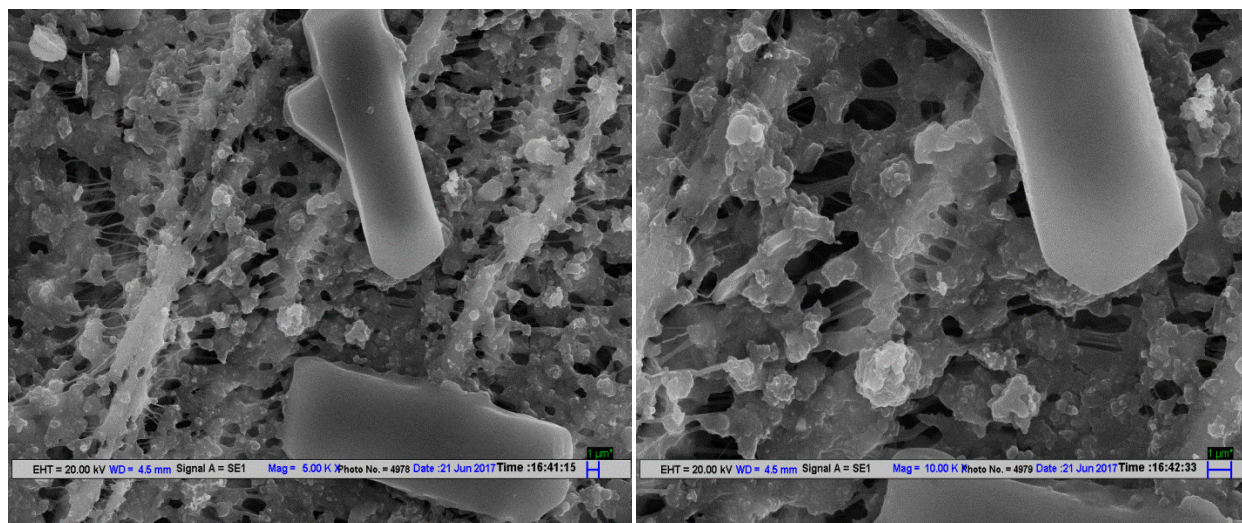


Figure A4: IIT (HE) (Thursday) (09.2.17)

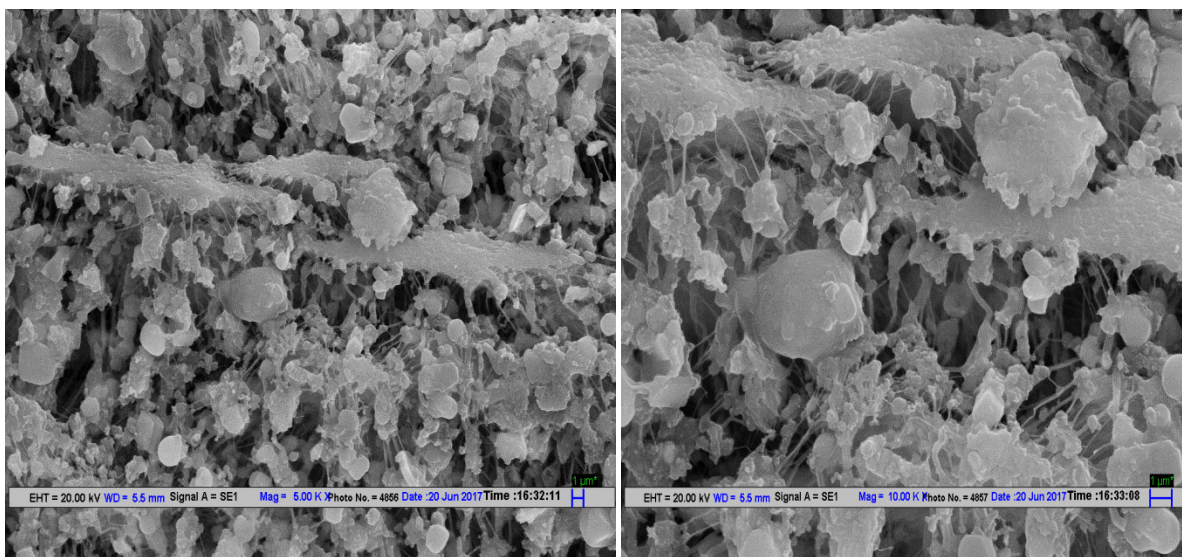


Figure A5: Okhla (LE) (Monday) (6.2.17)

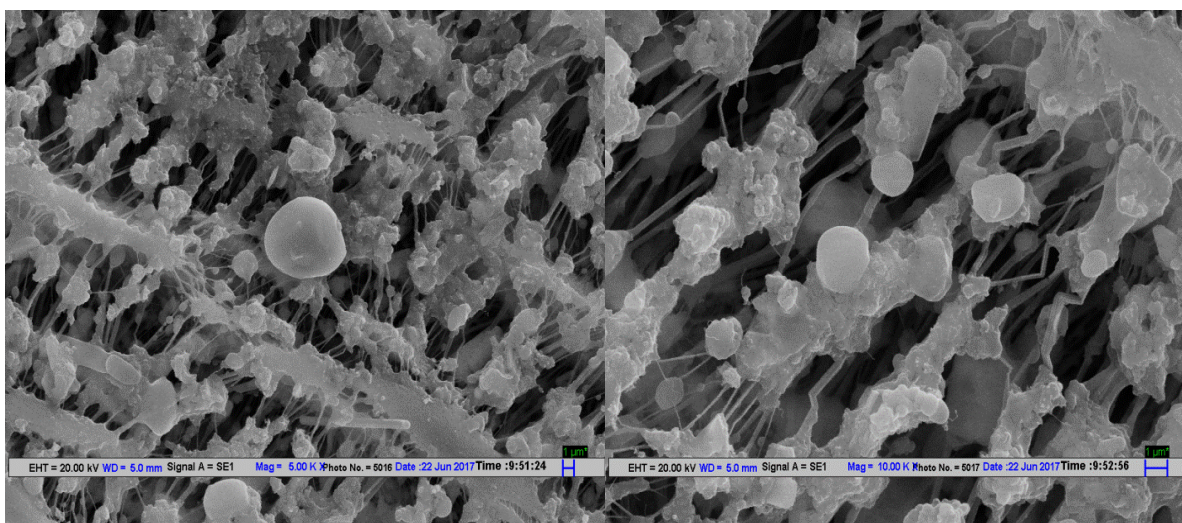


Figure A6: Okhla (HE) (Thursday)(16.2.17)

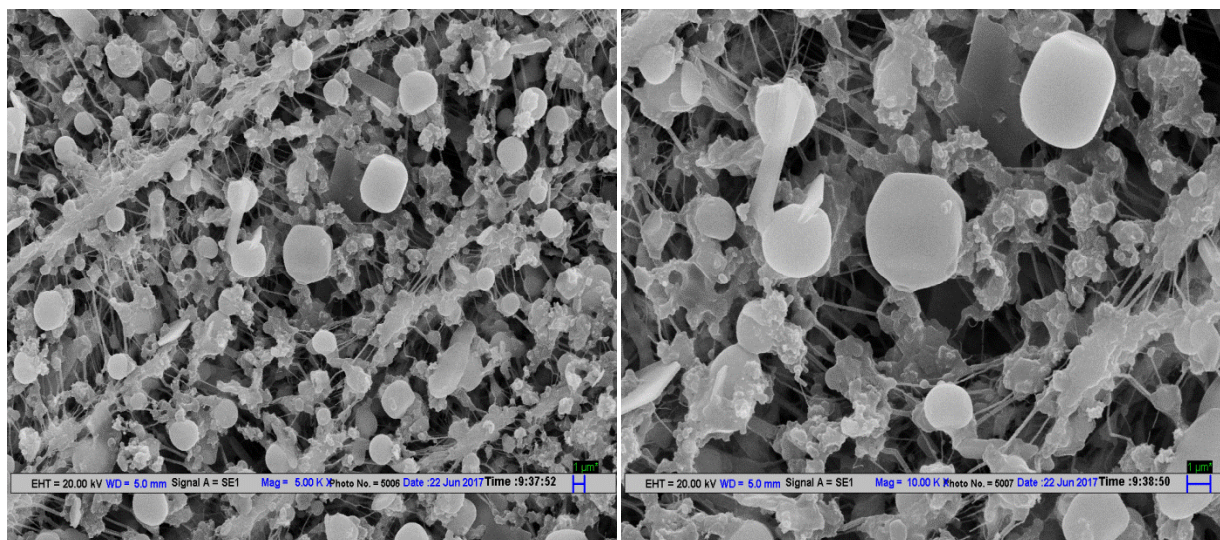


Figure A7: Okhla (HE) (Saturday) (25.2.17)

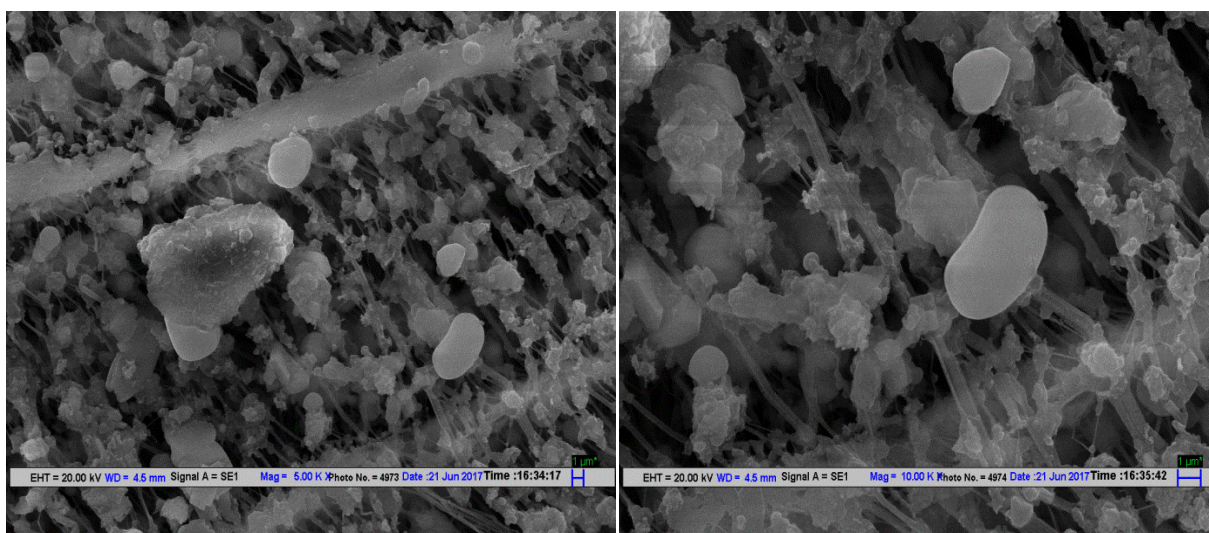


Figure A8: Okhla (HE) (Monday) (06.2.17)

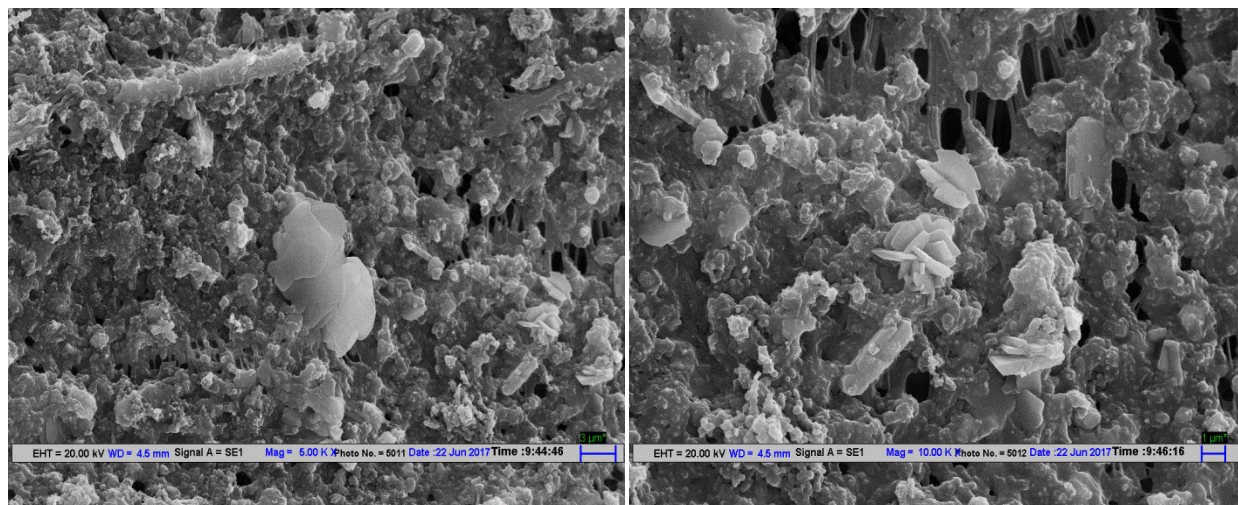


Figure A9: DCE (HE) (Tuesday) (14.2.17)

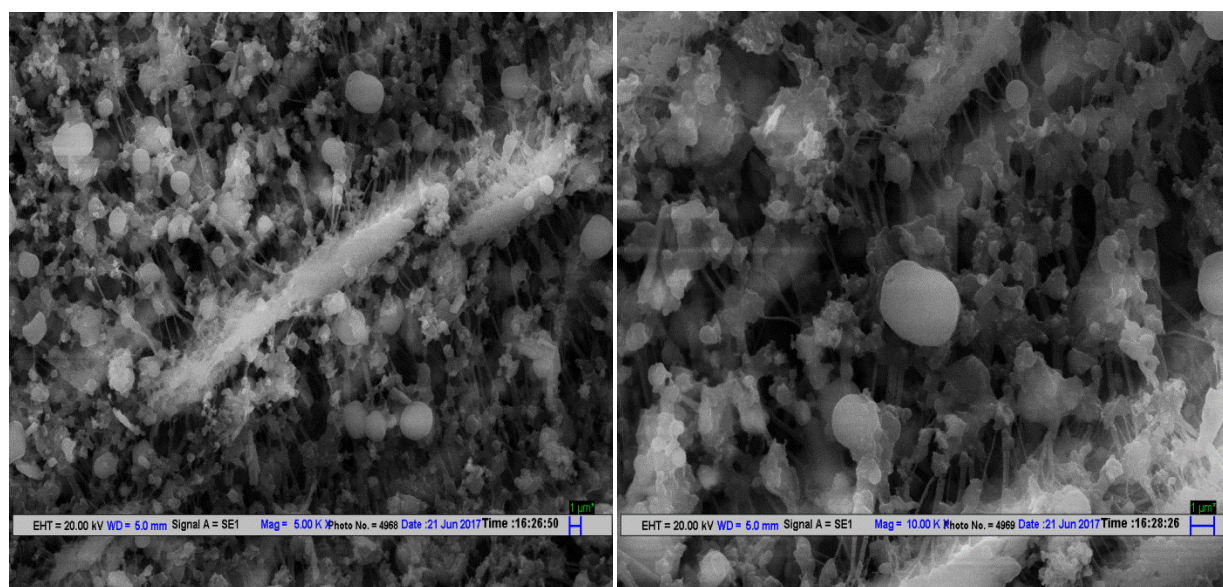


Figure A10: DCE (HE) (Thursday) (23.2.17)

Summer (March-May)

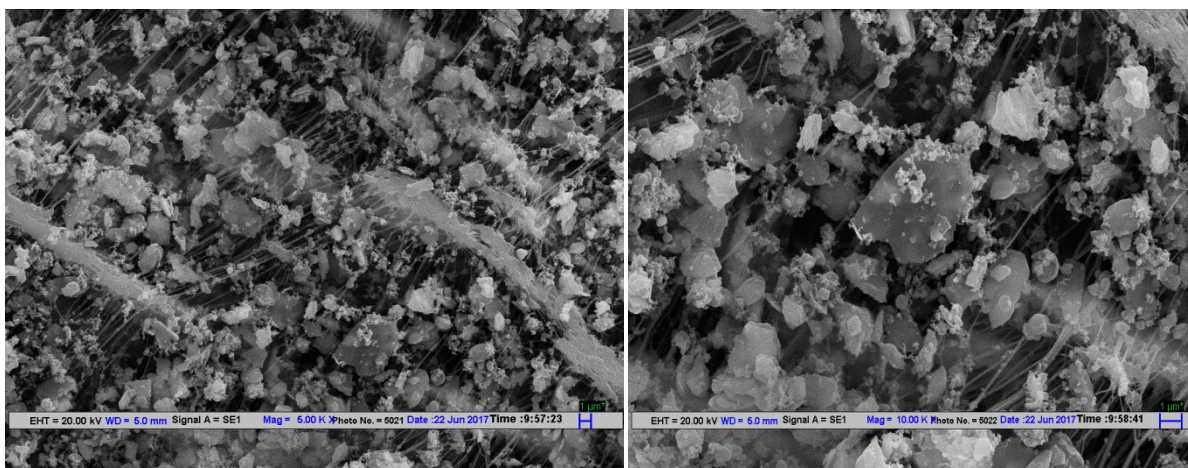


Figure A11: DCE (HE) (Thursday) (6.4.17)

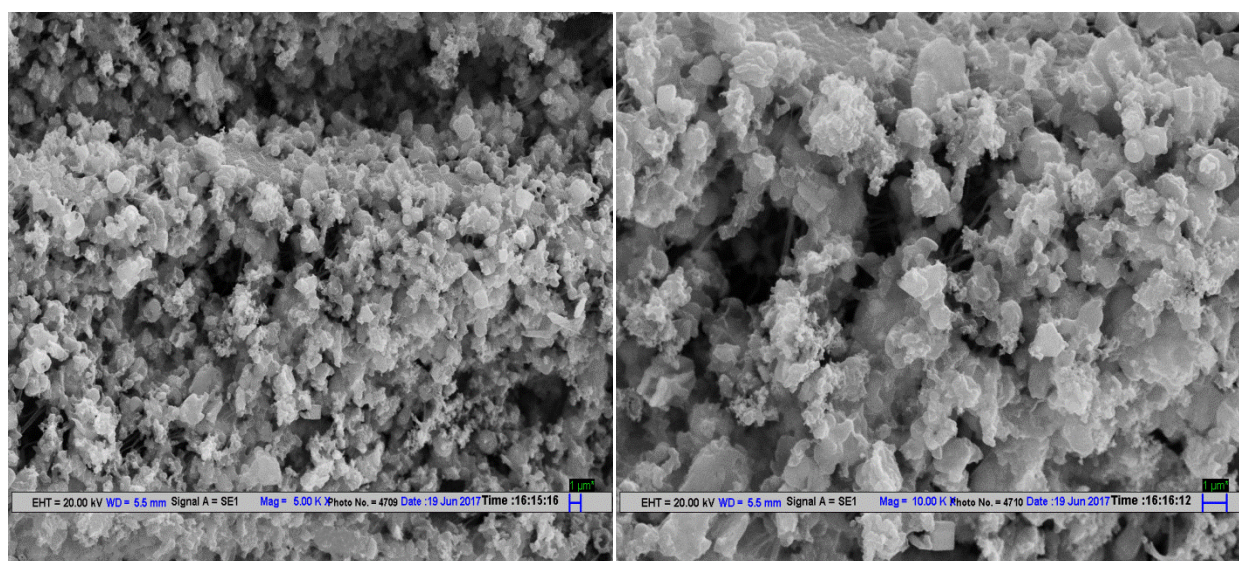


Figure A12: DCE (HE) (Sunday) (5.3.17)

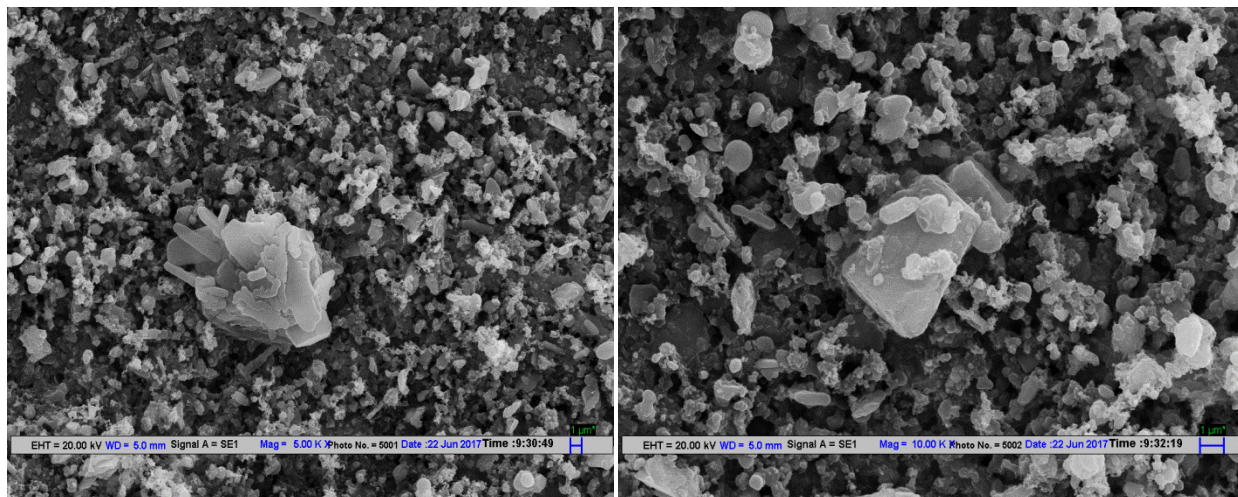


Figure A13: DCE (HE) (Monday) (20.3.17)

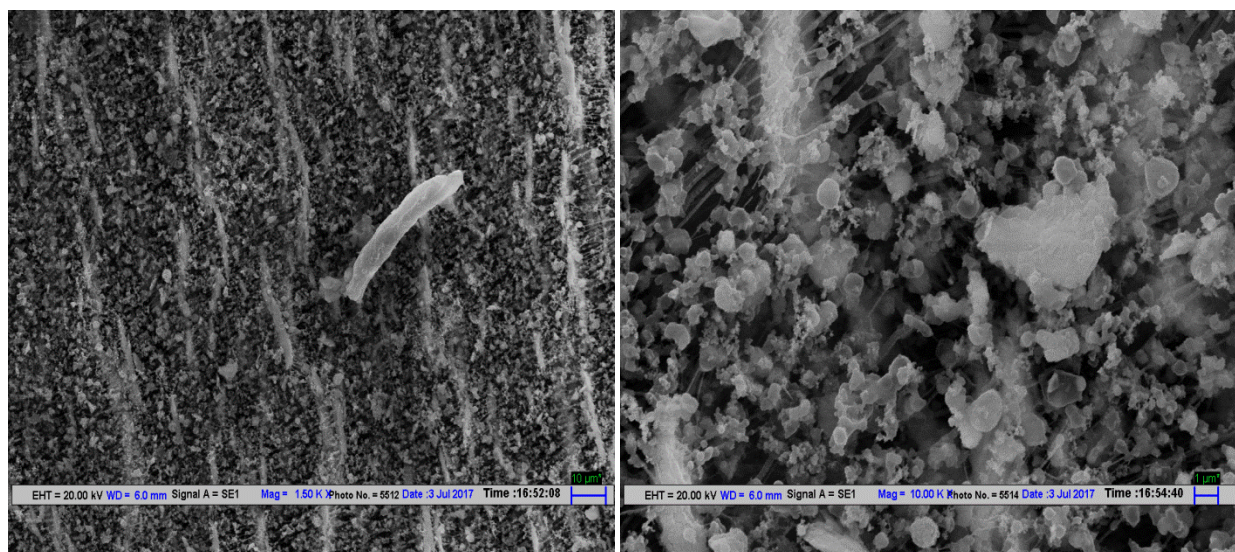


Figure A14:DCE (LE) (Monday) (3.4.17) (1.5KX and 10KX)

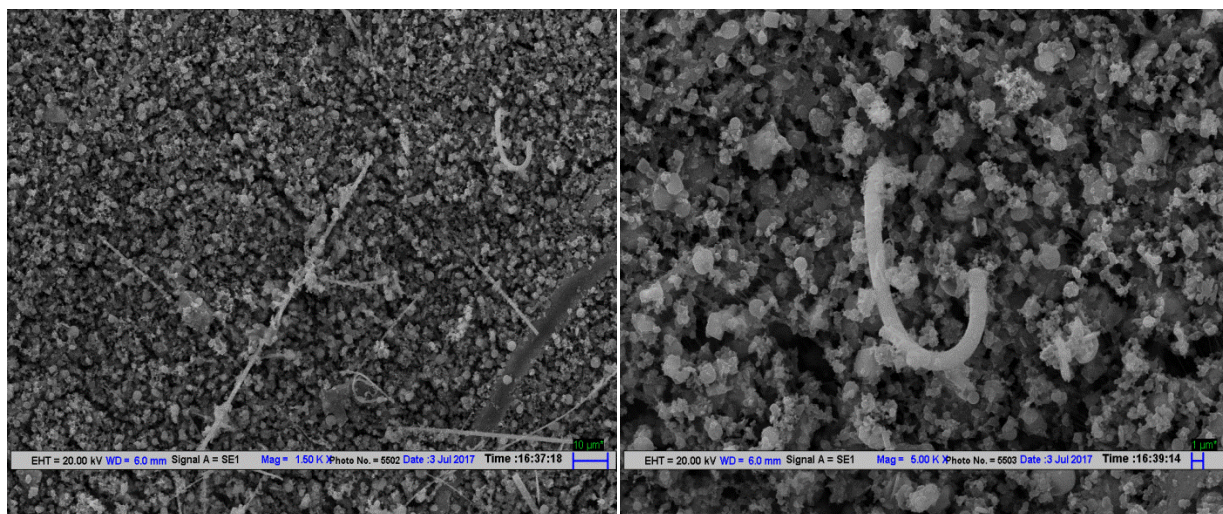


Figure A15: DCE (LE) (Sunday) (5.3.17) (1.5KX, 5KX)

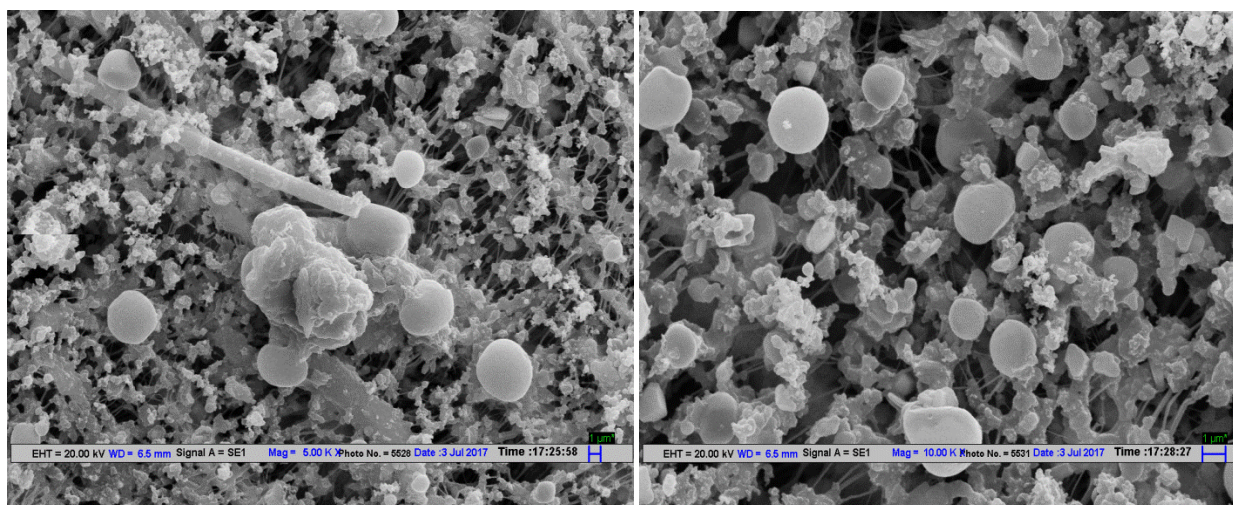


Figure A16: IIT (HE) (Sunday) (5.3.17)

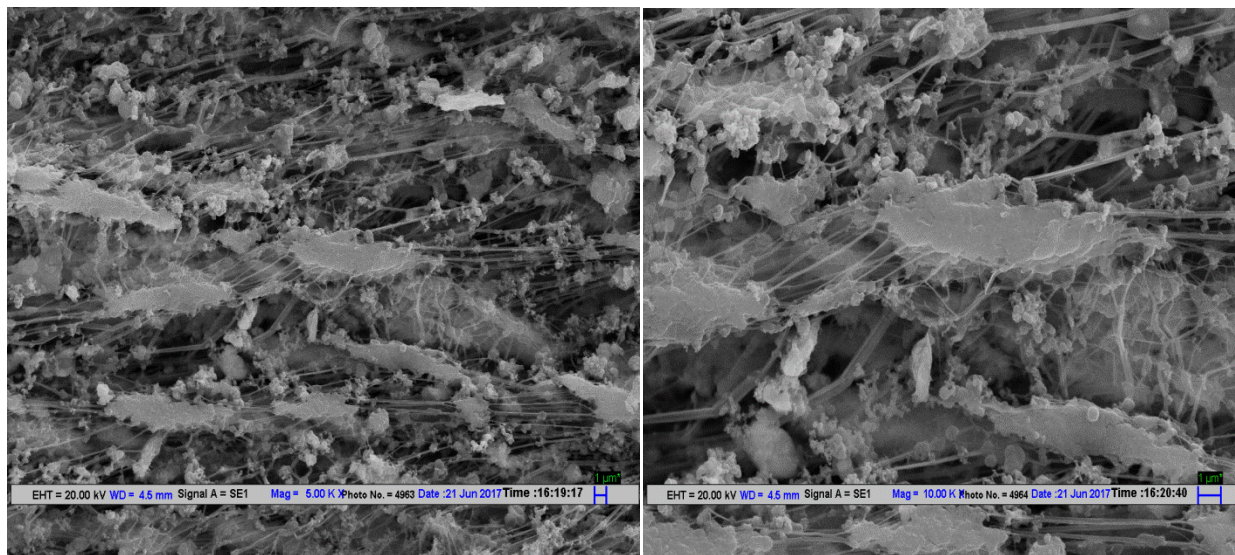


Figure A17: IIT (LE) (Monday) (03.04.17)

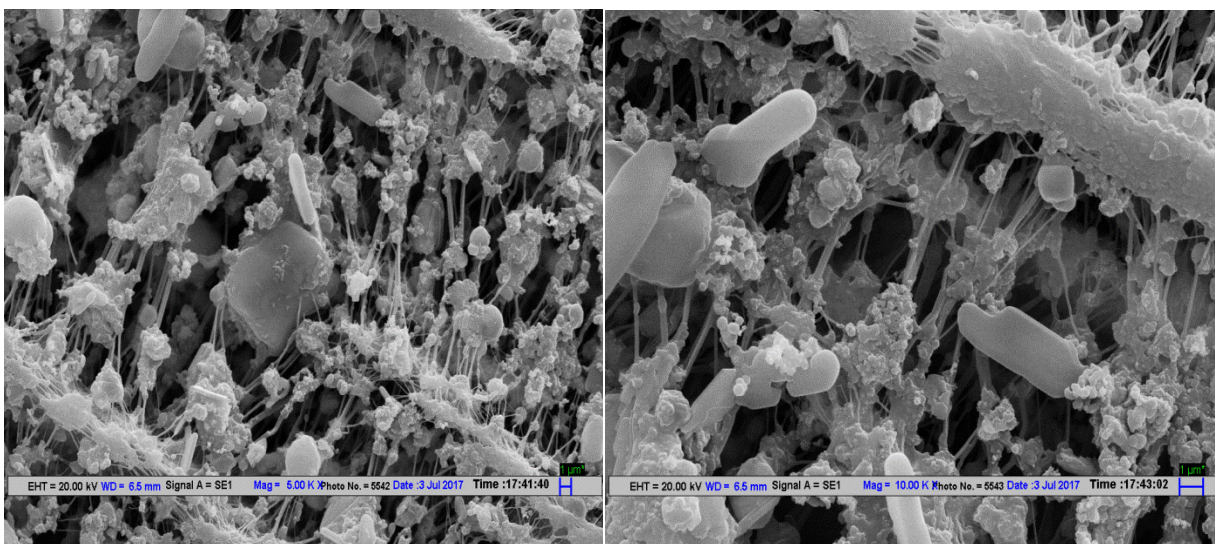


Figure A18: IIT (HE) (Thursday) (16.3.17)

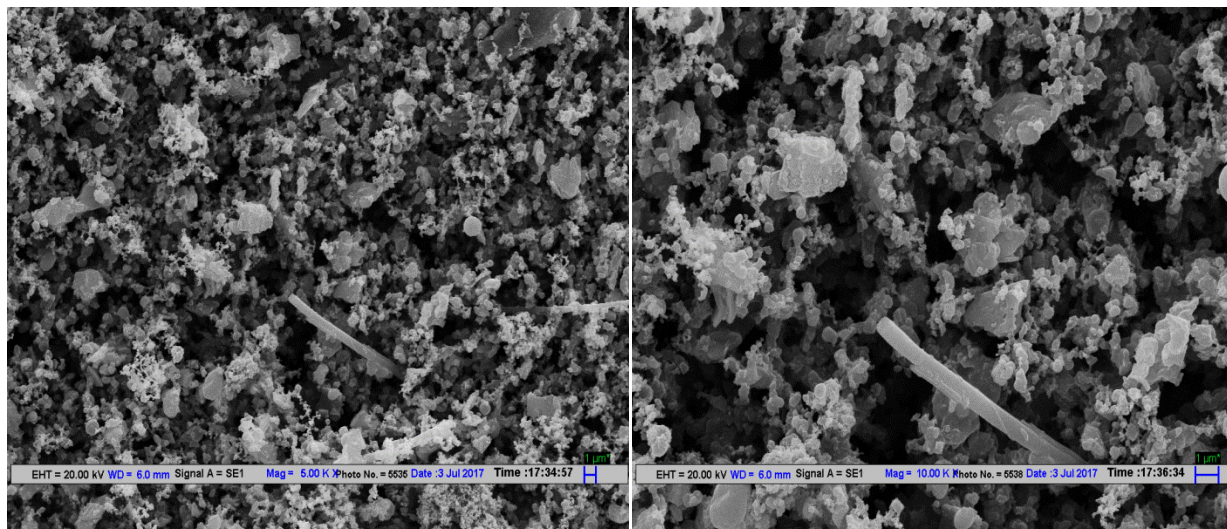


Figure A19: IIT (HE) (Monday) (Quartz) (10.4.17)

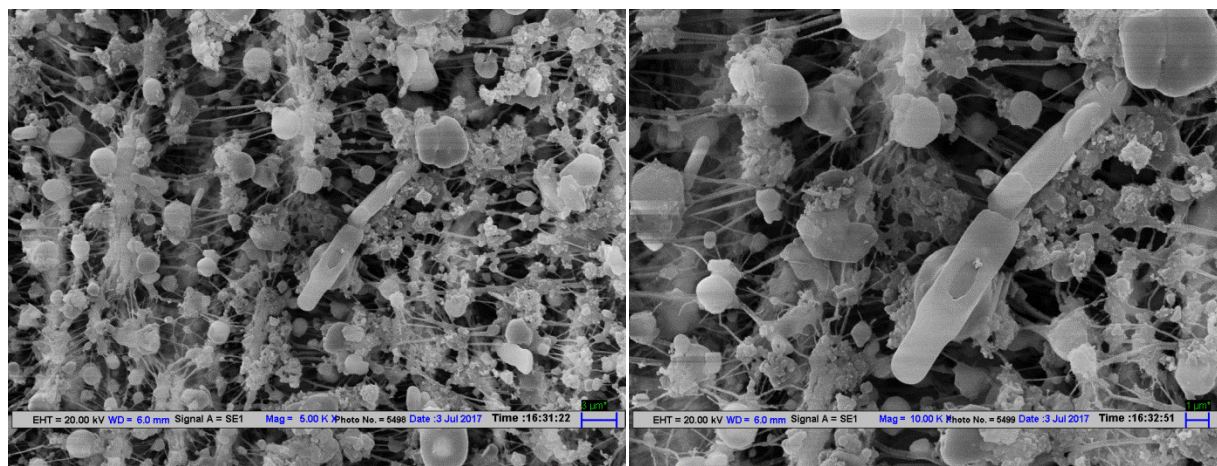


Figure A20: IIT (LE) (Sunday) (19.3.17)

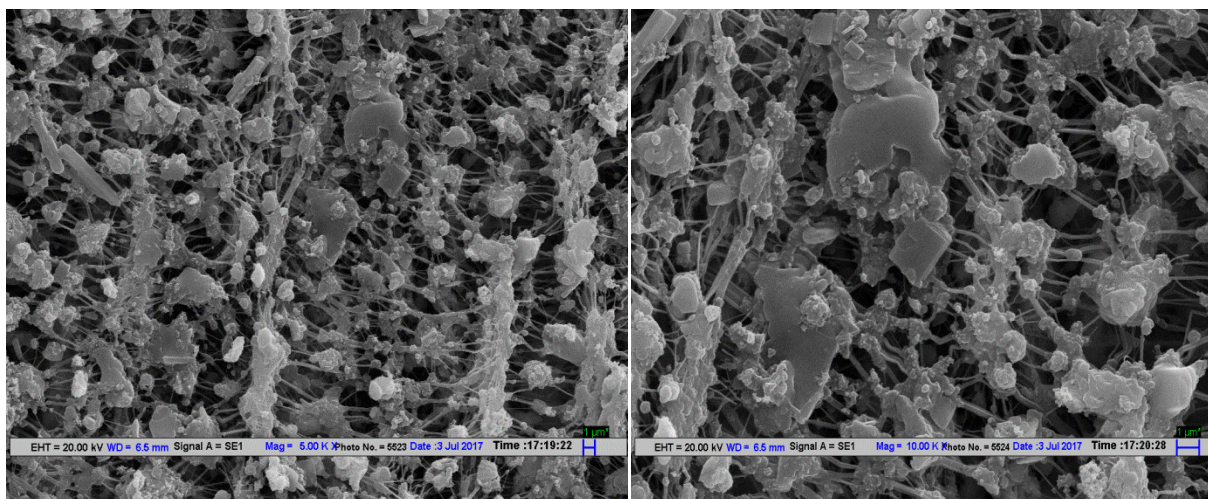


Figure A21 : Okhla (HE) (Thursday) (9.3.17)

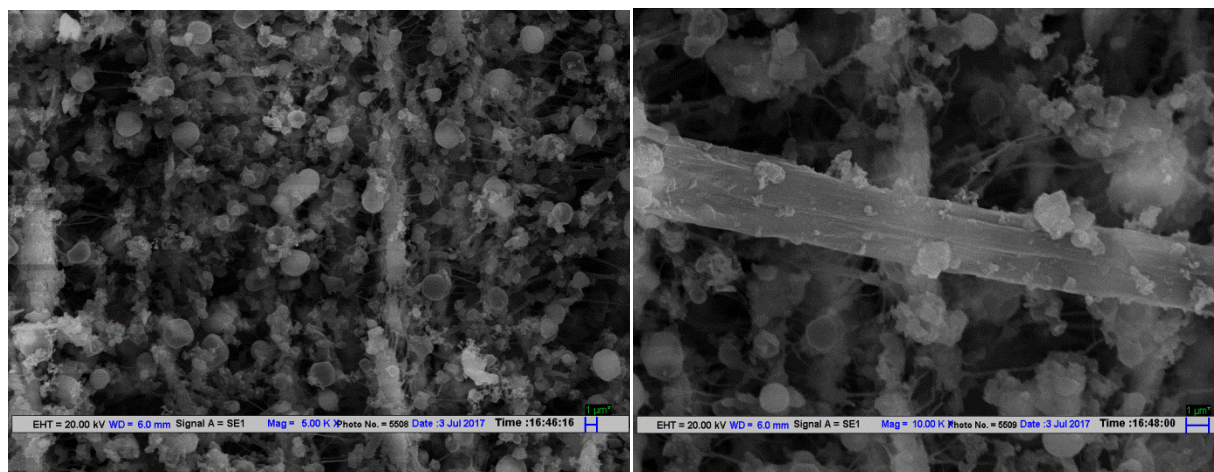


Figure A221: Okhla (LE) (Sunday) (5.3.17)

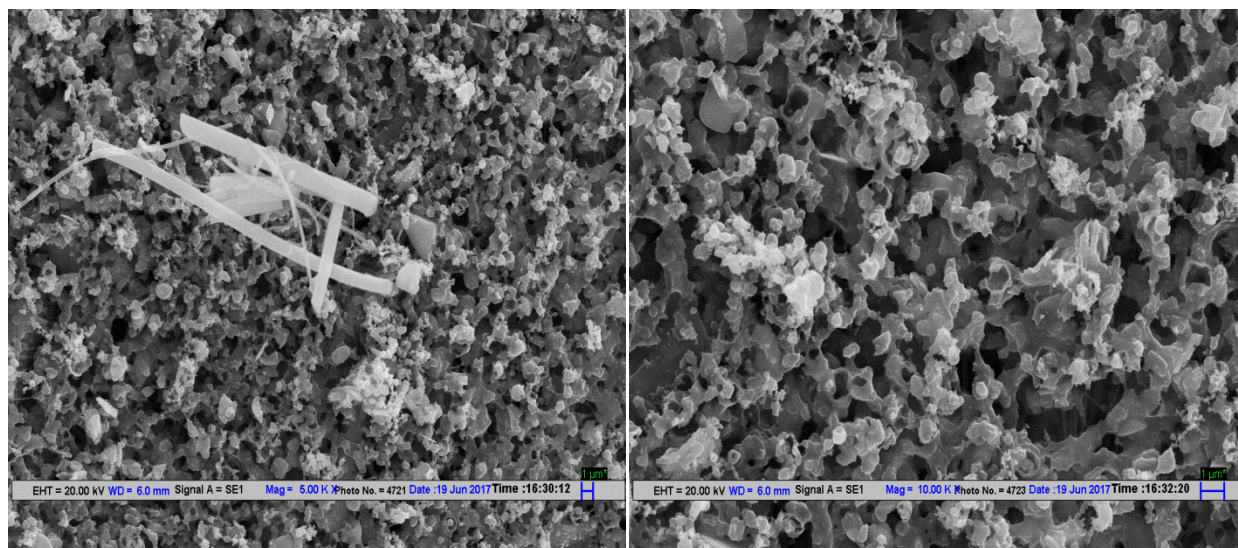


Figure A23: SBIT (HE) (Sunday) (7.5.17)

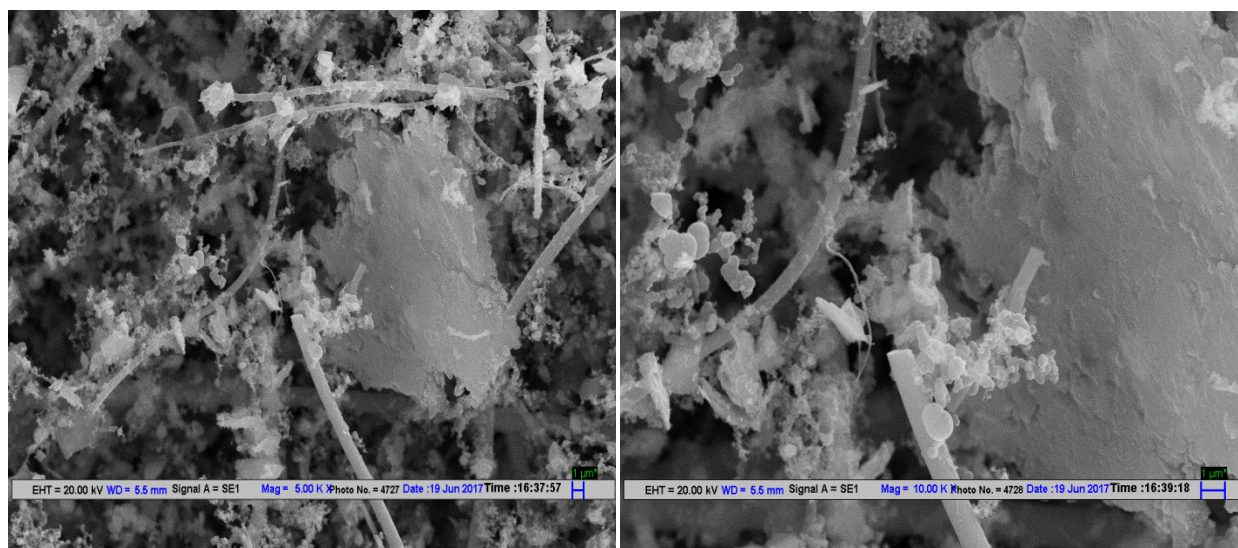
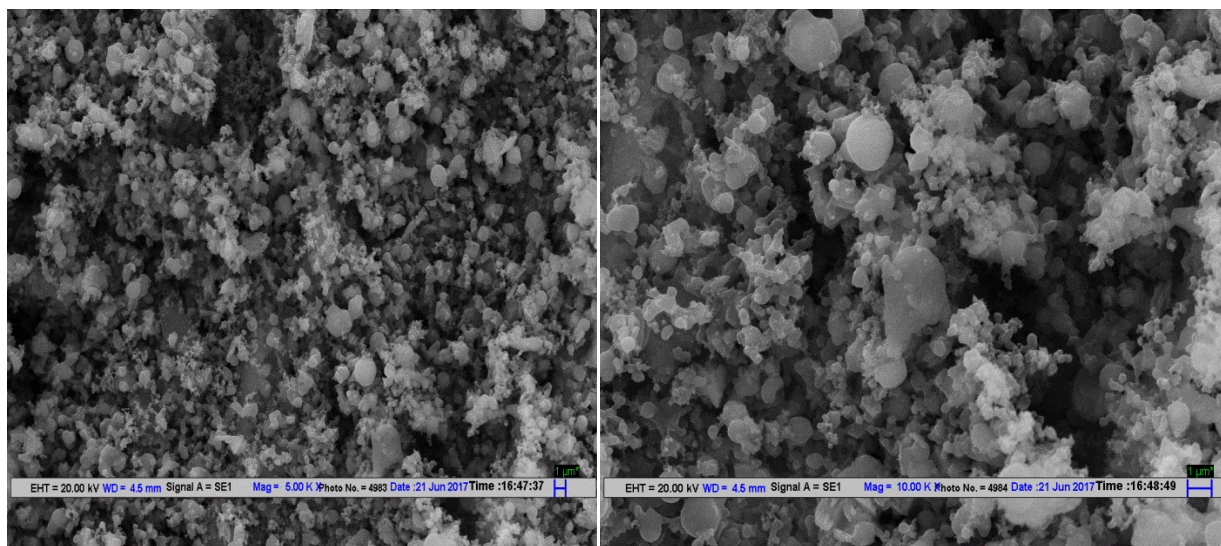


Figure A24: SBIT (HE) (Monday) (8.5.17)



FigureA 25: SBIT (LE) (Saturday) (13.5.17)

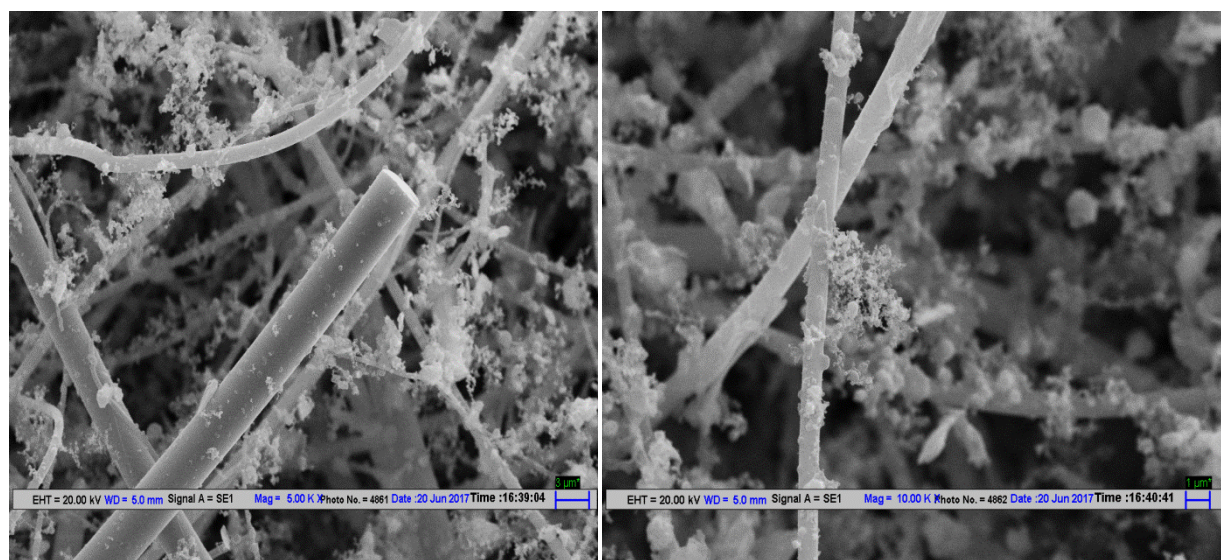


FigurA26: SBIT (LE) (Monday) (8.5.17)

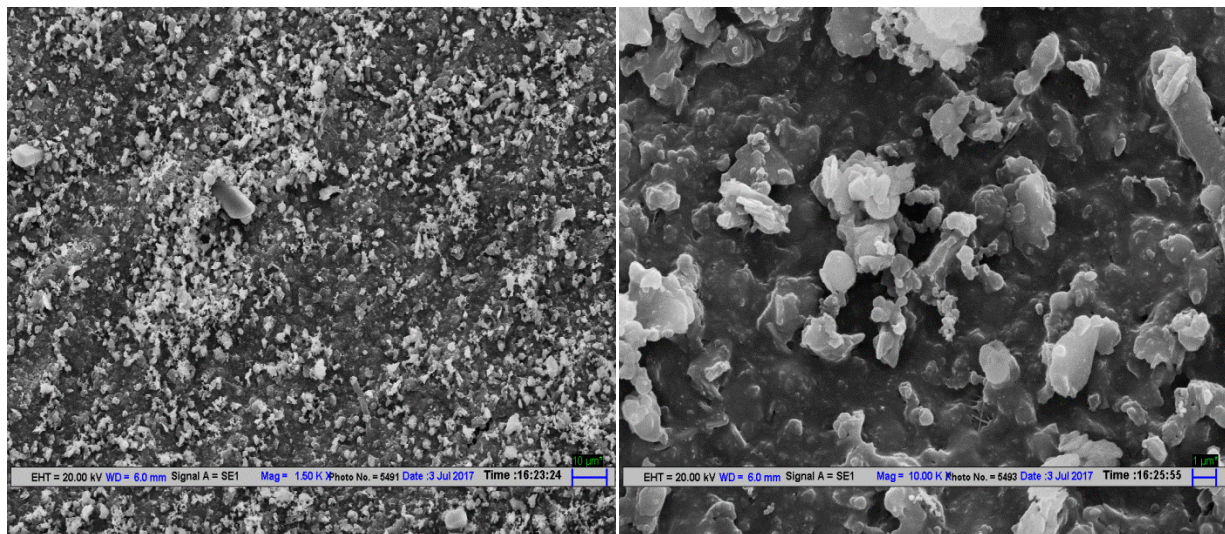


Figure A27: SBIT (HE) (Thursday) (4.5.17) (1.5KX, 10KX)

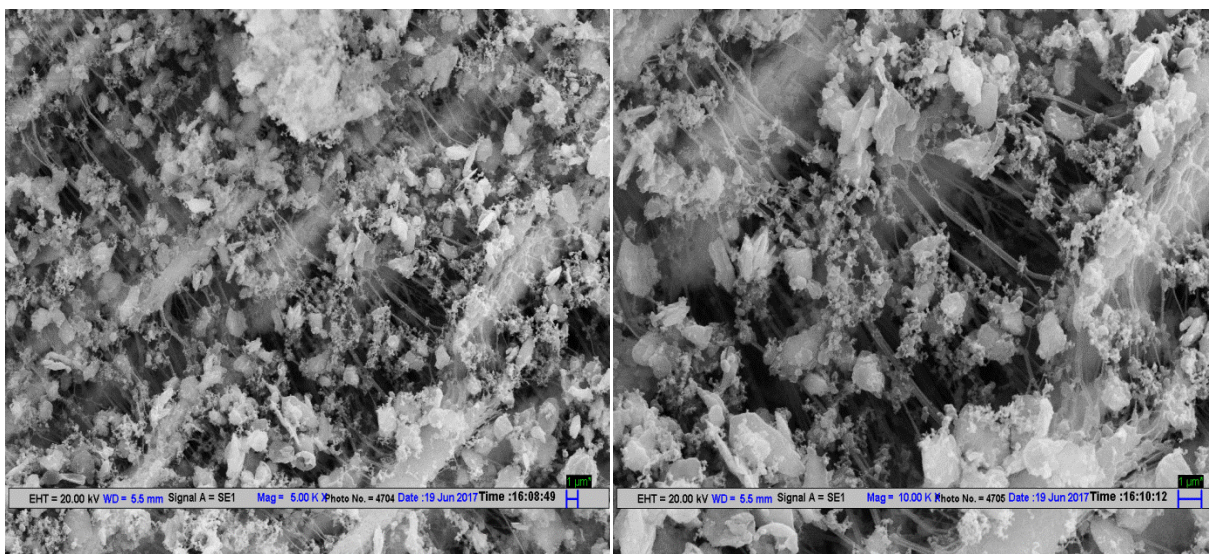
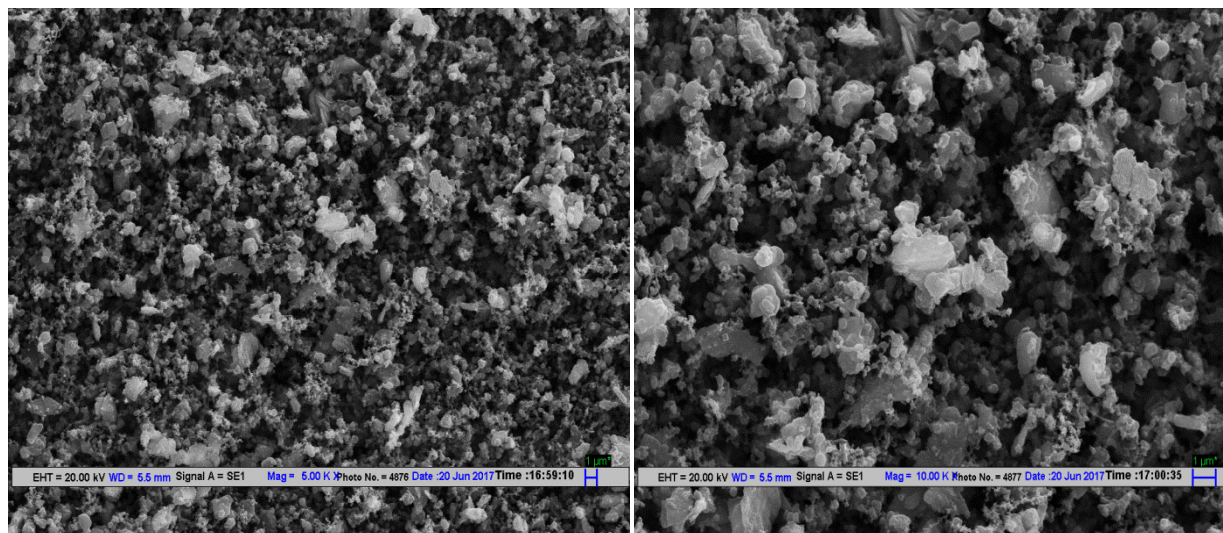


Figure A28: PNB (Thurs) (6.4.17) (DPCC location)



FigureA29: Anand Vihar (Sunday) (14.5.17) (DPCC location)

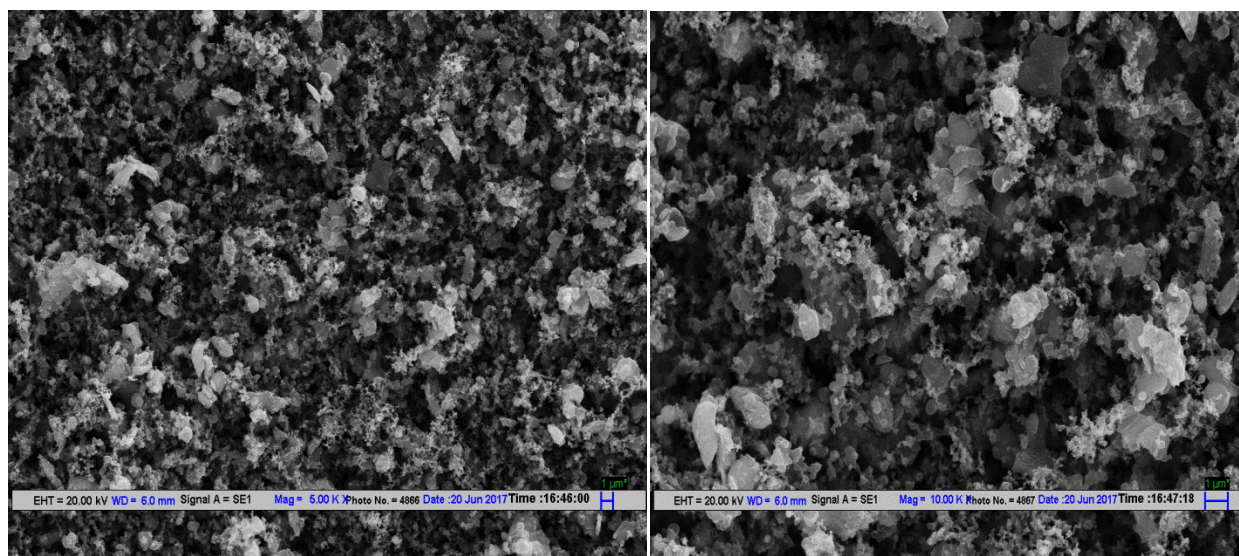


Figure A30: Anand Vihar (Monday) (15.5.17)

Source apportionment of ambient particulate matter during winter season in Delhi

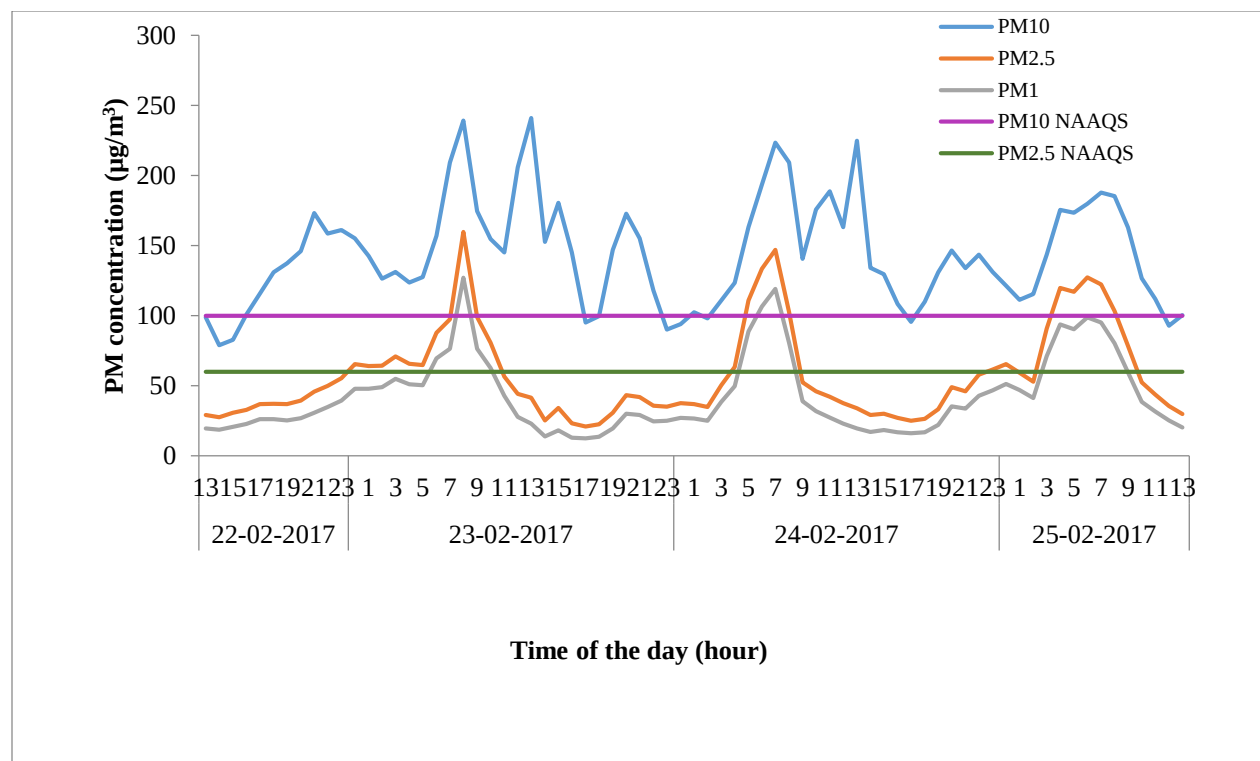


Figure A31: Average PM₁₀, PM_{2.5} and PM₁ concentrations at LE



Source apportionment of ambient particulate matter during winter season in Delhi

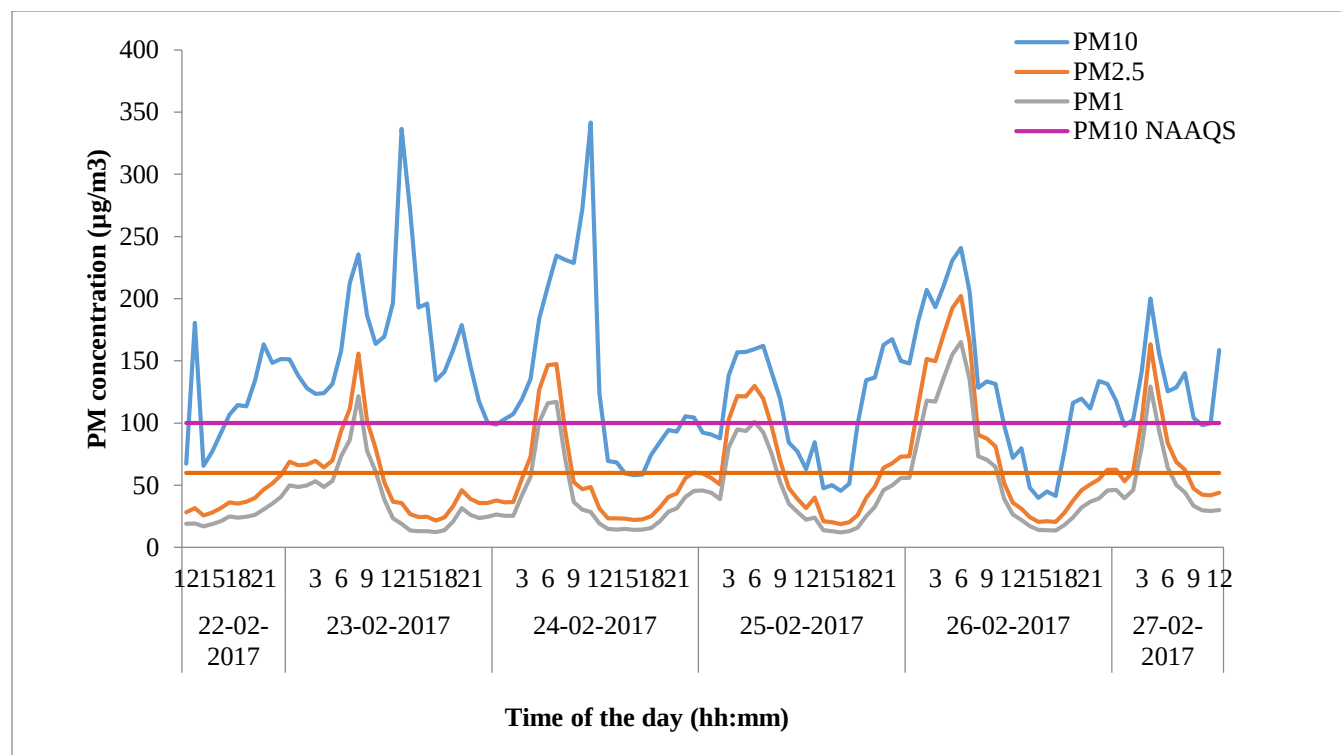


Figure A32: Average PM₁₀, PM_{2.5} and PM₁ concentrations at HE



Table A1: Filter paper details for SEM analysis

Winter (HE)	January-February			
Location	Monday	Thursday	Sunday	Analyzed
IIT Delhi HE	1	1	1	3
Okhla HE	1	1	1	3
DCE HE	1	1	1	3
SBIT Sonapat HE	NA			
Summer (HE)	March-May			
Location	Monday	Thursday	Sunday	Analyzed
IIT Delhi HE	1	1	1	3
Okhla HE	1	1	1	3
DCE HE	1	1	1	3
SBIT Sonapat HE	1	1	1	3
Total samples analyzed for HE study sites				21
Winter	January-February			
Location	Monday	Saturday/Sunday		Analyzed
IIT Delhi LE	1	1		2
Okhla LE	1	1		2
DCE LE	1	1		2
SBIT Sonapat LE	NA			
Summer	March-May			
Location	Monday	Saturday		Analyzed
IIT Delhi LE	1	1		2
Okhla LE	1	1		2
DCE LE	1	1		2
SBIT Sonapat LE	1	1		2
Total samples analyzed for LE study sites				14
DPCC LOCATIONS				
Punjabi Bagh	NA	1	NA	1
Anand Vihar	1	NA	1	2
Blank samples (for QA/QC)				
Field Blank	1			1
Lab Blank	1			1
Total samples analyzed (Winter + Summer) (HE+LE+ DPCC location+ Blank)= (21+14+3+2)= 40				

