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IDENTIFICATION OF POLLUTING SOURCES FOR BENGALURU – SOURCE APPORTIONMENT STUDY

Identification of Polluting Sources for Bengaluru – Source Apportionment Study

Center for Study of Science, Technology and Policy

February 2022

Designed and edited by CSTEP

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Foreword

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

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

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

04/02/2022

(Dr. Shanth A. Thimmaiah)
Chairman
KSPCB

Date: 04.02.2022
Place: Bengaluru.

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This study would not have been possible without the unconditional support and guidance of Dr B R Balagangadharan, then Chief Scientific Officer - Central Environmental Laboratory, KSPCB, who facilitated the sampling exercise at various monitoring locations across the city. Under his guidance, we could build the capacity of the regional officials and field assistants for helping in conducting this study. We express our heartfelt gratitude to all the KSPCB officials and lab technicians at the Central Environmental Laboratory, KSPCB, for extending support in all forms. We also thank the ground support/field assistants for handling the monitoring stations in the city, ensuring a smooth functioning of the instruments and conditioning the filter papers to place the filters, carrying out pre and post analysis of the filters, and meticulously following the Central Pollution Control Board (CPCB) protocol for sample collection.

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Executive Summary

The Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, launched the National Clean Air Programme (NCAP) in 2019, with the aim to improve air-quality levels in non-attainment cities. NCAP has identified 122 non-attainment cities (cities that violate the national ambient air quality standards). Bengaluru, the capital of Karnataka state, is one of the non-attainment cities. In this context, the Karnataka State Pollution Control Board (KSPCB) has put forth action points for reducing the air-pollution levels in the city. These action points are dynamic and would evolve with scientific evidence. The present Source Apportionment (SA) study presents the scientific evidence and sectoral action items for implementation towards clean Bengaluru.

The source apportionment of particulate matter (PM) will help in understanding the emission sources and estimating the share of contributing sectors at different locations in Bengaluru city. Further, the information on of $PM_{2.5}$ and PM_{10} sources will help identify implementable policies and targeted measures to reduce their concentration in the atmosphere.

Hence, with the aim to bridge the existing knowledge gap for air pollution concerns in Bengaluru, the Center for Study of Science, Technology and Policy (CSTEP) – under the aegis of KSPCB – carried out a source apportionment of particulate matter concentrations for Bengaluru.

The study had three major components:

(i) Sampling of $PM_{2.5}$ and PM_{10} through fine particulate sampler and respirable dust sampler, respectively. The study quantified the sources of $PM_{2.5}$ and PM_{10} at the 13 sites monitored by KSPCB in Bengaluru, which were representative of residential, kerbside, industrial, sensitive, and background locations.

(ii) Quantification of the chemical species through various analytical instruments such as inductively-coupled plasma, ion chromatography, gas chromatography and thermal optical transmittance.

(iii) Source apportionment of $PM_{2.5}$ and PM_{10} through receptor modelling using the chemical mass balance model. The quantified chemical data was then used as an input for running the receptor model to derive the sector-wise contribution to pollution.

The main findings of the study are:

- The annual mean ± standard deviation (SD) of $PM_{2.5}$ mass concentration was observed to be 30.9 ± 12.3 μg m^{-3}, which is less than the annual permissible limit (40 μg m^{-3}) specified by the Central Pollution Control Board (CPCB). On the other hand, the annual mean ± SD of PM_{10} mass concentration observed was 78.9 ± 23.6 μg m^{-3}, which is around 1.3 times higher than the annual permissible limit (60 μg m^{-3}) set by CPCB.

- The annual mean concentration of $PM_{2.5}$ consists of metals, Organic Carbon, Elemental Carbon, and ions, each of which was quantified to be 7.9 μg m^{-3}, 7.8 μg m^{-3}, 2.9 μg m^{-3}, and 9.1 μg m^{-3}, respectively. This suggests that ions occupy the maximum share (33%), followed by metals (28.4%), OC (28.1%) and EC (10%). The annual mean concentration of PM_{10} also consisted of metals, OC, EC, and ions, each of which was quantified as 17.2 μg m^{-3}, 11 μg m^{-3}, 3.4 μg m^{-3}, and 21.3 μg m^{-3}, respectively. Further, the trend seen here was similar to that seen in $PM_{2.5}$ in terms of

chemical composition (ions [40%], metals [32%], OC [21%] and EC [6%]). It is evident that the share of chemical composition (metals, ions, OC, and EC) in PM_{10} is higher than in $PM_{2.5}$.

- In $PM_{2.5}$, emissions from transportation sector emerged as the primary contributor (with a 40% share in $PM_{2.5}$ pollution), followed by soil dust (25%). Soil dust includes re-suspended dust and long-range transported soil dust. The next highest contributor was secondary particulate matter consisting of SO_4^{2-} and NO_3^- with 16% share. However, the share of secondary SO_4^{2-} was observed to be around 5 times higher than secondary NO_3^-. This indicates that coal burning is relatively high in the city. Other reasons include low temperature and other meteorological conditions that support/encourage the formation of SO_4^{2-}. Fuel oil was also observed to be one of the source of pollution with 6% share across the city. This fuel oil contribution is majorly from two industrial sites, SWAN and UEP. Other sources of pollution observed are wood combustion, construction dust, diesel generator (DG) sets, and coal combustion, contributing around only 5%.

- In the case of PM_{10} pollution, soil dust emerged as the top contributor with a 51% share, as indicated by receptor model output. It is interesting to see that the concentration of soil dust in PM_{10} is 5 times higher than $PM_{2.5}$. The next highest contributor, around 19% was observed to be transportation sector. The secondary particulate matter contribution was 8%, followed by construction dust 6%, while the wood combustion contribution was 6%. The pollution share from DG sets, coal combustion, and fuel oil contribution was observed to be less than 1%.

- Based on the study findings, the study recommends following action items for improving air quality levels of Bengaluru city, 1) Road side plantation for reducing dust re-suspension, 2) Geo-synthetic materials to cover the open areas on road dividers and footpaths, 3) Widen junction roads to reduce congestion, 4) Increase LPG connectivity, 5) Green buffer around road sides, 6) Improve last mile connectivity access for public transportation (bus & train). 7) Retrofitting heavy vehicles with Diesel Particulate Filter (DPF).

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Abbreviations

AMCO	AMCO batteries, Mysore Road
BBMP	Bruhat Bengaluru Mahanagara Palike
BPS	Banaswadi Police Station
CMB	Chemical Mass Balance
CSB	Central Silk Board, Hosur Road
Dept.	Department
DG	Diesel Generator
DPF	Diesel Particle Filter
EC	Elemental Carbon
IGCHC	Indira Gandhi Child Health Care
IC	Ion Chromatography
ICP	Inductively Coupled Plasma
ITPL	Export Promotion Industrial Park
KSPCB	Karnataka State Pollution Control Board
LPM	Liter Per Minute
MADH	Mr. Madhavchari's house
NAAQS	National Ambient Air Quality Standard
NCAP	National Clean Air Programme
OC	Organic Carbon
PM	Particulate Matter
PM_{10}	PM having aerodynamic diameter of less than 10 microns
$PM_{2.5}$	PM having aerodynamic diameter of less than 2.5 microns
RWF	Railwheel Factory, Yelahanka
SA	Source Apportionment
SKSJ	Government SKSJ Technological Institute, KR Circle
SWAN	Swan Silk Ltd, Peenya
TERI	TERI Office, Domlur
VICH	Victoria Hospital, KR Road
UEP	Urban Eco Park, Peenya
YPS	Yeshwantpura Police Station

1. Introduction

Air pollution is one of the gravest problems being faced by India today. There is strong evidence on the extent and severity of air-pollution impacts on both human health and the economy. Recognising the urgency to address the issue of air pollution in India, the Ministry of Environment, Forest and Climate Change (MoEFCC) launched the National Clean Air Programme (NCAP) in 2019 to strategise air-quality improvement in non-attainment cities across the country in a comprehensive and time-bound manner (PIB, 2019). These non-attainment cities need to reduce their respective particulate matter levels by 20–30% by 2024, with 2017 as the base year.

Bengaluru, a metropolitan city and the capital of Karnataka state, has been witnessing rapid urbanisation, accompanied by a massive increase in vehicular, construction, commercial, and industrial activities. While these activities aid economic growth, they are also responsible for the city's burgeoning pollution. Due to its poor air quality, Bengaluru has been identified as one of the non-attainment cities under NCAP. To achieve its target (of reducing its particulate matter levels by 20–30% by 2024), Bengaluru needs to identify the polluting sources and understand their respective share in the city's total pollution load. This source apportionment (SA) study aims to help in identifying the various pollutants and their share in a comprehensive manner, with a view to guide the formulation of implementable policy actions for the city.

The last SA study for Bengaluru was carried out in the year 2009 by The Energy Research Institute (TERI). The study findings recognised transportation as the main contributor to ambient $PM_{2.5}$ (particulate matter mass concentration of aerodynamic size ≤2.5), and re-suspended dust (from paved roads and natural soil) as the highest contributor to PM_{10} (particulate matter mass concentration of aerodynamic size ≤10) (TERI, 2010). It is important that SA studies be carried out every four to five years, to include new sources and understand their share in the ambient $PM_{2.5}$ and PM_{10} levels. With this purpose, CSTEP, under the aegis of KSPCB, carried out an SA study to identify and understand the sources contributing to the ambient PM_{10} and $PM_{2.5}$ levels in Bengaluru.

CSTEP's source apportionment study involved carrying out measurements of air-filter samples, performing chemical analysis to quantify the composition of pollutants, and estimating their respective shares using the receptor model (chemical mass balance or CMB). This provided a comprehensive understanding of the various polluting sources in the city, thus aiding in the identification of challenging sources and their hotspots. The findings of the study will help devise implementable strategies for achieving the NCAP targets for the city.

1.1. Background of the city

Located on the Deccan Plateau in southern peninsular India, Bengaluru (formerly Bangalore), the capital of Karnataka state, is the second fastest-growing metropolitan city in the country. According to the Census of India (2011), Bengaluru urban district recorded a population growth of about 47% during the decade 2001–2011. The area under the city's Municipal Corporation—Bruhat Bengaluru Mahanagara Palike (BBMP)— is around 709 km^2 , situated at a height of ~920 m above sea level. The climate of the region is classified as seasonal dry tropical savanna climate, with three distinct seasons: summer (March to May), monsoon (June to September), and winter

(October to February). Seasonal variation in meteorological parameters such as temperature, relative humidity, wind speed, and barometric pressure recorded during March 2019 and February 2020 is given in Table 1.

Table 1: Seasonal variation in meteorological parameters.

Parameter	Summer (mean ± SD)	Monsoon (mean ± SD)	Winter (mean ± SD)
Temperature (°C)	26.5 ± 2.5	26.1 ± 2.8	25.7 ± 2.8
Relative Humidity (%)	51.9 ± 13.6	73.3 ± 7.9	64.7 ± 7.9
Wind Speed (m/s)	1.1 ± 0.5	1.4 ± 0.9	1.1 ± 0.6
Barometric Pressure (mmHg)	843 ± 145	834 ± 142	795 ± 119

(Source: CPCB; https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/data)

1.1.1 Population Growth

According to the World Population Review (2021), the estimated population of Bengaluru in 2021 stood at 12.7 million, an increase of about 48% from 2011 (Figure 1). This makes it the twenty-fourth most populous city in the world and the fastest-growing Indian metropolis. Considering the present population, the annual population growth of the city is projected to be around one million. Such growth would burden the city's resources and create environmental challenges. Thus, without a sound understanding of the carrying capacity of the city and the associated measures, such growth is likely to be unsustainable.

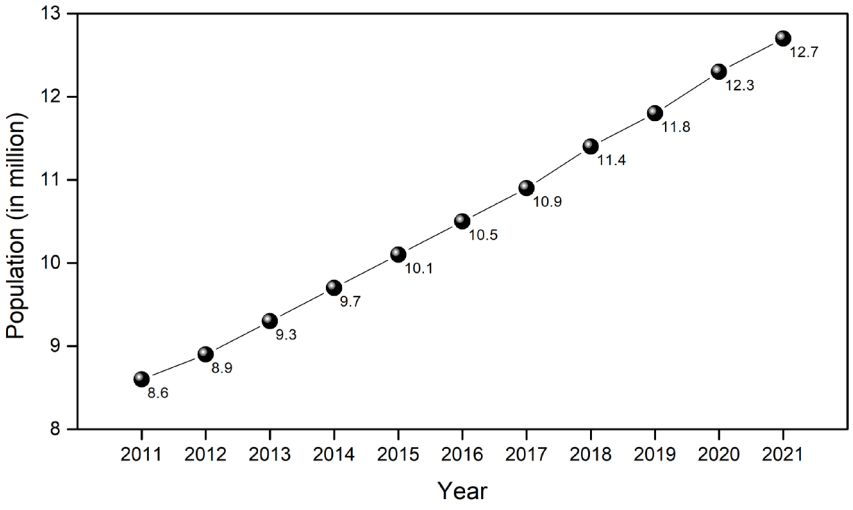

Figure 1: Population of Bengaluru (2011 – 2021).

1.1.2 Land Use

For clarity on the share of the different land-use patterns, such as build-up area, water bodies, green cover, barren land, etc, understanding the land-use and land-cover (LULC) profile of a city is crucial. Table 2 shows the land-use pattern for the city of Bengaluru for 2016 and 2011 (Verma

et al., 2016). As seen in the table, the share of built-up area increased from 38.7% in 2011 to 48.6% in 2016. However, there is a considerable reduction in the areas of barren land, vegetation, water bodies, and wetland. This underlines the importance of spatial analysis and urban sprawl measurement for informing future urbanisation plans and policies.

Table 2: Comparison of land-use pattern in 2016 and 2011

Land Use Pattern	Area (%)	
	2016	2011
Barren land	14.9	10.7
Dense vegetation (Tree cover)	8.1	13.4
Built-up area	48.6	38.7
Agriculture (Pasture land)	25.4	33.1
Water body	1.2	1.3
Wetland	1.8	2.8

1.1.3 Transportation Growth

Bengaluru has been experiencing a vast increase in the number of personalised transport, mainly two-wheelers. According to a study by Karnataka Transport Department (2019), the number of two-wheelers registered in the city increased by 18% within a span of three years (2017 to 2019). For the same period, the number of vehicles used for construction activities increased by 38% (Figure 2), indicating increased construction activity in the city. The transport study also mentions that the number of diesel-operated vehicles (such as lorries, trucks, tractors, and buses) showed an increase of around 11% to 17.5% for the three-year period. The increased vehicular count—coupled with inadequate road infrastructure and other bottlenecks—has led to frequent road-congestion instances, deteriorating the air quality in the city further.

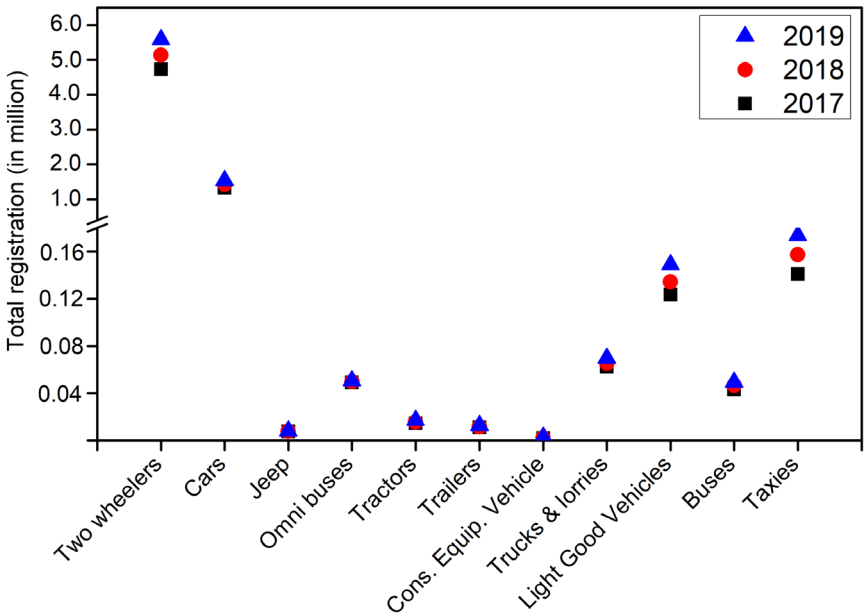

Figure 2: Number of registered vehicles in Bengaluru.

1.1.4 Industrial Emissions

The city of Bengaluru does not have any highly-polluting industries or thermal power plants. However, numerous small- and medium-scale industries, such as metallurgical, chemical/chemical-based, electroplating, cloth dying, and power-painting units operate here. An estimate by the Ministry of Micro, Small and Medium Enterprises (2016) shows that there were around 91,312 registered micro, small and medium enterprises (MSMEs) in Bengaluru in 2016. These industries are mostly located in clusters around Peenya, ITPL, Whitefield, Electronic City, and other locations, as shown in Figure 3.

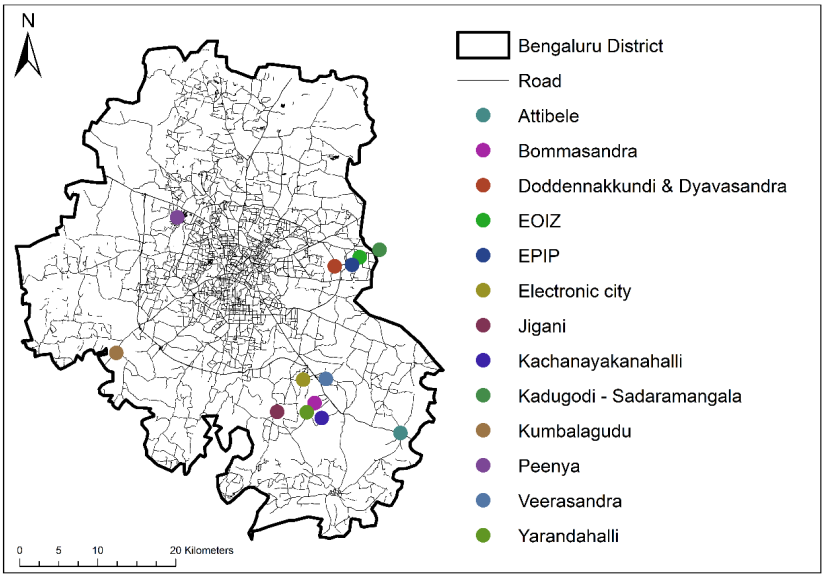

Figure 3: Industrial areas in Bengaluru urban district.

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1.1.5 Solid Waste

According to Naveen and Sivapullaiah (2020), Bengaluru generates around 5000 tonnes of municipal solid waste (MSW) per day, at an average generation rate of 0.5 kg per capita per day. However, at present, Bengaluru has the capacity to handle only around half of the waste generated. The state government has identified several new landfill sites and collection centres in each ward for achieving 100% waste collection. Post collection, the dry waste is segregated (into categories like paper, cardboard, bottle, etc.) and sold for recycling. However, around 60% of the dry waste remains non-recyclable. The collected MSW is usually disposed of through composting, landfilling, incineration, etc. Several peer-reviewed publications (Guttikunda et al., 2019; Vreeland 2016) mention the adverse impact of waste burning on the city's air quality.

1.1.6 Air Pollution (PM_{10} and $PM_{2.5}$)

Under the National Ambient Air Quality Monitoring (NAAQM) programme, the Karnataka State Pollution Control Board (KSPCB), in 1989, commenced manual PM monitoring at three sites, which increased to 13 sites in 2019. The sites cover industrial, residential, commercial, and

kerbside land-use patterns. According to KSPCB (2019), the annual PM_{10} and $PM_{2.5}$ levels in 2018-19 over Bengaluru were 89.9 and 42.4 µg m^{-3} respectively, which is around 50% (PM_{10}) and 6% ($PM_{2.5}$) higher than the annual PM_{10} and $PM_{2.5}$ levels specified by the Central Pollution Control Board (CPCB). However, it can be seen from Figure 4 that the PM levels (10 and 2.5) have seen a gradual decrease over the last few years. This is because of the proactive approach taken by the State Pollution Control Board and the municipal bodies towards improving the air quality levels for the city of Bengaluru. The initiatives include improving the road infrastructure, moving industries outside city boundaries, and efficient public transportation. Figure 4 shows that during 2015-19, the PM_{10} and $PM_{2.5}$ levels exceeded the annual permissible limit specified by CPCB, which calls for identifying the PM sources contributing to the deterioration of air quality.

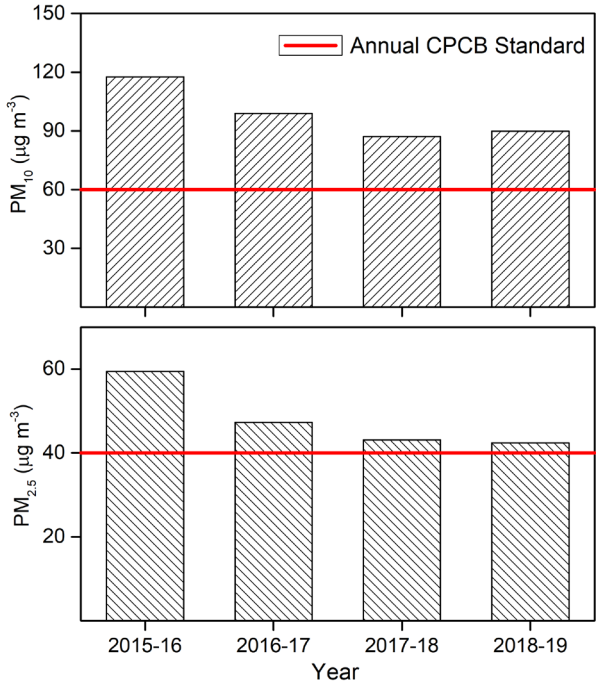


Figure 4: Annual average (PM10 and PM2.5 in Bengaluru)

1.2. Objectives and Scope of the Study

The SA study aimed to identify the sources of ambient $PM_{2.5}$ and PM_{10} pollution and their contribution from the selected sites in the city of Bengaluru. The specific objectives of the study include:

- Assessing the presence of various pollutants in the city by collecting ambient PM samples;
- Estimating the share of the pollutants by conducting chemical analysis of the samples;
- Quantifying source contribution of various pollutants through receptor modelling;

The scope of the study covers identifying the sites of $PM_{2.5}$ and PM_{10} sources, along with their seasonal variation. The findings of the study will guide policymakers in devising site-wise implementable solutions for improving air quality.

The overall project involves air-quality monitoring, chemical characterisation of ambient PM_{10} and $PM_{2.5}$, and source apportionment using receptor models, as given below:

- Ambient air-quality monitoring was done at 13 sites covering all the three seasons in a year to obtain a representative dataset on seasonal variations.
- The monitoring sites were classified into five categories—residential, sensitive, background, kerbside, and industrial. Of these, two sites each were representative of residential and sensitive categories, four sites each were representative of kerbside and industrial categories, and one site represented the background category, as shown in Table 3. Under the study, sampling at all the 13 sites identified in the city by KSPCB was carried out.

Table 3: Sampling sites for the city of Bengaluru

Land Use Pattern	Site Name
Residential	• TERI Office (TERI) • Banaswadi Police Station (BPS)
Sensitive	• Indira Gandhi Child Health Care (IGCHC) • Victoria Hospital, K.R Road (VICH)
Background	• Mr. Madhavchari House (MADH)
Kerbside	• Central Silk Board, Hosur Road (CSB) • Govt. SKSJ Technological Institute, KR Circle (SKSJ) • Yeshwantpur Police Station (YPS) • AMCO Batteries, Mysore Road (AMCO)
Industrial	• Export Promotion Industrial Park, ITPL, Whitefield (ITPL) • Swan Silk Ltd, Peenya (SWAN) • Urban Eco Park, Peenya (UEP) • Rail Wheel Factory, Yelahanka (RWF)

- Chemical characterisation (metals, ions, elemental carbon, organic carbon, and molecular markers) of the collected samples was performed.
- Receptor modelling through chemical mass balance model (version 8.2) was done for source apportionment. The measured PM, chemical concentration data, and source profiles were considered as inputs to the model.
- The deliverables included presenting the air-quality status of Bengaluru, and the percentage share of PM_{10} and $PM_{2.5}$ from various sources.

1.3. Approach

The approach of the study was primarily quantitative, and involved extensive data collection and statistical analysis. The process followed for conducting this study can be broadly divided into three components - air sampling, chemical characterisation, and receptor modelling analysis. Air samples were collected for PM_{10} and $PM_{2.5}$ from 13 locations in Bengaluru. These locations were identified by KSPCB and covered industrial, residential, commercial, and kerbside land-use patterns. For the sampling exercise, glass-fibre (8'' × 10''), quartz, and poly tetra fluoro ethylene

(47 mm) filter papers were used in the respirable dust sampler and fine particulate sampler. Well-trained field assistants were involved in handling the filter papers—from transporting the filters to the field, installing them in the samplers, and transporting them back to the laboratory after sampling. The pre- and post- sampling protocol was followed as per the CPCB guidelines. KSPCB's Central Environment Laboratory (CEL) determined the $PM_{2.5}$ and PM_{10} levels by gravimetrically weighing the filter papers and the data was provided to CSTEP.

Post weighing, the sampled filter papers were stored in refrigeration (-4°C) at KSPCB's CEL. For chemical analysis, the sampled filter papers were transported to IIT Kanpur. For chemical characterisation, various analytical instruments (ICP, IC, GC, and EC/OC analyser) were used for quantifying the concentration of metals, ions, EC, OC, and molecular markers. After analysis, the remaining portion of filter papers were stored in refrigeration (-4°C) for a period of six months. The concentration and minimum detection limit of every chemical species was provided by IIT Kanpur.

Post chemical analysis, various statistical techniques (correlation, one-way ANOVA, regression, t-test) were used for analysing the PM and chemical species data. Finally, the PM and chemical species data was used as an input for running the receptor model (chemical mass balance) to determine the sector-wise contribution of the polluting sources. On the basis of SA results, site-specific control measures were suggested. Additionally, the association between the pollutants' share from the transportation sector and road-network density was analysed. The road-network density was obtained from open street map (OSM). The framework of approach used in the study is presented in Figure 5.

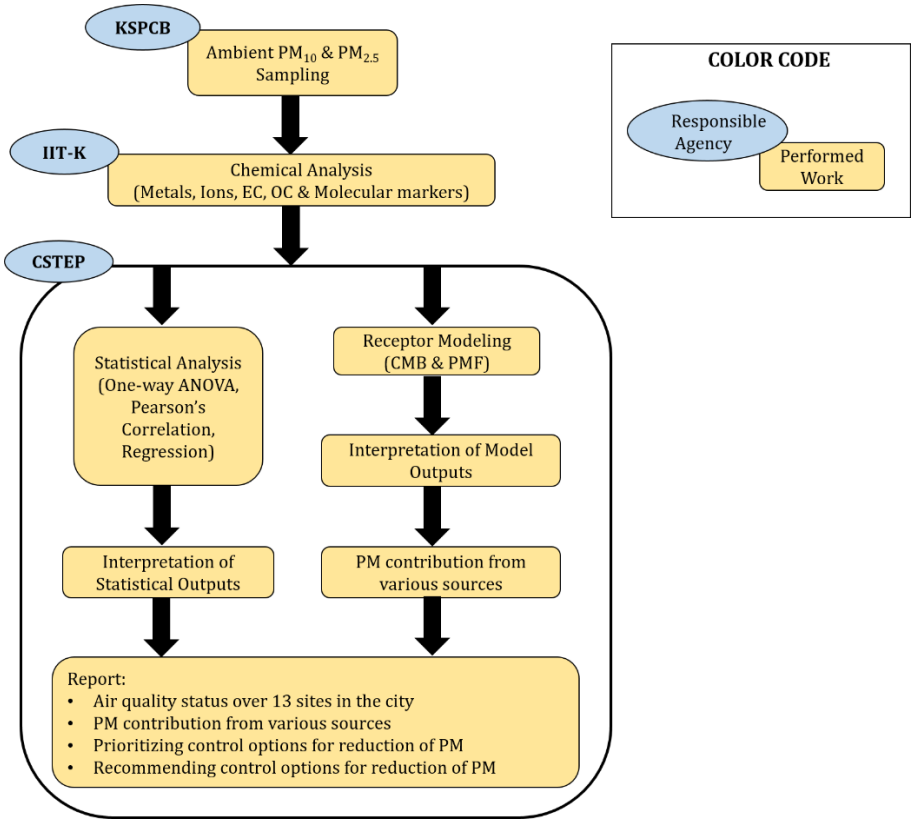


Figure 5: Study approach framework

1.4. Structure of the Report

The report structure is mentioned briefly here. Section 1 provides an introduction to the study, followed by Section 2 which describes the methodology used for sample collection, chemical characterisation, and receptor modelling. Section 3 presents the study area and details of samples collected, while Section 4 describes the results obtained from sampling, chemical characterisation, and receptor modelling. Finally, overall findings and recommendations are presented in Section 5, and way forward in Section 6.


FINE PARTICULATE
SAMPLER
Envirotech APM 550 MFC
OIL - LESS VACUUM PUMP
Envirotech APM 550 MFC

2. Materials and Methods

This section describes the materials and methods followed for sampling, chemical characterisation, and receptor modelling. Standard protocols prescribed by CPCB were followed for carrying out PM sampling, while for quantifying the chemical composition and performing receptor modelling, inputs from various experts and peer-reviewed publications were adopted as guidelines. The same has been explained in the following sub-sections.

2.1. Sampling Methodology

Ambient sampling of the criteria pollutants (PM_{10} and $PM_{2.5}$) was carried out from March 2019 to February 2020. The seasons covered included the summer months (March to May 2019), the monsoon months (June to September 2019), and the winter months (October 2019 to February 2020).

Details of the PM_{10} and $PM_{2.5}$ sampling schedule, instruments and types of filter paper used, and the storage conditions are mentioned below:

2.1.1 PM_{10} and $PM_{2.5}$ sample collection

- The PM_{10} samples were collected at 8-hour intervals from 6 a.m. to 2 p.m., 2 p.m. to 10 p.m., and 10 p.m. to 6 a.m. of the next day, through the respirable dust sampler (model APM 460DXNL; Envirotech). The $PM_{2.5}$ samples were collected at 24-hour intervals from 6 a.m. of the first day to 6 a.m. of the next day through fine particulate sampler (model APM550; Envirotech) (Figure 6).
- The PM_{10} samples were collected using glass-fibre filter paper (8'' × 10''). The samples were collected on 47-mm quartz and poly tetra fluoro ethylene (PTFE) filters in alternation. Quartz filter was used for quantifying EC, OC, and metals, while PTFE filters were used for quantifying ions and molecular markers.
- The filter papers were desiccated for 24 hours and weighed in triplicate. This process was performed pre-sampling and post-sampling. The CPCB (2003) protocol was followed for sampling and storage of the filter samples. The collected samples, along with laboratory blank samples, were sent to IIT-Kanpur in a completely sealed package for chemical analysis.

2.1.2 Monitoring-site classification

- For the study, the monitoring sites were classified into five categories —residential, sensitive, kerbside, industrial, and background.
- The residential sites mainly consist of institutions, residential apartments, houses, and offices.
- The sensitive sites are located within hospitals premises, surrounded by green cover.
- The kerbside sites are basically those that are located near heavy traffic junctions, and roadside location. According to the guidelines mentioned in CPCB (2003), a kerbside location is typically within 5 m of the kerbside and the sampling height is around 3 m.
- The industrial sites are those that are located within industrial clusters, and have industrial exhaust emissions and heavy vehicular transportation.
- The background site represents the pollution level in the upwind of the city.

2.2. Chemical Characterisation

Chemical characterisation is essential for understanding the composition of particulate matter. Therefore, the $PM_{2.5}$ and PM_{10} samples were analysed for quantifying the mass concentration of elements, ions, EC, OC, and molecular markers. The details of chemical components, instruments, and the protocol followed for carrying out the chemical analysis are given in Table 4.

Additional information on the protocol followed for chemical analysis can be accessed from Bhowmik et al. (2020); Birch and Cary (1996); Chow et al. (2004); Engling et al. (2009); Gupta et al. (2018); Sharma et al. (2020); and USEPA (1999a, 1999b).

Table 4: Chemical species and the methodology followed for characterisation

Components/Species		Methodology
Elements	Li, Mg, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, As, Se, Rb, Sr, Zr, Mo, Pd, Cd, Sn, Sb, Cs, La, Ce, Pt, Tl, and Pb	• For quantification of metals in PM_{10} samples, the glass filter papers were punched by a cutter of area 1.5 cm^2. A total of 10 cuts were made randomly in the filter paper, thereby creating a total area of 15 cm^2 for analysis. In case of $PM_{2.5}$ samples, half of the $PM_{2.5}$ quartz filter paper was used. • The filter portions taken for the analysis were digested by open-air digestion. Post open-air digestion, the filtrate was filtered through Whatmann-42 filter paper and then increased to 25 ml by adding double distilled water. • Finally, the solution was analysed through Inductive Coupled Plasma Mass spectrometry. A multi-element standard solution was used for preparing the calibration curve before analysing the samples.
Ions	Cl^-, NO_3^-, SO_4^{2-}, K^+, NH_4^+,Na^+, and Ca^{2+}	• For quantification of ions in PM_{10} samples, the glass filter papers were punched by a cutter of area 1.5 cm^2. A total of 10 cuts were made randomly in the filter paper, creating a total area of 15 cm^2. For $PM_{2.5}$, half of the Teflon filter paper was used. • The filter portions taken for analysis were mixed with milli-q water (20ml) and subjected to sonication for a duration of about 20 minutes. • Finally, the solution was analysed for cations and anions through Ion Chromatography.
Carbon	EC and OC	• One-half of the portion of quartz-fiber filter paper was subjected to carbon analysis through EC and OC analyser (Model no. 4F; Sunset laboratory Inc., USA). An area of 1.5 cm^2 from each quartz-fiber filter paper was carefully cut and then subjected to analysis. • The EC and OC were quantified by following the NIOSH 5040 protocol (based on thermal optical transmittance).
Molecular Markers	Levoglucosan and 1-Nitropyrene	• One-half of teflon filter paper was subjected to molecular marker analysis through Gas Chromatography (GC). The filter paper was shredded randomly and was first extracted using a dichloromethane and hexane mixture. • The extracted mixture was subjected to sonication for 5 minutes at room temperature, three times. The sample extracts were then filtered through a 0.22 µm filter cartridge and nitrogen gas was used as dry gas for making exactly 1 ml of sample solution as inlet for the GC. • The identification of the compounds was performed using GC retention times.

2.3. Statistical Analysis

The statistical analysis was carried out to understand the significance of site-wise PM variations. For this analysis, a one-way ANOVA (Kruskal-wallis test) was performed, which determines if PM levels vary from one site to another or not. Similarly, the seasonal variation of PM levels over each site was analysed using the same test.

Pearson's correlation coefficient was used to find the association between road network and transportation sector, with regard to the increase in PM. This analysis provides information on the relationship between the length of different roads and the transportation sector contribution to PM.

Further, linear regression was performed to find the association between the measured and the modelled PM. A good association was found, which indicates that the methodology followed for running the CMB model is acceptable.

A p-value of less than 0.5 was considered to be statistically significant for all the tests performed.

2.4. Mass Closure

Mass closure or reconstructed mass (RCM) is used to validate the consistency and uncertainties in the quantified chemical species concentration and PM mass concentration. RCM is used prior to, and in conjunction with air-quality modelling to develop mitigation strategies, as well as to check model performance (Kumar and Sunder Raman, 2020).

RCM includes all the estimated chemical species concentration. Moreover, RCM applies multipliers to the measured chemical species to estimate the unmeasured components. The equation for deriving RCM is mentioned below:

$$RCM = Trace\ Metals + (1.2 \times OC) + EC + Ions + (1.29 \times NO_3^-) + (1.37 \times SO_4^{2-}) + 2.42\,(Fe) + 1.63\,(Ca) + 1.94\,(Ti)$$

For organic matter (OM), the OC was multiplied by 1.2. Similarly, the adoption of multipliers for other compounds is explained in detail by Chow et al. (2015).

2.5. Receptor Modelling

Receptor models use the PM mass concentration and the chemical composition of ambient pollutant concentration to estimate the contribution of different source types to the measured pollutant concentration. The CMB (version 8.2) air-quality model is one of the several receptor models that have been used for air-quality management. The CMB model used in this study for source apportionment was accessed from https://www3.epa.gov/scram001/receptor_cmb.htm.

The mass balance equation that accounts for all 'm' chemical species in the 'n' samples as contributions from 'p' independent sources, can be written as follows:

$$C_i = \sum_j m_j x_{ij}\, a_{ij}$$

Where, C_i is the concentration of species 'i' measured at a receptor site; x_{ij} is the ith elemental concentration measured in the jth sample; and m_j is the airborne mass concentration of material from the jth source contributing to the jth sample. The term a_{ij} is included as an adjustment for any gain or loss of species i between the source and the receptor.

According to USEPA (1997), the indicators of a good model fit measure are R^2 (0.8>), χ^2 (<4), % mass (80 to 120), and degree of freedom (>5). For the chemical species, if the value of residual (R)/uncertainty (U) is between 0.5 and 2, then the combination of chemical species selected for the model run is acceptable.

Assumptions of CMB model

Following are the main assumptions:

- The composition of source emissions are constant throughout the ambient and source sampling;
- Chemical species do not react with each other (i.e., they add linearly);
- All the sources with a potential for contributing to the receptor have been identified and have had their emissions characterised;
- The number of sources or source categories is less than/equal to the number of species;
- The source profiles are linearly independent of each other;
- Measurement uncertainties are random, uncorrelated, and normally distributed.

Source profile information

The source-profile abundances (i.e., the mass fraction of a chemical from each source type) and the receptor concentrations, with appropriate uncertainty estimates, served as an input data for CMB. The source profiles used for the CMB model were obtained from the open-access database developed by ARAI Pune and IIT Bombay (CPCB, 2010), and from Matawle et al. (2014, 2015). The study ensured adoption of profiles specific to Indian conditions.

Protocol for running the CMB model

Bangalore city has 13 manual monitoring sites, which need to be studied individually at the local level, along with the city as a whole. To understand the hotspots and local challenges, it is crucial to study and analyse the local data. Hence, this study preferred the CMB model, which can be run using lesser number of samples, as compared to PMF which requires large samples. The CMB model requires a prior estimate of the number and composition of various elements, and knowledge of parameters such as the types of polluting sectors, and the time period of the analysis. CMB provides the source contribution estimates of the polluting sectors. The emission inventory study by CSTEP also gives a good idea of possible sources in the area (CSTEP, 2022). Figure 6 presents the steps followed for deriving the source contribution estimated (SCE) from the CMB model.

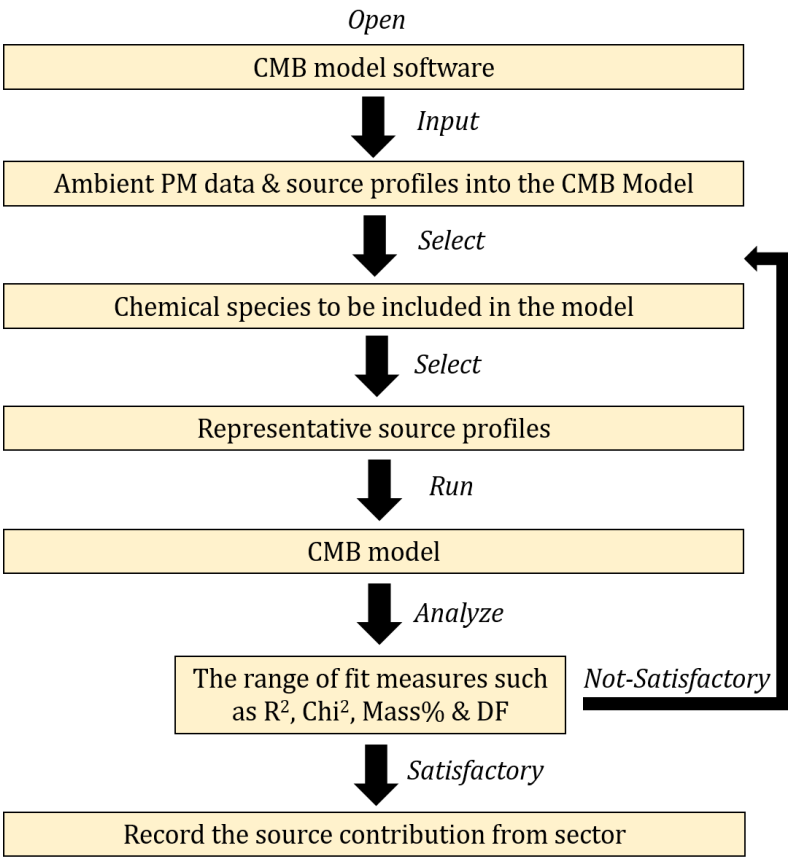


Figure 6: Protocol followed for running CMB model

The input files, such as ambient PM and source profile, were arranged in the required format for running the CMB model. The ambient PM file contains PM and chemical species concentration with their respective uncertainty. The source profile file contains the fraction of chemical species and their respective uncertainty. Further, information such as units (μg m^{-3}), decimal places display (2 decimal), output file format (.csv) were entered in the model. The default value of 0.95 for minimum source projection, 20 for the number of iterations and maximum source uncertainty were retained as mentioned in the CMB manual.

After uploading the input files, the model was run by selecting the ambient data samples, fitting species, and fitting sources. This process was followed several times until the range of fit measures such as R^2, χ^2, Mass% and Degree of Freedom (DF) was satisfactory. As the CMB model is sensitive to the source profiles, a sensitivity test was performed as suggested by Chen et al. (2010). This involved running the model with various combinations of source profiles to find the optimal source profile for each sample.

Positive matrix factorisation (PMF)

PMF requires mass concentration of the chemical species and their respective uncertainties (according to the PMF methodology) as inputs for the model. PMF provides an understanding of the possible polluting sources present at the study area.

3. Study Area

3.1. Sampling Sites

PM_{10} and $PM_{2.5}$ were measured at 13 locations around Bengaluru city (Figure. 7). The sites were selected, keeping in mind the inclusion of various types of land-use patterns in the city. All the study locations are within the Bruhat Bengaluru Mahanagara Palike (BBMP) boundary, except the background site (MADH).

At each site, the samplers were placed according to the standard guidelines framed by CPCB. Also, it was ensured that all the monitoring sites had unrestricted flow of air (which means no buildings, trees, etc. present around the site). The details of monitoring sites, along with the site description in the study zone and possible sources of PM are shown site-wise in Table 5.

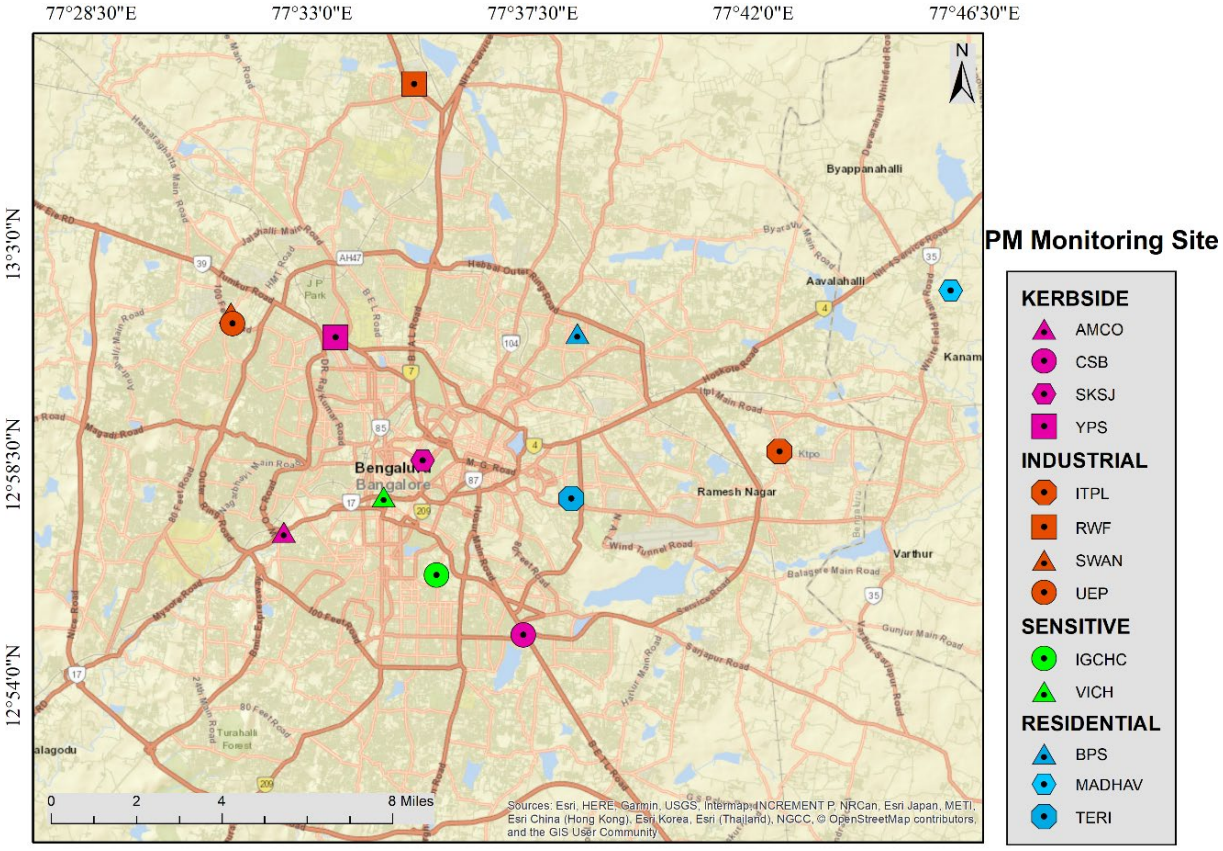
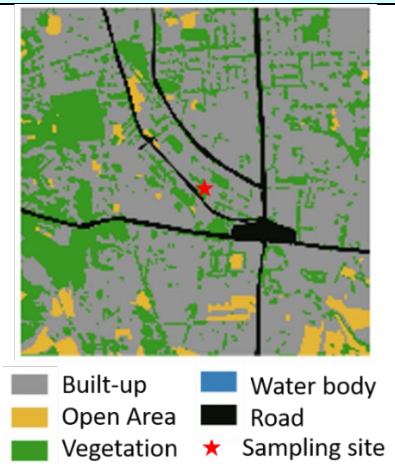
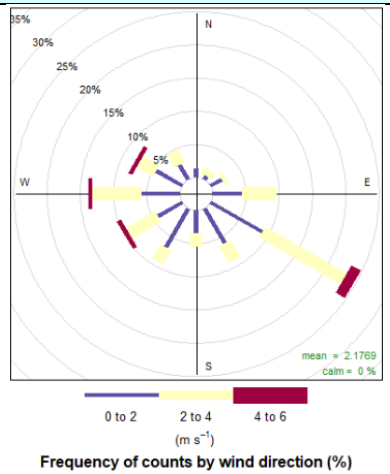
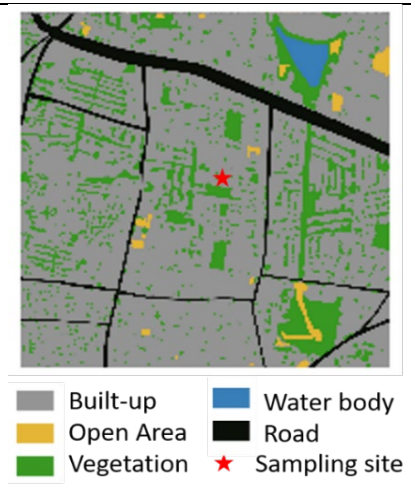
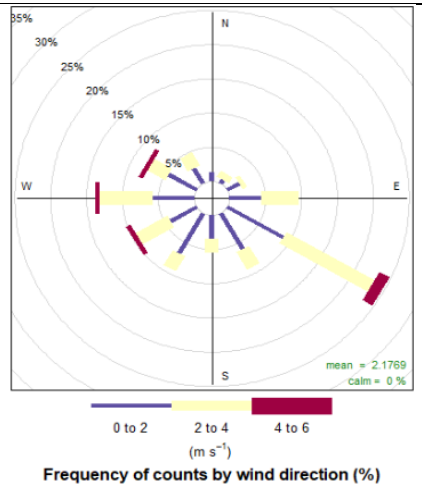
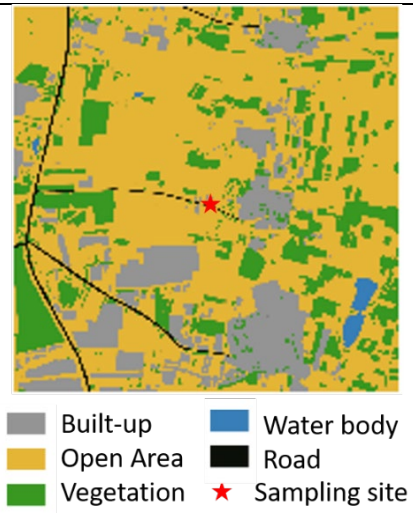
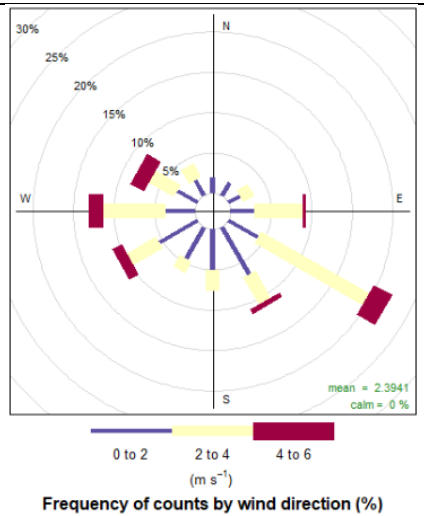
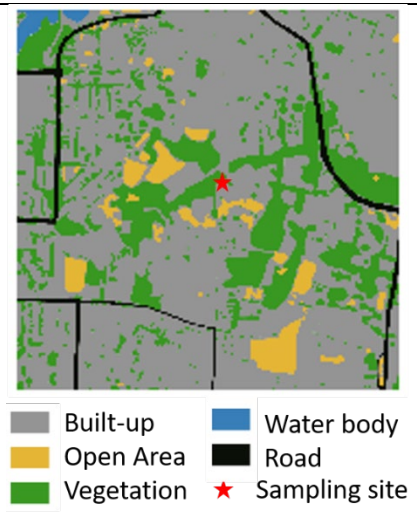
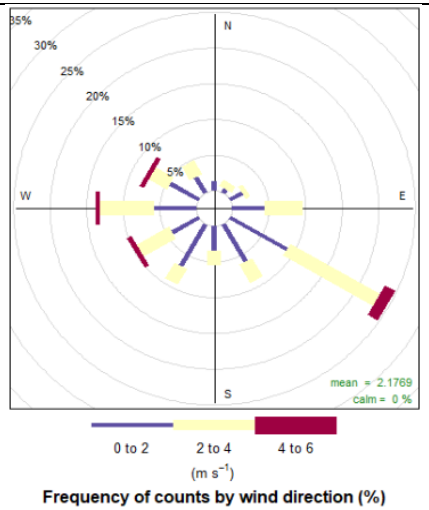
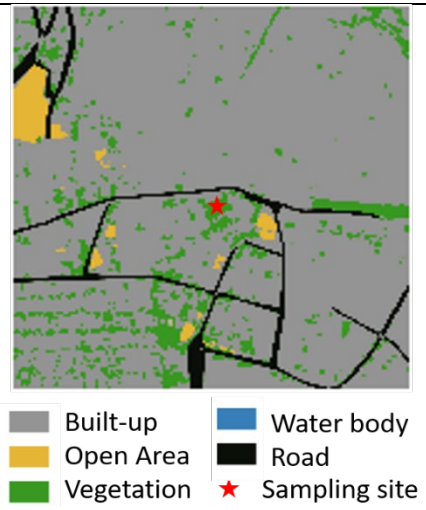
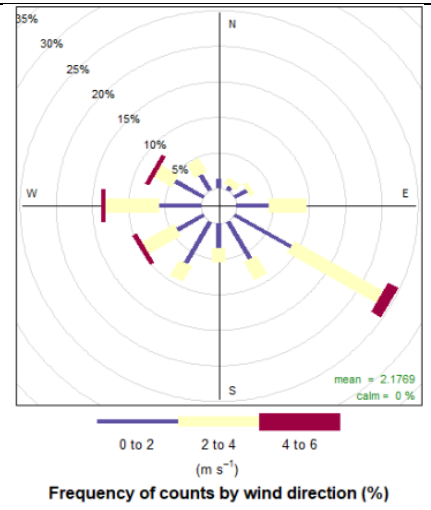


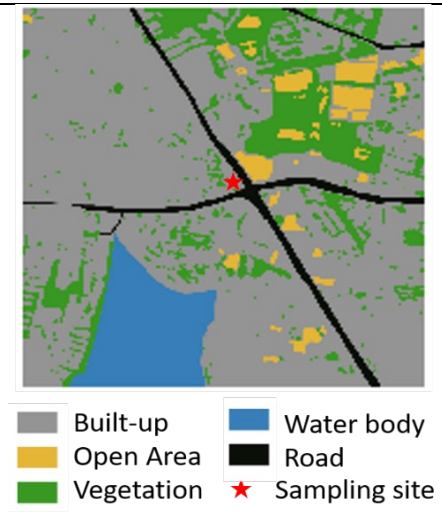
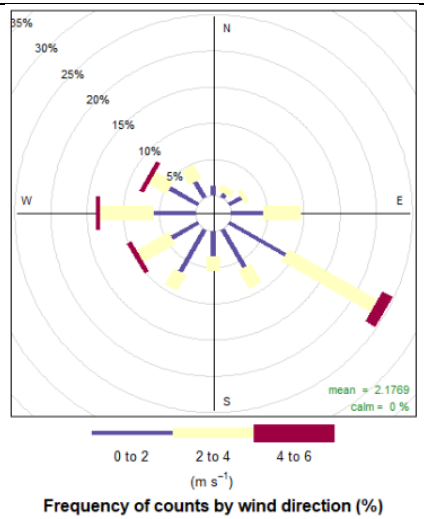
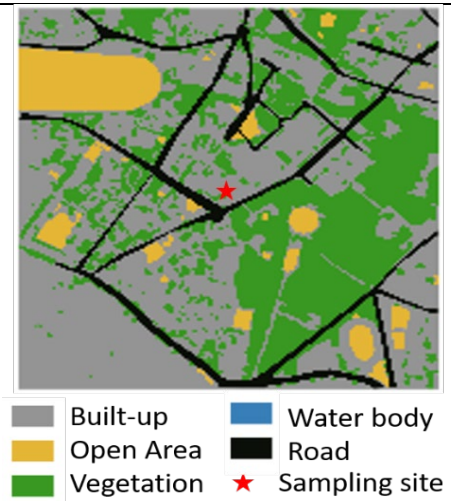
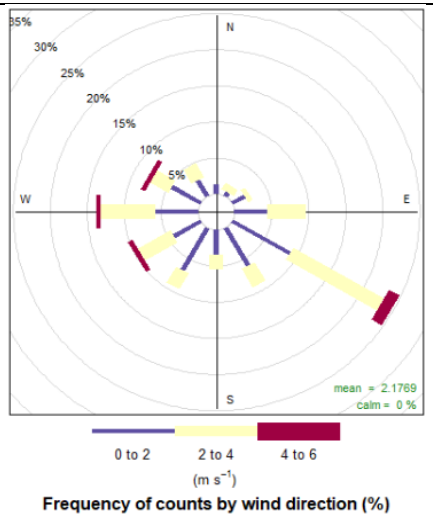
Figure 7: Location of monitoring sites in Bengaluru

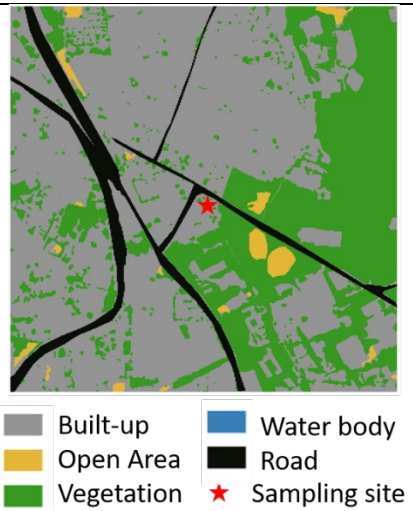
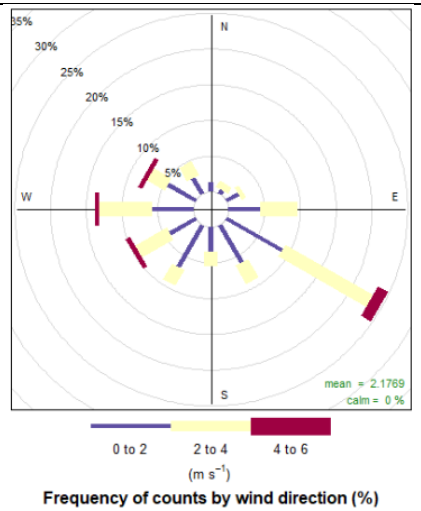
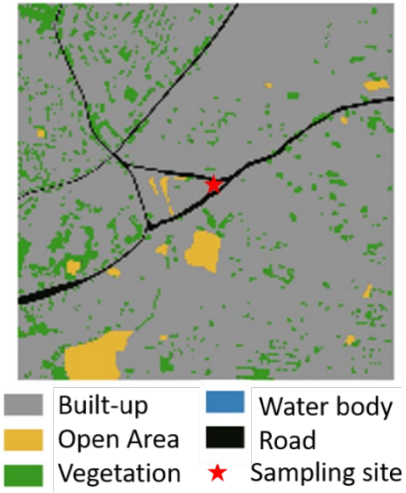
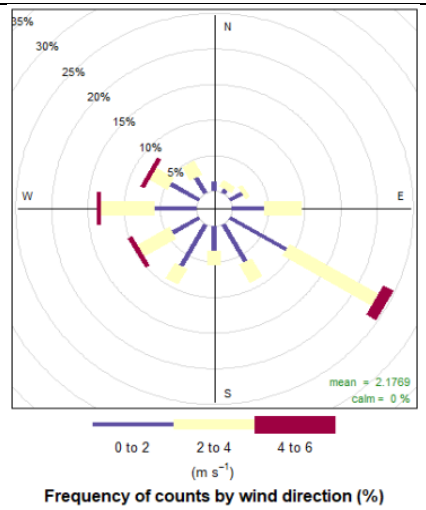
Table 5: Details of monitoring sites along with the site description in the influence zone and possible sources of PM

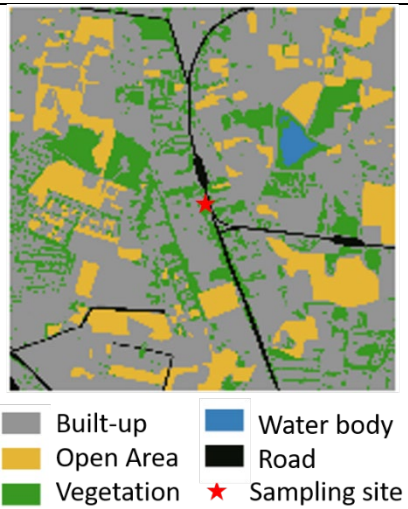
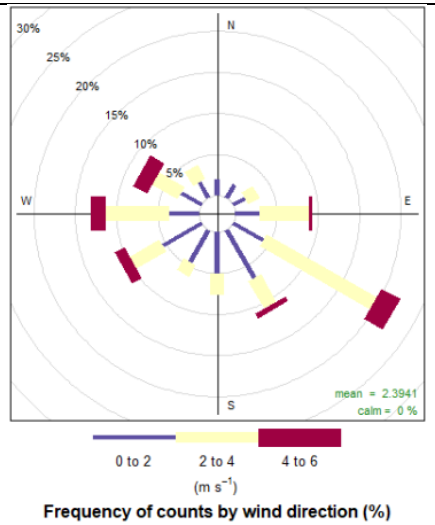
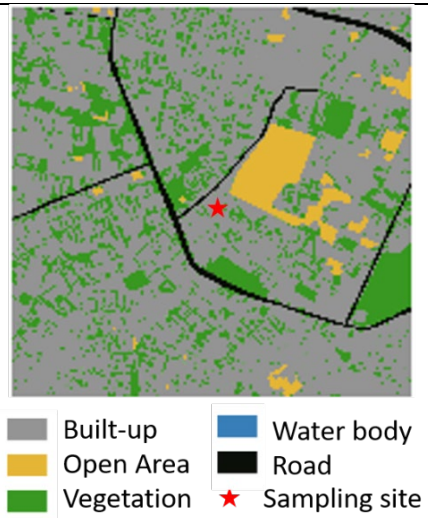
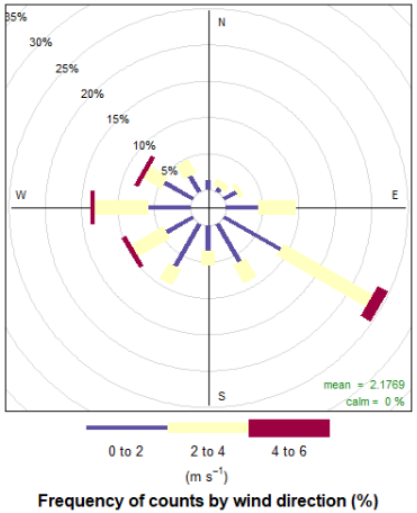
Site name (Abbreviation) (Latitude, Longitude)	Land use pattern (2 × 2 km) (Source: Google earth; Resolution: 15 m)	Wind rose (annual)	Site description in the influence zone (2 × 2 km)
TERI Office (TERI) (12.96°, 77.63°)			• This site represents a residential location. The sampler is placed in the premise of TERI office (height from ground: ~6 m). • The vicinity has green cover around the site, and barren land in the south and south-west direction can be observed around the site. • Domlur flyover junction is located in the south-east direction at a distance of ~0.5 km from the sampling site. • The prevailing winds blow from the south-easterly direction.

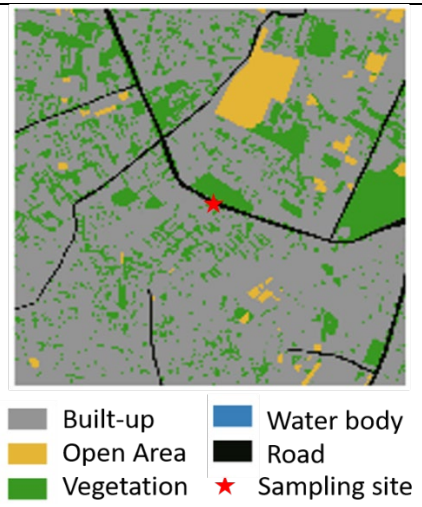
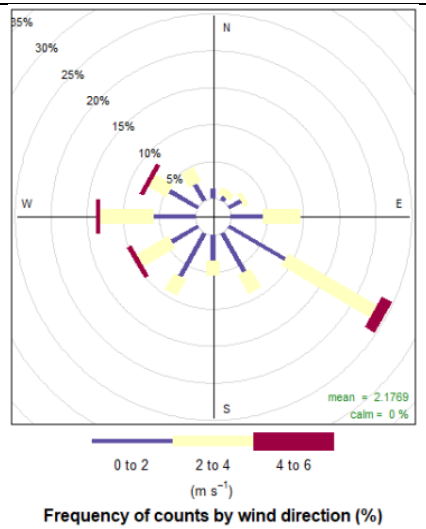
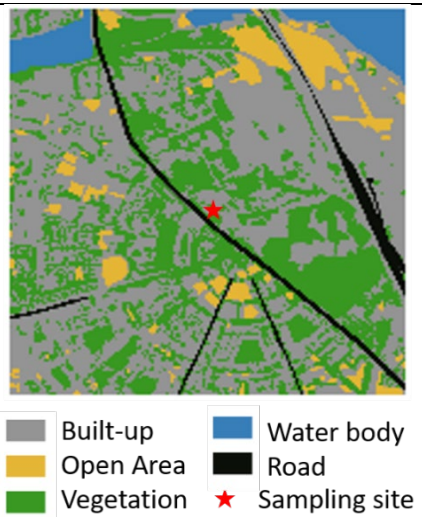
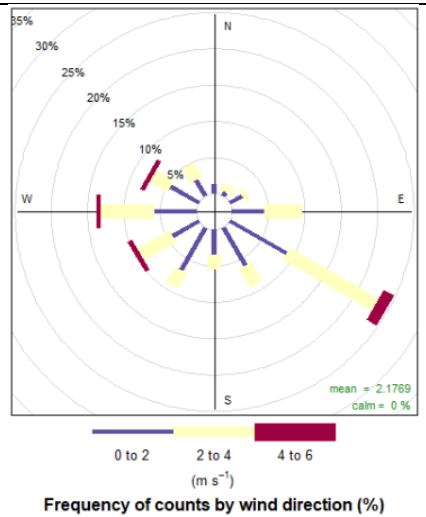
Banaswadi Police Station (BPS) (13.01°, 77.64°)			• This site represents a residential location with a high density of built-up area in the vicinity. • The sampler is placed in the premise of BPS (height from ground: ~4 m). • The outer ring road runs from the west to east direction near the site. The closest distance of the road is ~0.6 km from the site. • Moderate construction activity can be seen in the vicinity. • The prevailing winds blow from the south-easterly direction.
Mr. Madhavchari's House (MADH) (13.03°, 77.76°)			• The sampler is placed on the rooftop of a single-storey house (height from ground: ~4 m) • This site is representative of the background location for this study. Farming/agricultural activities can be observed in the influence zone. • A major portion of the land around the site is barren. The green cover present in the area is due to agricultural crops. • Unpaved roads can be observed in the vicinity of the site, while the nearby paved road is ~0.8 km from the site. • The prevailing winds blow from the south-easterly direction.

Indira Gandhi Child Health Care (IGCHC) (12.93°, 77.59°)			• This site represents a sensitive site. However, high vehicular flow can be observed here throughout the day. • The sampler is placed in the premise of IGCHC hospital (height from ground: ~4 m). • Yediyur lake is located at ~1.7 km in the south-west direction from the site. • Lalbagh Garden is located at ~1.4 km in the north-west direction from the site. • The prevailing winds blow from the south-easterly direction.
Victoria Hospital, K.R Road (VICH) (12.96°, 77.57°)			• This site represents a sensitive site. However, high vehicular flow can be observed here throughout the day. • The sampler is placed in the premise of VICH (height from ground: ~4 m). • In the vicinity of the site, the major portion consists of built-up area. • DG sets of various capacities are operated during power failures by shopping complexes, hotels, IT establishments, and hospitals, etc. that are located in the influence zone. • The prevailing winds blow from the south-easterly direction.

Central Silk Board, Hosur Road (CSB) (12.91°, 77.62°)			• This site represents a kerbside location. • The sampler is placed within the premises of the Central Silk Board quarters (height from ground: ~4 m). • There is heavy traffic movement on National Highway - 7 (NH-7), which is located besides the sampling site. • Residential areas constitute a major portion of the site. • Madiwala lake (one of the largest lakes in Bengaluru) is located in the south-west direction of the site. • Several playgrounds are located in north and north-east directions of the site. • The prevailing winds blow from the south-easterly direction.
Government SKSJ Technological Institute, KR Circle (SKSJ) (12.97°, 77.58°)			• This site represents a kerbside location. • The sampler is placed within the premises of the Government SKSJ Institute (height from ground: ~4 m). • Several heavy traffic junctions can be found in the vicinity of the site. • Ample green cover can be found at ~0.2 km from the sampling site. • Majestic bus stand is located at ~1.9 km in the western direction of the sampling site. • The prevailing winds blow from the south-easterly direction.

Yeshwantpur Police Station (YPS) (13.01°, 77.54°)			• This site represents a kerbside location. • The sampler is placed on the rooftop of YPS (height from ground: ~4 m). • The site is located besides a traffic junction with heavy vehicular flow. • The railway track at a distance of ~0.3 km, runs in a north-west to south-west direction of the site. • Institutional areas with extensive green cover are located in the eastern direction. • The prevailing winds blow from the south-easterly direction.
AMCO Batteries, Mysore Road (AMCO) (12.95°, 77.54°)			• This site represents a kerbside location. • The sampler is placed in the premise of AMCO Batteries (height from ground: ~8 m). • The site is located besides a traffic junction (~0.1 km from the site) that has high vehicular flow. • A railway track runs in a north-east to south-west direction, where its closest distance is ~0.5 km from the site. • The Nice Road toll gate is located at ~1.9 km in the south-west direction. • Burning of garbage and solid waste can be observed near the site. • The prevailing winds blow from the south-easterly direction.

Export Promotion Industrial Park, ITPL, Whitefield (ITPL) (12.97°, 77.70°)			• This site represents an industrial location. • The sampler is placed in the premises of Graphite India Ltd. (height from ground: ~4 m). • The sampler is located besides Graphite India Ltd. main road, which has heavy traffic movement. • Several lakes are situated in the vicinity of the site. • Metro rail construction activity was carried out during the sampling period of the study. • The prevailing winds blow from the south-easterly direction.
Swan Silk Ltd, Peenya (SWAN) (13.02°, 77.52°)			• This site represents an industrial location. • The sampler is placed in the premises of Swan Silk Ltd (height from ground: ~4 m). • The sampler is located in Peenya Industrial Area III phase that has extensive manufacturing, packaging, and electrical work industries. • There is scarce green cover in the southern direction of the site. • Diesel generator sets of various capacities are used extensively in the influence zone. • The prevailing winds blow from the south-easterly direction.

Urban Eco Park, Peenya (UEP) (13.02°, 77.52°)			• This site represents an industrial location. • The sampler is placed in the premise of UEP (height from ground: ~2 m). • The sampler is located in Peenya Industrial Area III phase and has extensive manufacturing, packaging, and electrical work industries. • There is scarce green cover in the southern direction of the site. • The outer ring road runs along in a north-east to south-east direction, the closest distance from the site being ~1.2 km. • Diesel generator sets of various capacities are used extensively in the influence zone. • The prevailing winds blow from the south-easterly direction.
Rail Wheel Factory, Yelahanka (RWF) (13.10°, 77.58°)			• This site represents an industrial location. • The sampler is placed in the premises of RWF (height from ground: ~8 m). • The sampler is placed inside the RWF premises and located <100 m from Doddaballapur road. • Good green cover can be seen around within a radius of 0.2 km from the sampling site. • Yelahanka kere, Puttanahalli, and Alllasandra lakes can be found in the vicinity of the site. • National Highway-7 (NH7) runs in the north-south direction, the closest distance from the site being ~1.7 km. • The prevailing winds blow from the south-easterly direction.

3.2. Number of PM_{10} and $PM_{2.5}$ samples collected

Based on the sampling schedule of KSPCB, every week, two samples were collected from each site for a duration of one year, covering all three seasons. However, due to various unavoidable factors, such as instrument malfunction, meteorological conditions, and shortage of human resource, the number of PM_{10} and $PM_{2.5}$ samples collected varied slightly from site to site. The number of PM_{10} and $PM_{2.5}$ samples collected from each site are given in Tables 6 and 7, respectively.

3.2.1 PM_{10}

At the BPS site, no sample could be collected from April to July due to instrument malfunction. At the RWF site, the instrument fell down due to strong winds and so, no sample could be collected during March and April. At the SWAN site, no sample could be collected from July to September due to instrument flow-rate problem. The maximum samples were collected from the VICH site (288), while the minimum samples were collected from the UEP site (123). At the SKSJ site, 24-hour PM_{10} sample was collected during the study period, while at the other sites 8-hour PM_{10} samples were collected. On analysing the month–wise sample collection, it was observed that the maximum samples (315) were collected during the month of December, while the minimum samples (113) were collected in the month of March.

3.2.2 $PM_{2.5}$

For $PM_{2.5}$, teflon and quartz filter paper samples were collected in alternation. However, due to some unavoidable factors, the intended number of samples could not be collected. At the BPS and SKSJ sites, no quartz filter paper sample could be collected due to instrument malfunction. Similarly, at the SWAN and RWF sites, no sample could be collected due to instrument flow-rate problem.

The maximum number of teflon samples were collected from the AMCO site (48), while from the SKSJ site (2) the minimum number of samples were collected. Similarly, the maximum number of quartz samples were collected from MADH site (39), but no quartz samples were collected from the BPS and SKSJ sites. On analysing the month-wise variation, it was observed that the maximum teflon samples (45) were collected during July, while the maximum quartz samples (44) were collected during January. Similarly, during the month of October, minimum teflon (14) and quartz (11) samples were collected.

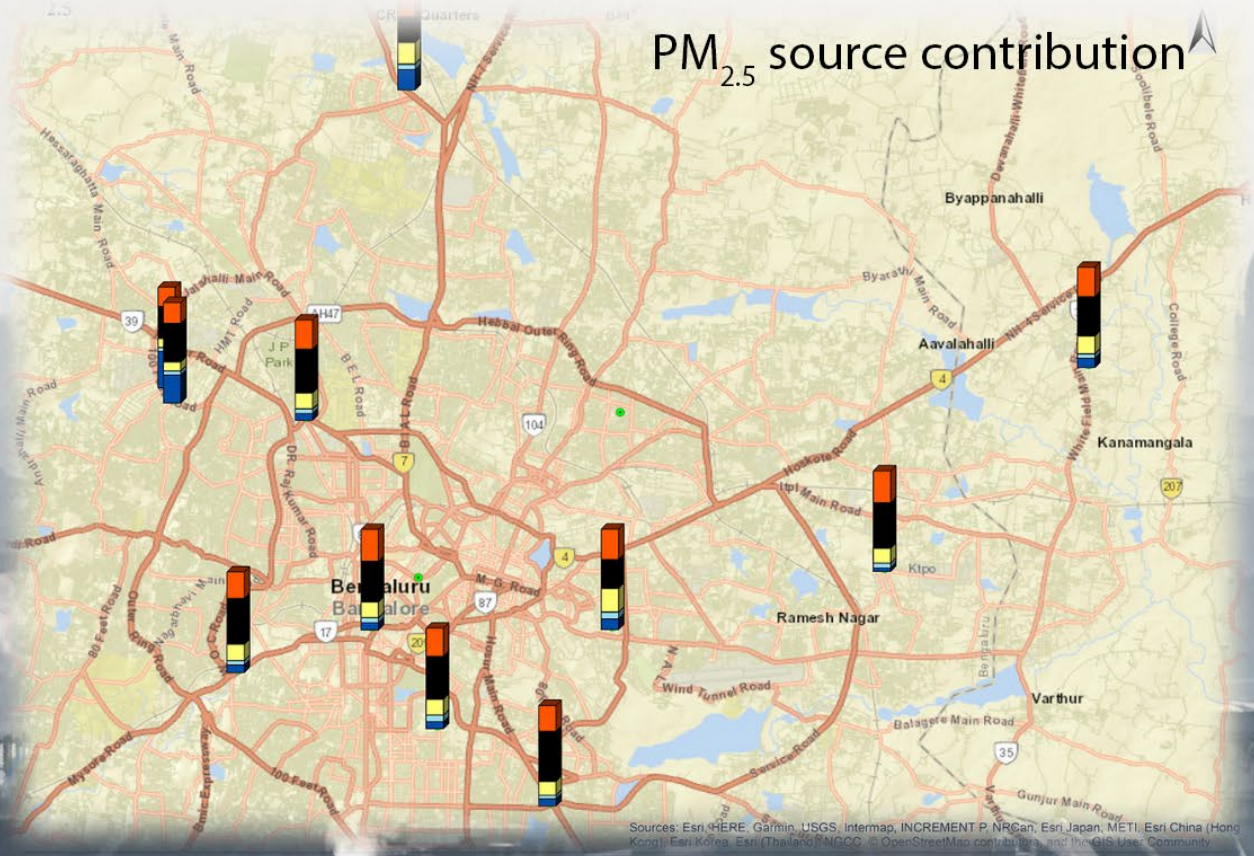
Table 6: PM_{10} samples collected during the study period

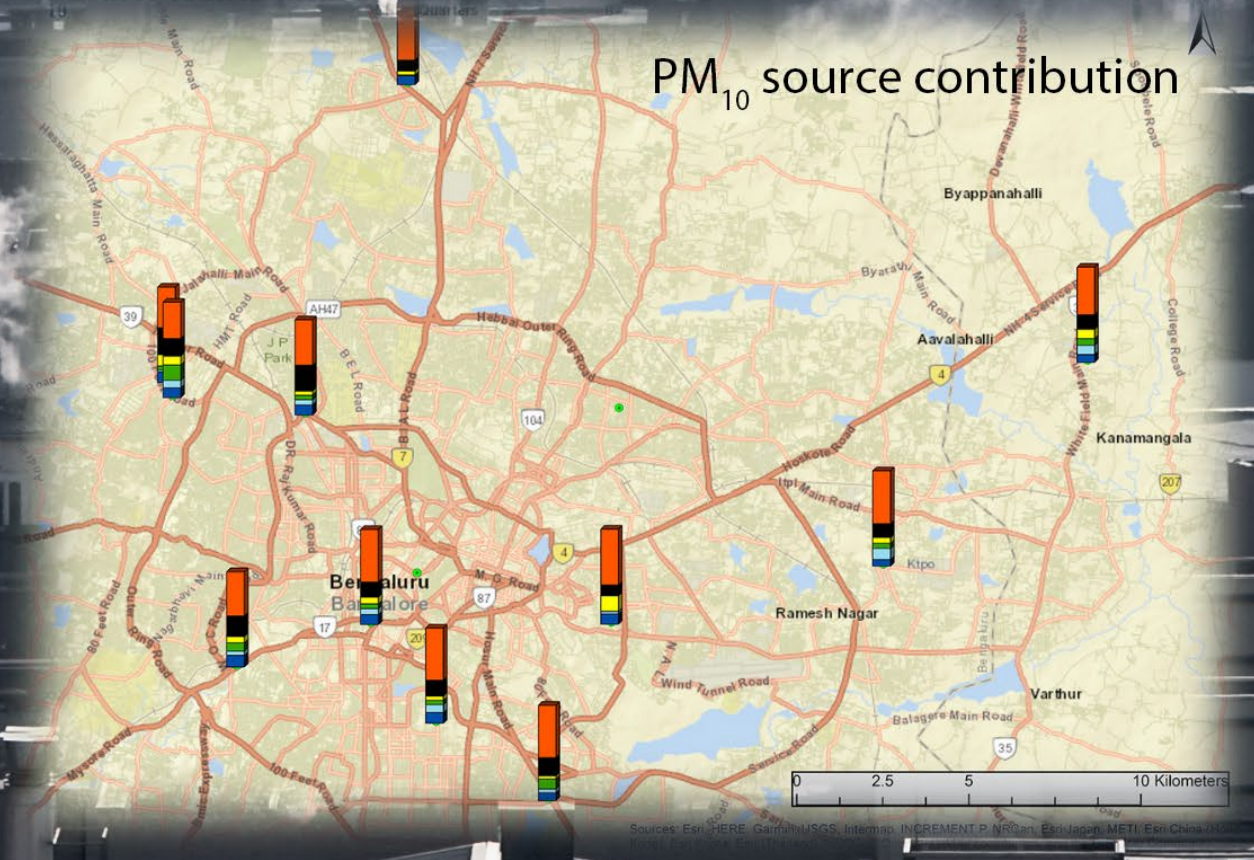
SITE	Number of PM_{10} samples collected during the study period (MAR 2019 to FEB 2020)												Total
	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	
TERI	12	21	24	21	23	24	30	12	18	27	27	30	269
BPS	4	**0**	**0**	**0**	**0**	21	21	15	24	24	18	3	130
MADH	12	24	27	24	27	27	27	12	15	27	24	24	270
IGCHC	12	27	27	27	30	24	18	18	27	27	24	24	285
VICH	12	27	27	24	24	24	27	18	24	30	27	24	**288**
CSB	12	15	30	27	33	24	17	15	17	24	24	24	262
SKSJ	4	6	6	5	19	18	21	12	24	12	12	12	151
YPS	12	24	19	24	24	24	0	9	21	27	33	27	244
AMCO	12	24	27	30	33	15	24	18	24	27	24	24	282
ITPL	12	24	21	24	24	26	24	12	12	27	21	24	251
SWAN	12	21	18	6	**0**	**0**	**0**	3	21	15	24	21	141
UEP	0	12	3	6	6	6	12	3	12	15	27	21	**123**
RWF	**0**	**0**	9	21	33	30	27	12	24	33	33	27	249
TOTAL	116	225	238	239	276	263	248	159	263	315	318	285	2945

Table 7: $PM_{2.5}$ samples (teflon and quartz) collected during the study period

SITE	Number of $PM_{2.5}$ samples collected during the study period (MAR 2019 to FEB 2020)																						Total	
	MAR		APR		MAY		JUN		JUL		AUG		SEP		OCT		NOV		DEC		JAN		FEB			
	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q	T	Q
TERI	0	0	3	0	2	0	0	0	7	0	7	1	9	1	3	1	4	2	4	4	3	6	4	6	46	21
BPS	0	0	6	0	4	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**18**	**0**
MADH	2	2	3	5	5	4	4	4	4	5	5	4	4	5	2	1	2	3	4	5	2	1	0	0	37	39
IGCHC	2	2	5	4	5	5	4	5	6	5	4	4	3	3	1	1	0	0	2	3	4	3	0	0	36	35
VICH	2	1	4	5	4	3	4	4	3	3	3	2	0	0	2	2	3	4	5	5	5	4	4	4	39	37
CSB	2	2	5	3	5	5	4	5	6	5	3	3	0	0	0	0	4	4	2	4	4	4	2	3	37	38
SKSJ	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**
YPS	2	2	4	4	4	3	3	4	3	3	4	3	0	0	0	0	4	3	5	4	6	5	6	3	41	34
AMCO	2	1	4	3	4	5	6	4	6	5	3	2	4	4	2	3	5	3	5	4	3	5	4	4	48	43
ITPL	2	2	3	5	3	4	4	4	4	5	4	4	2	3	2	1	1	3	3	5	4	3	3	3	35	42
SWAN	0	0	3	2	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	2	2	3	2	4	5	4	3	16	14
UEP	1	2	3	2	0	1	1	0	0	2	1	1	2	2	1	2	3	2	3	2	3	5	3	3	21	24
RWF	**0**	**0**	**0**	**0**	2	1	3	2	1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	6	2	8	3	3	3	6	3	29	14
TOTAL	15	14	43	33	38	31	37	32	**45**	33	34	24	24	18	**14**	**11**	34	28	44	41	41	**44**	36	32	405	341

(* T = teflon and Q = quartz)


PM2.5 source contribution
Byappanahalli
Aavalahalli
Kanamangala
Ramesh Nagar
Varthur
Hebbal Outer Ring Road
Wind Tunnel Road
Balagere Main Road
Gunjur Main Road
Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, © OpenStreetMap contributors, and the GIS User Community


PM10 source contribution
Byappanahalli
Aavalahalli
Kanamangala
Ramesh Nagar
Varthur
Hebbal Outer Ring Road
Wind Tunnel Road
Balagere Main Road
0 2.5 5 10 Kilometers

4. Results and Discussion

The study estimated the $PM_{2.5}$ and PM_{10} concentration levels and the share of the pollutants monitored over 13 sites in Bengaluru city. All sites, except the background site, are within the Bruhat Bengaluru Mahanagara Palike (BBMP) boundary. The monitoring sites were classified into five categories – residential, sensitive, kerbside, industrial, and background.

Of these, two sites each were representative of residential and sensitive category, four sites each represented kerbside and industrial category, and one site represented background category. The study conducted sampling at all the 13 sites identified by KSPCB in the city. At all these sites, the $PM_{2.5}$ and PM_{10} mass concentration levels were quantified through fine particulate sampler and respirable dust sampler, respectively. The results show that there is site-wise variation, as well as seasonal variation in $PM_{2.5}$ and PM_{10} levels.

The chemical analysis of the $PM_{2.5}$ and PM_{10} samples quantified the concentration of metals, EC, OC, ions, and molecular markers. Using chemical species mass concentration, receptor modelling was performed to identify the source contribution from various sectors. Model results indicate that there is site-wise and season-wise variation in sources. These analyses enabled an in-depth understanding of the site-specific variations, with respect to the sources and seasons.

4.1. Spatio-temporal analysis of $PM_{2.5}$ and PM_{10}

The study estimated the $PM_{2.5}$ and PM_{10} mass concentration at 13 monitoring locations in Bengaluru city. The variations in $PM_{2.5}$ and PM_{10} mass concentration over each monitoring location is explained in *Annexure II*. Since the air-quality levels varied from one monitoring location to the other within Bengaluru, the averaging method was adopted to present the values, in order to understand the air quality of the city.

4.1.1 $PM_{2.5}$

The annual mean $PM_{2.5}$ mass concentration observed over Bengaluru was 30.9 ± 12.3 µg m^{-3} (mean ± standard deviation), which is less than the CPCB's annual permissible limit (40 µg m^{-3}). Overall, about seven sampling days (2% of total sampling days) showed concentrations higher than the CPCB's daily permissible limit (60 µg m^{-3}).

On analysing the site-wise exceedance days, it was found that the highest number of exceedance days were at kerbside site CSB (three days), while eight sites did not have even a single exceedance day. This shows that during most of the sampling days (425 days; 98% of the total sampling days), the $PM_{2.5}$ levels were within the CPCB's daily permissible limit. The site-wise and season-wise number of exceedance days for $PM_{2.5}$ (*w.r.t* to CPCB standards) are mentioned in Table 8.

Table 8: Number of exceedance days for $PM_{2.5}$ mass concentration *w.r.t* to CPCB standard

Site	No. of exceedance days for $PM_{2.5}$ *w.r.t* CPCB standard of 60 µg m^{-3} (Seasonal)			No. of exceedance days for $PM_{2.5}$ *w.r.t* CPCB standard of 60 µg m^{-3} (Overall)
	Summer	Monsoon	Winter	
TERI	*NED*	*NED*	*NED*	*NED*
BPS	*NED*	*NED*	*NED*	*NED*
MADH	1	*NED*	*NED*	1
IGCHC	*NED*	*NED*	*NED*	*NED*
VICH	*NED*	*NED*	*NED*	*NED*
CSB	2	*NED*	1	3
SKSJ	*NED*	*NED*	*NED*	*NED*
YPS	*NED*	*NED*	1	1
AMCO	*NED*	*NED*	1	1
ITPL	*NED*	*NED*	*NED*	*NED*
SWAN	*NED*	*NED*	*NED*	*NED*
UEP	*NED*	*NED*	1	1
RWF	*NED*	*NED*	*NED*	*NED*

(**NED* = No Exceedance Day)

The analysis of site-wise variation in $PM_{2.5}$ mass concentration revealed the highest annual mean $PM_{2.5}$ at the industrial site UEP (41.3 ± 12.2 µg m^{-3}) and the lowest at the sensitive site IGCHC (23.3 ± 7.7 µg m^{-3}). This shows the influence of industrial sources on the PM levels (while UEP has a high industrial source contribution, IGCHC does not have any such source contributions except vehicular emissions). The high concentration over the UEP site is mainly due to source contribution from the industrial operations and heavy vehicular movement. The site and seasonal variation of $PM_{2.5}$ is presented in Table 9.

Table 9 : Site and seasonal variation of $PM_{2.5}$ mass concentration

Site	Seasonal $PM_{2.5}$ Mean ± Standard deviation (µg m^{-3})			Annual (µg m^{-3})
	Summer	Monsoon	Winter	
TERI	33.4 ± 3.8	20.3 ± 6.9	34.9 ± 11.4	27.2 ± 11.2
BPS	33.1 ± 6.4	24.5 ± 10.9	No sample	29.5 ± 9.4
MADH	39.7 ± 11.8	19.7 ± 6.2	29.5 ± 11.9	27.8 ± 12.6
IGCHC	30.9 ± 5.6	18.6 ± 6.1	22.0 ± 3.8	23.4 ± 7.8
VICH	29.8 ± 11.3	19.0 ± 7.7	25.1 ± 9.6	24.6 ± 10.1
CSB	47.3 ± 14.7	24.0 ± 4.3	36.6 ± 10.7	35.6 ± 14.2
SKSJ	No sample	13.0	26.0	19.5
YPS	39.4 ± 6.6	23.7 ± 7.0	36.5 ± 13.4	33.8 ± 12.2
AMCO	40.7 ± 8.9	26.2 ± 6.4	37.9 ± 11.4	34.0 ± 11.0
ITPL	44.7 ± 10.7	26.7 ± 7.9	27.0 ± 8.6	30.9 ± 11.5
SWAN	49.7 ± 9.4	No sample	35.2 ± 11.6	37.9 ± 12.4
UEP	49.0 ± 5.2	35.2 ± 6.9	40.4 ± 14.0	41.3 ± 12.2
RWF	40.0 ± 9.9	24.3 ± 1.1	33.9 ± 12.2	33.3 ± 11.7

Also, from the table it can be inferred that the background site MADH showed a $PM_{2.5}$ level higher than the residential site TERI and the sensitive site IGCHC. This indicates increasing vehicular activity in the vicinity of the background site MADH. On the kerbside site SKSJ, only two samples could be collected due to instrument malfunction. Hence, sufficient information on $PM_{2.5}$ could not be collected for this site.

The analysis of the variation in $PM_{2.5}$ levels with a change in land-use category showed that the average $PM_{2.5}$ was highest over the industrial (35.8 µg m^{-3}) category, followed by kerbside (34.5 µg m^{-3}), residential (28.1 µg m^{-3}), and sensitive locations (23.9 µg m^{-3}) (Figure. 8). High concentration over the industrial sites is mainly due to source contribution from the industrial operations and heavy vehicular movement. High concentration over kerbside sites is mainly due to vehicular movement and roadside dust re-suspension. To substantiate the observation, Kruskal-wallis test was performed on the mean $PM_{2.5}$ observed over every land-use category, and the results revealed significant difference ($p < 0.05$) in the $PM_{2.5}$ levels, indicating that the mean values of at least one land-use type differs from the other land-use types.

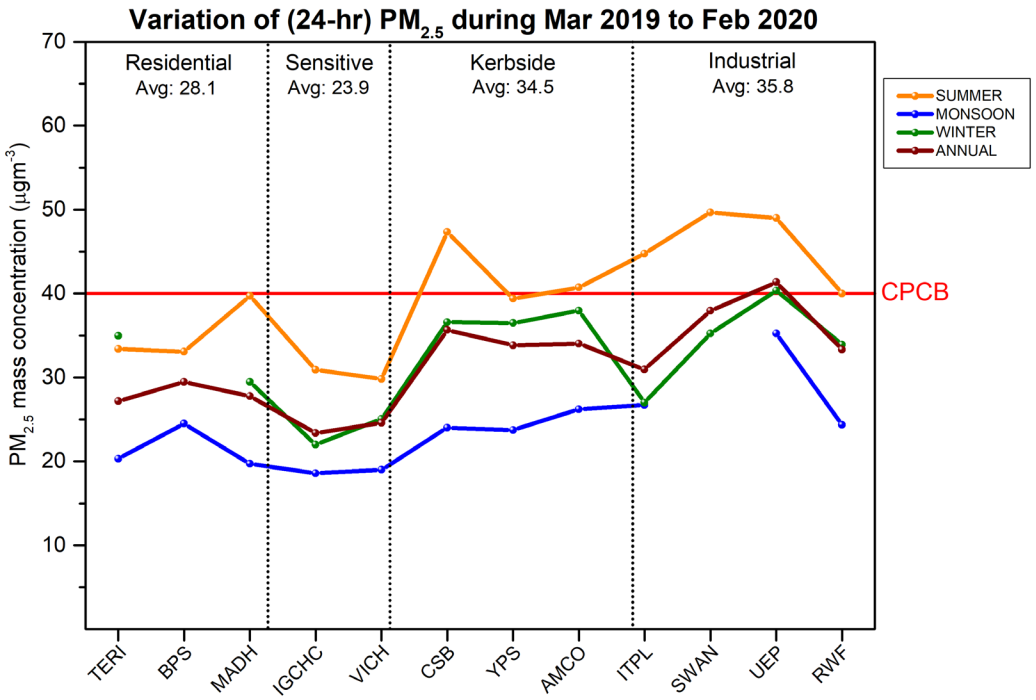


Figure 8: Site-wise variation of $PM_{2.5}$ during the study period

4.1.2 PM_{10}

The annual mean PM_{10} mass concentration observed over Bengaluru was 78.9 ± 23.6 µg m^{-3}, which is around 1.3 times higher than the CPCB's annual permissible limit (60 µg m^{-3}). Overall, about 150 sampling days (15% of total sampling days) showed concentration higher than the CPCB's daily permissible limit (100 µg m^{-3}). On analysing the site-wise exceedance days, it was observed that the highest number of exceedance days were at kerbside site CSB (24 days), while the sensitive site IGCHC showed no exceedance day. The high number of exceedance days at kerbside site CSB is due to the continuous traffic movement in its vicinity. The site- and season-wise number of exceedance days of $PM_{2.5}$ *w.r.t* to CPCB standards is mentioned in Table 10.

Table 10: Number of exceedance days for PM_{10} mass concentration w.r.t CPCB standard

Site	Seasonal no. of exceedance days for PM_{10} *w.r.t* CPCB standard of 100 µg m^{-3}			Overall (No. of sampling days exceeding CPCB standard)
	Summer	Monsoon	Winter	
TERI	1	2	26	29
BPS	*NED*	*NED*	13	13
MADH	11	*NED*	2	13
IGCHC	*NED*	*NED*	*NED*	*NED*
VICH	2	*NED*	*NED*	2
CSB	14	*NED*	10	24
SKSJ	*NED*	8	11	19
YPS	4	*NED*	1	5
AMCO	7	*NED*	4	11
ITPL	6	1	1	8
SWAN	9	*NED*	3	12
UEP	1	4	3	8
RWF	3	2	1	6

(**NED* = No Exceedance days)

Site-wise variation of PM_{10} showed the maximum annual mean PM_{10} at the kerbside site CSB (92.7 ± 25.5 µg m^{-3}) and the minimum at sensitive sites VICH (59.1 ± 14.8 µg m^{-3}) and IGCHC (59.5 ± 13.3 µg m^{-3}). This indicates the influence of road-dust re-suspension, soil dust, and vehicular activity on the PM_{10} levels at the kerbside site, while the sensitive sites VICH and IGCHC have educational institutions, parks, residential apartments in the vicinity. Interestingly, the background site (MADH) showed high concentration in the range of 3% to 34%, as compared to the other sites. This high concentration is attributed to the increase in anthropogenic activities (construction activities in the periphery of the city) around the background site in the recent years. The site and seasonal variations of PM_{10} is presented in Table 11.

Table 11: Site-wise variation of PM_{10} mass concentration

Site	Seasonal PM_{10} Mean ± Standard deviation (µg m^{-3})			Annual (µg m^{-3})
	Summer	Monsoon	Winter	
TERI	69.7 ± 19.0	78.3 ± 15.4	110.3 ± 20.2	90.1 ± 25.4
BPS	53.2 ± 12.5	76.8 ± 14.7	101.4 ± 22.2	89.7 ± 24.9
MADH	102.4 ± 22.1	65.9 ± 14.8	79.0 ± 14.6	79.4 ± 21.6
IGCHC	70.5 ± 18.4	53.6 ± 6.1	58.5 ± 10.7	59.5 ± 13.3
VICH	68.1 ± 21.5	55.4 ± 12.2	57.1 ± 9.9	59.1 ± 14.8
CSB	121.4 ± 25.8	75.6 ± 14.8	94.1 ± 18.8	92.7 ± 25.5
SKSJ	48.9 ± 13.8	75.5 ± 31.6	98.0 ± 25.4	77.2 ± 31.8
YPS	89.1 ± 16.2	66.6 ± 10.2	72.7 ± 12.9	74.5 ± 15.3
AMCO	98.4 ± 16.1	76.7 ± 12.7	83.7 ± 19.2	84.4 ± 18.1
ITPL	101.7 ± 18.6	76.2 ± 14.7	78.1 ± 17.1	82.7 ± 19.3
SWAN	110.0 ± 19.9	55.5 ± 4.0	79.5 ± 20.5	89.5 ± 19.9
UEP	97.6 ± 14.4	99.5 ± 15.6	83.9 ± 17.3	89.4 ± 17.8
RWF	123.3 ± 10.2	71.8 ± 18.3	75.4 ± 14.2	75.5 ± 18.5

Further, from the table, it is inferred that all the sites showed an annual mean PM_{10} higher than the CPCB permissible limit of 60 µg m^{-3}. Interestingly, the winter season PM_{10} over the residential sites was substantially higher than that observed during other seasons. This could be due to increased construction activities, and leaf- and waste-burning activities.

On analysing the variation in PM_{10} with change in the land-use category, it was observed that the average PM_{10} was maximum over residential category (86.4 µg m^{-3}), followed by industrial (84.3 µg m^{-3}), kerbside (82.2 µg m^{-3}), and sensitive locations (59.3 µg m^{-3}) (Figure. 9). The high concentration in residential category is mainly due to source contribution from construction activity, vehicular movement, road-dust re-suspension, and leaf burning activities. The high concentration in the kerbside category is mainly due to the influence of vehicular movement and road-side dust re-suspension. To substantiate the observation, Kruskal-wallis test was performed on the mean PM_{10} observed over every land-use category, and the results revealed significant difference ($p < 0.05$) in the PM_{10} levels, indicating that the mean values of at least one land-use type differs from those of other land-use types.

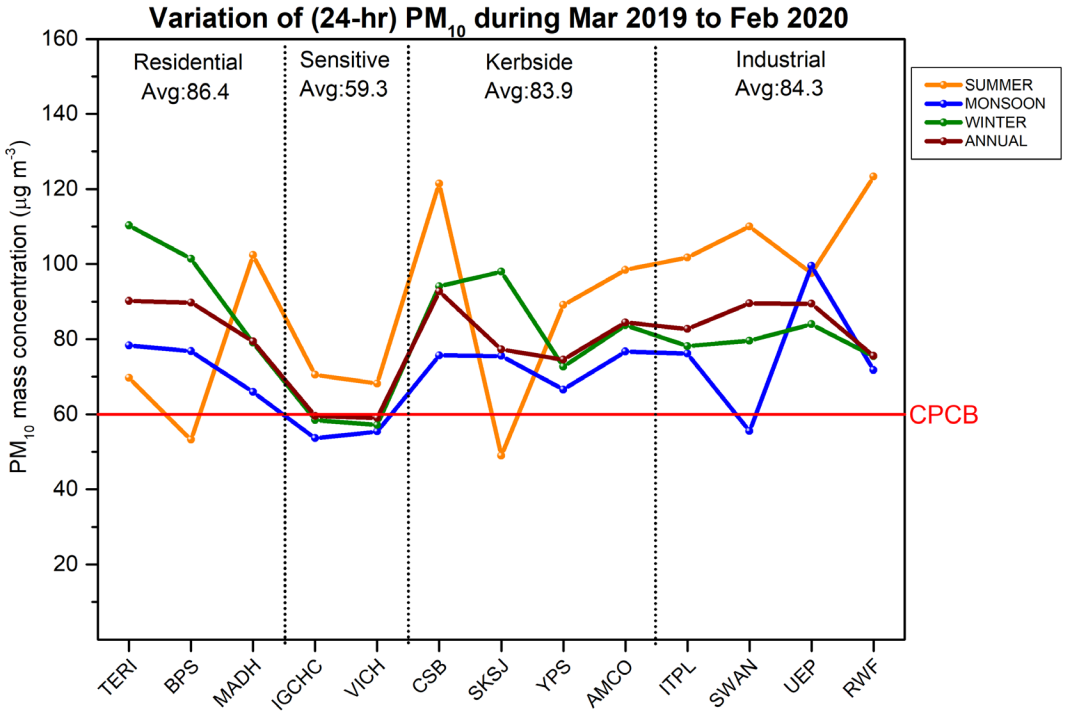


Figure 9: Site-wise variation of PM_{10} during the study period

4.2. Chemical composition of $PM_{2.5}$ and PM_{10}

In the collected $PM_{2.5}$ and PM_{10} samples, chemical species such as metals, ions, EC, OC, and molecular markers were quantified to understand the composition of the aerosols. Seasonal variation of chemical species in $PM_{2.5}$ and PM_{10} over each monitoring location is explained in *Annexure IV*. In this section, the overall seasonal variation of the chemical species in $PM_{2.5}$ and PM_{10} is explained.

4.2.1 $PM_{2.5}$

The seasonal analysis of the chemical species (metals, OC, EC, ions, and molecular markers) associated with $PM_{2.5}$ was carried out. The results revealed that the sum of chemical species was maximum during the summer season, followed by the winter and the monsoon season (Figure. 10).

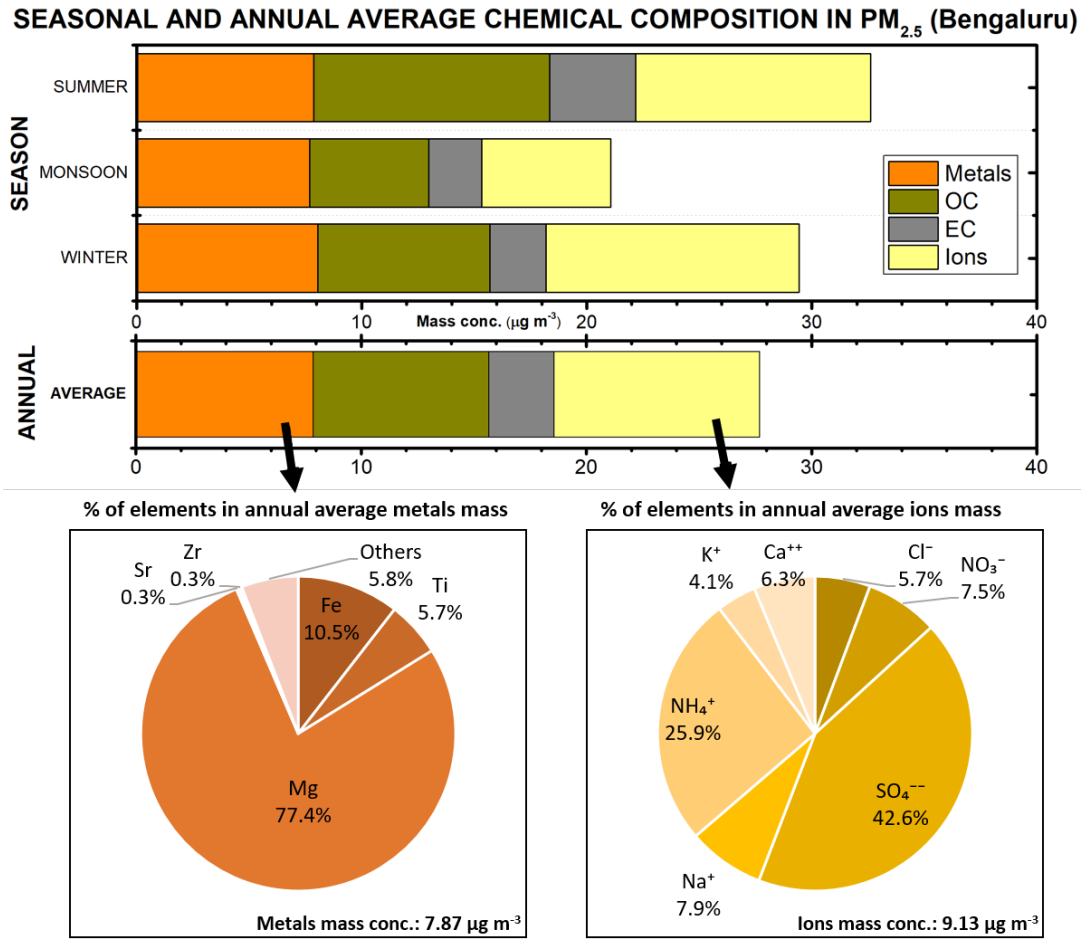


Figure 10: Seasonal and annual average chemical composition in $PM_{2.5}$ over Bengaluru. Pie charts indicate the % of elements in annual average of metals and ions mass.

The high value observed during summer was due to a rise in the OC, EC, SO_4^{2-}, and Ca^{2+} concentration. This shows the influence of construction, transportation, and burning activities. However, the average metals concentration was almost similar in all the seasons, indicating constant sources of metals throughout the year.

Overall, the annual average of metals, OC, EC, and ions concentration was observed to be 7.9 µg m^{-3}, 7.8 µg m^{-3}, 2.9 µg m^{-3}, and 9.1 µg m^{-3}, respectively (Table 12). For the metals analyses, it was observed that the contribution of Mg was highest (77%), followed by Fe (10%), indicating the presence of an aerosol source from crustal materials. Also, the metal concentration varied between 4% and 16% for the 13 sites analysed. In the ions concentration analysed, the contribution of SO_4^{2-} was highest (43%), followed by NH_4^+ (26%), indicating the presence of a secondary aerosols source. It was also observed that ions concentration varied by a factor of 1.5 among the sites.

The annual mean OC and EC was 7.8 µg m^{-3} and 2.9 µg m^{-3}, respectively. The OC/EC > 3 represents substantial contribution from secondary organic aerosols (SOA) (NEERI, 2019). However, in the study, the ratio was observed as 2.7. This denotes that besides SOA, other primary sources such as vehicular, industrial, leaf, waste burning, etc. also contribute to the increase in OC and EC levels.

The analysis of molecular markers revealed that the annual mass concentration of 1-NP in $PM_{2.5}$ was 2.0 ng m^{-3}. The seasonal variation showed a summer maximum (2.4 ng m^{-3}), followed by winter (2.4 ng m^{-3}) and monsoon (1.5 ng m^{-3}). High 1-NP concentration was observed over industrial site UEP, which can be attributed to the use of DG sets and heavy diesel vehicular movements. The annual mass concentration of Levoglucosan was observed to be 68.5 ng m^{-3}. The seasonal variation revealed the highest concentration during winter (106.3 ng m^{-3}), followed by summer (51.9 ng m^{-3}) and monsoon (14.3 ng m^{-3}). High Levoglucosan concentration was observed over industrial site SWAN, where roadside leaf and waste burning was observed. Interestingly, over kerbside site CSB, a low concentration of Levoglucosan was observed. This is due to low leaf- and waste-burning activities in the vicinity of the site.

Table 12: Mass concentration of chemical species associated with the $PM_{2.5}$ over each site

SITE	Annual average mass concentration					
	Metals (µg m^{-3})	Ions (µg m^{-3})	EC (µg m^{-3})	OC (µg m^{-3})	1-NP (ng m^{-3})	Levoglucosan (ng m^{-3})
TERI	7.6	10.9	1.8	5.8	2.0	BDL
BPS	No sample					
MADH	8.4	8.5	1.4	7.3	1.8	BDL
IGCHC	7.5	7.4	1.6	5.3	1.8	105.7
VICH	8.2	7.7	2.1	7.1	2.0	52.5
CSB	7.6	8.7	4.3	9.7	2.2	14.4
SKSJ	No sample					
YPS	8.2	8.9	3.6	8.8	2.1	BDL
AMCO	8.2	9.3	4.1	8.1	1.7	27.8
ITPL	7.8	8.0	2.7	6.8	2.1	BDL
SWAN	7.7	14.2	2.4	8.9	2.7	136.9
UEP	8.0	10.5	3.4	9.3	2.8	BDL
RWF	7.2	10.6	1.0	4.0	2.2	BDL

(*BDL = Below Detection Limit)

Moreover, from Table 11, it is inferred that the range of metal concentration was between 7.2 to 8.4 µg m^{-3} across the sites. This narrow range denotes the presence of activities at every site, which constantly release metals into the ambient air. However, concentration of ions varied in the range of 7.4 to 14.2 µg m^{-3}, which can be attributed to the industrial operations that generate sulphate and nitrate ions.

The range of EC was observed to be in the range of 1.0 to 4.3 µg m^{-3}. Kerbside sites showed high EC values, denoting substantial impact from vehicular movement. The range of OC was observed as 4.0 to 9.7 µg $m^{-3;}$ high levels in every site denote leaf and waste burning activities.

The range of 1-NP was observed to be in the range of 1.7 to 2.8 ng m^{-3}, indicating diesel exhaust emission at every site. The range of Levoglucosan was observed to be 14.4 to 136.9 ng m^{-3}, where high levels were observed over SWAN industrial site and lowest over CSB kerbside. Interestingly, Levoglucosan was detected at five sites, denoting the presence of a considerable amount of leaf-burning activities at these sites.

4.2.2 PM_{10}

The seasonal analysis of the chemical species (metals, OC, EC, and ions) was carried out for PM_{10}, and the results indicate that the sum of chemical species was highest during summer, followed by winter and monsoon (Figure. 11).

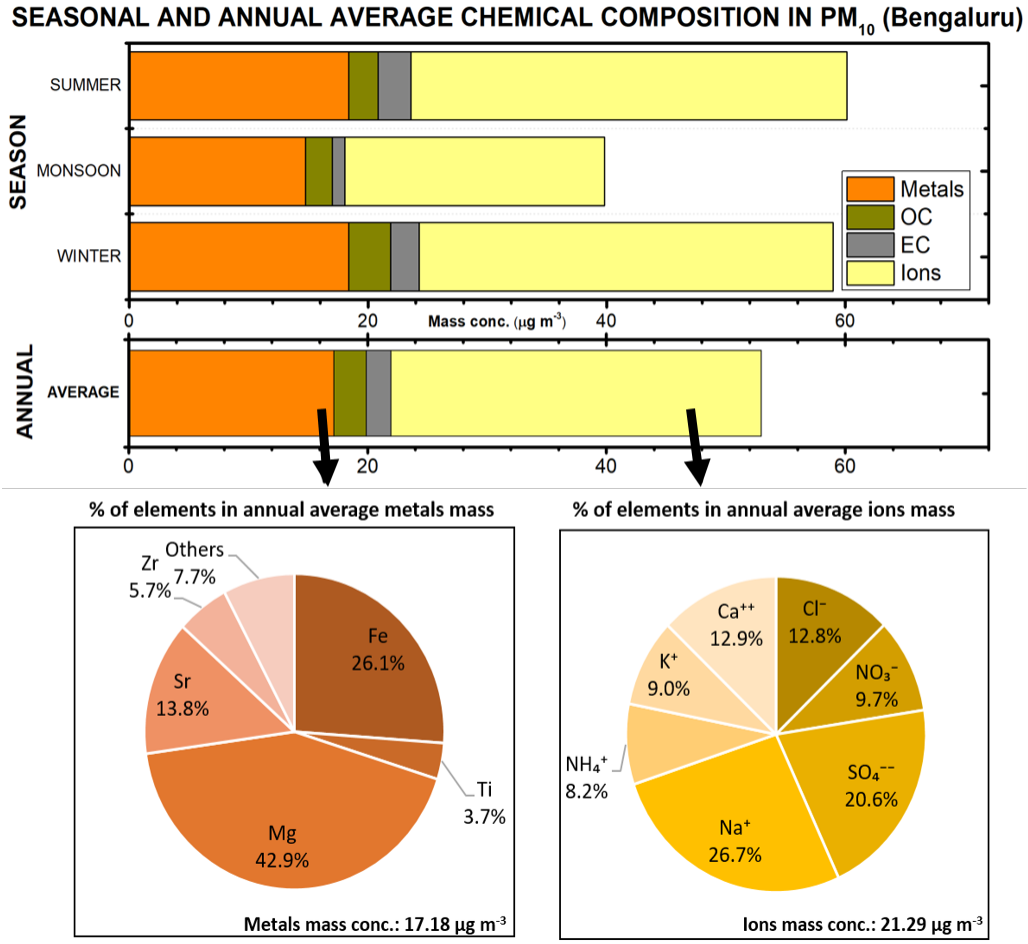


Figure 11: Seasonal and annual average chemical composition in PM_{10} over Bengaluru. Pie charts indicate the % of elements in annual average of metals and ions mass.

The high values during summer were due to the elevation in the OC, EC, SO_4^{2-}, and NO_3^- concentration. This shows the influence of transportation and burning activities. However, the average metals concentration was almost similar during summer and winter seasons, indicating constant sources of metals throughout the year.

Overall, the annual average metal and ions concentration was observed to be 17.2 and 21.3 µg m^{-3}, respectively. Of the average metals concentration, the contribution of Mg was high (43%), followed by Fe (26%), indicating sources from crustal material. Of the ions, the contribution of Na^+ was high (27%), followed by SO_4^{2-} (21%), indicating sources from road dust and secondary aerosols.

On analysing the site-wise variation of chemical species, it was observed that the metals ranged from 13.0 to 20.5 µg m^{-3} (Table 13). The high concentration of metals over residential site TERI was due to the elevated contribution from crustal elements such as Mg and Fe. Moreover, the range of metals was almost similar at all the sites, indicating the presence of similar source-contributing activities at all the sites.

The range of ions was observed as 13.4 to 33.0 µg $m^{-3;}$ high concentration was observed in residential site TERI, which was due to elevated Ca^{2+} concentration. This indicates the impact of construction activities in the vicinity.

The range of EC was observed as 1.2 to 5.6 µg m^{-3}, where kerbside site CSB showed high concentration; this indicates the influence of vehicular movement. Low concentration of EC was observed over background site MADH and industrial site RWF, indicating less vehicular movement. The range of OC was observed as 5.7 to 15.4 µg m^{-3}, where kerbside site CSB showed high concentration, indicating vehicular movement and leaf-burning activities.

Table 13: Annual average mass concentration of chemical species associated with PM_{10}

SITE	Annual average mass concentration			
	Metals (µg m^{-3})	**Ions (µg m^{-3})**	**EC (µg m^{-3})**	**OC (µg m^{-3})**
TERI	20.5	33.0	2.2	8.9
BPS	20.2	28.0	*NS*	
MADH	17.4	25.3	1.7	10.3
IGCHC	13.3	15.8	1.9	8.0
VICH	16.5	15.2	2.4	9.8
CSB	18.9	20.9	5.6	15.4
SKSJ	13.0	19.7	*NS*	
YPS	15.0	18.1	4.2	12.3
AMCO	18.6	20.8	4.9	11.7
ITPL	16.1	19.0	3.3	9.9
SWAN	18.1	32.3	3.0	13.3
UEP	19.5	27.3	3.8	12.4
RWF	16.5	13.4	**1.2**	**5.7**

(**NS* = No Sample)

Furthermore, the mass concentration of criteria pollutants (Ni, As and Pb) was compared with the permissible limits framed under National Ambient Air Quality Standards (NAAQS) (Table 14). The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.04, 0.12, and 0.12 µg m^{-3}, respectively. The As and Ni showed 20 and 2 times higher concentration compared to their respective annual permissible limit of 0.006 and 0.02 µg m^{-3}. Interestingly, the As and Ni concentrations was found to be higher over sites that experience heavy vehicular movement, as was observed over kerbside site CSB (which has heavy vehicular movement). Notably, the Pb concentration was not found to exceed the NAAQS for any of the sites, indicating the impact of phasing out of lead addition in fuel.

Table 14: Mass concentration of metals (Ni, As, and Pb) and comparison with NAAQS standard

SITE	Metals			Times higher than CPCB standard		
	Nickel ($\mu g\ m^{-3}$)	Arsenic ($\mu g\ m^{-3}$)	Lead ($\mu g\ m^{-3}$)	Nickel (0.02 $\mu g\ m^{-3}$)	Arsenic (0.006 $\mu g\ m^{-3}$)	Lead (0.5 $\mu g\ m^{-3}$)
TERI	0.04	0.122	0.09	1.9	20.4	LTS
BPS	0.02	0.125	0.06	1.1	20.9	LTS
MADH	0.05	0.163	0.28	2.7	27.2	LTS
IGCHC	0.03	0.072	0.04	1.7	12.0	LTS
VICH	0.03	0.145	0.07	1.6	24.3	LTS
CSB	0.05	0.194	0.15	2.6	32.4	LTS
SKSJ	0.02	0.087	0.04	1.1	14.5	LTS
YPS	0.07	0.078	0.06	3.4	13.0	LTS
AMCO	0.04	0.092	0.16	2.2	15.3	LTS
ITPL	0.04	0.078	0.09	2.0	13.1	LTS
SWAN	0.03	0.092	0.09	1.7	15.3	LTS
UEP	0.04	0.101	0.09	2.0	16.9	LTS
RWF	0.08	0.107	0.05	4.2	17.8	LTS

(*LTS = Less Than Standard)

4.3. Performance fit measures for PM_{10} and $PM_{2.5}$

The source apportionment of PM was carried out using Chemical Mass Balance (CMB) model for all the samples collected at the various locations in the city. According to the US Environmental Protection Agency (EPA), the source apportionment results from CMB model are considered acceptable only if they satisfy the targets set for parameters such as R^2, χ^2, %Mass, and degree of freedom (DF).

- R^2 is a measure of variance of the ambient concentration explained by the calculated concentration (target of R^2 is >0.8).
- χ^2 compares the difference between the calculated and measured ambient concentrations to the uncertainty of the difference (target of χ^2 is <4).
- % mass is the ratio of the total calculated to measured mass (target of %mass is 80% to 120%).
- DF is the difference between the number of fitting species and the number of fitting sources (target of DF is >5).

The targets specified for these parameters (R^2, χ^2, %mass, and DF) were satisfied in all the samples. Thus, good model fit was established in the study.

The CMB performance fit measures for site-wise PM_{10} variation showed that the MADH and UEP sites showed high R^2 (0.88), with denotes good fit, while the TERI site showed low R^2 (0.74), which is due to fewer samples collected at this site. Similarly, χ^2 value was good for MADH (1.6) and high for TERI (3.7). The DF was high over RWF and low for SWAN (table 15).

Table 15: CMB: Performance criteria for PM_{10}

SITE	Measured Mass (µg m^{-3})	Calculated Mass (µg m^{-3})	Mass (%)	R^2	χ^2	DF
TERI	91.6 ± 18.4	81.8 ± 32.9	88.6 ± 10.9	0.74 ± 0.12	3.7 ± 1.4	12.0 ± 2.2
MADH	79.8 ± 19.4	81.9 ± 19.5	99.7 ± 13.0	0.88 ± 0.06	1.6 ± 0.9	10.9 ± 2.0
IGCHC	58.3 ± 12.8	54.1 ± 12.4	93.0 ± 10.9	0.87 ± 0.05	1.8 ± 0.7	12.7 ± 1.0
VIC	59.5 ± 10.6	54.7 ± 10.9	92.1 ± 13.3	0.81 ± 0.08	2.7 ± 1.1	13.3 ± 1.2
CSB	92.6 ± 25.7	89.2 ± 24.3	96.9 ± 12.0	0.82 ± 0.06	2.4 ± 0.9	13.4 ± 1.3
YPS	73.4 ± 16.1	69.9 ± 18.9	94.9 ± 13.5	0.86 ± 0.06	1.8 ± 0.7	14.4 ± 1.2
AMCO	82.8 ± 19.4	76.6 ± 16.1	93.6 ± 14.7	0.78 ± 0.06	2.8 ± 0.8	13.7 ± 1.2
ITPL	81.6 ± 16.7	80.4 ± 21.1	98.0 ± 14.3	0.87 ± 0.07	1.8 ± 1.0	12.7 ± 1.8
SWAN	86.3 ± 23.2	82.5 ± 14.4	98.3 ± 10.3	0.85 ± 0.06	2.4 ± 0.9	10.2 ± 1.1
UEP	87.9 ± 16.5	85.9 ± 15.9	98.3 ± 12.6	0.88 ± 0.05	1.7 ± 0.7	12.4 ± 1.3
RWF	81.4 ± 20.8	75.2 ± 16.7	92.8 ± 11.8	0.75 ± 0.12	2.9 ± 1.4	15.5 ± 3.1
CRITERIA	-	-	80% to 120%	>0.7	<4	>5
REASON	-	-	Sampling & the type of chemical species selected for the model run is acceptable	The indicators of the model fit	Combination of chemical species selected for the model run is acceptable	If the Degree of Freedom is > 5, then the number of samples collected is acceptable

Table 16: CMB: Performance criteria for $PM_{2.5}$

SITE	Measured Mass (µg m^{-3})	Calculated Mass (µg m^{-3})	Mass (%)	R^2	χ^2	Degree of Freedom (DF)
TERI	28.3 ± 7.8	25.1 ± 5.7	89.5 ± 5.6	0.82 ± 0.04	1.4 ± 0.3	11.3 ± 0.7
MADH	29.5 ± 10.0	27.0 ± 9.27	91.6 ± 6.9	0.85 ± 0.05	1.6 ± 0.6	11.3 ± 0.9
IGCHC	25.1 ± 7.9	24.2 ± 9.3	94.6 ± 9.0	0.88 ± 0.04	1.3 ± 0.4	10.6 ± 0.7
VIC	28.9 ± 8.0	27.3 ± 8.0	94.4 ± 8.5	0.86 ± 0.06	1.0 ± 0.4	10.5 ± 1.1
CSB	38.7 ± 17.0	36.7 ± 16.0	95.0 ± 8.8	0.85 ± 0.06	1.6 ± 0.6	11.0 ± 0.9
YPS	33.7 ± 10.8	32.4 ± 11.4	95.6 ± 8.6	0.82 ± 0.04	1.4 ± 0.3	11.7 ± 2.9
AMCO	33.0 ± 8.7	31.9 ± 9.5	95.8 ± 8.9	0.82 ± 0.05	1.4 ± 0.4	11.6 ± 0.9
ITPL	29.1 ± 8.0	29.1 ± 8.0	100.4 ± 7.8	0.85 ± 0.04	1.4 ± 0.5	11.3 ± 0.8
SWAN	40.1 ± 12.5	39.8 ± 13.7	99.0 ± 9.02	0.81 ± 0.04	1.7 ± 0.3	10.7 ± 1.3
UEP	36.7 ± 10.9	35.1 ± 11.8	95.4 ± 9.5	0.82 ± 0.08	1.6 ± 0.7	10.8 ± 1.1
RWF	26.0 ± 7.2	21.1 ± 6.9	80.9 ± 13.00	0.79 ± 0.03	1.7 ± 0.3	11.1 ± 1.2
CRITERIA	**-**	**-**	**80% to 120%**	**>0.7**	**<4**	**>5**

Similarly, the CMB performance fit measures for site-wise $PM_{2.5}$ variation showed that the IGCHC sites indicate high R^2 (0.88), which denotes good fit, while RWF site showed low R^2 (0.79), which is due to high unexplained concentration. Similarly, χ^2 value was good for VICH

(1.0) and high for SWAN and RWF (1.7). The DF was high over YPS (11.7) and low for VIC (10.5) (Table 16).

In addition to satisfying the performance fit measures for individual sites, the association between the measured and the model calculated PM values was analysed to determine if the protocol followed for running the CMB was valid. The results of the PMF model run on the collected samples is given in the Annexure 5.

Association between measured and modelled PM concentrations

Linear regression was established between the measured and model calculated PM_{10} values (Figure 12). On observing the results, it was found that the association between measured and model calculated PM_{10} was good ($R^2 = 0.77$). This validates the robustness of the protocol followed for running the CMB model. Similarly, the association between the measured and model calculated $PM_{2.5}$ was found to be good ($R^2 = 0.91$).

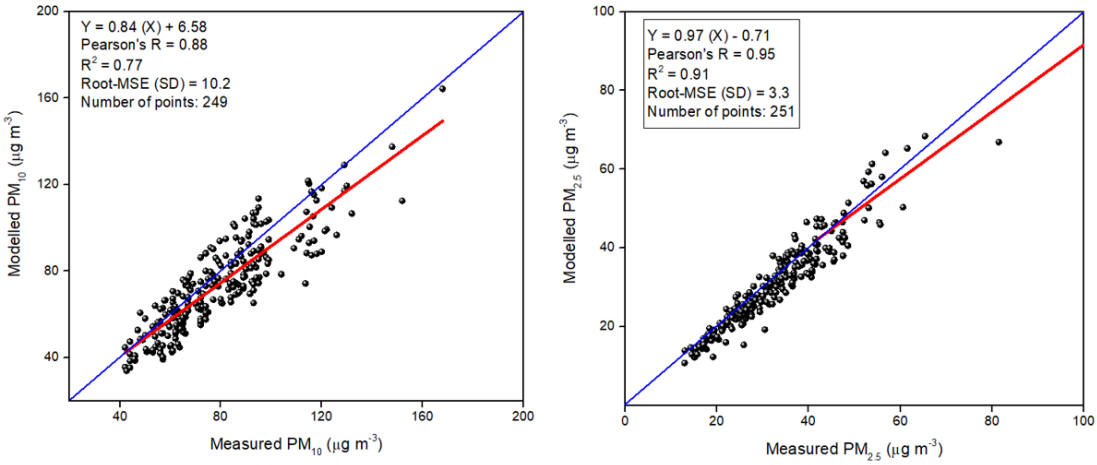


Figure 12: Association between measured and modelled PM_{10} and $PM_{2.5}$

4.4. Site-wise sources of $PM_{2.5}$ and PM_{10}

This section discusses the seasonal variation of $PM_{2.5}$ and PM_{10} sources with respect to each site. The results obtained in terms of source concentration for individual daily samples for a site were averaged to calculate the seasonal source concentration.

4.4.1 TERI Office (TERI)

TERI station represents a residential location as per CPCB sampling location selection guidelines. In the vicinity of the site, there are numerous residential apartments, commercial complexes, parks, restaurants, independent houses, etc., indicating wide sectoral sources of pollution over the site.

Seasonal variation of $PM_{2.5}$ sources revealed major share from the transportation sector, which ranged between 28% in winter and 37% in monsoon (Table 17). Similarly, the seasonal variation of PM_{10} sources revealed considerable share from the transportation sector, which

ranged between 10% in monsoon and 33% in summer. Although TERI station represents a residential location, there is heavy traffic flow in the vicinity of the station. Noticeably, the wind movement towards the site is prominent from South and South-Easterly direction, where the Domlur flyover and a bus terminal are located. These areas have high vehicular movement throughout the year.

Seasonal soil dust contribution in $PM_{2.5}$ ranged between 7.8 in monsoon and 7.9 μg m^{-3} in winter, while in PM_{10}, the range was between 12.9 μg m^{-3} in summer and 57.7 μg m^{-3} in in winter. High contribution from soil dust is chiefly due to the vehicular-induced road dust re-suspension. The road network around the site is mostly of paved road; however, due to vehicular movement, the dust settled along the roadsides gets re-suspended and elevates the PM loading over the site.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (27% in $PM_{2.5}$; 24% in PM_{10}) during winter. High concentration of secondary aerosols during winter is due to low temperature, which favours the formation of secondary aerosols. Moreover, sources of secondary aerosols in this site are chiefly from vehicular, coal burning in restaurants, and leaf-burning activities.

The construction dust share in $PM_{2.5}$ and PM_{10} was <1% during all the seasons, denoting less impact of construction activities on the PM loading over this site.

The contribution of wood burning to $PM_{2.5}$ varied between 5% in monsoon and 6% in winter, and for PM_{10}, it varied between 2% in winter and 30% in summer, denoting the effect of using wood for cooking, and burning of leaves and twigs along the roadside.

Interestingly, DG Set contribution was observed during monsoon season for $PM_{2.5}$, while for PM_{10}, it was not observed. Additionally, the presence of 1-NP in $PM_{2.5}$ samples collected from this site substantiates diesel exhaust emission sources. Furthermore, coal combustion was observed for PM_{10} during monsoon, while it was not observed for $PM_{2.5}$. Coal is generally used in the restaurants for cooking purpose.

Note: Due to instrument malfunction, less than 7 samples were collected during each season for $PM_{2.5}$ and PM_{10}. Therefore, the results should be inferred accordingly.

Table 17: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at TERI site

Source	$PM_{2.5}$		PM_{10}		
	Monsoon mean concentration 23.9 µg m^{-3}	**Winter mean concentration 28.9 µg m^{-3}**	**Summer mean concentration 70.1 µg m^{-3}**	**Monsoon mean concentration 77.2 µg m^{-3}**	**Winter mean concentration 109.5 µg m^{-3}**
Transportation	8.9 (37%)	8.0 (28%)	22.9 (33%)	8.2 (10%)	13.5 ± 8.8 (12%)
Wood comb.	1.1 (5%)	1.8 (6%)	21.3 (30%)	3.1 (4%)	2.4 ± 3.4 (2%)
Soil dust	7.8 (33%)	7.9 (27%)	12.9 (18%)	51.9 (67%)	57.7 ± 18.6 (53%)
Sec. Nitrate	<1 (1%)	1.0 (4%)	<1 (1%)	<1 (1%)	3.0 ± 2.6 (3%)
Sec. Sulphate	1.5 (7%)	6.6 (23%)	*ND*	1.9 (2%)	22.7 ± 22.1 (21%)
Const. Dust	<1 (<1%)	<1 (<1%)	<1 (1%)	*ND*	<1 ± <1 (<1%)
DG set	<1 (2%)	*ND*	*ND*	*ND*	*ND*
Coal Comb.	*ND*	*ND*	*ND*	2.1 (3%)	*ND*
Unaccounted	3.6 (15%)	(11%)	11.0 (16%)	8.9 (12%)	9.6 ± 3.5 (9%)

(**ND* = Not Detected)

4.4.2 Banaswadi Police Station (BPS)

Due to $PM_{2.5}$ instrument malfunctioning, there was no quartz sample collected from this station throughout the study period. Although PM_{10} samples were collected, due to missing EC and OC mass concentration from $PM_{2.5}$ samples, the CMB model run could not be carried out for both $PM_{2.5}$ and PM_{10}.

4.4.3 Madhavchari (MADH)

MADH station represents a background location as per CPCB sampling location selection guidelines. In the vicinity of this site, mostly barren lands, agricultural fields, low- and medium-income houses, few gated community apartments etc. were observed, indicating less influence of emissions from the congested urban areas of the city.

On analysing the seasonal variation of $PM_{2.5}$ sources, it was observed that the transportation sector contribution ranged between 36% in winter and 41% in monsoon (Table 18). Similarly, in PM_{10}, it ranged between 14% in winter and 17% in summer. Although MADH station represents a background site, the wind rose plot indicates prevailing winds blowing mostly from South-Easterly, South, and West directions, where several multi-storied apartments are located. Developments in these areas increase the anthropogenic sources such as vehicular, construction, and DG Sets contribution over this site.

Seasonal soil dust contribution in $PM_{2.5}$ ranged between 6.5 µg m^{-3} in monsoon and 12.3 µg m^{-3} in summer, while in PM_{10}, the range was between 35.3 in monsoon and 43.3 µg m^{-3} in summer. Contribution from soil dust is chiefly due to the dust particles re-suspending from the nearby barren lands with less vegetation cover. Moreover, the road network around the site is mostly unpaved, which can play a major role in re-suspension of dust due to vehicular movement.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (32% in $PM_{2.5}$; 18% in PM_{10}) during winter. High concentration of secondary aerosols during winter is due

to low temperature, which favours the formation of secondary aerosols. Sources of secondary aerosols in this site are chiefly from vehicular, and wood- and leaf-burning activities.

The construction dust share in PM_{10} ranged between 6% in winter and 8% in summer, while in $PM_{2.5}$, it ranged between 0.2% in winter and 0.9% in summer, denoting continuous construction activities in the vicinity of the site.

Wood-burning contribution to $PM_{2.5}$ varied between 3% in monsoon and 6% in winter, and for PM_{10}, the range varied between 6% in monsoon and 15% in summer, denoting high usage of wood for cooking, and leaf- and twigs-burning activities in the surrounding areas.

Interestingly, DG Set contribution and coal combustion were observed during monsoon season in $PM_{2.5}$, denoting contribution from areas in the west of the site (the prevailing direction of winds during monsoon season was from the west). In the west of the site, there are some residential apartments and restaurants that use DG Sets during power cuts and coal for cooking activities, respectively.

Table 18: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at MADH site

Source	$PM_{2.5}$			PM_{10}		
	Summer mean concentration 37.3 µg m^{-3}	**Monsoon mean concentration 21.6 µg m^{-3}**	**Winter mean concentration 36.6 µg m^{-3}**	**Summer mean concentration 101.5 µg m^{-3}**	**Monsoon mean concentration 63.1 µg m^{-3}**	**Winter mean concentration 82.1 µg m^{-3}**
Transportation	13.6 ± 4.6 (37%)	8.8 ± 2.8 (41%)	13.3 ± 3.3 (36%)	17.3 ± 5.6 (17%)	9.4 ± 4 (15%)	11.8 ± 5.1 (14%)
Wood comb.	1.4 ± 1.2 (4%)	<1 ± <1 (3%)	2.0 ± 1.1 (6%)	15.6 ± 7.1 (15%)	3.8 ± 3.6 (6%)	7.8 ± 6 (10%)
Soil dust	12.3 ± 5.4 (33%)	6.5 ± 3 (30%)	6.6 ± 1.3 (18%)	43.3 ± 8.7 (43%)	35.3 ± 14.7 (56%)	38.5 ± 14 (47%)
Sec. Nitrate	<1 ± <1 (<1%)	<1 ± <1 (3%)	1.7 ± <1 (5%)	6.5 ± 3.4 (6%)	1.3 ± 1.3 (2%)	4.4 ± 1.4 (5%)
Sec. Sulphate	5.7 ± 2 (15%)	2.4 ± 1.3 (11%)	9.7 ± 8.8 (27%)	<1 ± 1.8 (<1%)	<1 ± <1 (1%)	10.6 ± 9 (13%)
Const. Dust	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	7.9 ± 6.8 (8%)	4.7 ± 4.4 (7%)	5.2 ± 3.7 (6%)
DG set	*ND*	<1± <1 (<1%)	*ND*	*ND*	<1 ± <1 (<1%)	*ND*
Coal Comb.	*ND*	<1 ± <1 (1%)	*ND*	*ND*	*ND*	*ND*
Unaccounted	3.3 ± 2.6 (9%)	2.1 ± 1.9 (10%)	2.8 ±1.4 (8%)	9.9 ± 10.3 (10%)	7.5 ± 7.2 (12%)	3.5 ± 5.5 (4%)

(**ND* = Not Detected)

4.4.4 Indira Gandhi Institute of Child Health Care (IGCHC)

The IGCHC station represents a sensitive location (as per CPCB sampling location selection guidelines). In the vicinity of this site, there are numerous healthcare clinics, hospitals, educational institutions, residential apartments, commercial complexes, botanical gardens, restaurants, independent houses, etc., indicating a wide range of polluting sources over the site.

On analysing the seasonal variation of $PM_{2.5}$ sources, it was observed that the transportation sector contribution ranged between 37% (in winter) and 53% (in summer) (Table 19). Similarly, the seasonal variation in the share of transportation sector in PM_{10} concentration ranged between 12% (in monsoon) and 24% (in summer). Although IGCHC station represents a sensitive location, there are many congested traffic junctions in the vicinity of the station. Noticeably, these areas have high vehicular movement during the peak hours of the day.

The seasonal soil-dust contribution to $PM_{2.5}$ levels varied between 5.8 $\mu g\ m^{-3}$ (in monsoon) and 7.2 $\mu g\ m^{-3}$ (in summer), while in case of PM_{10}, the variation was between 32.3 $\mu g\ m^{-3}$ (in winter) and 36.6 $\mu g\ m^{-3}$ (in monsoon). High percentage contribution from soil dust during summer and monsoon is chiefly due to vehicular-induced road dust re-suspension. Though the road network around the site is mostly paved, due to continuous vehicular movement, the dust settled along the roadsides gets re-suspended and contributes to PM loading over the site.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (20% in $PM_{2.5}$; 10% in PM_{10}) during winter. High concentration of secondary aerosols during winter is due to low temperature, which favours the formation of secondary aerosols. Sources of secondary aerosols in this site are chiefly from vehicular, coal-burning in restaurants, and leaf-burning activities.

The construction-dust share was observed during all the seasons. In PM_{10}, it ranged between 2% (in monsoon) and 9% (in summer,) while in $PM_{2.5}$, it ranged between 0.1% in summer and 0.7% in winter, denoting high construction activities throughout the year.

Wood burning contribution to $PM_{2.5}$ varied between 5% in summer and 7% in monsoon, and for PM_{10}, the range varied between 4% in monsoon and 15% in summer, denoting usage of wood for cooking, burning of leaves and twigs in the roadside. Additionally, the presence of Levoglucosan in $PM_{2.5}$ samples collected from this site substantiates the presence of leaf and wood burning.

Interestingly, DG set contribution was observed during monsoon season in $PM_{2.5}$ while in PM_{10}, approx. 1% contribution was observed during all seasons. Near the site, there are many commercial complexes, institutions, and residential apartments that use DG sets during power cuts. Additionally, the presence of 1-NP in $PM_{2.5}$ samples collected from this site substantiates the presence of diesel exhaust emissions. Similarly, coal combustion was observed in PM_{10}, which ranged between 0.8% in monsoon and 2.0% in winter, while it was not observed in $PM_{2.5}$. This denotes the contribution of coal emissions adding to the concentration of coarse size fraction. Coal is generally used in restaurants for cooking purpose.

Table 19: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at IGCHC site

Source	$PM_{2.5}$			PM_{10}		
	Summer mean concentration 33.5 µg m^{-3}	**Monsoon mean concentration 19.2 µg m^{-3}**	**Winter mean concentration 25.9 µg m^{-3}**	**Summer mean concentration 65.0 µg m^{-3}**	**Monsoon mean concentration 52.4 µg m^{-3}**	**Winter mean concentration 61.4 µg m^{-3}**
Transportation	17.6 ± 3.3 (53%)	7.3 ± 3.2 (38%)	9.6 ± 1.8 (37%)	15.3 ± 6.7 (24%)	6.2 ± 3.1 (12%)	8.2 ± 3.2 (13%)
Wood comb.	1.7 ± <1 (5%)	1.3 ± <1 (7%)	1.7 ± <1 (6%)	9.5 ± 9.6 (15%)	2.2 ± 1.1 (4%)	5.6 ± 6.5 (9%)
Soil dust	7.2 ± <1 (21%)	5.8 ± 1.2 (31%)	6.7 ± <1 (26%)	21.2 ± 8.3 (33%)	36.6 ± 9.7 (70%)	32.3 ± 3.7 (53%)
Sec. Nitrate	<1 ± <1 (2%)	<1 ± 1.3 (4%)	1.2 ± <1 (5%)	1 ± <1 (2%)	<1 ± <1 (1%)	2.8 ± <1 (5%)
Sec. Sulphate	6.1 ± 2.2 (18%)	1.7 ± 1.3 (9%)	3.9 ± 2.5 (15%)	2.4 ± 1.9 (4%)	<1 ± <1 (1%)	2.8 ± 1.9 (5%)
Const. Dust	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	6.1 ±15.3 (9%)	1.1 ± 1.9 (2%)	2.8 ± 2.9 (5%)
DG set	*ND*	<1 ± <1 (<1%)	*ND*	<1 ± 1.7 (1%)	<1 ± <1 (<1%)	<1 ± 1.8 (1%)
Coal Comb.	*ND*	*ND*	*ND*	1.2 ± 1.3 (2%)	<1 ± <1 (<1%)	1.2 ± 1.2 (2%)
Unaccounted	<1 ± <1 (<1%)	1.9 ± <1 (10%)	2.4 ± 2.2 (10%)	7.1 ± 5.2 (11%)	4.2 ± 4 (8%)	4.6 ± 5.6 (7%)

(**ND* = Not Detected)

4.4.5 Victoria Hospital (VICH)

The VICH station represents a sensitive location as per CPCB sampling location selection guidelines. In the vicinity of this site, there is a main bus terminal, central railway station, several commercial markets, traffic junctions, residential apartments, commercial complexes, restaurants, etc., indicating a wide range of sectoral sources of pollution over the site.

On analysing the seasonal variation of $PM_{2.5}$ sources, it was observed that the transportation sector contribution ranged between 37% (in summer) and 47% (in monsoon) (Table 20). Similarly, the seasonal variation of transport sector share in PM_{10} ranged between 13% in monsoon and 18% in summer. Although VICH station represents a sensitive location, there are numerous congested traffic junctions in the vicinity of the station. Notably, transport vehicles carrying essential items to nearby commercial areas were observed on a regular basis.

Seasonal soil-dust contribution in $PM_{2.5}$ ranged between 5.3 $\mu g\ m^{-3}$ (in monsoon) and 10.4 $\mu g\ m^{-3}$ (in winter), while in PM_{10}, the range was between 25.4 $\mu g\ m^{-3}$ in summer and 36.5 $\mu g\ m^{-3}$ in winter. Contribution from soil dust is chiefly due to the vehicular-induced road dust re-suspension. The road network around the site mostly consists of paved road; however, due to vehicular movement, the dust settled along the roadsides gets re-suspended and contributes to PM loading over this site.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (20% in $PM_{2.5}$; 9% in PM_{10}) during winter. High concentration of secondary aerosols during winter is due to low temperature, which favours the formation of secondary aerosols. Sources of secondary aerosols in this site are chiefly from vehicular, coal-burning in restaurants, and leaf-burning activities. The construction dust contribution was observed in all the seasons, where in PM_{10}, it ranged between 2% in monsoon and 6% in summer, while in $PM_{2.5}$, it ranged between 0.2% in summer and 0.4% in winter, denoting continuous construction activities in the vicinity of the site.

The contribution of wood burning to $PM_{2.5}$ varied between 4% (in winter) and 6% (in monsoon) and for PM_{10}, it varied between 2% in monsoon and 11% in summer, denoting usage of wood for cooking, burning of leaves and twigs in the roadside. Additionally, the presence of Levoglucosan in $PM_{2.5}$ samples collected from this site substantiates the presence of leaf and wood burning.

The DG set contribution to $PM_{2.5}$ was approx. 0.3% in winter and monsoon season, while in PM_{10}, it was observed between <1% in winter and 2% in summer. There are many commercial complexes, institutions, and residential apartments near the site, which use DG sets during power cuts. Additionally, the presence of 1-NP in $PM_{2.5}$ samples collected from this site substantiates the presence of diesel exhaust emissions. Interestingly, coal combustion was observed for $PM_{2.5}$ during winter (1%), while it was not observed for PM_{10}. Coal is generally used in restaurants for cooking purpose.

Table 20: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at VICH site

Source	$PM_{2.5}$			PM_{10}		
	Summer mean concentration 28.2 µg m^{-3}	**Monsoon mean concentration 19.2 µg m^{-3}**	**Winter mean concentration 33.5 µg m^{-3}**	**Summer mean concentration 58.9 µg m^{-3}**	**Monsoon mean concentration 49.2 µg m^{-3}**	**Winter mean concentration 62.1 µg m^{-3}**
Transportation	10.5 ± 2.5 (37%)	9.0 ± 2.5 (47%)	13 ± 4.4 (39%)	10.9 ± 5.6 (18%)	6.4 ± 2.1 (13%)	9.6 ± 4 (15%)
Wood combustion	1.4 ± <1 (5%)	1.1 ± <1 (6%)	1.3 ± <1 (4%)	6.2 ± 4.4 (11%)	<1 ± 1 (2%)	3 ± 1.1 (5%)
Soil dust	9.6 ± 3.4 (34%)	5.3 ± 1.2 (28%)	10.4 ± 2.7 (31%)	25.4 ± 8.2 (43%)	33 ± 11.4 (67%)	36.5 ± 8.7 (59%)
Secondary nitrate	<1 ± <1 (1%)	<1 ± <1 (2%)	<1 ± <1 (3%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	2.3 ± 1.5 (4%)
Secondary sulphate	4.0 ± 2.4 (14%)	2.2 ± 1.1 (12%)	4.9 ± 3.9 (15%)	1.5 ± <1 (3%)	<1 ± <1 (<1%)	3.5 ± 1.8 (6%)
Construction Dust	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	3.3 ± 3.9 (6%)	1.2 ± 2 (2%)	3.4 ± 3.1 (5%)
DG set	*ND*	<1 ± <1 (<1%)	<1 ± <1 (<1%)	1 ± <1 (2%)	<1 ± <1 (1%)	<1 ± <1 (<1%)
Coal combustion	*ND*	*ND*	*ND*	*ND*	*ND*	<1 ± 2.2 (1%)
Unaccounted	2.1 ± 1.9 (7%)	<1 ± <1 (5%)	2.5 ± 2.6 (7%)	10.2 ± 6.9 (17%)	6.1 ± 5.3 (12%)	2.7 ± 4.1 (4%)

(**ND* = Not Detected)

4.4.6 Central Silk Board (CSB)

The CSB station represents a kerbside location as per CPCB sampling location selection guidelines. In the vicinity of this site, there are numerous traffic junctions, residential apartments, commercial complexes, restaurants, etc., indicating a wide range of sectoral sources of pollution over the site.

On analysing the seasonal variation of $PM_{2.5}$ sources, it was observed that the transportation sector contribution ranged between 50% in monsoon and 53% in winter. Similarly, the seasonal variation of transport sector share in PM_{10} ranged between 12% in monsoon and 21% in winter. Although there are several flyovers near the site, traffic congestion was observed in most of the surrounding roads. Notably, vehicles from the southern states mostly use this route to enter Bengaluru city.

The seasonal soil-dust contribution in $PM_{2.5}$ varied between 5.5 $\mu g\ m^{-3}$ (in monsoon) and 10.0 $\mu g\ m^{-3}$ (in winter), while in PM_{10}, the variation was between 38.2 $\mu g\ m^{-3}$ (in summer) and 54.0 $\mu g\ m^{-3}$ (in winter) (Table 21). Similarly, the construction dust contribution in $PM_{2.5}$ ranged between 0.2% in summer and 0.4% in winter, while in PM_{10}, it ranged between 3% in winter and 23% in summer. During sampling period, flyover construction was ongoing, whose influence can be observed in the soil dust and construction dust share in PM.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (17% in $PM_{2.5}$; 5% in PM_{10}) during winter. High concentration of secondary aerosols during winter is due to low temperature, which favours the formation of secondary aerosols. Sources of secondary aerosols in this site are chiefly from vehicular, coal-burning in restaurants, and leaf-burning activities.

Wood burning and DG set contribution was observed in $PM_{2.5}$ and PM_{10} during all the seasons. This indicates usage of wood for cooking, burning of leaves and twigs in the roadside, and DG set usage during power cuts, respectively.

The DG set contribution to $PM_{2.5}$ was approx. 0.3% in winter and monsoon season, while in PM_{10}, it was observed between <1% in winter and 2% in summer. There are many commercial complexes, institutions, and residential apartments near the site, which use DG sets during power cuts.

Interestingly, coal combustion contribution of approx. 1% was observed in $PM_{2.5}$ and PM_{10}, indicating usage of coal in nearby areas.

Table 21: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at CSB site

Source	$PM_{2.5}$			PM_{10}		
	Summer mean concentration 38.0 µg m^{-3}	**Monsoon mean concentration 21.0 µg m^{-3}**	**Winter mean concentration 50.5 µg m^{-3}**	**Summer mean concentration 128.6 µg m^{-3}**	**Monsoon mean concentration 72.6 µg m^{-3}**	**Winter mean concentration 87.0 µg m^{-3}**
Transportation	19.8 ± 5.6 (52%)	10.5 ±8.3 (50%)	26.6 ± 10.7 (53%)	26.3 ± 8.6 (20%)	9.0 ± 7.6 (12%)	18.3 ± 6 (21%)
Wood comb.	1.3 ± <1 (3%)	1.0 ± <1 (5%)	<1 ± <1 (1%)	14.3 ± 14.9 (11%)	1.7 ± 1.2 (2%)	1.8 ± 1.9 (2%)
Soil dust	9.6 ± 4.4 (25%)	5.5 ± 2.3 (26%)	10 ± 2.6 (20%)	38.2 ± 19.8 (30%)	47.9 ± 13.1 (66%)	54 ± 20.7 (62%)
Sec. Nitrate	<1 ± <1 (1%)	<1 ± <1 (1%)	<1 ± <1 (2%)	2.1 ± 1 (2%)	<1 ± <1 (<1%)	1.5 ± <1 (2%)
Sec. Sulphate	4.6 ± 3.6 (12%)	1.6 ± 1.8 (8 %)	7.5 ± 4 (15%)	1.8 ± 2.9 (1%)	<1 ± <1 (<1%)	2.2 ± 3.1 (2%)
Const. Dust	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ±<1 (<1%)	29.2 ± 33.5 (23%)	10.1 ± 10.5 (14%)	2.3 ± 3.6 (3%)
DG set	<1 ±<1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	3.6 ± 6.5 (3%)	<1 ± <1 (<1%)	1 ± 3.2 (1%)
Coal Comb.	*ND*	*ND*	<1 ± <1 (<1%)	<1 ± <1 (0.2%)	*ND*	<1 ± 1 (<1%)
Unaccounted	1.7 ± 2.6 (5%)	1.9 ± 1.7 (9%)	3.9 ± 4.9 (8%)	12.4 ± 11.2 (10%)	3 ± 3.3 (4%)	5 ± 6.6 (6%)

(**ND* = Not Detected)

4.4.7 Govt. SKSJ Technological Institute (SKSJ)

Due to $PM_{2.5}$ instrument malfunctioning, there was no quartz sample collected from this station throughout the study period. Although PM_{10} samples were collected, due to missing of EC and OC mass concentration from $PM_{2.5}$ samples, the CMB model run could not be carried out for both $PM_{2.5}$ and PM_{10}.

4.4.8 Yeshwantpur Police Station (YPS)

The YPS station represents a kerbside location as per CPCB sampling location selection guidelines. In the vicinity of this site, there is a railway station, bus depot, numerous traffic junctions, commercial complexes, restaurants, institutions, etc., indicating a wide range of sectoral sources of pollution over the site.

On analysing the seasonal variation of $PM_{2.5}$ sources, it was observed that the transportation sector contribution ranged between 41% in winter and 49% in summer (Table 22). Similarly, the seasonal variation of transport sector share in PM_{10} ranged between 26% in monsoon and 29% in summer. Although there are several flyovers near the site, traffic congestion was observed in most of the surrounding roads.

Seasonal soil dust contribution in $PM_{2.5}$ ranged between 8.2 $\mu g\ m^{-3}$ in winter and 12.8 $\mu g\ m^{-3}$ in summer, while in PM_{10}, the range was between 31.7 $\mu g\ m^{-3}$ in monsoon and 34.1 $\mu g\ m^{-3}$ in summer. Similarly, the construction dust contribution in $PM_{2.5}$ ranged between 0.1% in monsoon and 0.6% in summer, while in PM_{10}, it ranged between 4% in monsoon and 7% in summer.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (21% in $PM_{2.5}$; 7% in PM_{10}) during winter. High concentration of secondary aerosols during winter is due to low temperature, which favours the formation of secondary aerosols. Sources of secondary aerosols in this site are chiefly from leaf-burning activities besides the railway tracks and vehicular emissions.

Wood-burning and DG set contribution was observed in $PM_{2.5}$ and PM_{10} during all the seasons. This indicates usage of wood for cooking, burning of leaves and twigs in the roadside, and DG set usage during power cuts, respectively.

Interestingly, coal combustion contribution of approx. 2% was observed in $PM_{2.5}$ and PM_{10}, indicating usage of coal in nearby areas.

Table 22: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at YPS site

Source	$PM_{2.5}$			PM_{10}		
	Summer mean concentration 44.9 µg m^{-3}	**Monsoon mean concentration 25.6 µg m^{-3}**	**Winter mean concentration 33.9 µg m^{-3}**	**Summer mean concentration 85.8 µg m^{-3}**	**Monsoon mean concentration 62.2 µg m^{-3}**	**Winter mean concentration 75.7 µg m^{-3}**
Transportation	21.8 ± 5.4 (49%)	11.7 ± 4.7 (46%)	13.9 ± 5.4 (41%)	24.8 ± 10.6 (29%)	16.1 ± 10.3 (26%)	20.3 ± 6.7 (27%)
Wood comb.	<1 ± 1 (2%)	1.4 ± <1 (6%)	1.3 ± <1 (4%)	6.7 ± 6.2 (8%)	1.8 ± 2.2 (3%)	4.3 ± 3.1 (6%)
Soil dust	12.8 ± 4.9 (28%)	8.4 ± 3 (33%)	8.2 ± 1.3 (24%)	34.1 ± 15.4 (40%)	31.7 ± 13.6 (51%)	39.2 ± 14.9 (52%)
Sec. Nitrate	<1 ± <1 (<1%)	<1 ± <1 (<1%)	1.4 ± <1 (4%)	<1 ± <1 (1%)	<1 ± <1 (<1%)	1.9 ± <1 (2%)
Sec. Sulphate	6.9 ± 4 (15%)	2 ± 1.9 (8%)	5.6 ± 3.4 (17%)	1.6 ± 1 (2%)	<1 ± <1 (<1%)	3.5 ± 3.1 (5%)
Const. Dust	<1 ± <1 (%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	5.7 ± 6.4 (7%)	2.4 ± 2.7 (4%)	3.1 ± 3.5 (4%)
DG set	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	1.2 ± 1.1 (1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)
Coal Comb.	<1 ± <1 (<1%)	*ND*	*ND*	1.8 ± 1.5 (2%)	1.3 ± 1.7 (2%)	<1 ± 1 (<1%)
Unaccounted	1.3 ± 2.2 (3%)	1.3 ± 1.7 (5%)	3.1 ± 2.3 (9%)	8.6 ± 6.5 (10%)	7.6 ± 6.4 (12%)	2.7 ± 5.2 (3%)

(**ND* = Not Detected)

4.4.9 AMCO Batteries (AMCO)

The AMCO station represents a kerbside location as per CPCB sampling location selection guidelines. In the vicinity of this site, there is a toll gate, bus stand, and numerous traffic junctions, low- and middle-income houses, restaurants, packaging industries, etc., indicating a wide range of sectoral sources of pollution over the site.

On analysing the seasonal variation of $PM_{2.5}$ sources, it was observed that the transportation sector contribution ranged between 39% in winter and 54% in summer. Similarly, the seasonal variation of transport sector share in PM_{10} ranged between 14% in monsoon and 34% in summer. Although the road network has been widened in the recent past, traffic congestion was observed in most of the surrounding roads. Notably, heavy vehicles were observed frequently, besides two- and four-wheelers.

The seasonal soil-dust contribution to $PM_{2.5}$ varied between 7.4 in monsoon and 8.4 $\mu g\ m^{-3}$ in summer, while in case of PM_{10}, the variation was between 35.5 $\mu g\ m^{-3}$ in summer and 40.5 $\mu g\ m^{-3}$ in winter (Table 23). Similarly, the construction-dust contribution to $PM_{2.5}$ ranged between 0.1% (in summer) and 0.3% (in winter), while for PM_{10}, it ranged between 6% (in summer) and 12% (in monsoon). Considerable source contribution from soil and construction dust during all the seasons indicate presence of source activities throughout the year.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (21% in $PM_{2.5}$; 13% in PM_{10}) during winter. High concentration of secondary aerosols during winter is due to low temperature which favours the formation of secondary aerosols. Sources of secondary aerosols in this site are chiefly from vehicular, coal-burning in restaurants, and leaf-burning activities.

Wood burning and DG set contribution was observed in $PM_{2.5}$ and PM_{10} during all the seasons. This indicates usage of wood for cooking, burning of leaves and twigs in the roadside, and DG set usage during power cuts, respectively.

Interestingly, coal combustion was observed during all seasons for PM_{10}, monsoon and winter for $PM_{2.5}$. The Emission Inventory Study by CSTEP (2022) reported similar observation around this ward. This indicates coal usage in the slums and restaurants for cooking.

Table 23: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at AMCO site

Source	$PM_{2.5}$			PM_{10}		
	Summer mean concentration 37.5 µg m^{-3}	**Monsoon mean concentration 27.9 µg m^{-3}**	**Winter mean concentration 35.3 µg m^{-3}**	**Summer mean concentration 91.5 µg m^{-3}**	**Monsoon mean concentration 77.7 µg m^{-3}**	**Winter mean concentration 84.1 µg m^{-3}**
Transportation	20.1 ± 9 (54%)	13.8 ± 4.2 (50%)	13.7 ± 4.5 (39%)	31 ± 6.9 (34%)	11.3 ± 10.5 (14%)	13 ± 9.8 (15%)
Wood comb.	1.3 ± <1 (4%)	<1 ± <1 (3%)	2.1 ± 1.3 (6%)	4.4 ± 3.6 (5%)	5.3 ± 4.8 (7%)	2 ± 3.5 (2%)
Soil dust	8.4 ± 1.6 (22%)	7.4 ± 3.3 (26%)	9.4 ± 2.5 (26%)	35.5 ± 6.9 (39%)	39.3 ± 11.8 (51%)	40.5 ± 15.1 (48%)
Sec. Nitrate	<1 ± <1 (1%)	<1 ± <1 (2%)	1.4 ± <1 (4%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	3.6 ± 2.2 (4%)
Sec. Sulphate	5.9 ± 2.7 (16%)	2.4 ± 1.2 (8%)	5.8 ± 3.9 (16%)	1.5 ± 1.5 (2%)	<1 ± <1 (<1%)	7 ± 3.6 (8%)
Const. Dust	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	5.1 ± 7.3 (6%)	9.5 ± 7.3 (12%)	6.8 ± 4.7 (8%)
DG set	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	2.3 ± 1.3 (2%)	1.4 ± 2.2 (2%)	<1 ± <1 (<1%)
Coal Comb.	*ND*	<1 ± <1 (2%)	<1 ± <1 (1%)	1.6 ± 4.9 (2%)	<1 ± 1.9 (<1%)	2.7 ± 5.8 (3%)
Unaccounted	1.1 ± 1.7 (17%)	2.1 ± 1.6 (11%)	2.2 ± 2.5 (21%)	9.3 ± 7.9 (10%)	9.2 ± 8.5 (12%)	8.1 ± 8.7 (10%)

(**ND* = Not Detected)

4.4.10 Export Promotion Industrial Park (ITPL)

The ITPL station represents an industrial location as per CPCB sampling location selection guidelines. In the vicinity of this site, there are several engineering works industries, packaging industries, residential apartments, restaurants, business parks, etc., indicating a wide range of sectoral sources of pollution over the site.

On analysing the seasonal variation of $PM_{2.5}$ sources, it was observed that the transportation sector contribution ranged between 37% (in winter) and 50% (in summer). Similarly, the seasonal variation of transport sector share in PM_{10} ranged between 11% in monsoon and 22% in summer. Although the road network has been widened in the recent past, traffic congestion was observed in most of the surrounding roads. Notably, goods transport vehicles were observed frequently, besides two- and four-wheelers.

The seasonal soil-dust contribution in $PM_{2.5}$ varied between 7.2 in monsoon and 10.9 $\mu g\ m^{-3}$ in summer, while in case of PM_{10}, the variation was between 35.0 $\mu g\ m^{-3}$ in summer and 47.5 $\mu g\ m^{-3}$ in monsoon (Table 24). Similarly, the construction dust contribution in $PM_{2.5}$ ranged between 0.1% in summer and 0.3% in winter, while in PM_{10}, it ranged between 6% in summer and 12% in monsoon. Significant source contribution from soil and construction dust was observed during all the seasons. This is attributed chiefly to the construction of a metro line, which was in progress near the site during the sampling period.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (21% in $PM_{2.5}$; 13% in PM_{10}) during winter. High concentration of secondary aerosols during winter is due to low temperature, which favours the formation of secondary aerosols. Sources of secondary aerosols in this site are chiefly from vehicular, coal-burning in restaurants, and leaf-burning activities.

Wood-burning and DG set contribution was observed in $PM_{2.5}$ and PM_{10} during all the seasons. This indicates usage of wood for cooking, burning of leaves and twigs in the roadside, and DG set usage during power cuts, respectively.

Interestingly, coal combustion was observed during all seasons for PM_{10}, monsoon and winter for $PM_{2.5}$. The Emission Inventory Study also substantiated similar observation around this ward (CSTEP, 2022). This indicates coal usage in the restaurants for cooking.

Table 24: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at ITPL site

Source	$PM_{2.5}$			PM_{10}		
	Summer mean concentration 33.3 µg m^{-3}	**Monsoon mean concentration 22.7 µg m^{-3}**	**Winter mean concentration 34.9 µg m^{-3}**	**Summer mean concentration 98.4 µg m^{-3}**	**Monsoon mean concentration 71.9 µg m^{-3}**	**Winter mean concentration 81.6 µg m^{-3}**
Transportation	16.7 ± 2.7 (50%)	11 ± 3.4 (48%)	13 ±6 (37%)	21.3 ± 12.2 (22%)	8.2 ± 2.1 (11%)	10.6 ± 4.9 (13%)
Wood comb.	1.6 ± <1 (5%)	1.1 ± <1 (5%)	1 ± <1 (3%)	15.2 ± 1.2 (15%)	6 ± 5.2 (8%)	10.3 ± 5 (13%)
Soil dust	10.9 ± 3.4 (33%)	7.2 ± 3.5 (32%)	10.1 ± 2.3 (29%)	35 ± 21.8 (36%)	47.5 ± 18.1 (66%)	47.2 ± 12.9 (58%)
Sec. Nitrate	<1 ± <1 (2%)	<1 ± <1 (2%)	1.4 ± <1 (4%)	2.7 ± 1.8 (3%)	<1 ± <1 (<1%)	2.6 ± <1 (3%)
Sec. Sulphate	2.8 ± 2.2 (8%)	2.1 ± 1.5 (9%)	6.5 ± 4.2 (19%)	2.2 ± 1.8 (2%)	1 ± <1 (1%)	4.8 ± 3.3 (6%)
Const. Dust	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	15.8 ± 17.8 (16%)	2.1 ± 2.8 (3%)	1.6 ± 2.6 (2%)
DG set	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	*ND*	<1 ± 1.8 (1%)	<1 ± <1 (<1%)
Coal Comb.	*ND*	<1 ± <1 (<1%)	<1 ± <1 (<1%)	*ND*	<1 ± <1 (<1%)	*ND*
Unaccounted	<1 ± <1 (<1%)	<1 ± <1 (2%)	2.2 ± 2.6 (6%)	5.9 ± 10.7 (6%)	5.3 ± 6.9 (7%)	4.2 ± 4.8 (5%)

(**ND* = Not Detected)

4.4.11 SWAN Silk (SWAN)

The SWAN site represents a kerbside location as per CPCB sampling location selection guidelines. This site is located in Peenya industrial area, which is considered as one of the largest industrial areas in South-East Asia. Notably, there are electroplating, galvanising, textile dyeing, garment washing, lead processing, spray painting, pharmaceutical industries, etc., which can elevate the PM levels.

On analysing the seasonal variation of $PM_{2.5}$ sources, it was observed that the industrial sector contribution was high during winter (32%) and low during summer (26%) in $PM_{2.5}$, while in PM_{10}, it ranged between 3% in winter and 7% in summer (Table 25). For detecting the industrial emissions, fuel oil combustion-source profile was used, as industries use heavy fuel oil for operations, the emissions are detected using this source profile.

The major contribution to $PM_{2.5}$ levels came from the transportation sector, which ranged between 29% in winter and 42% in summer. Similarly, the seasonal variation of transport sector share in PM_{10} ranged between 26% in winter and 32% in summer. Notably, movement of transport vehicles that carry industrial raw material and finished products were observed frequently in the area.

The seasonal soil-dust contribution in $PM_{2.5}$ ranged between 6.8 μg m^{-3} in winter and 7.8 μg m^{-3} in summer; similarly, in PM_{10}, the range was between 34.1 μg m^{-3} in winter and 38.0 μg m^{-3} in summer. The construction dust contribution in $PM_{2.5}$ ranged between 0.1% in summer and 0.4% in winter; likewise, in PM_{10}, it ranged between 0.2% in summer and 7% in winter. This denotes continuous construction activities in the vicinity of the site.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (15% in $PM_{2.5}$; 12% in PM_{10}) during summer. Sources of secondary aerosols in this site are chiefly from industrial, vehicular, coal-burning in restaurants, and leaf- and waste-burning activities.

Interestingly, DG set contribution was observed in $PM_{2.5}$ and PM_{10} during the sampling seasons. This indicates usage of DG sets in industrial units. CSTEP's Emission Inventory Study also indicates high usage of DG sets in this area (CSTEP, 2022).

Table 25: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at SWAN site

Source	$PM_{2.5}$		PM_{10}	
	Summer mean concentration 57.7 µg m^{-3}	**Winter mean concentration 36.2 µg m^{-3}**	**Summer mean concentration 119.0 µg m^{-3}**	**Winter mean concentration 70.0 µg m^{-3}**
Transportation	24.3 ± 4.5 (42%)	10.4 ± 3.2 (29%)	38 ± 2.7 (31%)	17.8 ± 2.1 (25%)
Wood comb.	1.7 ± <1 (3%)	1.2 ± <1 (3.4%)	*ND*	2 ± 4.1 (2.9%)
Soil dust	7.8 ± 2.4 (13%)	6.8 ± 1.1 (19%)	38 ± <1 (32%)	34.1 ± 9.8 (49%)
Sec. Nitrate	2.3 ± <1 (4%)	1.2 ± <1 (3%)	4.8 ± 1.4 (4%)	2.3 ± <1 (3.4%)
Sec. Sulphate	6.3 ± 1.8 (11%)	1.5 ± 3 (4.2%)	9 ± 2.2 (7.5%)	5.6 ± 2 (8.0%)
Const. Dust	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	4.8 ± 2.5 (7%)
DG set	<1 ± <1 (<1%)	<1 ± <1 (<1%)	3.3 ± 4.4 (3%)	<1 ± <1 (<1%)
Coal Comb.	*ND*	<1 ± <1 (1%)	*ND*	*ND*
FO Comb.	14.8 ± 1.3 (26%)	11.7 ± 6.8 (32%)	8.1 ± <1 (7%)	2.4 ± 2.4 (3%)
Unaccounted	*ND*	2.0 + 3.2 (6%)	17 ± 8.1 (14%)	<1 ± 1.3 (<1%)

(**ND* = Not Detected)

4.4.12 Urban Eco Park (UEP)

The UEP station represents an industrial location as per CPCB sampling location selection guidelines. This site is located in Peenya industrial area, which has heterogeneous industrial activities, commercial complexes, etc.

On analysing the seasonal variation of $PM_{2.5}$ sources, it was observed that the industrial sector contribution was high during winter (23%) and low during monsoon (11%) in $PM_{2.5}$, while it was 2% in winter and 7% in summer for PM_{10} (table 26). High percentage share in fine size fraction ($PM_{2.5}$) compared to coarse size fraction (PM_{10}) denotes the smaller size characteristics of emissions from the industrial operations.

Transportation share was maximum in $PM_{2.5}$, which ranged from 34% in winter to 54% in summer, while in PM_{10}, it ranged from 17% in winter to 25% in summer. Notably, movement of heavy vehicles that transport industrial raw material and finished products was observed frequently in the area.

Seasonal soil dust contribution in $PM_{2.5}$ ranged between 5.9 μg m^{-3} in summer and 7.4 μg m^{-3} in monsoon, while in PM_{10}, the range was between 35.3 μg m^{-3} in winter and 50.8 μg m^{-3} in summer. The construction dust contribution in $PM_{2.5}$ ranged between 0.1% in summer and 0.4% in winter; similarly, in PM_{10}, the range was between 2% in summer and 13% in winter. This denotes continuous construction activities in the vicinity of the site.

Wood burning and DG set contribution was observed in $PM_{2.5}$ and PM_{10} during all the seasons. This indicates usage of wood for cooking, burning of leaves and twigs in the roadside, and DG set usage during power cuts, respectively. The Emission Inventory Study also points to high usage of DG sets in this area (CSTEP, 2022).

Interestingly, coal combustion was observed during winter seasons in $PM_{2.5}$ and PM_{10}. This indicates substantial coal usage during winter season. However, to exactly point out the source of coal combustion, further research is needed.

Table 26: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at UEP site

Source	$PM_{2.5}$			PM_{10}		
	Summer mean concentration 42.3 µg m^{-3}	**Monsoon mean concentration 24.3 µg m^{-3}**	**Winter mean concentration 37.4 µg m^{-3}**	**Summer mean concentration 82.0 µg m^{-3}**	**Monsoon mean concentration 86.0 µg m^{-3}**	**Winter mean concentration 88.6 µg m^{-3}**
Transportation	22.5 ± 7.9 (53%)	10.7 ± 2.7 (44%)	12.7 ± 4.6 (34%)	20.6 (25%)	16.6 (19%)	15.3 ± 8.7 (17 %)
Wood comb.	2.4 ± 1.5 (6%)	*ND*	1.4 ± 1 (4%)	*ND*	1.1 (1%)	8.3 ± 5.9 (9%)
Soil dust	5.9 ± <1 (14%)	7.4 ± 3.5 (31%)	7.1 ± 4.6 (19%)	50.8 (62%)	45.2 (53%)	35.3 ± 10.2 (40%)
Sec. Nitrate	1.2 ± <1 (3%)	<1 ± <1 (2%)	1.4 ± 1 (4%)	*ND*	*ND*	<1 ± 1.6 (<1%)
Sec. Sulphate	3.6 ± 3.1 (9%)	1 ± 1 (4%)	2 ± 2.8 (5%)	2.8 (3%)	2.7 (3%)	8.2 ± 2.6 (9%)
Const. Dust	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	1.3 (2%)	8.2 (10%)	11.3 ± 7.5 (13%)
DG set	<1 ± <1 (1%)	<1 ± <1 (2%)	<1 ± <1 (<1%)	<1 (<1%)	<1 (<1%)	<1 ± <1 (<1%)
Coal Comb.	*ND*	*ND*	<1 ± <1 (<1%)	*ND*	*ND*	1.6 ± 2.5 (1.8%)
FO Comb.	5.2 ± 2.9 (12%)	2.6 ± 2.6 (11%)	8.6 ± 5.3 (23%)	5.6 (7%)	*ND*	2 ± 2.8 (2%)
Unaccounted	<1 ± <1 (1%)	1.3 ± <1 (5%)	3.2 ± 3 (9%)	*ND*	11.5 (13%)	5.5 ± 7 (2%)

(**ND* = Not Detected)

4.4.13 Rail Wheel Factory (RWF)

The RWF station represents an industrial location as per CPCB sampling location selection guidelines. In the vicinity of this site, there is a bus depot, state power corporation industry, and Yelahanka New Town (an established locality having residential apartments, educational institutions, hospitals shopping complexes, restaurants).

Seasonal variation of $PM_{2.5}$ sources revealed major share from the transportation sector, which ranged between 18% in winter and 69% in summer (Table 27). As for PM_{10}, it ranged between 9% in winter and 21% in monsoon. Notably, continuous movement of vehicles was observed on National Highway-44 (~1.7 km east of the site) that connects the airport to the city.

Seasonal soil dust contribution in $PM_{2.5}$ ranged between 3.8 μg m^{-3} in summer and 7.4 μg m^{-3} in winter, while in PM_{10}, the range was between 46.5 μg m^{-3} in monsoon and 104.7 μg m^{-3} in summer. The construction dust contribution was also found to be high in summer (1%) in $PM_{2.5}$, (0.5%) in PM_{10}. This denotes the role of summer season wind-transported soil and construction dust impacting the PM levels in site.

Secondary aerosols (secondary nitrate and sulphate) were observed to be high (25% in $PM_{2.5}$; 5% in PM_{10}) during winter. High concentration of secondary aerosols during winter is due to low temperature, which favours the formation of secondary aerosols. Sources of secondary aerosols in this site are chiefly from industrial, vehicular, and coal-burning in restaurants.

Interestingly, DG set contribution of <1% was observed in winter season in $PM_{2.5}$ and PM_{10}. This indicates considerable power cuts during winter, which prompts DG set usage.

Table 27: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) at RWF site

Source	$PM_{2.5}$			PM_{10}		
	Summer mean concentration 30.8 µg m^{-3}	**Monsoon mean concentration 28.5 µg m^{-3}**	**Winter mean concentration 25.3 µg m^{-3}**	**Summer mean concentration 132.0 µg m^{-3}**	**Monsoon mean concentration 75.0 µg m^{-3}**	**Winter mean concentration 76.8 µg m^{-3}**
Transportation	21.4 (69%)	11.3 (40%)	4.4 ± 2.8 (18%)	24.7 (19%)	15.8 (21%)	6.9 ± 4.3 (9%)
Wood comb.	<1 (1%)	1.7 (6%)	1.2 ± <1 (5%)	*ND*	*ND*	<1 ± 1.1 (<1%)
Soil dust	3.8 (12%)	5.1 (18%)	7.4 ± 3.5 (29%)	105 (79%)	46.5 (62%)	57.1 ± 8.3 (74%)
Sec. Nitrate	<1 (1%)	<1 (3%)	1.1 ± <1(4%)	1.9 (1%)	<1 (<1%)	2.7 ± 2.1 (3%)
Sec. Sulphate	2.4 (8%)	4.1 (14%)	5.1 ± 5 (20%)	*ND*	*ND*	1.1 ± 1.4 (1%)
Const. Dust	<1 (1%)	<1 (<1%)	<1 ± <1 (<1%)	<1 (<1%)	<1 (<1%)	<1 ± <1 (<1%)
DG set	*ND*	*ND*	<1 ± <1 (<1%)	*ND*	*ND*	<1 ± <1 (<1%)
Coal Comb.	*ND*	*ND*	<1 ± 1.4 (2%)	*ND*	*ND*	*ND*
Unaccounted	2.0 (6%)	5.0 (18%)	5.2 ± 3.7 (21%)	*ND*	11.9 (16%)	7.7 ± 8 (10%)

(**ND* = Not Detected)

4.5. Comparative analysis of $PM_{2.5}$ and PM_{10} sources

4.5.1 $PM_{2.5}$

The $PM_{2.5}$ sources were compared among the sites and seasons to understand the effect of change in meteorological conditions and anthropogenic activities on the sources (Table 28).

The transportation sector share showed maximum concentration during summer in eight sites, while two other sites showed the maximum in winter. However, on calculating the difference in the summer and winter mass concentration of this source over each site, it was found that a narrow difference exists, where it was around 1.0 times in background-MADH site, while around 5 times in industrial-RWF site. This shows that there is continuous emission from the transportation sector throughout the year without any significant seasonal inclination.

Soil and construction dust contribution was high during summer in five sites, while five other sites showed a high concentration during winter. However, the difference in the summer and winter mass concentration of this source was narrow (around 1 time in residential site IGCHC to 3 times in industrial site UEP). This shows that there is continuous presence of this source, which indicates that besides wind-transported soil dust, the road dust re-suspended due to vehicular movement is prominent in the city.

Secondary aerosols concentration was high in winter at six sites, while in five other sites, summer season showed a high concentration. However, the difference in the summer and winter mass concentration of this source was narrow (around 1 times in kerbside-YPS site to 3 times in industrial-SWAN site). This shows that there is continuous presence of the source activities and favourable metrological factors that aid in formation of secondary aerosols.

Interestingly, significant seasonal difference in the source contribution from DG sets, and coal- and wood-combustion sources was not observed. This indicates the presence of activities that continuously generate these sources over the city.

Fuel-oil combustion was observed only over industrial sites (SWAN and UEP). The SWAN site showed high concentration during summer, while in UEP, high concentration was observed in winter season.

4.5.2 PM10

The PM_{10} sources were compared among the sites and seasons to understand the effect of change in meteorological conditions and anthropogenic activities on the sources (Table 29).

The transportation sector share showed the maximum concentration during summer for all the sites. However, the difference in the summer and winter mass concentration of this source over every site was narrow (around 1.1 times in sensitive-VIC site to 3.5 times in industrial-RWF site). This shows that there is continuous emission from the transportation sector throughout the year without any significant seasonal inclination.

Soil and construction-dust contribution was high during summer at five sites, while at only four sites a high concentration was observed during winter. However, the difference in the summer and winter mass concentration of this source was narrow (around 1.0 times in

residential-ITPL and SWAN site to 4 times in residential-TERI site). This shows that there is continuous presence of this source, which indicates that besides wind-transported soil dust, the road dust re-suspended due to vehicular movement is prominent in the city.

Secondary aerosols concentration was high in winter at eight sites, while it was high during summer at only two sites. However, the difference in the summer and winter mass concentration of this source ranged between 1.1 times in kerbside-CSB site and 31 times in residential-TERI site. Huge difference in the seasonal share at TERI site needs to be investigated further. Since only <7 samples were collected from TERI station, the results should be inferred accordingly.

Interestingly, no significant seasonal difference in the source contribution from DG sets was observed. This indicates frequent power cuts in the city, which lead to regular use of DG sets.

Table 28: Mass concentration of seasonal PM2.5 sources among sites

Site	Transportation			Soil + const. dust			Sec. Aerosols			DG sets			Coal + wood comb.			Fuel Oil Comb.		
	SUM	MON	WIN	SUM	MON	WIN	SUM	MON	WIN	SUM	MON	WIN	SUM	MON	WIN	SUM	MON	WIN
TERI	*NS*	8.9	8.0	*NS*	7.8	8.1	*NS*	1.8	**7.7**	*NS*	<1	*ND*	*NS*	1.1	**1.8**	*NS*	*ND*	*ND*
BPS	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
MADH	**13.6**	8.8	13.3	**12.6**	6.6	6.7	6.0	3.0	**11.5**	*ND*	<1	*ND*	1.4	1.0	**2.0**	*ND*	*ND*	*ND*
IGCHC	**17.6**	7.3	9.6	**7.2**	5.9	6.9	**6.7**	2.5	5.1	*ND*	<1	*ND*	1.7	1.3	**1.7**	*ND*	*ND*	*ND*
VICH	10.5	9.0	**13.0**	9.7	5.4	**10.5**	4.4	2.5	**5.8**	*ND*	<1	<1	**1.4**	1.1	1.3	*ND*	*ND*	*ND*
CSB	19.8	10.5	**26.6**	9.7	5.6	**10.2**	5.2	1.8	**8.5**	<1	<1	<1	**1.3**	1.0	<1	*ND*	*ND*	*ND*
SKSJ	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
YPS	**21.8**	11.7	13.9	**13.1**	8.5	8.4	**7.3**	2.4	7.1	<1	<1	<1	1.1	**1.4**	1.3	*ND*	*ND*	*ND*
AMCO	**20.1**	13.8	13.7	8.4	7.4	**9.5**	**6.3**	3.0	7.2	<1	<1	<1	1.3	1.3	**2.5**	*ND*	*ND*	*ND*
ITPL	**16.7**	11.0	13.0	**11.0**	7.3	10.2	3.5	2.6	**7.9**	<1	<1	<1	**1.6**	1.2	1.4	*ND*	*ND*	*ND*
SWAN	**24.3**	*NS*	10.4	**7.9**	*NS*	7.0	**8.6**	*NS*	2.7	<1	*NS*	<1	1.7	*NS*	**1.7**	**14.8**	*NS*	11.7
UEP	**22.5**	10.7	12.7	6.0	7.5	**7.3**	**4.9**	1.4	3.4	<1	<1	<1	**2.4**	*ND*	1.7	5.2	2.6	**8.6**
RWF	**21.4**	11.3	4.4	4.2	5.2	**7.6**	2.7	5.1	**6.2**	*ND*	*ND*	<1	<1	**1.7**	1.6	*ND*	*ND*	*ND*

Table 29: Mass concentration of seasonal PM10 sources among sites

Site	Transportation			Soil + const. dust			Sec. Aerosols			DG sets			Coal + wood comb.			Fuel Oil Comb.		
	SUM	MON	WIN	SUM	MON	WIN	SUM	MON	WIN	SUM	MON	WIN	SUM	MON	WIN	SUM	MON	WIN
TERI	**22.9**	8.2	13.5	13.8	51.9	**58.2**	<1	2.7	25.7	*ND*	*ND*	*ND*	**21.3**	5.3	2.4	*ND*	*ND*	*ND*
BPS	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
MADH	**17.3**	9.4	11.8	**51.2**	40.0	43.8	7.3	2.2	**15.0**	*ND*	<1	*ND*	**15.6**	3.8	7.8	*ND*	*ND*	*ND*
IGCHC	**15.3**	6.2	8.2	27.4	**37.7**	35.1	3.4	1.1	**5.7**	<1	<1	<1	**10.7**	2.6	6.8	*ND*	*ND*	*ND*
VICH	**10.9**	6.4	9.6	28.7	34.2	**40.0**	1.6	<1	**5.9**	1.0	<1	<1	**6.2**	<1	3.7	*ND*	*ND*	*ND*
CSB	**26.3**	9.0	18.3	**67.4**	58.0	56.3	**4.0**	<1	3.7	3.6	<1	1.0	**14.6**	1.7	2.5	*ND*	*ND*	*ND*
SKSJ	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*
YPS	**24.8**	16.1	20.3	39.9	34.2	**42.3**	2.5	<1	**5.4**	1.2	<1	<1	**8.6**	3.2	4.8	*ND*	*ND*	*ND*
AMCO	**31.0**	11.3	13.0	40.6	**48.9**	47.4	2.0	<1	**10.7**	2.3	1.4	<1	**6.1**	5.9	4.7	*ND*	*ND*	*ND*
ITPL	**21.3**	8.2	10.6	**50.9**	49.7	48.8	5.0	1.6	**7.5**	*ND*	<1	<1	**15.2**	6.1	10.3	*ND*	*ND*	*ND*
SWAN	**38.0**	*NS*	17.8	38.3	*NS*	**38.9**	**13.9**	*NS*	8.0	3.3	NS	<1	*ND*	NS	2.0	8.7	*NS*	2.4
UEP	**20.6**	16.6	15.3	**52.2**	53.5	46.6	2.8	2.7	**8.9**	<1	<1	<1	*ND*	1.1	10.0	5.6	*ND*	2.0
RWF	**24.7**	15.8	6.9	**105.3**	46.7	57.4	1.9	<1	**3.8**	*ND*	*ND*	<1	*ND*	*ND*	*ND*	*ND*	*ND*	*ND*

4.6. $PM_{2.5}$ and PM_{10} sources

Bengaluru city's urban environment is complex in terms of air-pollution sources. The variation in $PM_{2.5}$ and PM_{10} sources is distinct with respect to each land-use characteristic. Moreover, significant seasonal variations were also observed in $PM_{2.5}$ and PM_{10} levels, which are discussed in detail below.

4.6.1 Seasonal variation of $PM_{2.5}$ and PM_{10} sources

Seasonal source apportionment of $PM_{2.5}$ revealed maximum share from the transportation sector during all the seasons. This trend was observed in all sites, irrespective of the land use pattern, which signifies the extent of impact vehicular movement has on the $PM_{2.5}$ loading in the city (table 30). Following the transportation sector, soil dust contribution percentage was high in $PM_{2.5}$. The soil dust contribution includes the roadside dust and soil blown from far off distances. Interestingly, considerable contribution from this source during both summer and winter seasons, irrespective of the meteorological conditions, indicates that this component is mostly of road dust, which gets re-suspended due to vehicular movement, rather than long-range transported soil dust.

In the case of PM_{10}, the maximum share was from soil dust during all the seasons. Interestingly, the seasonal mean of soil dust concentration was observed in a narrow range (39.9 – 42.9 $\mu g\ m^{-3}$); this denotes that this component is mostly affected by anthropogenic activities such as vehicular movement rather than meteorological conditions (such as wind speed and direction), which varies with seasons. As shown in the Table 30, the soil dust contribution and transportation share were high in PM_{10} during all the seasons.

Substantiating the presence of anthropogenic contribution in the city, the secondary aerosols (Sec. Sulphate and Sec. Nitrate) were observed in all seasons, while a high percentage was observed during winter season in $PM_{2.5}$ and PM_{10}. This is due to the role of low temperature in the formation of secondary aerosols. Notably, the sources of secondary aerosols in the city are mainly from the vehicular, industrial, and leaf- and waste-burning emission.

Interestingly, sources such as DG sets and coal combustion contribution were almost similar in all the seasons. This shows the occurrence of frequent power cuts, which leads to DG set usage, and unclean fuel source for cooking activities, which leads to contribution from sources such as coal combustion.

Table 30: Seasonal variation of $PM_{2.5}$ and PM_{10} source concentration (%) over Bengaluru city

Source	$PM_{2.5}$			PM_{10}		
	Summer Conc. 38.3 µg m^{-3}	**Monsoon Conc. 23.4 µg m^{-3}**	**Winter Conc. 34.4 µg m^{-3}**	**Summer Conc. 93.9 µg m^{-3}**	**Monsoon Conc. 68.8 µg m^{-3}**	**Winter Conc. 79.9 µg m^{-3}**
Transportation	**18.8 ± 4.2 (49%)**	10.3 ± 1.8 (44%)	12.6 ± 5.7 (37%)	23 ± 7.4 (25%)	10.7 ±4 (16%)	13.2 ± 4.3 (16%)
Soil dust	**8.8 ± 2.8 (23%)**	6.4 ± 6.7 (27%)	**8.2** ±1.4 **(24%)**	**39.9 ± 23.9 (43%)**	**41.5 ± 7.1 (60%)**	**42.9 ± 9.4 (53%)**
Sec. Nitrate.	<1 ± <1 (2%)	<1 ± <1 (2%)	**1.2 ± <1 (4%)**	1.9 ± 2.1 (2%)	<1 ± <1 (1%)	**2.5** ± <1 **(3%)**
Sec. Sulphate	4.8 ± 1.5 (13%)	2.2 ± <1 (10%)	**5.4 ± 2.4 (16%)**	2.1 ± 2.5 (2%)	<1 ± <1 (1%)	**6.5 ± 6 (8%)**
DG set	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	1.2 ± 1.4 (1%)	< 1 ± <1 (<1%)	<1 ± <1 (<1%)
Coal Comb.	<1 ± (<1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)	<1 ± <1 (1%)	<1 ± <1 (<1%)	<1 ± <1 (<1%)
FO Comb.	**2 ± (5%)**	<1 ± <1 (1%)	1.8 ± 4.4 (6%)	1.2 ± 2.9 (1%)	*ND*	<1 ± <1 (<1%)
Const. Dust	<1 ± (<1%)	<1 ± <1 (<1%)	**<1 ± <1 (<1%)**	**6.9** ± 8.6 **(7%)**	3.9 ± 3.9 (6%)	3.8 ± 3.2 (5%)
Wood comb.	1.4 ± (4%)	<1 ± <1 (4%)	**1.4 ± <1 (4%)**	**8.5 ± 7.3 (9%)**	2.6 ± 2 (4%)	4.4 ± 3.2 (5%)
Unaccounted	1.2 ± (3.3%)	2 ± < 1.4 (8.7%)	**3 ± <1 (8.8%)**	**8.3 ± 5 (9%)**	7.5 ± 3 (11%)	4.9 ± 2.7 (6.2%)

(* *ND* = Not Detected)

Fuel-oil combustion was observed during all the seasons, which indicates continuous industrial operations. However, summer and winter concentration was slightly higher than that observed during monsoon season. Less contribution during monsoon season is attributed to wet removal phenomenon and also because there was no sampling carried out over one of the industrial sites – SWAN.

Construction dust contribution was around 0.5% in $PM_{2.5}$ during all the seasons. Similarly, in PM_{10}, the source contribution from construction dust was in a narrow range (5% in winter to 7% in summer). This indicates the presence of construction activities throughout the year.

Wood-residue combustion indicates usage of wood for cooking, and leaf and twig burning on the roadsides. The percentage contribution of this source was >3% during every season, which indicates considerable biomass (wood and leaf) burning activities. Moreover, there is no seasonal inclination/skewness in this source contribution, which shows that there is no season-specific events such as kharif crop burning, rabi crop burning, etc. that impacts the PM levels in the city.

4.6.2 Site-wise variation of $PM_{2.5}$ and PM_{10} sources

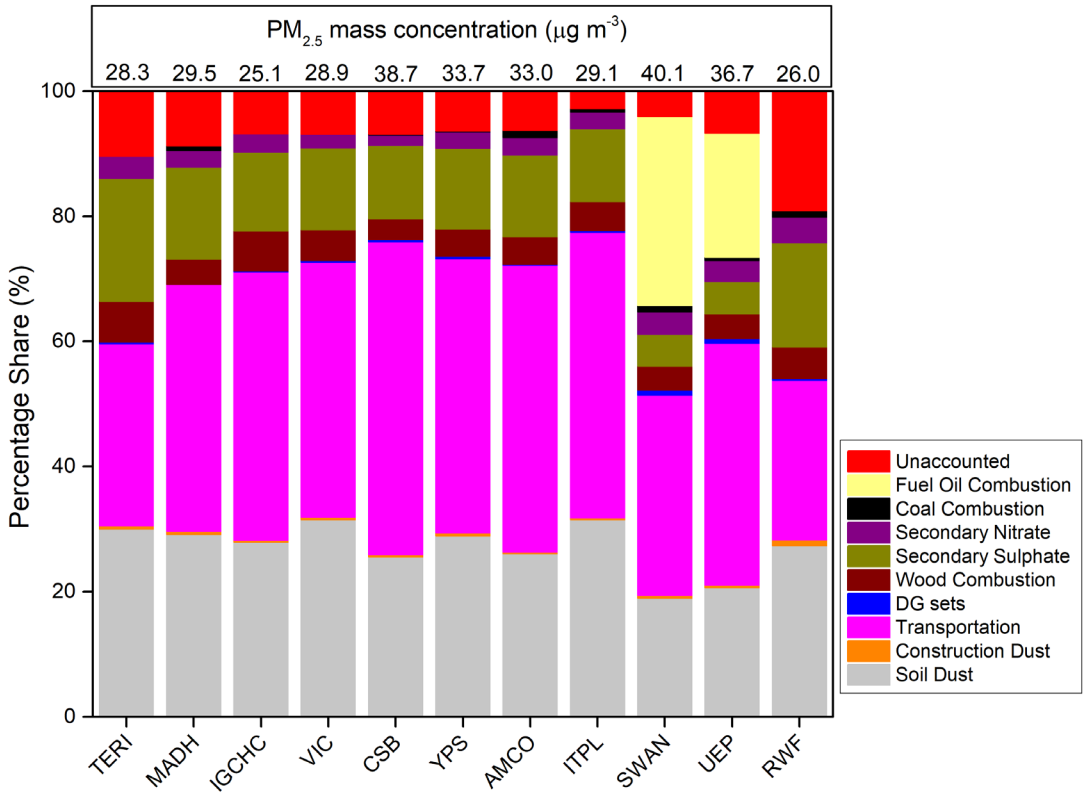


Figure 13: Site-wise variation of $PM_{2.5}$ sources (represented as µg m^{-3}, % of $PM_{2.5}$)

For all sampling sites, the transportation sector was found to contribute the maximum to the $PM_{2.5}$ mass concentration (Figure. 13). This is attributed to the increase in vehicular registrations in the last few years. According to Karnataka Transport Department (2019), an average of 1,600 vehicles, including 1,100 two-wheelers and 300 four-wheelers, are registered every day in the city.

Site-wise variation in transportation share revealed maximum percentage contribution over kerbside-CSB site (50%), where traffic flow is high even in the non-peak hours, while minimum percentage contribution from the transportation sector was observed in industrial RWF site. The RWF site is located far away from the urban centre of the city. Moreover, there is no major congested traffic junction around this site.

On analysing the relationship between length of road network in 2 km radius of each sampling site, a moderate R^2 (0.52) was observed between length of trunk and tertiary roads vs transportation share in $PM_{2.5}$. Further details are provided in Annexure III.

After transport sector, soil dust was the second-highest contributor at all the sites. The site-wise variation revealed maximum share from industrial ITPL site and sensitive VIC site. The increase in soil dust contribution over the ITPL site is attributed chiefly to the metro-line construction activity near the site. Minimum percentage contribution from this source was observed over industrial SWAN and UEP site. This can be attributed to the regular and effective cleaning of the roadside dust in the surrounding area.

Construction dust was less than 1% in all the sites, denoting less impact on $PM_{2.5}$ aerosols due to construction activities. The construction dust source marker (Ca^{2+}) exist mostly in the PM_{10} size range, while in the $PM_{2.5}$ size range, it is less prominent.

The DG set emissions were less than 1% in all the sites; however, the industrial SWAN and UEP site showed slightly higher contribution from DG sets compared to other sites because, over these sites, the industrial units use DG sets at regular intervals for power.

Fuel-oil combustion contribution was observed only over the industrial sites such as SWAN (30%) and UEP (20%). Absence of fuel oil combustion at other industrial sites such as ITPL and RWF indicates adoption of cleaner fuel sources in the industries and presence of small-scale industries (packaging, engineering, electroplating, and others), which use little or negligible fuel for the process.

The range of secondary sulphate was between 5% and 20%, while the range of secondary nitrate was between 2% and 4%. The source of secondary aerosols can arise from anthropogenic activities such as vehicular movement, industrial operations, waste burning, etc. These aerosols are in gaseous form while released; however, due to photochemical transformation, these gaseous particles transform to particulate form and reduce the air quality.

Wood combustion was observed in all the sites where the range was between 3% and 6%, denoting usage of biomass-based fuel source. Although Bengaluru city has good coverage of LPG for domestic purpose, in economically poorer areas, there are continuing wood-burning practices (CSTEP, 2022).

Coal combustion was observed in all the kerbside and industrial locations. Notably, around 1% coal combustion contribution was observed over kerbside AMCO site, industrial RWF, and SWAN site. In the vicinity of AMCO, there are slum areas where coal might be used regularly (CSTEP, 2022); also, coal is used in hotels, bakeries, challahs, etc. In industrial sites, coal is used in some industrial processes.

The unexplained mass varied between 3% and 19%. Over the RWF site, the unexplained/unaccounted source was around 19%; this denotes the presence of considerable quantity of other sources that were not part of apportionment in this study. The unexplained mass can be of any other sources, such as vehicular non-exhaust emissions, waste burning, sea salt, electric arc furnace, steel and iron smelting, etc. Since there is no local source profile for these sources, it is challenging to quantify them.

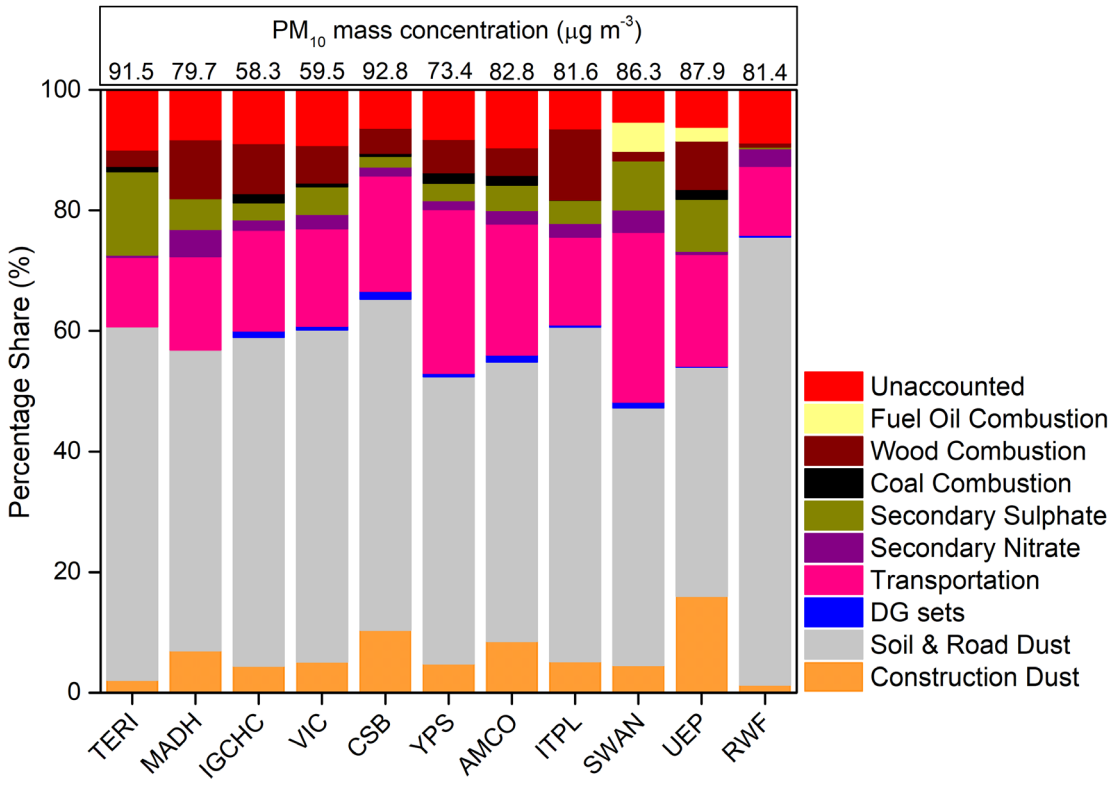


Figure 14: Site-wise variation of PM_{10} sources (represented as µg m^{-3}, % of PM_{10})

Over all the sampling sites, soil dust contributed maximum to the PM_{10} mass concentration (figure. 14). This is attributed to the vehicular-induced roadside dust re-suspension and wind-blown soil dust. Site-wise variation showed maximum contribution of soil dust from industrial RWF site (74%). The RWF site is surrounded mainly by barren lands with less vegetation cover. The crustal dust present in these areas gets re-suspended due to the action of wind and adds to the PM_{10} mass concentration. Moreover, this source category includes the contribution from the roadside dust also, which gets re-suspended due to vehicular movement. The road dust can be observed in the fringe areas of the road, which gets re-suspended due to vehicular movement.

After soil dust, the transportation sector was observed to be the second-highest contributor over all the sites. Site-wise variation revealed maximum share over industrial SWAN site (28%). Notably, movement of transport vehicles that carry industrial raw material and finished products was observed frequently in the area.

The share of construction dust varied considerably among sites, where over the industrial UEP site, 11% was observed, while over RWF, <1% was observed. This denotes continuous construction activities in the vicinity of the industrial UEP site. However, the area

surrounding RWF are mainly barren lands, agricultural lands, etc., while construction activities are less.

DG set share was almost less than 1% in most of the sites, denoting less impact on $PM_{2.5}$ aerosols due to DG set operations. Interestingly, DG set contribution was not observed over residential TERI site and background MADH site.

Fuel oil combustion was observed only over the industrial sites such as SWAN (5%) and UEP (2%). The range of secondary sulphate was between 1% and 14%, while the range of secondary nitrate was between 0.5% and 4%.

Wood combustion was observed in all the sites, where the range was between 0.6% and 12%, denoting usage of biomass-based fuel source. Coal combustion was observed over all sites except over the background site.

The unexplained mass varied between 5% and 10%. The unexplained mass can be of any other sources such as vehicular non-exhaust emissions, waste burning, sea salt, electric arc furnace, steel and iron smelting, etc. Since there is no local source profile for these sources, it is challenging to quantify them.

4.6.3 Annual $PM_{2.5}$ and PM_{10} sources in Bengaluru

Overall source apportionment of $PM_{2.5}$ revealed maximum share from the transportation sector (12.7 µg m^{-3}) (figure. 15). This is attributed to the vehicular movement and frequent traffic congestion. Following the transportation sector, soil dust contribution was high (8.0 µg m^{-3}). This is attributed to the heavy traffic flow and subsequent entrainment of road dust.

Wood combustion was observed to be 4%, denoting usage of biomass-based fuel source. This observation is supported by the Emission Inventory. CSTEP (2022) study has reported that the economically poorer areas in the city use wood as one of the fuel sources.

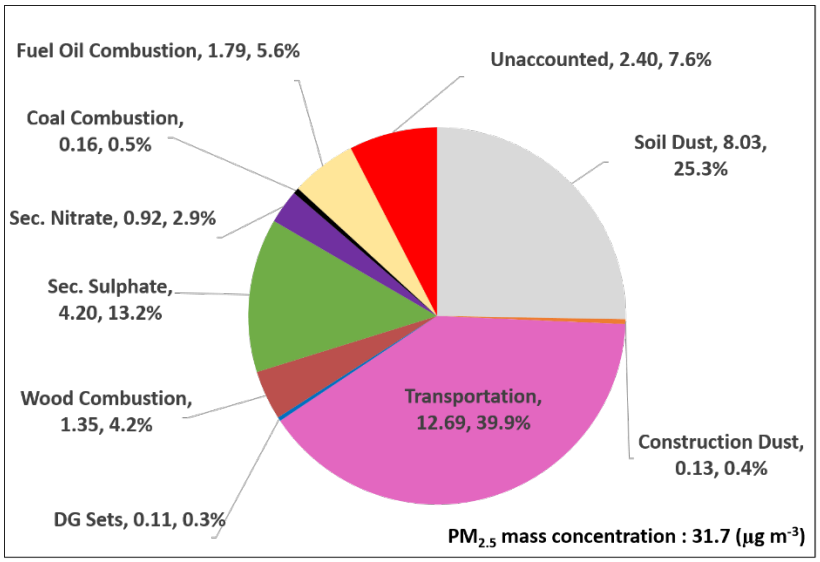


Figure 15: $PM_{2.5}$ sources (represented as µg m^{-3}, % of $PM_{2.5}$) over Bengaluru

The contribution of secondary aerosols was 16%, denoting anthropogenic activities such as vehicular movement, industrial operations, etc. The mass concentration of secondary

sulphate was around 5 times higher than the secondary nitrate mass concentration. The source of secondary sulphate is mostly from coal, wood combustion, industrial operations, etc.

The construction dust and coal combustion was observed to be <1%, denoting less contribution from these sectors. The construction dust contribution is noticeably observed in PM_{10} rather than in $PM_{2.5}$ size fraction. The contribution of DG sets is <1%, the low contribution is due to improved technology of DG sets, good quality of fuel, and stack emissions released at a higher level from ground.

Fuel-oil contribution was around 6%, denoting impact on $PM_{2.5}$ aerosols from industrial sources; however, only over Peenya Industrial area, the contribution from fuel oil combustion was observed.

The unexplained mass was 7%. The unexplained/unaccounted mass can be vehicular non-exhaust emissions, waste burning, sea salt, etc.

Overall source apportionment of PM_{10} revealed maximum share from soil dust (51%) (Figure. 16). The contribution of soil and road dust share was around five times higher for PM_{10} level than $PM_{2.5}$ level.

This is due to the fact that the source markers for soil dust mainly exist in the coarse size range rather than in the fine size range. Interestingly, the soil dust contribution in PM_{10} was reported as 51% by the earlier source apportionment study conducted over Bengaluru (TERI, 2010).

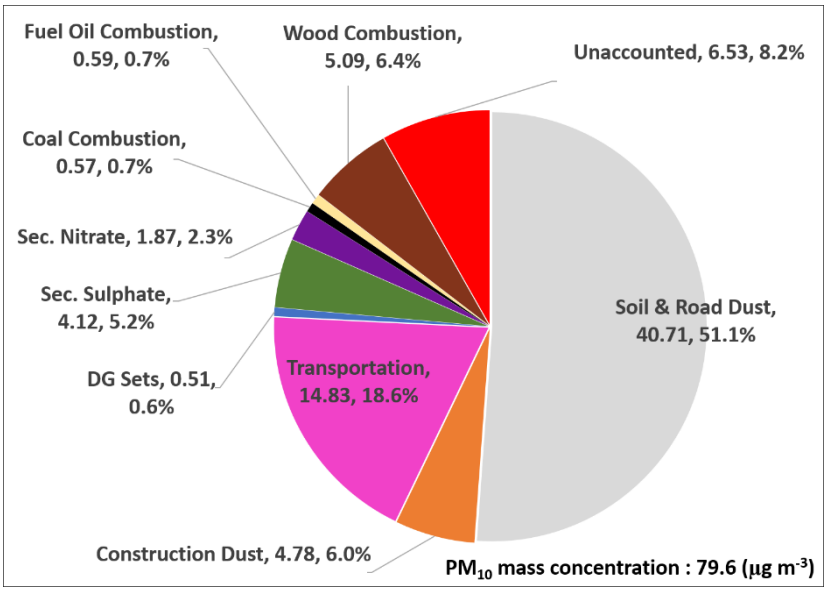


Figure 16: PM_{10} sources (represented as µg m^{-3}, % of PM_{10}) over Bengaluru

After soil-dust contribution, transportation contribution was high (14.8 µg m^{-3}). Transportation contribution in the PM_{10} fraction was almost similar to that observed in $PM_{2.5}$ fraction (12.7 µg m^{-3}). The construction dust was observed to be 6%, denoting construction

activity. The contribution of construction share was around 36 times higher in PM_{10} compared to $PM_{2.5}$, which denotes the impact of construction dust on PM_{10} aerosols. The contribution of secondary aerosols was 8%, denoting anthropogenic activities such as industrial, vehicular movement, etc.

Wood combustion was observed to be 6%, denoting usage of biomass-based fuel source. The wood combustion was observed in several economically lower strata of society. The DG set, coal combustion, and fuel oil contribution was less than 1%, denoting less impact on PM_{10} aerosols from these sources. In the earlier study, the DG set contribution was 13% (TERI, 2010), which reduced to <1% in the present study. This is attributed to the improvement in the quality of DG sets, fuel composition, and adoption of proper protocol on the height of stacks.

The industrial contribution was 4% in the earlier study (TERI, 2010), which reduced to 0.8% in the present study; this is mainly attributed to the installing of effective control measures in industrial operations.

Overall, the unaccounted for/unexplained mass was 8%. The unexplained mass can belong to any other source, such as vehicular non-exhaust emissions, waste burning, sea salt, electric arc furnace, steel and iron smelting, etc. These sources can also be quantified if there is availability of local source profiles. However, due to the absence of local source profiles, it was challenging to quantify these sources. As such, these sources were not part of apportionment under this study.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5. Findings and Recommendations

This study reports the source apportionment of $PM_{2.5}$ and PM_{10} concentrations over multiple receptor locations in Bengaluru. Besides conducting measurements of air-filter samples, the study performed a chemical analysis to quantify the composition of pollutants, and estimated their respective shares using a receptor model, to enable a thorough understanding of the polluting sources in the city.

The following key conclusions emerge from the study:

- The highest annual mean $PM_{2.5}$ concentration was observed over an industrial site UEP, and the lowest in over a sensitive site IGCHC. Overall, the highest $PM_{2.5}$ level was observed over industrial land-use sites, followed by kerbside, residential, and sensitive locations.
- The highest annual mean $PM_{2.5}$ level was observed over a kerbside site CSB, and the lowest over sensitive sites VICH and IGCHC. Overall, the highest PM_{10} concentration was observed over residential land-use category, followed by industrial, kerbside, and sensitive locations.
- In the annual average metals concentration in $PM_{2.5}$, the contribution of Mg was the highest (77%), followed by Fe (10%), indicating the presence of an aerosol source from crustal materials. In ions concentration, the contribution of SO_4^2 was the highest (43%), followed by NH_4^+ (26%), indicating the presence of sources from secondary aerosols. The annual mean OC and EC concentrations of $PM_{2.5}$ revealed that besides secondary organic aerosols, other primary sources such as vehicular, industrial, leaf, waste burning, etc. also contribute in raising OC and EC levels. The analysis of molecular markers revealed a high 1-NP concentration over industrial site UEP, which can be attributed to the high usage of DG sets and heavy diesel vehicular. Similarly, high Levoglucosan concentrations was observed over industrial site-SWAN, where roadside leaf and waste burning was observed. Interestingly, over kerbside site CSB, the concentration of Levoglucosan was observed to be low.
- In the annual average metals concentration in PM_{10}, the contribution of Mg was highest (43%), followed by Fe (26%), indicating the presence of sources from crustal material. In ions concentration, the contribution of Na^+ was highest (27%), followed by SO_4^{2-} (21%), indicating the presence of sources from road dust and secondary aerosols. Further, on comparing the mass concentration of criteria pollutants (Ni, As and Pb) with the permissible limits framed under NAAQS, it was found that the As and Ni concentrations were around 20 and 2 times higher than their respective annual permissible limit of 0.006 and 0.02 $\mu g\ m^{-3}$. Interestingly, As and Ni were found to be higher over sites that experience heavy vehicular movement, as was observed over kerbside site CSB (which has heavy vehicular movement). Notably, Pb concentration was not found to exceed the NAAQS for any of the sites, indicating the impact of phasing out of lead addition in fuel.
- The receptor model output shows the transportation sector as the main contributor to $PM_{2.5}$ levels, with a 40% share, followed by soil dust (25% share), which consists of re-suspended dust and long-range transported soil dust. Secondary particulate matter, consisting of SO_4^{2-} and NO_3^- , was found to be the next highest contributor, with a 16%

share. However, the share of secondary SO_4^{2-} was observed to be around five times more than secondary NO_3^-. This implies that coal burning is relatively high in the city. It is also because of low temperature and other meteorological conditions required for the formation of SO_4^{2-}. Fuel oil was also observed to be one of the sources of pollution, with a 6% share across the city. This fuel-oil contribution is mainly from two industrial sites, SWAN and UEP. Other sources of pollution observed are wood combustion, construction dust, diesel generator (DG) sets, and coal combustion, with a collective share of around 5% only.

- For PM_{10}, the receptor model output shows soil dust as the major contributor, with a 51% share. It is interesting to see that the concentration of soil dust in PM_{10} is five times more than that in $PM_{2.5}$. Transportation sector was found to be the next highest contributor, with a share of around 19%. The contribution of secondary particulate matter contribution was found to be 8%, followed by construction dust (6%) and wood combustion (6%). The pollution share from DG sets, coal combustion, and fuel-oil contribution was found to be less than 1%.

Prioritisation of control options and policy interventions

The study—on the basis of its findings—recommends the following control options (for several sources) and policy interventions:

Road and soil dust

Roadside and soil-dust particles constitute the largest share in PM_{10} concentrations and the second-largest share in $PM_{2.5}$ concentrations. Control of dust re-suspension requires a multipronged approach. It is imperative that an effective technique to control road dust be identified. Some of the available control options that can be considered include:

- Vacuum sweeping of dust from paved roads.
- Laying end-to-end payments with the provision of a green cover for the barren areas along the road (geoengineering), to help reduce the re-suspension of dust.
- Since the deployment of mechanical sweepers without a sound scientific study can lead to wastage of resources, it is recommended that the effectiveness of mechanical sweepers be researched to assess their suitability and operating conditions, before deployment.

Vehicular exhaust

Vehicular pollution constitutes the largest share in $PM_{2.5}$ concentrations and the second-largest share in PM_{10} concentrations. The control options that can be considered for vehicular pollution include:

- Introduction of electric vehicles (EV), with an adequate and efficient EV-charging infrastructure.
- Proper implementation of vehicle scrappage policy, along with improvements in the scrapping infrastructure and automated fitness-check centres.
- Retrofitting of diesel particulate filter (DPF) for heavy vehicles.
- Regular servicing of public transport vehicles, such as shared autos and buses, as well as heavy government vehicles such as dumper trucks, trolleys, etc.

Construction dust

Construction dust can arise not only from construction sites, but also from the vehicles that transport construction material. Therefore, it is important to keep all construction material fully covered while in transit. Further, all under-construction buildings should be covered vertically with a fine screen, and the material stored on construction sites should also be covered properly.

Besides controlling dust from construction sites, improvements (such as those given below) should be made to the Construction & Demolition(C&D) processing plants for reducing ambient PM levels:

- Including the provision of last-mile connectivity for transporting the C&D debris to the processing plant.
- Creating public awareness on the process of purchasing the re-processed bricks from the C&D processing plant.

Diesel Generator sets

DG sets should be properly maintained, with regular inspection. Concrete efforts—including those towards ensuring a regular power supply—should be made to reduce the usage of DG sets. Also, the use of solar power generators should be encouraged.

Industrial exhaust

The industrial units are mainly located in the Peenya industrial area, where the contribution of fuel oil combustion was observed over the stations located in the area. This source can be reduced by promoting alternate forms of energy and also by enabling a stringent pollution auditing system.

Wood and coal burning

To reduce pollution from combustion, LPG access should be provided to eligible households at a subsidised rate. Also, the coal used in restaurants, hotels, eateries, etc. for preparing food should be replaced by a cleaner source of energy.

Site-specific implementation plan

Site	Prominent PM Sources	Control Measures
TERI	• Soil dust • Vehicle • Wood residue comb.	• Reduce dust re-suspension by road side plantation, laying of pebbles, geo-synthetic materials to cover the open areas in road dividers and footpaths • Reduce congestion in junctions (Domlur flyover; Trinity circle); widen road network • Increase LPG connectivity; reduce leaf burning on road sides
MADH	• Soil dust • Vehicle • Wood residue comb.	• Convert unpaved to paved roads. Increase road side plantation • Increase improve last mile connectivity access to public transportation (bus & train); • Increase LPG connectivity; reduce leaf burning on road sides
IGCHC	• Soil dust • Vehicle • Wood residue comb.	• End to end pavement & training to municipal workers on effective cleaning of roads • Reduce congestion in junctions (Dairy circle); build flyovers • Increase LPG connectivity; reduce leaf burning on road sides
VICH	• Soil dust • Vehicle • Wood residue comb.	• End to end pavement & training to municipal workers on effective cleaning of roads • Widen road network; fit DPF in heavy vehicles; improve last mile connectivity to metro station • Increase LPG connectivity; reduce leaf burning on road sides
CSB	• Soil dust • Vehicle • Construction	• End to end pavement & usage of mechanical sweepers • Reduce congestion in junctions (Silk board Junction); fitting DPF in heavy vehicles • Cover construction site with tarp
YPS	• Soil dust • Vehicle • Wood residue comb.	• Reduce dust re-suspension by road side plantation, laying of pebbles, geo-synthetic materials to cover the open areas in road dividers and footpaths • Reduce congestion in junction (Yeshwantpura circle; Soap factory circle, Maramma circle) by building alternative routes; fit DPF in heavy vehicles • Reduce leaf burning on road sides and near railway tracks
AMCO	• Soil dust • Vehicle • Construction	• End to end pavement and usage of mechanical sweepers • Widen the road network; improve last mile connectivity to metro station • Covering construction site with tarp
ITPL	• Soil dust • Vehicle • Wood residue comb.	• End to end pavement & covering the metro construction sites by tarp • Widen the road network • Increase LPG connectivity; reduce leaf burning on road sides
SWAN	• Soil dust • Vehicle • Fuel Oil Comb.	• End to end pavement • Widen the road network and fit DPF in heavy vehicles • Usage of cleaner industrial fuel
UEP	• Soil dust • Vehicle • Construction	• End to end pavement • Widen the road network and fit DPF in heavy vehicles • Covering construction site with tarp
RWF	• Soil dust • Vehicle • Wood residue comb.	• End to end pavement • DPF in heavy vehicles and increase public transportation • Increase LPG connectivity; reduce leaf burning on road sides


Bengaluru

6. Way Forward

As a non-attainment city, Bengaluru ought to reduce its PM levels by 20–30% by 2024, taking 2017 as its base year. However, in order to improve the air quality, adequate knowledge of PM sources is essential. The findings of this research-based SA study can help in understanding the sources of PM, thereby aiding the formulation of effective and targeted air-pollution control measures.

Our study revealed that Bengaluru's annual PM_{10} level was around 1.2 times higher than the CPCB's limit of 60 µg m^{-3}. The primary contributing source of PM_{10} was soil and road dust, which, if controlled effectively, can reduce the PM_{10} levels by almost half. Measures like deployment of vacuum-based sweeping systems can be quite effective. However, the availability of financial resources needs to be explored before switching from manual to vacuum-based sweeping systems.

For $PM_{2.5}$, transportation was the largest contributor, which needs immediate attention due to the carcinogenic elements (Cd, Ni, and Pb) released from vehicular exhaust emissions. Steps like switching to cleaner fuels and improving the public transportation network are recommended.

Observations made on other sources (such as DG sets, construction, and wood and coal burning) at most of the sampling sites denote the need for implementing more effective control measures. Fuel-oil combustion, which is an indicator of industrial exhaust emissions, was observed only over Peenya industrial area. Promoting alternative forms of energy, while also enabling stringent pollution-auditing systems, can reduce industrial emissions.

KSPCB has already laid down 44 action points for improving the air quality in Bengaluru city. This report, by apportioning the sources of PM_{10} and $PM_{2.5}$, and examining their composition, will help further in framing targeted air-pollution control measures for the city. But while government efforts are indispensable for lowering the PM concentrations, achieving the desired goal also requires initiative and participation of the citizens. For instance, to mitigate pollution loading from waste burning, transportation, and industrial operations, active involvement of the public in adopting and implementing the control measures effectively is needed. Thus, there is a need to elicit collaborative community response that enables effective implementation of air-pollution control policies and action.

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8. Annexures

Annexure I

Figure 1: Respirable dust sampler (Envirotech APM 460DXNL) used for PM_{10} sampling

Figure 2: Fine particulate sampler (Envirotech APM 550 MFC) used for $PM_{2.5}$ sampling

Annexure II

Site-wise variation in $PM_{2.5}$ and PM_{10} levels

The $PM_{2.5}$ and PM_{10} levels over 13 sites in Bengaluru are discussed in this section. Seasonal variations, $PM_{2.5}$ to PM_{10} ratio, and the number of days that showed a concentration higher than the CPCB standard was investigated and the results are presented below:

I. TERI Office (TERI)

The study observed that the seasonal mean PM_{10} mass concentration values were around two times higher in winter (110.3 µg m^{-3}), as compared to the PM_{10} values observed during the summer season (69.7 µg m^{-3}) (Figure 3). Similarly, the seasonal mean $PM_{2.5}$ winter-season concentration values were around two times higher (34.9 µg m^{-3}) than the monsoon season (20.3 µg m^{-3}). This can be attributed to the meteorological conditions, construction, and leaf-burning activities. This was substantiated by the results of Kruskal-wallis test (non-parametric one way ANOVA), which revealed that the PM_{10} and $PM_{2.5}$ concentration levels varied significantly with the seasons ($p<0.05$).

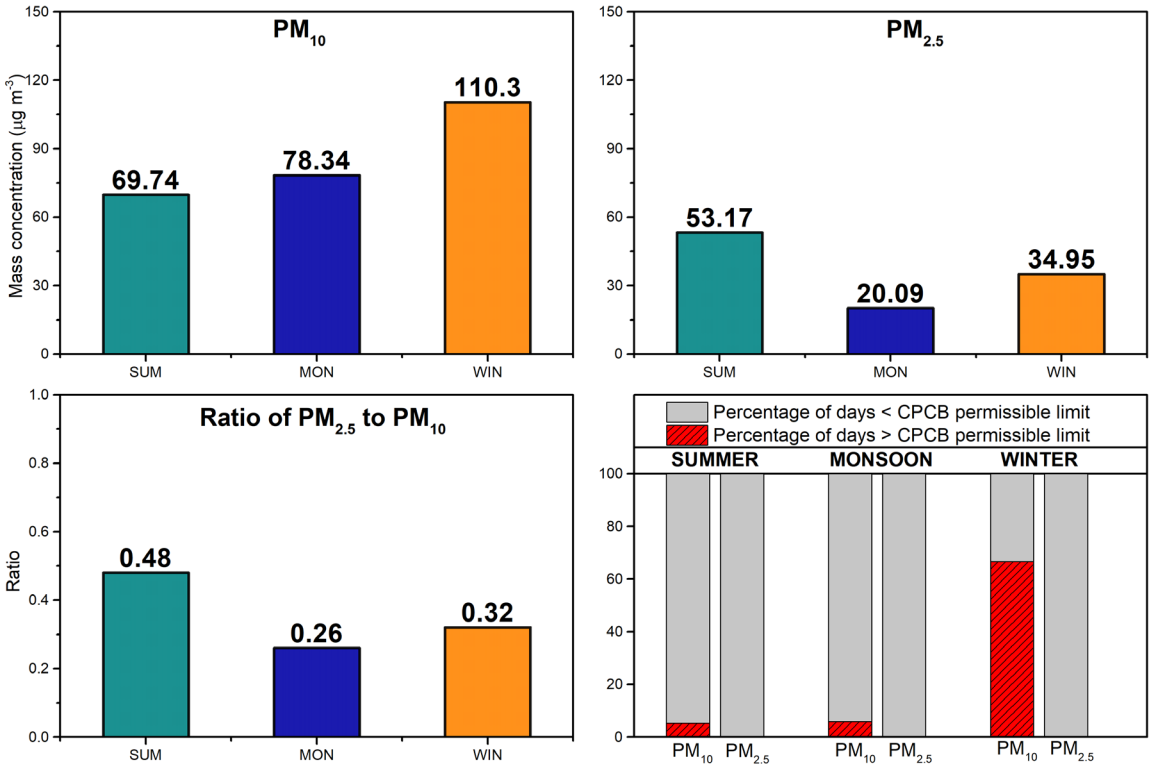

Figure 3: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at TERI

At the TERI site, during about ~32% of the sampling days, the PM_{10} mass concentration exceeded the CPCB's annual permissible limit (100 µg m^{-3}). Interestingly, during the winter season (for about 68% of the sampling days), it exceeded the CPCB's daily permissible limit (60 µg m^{-3}). Conversely, concentration values of $PM_{2.5}$ were observed to be less than the CPCB limits (60 µg m^{-3}) for all the sampling days. Furthermore, the mean ratio of $PM_{2.5}$ to PM_{10} was

observed to be 0.31, which denotes dominance of coarse size particles in the area. The reason is due to construction activities and road dust re-suspension.

II. Banaswadi Police Station (BPS)

The mean PM_{10} showed winter maximum (101.4 µg m^{-3}) and summer minimum (53.2 µg m^{-3}). The mean PM_{10} observed during winter season was around two times higher than the summer (Figure. 4). In case of $PM_{2.5}$, the summer maximum (33.0 µg m^{-3}) and monsoon minimum (24.5 µg m^{-3}) were observed. The $PM_{2.5}$ observed during summer was around 1.3 times higher than that observed during monsoon.

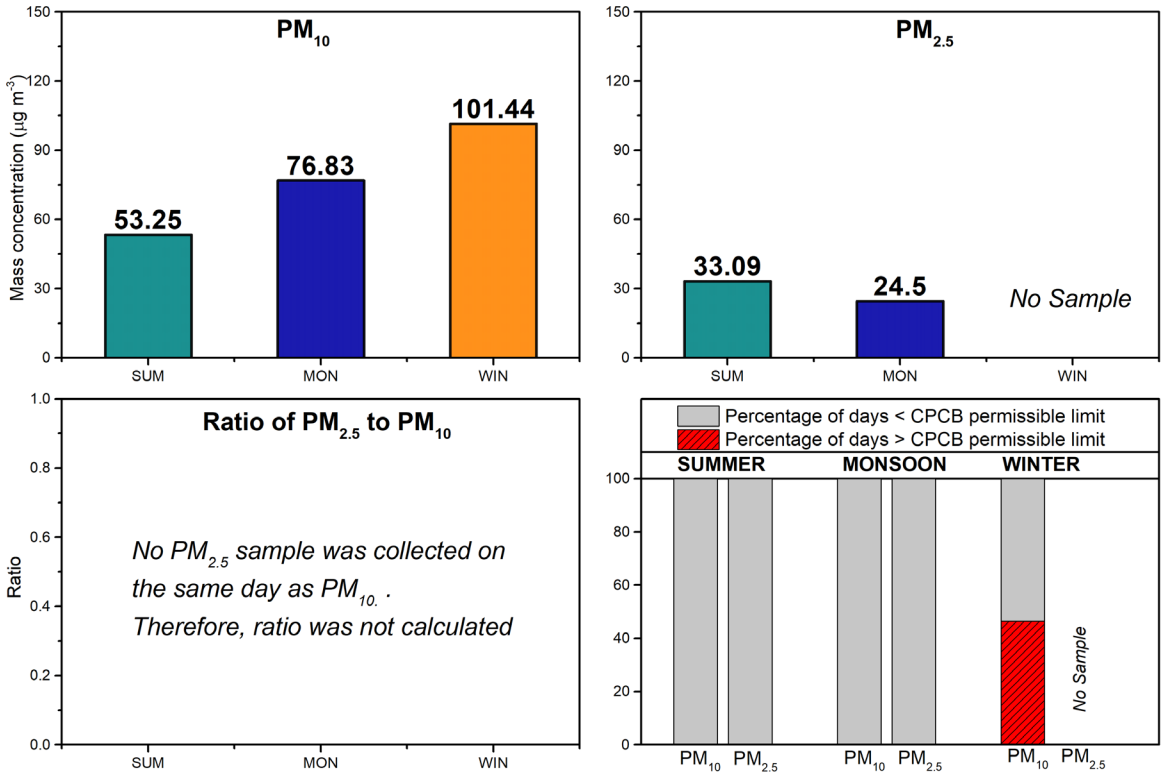

Figure 4: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at BPS

The ratio of $PM_{2.5}$ to PM_{10} could not be calculated as there was no $PM_{2.5}$ sample collected on the same day as PM_{10}.

Overall, ~28% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 46% of the sampling days during winter was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than the CPCB limit of 60 µg m^{-3}.

Results of Kruskal-wallis test revealed significant difference ($p<0.05$) in the PM_{10} with seasons, while $PM_{2.5}$ showed non-significant difference between seasons ($p>0.05$).

III. Madhavchari (MADH)

The mean PM_{10} observed during summer was maximum (102.3 µg m^{-3}) while monsoon showed the minimum (65.9 µg m^{-3}). The mean PM_{10} observed during summer was around 1.5 times higher than the monsoon (Figure 5). In case of $PM_{2.5}$, summer maximum (39.7 µg m^{-3}) and monsoon minimum (19.7 µg m^{-3}) were observed. The $PM_{2.5}$ observed during summer was around 1.3 times higher than that observed during monsoon.

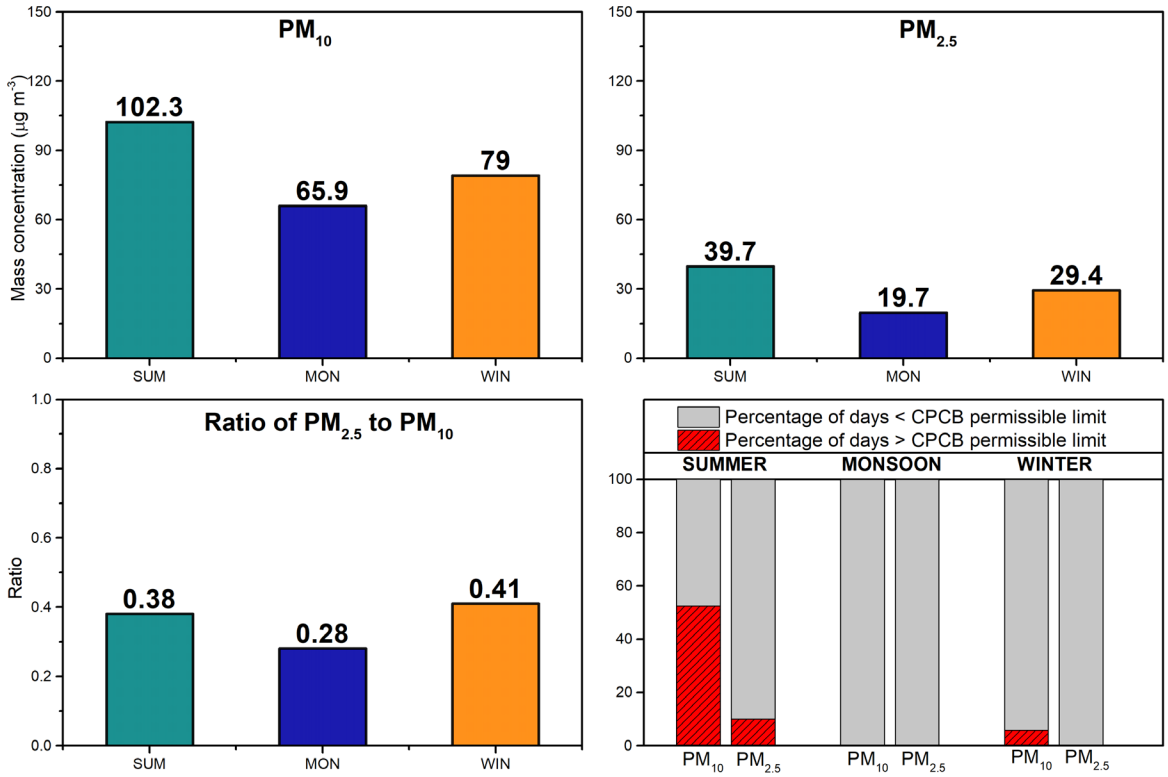

Figure 5: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at MADH

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.35, with winter showing a high ratio (0.41) followed by summer (0.38) and monsoon (0.28).

Overall, ~14% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 52% of the sampling days during summer was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than the CPCB limit of 60 µg m^{-3}.

Results of Kruskal-wallis test revealed that the PM_{10} and $PM_{2.5}$ levels varied significantly with seasons.

IV. Indira Gandhi Child Health Care (IGCHC)

The mean PM_{10} observed showed summer maximum (70.5 µg m^{-3}) and monsoon minimum (54.0 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during summer was 1.3 times higher than the monsoon (Figure. 6). In case of $PM_{2.5}$, summer maximum (31.3 µg m^{-3}) and monsoon minimum (18.58 µg m^{-3}) were observed. The $PM_{2.5}$ observed during summer was around 2 times higher than that observed during monsoon.

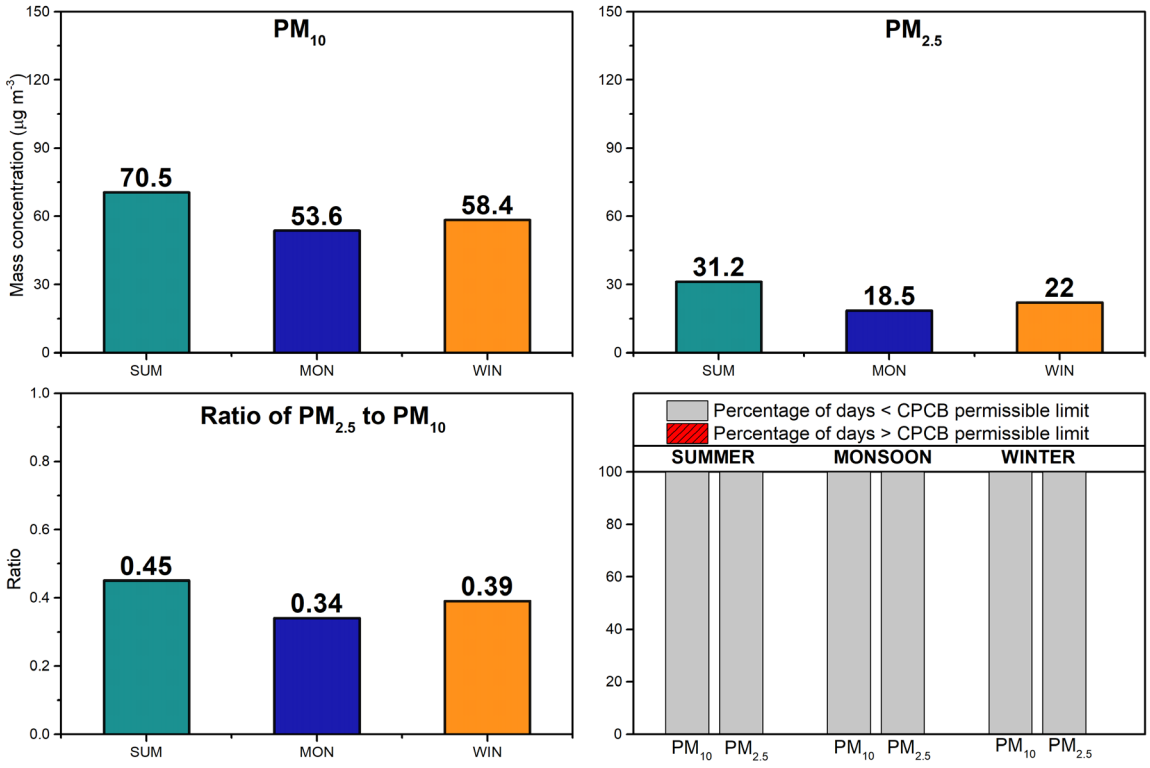

Figure 6: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at IGCHC

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.39, with summer showing a high ratio (0.45) followed by winter (0.39) and monsoon (0.34). High ratio during summer denotes dominance of coarse size particles, which is chiefly attributed to meteorological conditions such as wind speed and direction.

Overall, none of the sampling days for both PM_{10} and $PM_{2.5}$ exceeded the CPCB permissible limit. Results of Kruskal-wallis test revealed significant difference ($p<0.05$) in the PM_{10} and $PM_{2.5}$ levels between seasons.

V. Victoria Hospital (VICH)

Figure 7 shows the seasonal variations in PM, with summer maximum (68.1 µg m^{-3}) and monsoon minimum (55.4 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during summer was 1.2 times higher than in monsoon. In case of $PM_{2.5}$, summer maximum (29.8 µg m^{-3}) and monsoon minimum (19.0 µg m^{-3}) were observed. The $PM_{2.5}$ observed during summer was around 2 times higher than that observed during monsoon.

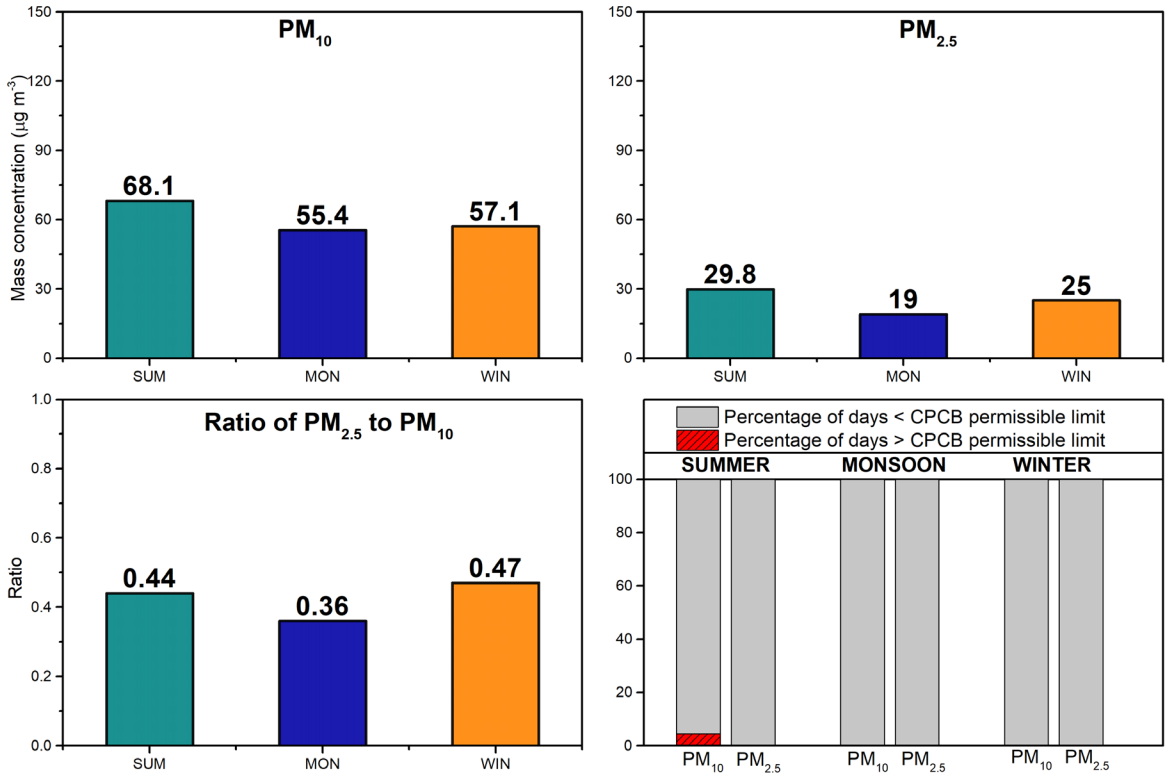

Figure 7: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at VICH

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.44, with winter showing a high ratio (0.47), followed by summer (0.44), and monsoon (0.36), when it was the minimum. A high ratio denotes a prominence of coarse size particles, which is chiefly attributed to meteorological conditions such as wind speed and direction.

Overall, ~2% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 9% of the sampling days during summer was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than the CPCB limit of 60 µg m^{-3}.

Results of Kruskal-wallis test revealed significant difference ($p<0.05$) in the PM_{10} and $PM_{2.5}$ levels between seasons.

VI. Central Silk Board (CSB)

Figure 8 shows the seasonal variations in PM, with summer maximum (121.4 µg m^{-3}) and monsoon minimum (75.6 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during summer was around two times higher than that observed during monsoon. In case of $PM_{2.5}$, summer maximum (47.3 µg m^{-3}) and monsoon minimum (24.0 µg m^{-3}) were observed. The $PM_{2.5}$ observed during summer was around two times higher than that observed during monsoon.

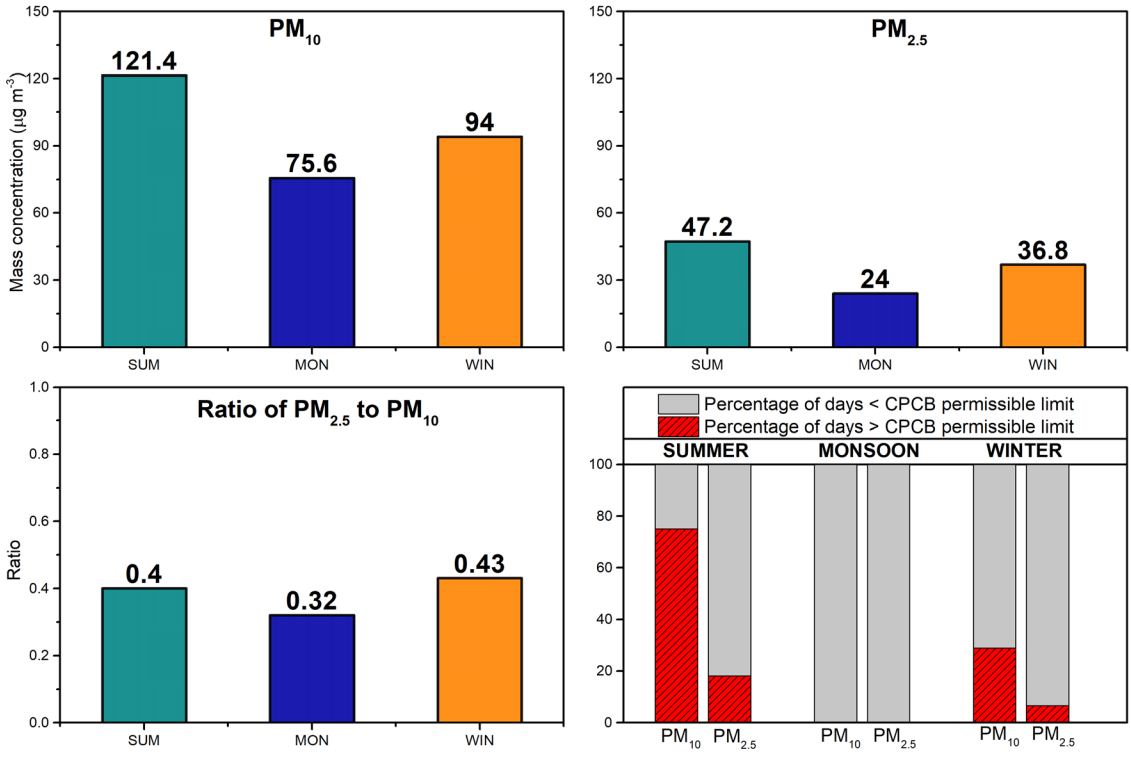

Figure 8: Seasonal variations in PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at CSB

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.39, with winter showing a high ratio (0.44) followed by summer (0.41) and minimum during monsoon. High ratio denotes dominance of coarse size particles, which is chiefly attributed to meteorological conditions such as wind speed and direction.

Overall, ~29% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 78% of the sampling days during summer was found to exceed the CPCB limit. In case of $PM_{2.5}$, 16 and 8% of sampling days during summer and winter, respectively, showed concentration higher than the CPCB limit of 60 µg m^{-3}.

Results of Kruskal-wallis test revealed significant difference ($p<0.05$) in the PM_{10} and $PM_{2.5}$ levels between seasons.

VII. Govt. SKSJ Technological Institute (SKSJ)

Figure 9 shows the seasonal variations in PM concentrations, with winter maximum (98.0 µg m^{-3}) and summer minimum (49.0 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during winter was two times higher than in summer. In case of $PM_{2.5}$, only two days of sampling was performed, with one in winter and one in monsoon. The $PM_{2.5}$ value was observed to be 26 and 13 µg m^{-3} during winter and monsoon, respectively.

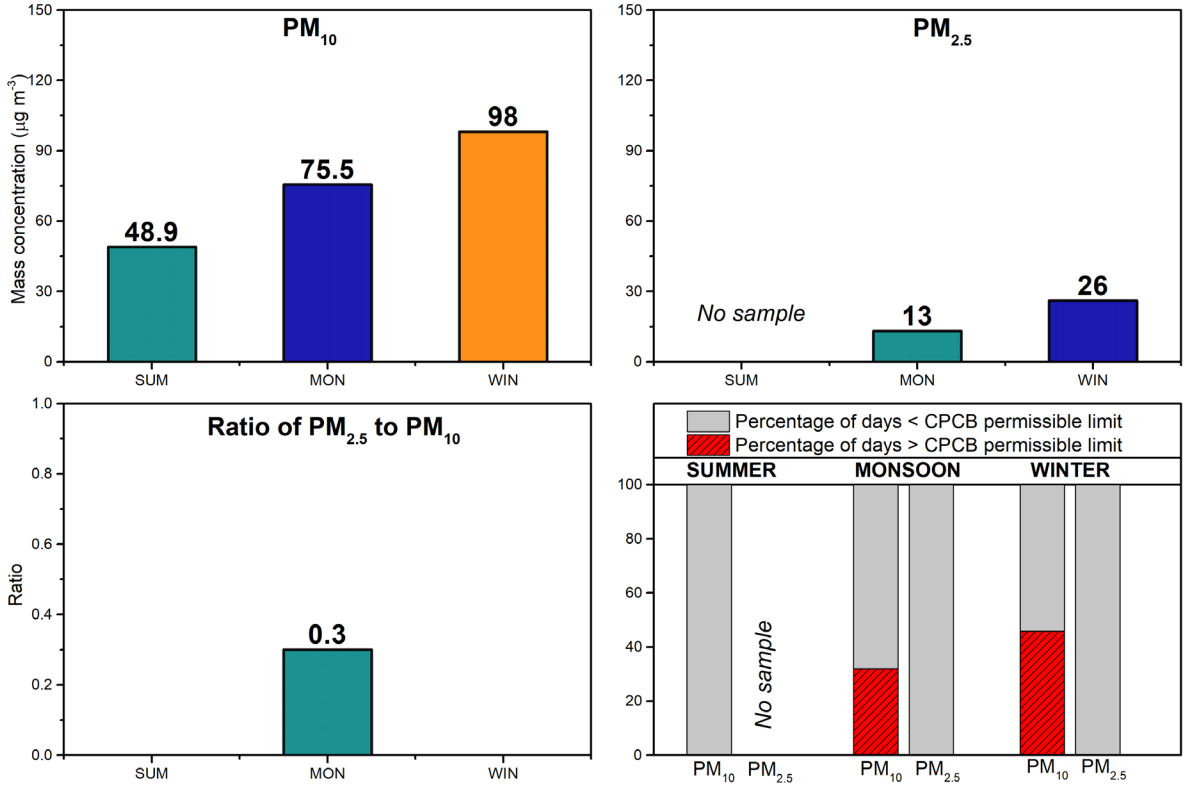

Figure 9: Seasonal variations in PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at SKSJ

The ratio of $PM_{2.5}$ to PM_{10} could be calculated only during winter, where the value was observed to be 0.30.

Overall, ~29% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 46 % of the sampling days during winter was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than the CPCB limit of 60 µg m^{-3}.

Results of Kruskal-wallis test revealed significant difference ($p<0.05$) in the PM_{10}. Non-significant difference ($p>0.05$) was observed in $PM_{2.5}$ levels between seasons.

VIII. Yeshwantpur Police Station (YPS)

Figure 10 shows the seasonal variation in PM concentrations, with summer maximum (89.1 µg m^{-3}) and monsoon minimum (66.5 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during summer was 1.3 times higher than in monsoon. In case of $PM_{2.5}$, summer maximum (39.4 µg m^{-3}) and monsoon minimum (23.7 µg m^{-3}) were observed. The summer mean was around 2 times higher than in monsoon.

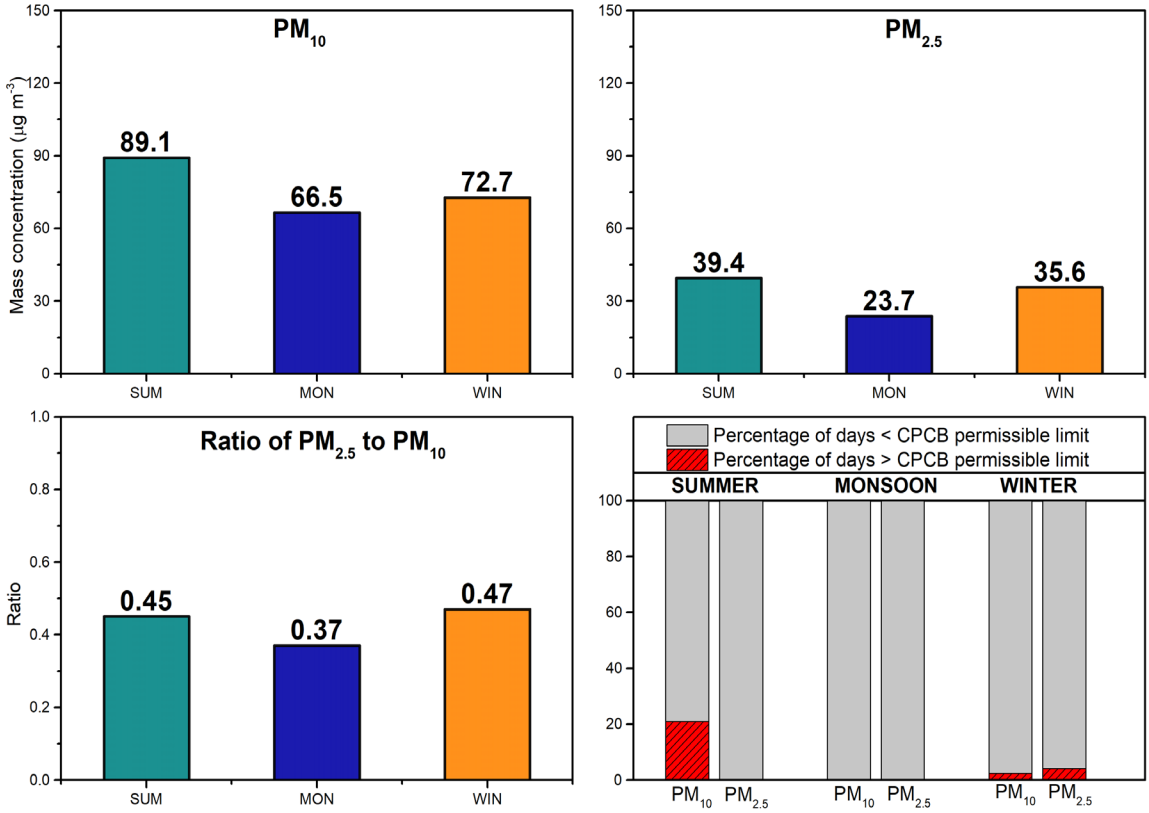

Figure 10: Seasonal variations in PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at YPS

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.45, with winter showing a high ratio (0.4) followed by summer (0.45), and monsoon (0.37), when it was minimum. A high ratio denotes the prominence/presence of coarse size particles, which is chiefly attributed to meteorological conditions such as wind speed and direction.

Overall, 6% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 22% of the sampling days during summer was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than the CPCB limit of 60 µg m^{-3} during summer and monsoon. However, during winter, only one day among 24 days was found to exceed the CPCB limit.

Results of Kruskal-wallis test revealed significant difference ($p<0.05$) in the PM_{10} and $PM_{2.5}$ levels between seasons.

IX. AMCO Batteries (AMCO)

Figure 11 shows the seasonal variations in PM, with summer maximum (98.4 µg m^{-3}) and monsoon minimum (76.7 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during summer was 1.3 times higher than in monsoon. In case of $PM_{2.5}$, summer maximum (40.7 µg m^{-3}) and monsoon minimum (26.2 µg m^{-3}) were observed. The summer $PM_{2.5}$ was 1.5 times higher than that of monsoon.

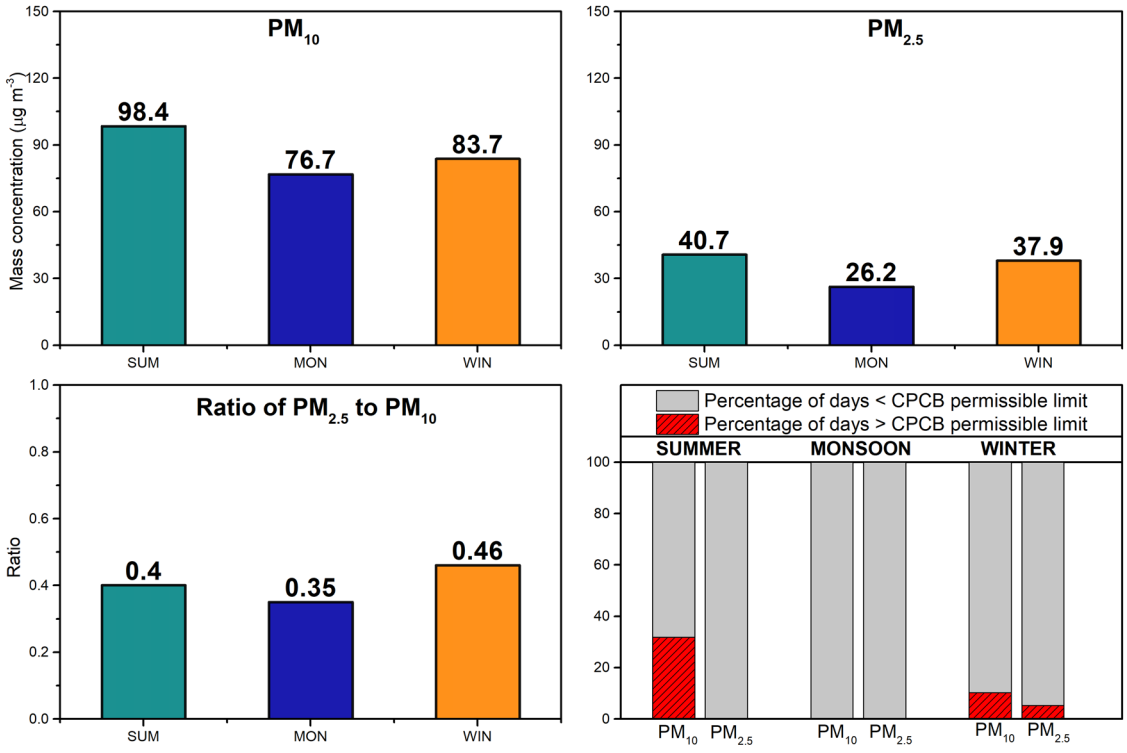

Figure 11: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at AMCO

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.41, with winter showing high ratio (0.46), followed by summer (0.40), and minimum during monsoon (0.35). High ratio denotes dominance of coarse size particles, which is chiefly attributed to meteorological conditions such as wind speed and direction.

Overall, 11% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 33% of the sampling days during summer was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than the CPCB limit of 60 µg m^{-3} during summer and monsoon. However, during winter, only one day among 20 days was found to exceed the CPCB limit.

Results of Kruskal-wallis test revealed significant difference ($p<0.05$) in the PM_{10} and $PM_{2.5}$ levels between seasons.

X. Export Promotion Industrial Park (ITPL)

Figure 12 shows the seasonal variations in PM, with summer maximum (101.7 µg m^{-3}) and monsoon minimum (76.2 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during summer was 1.3 times higher than in monsoon. In case of $PM_{2.5}$, summer maximum (44.7 µg m^{-3}) and winter minimum (27.0 µg m^{-3}) were observed. The mean $PM_{2.5}$ during summer was 1.7 higher than in monsoon.

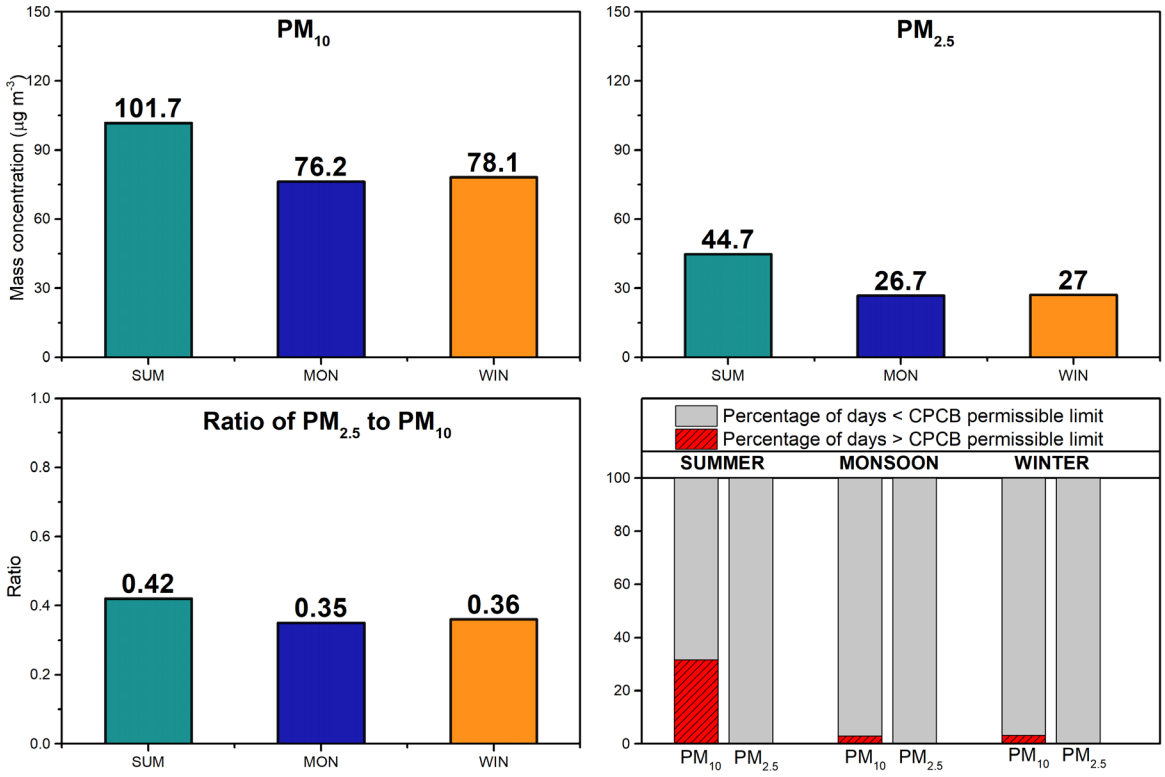

Figure 12: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at ITPL

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.37, with summer showing a high ratio (0.43), followed by winter (0.36), and minimum during monsoon (0.35). High ratio denotes dominance of coarse size particles, which is chiefly attributed to meteorological conditions such as wind speed and direction.

Overall, 9% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 31% of the sampling days during summer was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than the CPCB limit of 60 µg m^{-3}.

Results of Kruskal-wallis test revealed significant difference ($p<0.05$) in the PM_{10} and $PM_{2.5}$ levels between seasons.

XI. SWAN SILK (SWAN)

Figure 13 shows the seasonal variations in PM, with summer maximum (110.0 µg m^{-3}) and monsoon minimum (55.5 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during summer was around 2 times higher than in monsoon. In case of $PM_{2.5}$, summer maximum (49.7 µg m^{-3}), and winter minimum (35.2 µg m^{-3}) were observed. The mean $PM_{2.5}$ during summer was 1.4 higher than in winter.

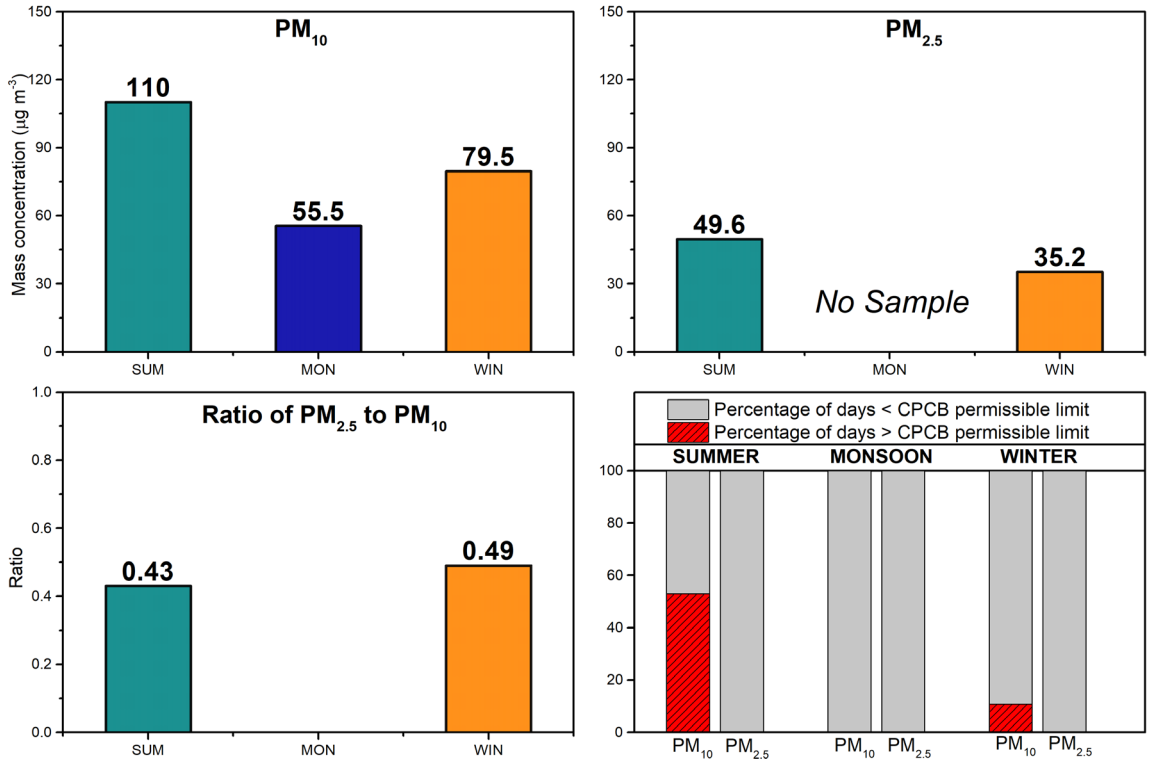

Figure 13: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at SWAN

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.48, with winter showing a high ratio (0.50) and summer showing low ratio (0.43). High ratio denotes dominance of coarse size particles, which is chiefly attributed to meteorological conditions such as wind speed and direction.

Overall, 25% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 53% of the sampling days during summer was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than the CPCB limit of 60 µg m^{-3}.

Results of Kruskal-wallis test revealed significant difference ($p < 0.05$) in the PM_{10}. Non-significant difference ($p > 0.05$) was observed in the $PM_{2.5}$ levels between seasons.

XII. Urban Eco Park (UEP)

Figure 14 shows the seasonal variations in PM, with monsoon maximum (99.5 µg m^{-3}) and winter minimum (84.0 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during monsoon was around 1.2 times higher than in winter. In case of $PM_{2.5}$, summer maximum (49.0 µg m^{-3}) and monsoon minimum (35.2 µg m^{-3}) were observed. The summer $PM_{2.5}$ was around 1.4 times higher than in the monsoon.

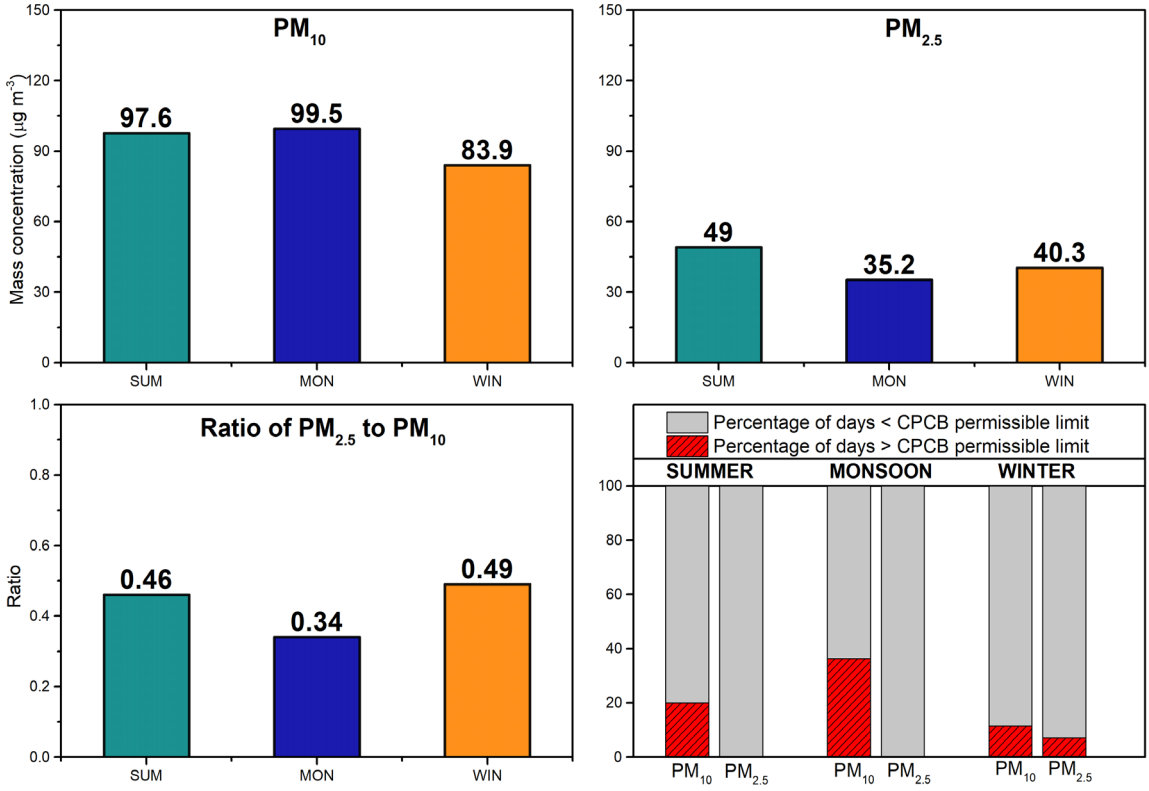

Figure 14: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at UEP

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.46, with winter showing a high ratio (0.50), followed by summer (0.47), and minimum during monsoon (0.34). High ratio denotes dominance of coarse size particles, which is chiefly attributed to meteorological conditions such as wind speed and direction.

Overall, 19% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, around 40% of the sampling days during monsoon was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than CPCB limit of 60 µg m^{-3} during summer and monsoon. However, during winter, only one day among 15 days was found to exceed the CPCB limit.

Results of Kruskal-wallis test revealed a non- significant difference ($p>0.05$) in $PM_{2.5}$ levels between seasons.

XIII. Rail Wheel Factory (RWF)

Figure 15 shows the seasonal variations in PM, with summer maximum (123.3 µg m^{-3}) and monsoon minimum (71.8 µg m^{-3}) for PM_{10}. The mean PM_{10} observed during summer was around 2 times higher than in monsoon. In case of $PM_{2.5}$, summer maximum (47.0 µg m^{-3}) and monsoon minimum (24.3 µg m^{-3}) were observed. The summer $PM_{2.5}$ was around 2 times higher than in the monsoon.

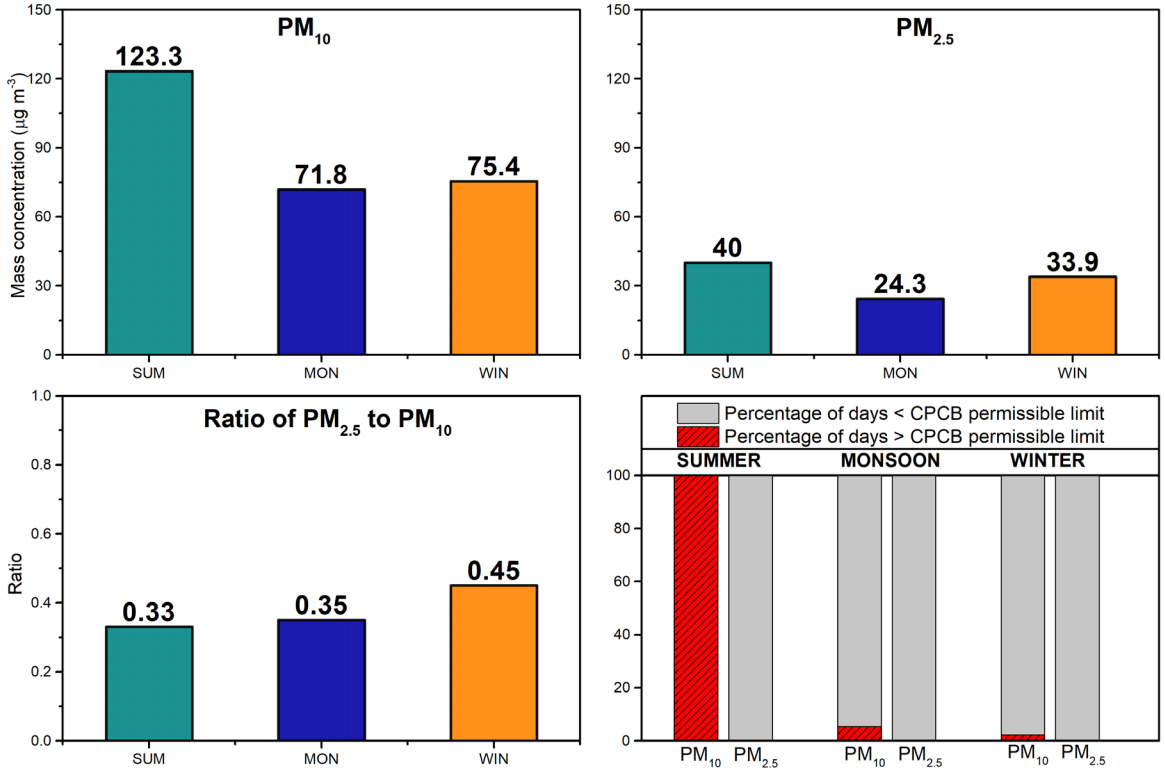

Figure 15: Seasonal variation of PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ and % of days above or below CPCB permissible limits at RWF

The mean ratio of $PM_{2.5}$ to PM_{10} was observed to be 0.43, with winter showing a high ratio (0.45), followed by monsoon (0.35), and minimum during summer (0.33). High ratio denotes dominance of coarse size particles, which is chiefly attributed to meteorological conditions such as wind speed and direction.

Overall, 7% of the sampling days was found to exceed the CPCB limit of 100 µg m^{-3} for PM_{10}. Notably, all the PM_{10} samples during summer was found to exceed the CPCB limit. Conversely, in case of $PM_{2.5}$, all the sampling days showed concentration less than the CPCB limit of 60 µg m^{-3} during summer and monsoon.

Results of Kruskal-wallis test revealed significant difference ($p < 0.05$) in the PM_{10}. Non-significant difference ($p > 0.05$) was observed in the $PM_{2.5}$ levels between seasons.

Annexure III

Chemical Composition ($PM_{2.5}$ and PM_{10})

The chemical species (metals, ions, EC, OC, and molecular markers) were quantified from the collected $PM_{2.5}$ and PM_{10} samples. Results revealed site-wise and seasonal variations in the concentration of the chemical species.

I. TERI Office (TERI)

$PM_{2.5}$ (Chemical composition):

On analysing the seasonal variation of the chemical species (metals, OC, EC, ions, and molecular markers), it was observed that the sum of chemical species was high in winter compared to monsoon season (Figure. 16). Low value during monsoon is due to the effect of rainfall that can settle the particles present in the atmosphere. Sampling for summer season could not be carried out due to malfunctioning of the sampling instrument.

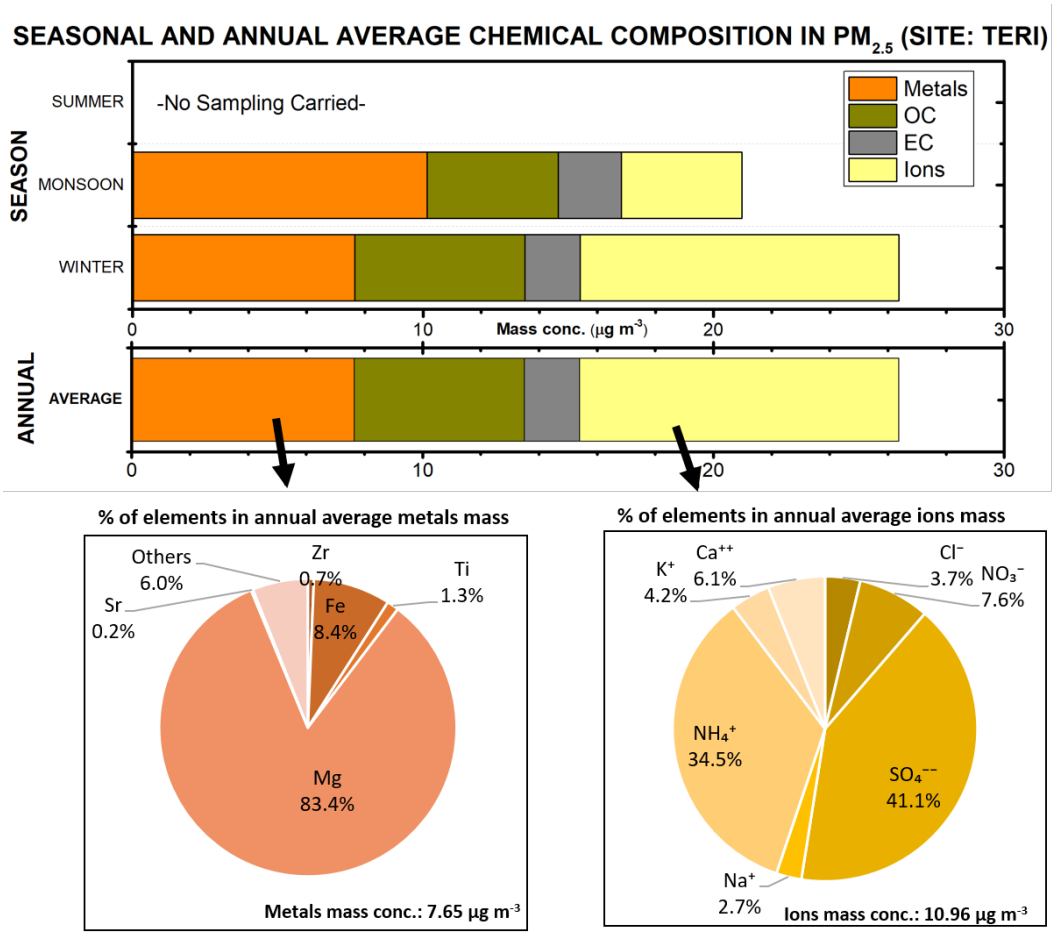

Figure 16: Seasonal and average chemical composition in $PM_{2.5}$. Pie chart indicates the elemental % in metals and ionic mass.

The annual average concentration values for metals, OC, EC, and ions was observed to be 7.6, 5.8, 1.9, and 10.9 µg m^{-3}, respectively. In the annual average metals concentration, Mg (83.4%)

contribution was high, followed by Fe (8.4%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (41.1%) contribution was high, followed by NH_4^+ (34.5%), indicating sources from secondary aerosols.

The annual mean OC and EC was quantified as 5.8 µg m^{-3} and 1.9 µg m^{-3}. The ratio of OC to EC was calculated as 3.1. OC/EC > 3 indicates contribution from secondary organic aerosols (SOA) (NEERI, 2019). The ratio of K^+ to EC was observed as 0.24, suggesting contribution from biomass burning. K^+/EC > 0.21 indicates biomass burning (Andrea and Merlet, 2001; Tiwari et al., 2016).

The annual mass concentration of 1-Nitropyrene (1-NP) in $PM_{2.5}$ was observed as 2.03 ng m^{-3}. Seasonal variation revealed high concentration during winter (2.7 ng m^{-3}), followed by summer (2.3 ng m^{-3}) and monsoon (1.4 ng m^{-3}). The 1-NP is a source marker for diesel exhaust (Shrivastava et al., 2018). Interestingly, Levoglucosan was not observed in the collected samples, which indicates negligible leaf-burning activities.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species was high in winter compared to monsoon and summer season (Figure 17). High values during winter can be attributed to construction activities, which is indicated by the elevated Ca^{2+} concentration during winter.

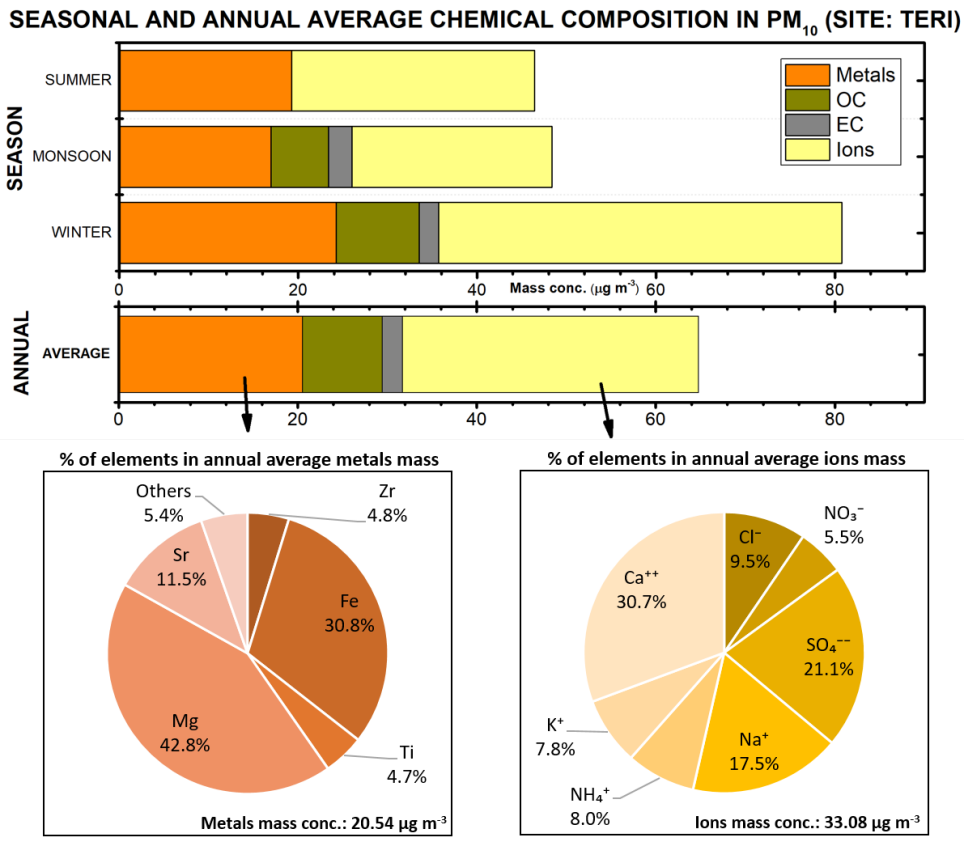

Figure 17: Seasonal and average chemical composition in PM_{10}. Pie chart indicates the elemental % in metals and ionic mass.

Overall, the annual average metal and ions concentration was observed to be 20.5 and 33.1 µg m^{-3}, respectively. Among the average metals concentration, Mg (42.8%) contribution was

high, followed by Fe (30.8%), indicating sources from crustal materials. Among the ions, Ca^{2+} (30.7%) contribution was high, followed by SO_4^{2-} (21.1%) and Na^+ (17.5%), indicating sources from road dust and secondary aerosols. OC and EC were not quantified in the summer season.

The annual average concentration of criteria pollutants such as Nickel (Ni), Arsenic (As), and Lead (Pb) was found to be 0.4, 0.1, and 1.0 µg m^{-3}, respectively. As and Ni showed 20 and 2 times higher concentration compared to their annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to the coal burning and vehicular movement. The annual average OC and EC were quantified as 8.9 µg m^{-3} and 2.2 µg m^{-3}. The ratio of OC to EC was calculated to be 3.9, which denotes contribution from SOA. The ratio of K^+ to EC was observed to be 1.1, which denotes contribution from biomass burning.

II. Banaswadi Police Station (BPS)

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species were high in monsoon compared to winter and summer season (Figure 18). High concentration during monsoon is attributed to the elevated Na^+, Mg and Fe concentration. These elements are generated due to soil dust, vehicular movement, and construction activities.

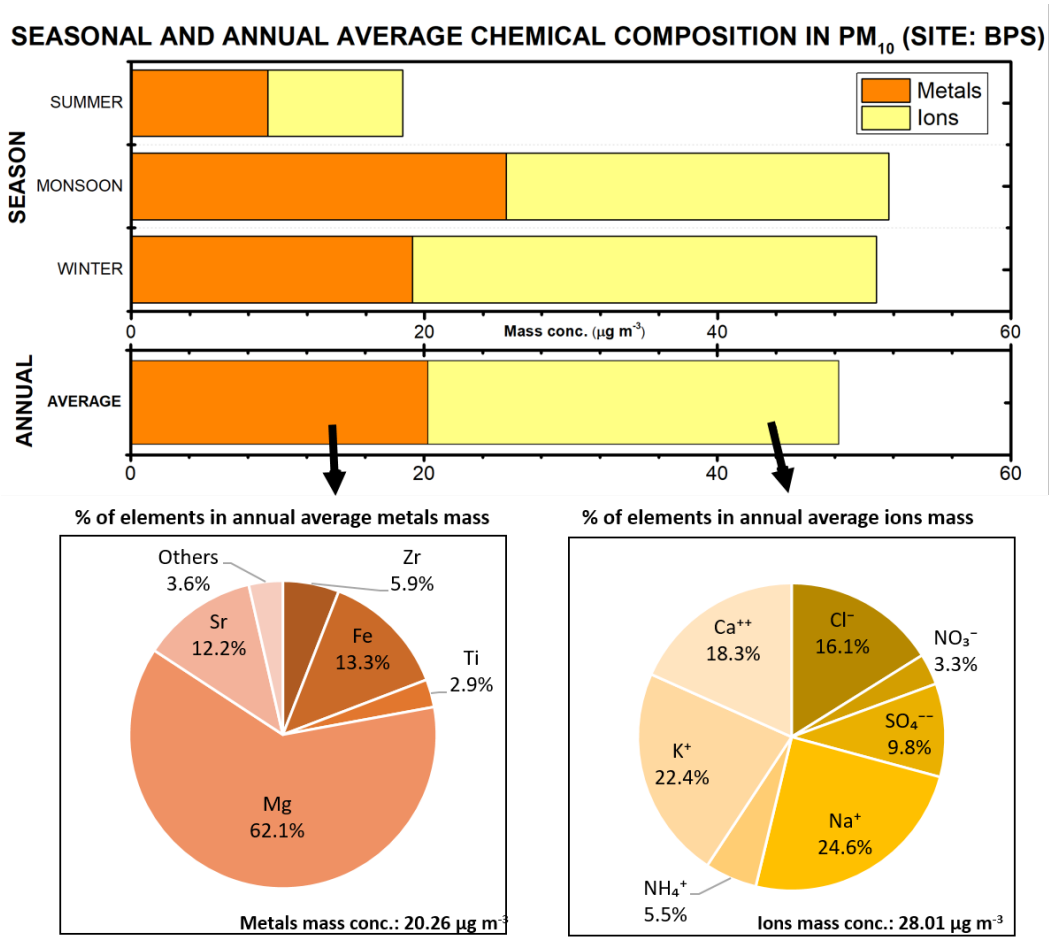

Figure 18: Seasonal and average chemical composition in PM_{10}. Pie chart indicates the elemental % in metals and ionic mass.

Overall, the annual average metal and ions concentration was observed to be 20.3 and 28.0 μg m^{-3}, respectively. Among the average metals concentration, Mg (62.1%) contribution was high, followed by Fe (13.3%), indicating sources from crustal material. Among the ions, Na^+ (24.2%) contribution was high, followed by K^+ (22.6%), indicating sources from biomass burning and road dust. OC and EC was not quantified in this site.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.02, 0.13 and 0.06 μg m^{-3}, respectively. As and Ni showed 21 and 1.1 times higher concentration compared to their annual permissible limit of 0.006 and 0.02 μg m^{-3}, respectively. High As and Ni concentration is attributed to the coal-burning and vehicular movement.

III. Madhavchari (MADH)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions, and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 19). High value during summer is mainly attributed to the elevated OC concentration observed during summer. Low value during monsoon is the due to the effect of rainfall that can settle the particles present in the atmosphere.

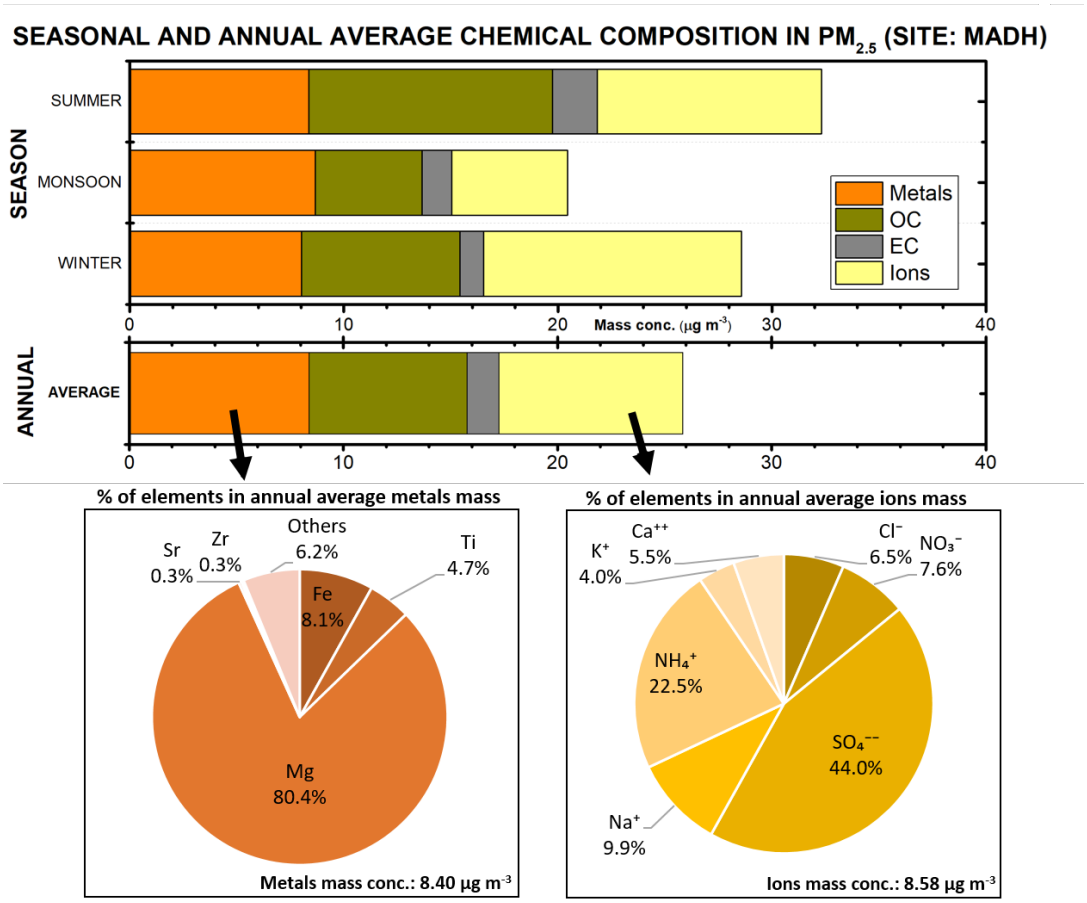

Figure 19: Seasonal and annual average chemical composition in $PM_{2.5}$. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metals, OC, EC, and Ions concentration was observed to be 8.4, 7.4, 1.5, and 8.6 μg m^{-3}, respectively. In the annual average metals concentration, Mg (80.4%)

contribution was high, followed by Fe (8%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (44%) contribution was high, followed by NH_4^+ (22%), indicating source from secondary aerosols. The OC and EC were quantified as 7.31 ± 3.24 µg m^{-3} and 1.48 ± 0.67 µg m^{-3}. The ratio of OC to EC was calculated to be 4.9, indicating contribution from SOA. The ratio of K^+ to EC was observed to be 0.2, suggesting contribution from biomass burning.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 1.9 ng m^{-3}. The seasonal variation of 1-NP indicated high value during summer (2.67 ng m^{-3}), followed by winter (2.2 ng m^{-3}) and monsoon (1.2 ng m^{-3}). This indicates high diesel exhaust emission during summer, as 1-NP is a source marker for diesel emission. At this site, Levoglucosan was not observed in the collected samples.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species were high in summer compared to monsoon and winter season. High values during summer are attributed to the presence of transported dust, vehicular, construction and burning activities, which is indicated by the elevated Ca^{2+}, Mg, K^+, EC, and OC concentration (Figure. 20).

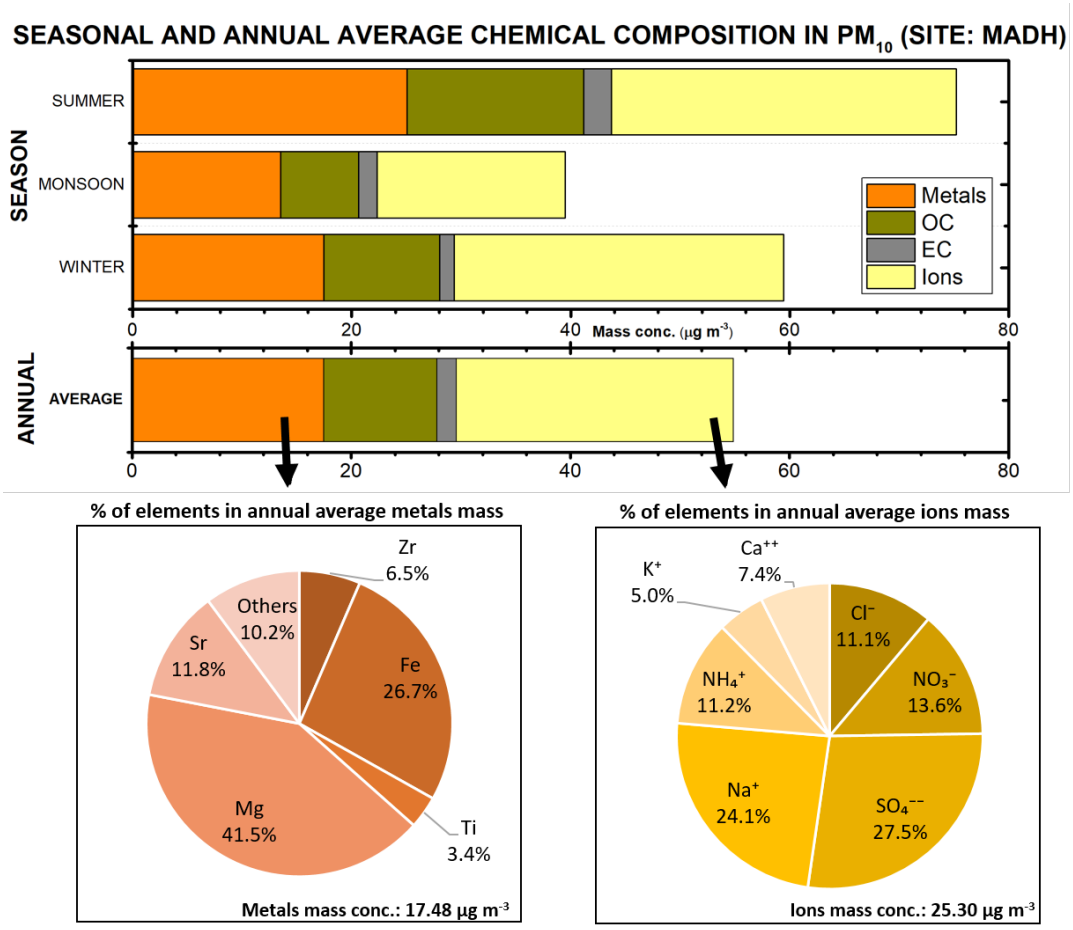

Figure 20: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and ions concentration was observed to be 17.4 and 25.3 µg m^{-3}, respectively. Among the average metals concentration, Mg (41.5%) contribution was

high, followed by Fe (26.7%), indicating sources from crustal material. Among the ions, SO_4^{2-} (27.5%) contribution was high, followed by Na^+ (24.1%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.05, 0.16, and 0.29 µg m^{-3}, respectively. As and Ni showed around 27 and 3 times higher concentration compared to their annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to coal burning and vehicular movement.

The mean OC and EC was quantified to be 10.3 µg m^{-3} and 1.8 µg m^{-3}. The ratio of OC to EC was calculated to be 5.8, indicating sources from SOA. The ratio of K^+ to EC was observed to be 0.71, which denotes contribution from biomass burning.

IV. Indira Gandhi Institute of Child Health Care (IGCHC)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 21).

High value during summer is mainly attributed to the elevated OC, EC, SO_4^{2-} and K^+ concentration observed during summer, which indicates increased vehicular movement and leaf-burning activities in the vicinity. Low value during monsoon is due to the effect of rainfall that settles the particles present in the atmosphere.

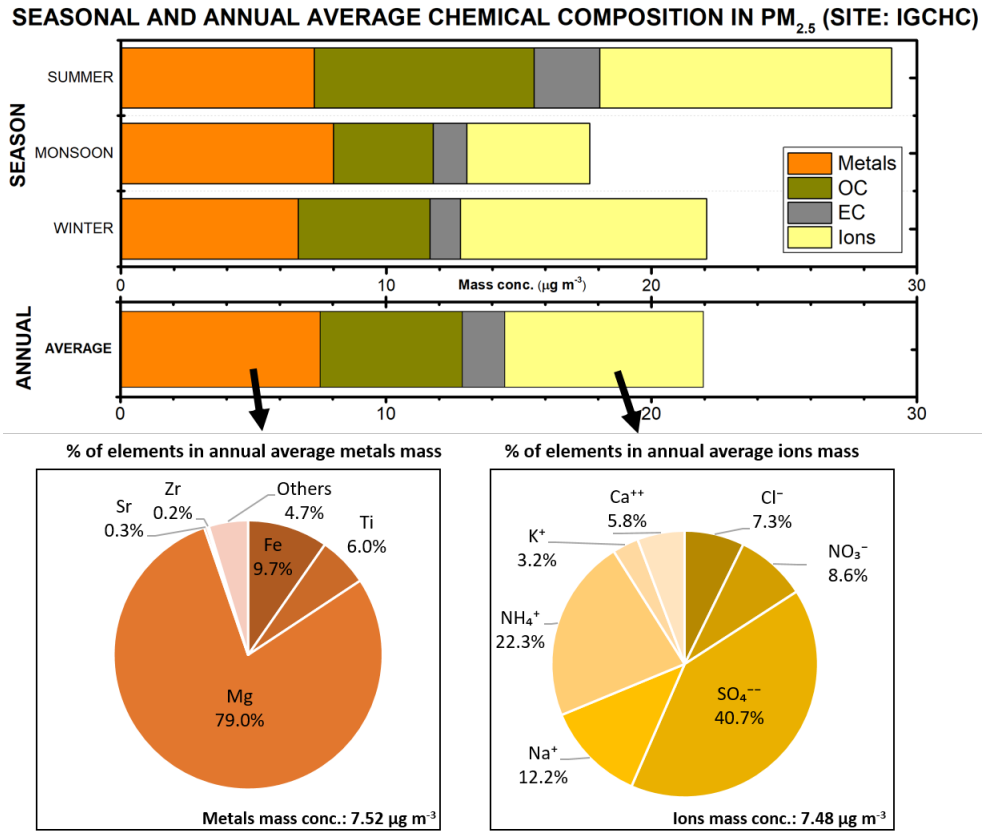

Figure 21: Seasonal and average chemical composition in $PM_{2.5}$. Pie chart indicates the elemental % in metals and ionic mass.

Overall, the annual average metals, OC, EC, and ions concentration was observed to be 7.5, 5.4, 1.6, and 7.5 µg m^{-3}, respectively. In the annual average metals concentration, Mg (79%) contribution was high, followed by Fe (9.7%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (40.7%) contribution was high, followed by NH_4^+ (22.3%), indicating source from secondary aerosols. The annual average OC and EC were observed to be 5.4 and 1.6 µg m^{-3}, respectively. The ratio of OC to EC was calculated to be 3.4, indicating contribution from SOA.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 1.8 ng m^{-3}. The seasonal variation revealed high concentration during winter (2.8 ng m^{-3}), followed by summer (2.1 ng m^{-3}) and monsoon (1.2 ng m^{-3}). The 1-NP is a source marker for diesel exhaust.

The annual mass concentration of Levoglucosan in $PM_{2.5}$ was found to be 105.7 ng m^{-3}. The seasonal variation revealed high concentration during winter (264.4 ng m^{-3}), followed by summer (90.2 ng m^{-3}) and monsoon (21.5 ng m^{-3}). Levoglucosan is a source marker for biomass burning.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season.

High values during summer can be attributed to the presence of transported dust, construction, and burning activities, which is indicated by the elevated Na^+, SO_4^{2-}, Ca^{2+}, K^+, and OC concentration during summer (Figure. 22).

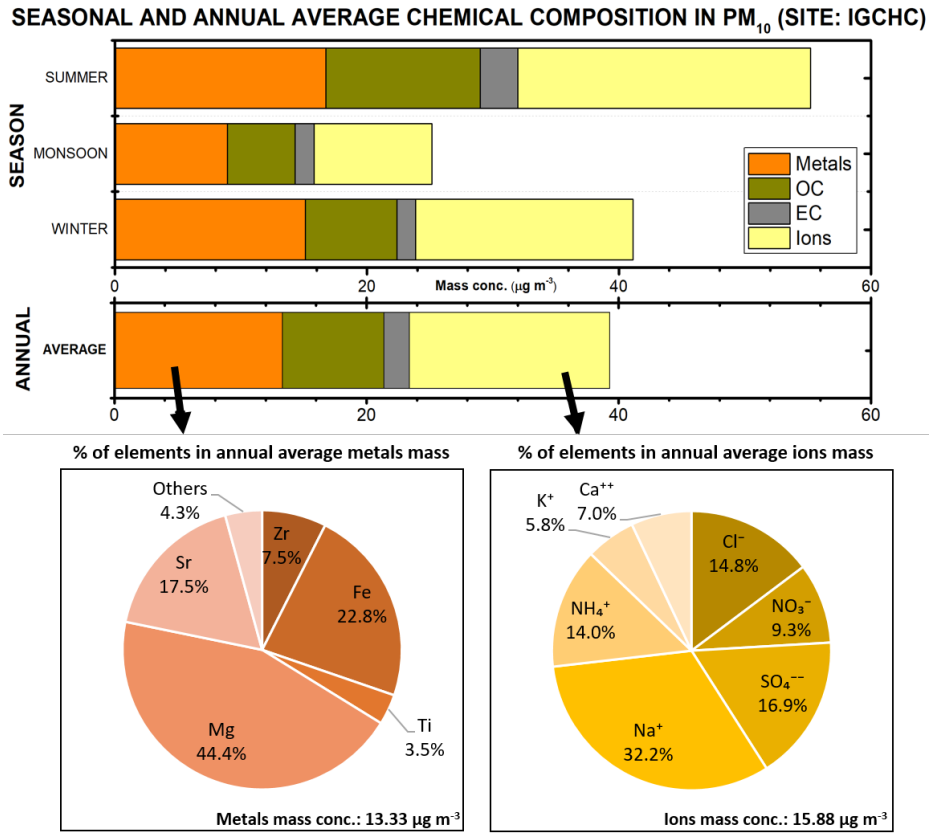

Figure 22: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and Ions concentration was observed to be 13.3 and 15.8 µg m^{-3}, respectively. Among the average metals concentration, Mg (44%) contribution was high, followed by Fe (23%), indicating sources from crustal material. Among the ions, Na^+ (32%) contribution was high, followed by SO_4^{2-} (17%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.03, 0.07, and 0.04 µg m^{-3}, respectively. As and Ni showed around 12 and 2 times higher concentration compared to the annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to the coal-burning and vehicular movement.

The mean OC and EC were quantified to be 8.06 µg m^{-3} and 1.99 µg m^{-3}. The ratio of OC to EC was calculated to be 4.03, indicating sources from SOA. The ratio of K^+ to EC was observed to be 0.46, which denotes contribution from biomass burning.

V. Victoria Hospital (VICH)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions, and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in winter, as compared to the summer and monsoon season (Figure 23). The high value during winter is mainly attributed to the elevated OC, EC, NH_4^+, Ca^{2+}, SO_4^{2-}, and NO_3^- concentrations observed during winter, which indicates increased vehicular movement, leaf-burning, and construction activities during this season. The low value during monsoon is due to the effect of rainfall that can settle the particles present in the atmosphere.

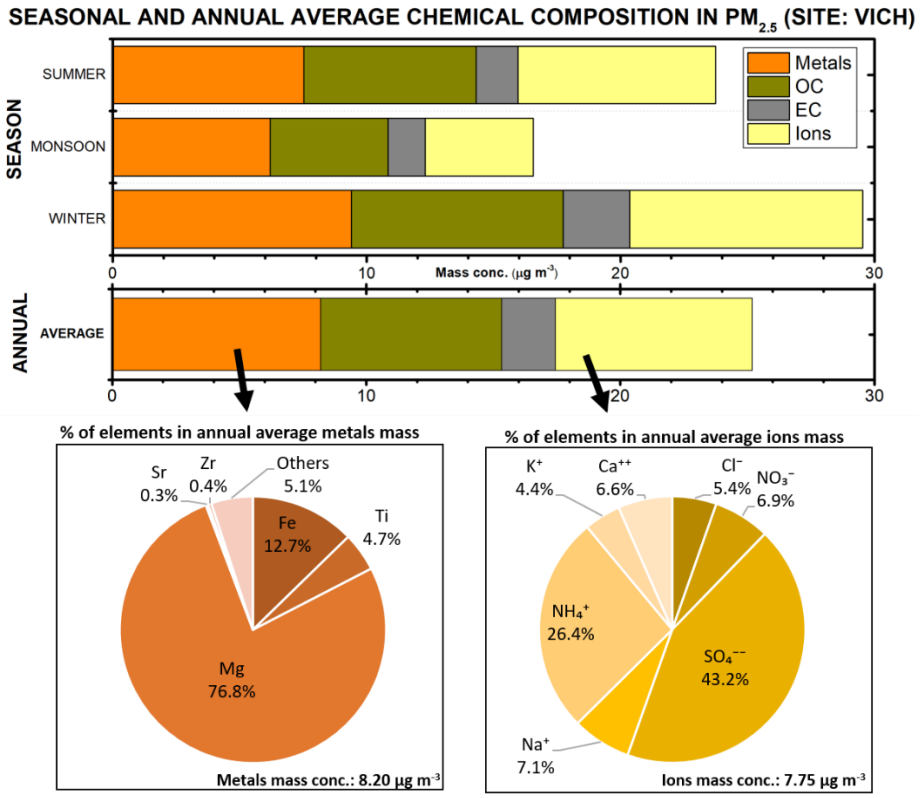

Figure 23: Seasonal and annual average chemical composition in $PM_{2.5}$. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metals, OC, EC, and ions concentration was observed to be 8.2, 7.1, 2.1, and 7.7 μg m^{-3}, respectively. In the annual average metals concentration, Mg (77%) contribution was high, followed by Fe (12.7%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (43.2%) contribution was high, followed by NH_4^+ (26.4%), indicating source from secondary aerosols. The annual average OC and EC were observed to be 7.1 and 2.1 μg m^{-3}, respectively. The ratio of OC to EC was calculated to be 3.4, indicating contribution from SOA.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 2.0 ng m^{-3}. The seasonal variation revealed high concentration during summer (2.6 ng m^{-3}), followed by winter (2.1 ng m^{-3}) and monsoon (1.2 ng m^{-3}). High concentration during summer indicates increased diesel exhaust emissions.

The annual mass concentration of Levoglucosan in $PM_{2.5}$ was observed to be 52.5 ng m^{-3}. The seasonal variation revealed high concentration during winter (71.5 ng m^{-3}), followed by summer (43.3 ng m^{-3}) and monsoon (14.1 ng m^{-3}). High value during winter indicates increased leaf-burning activity.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 24). High values during summer can be attributed to the presence of transported dust, construction, and burning activities, which is indicated by the elevated Na^+, SO_4^{2-}, Ca^{2+}, and K^+ concentration during summer.

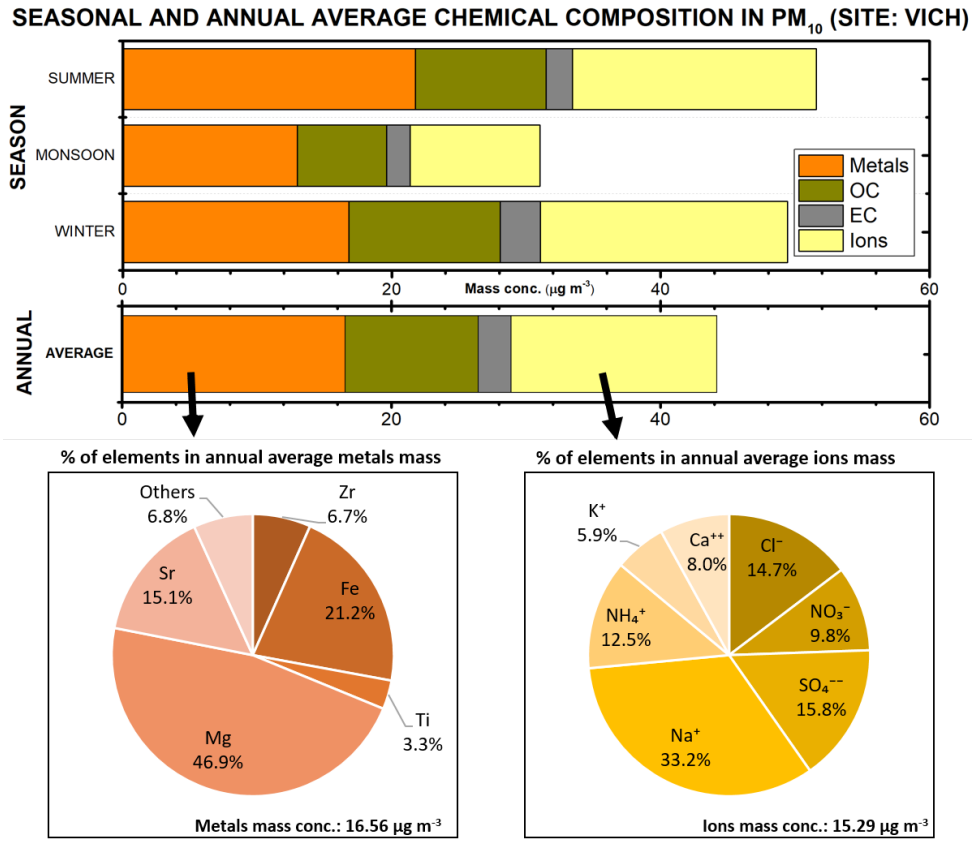

Figure 24: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and Ions concentration was observed to be 16.5 and 15.2 µg m^{-3}, respectively. Among the average metals concentration, Mg (42%) contribution was high, followed by Fe (27%), indicating sources from crustal material. Among the ions, Na^+ (33%) contribution was high, followed by SO_4^{2-} (16%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.03, 0.14, and 0.07 µg m^{-3}, respectively. As and Ni showed around 24 and 2 times higher concentration compared to the annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to the coal-burning and vehicular movement.

The mean OC and EC were quantified to be 9.9 µg m^{-3} and 2.4 µg m^{-3}. The ratio of OC to EC was calculated to be 4.1, indicating source contribution from SOA. While the ratio of K^+ to EC was observed to be 0.4, which denotes contribution from biomass burning.

VI. Central Silk Board (CSB)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in winter compared to summer and monsoon season (Figure 25). High value during winter is mainly attributed to the elevated OC, NH_4^+, SO_4^{2-}, and NO_3^- concentration, which indicates increased vehicular movement and leaf-burning activities. Low value during monsoon is the due to the effect of rainfall that can settle the particles present in the atmosphere.

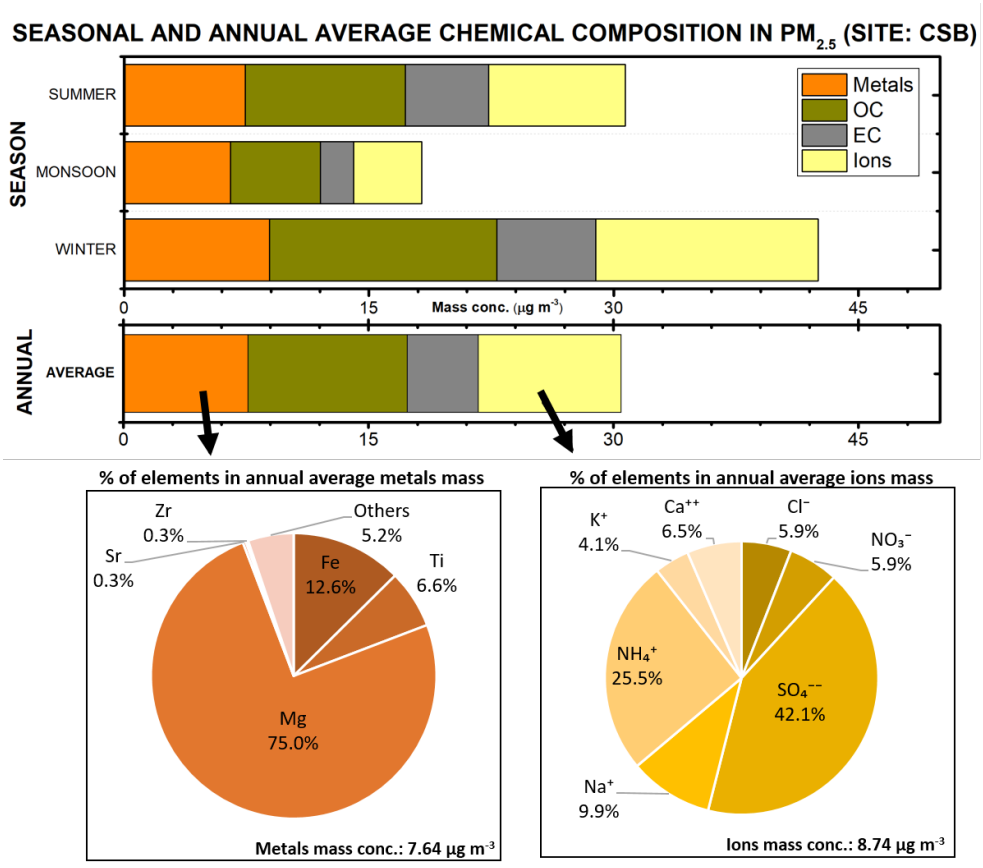

Figure 25: Seasonal and annual average chemical composition in $PM_{2.5}$. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metals, OC, EC and ions concentration was observed to be 7.6, 9.7, 4.4, and 8.7 µg m^{-3}, respectively. In the annual average metals concentration, Mg (75%) contribution was high, followed by Fe (12%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (42%) contribution was high, followed by NH_4^+ (25%), indicating source from secondary aerosols. The OC and EC were quantified to be 9.7 µg m^{-3} and 4.4 µg m^{-3}. The ratio of OC of EC was calculated to be 2.2. The ratio of K^+ to EC was observed to be 0.08.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 2.3 ng m^{-3}. The seasonal variation of 1-NP revealed high concentration during summer (2.9 ng m^{-3}), followed by winter (2.4 ng m^{-3}) and monsoon (1.6 ng m^{-3}). The 1-NP is a source marker for diesel exhaust.

The annual mass concentration of Levoglucosan in $PM_{2.5}$ was observed to be 14.4 ng m^{-3}. The seasonal variation of Levoglusosan revealed high concentration during winter (28.6 ng m^{-3}), followed by summer (13.9 ng m^{-3}) and monsoon (3.29 ng m^{-3}). High concentration during summer indicate leaf-burning activities in the vicinity of the site.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 26). High values during summer can be attributed to the presence of transported dust, construction, and burning activities, which is indicated by the elevated Na^+, SO_4^{2-}, Ca^{2+}, and K^+ concentration during summer.

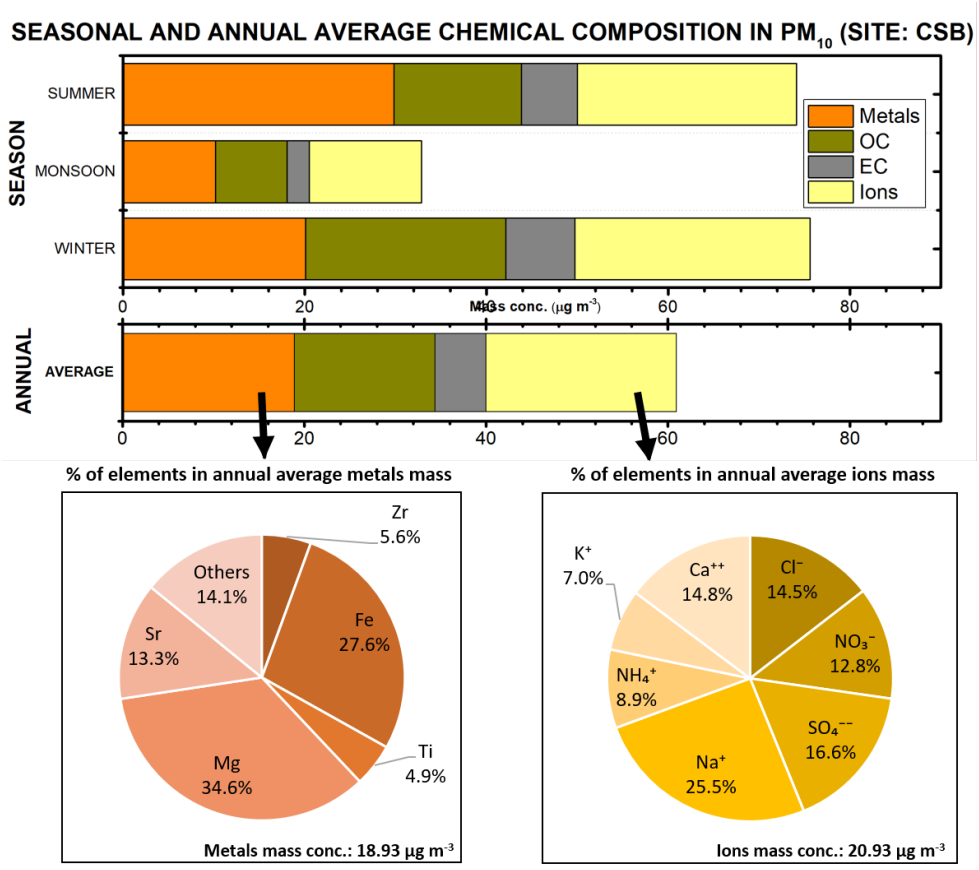

Figure 26: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and Ions concentration was observed to be 18.9 and 20.9 µg m^{-3}, respectively. Among the average metals concentration, Mg (35%) contribution was high, followed by Fe (27%), indicating sources from crustal material. Among the ions, Na^+ (25%) contribution was high, followed by SO_4^{2-} (17%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.05, 0.19, and 0.15 µg m^{-3}, respectively. As and Ni showed around 32 and 3 times higher concentration compared to the annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to coal-burning and vehicular movement.

The mean OC and EC was quantified to be 15.4 µg m^{-3} and 5.6 µg m^{-3}. The ratio of OC to EC was calculated to be 2.7. The ratio of K^+ to EC was observed to be 0.26, which denotes contribution from biomass burning.

VII. Govt. SKSJ Technological Institute (SKSJ)

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species was high in winter season compared to winter and monsoon season (Figure. 27). High values during summer can be attributed to the presence of transported dust, construction, and burning activities, which is indicated by the elevated Mg, Cl, Na^+, SO_4^{2-}, Ca^{2+}, and K^+ concentration during summer.

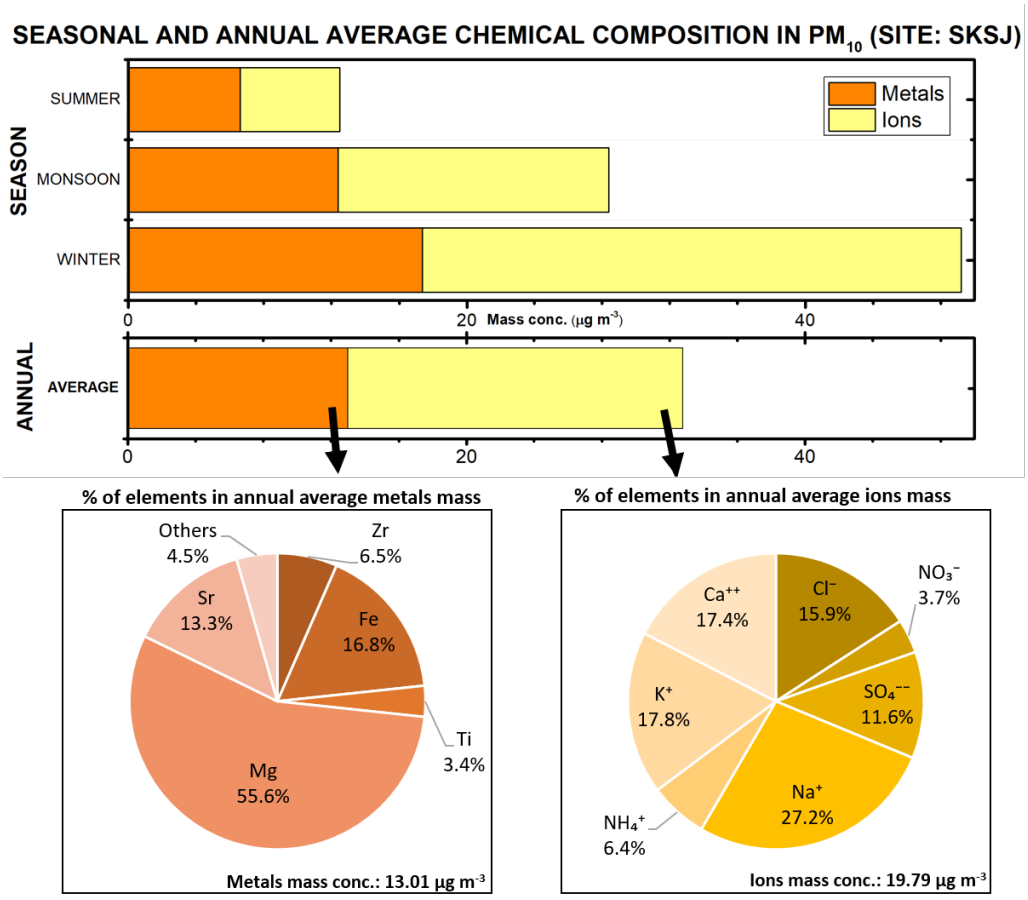

Figure 27: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and ions concentration was observed to be 13.0 and 19.7 µg m^{-3}, respectively. Among the average metals concentration, Mg (56%) contribution was high, followed by Fe (17%), indicating sources from crustal material. Among the ions, Na^+ (27%) contribution was high, followed by K^+ (18%), indicating sources from road dust and biomass burning. OC and EC were not quantified in this site.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.02, 0.09, and 0.04 µg m^{-3}, respectively. As and Ni showed around 14.5 and 1.1 times higher concentration compared to their annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to the coal-burning and vehicular movement.

VIII. Yeshwantpur Police Station (YPS)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions, and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in winter compared to summer and monsoon season (Figure. 28). High value during winter is mainly attributed to the elevated Mg, OC, Ca^{2+}, NH_4^+, and NO_3^- concentration, which indicates increased vehicular movement, road dust, construction, and leaf-burning activities. Low value during monsoon is due to the effect of rainfall that can settle the particles present in the atmosphere.

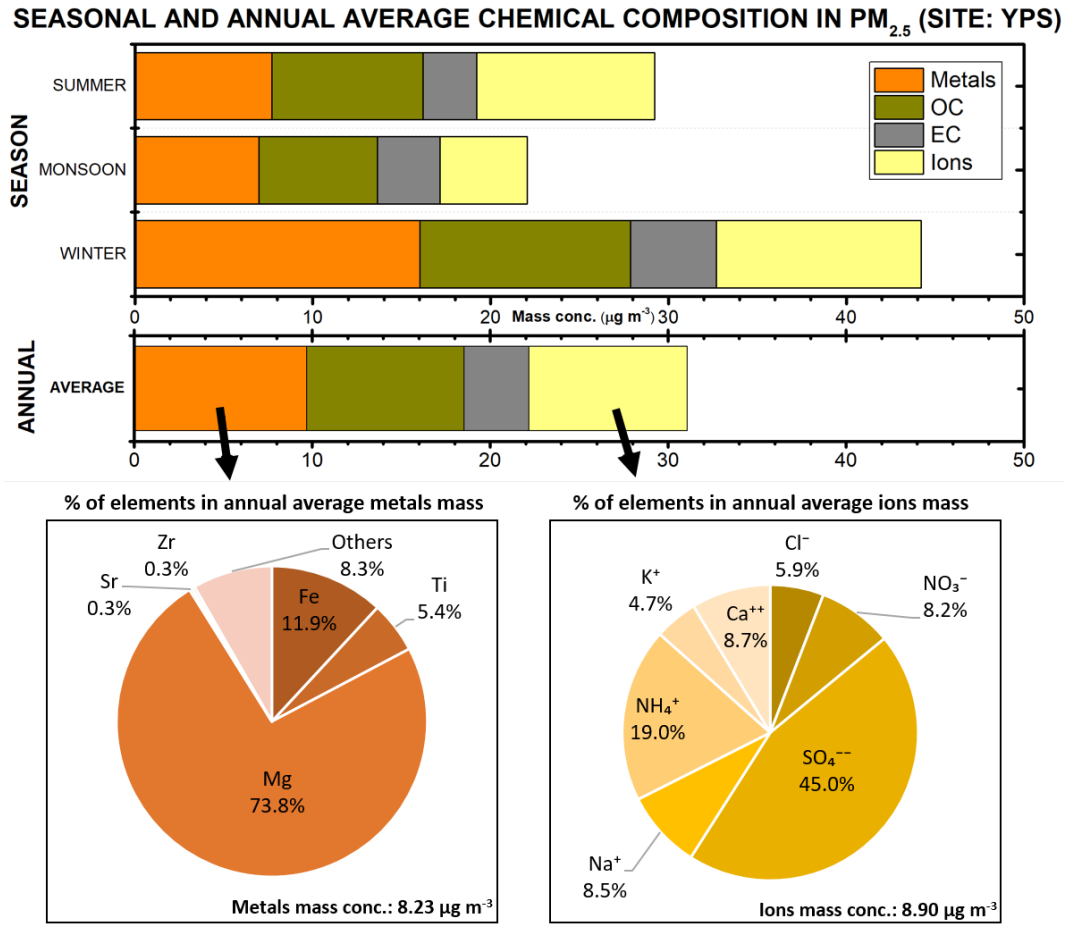

Figure 28: Seasonal and annual average chemical composition in $PM_{2.5}$. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metals, OC, EC and ions concentration was observed to be 9.69, 8.84, 3.63, and 8.90 µg m^{-3}, respectively. In the annual average metals concentration, Mg (63%) contribution was high, followed by Fe (26%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (45%) contribution was high, followed by NH_4^+ (19%), indicating source from secondary aerosols. The OC and EC were quantified to be 8.84 µg m^{-3} and 3.6 µg m^{-3}. The ratio of OC of EC was calculated to be 2.4. The ratio of K^+ to EC was observed to be 0.12.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 2.14 ng m^{-3}. The seasonal variation of 1-NP indicates high concentration during winter (2.6 ng m^{-3}), followed by summer (2.1 ng m^{-3}), and monsoon (1.2 ng m^{-3}). The 1-NP is a source marker for diesel exhaust. At this site, Levoglucosan was not observed in the collected samples.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species were high in winter season compared to winter and monsoon season (Figure. 29). High values during winter can be attributed to the presence of transported dust, construction, and burning activities, which is indicated by the elevated Mg, Cl, Na^+, SO_4^{2-}, Ca^{2+}, and K^+ concentration during summer.

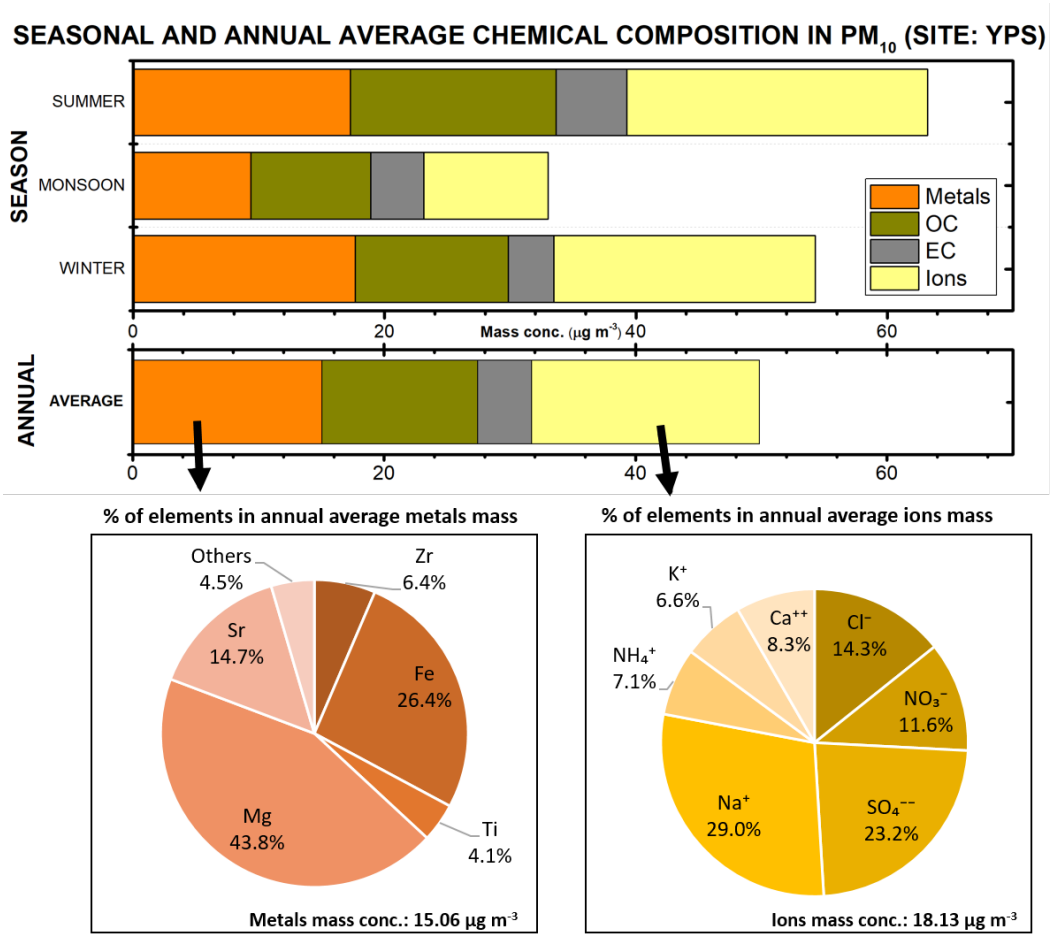

Figure 29: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and Ions concentration was observed to be 15.0 and 18.1 µg m^{-3}, respectively. Among the average metals concentration, Mg (44%) contribution was

high, followed by Fe (26%), indicating sources from crustal material. Among the ions, Na^+ (29%) contribution was high, followed by SO_4^{2-} (23%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.07, 0.08, and 0.06 µg m^{-3}, respectively. As and Ni showed around 13 and 3 times higher concentration compared to the annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to coal-burning and vehicular movement.

The mean OC and EC were quantified to be 12.4 µg m^{-3} and 4.3 µg m^{-3}. The ratio of OC to EC was calculated to be 2.89. The ratio of K^+ to EC was observed to be 0.28, which denotes contribution from biomass burning.

IX. AMCO Batteries (AMCO)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions, and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 30). High value during summer is mainly attributed to the elevated EC and OC concentration, which indicates increased vehicular movement and leaf-burning activities. Low value during monsoon is due to the effect of rainfall that can settle the particles present in the atmosphere.

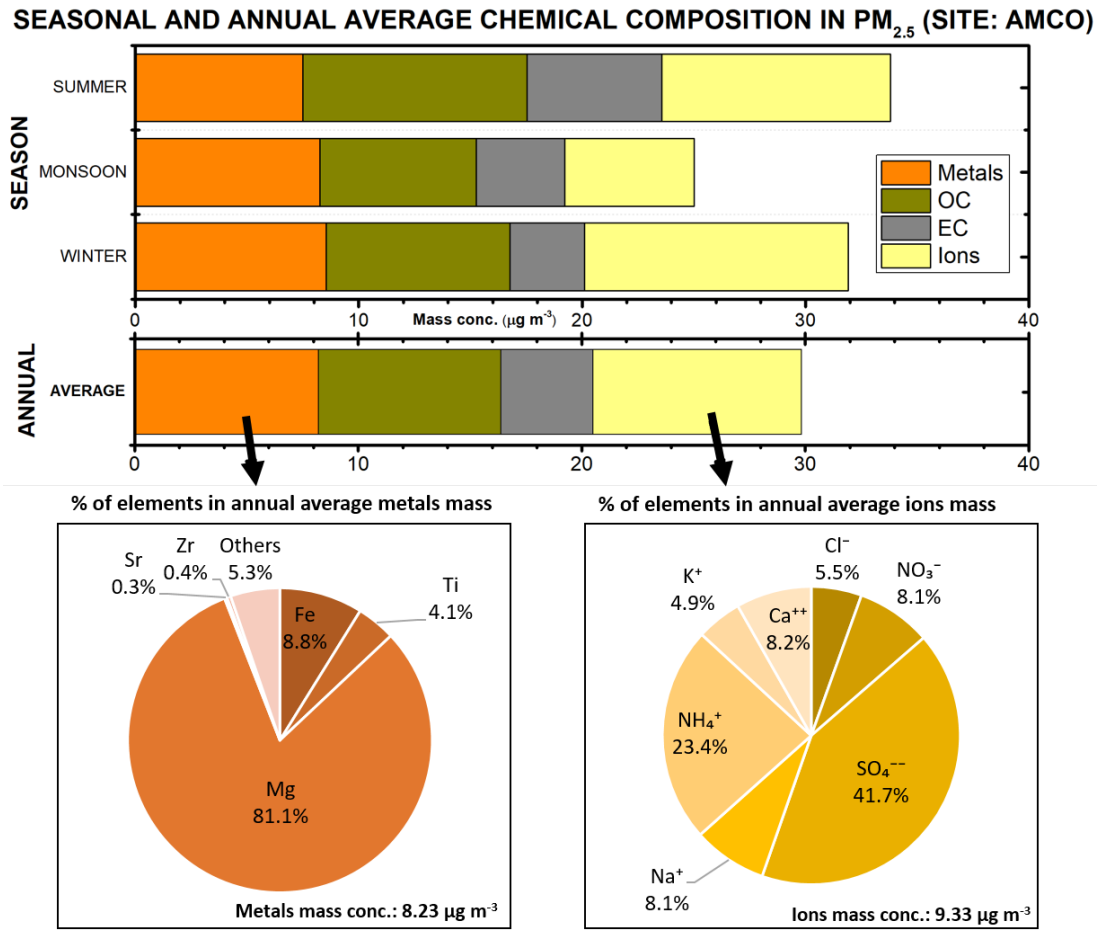

Figure 30: Seasonal and annual average chemical composition in $PM_{2.5}$. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metals, OC, EC, and Ions concentration was observed to be 8.23, 8.15, 4.11, and 9.33 µg m^{-3}, respectively. In the annual average metals concentration, Mg (81%) contribution was high, followed by Fe (9%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (42%) contribution was high, followed by NH_4^+ (23%), indicating source from secondary aerosols. The OC and EC were quantified to be 8.1 µg m^{-3} and 4.1 µg m^{-3}. The ratio of OC to EC was calculated to be 2.0. The ratio of K^+ to EC was observed to be 0.11.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 1.7 ng m^{-3}. The seasonal variation of 1-NP revealed high concentration during winter (2.4 ng m^{-3}), followed by summer (1.8 ng m^{-3}) and monsoon (1.0 ng m^{-3}). The 1-NP is a source marker for diesel exhaust. Only during winter season, Levoglucosan was observed (27.8 ng m^{-3}), indicating high leaf-burning activities in the vicinity of the site.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species were high in summer compared to winter and monsoon season (Figure. 31). High values during summer can be attributed to the presence of vehicular movement and leaf-burning activities, which is indicated by the elevated OC and EC concentration during summer.

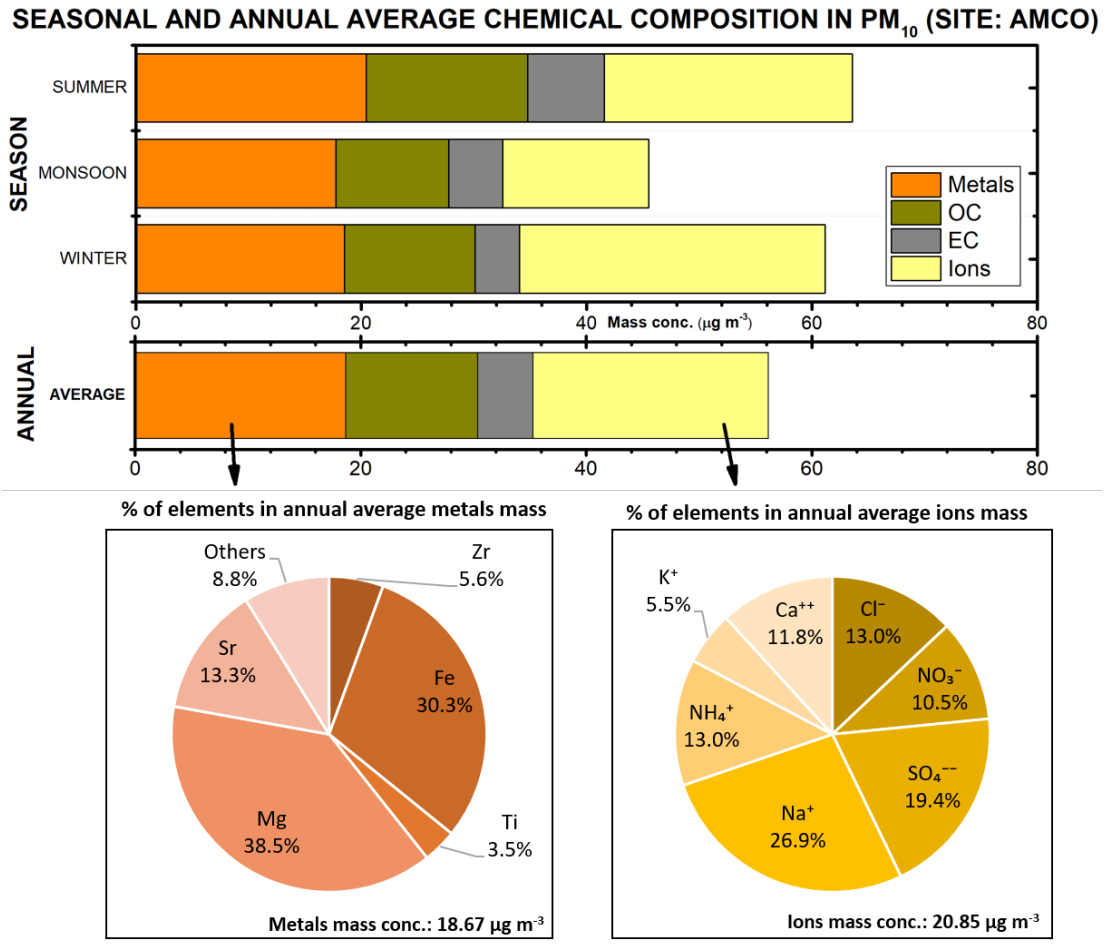

Figure 31: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and ions concentration was observed to be 18.6 and 20.8 µg m^{-3}, respectively. Among the average metals concentration, Mg (38%) contribution was high, followed by Fe (30%), indicating sources from crustal material. Among the ions, Na^+ (27%) contribution was high, followed by SO_4^{2-} (19%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.04, 0.10, and 0.17 µg m^{-3}, respectively. As and Ni showed around 15 and 2 times higher concentration compared to the annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to coal-burning and vehicular movement.

The mean OC and EC were quantified to be 11.7 µg m^{-3} and 4.9 µg m^{-3}. The ratio of OC to EC was calculated to be 2.4. The ratio of K^+ to EC was observed to be 0.23, which denotes contribution from biomass burning.

X. Export Promotion Industrial Park (ITPL)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 32). High value during summer is mainly attributed to the elevated EC and OC concentration, which indicates increased vehicular movement and leaf-burning activities. Low value during monsoon is due to the effect of rainfall that can settle the particles present in the atmosphere.

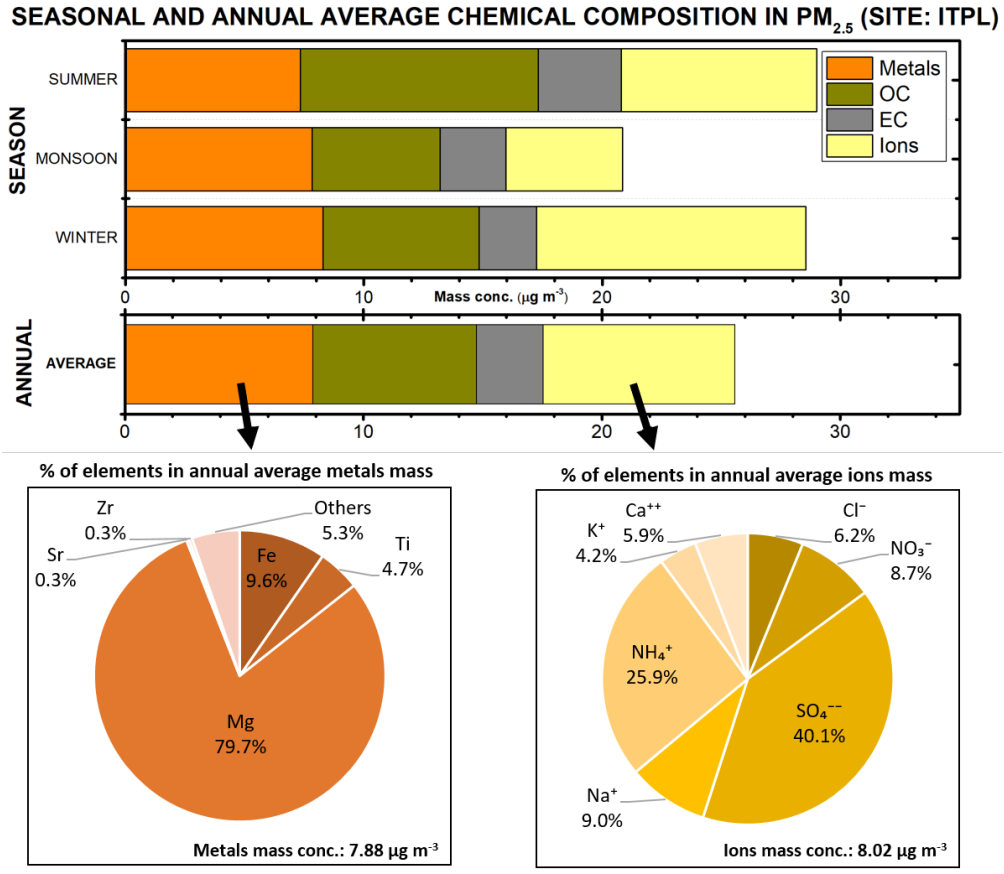

Figure 32: Seasonal and annual average chemical composition in $PM_{2.5}$. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metals, OC, EC and ions concentration was observed to be 7.9, 6.9, 2.8, and 8.0 µg m^{-3}, respectively. In the annual average metals concentration, Mg (80%) contribution was high, followed by Fe (10%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (40%) contribution was high, followed by NH_4^+ (26%), indicating source from secondary aerosols. The OC and EC were quantified to be 6.86 µg m^{-3} and 2.8 µg m^{-3}. The ratio of OC to EC was calculated to be 2.7. The ratio of K^+ to EC was observed to be 0.12.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 2.1 ng m^{-3}. The seasonal variation of 1-NP indicated high concentration during summer (2.9 ng m^{-3}), followed by winter (25 ng m^{-3}) and monsoon (1.4 ng m^{-3}). The 1-NP is a source marker for diesel exhaust. At this site, Levoglucosan was not observed in the collected samples.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species were high in summer compared to winter and monsoon season (Figure. 33). High values during summer can be attributed to the presence of vehicular movement and leaf-burning activities, which is indicated by the elevated OC and EC concentration during summer.

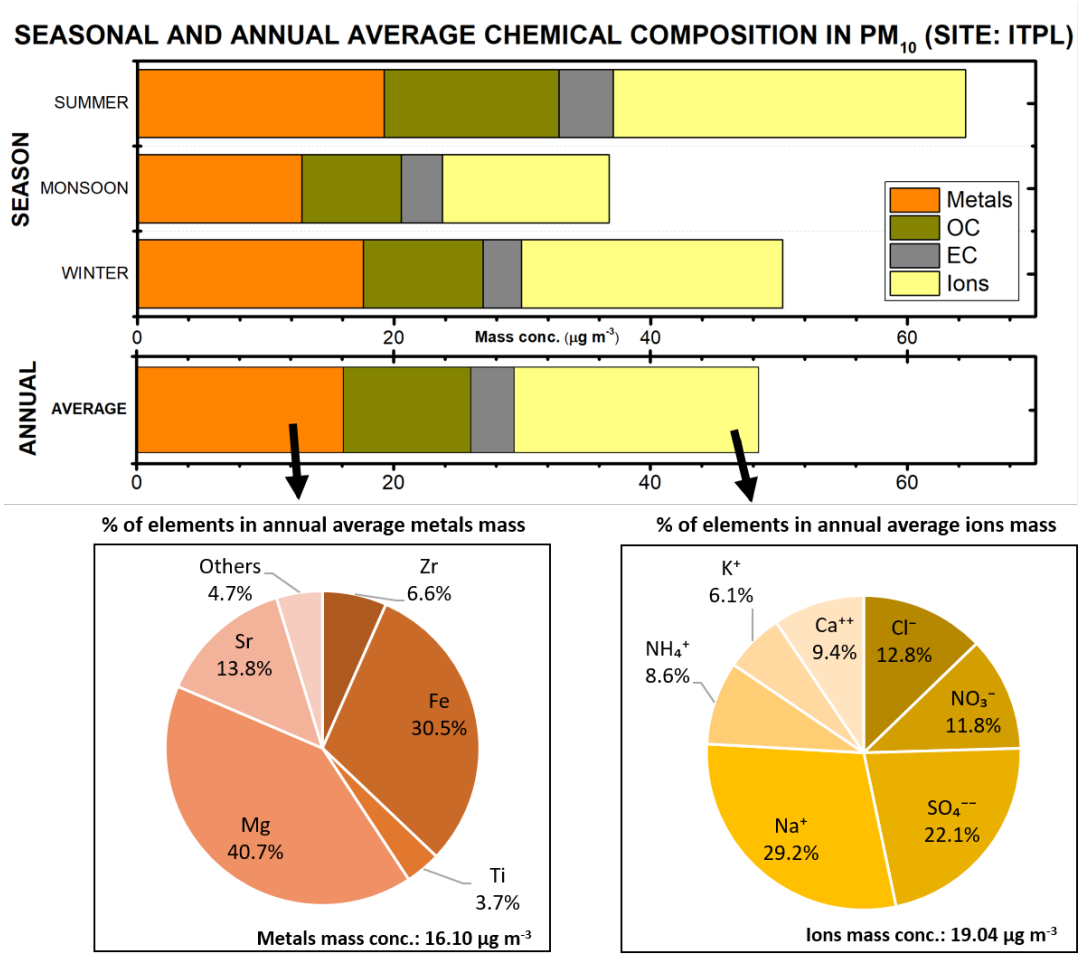

Figure 33: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and ions concentration was observed to be 16.1 and 19.0 µg m^{-3}, respectively. Among the average metals concentration, Mg (41%) contribution was high, followed by Fe (30%), indicating sources from crustal material. Among the ions, Na^+ (29%) contribution was high, followed by SO_4^{2-} (22%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.04, 0.08, and 0.07 µg m^{-3}, respectively. As and Ni showed around 13 and 2 times higher concentration compared to the annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to coal-burning and vehicular movement.

The mean OC and EC were quantified to be 9.90 µg m^{-3} and 3.38 µg m^{-3}. The ratio of OC to EC was calculated to be 2.92. The ratio of K^+ to EC was observed to be 0.34, which denotes contribution from biomass burning.

XI. SWAN Silk (SWAN)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 34). High value during summer is mainly attributed to the elevated EC, OC, SO_4^{2-}, and Ca^{2+} concentration, which indicates increased vehicular movement, construction, and burning activities. Low value during monsoon is due to the effect of rainfall that can settle the particles present in the atmosphere.

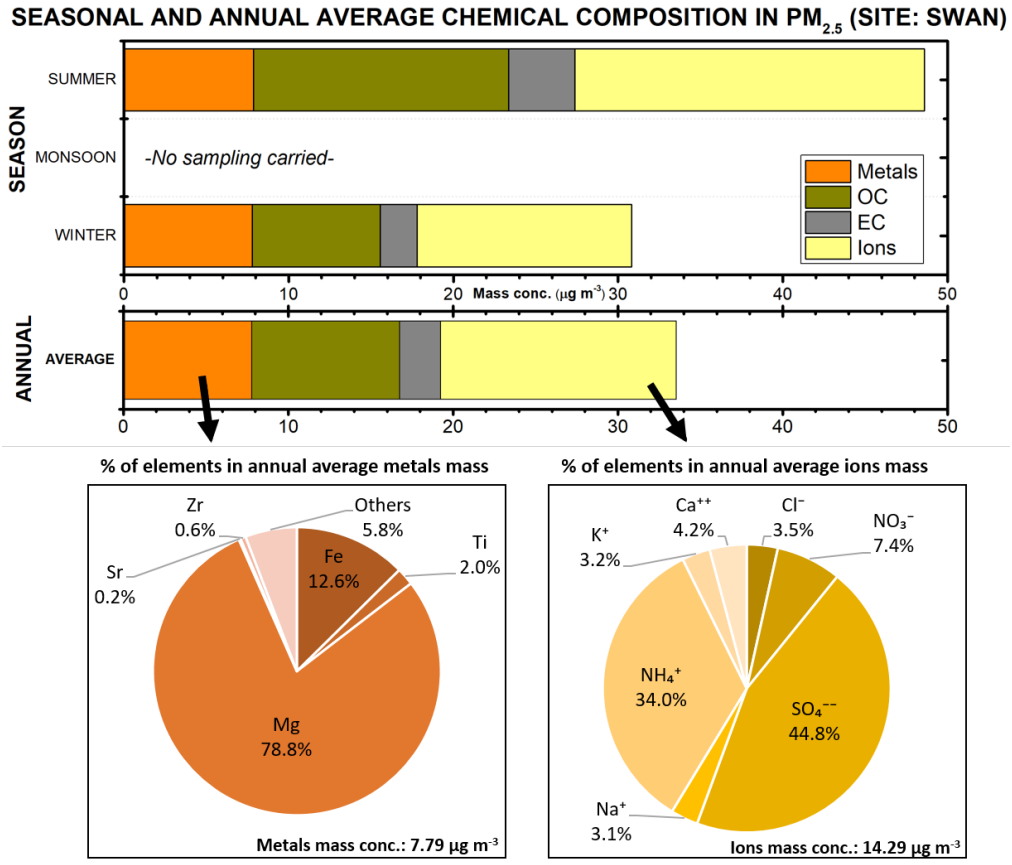

Figure 34: Seasonal and annual average chemical composition in $PM_{2.5}$. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metals, OC, EC, and Ions concentration was observed to be 7.79, 8.97, 2.49, and 14.29 µg m^{-3}, respectively. In the annual average metals concentration, Mg (78.8%) contribution was high, followed by Fe (13%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (44.7%) contribution was high, followed by NH_4^+ (33.9%), indicating source from secondary aerosols. The OC and EC were quantified to be 8.97 µg m^{-3} and 2.49 µg m^{-3}. The ratio of OC to EC was calculated to be 3.59, indicating sources from SOA. The ratio of K^+ to EC was observed to be 0.18.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 2.77 ng m^{-3}. The seasonal variation of 1-NP revealed high concentration during summer (2.92 ng m^{-3}), followed by winter (2.74 ng m^{-3}). The 1-NP is a source marker for diesel exhaust.

The annual mass concentration of Levoglucosan in $PM_{2.5}$ was found to be 136.9 ng m^{-3}. The seasonal variation of Levoglucosan revealed high concentration during winter (150.0 ng m^{-3}), followed by summer (80.0 ng m^{-3}). High concentration during winter indicates high leaf-burning activities.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 35). High values during summer can be attributed to the presence of vehicular movement and leaf-burning activities, which is indicated by the elevated OC and EC concentration during summer.

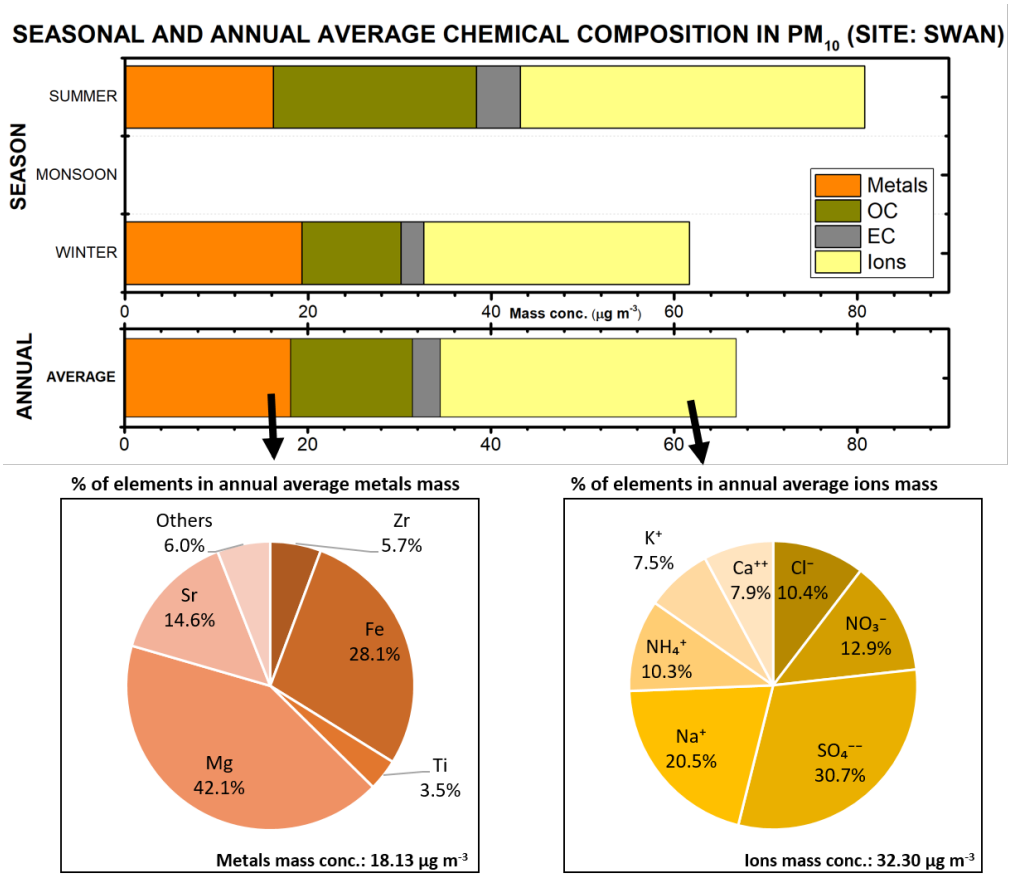

Figure 35: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and Ions concentration was observed to be 18.1 and 32.3 µg m^{-3}, respectively. Among the average metals concentration, Mg (42.1%) contribution was high, followed by Fe (28.1%), indicating sources from crustal material. Among the ions, SO_4^{2-} (30.6%) contribution was high, followed by Na^+ (20.4%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.034, 0.092, and 0.090 µg m^{-3}, respectively. As and Ni showed around 15 and 2 times higher concentration compared to their annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to coal-burning and vehicular movement.

The OC and EC were quantified to be 13.32 µg m^{-3} and 3.00 µg m^{-3}. The ratio of OC to EC was calculated to be 4.42, indicating sources from SOA. The ratio of K^+ to EC was observed to be 0.80, which denotes contribution from biomass burning.

XII. Urban Eco Park (UEP)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions, and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 36). High value during summer is mainly attributed to the elevated EC and OC concentration, which indicates increased vehicular movement and burning activities. Low value during monsoon is due to the effect of rainfall that can settle the particles present in the atmosphere.

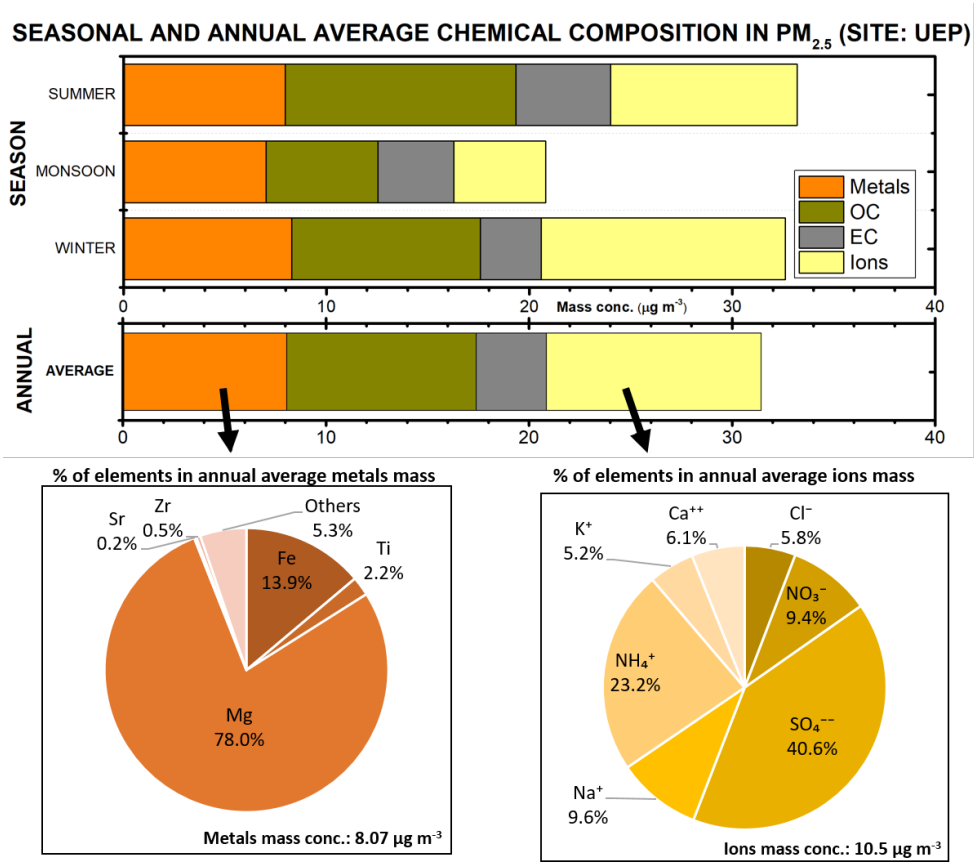

Figure 36: Seasonal and annual average chemical composition in $PM_{2.5}$. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metals, OC, EC and Ions concentration was observed to be 8.07, 9.33, 3.45, and 10.56 µg m^{-3}, respectively. In the annual average metals concentration, Mg (78%) contribution was high, followed by Fe (13.9%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (40.6%) contribution was high, followed by NH_4^+ (23.2%), indicating source from secondary aerosols. The OC and EC were quantified to be 9.33 µg m^{-3} and 3.45 µg m^{-3}. The ratio of OC to EC was calculated to be 2.70. The ratio of K^+ to EC was observed to be 0.16.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 2.87 ng m^{-3}. The seasonal variation of 1-NP indicates high concentration during monsoon (3.34 ng m^{-3}), followed by summer (3.03 ng m^{-3}) and winter (2.67 ng m^{-3}). The 1-NP is a source marker for diesel exhaust. At this site, Levoglucosan was not observed in the collected samples.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species were high in summer compared to winter and monsoon season (Figure. 37). High values during summer can be attributed to the presence of vehicular movement and leaf-burning activities, which is indicated by the elevated OC and EC concentration during summer.

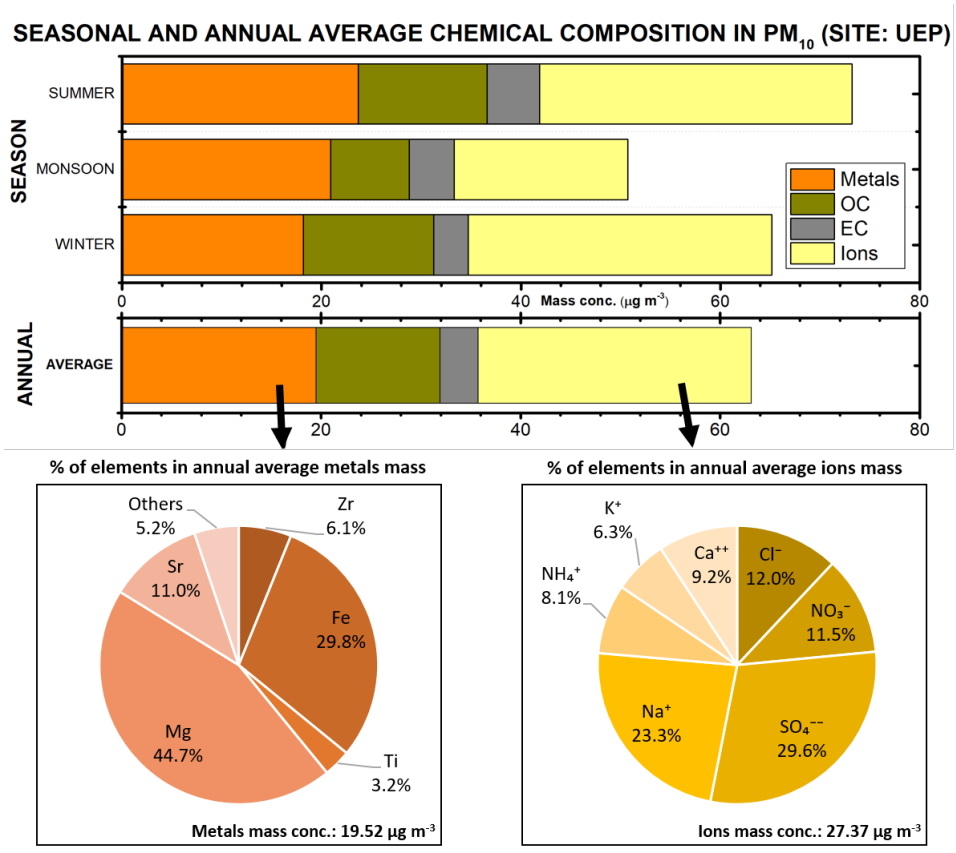

Figure 37: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and Ions concentration was observed to be 19.5 and 27.3 µg m^{-3}, respectively. Among the average metals concentration, Mg (44.7%) contribution was high, followed by Fe (29.8%), indicating sources from crustal material. Among the ions, Na^+

(23.2%) contribution was high, followed by SO_4^{2-} (29.6%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.04, 0.10 and 0.09 µg m^{-3}, respectively. As and Ni showed around 17 and 2 times higher concentration compared to their annual permissible limit of 0.006 and 0.02 µg m^{-3}, respectively. High As and Ni concentration is attributed to coal-burning and vehicular movement.

The OC and EC was quantified to be 12.42 µg m^{-3} and 3.81 µg m^{-3}. The ratio of OC to EC was calculated to be 3.25, indicating sources from SOA. The ratio of K^+ to EC was observed to be 0.45, which denotes contribution from biomass burning.

XIII. Rail Wheel Factory (RWF)

$PM_{2.5}$ (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, ions, and molecular markers) associated with $PM_{2.5}$ was carried out. Results revealed that the sum of chemical species was high in monsoon compared to winter and summer season (Figure. 38). High value during monsoon is mainly attributed to the elevated NH_4^+ and Mg concentration, which indicates increased burning activities and soil dust.

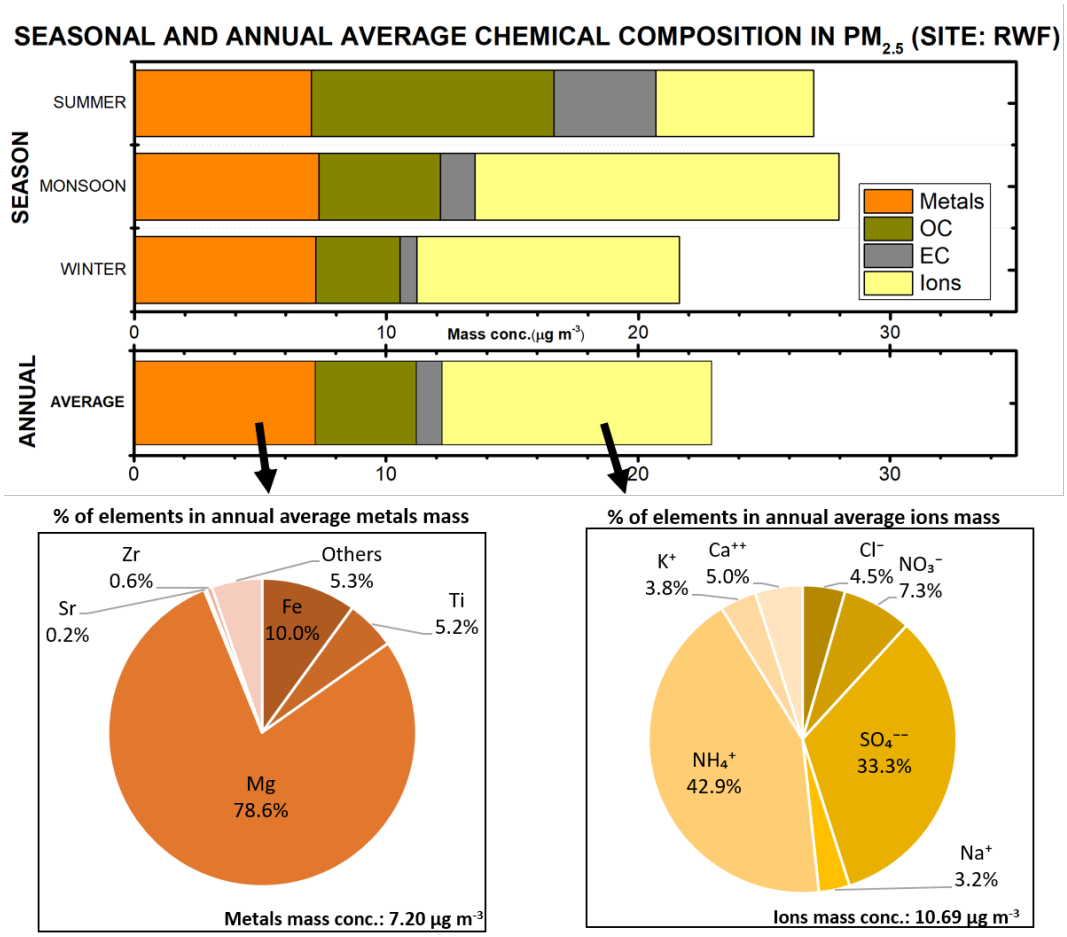

Figure 38: Seasonal and annual average chemical composition in $PM_{2.5}$. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metals, OC, EC, and ions concentration was observed to be 7.2, 4.0, 1.0, and 10.7 µg m^{-3}, respectively. In the annual average metals concentration, Mg (78.6%) contribution was high, followed by Fe (10%), indicating aerosol source from crustal materials. Among ions concentration, SO_4^{2-} (33.2%) contribution was high, followed by NH_4^+ (42.9%), indicating source from secondary aerosols. The OC and EC were quantified as 4.00 µg m^{-3} and 1.01 µg m^{-3}. The ratio of OC to EC was calculated to be 3.95, indicating sources from SOA. The ratio of K^+ to EC was observed to be 0.40, suggesting contribution from biomass burning.

The annual mass concentration of 1-NP in $PM_{2.5}$ was observed to be 2.20 ng m^{-3}. The seasonal variation revealed high concentration during winter (2.25 ng m^{-3}), followed by monsoon (1.93 ng m^{-3}). The 1-NP is a source marker for diesel exhaust. At this site, Levoglucosan was not observed in the collected samples.

PM_{10} (Chemical composition): The seasonal analysis of the chemical species (metals, OC, EC, and ions) associated with PM_{10} was carried out. Results revealed that the sum of chemical species was high in summer compared to winter and monsoon season (Figure. 39). High values during summer can be attributed to the presence of vehicular movement and leaf-burning activities, which is indicated by the elevated OC and EC concentration during summer.

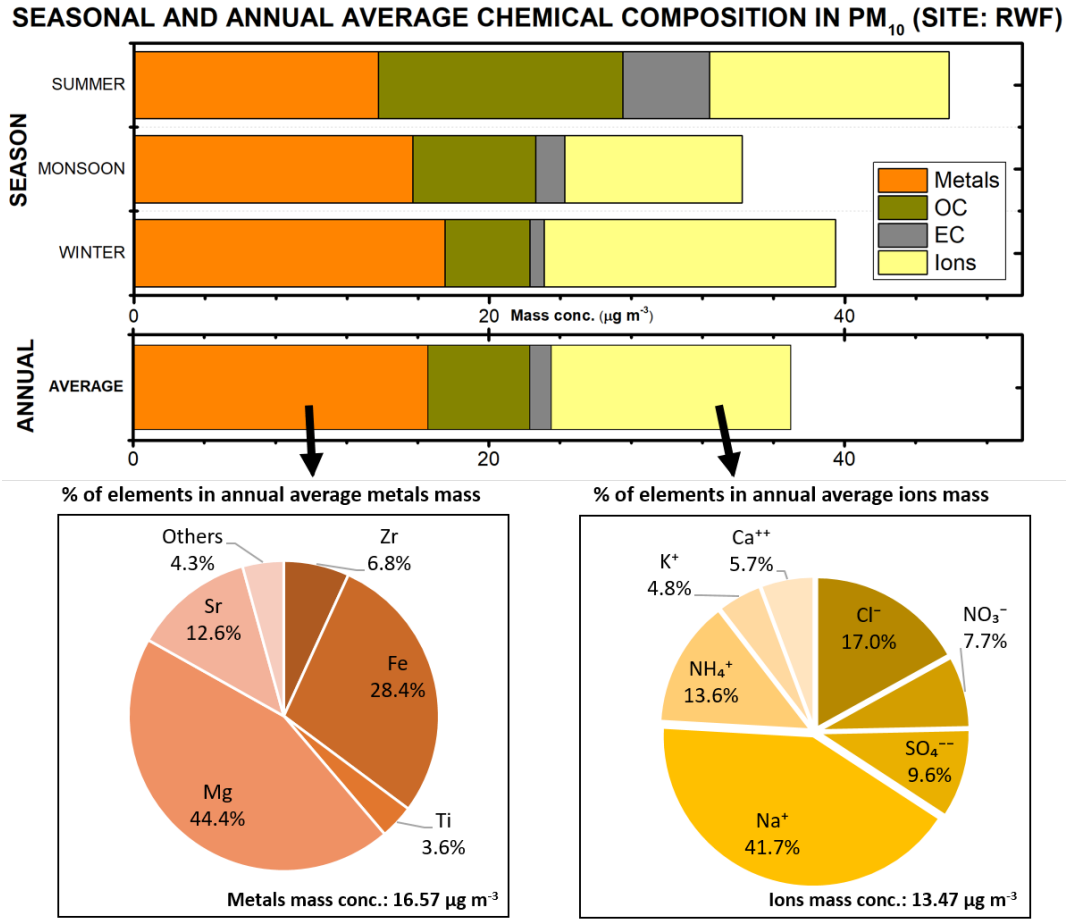

Figure 39: Seasonal and annual average chemical composition in PM_{10}. The pie charts indicate the % of elements in annual average of metals and ions mass.

Overall, the annual average metal and ions concentration was observed to be 16.5 and 13.4 μg m^{-3}, respectively. Among the average metals concentration, Mg (44.4%) contribution was high, followed by Fe (28.4%), indicating sources from crustal material. Among the ions, Na^+ (41.7%) contribution was high, followed by Cl^- (17.0%), indicating sources from road dust and secondary aerosols.

The annual average concentration of criteria pollutants such as Ni, As, and Pb was found to be 0.08, 0.107, and 0.05 μg m^{-3}, respectively. As and Ni showed around 18 and 4 times higher concentration compared to their annual permissible limit of 0.006 and 0.02 μg m^{-3}, respectively. High As and Ni concentration is attributed to coal-burning and vehicular movement.

The OC and EC were quantified to be 5.72 μg m^{-3} and 1.22 μg m^{-3}. The ratio of OC to EC was calculated to be 4.68, indicating sources from SOA. The ratio of K^+ to EC was observed to be 0.53, which denotes contribution from biomass burning.

Annexure IV

Association between road network and transportation sector share in PM concentrations

The road network shape files over Bengaluru were downloaded from Open Street Map (OSM) (https://www.openstreetmap.org/). The road network information was extracted for an area of 2 km radius around each of the 13 sampling sites. In OSM, the road types are classified as primary, residential, secondary, tertiary, trunk, and others. 'Others' include construction, footway, living street, motorway, track, service, and unclassified roads. The length of each road types found around every site is mentioned in the table 1.

Moreover, a moderate R^2 (0.52) was observed between road length (trunk + tertiary roads) and the transportation sector source contribution to $PM_{2.5}$. This shows the relationship between length of trunk roads and the transportation sector contribution. However, no relationship was found between trunk road length and transportation sector source contribution to PM_{10}.

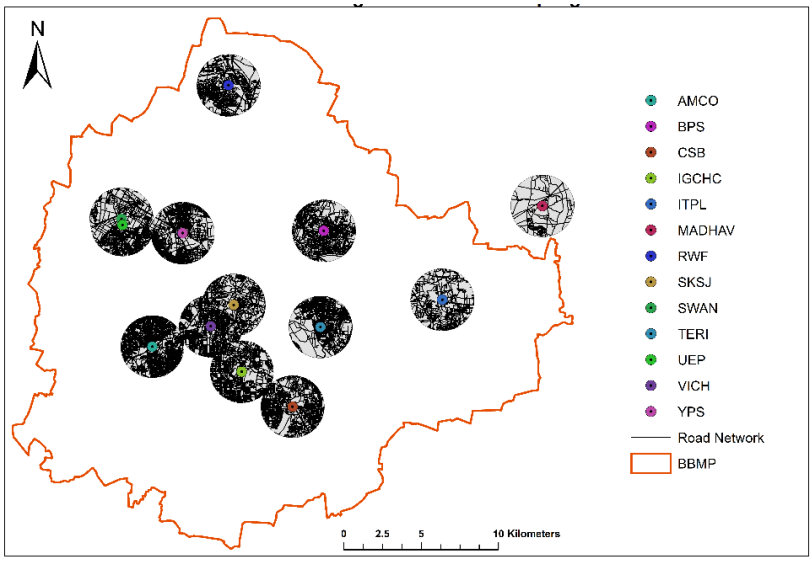

Figure 40: Road network around 2 km radius of each sampling site

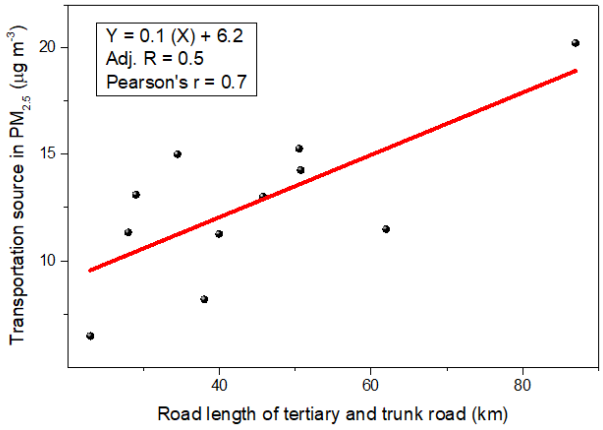

Figure 41: Association between road length (tertiary & trunk) and transportation source in $PM_{2.5}$.

Table 1: Road lengths of various road types around 2 km radius of sampling sites

SITE	Road lengths (km)					$PM_{2.5}$ source contribution from Transportation (µg m^{-3})	$PM_{2.5}$ source contribution from Transportation (µg m^{-3})
	Residential + Primary	Secondary	Tertiary + Trunk	Others	Total		
TERI	760	24	38	808	1630	8.2	15.6
MADH	17	7	40	191	255	11.3	12.3
IGCHC	181	41	29	185	436	11.3	9.6
VICH	640	80	96	1049	1865	11.5	9.5
CSB	1032	32	87	359	1510	20.2	17.6
YPS	96	30	34	261	422	15.0	19.9
AMCO	265	20	50	146	482	15.3	17.7
ITPL	70	14	29	290	402	13.1	12.0
SWAN	95	23	46	193	347	13.0	24.6
UEP	109	14	51	200	374	14.3	15.8
RWF	132	26	23	296	477	6.5	9.5
BPS	176	16	41	103	337	NS	NS
SKSJ	424	88	160	1215	1887	NS	NS

(**NA = Not Available; NS = No Sample*)

Annexure V: Comparative analysis of CMB and PMF

PMF is a powerful multivariate statistical method which has been extensively used for identification of various pollutants. The model carries out multiple iterations to finalise the best possible factor contributions and the sources. The mass concentration of the chemical species and its respective uncertainties are used as inputs for the PMF.

For running the PMF model with a statistically valid sample size, all the samples were clubbed to ascertain the source contribution of PM_{10} in the city. The clubbed samples are part of the city and represent the sources in the city, with some local variations. Result revealed the presence of vehicular, construction, waste burning, soil dust, secondary aerosols, and combustion sources.

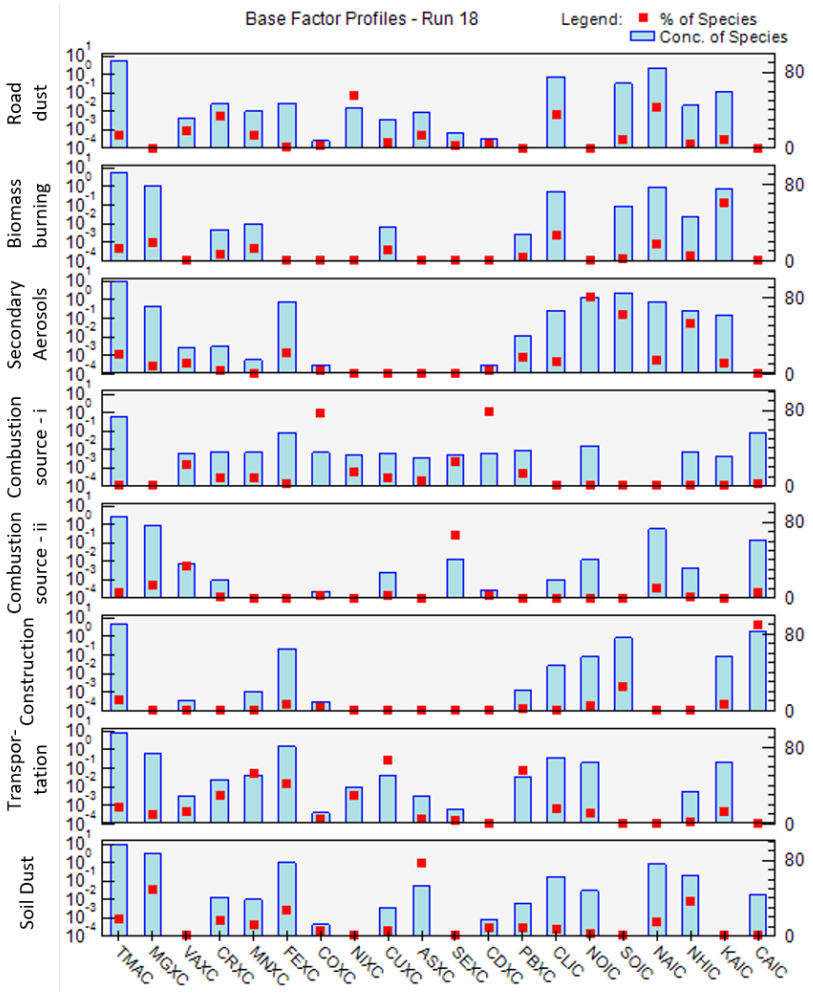

Figure: Source profiles or factors identified by PMF

The CMB analysis performed at the sampling sites also revealed similar sources with some local variations. Hence, both the approaches (CMB and PMF) showed similar results and provide confidence in the datasets.

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