Receptor Modelling Based Source Apportionment Study of Ambient Particulate Matter in Patna City, Bihar

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THE ENERGY AND RESOURCES INSTITUTE
Creating Innovative Solutions for a Sustainable Future

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PREFACE

The expeditious growth of industrial setup and urbanization in Indian cities have resulted in consequential increase in air pollution. Epidemiological studies reported that air pollution in developing countries accounts for large number of deaths and billions of dollars being lost in medical expenses every year. Air quality data shows that most cities in India violate the standards of national ambient air quality. There is a growing need to determine the state of urban air quality and to identify the most effective measures to protect human health and environment.

The problem has been acknowledged and some of the required steps are being taken to curb this problem without any further ado. The Ministry of Environment, Forest and Climate Change (MoEF&CC), Government of India launched the National Clean Air Programme (NCAP) with concerned government agencies, NGOs, experts and citizens, with the objective of defining a plan of action to combat ambient air pollution aiming for a 20–30% reduction in PM_{10} and $PM_{2.5}$ concentrations by 2024, compared to their respective concentrations in 2017. Under the NCAP, 122 cities in India were identified as non-attainment cities in which the prescribed annual National Ambient Air Quality Standards (NAAQS) of PM_{10} were violated for over five consecutive years. Patna has been identified as one of the non-attainment cities under the NCAP.

Hence, this report is a detailed analysis of relationship between pollutant (PM) concentration and the contributions of prevailing emissions sources. The study includes ambient air quality monitoring, chemical characterization of PM samples, and subsequent use of receptor modelling tool, *i.e.* the Chemical mass Balance (CMB) model for quantification of source contributions. With support from Bloomberg Philanthropies, the study was completed in collaboration with the Bihar State Pollution Control Board (BSPCB) and Asian Development Research Institute (ADRI), Patna.

This report could provide useful insights for the policymakers to make informed decisions to manage ambient concentrations of fine and coarse particulate matter in Patna city following a time bound action plan. This report intends to provide a plan based on which future initiatives can be taken for air quality improvement in Patna.

ACKNOWLEDGEMENT

We extend our sincere gratitude to the Ministry of Environment, Forest and Climate Change (MoEF&CC) and Bihar State Pollution Control Board for their continued support and guidance in carrying out this study. We thank Bloomberg Philanthropies for their assistance in this study. The project team sincerely thanks Dr. Ashok Ghosh, Chairman, Bihar State Pollution Control Board (BSPCB); Mr. Alok Kumar, (Ex-) Member Secretary, BSPCB and Dr Ajay Mathur, former Director General, TERI for their encouragement in executing the project.

We sincerely thank Centre for Environment, Energy & Climate Change, at the Asian Development Research Institute (CEECC, ADRI), Patna for their co-operation during field monitoring and primary survey.

We are sincerely grateful to all peer reviewers for their valuable suggestions, which have helped us immensely in preparing this report.

ABBREVIATIONS

ARAI:	Automotive Research Association of India
Al:	Aluminum
As:	Arsenic
Ag:	Silver
BS:	Bharat Stage
Ba:	Barium
Br:	Bromine
Br-:	Bromide Ion
BSPCB:	Bihar State Pollution Control Board
cc:	Cubic Centimetre
CCAAP:	Comprehensive Clean Air Action Plan for city of Patna
CNG:	Compressed Natural Gas
CPCB:	The Central Pollution Control Board
CO:	Carbon Monoxide
Cl:	Chlorine
Ca:	Calcium
Co:	Cobalt
Cu:	Copper
Cr:	Chromium
Cd:	Cadmium
Cl^{-}:	Chloride Ion
Ca^{2+}:	Calcium Ion
DG Sets:	Diesel Generator Sets
EV:	Electric Vehicle
EC:	Elemental Carbon
Fe:	Iron
F^{-}:	Fluoride Ion
GAIL:	Gas Authority of India Limited
Ga:	Gallium
Hg:	Mercury
In:	Indium
km:	Kilometre
kg/cm^{2}:	Kilogram per square centimetre
K^{+}:	Potassium Ion
LPG:	Liquefied Petroleum Gas
La:	Lanthanum
MT:	metric tonne
Mg:	Magnesium

Mn:	Manganese
Mo:	Molybdenum
NH_4^+:	Ammonium Ion
Na^+:	Sodium Ion
Mg^{2+}:	Magnesium Ion
MSW $^+$:	Municipal Solid Waste
NAAQS:	National Ambient Air Quality Standards
NO_2:	Nitrogen Dioxide
NAMP:	National Air Monitoring Program
Na:	Sodium
Ni:	Nickel
NO_2^-:	Nitrate Ion
NO_3^-:	Nitrite Ion
OC:	Organic Carbon
PWD:	Public Works Department
PM:	Particulate Matter
PM_{10}:	Particulate matter less than 10 micrometer
$PM_{2.5}$:	Particulate matter less than 2.5 micrometer
P:	Phosphorous
Pd:	Palladium
Pb:	Lead
PIB:	Press Information Bureau
PMC:	Patna Municipal Corporation
Rb:	Rubidium
Sq km:	Square Kilometer
SO_2:	Sulphur Dioxide
Si:	Silicon
S:	Sulphur
Sn:	Strontium
Se:	Selenium
Sr:	Strontium
Sb:	Antimony
SO_4^{2}:	Sulphate Ion
TPD:	Tonnes per day
TOI:	Times of India
Ti:	Titanium
USEPA:	United States Environment Protection Agency
V:	Vanadium
Y:	Yttrium
Zn:	Zinc
Zr:	Zirconium
$\mu g/m^3$:	Microgram per cubicmeter
μm:	micrometer

EXECUTIVE SUMMARY

Photo: Mrinal Alexander Emmanuel

EXECUTIVE SUMMARY

Patna has been listed as one of the most polluted cities among 122 non-attainment cities in India. To effectively control pollution in the city it is important to determine the contribution of different sectors and sources to the ambient air pollution.

Systematic assessment of ambient air quality and quantification of sources of pollution is a pre-requisite for taking necessary measures for control. Hence, this study is a comprehensive evaluation of the concentration of particulate matter (PM) in the air, which is emitted from various sources in and around the city. Ground-based ambient air quality monitoring was conducted at several locations in Patna. It was based on the protocol and guidelines prescribed by the CPCB, which are used to assess the contribution of sources to pollution in the city.

Seven ambient air quality monitoring locations (receptor locations) were selected based on different land-use categories within the city: (i) background/reference (one towards seasonal prevailing wind direction outside the administrative boundary of the city), ii) residential (three locations based on different population density), iii) industrial (one), iv) commercial (one), and v) Kerbside (one). The 24-hourly ambient air quality monitoring was carried out at each of the selected locations continuously for 15 days for PM_{10} and $PM_{2.5}$ samples using quartz and teflon filters. The summer season monitoring was carried out in May–June 2019 and winter season monitoring was carried out in December 2019–January 2020. Chemical characterization of the collected PM_{10} and $PM_{2.5}$ samples was carried out. These were then fed along with source profiles into the CMB receptor model to derive source contributions of PM_{10} and $PM_{2.5}$ in the city of Patna. The results were also compared with the earlier conducted study under Comprehensive Clean Air Action Plan for City of Patna (CCAAP), 2019 and based on the source contributions, specific air quality strategies have been suggested. Major findings of this study are as follows:

1. Ambient PM_{10} and $PM_{2.5}$ concentrations were found to be higher than the prescribed standards, particularly in winter season. PM_{10} and $PM_{2.5}$ concentrations for summer season were 152±43 µg/m³ and 43±13 µg/m³ whereas PM_{10} and $PM_{2.5}$ concentrations for winter season were 241±60 µg/m³and 130±37 µg/m³, respectively. Concentrations of PM_{10} varied from 103 to 271 µg/m³ in summer season and 198 to 277 µg/m³ in winter season across different monitoring stations. Average concentration of $PM_{2.5}$ in summer season across different monitoring locations ranged between 32 and 64 µg/m³ and 82 and 197µg/m³ during winter season.
2. Average ambient concentrations of PM_{10} were approximately 1.73 to 2.71 times higher than the NAAQS during summer season. It was 1.98 to 2.77 times higher than the NAAQS during winter period. Average ambient $PM_{2.5}$ concentrations were approximately 1.37 to 3.28 times higher than the NAAQS limit during winter season.
3. Ions were identified as the most dominating chemical constituents in PM_{10} and $PM_{2.5}$. samples. NH_4^+, Ca^{2+}, Cl^-, SO_4^{2-} and NO_3 were found in major proportion in PM_{10} samples while NH_4^+, Cl^-, and SO_4^{2-} ions were found in major proportion in $PM_{2.5}$ samples in winter, ionic contribution was highest in $PM_{2.5}$ followed by total carbon and elements.
4. Receptor model results show that dust (soil, road, and construction) is the major contributor of PM_{10} in both winter (30%) and summer (57%). Secondary inorganic particulates, which are formed by reactions of gases such as ammonia, SO_2 and NOx, contribute to 24% in winter and 9% in summer in PM_{10} concentrations. In summer, another important source is the industrial sector which contributes to an average of 13% of PM_{10} concentration in Patna city. Vehicles and biomass burning contribute to 4–13% and 9–14% in the PM_{10} concentrations during the two seasons, respectively.
5. $PM_{2.5}$ source contributions are somewhat different than PM_{10}. Sources which emit particles more in fine range (e.g. biomass burning and vehicles) show more contributions in $PM_{2.5}$ than in PM_{10}. In winter, secondary particulates contribute to about 38% in the $PM_{2.5}$ concentration which is the highest

contribution from any source in the season. It ranges from 29% to 48% at different locations in the city. $PM_{2.5}$ contribution in winter from biomass (21%) and transport (18%) are found to be more than PM_{10}, depicting dominance of fine particulates from these sectors. Average industrial contributions to $PM_{2.5}$ range between 10% and 27% during the two seasons.

6. The results of receptor based modelling were compared with the dispersion modelling results of the CCAAP (2019) and were found to be in broad agreement with the findings of current study with some variations.
7. A comparative analysis of CMB and PMF models shows that both the models are congruent to each other and shows that dust (road, soil & construction) and industries/power plants are the major contributor to $PM_{2.5}$ concentrations in summer season. Whereas, in the winter season, secondary particulate contributed majorly to the $PM_{2.5}$ concentration followed by the residential sector.
8. Based on the results, specific strategies for control of pollution in the city of Patna have been suggested.
   a. Development of a regional scale plan for control of pollution in Bihar with Patna and other important cities as hotspots.
   b. A green belt with local dense canopy tree species on the bank of river Ganga to stop the windblown dust sediments reaching the city.
   c. Dust control at major construction sites in the city through barriers, cleaning, and dust suppressants.
   d. Regular mechanical sweeping of city roads (including minor roads), particularly near the construction sites.
   e. Legislation on use of cleaner fuels (gas/electricity) instead of biomass and coal in industries/brick kilns around Patna city, else real-time monitoring of stacks and mandatory use of high-efficiency control devices with standards to be made more stringent.
   f. Capacity building of SPCB with more budgetary allocations, staff, skill sets, and equipment.
   g. Penetration of LPG in district in a time-bound manner and distribution of two free cylinders, in winter, to people below poverty line.
   h. Improvement of vehicular inspection and maintenance programme (experiment with remote sensing technology) in and around Patna city.
   i. Enhancement of public transport system, preferably on electric modes, and installation of electric charging infrastructure.
   j. State-level fleet modernization plan with concessions on registration fees to old vehicle owners for early fleet modernization; heavy penalties on unregistered, visibility polluting vehicles.
   k. Awareness programme to encourage people for non-motorized transportation within 5 to 6 km in the city and introduction of non-motorized lanes wherever possible within the city.
   l. Increase plantation in open spaces within city, wherever possible.
   m. Development of graded response plan, emergency response plan, and forecasting system for early warnings.

Report Structure

Chapter 1: Introduction – Background, objectives and approach of the study.

Chapter 2: Ambient Particulate Matter Concentration – Ambient air quality status at the selected seven monitoring locations in Patna during both winter and summer seasons.

Chapter 3: Ambient Particulate Matter Characterization – Spatial variation of characterization and speciation of the ambient particulate matter related to ions, elements and carbon (elemental and organic) species concentration for both winter and summer seasons.

Chapter 4: Receptor Modeling – Air quality receptor modelling results to estimate the contributions of various sources to ambient particulate matter.

Chapter 5: Summary & Conclusions

1 INTRODUCTION

In the last decade, the ambient air pollutants concentrations have increased in several Indian cities. In 2019, in this regard, the National Clean Air Programme (NCAP) was launched with the aim to reduce the ambient particulate matter concentrations in the non-attainment cities by 20–30% by 2024, compared to their respective concentrations during 2017.

Detailed scientific studies are required to identify major sources of air pollution and their contribution to the ambient air quality of a region. Estimation of percent or fraction contributed by different sources to any receptor and relating emission of pollutants from different sources to their quantitative impact on ambient air pollution is referred to as source apportionment of air pollution. Different modelling techniques are used to assess the contribution of different sources to the ambient air pollution level in a region. These assessments have proven to be very effective in developing appropriate strategies for improvement of air quality in a region in a given timeframe.

The Central Pollution Control Board (CPCB) has identified 122 most polluted cities in India as non-attainment cities where the prescribed National Ambient Air Quality Standards (NAAQS) have been violated for over a period of five years. Patna has been identified as one of the three non-attainment cities in Bihar. In recent times, the city has witnessed unprecedented growth in population and economic status with more number of industries being set up and growing vehicular population on roads. This study envisages to provide scientifically backed information to the decision makers to make adequate measures for improvement in ambient air quality in Patna city.

1.1 Patna City – Background

Patna is one of the oldest cities in India. Reference to the existence of the city is found in ancient Buddhist literatures. Back in 490 BC, the city was known as Patliputra and was the capital of Mouryan Empire during 322 to 188 BC. The city extends along the south bank of river Ganga for about 12 miles (19 km) (Figure 1.1). Patna is under the Patna Sahib Assembly constituency. Patna has a designated regional development area that covers 234.70 km^2 and includes outgrowths within the Patna district [which are under the Patna Urban Agglomeration (Danapur, Khagaul and Phulwari Sharif)]. Patna is the twenty-first fastest growing city in the world, and the fifth fastest growing city in India. It is expected to grow at an average annual rate of 3.72% (city mayor).

The Patna Municipal Corporation (PMC) was established in 1952 in accordance with The Patna Municipal Corporation Act, 1951. It is spread over 109.45 km^2 and is divided into 72 wards which are managed through four Circles. The Circles are as follows:

1. New Capital Circle: This is the largest Circle comprising 29 Wards (1-28 and 37). The important Wards in this Circle cover Bailey Road, Boring Road, Khajpura, Kurji, Rajiv Nagar, Station area, Gandhi Maidan, etc.
2. Kankarbagh Circle: This Circle covers 11 Wards (29–35, 44–46 and 55). The main areas covered under this circle are New Bypass road, Kankarbagh, Chiraiyatadr railways bridge, Gandhi Setu and Saidpur.
3. Bankipore Circle: The Circle covers 12 Wards (36–43 and 47–51). The main areas covered under this circle are Ashok Rajpath, Saidpur main drain, Bakerganj, Gandhi Ghat and Bari path.

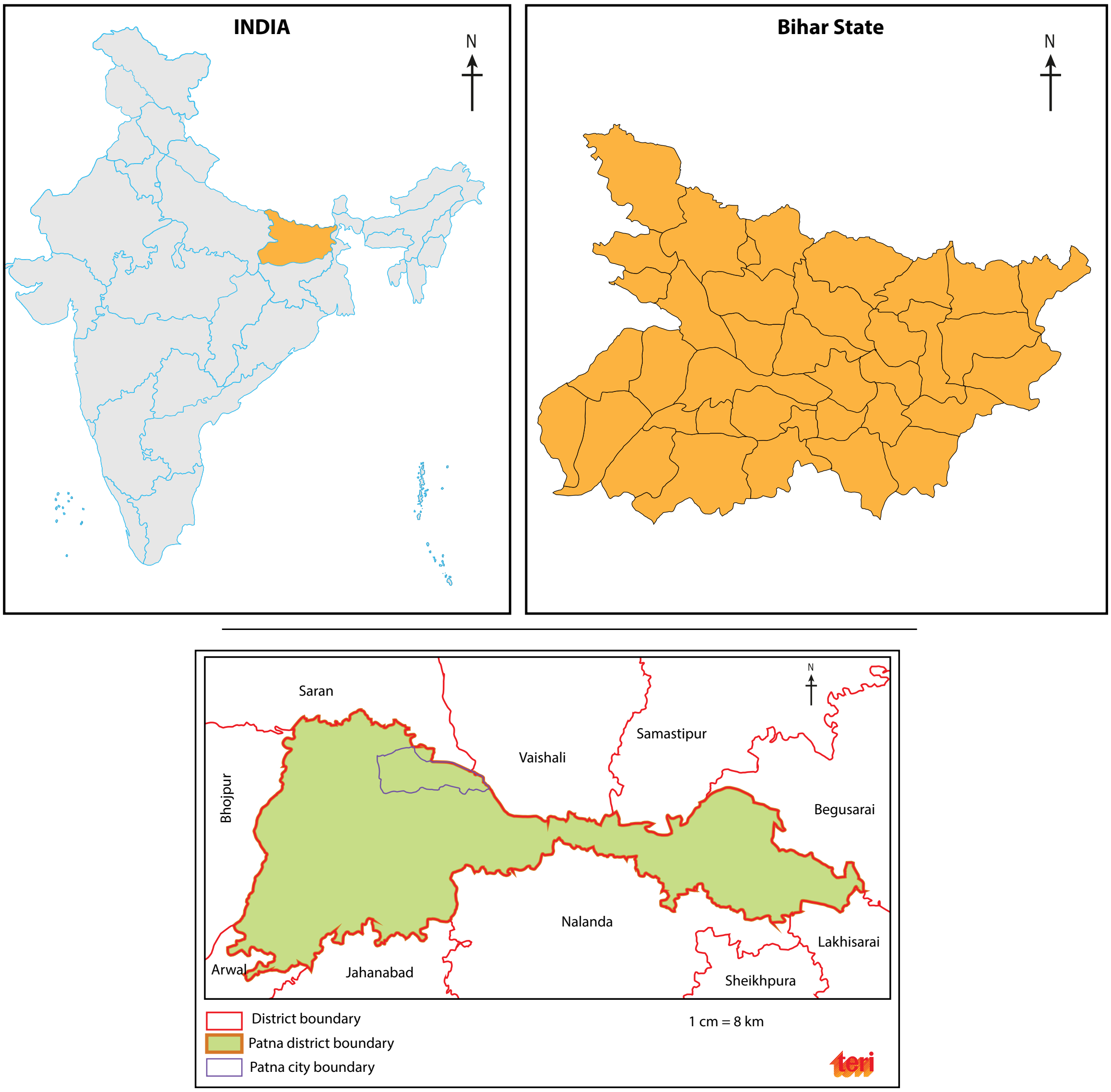


Figure 1.1 Geographical location of Patna city, India

4. Patna City Circle: The Circle covers 20 Wards (52–72). The main areas covered are Gaighat, Dundi Bazar , Mahatma Gandhi Setu road, New Bypass road, Patna Ghat and MaalGodam.

1.1.1 Demographics

Patna estimated population was 1.68 million in 2011, with a decadal population growth rate of 22.34% (Census, 2011) (Table 1.1). As per Census 2011, the population of Patna District is 5,838,465 (Male: 3,078,512 and Female: 2,759,953). The growth rate between 2001 and 2011 was 23.73%. The overall literacy rate is 70.68%; the male literacy rate is 78.48% and female literacy rate is 61.96%. With over million urban population, Patna is the eighteenth largest urban agglomerate in India (Press Information Bureau).

Table 1.1: Demographic Profile of Patna Municipal Corporation

Demographic	Year 2011–2012
Population City	1684222
Population (Male)	893,399
Population (Female)	790,823
Decadal Growth Rate (%)	22.34
Population Density(per km^2)	1803
Area (km^2)	99.45

Source: Census of India (2011)

1.1.2 Population Growth

Population of the city has increased by 22.3% from 2001-2011. According to 2011 census, the female population growth rate of the city was 27.5% which was 7.8% higher than male population growth rate of 19.7%. Patna has witnessed a decadal growth rate of 21.8% in 1951 to a surge to about 44% in 2001. However, the region witnessed a dip in the growth rate to about 22.34% during 2001–2011. The slum population in Patna is around 4.6% of the total population. Population growth and decadal population growth rate are shown in Figure 1.2.

1.1.3 Climate

Patna experiences extreme climate during some parts of the year; summer temperature can rise up to 46°C while in winter, it can go down to 4°C. Moreover, the city, being in the vicinity of three large rivers, experiences rather high humidity throughout the year. Summer begins in April and peaks in June/July till the moisture laden monsoon winds bring rains. The rains last through August and September and continue into early October. The northern Indian winters bring extremely cold nights from November to February till the arrival of the spring that brings the weather to a full cycle.

1.1.4 Vehicular Growth and Road Network

In 2011, the World Bank ranked Patna second after Delhi among the growing cities of the country (TOI). According to the 2011 Census of India, 32% of the households own a two-wheeler, and 10% own a four-wheeler. The existing road network in Patna is linear and the total road length in the city is about 3040 km, out of which arterial roads are 205 km, major are 183 km and collector are maximum of 2651 km. The city is well connected by road, rail and air. NH 19, NH 83 and NH 98 pass through the municipal corporation limits. The overall road density of the Patna Municipal Corporation area is 0.28 km per hectare and varies from ward to ward. It is projected that by 2030, at least 500 additional public buses need to ply in Patna to achieve the target modal share of 40% as prescribed under the city mobility plan (CCAAP, 2019). The total number of vehicles in the city has increased from nearly 2.2 lakh in 1996 to nearly 4.71 lakh in 2008, at a compounded growth rate of 6.7% and further to 11.36 lakh in 2016. In Patna, the mode share of public transportation is only around 21% (CCAAP, 2019). Enormous increase in the number of vehicles plying on road has resulted in severe traffic congestions and contributed in raising the air and noise pollution levels in the city. Vehicle parking is yet another issue that needs to

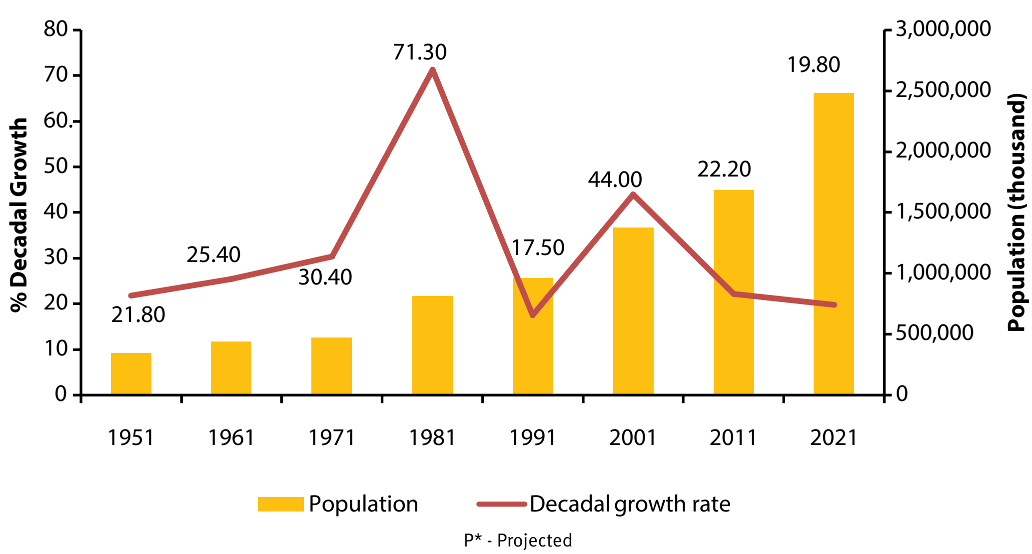


Figure 1.2 Decadal population and population growth rate for the city of Patna

Source: Census of India 2011

be addressed which is a concern at the moment and leads to increasing travel time and reducing vehicular efficiency in the city.

1.1.5 Economic Profile

Patna is an important commercial centre. Due to its central position at the junction of the three rivers, it has the additional advantage of transport of goods by river. Patna is majorly involved in export of grain, sugar cane, sesame, and medium-grained Patna rice. The municipal corporation area comprises large business quarters, namely Marufganj, Masurganj, Mirchiyaganj, Maharajaganj, etc. The commercial establishments within the city are mainly lined along the arterial and major roads, and there are several areas with mixed land use (commercial and residential) throughout the city (BIH).

Since 2005, Patna's economy has seen sustainable growth. The consumer goods industry and the service sector have witnessed fast paced growth and because of this the World Bank in 2009 declared Patna as the second best city in India to start up a business. In 2015, the gross domestic product (GDP) per capita of Patna was INR 106,000 and its GDP growth rate is 7.29 per cent (Patna Municipal Corporation). The urbanization rate in Patna was 43% in 2011, much higher than any other city in Bihar.

The first Software Technology Park of Bihar was developed in Patna by the Bihar State Electronics Development Corporation Limited (BSEDC), which is the nodal agency for development of IT industry in the State. The total worker population of Patna urban agglomeration is 25.2% of the total population; the male worker population is 3.8 lakh (41.4%) and that of females is 0.45 lakh (5.8%). The working population of Patna city is 33% of the total worker population of Bihar state (CEPT, 2014).

1.1.6 Land Use

Rapid growth and limited scientific land-use planning have led to reduction in open spaces and forest area (2.34 m² per capita) and formation of slum and rapid construction activity within the city. About 48% of the total land area of the city is under residential use, while 4% is in commercial zone, 10% is with public and semi-public areas, and 18% is vacant or agricultural land (Figure 1.3).

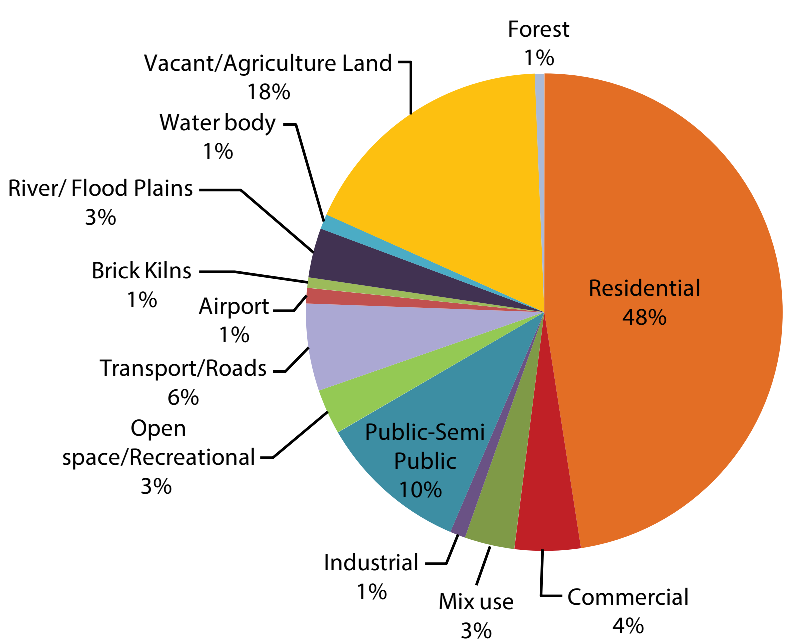


Figure 1.3 Land-use pattern of Patna city, 2014

Source – Patna Master Plan, 2031

1.1.7 Municipal Solid Waste (MSW) Management

At present 1000–1200 tonne per day (TPD) of waste is generated in the city with the per capita generation being approximately 450 gm to 600 gm per day. Out of this, 40% is residential waste and 60% is industrial and commercial waste (Bhanu et al., 2014). Solid waste comprises vegetable fractions (51%), combustible fractions (12.5%) and non-combustible fraction (38.5%) (Pandey et al., 2016) (Figure 1.4). PMC collects and currently dumps the wastes at the landfill area. A large proportion of the waste is generated from households, hotels, resorts, restaurants, and other businesses. The pick-up station (PS) collection system of solid waste is also not practiced scientifically. The number of collection points /vats is not adequate to receive the quantum of solid waste generated daily. Thus, the collected solid waste is transported to dumping sites by means of open trucks, tractors, and trailers (CEPT, 2014).

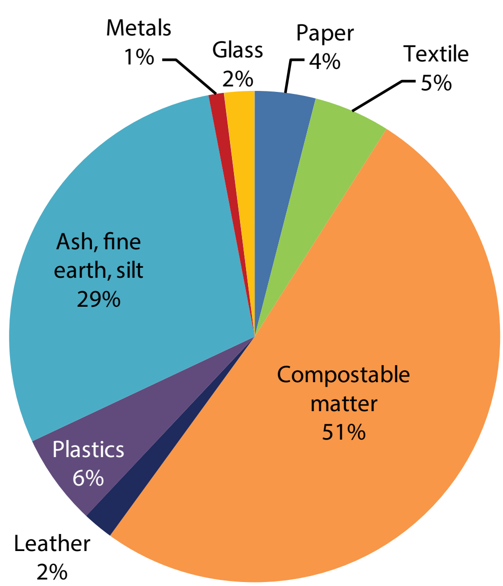


Figure 1.4 Composition of MSW generated in Patna city

1.1.8 Energy Consumption

The Bihar State Power Holding Company is the main supplier of electricity, with the supply for electricity supplemented by diesel generator sets. A 3300 MW coal-fired power plant, commissioned in two stages with 1980 MW in Barh I and 1320 MW in Barh II, is under construction. This facility has been named as a 'mega power' project for Bihar, and is owned by National Thermal Power Corporation (NTPC). This power plant is located approximately 140 km east of Patna and is expected to fully support the electricity demand of residential and industrial sectors (power technology. com).

Industries in Patna rely heavily on electricity (81%) for their energy needs. In June 2019, Patna had the highest consumption of electricity of 670 MW as against 2018 and 2017 consumption of 610 MW and 590 MW, respectively. Gas Authority of India (GAIL) is in the process of laying down piped cooking gas (Jagdishpur-Haldia) pipeline. From February 2019 onwards, over 1500 homes on Jagdeo path and about 5000 other households are receiving PNG (patnadaily.com).

The domestic sector emissions are based on fuel consumption estimates for cooking and biomass burning. In the city, the dominant fuel used is LPG, while coal, biomass, and agricultural waste are the major fuel source in slums, construction sites, restaurants and areas outside the municipal corporation (CCAAP, 2019).

1.1.9 Ambient Air Pollution in Patna

1.1.9.1 Ambient Air Quality

Patna is identified as one of the non-attainment cities in India. Ambient air quality monitoring is being carried out in Patna under the National Air Quality Monitoring Programme (NAMP) of CPCB. Bihar State Pollution Control is regularly monitoring the ambient air quality at Patna through Continuous Ambient Air Quality Monitoring Station (CAAQMS) installed at Indira Gandhi Science Complex; Planetarium premises and Beltron Bhawan, Shastrinagar & Gandhi Maidan, Bankipur Bus Depot under NAMP Ambient air quality trend monitored at the two manual monitoring stations from 2011 to 2019 shows that PM_{10} is on the rise since 2011 and has been consistently surpassing the NAAQS of 60 µg/m^3 (Figure 1.5). The concentration of SO_2 over the years is consistent and is well below the prescribed standard of 50 µg/m^3 (Figure 1.6). However, concentration of ambient NO_2 is above the NAAQS (40 µg/m^3) at one of the monitoring sites (Figure 1.7). The current and historical air quality level trend of $PM_{2.5}$ as recorded at

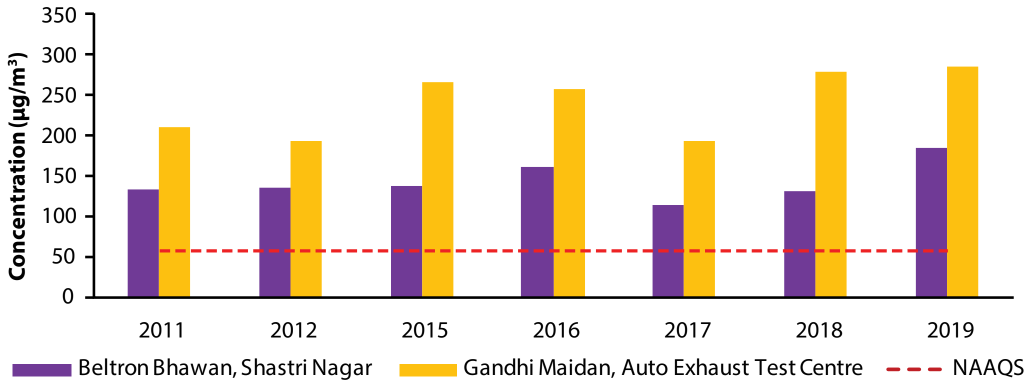


Figure 1.5 Annual ambient PM_{10} concentration in Patna city during 2011–2019

Source – CPCB (Manual monitoring data) 2011–2019

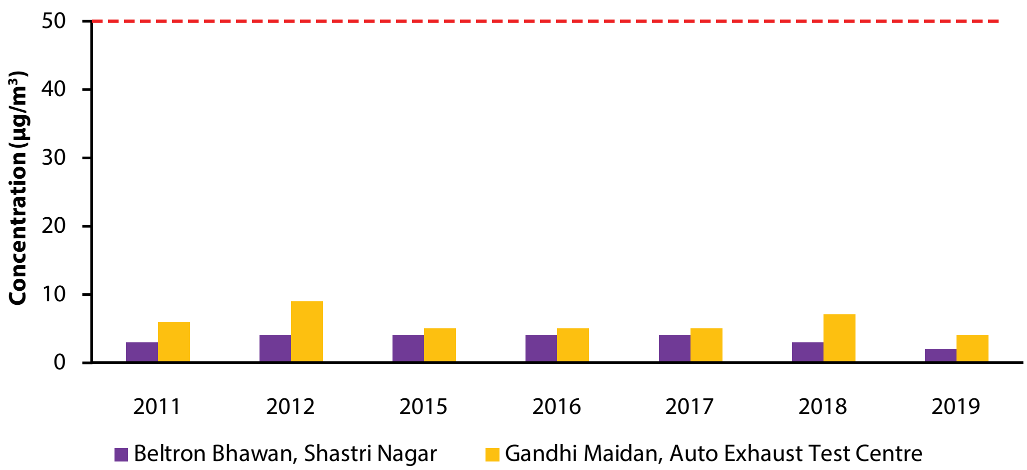


Figure 1.6 Annual ambient SO2 concentration in Patna city during 2011–2019

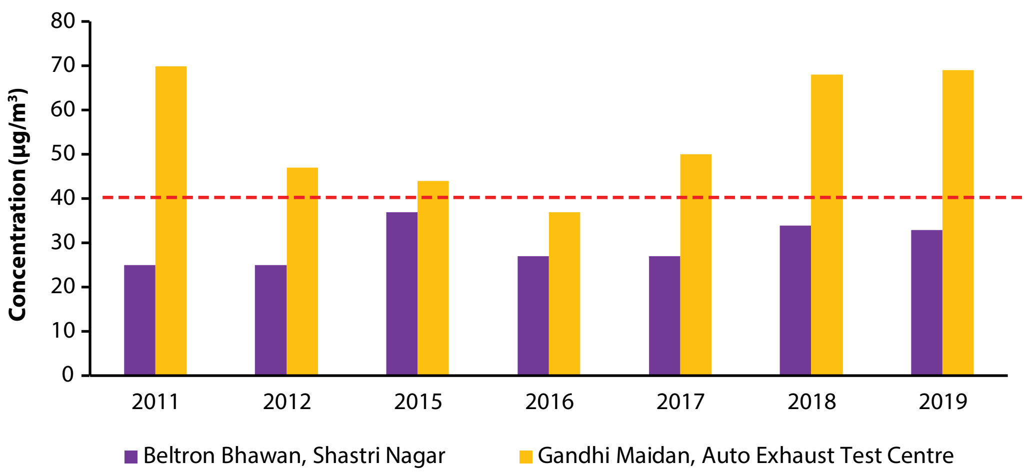


Figure 1.7 Annual ambient NO2 concentration in Patna city during 2011–2019

the continuous monitoring station of ISGC Planetarium for the Patna city shows that the concentration is far above the NAAQS (40 µg/m³). In November 2019, the air quality of Patna city continued to deteriorate as the air quality index (AQI) of the city reached 423. AQI above 400 is classified as 'severe' which can affect the health of the people and seriously impact those with existing diseases (CPCB, 2010).

1.1.9.2 Air Pollution Emission Inventory

Emission inventory developed by Comprehensive Clean Air Action Plan for Patna City (CCAAP, 2019) showed that construction activities are major sources of PM_{10} emission in Patna city and emit about 27% of the total PM_{10} followed by road dust share of 23% PM_{10}. Among gaseous pollutants, brick kilns emit 49% of the total SO_2. diesel generator (DG) sets emit 52% NO_x. Transport sector is the major emitter of CO (34%) followed by residential sector (29%) Emission inventory results of Patna city is shown in Figure 1.8. The transport sector emits 47% VOC followed by residential sector emitting 24% of the total VOC.

Source apportionment study conducted under CCAAP, 2019 on the basis of dispersion modelling showed that the domestic sector contributes about 22% of the total $PM_{2.5}$ concentration followed by transport sector which contributes about 19%. Other prominent contributors are dust (15%), industries (14%), brick kilns (14%), open waste burning (11%), and DG sets (5%).

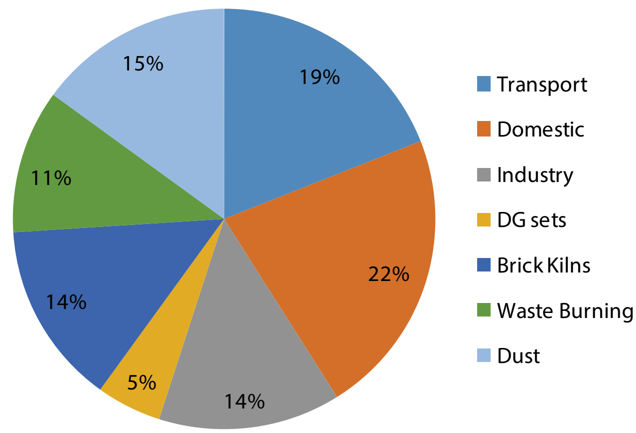


Figure 1.9 Source apportionment of ambient $PM_{2.5}$ concentration in Patna, 2018 using dispersion model

Source CCAAP (2019)

1.2 Objectives

The broad objectives of the present study are as follows:

- Monitoring of ambient air quality (PM_{10} and $PM_{2.5}$ concentrations) in Patna during summer and winter seasons

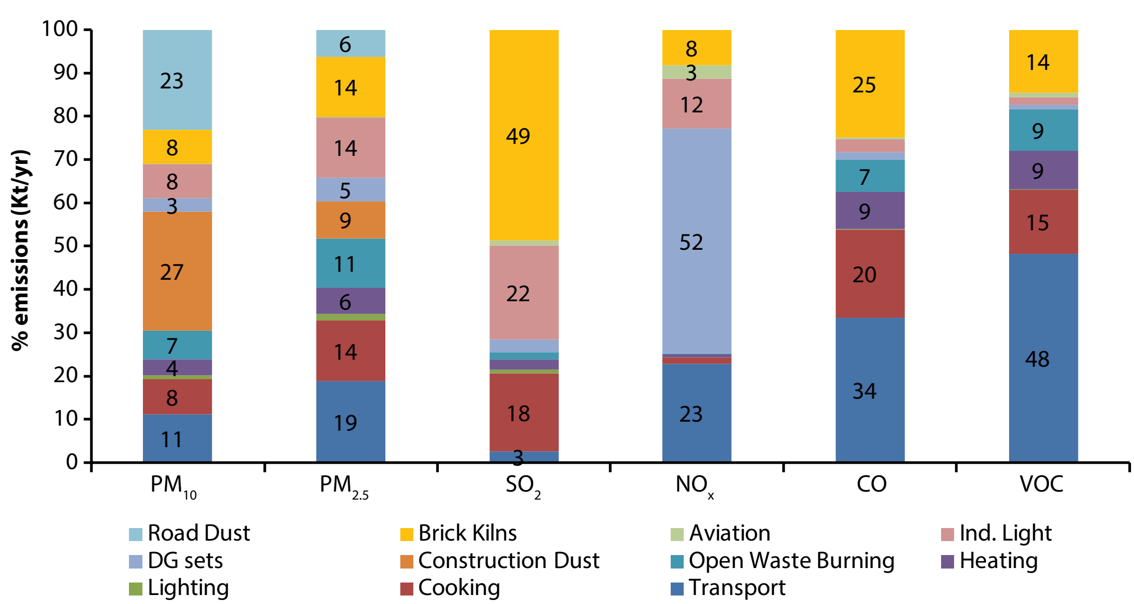


Figure 1.8 Emission inventory of air pollutants in Patna city in 2018

Source – CCAAP, Patna , 2019

- Chemical speciation of ambient PM_{10} and $PM_{2.5}$ samples for different ions, elements, and carbon fractions
- Source apportionment of ambient PM_{10} and $PM_{2.5}$ using receptor model
- Suggest measures to improve ambient air quality of the Patna city based on the study findings

1.3 Approach

The study focuses on ambient air quality monitoring, chemical characterization, and identification of major sources contributing to PM_{10} and $PM_{2.5}$ using receptor model.

Receptor-oriented models identify the source which contributes to ambient concentration of pollutants and source composition at specific sites (receptors); whereas, source-oriented models study the phenomenon starting from the source and follow the pollutants to the receptor sites. The Chemical Mass Balance (CMB) used as the receptor model uses the chemical and physical characteristics of gases and particles measured at source and receptor to identify both the presence and quantity of source contributions to pollutants measured at the receptor. The overall approach for the study is shown in Figure 1.10.

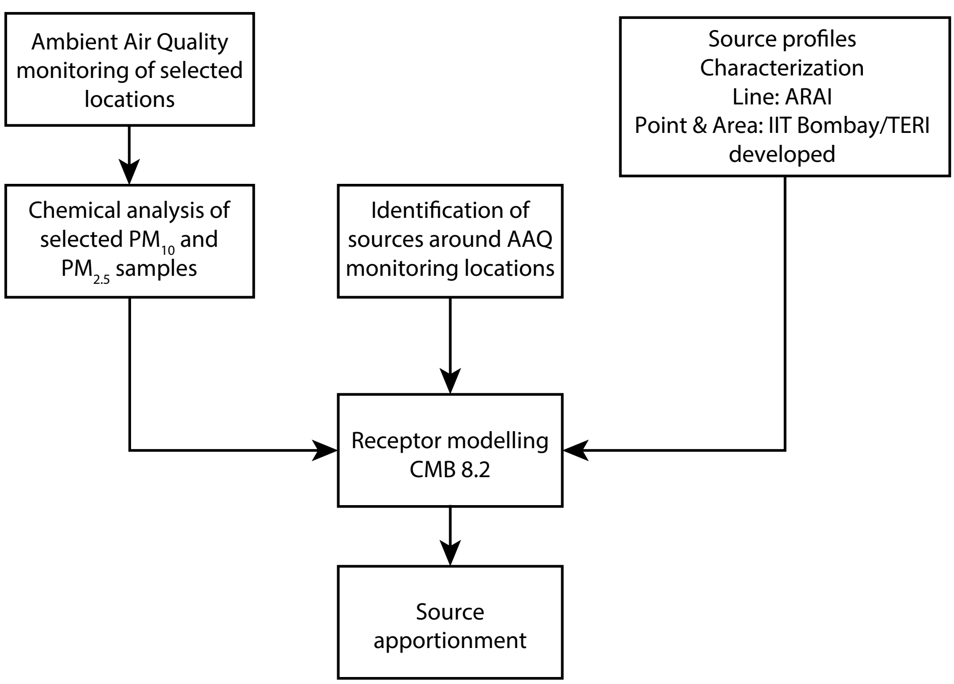


Figure 1.10: Methodology of receptor modelling-based source apportionment

2 AMBIENT AIR QUALITY MONITORING IN PATNA

Key Observations

- Daily ambient PM_{10} (198 µg/m^3 to 277 µg/m^3) and $PM_{2.5}$ (82 µg/m^3 to 136 µg/m^3) concentrations were higher than respective 24-h NAAQS at all monitoring locations during winter season.
- Daily ambient PM_{10} and $PM_{2.5}$ concentrations varied between 103 µg/m^3 and 271 µg/m^3 and 32 µg/m^3 and 64 µg/m^3 respectively, during summer season.
- The average ambient concentrations of PM_{10} across different monitoring sites were approximately 1.73 to 2.71 times and 1.98 to 2.77 times above the NAAQS during summer and winter seasons, respectively.
- The average ambient $PM_{2.5}$ concentrations across different monitoring locations were approximately 0.53 to 1.07 times and 1.37 to 3.28 times above the NAAQS during summer and winter seasons, respectively.
- $PM_{2.5}/PM_{10}$ ratio varied between 0.23 and 0.38 during summer season, while it was between 0.42 and 0.77 during winter season across different monitoring locations.

The main objective of carrying out ambient air quality monitoring is to generate primary data on spatial and temporal variations of ambient PM_{10} and $PM_{2.5}$ concentrations. This can help in assessing the spatial and temporal variations of major sources contributing to ambient PM_{10} and $PM_{2.5}$ concentrations in the city. In this study, the ambient air quality monitoring was carried out during summer (May to June 2019) and winter (December 2019 to January 2020) seasons at seven representative locations following the monitoring protocols and guidelines set up by the CPCB. Spatial distribution of PM_{10} and $PM_{2.5}$ for winter and summer season is shown in Figure – 2.9.

The wind trajectory of the Patna city suggested winds going towards west over the city during the summer season while it was going towards north-east during the winter season Figure 2.1 (b). Accordingly, a reference sampling location was selected towards the eastern and north-western side of the Patna Municipal Corporation area during summer and winter seasons respectively, and additionally six monitoring locations were selected based on the land use [Table 2.1 (a)] within the Patna Municipal Corporation area. These were 1 industrial, 3 residential, 1 commercial, and 1 kerb side locations (Figure 2.1) to measure PM concentrations in each season. All seven monitoring locations in each season were finalized in consultation with officials from Bihar State Pollution Control Board (BPCB). At each of the selected locations, ambient PM_{10} and $PM_{2.5}$ were measured for 15 continuous days (simultaneously) during summer and winter seasons. At the background station, the monitoring was carried out for 30 continuous days during each season.

The results of the ambient air quality monitoring at each location were compared with the NAAQS prescribed by the CPCB.

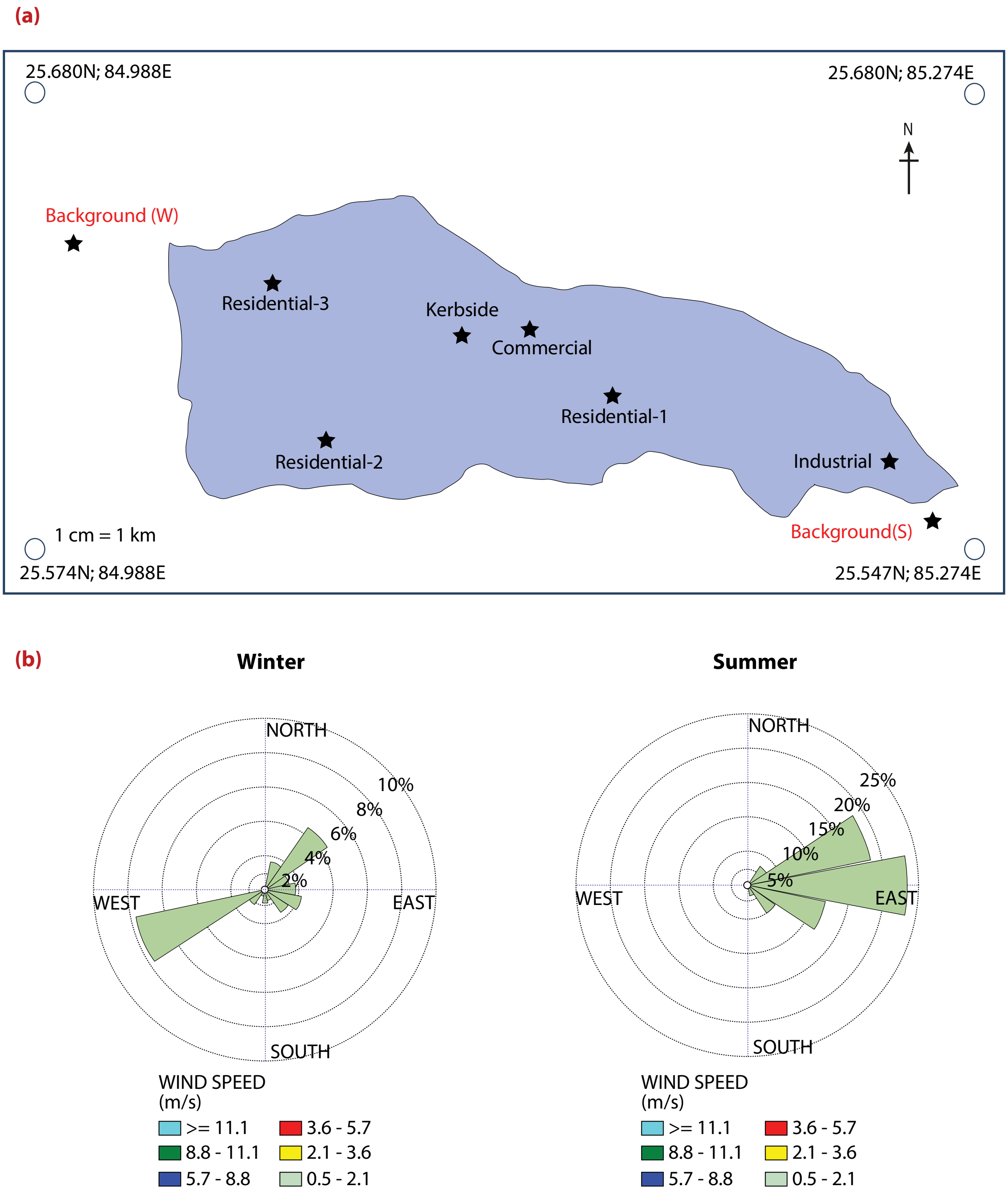


Figure 2.1 Air quality monitoring locations in Patna city

Table 2.1 Locations of ambient air quality monitoring stations and their co-ordinates

S. No.	Land-use category	Location	Activities around the site	GPS co-ordinate
1	Background	Nizampur (Summer)	Rural area, highway traffic, Brick kilns, Agricultural activities, DG sets	25.5522N; 85.2637E
	Background	Danapur (Winter)	Rural area, medium traffic, Brick kilns, Agricultural activities, DG sets	25.6397N; 85.0003E
2	Industrial	Didarganj	Industries, traffic, DG sets, unpaved roads, slum area	25.5732N; 85.2479E
3	Residential 1	Revenue colony	Densely populated, building construction, light traffic	25.5928N; 85.1636E
4	Residential 2	Phulwari Sherif	Institutional area, medium traffic, construction, DG sets	25.5799N; 85.0765E
5	Residential 3	East Gola Road	Construction activities nearby, Barren land, open burning, un paved road, DG sets, traffic and restaurant, dhabas, etc.	25.6269N; 85.0601E
6	Commercial	SDA Mission School	Heavy traffic, open burning, street sweeping, school nearby, restaurants, dhabas and small eateries	25.6133N; 85.1384E
7	Kerbside	Boring Canal Road	Heavy traffic and congestion, hotels and restaurants, small eateries, DG sets	25.6115N; 85.1182E

2.1 Daily Ambient Particulate Matter Concentrations

2.1.1 Industrial Location

For 15 days the daily ambient PM_{10} concentrations was monitored and found to exceed the NAAQ standards throughout the monitoring period during both summer and winter seasons. The daily ambient $PM_{2.5}$ concentrations were also above the NAAQ standard throughout the 15 days monitoring period during winter season; however, concentrations during summer season for most of the monitored period (10 days) were within the NAAQ standards (Figure 2.2). The daily ambient PM_{10} concentrations ranged between 129 µg/m³ and 360 µg/m³ (mean 271 µg/m³) and 110 µg/m³ and 459 µg/m³ (mean 277 µg/m³) during summer and winter seasons, respectively. On the other hand, the daily ambient $PM_{2.5}$ concentrations were between 41 µg/m³ and 126 µg/m³ (mean 64 µg/m³) and 89 µg/m³ and 225 µg/m³ (mean 136 µg/m³) during summer and winter seasons, respectively (Figure 2.2).

2.1.2 Residential Location–1

The daily ambient PM_{10} concentrations at this location during both summer and winter seasons exceeded the NAAQ standards during all the monitoring days (Figure 2.3). However, the daily ambient concentrations of $PM_{2.5}$ were within the NAAQ standard during most of the monitoring days in summer season and exceed the standard throughout the study period during winter season (Figure 2.3).

The daily ambient PM_{10} concentrations were observed between 61 µg/m³ and 210 µg/m³ (mean 121 µg/m³) during summer and 148 µg/m³ and 359 µg/m³ (mean

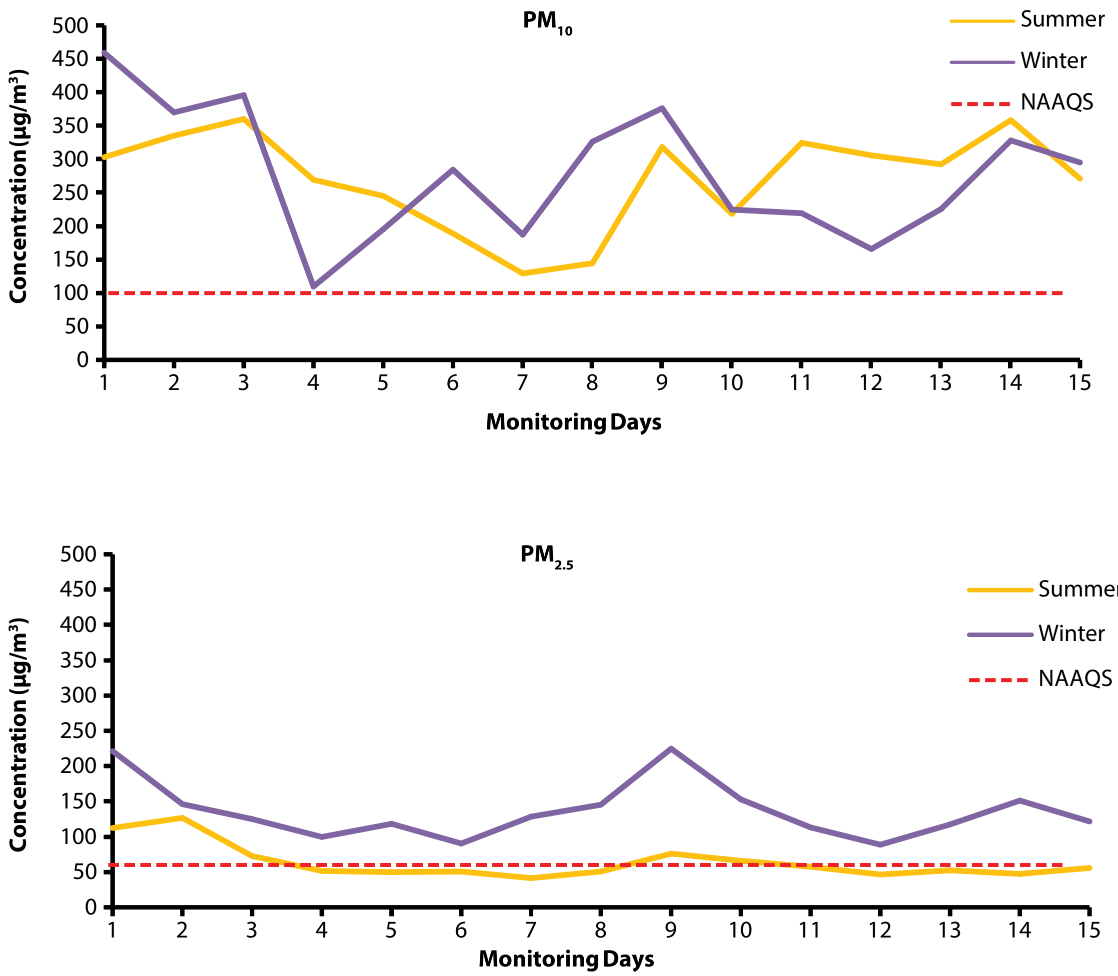


Figure 2.2 Trend of PM_{10} and $PM_{2.5}$ levels for different seasons at industrial location

250 µg/m³) during winter seasons. The daily ambient $PM_{2.5}$ concentrations were found between 24 µg/m³ and 74 µg/m³ (mean 43 µg/m³) during summer and 83 µg/m³ and 171 µg/m³ (mean 123 µg/m³) during winter seasons (Figure 2.3).

2.1.3 Residential Location – 2

The daily ambient PM_{10} concentrations at this location were above the NAAQS and that of $PM_{2.5}$ concentrations were below the NAAQS during the monitoring period in the summer season. On the other hand, the daily

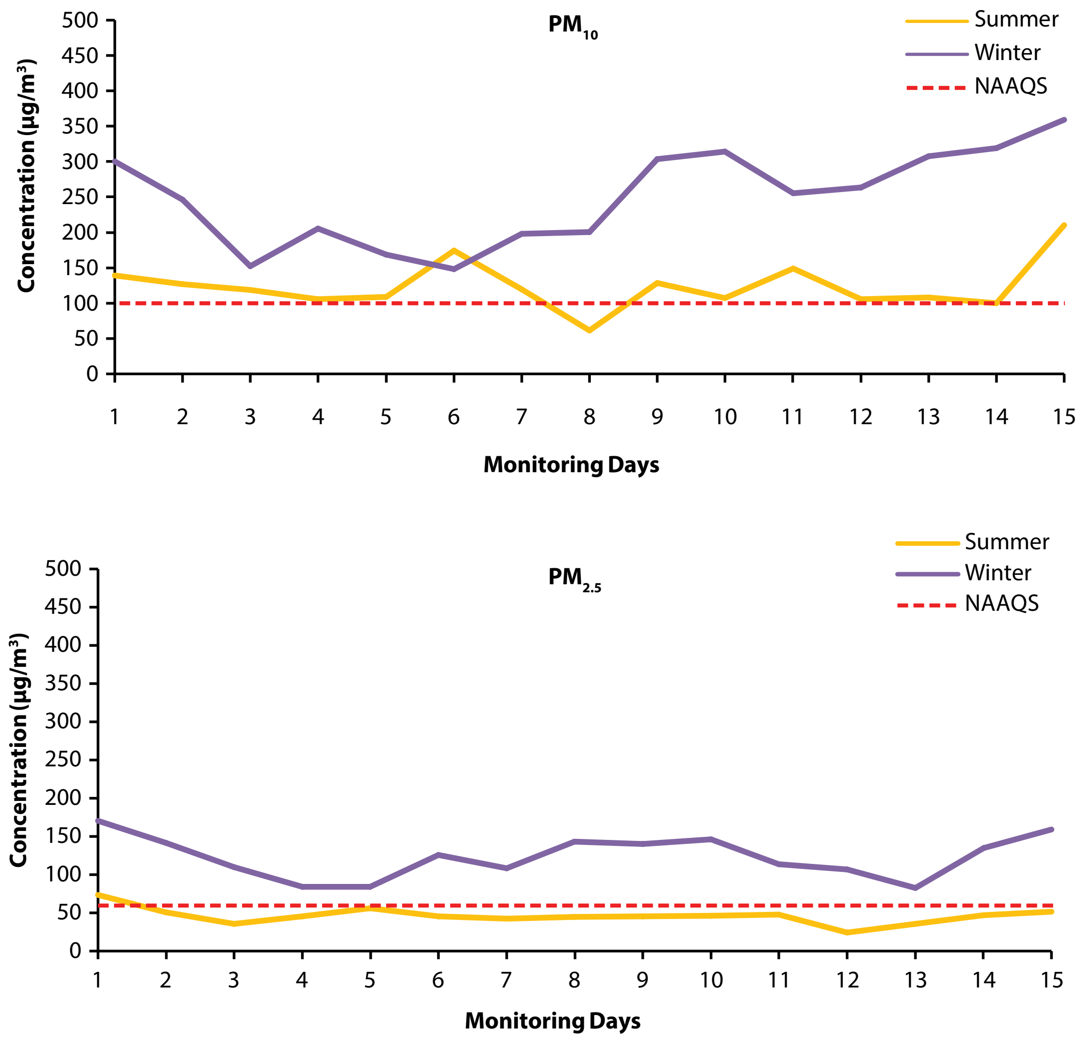


Figure 2.3 Trend of PM_{10} and $PM_{2.5}$ levels for different seasons at residential location–1

ambient PM_{10} and $PM_{2.5}$ concentrations were above the NAAQS in most of the monitoring days during winter season (Figure 2.4). The daily ambient PM_{10} concentrations ranged between 93 µg/m³ and 252 µg/m³ (mean 145 µg/m³) during summer season and 142 µg/m³ and 312 µg/m³ (mean 230 µg/m³) during winter season. On the other hand, the daily ambient $PM_{2.5}$ concentrations ranged between 23 µg/m³ and 45

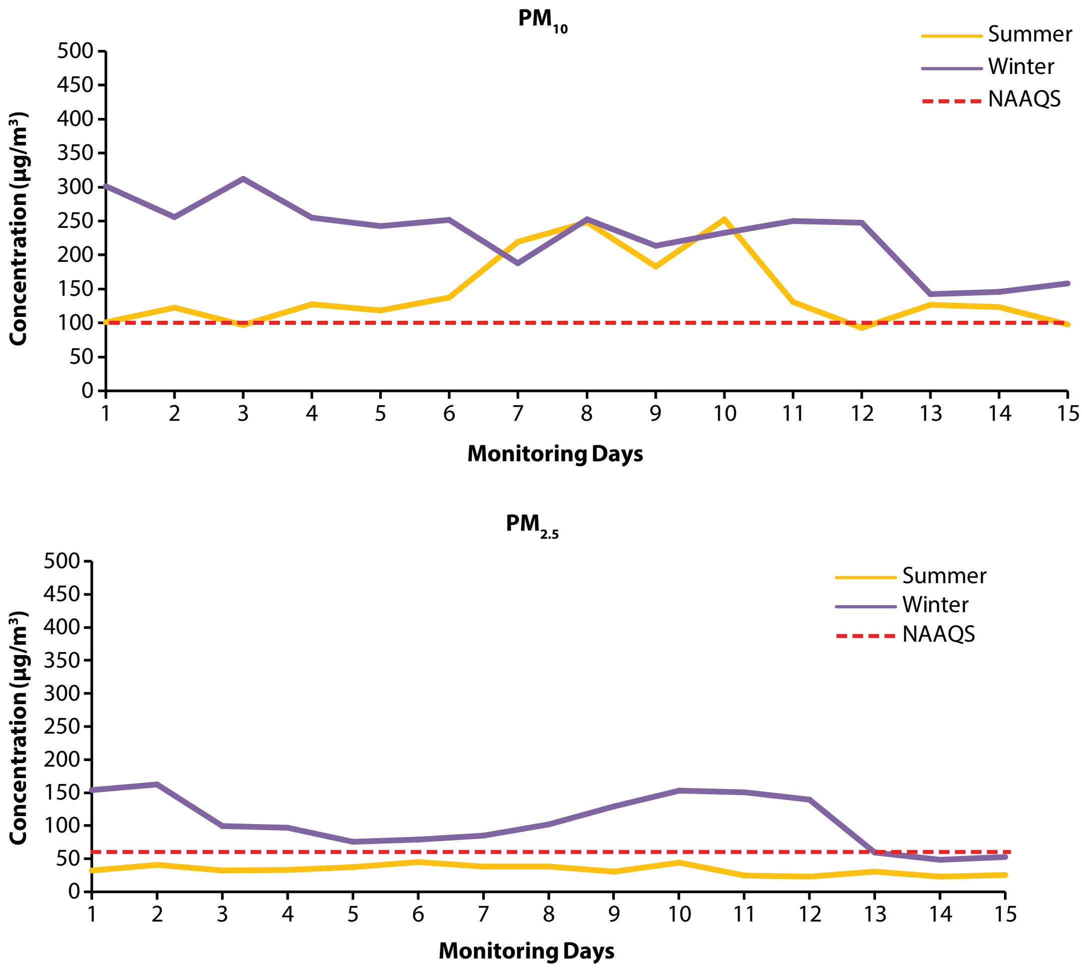


Figure 2.4 Trend of PM_{10} and $PM_{2.5}$ levels for different seasons at residential location-2

µg/m³ (mean 33 µg/m³) and 48 µg/m³ and 162 µg/m³ (mean 106 µg/m³) during summer and winter seasons, respectively.

2.1.4 Residential Location–3

Daily variations in ambient PM_{10} and $PM_{2.5}$ concentrations at residential location is given in Figure 2.5. It is evident from the figure that during the second half of the summer season, the daily ambient PM_{10} concentrations were above the NAAQ standards, whereas the daily ambient $PM_{2.5}$ concentrations were within the NAAQ standards throughout the summer season. However, daily ambient PM_{10} concentrations were above the NAAQ standards throughout the monitoring period during the winter season.

Daily ambient PM_{10} concentration varied between 70 µg/m³ and 220 µg/m³ (mean 115 µg/m³) during summer season and 156 µg/m³ and 254 µg/m³ (mean 198 µg/m³) during winter season. The $PM_{2.5}$ concentration ranged between 21 and 50 µg/m³ (mean 32 µg/m³) during summer season and 35 µg/m³ and 127 µg/m³ (mean 82 µg/m³) during winter season.

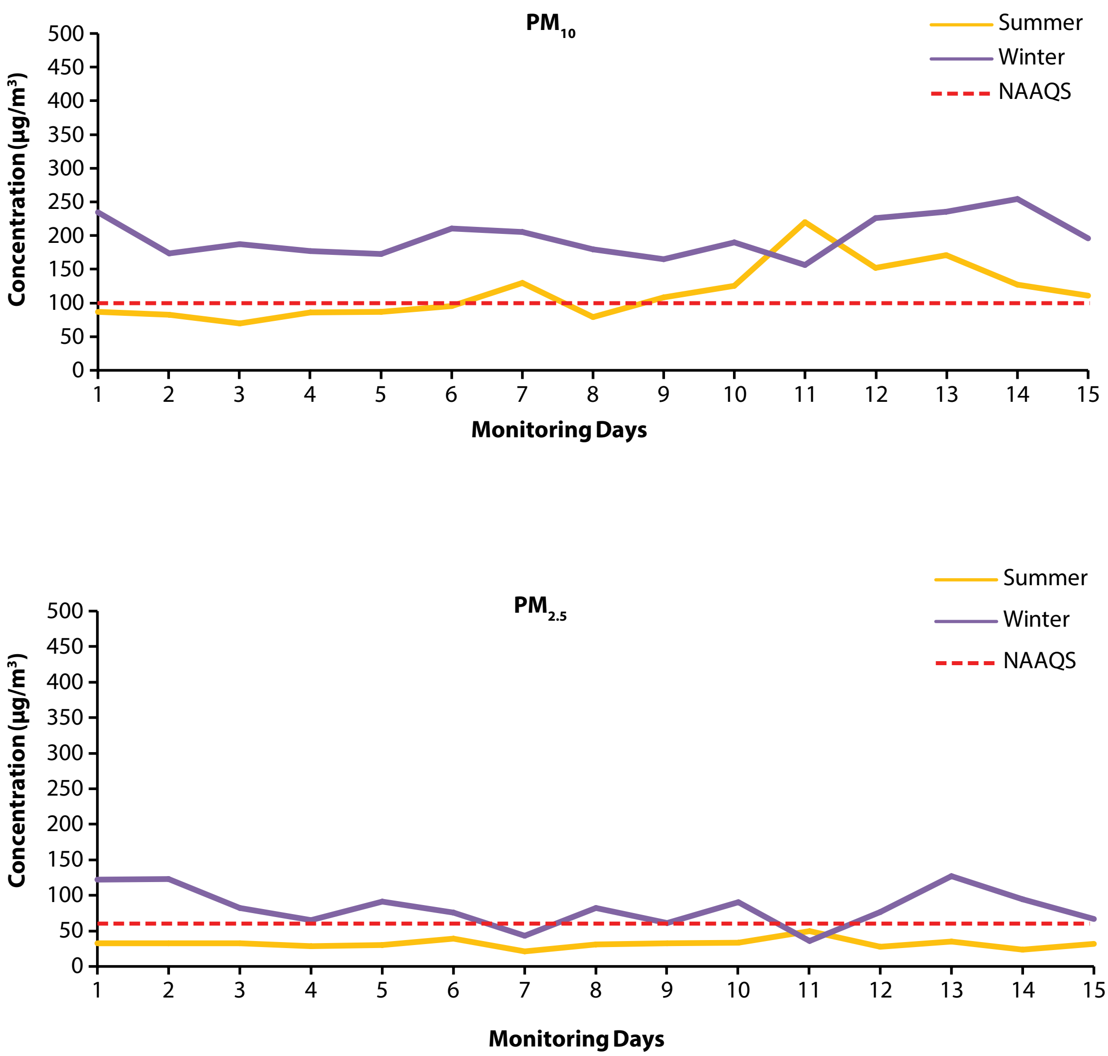


Figure 2.5 Trend of PM_{10} and $PM_{2.5}$ levels for different seasons at residential location-3

2.1.5 Commercial Location

Throughout the study period, the daily ambient PM_{10} concentrations at this location in both the seasons exceeded the NAAQS limit. The daily ambient $PM_{2.5}$ concentration at this location during winter season also violated the prescribed limit. However, ambient $PM_{2.5}$ concentrations during summer season were found to be within the prescribed NAAQS on most of the monitored days (Figure 2.6).

Daily ambient PM_{10} concentrations during summer and winter seasons ranged between 107 µg/m³ and

211 µg/m^3 (mean 154 µg/m^3) and 95 µg/m^3 and 415 µg/m^3 (mean 254 µg/m^3) respectively, at the commercial location. The daily ambient $PM_{2.5}$ concentrations during summer and winter seasons ranged between 39 µg/m^3 and 70 µg/m^3 (mean 49 µg/m^3) and 83 µg/m^3 and 332 µg/m^3 (mean 197 µg/m^3), respectively (Figure 2.6).

2.1.6 Kerbside Location

The daily ambient PM_{10} and $PM_{2.5}$ concentrations at the –kerbside location were below the NAAQS during most of the monitoring days in the summer season. The daily ambient PM_{10} and $PM_{2.5}$ concentrations throughout the winter season exceeded the prescribed limit.

The daily ambient PM_{10} concentrations ranged between 69 µg/m^3 and 158 µg/m^3 (mean 103 µg/m^3) during summer season while 181 µg/m^3 and 286 µg/m^3 (mean 236 µg/m^3) during winter season. The daily ambient $PM_{2.5}$ concentration ranged between 22 µg/m^3 and 85 µg/m^3 (mean 39 µg/m^3) during summer season while

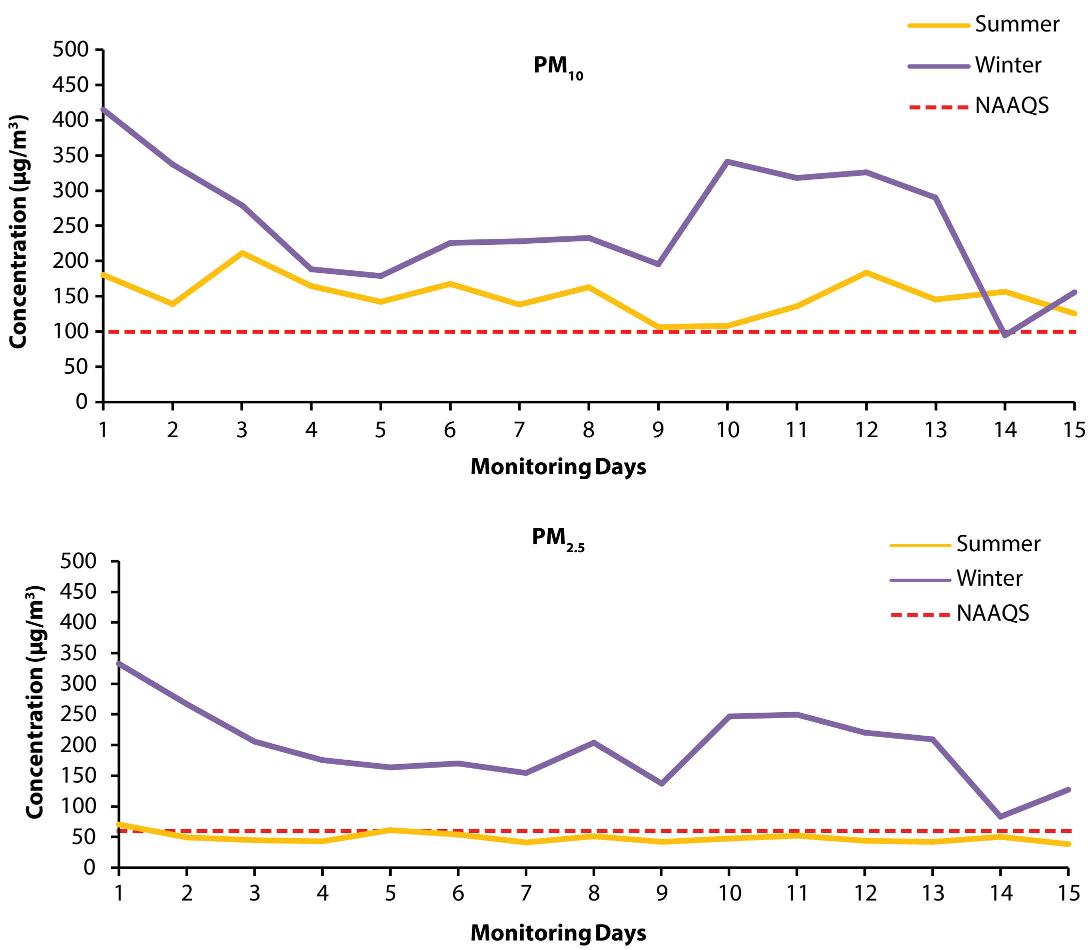


Figure 2.6 Trend of PM_{10} and $PM_{2.5}$ levels for different seasons at commercial location

92 µg/m³ and 187 µg/m³ (mean 133 µg/m³) during winter season (Figure – 2.7).

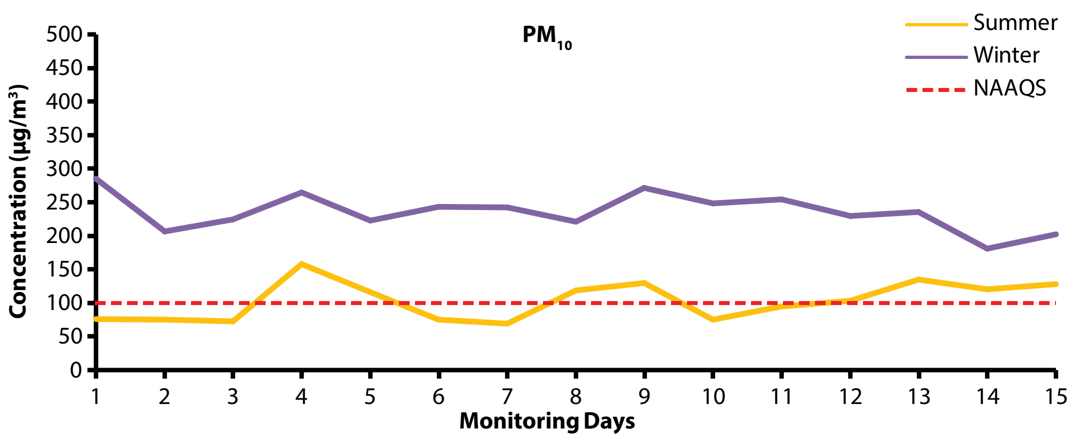
2.1.7 Background Location

The daily ambient PM_{10} concentrations at this location were above (except for a few observations) the 24-h NAAQS during most of the monitoring days, whereas the daily ambient $PM_{2.5}$ concentrations were mostly within the 24-h NAAQS during the summer season. However, the daily ambient PM_{10} and $PM_{2.5}$ concentrations throughout the study period during winter season were above the 24-h NAAQS (Figure 2.8).

The daily ambient PM_{10} concentrations during summer and winter seasons ranged between 36 µg/m³ – 202 µg/m³ (mean 108 µg/m³) and 135 µg/m³ and 331 µg/m³ (mean 221 µg/m³), respectively. The daily ambient $PM_{2.5}$ concentrations during summer and winter seasons ranged between 12 µg/m³ and 89 µg/m³ (mean µg/m³) and 52 µg/m³ and 239 µg/m³ (mean 110 µg/m³), respectively .

2.2 Seasonal Variation in Ambient Air Quality

The average seasonal ambient concentration of PM_{10} across six monitoring locations within the city varied between 103 µg/m³ and 271 µg/m³ and 198 µg/m³ and 277 µg/m³ during summer and winter seasons, respectively (Figure 2.10). The seasonal average ambient concentration of $PM_{2.5}$ across different locations varied between 32 µg/m³ and 64 µg/m³ and 82 µg/m³ and 136 µg/m³ during summer and winter seasons, respectively. Irrespective of monitoring locations, the ambient PM_{10} and $PM_{2.5}$ concentrations



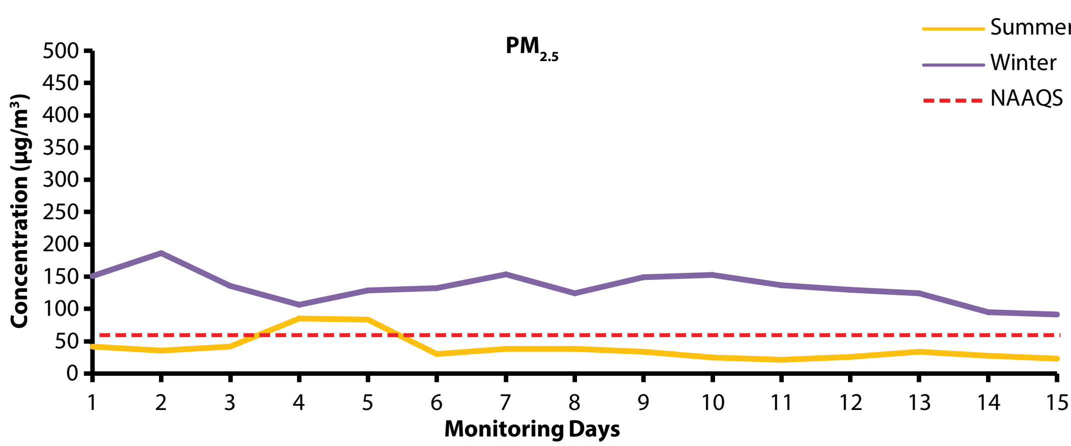


Figure 2.7 Trend of PM_{10} and $PM_{2.5}$ levels for different seasons at kerbside location

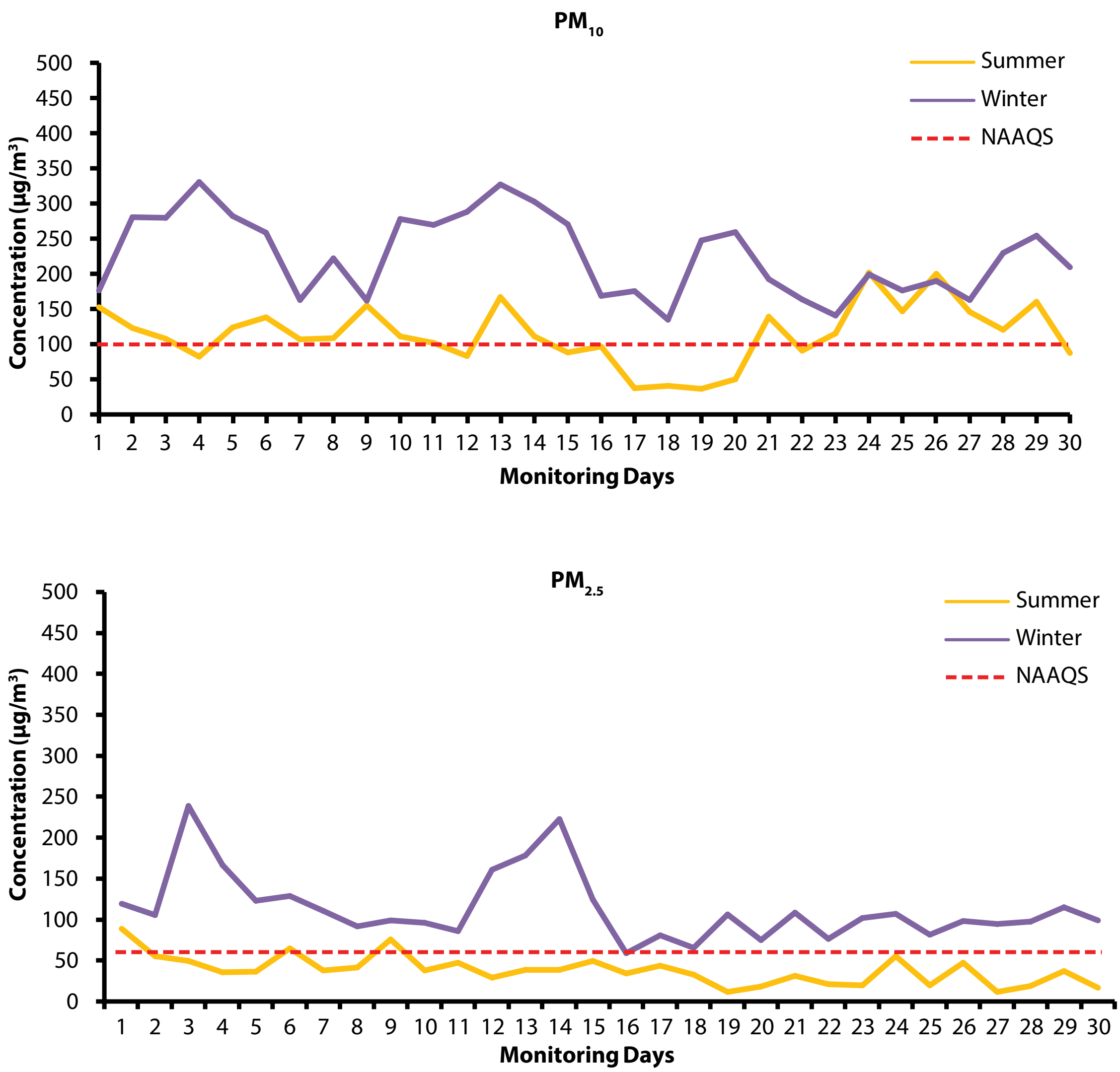


Figure 2.8 Daily ambient PM_{10} and $PM_{2.5}$ concentrations at background location

during the winter season were recorded higher than 24-h average NAAQ standard (PM_{10}: 100 µg/m³ and $PM_{2.5}$: 60 µg/m³), respectively. During summer season, the average ambient concentration of PM_{10} across different monitoring sites were approximately 1.73 to 2.71 times the NAAQS level while the average ambient concentration of $PM_{2.5}$ across different monitoring sites were approximately 0.53 to 1.07 times the NAAQS. Likewise, during the winter period, the average ambient PM_{10} levels across different monitoring locations were approximately 1.98 to 2.77 times the NAAQS whereas the average ambient $PM_{2.5}$ concentrations were approximately 1.37 to 3.28 times the NAAQS. Also, Spatial distribution of PM_{10} and $PM_{2.5}$ for winter and summer season is shown in Figure – 2.9.

High concentration of PM_{10} and $PM_{2.5}$ during winter season could be attributed to slow wind speed, low temperature and low mixing heights, which do not allow the particles to disperse. Comparatively lower average ambient concentration of PM_{10} and $PM_{2.5}$

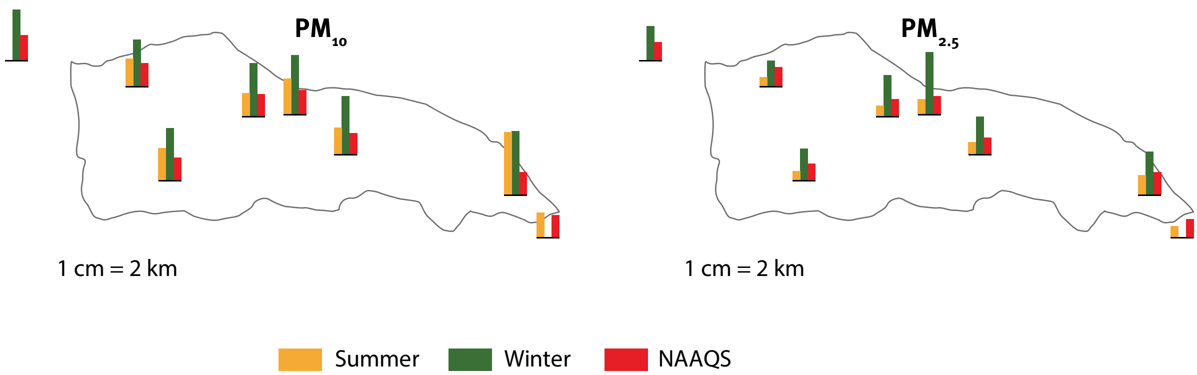


Figure 2.9 Spatial variations of PM_{10} and $PM_{2.5}$ in Patna city during winter and summer seasons

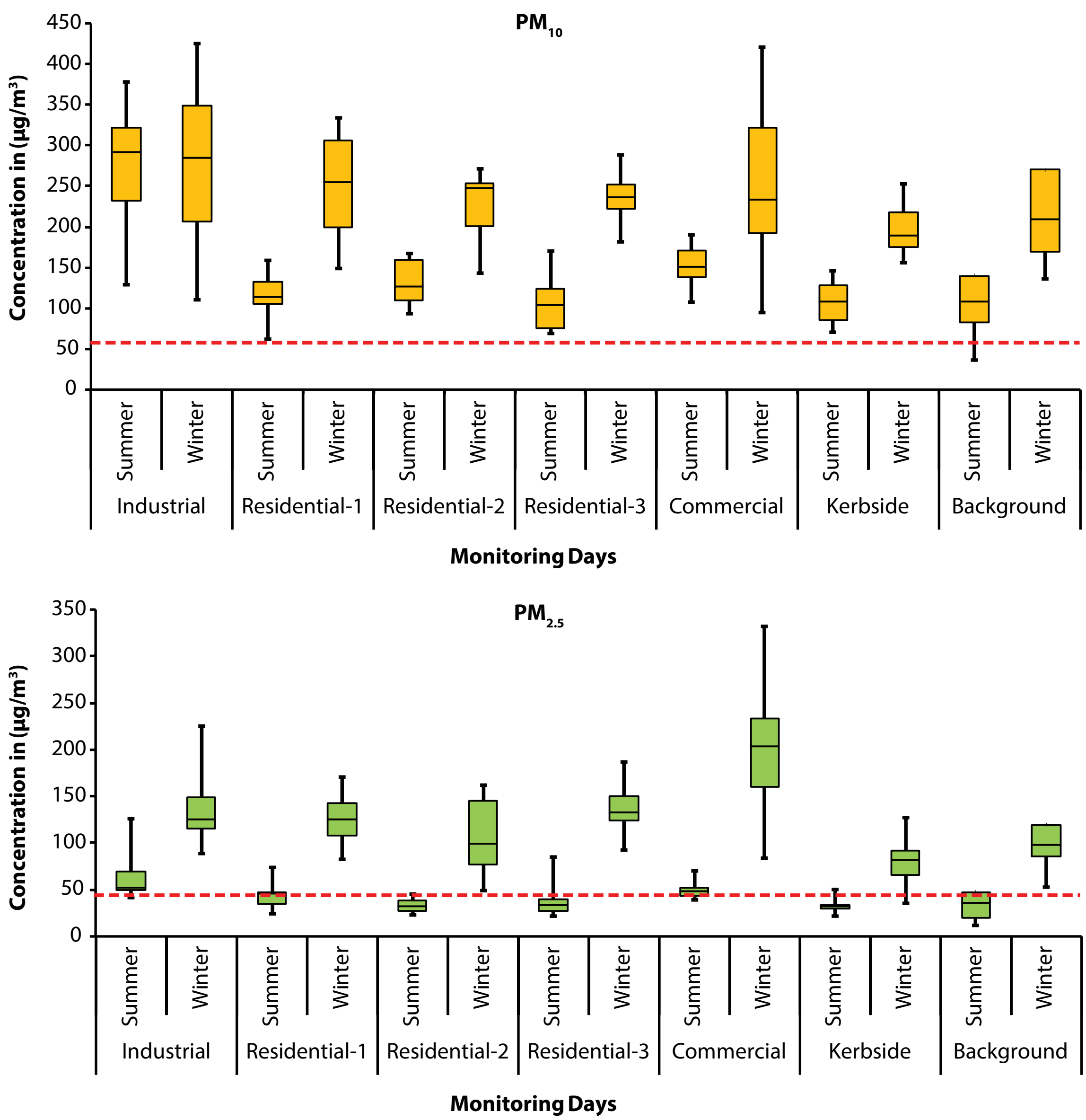


Figure 2.10 PM_{10} and $PM_{2.5}$ concentrations at monitoring locations during winter and summer seasons

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

Table 2.2: Seasonal variation of average PM_{10} and $PM_{2.5}$ at the seven monitoring locations

Monitoring locations	PM_{10} (µg/m³) ± Std error		$PM_{2.5}$ (µg/m³) ± Std error		$PM_{2.5}/PM_{10}$ (µg/m³)	
	Summer	Winter	Summer	Winter	Summer	Winter
Background	108 ± 8	221 ± 10	36 ± 3	110 ± 7	0.34	0.50
Industrial	271 ± 19	277 ± 25	64 ± 6	136 ± 10	0.24	0.49
Residential 1	121 ± 8	250 ± 17	43 ± 3	123 ± 7	0.36	0.49
Residential 2	145 ± 14	230 ± 13	33 ± 2	106 ± 10	0.23	0.46
Residential 3	115 ± 11	198 ± 8	32 ± 2	82 ± 7	0.28	0.42
Commercial	154 ± 7	254 ± 22	49 ± 2	197 ± 16	0.32	0.77
Kerbside	103 ± 7	236 ± 7	39 ± 5	133 ± 6	0.38	0.57

at all the sampling sites during summer season are attributable to higher wind speed and higher mixing height which causes faster dispersion of particulates emitted from local polluting sources to large distances.

2.3 Seasonal Variations of Ratios of Ambient PM_{10} and $PM_{2.5}$

The ambient $PM_{2.5}/PM_{10}$ ratio varied between 0.23 and 0.38 and 0.42 and 0.77during summer and winter seasons, respectively across all the monitoring sites (Table 2.2). Relatively higher $PM_{2.5}/PM_{10}$ ratio during winter season suggests higher contributions from combustion sources. On the other hand, relatively lower $PM_{2.5}/PM_{10}$ ratios during summer season can be attributed to higher contributions from dusty sources, e.g. dust from sediment river beds in the study region.

It is very much clear from Table 2.2 that the average PM_{10} and $PM_{2.5}$ concentrations at all locations in the downwind direction for both summer and winter seasons were higher than the corresponding levels at the background locations indicating the contributions from local sources in addition to the contribution from outside the city boundary. The average ambient concentration of PM_{10} at different monitoring sites showed that the highest concentration is observed at industrial location followed by commercial location and residential location-2 during summer season whereas industrial location, commercial location, and residential location-1 observed maximum concentration during winter season. Highest concentration of PM_{10} at industrial location could be attributed to emissions due to industrial activities and road dust generated due to frequent movement of heavy duty trucks on poorly maintained roads. Similarly, higher ambient concentration of PM_{10} at commercial and residential locations could be attributed to road dust, ongoing construction activities and biomass/refuse burning, and DG sets use near the vicinity of sampling location. On the other hand, the average ambient concentration of $PM_{2.5}$ at different sampling sites showed highest at industrial location followed by commercial and Kerbside locations during summer season whereas commercial, industrial and kerbside location during the winter season. Highest concentration of $PM_{2.5}$ at industrial and commercial locations could be attributed to emission due to industrial activities, formation of secondary aerosol, and biomass/refuse burning near the vicinity of sampling area. The higher concentration of $PM_{2.5}$ at Kerbside location could be attributed to tail pipe emissions from vehicles due to frequent vehicular movements. The higher concentrations at commercial, Kerbside and industrial locations can also be attributed to burning of biomass/coal in small eateries and *dhabas* surrounding the location.

3 CHEMICAL CHARACTERISATION OF PARTICULATE MATTER

Key Observations

Chemical characterization of PM_{10} suggests that elements were the most abundant chemical constituents across all the monitoring locations during summer season. However, carbon was the most abundant chemical constituent in ambient PM_{10} at different monitoring locations during winter season.

- Si, Al, Fe, and Ca were identified as the most dominating species in ambient PM_{10} concentration across respective monitoring locations during summer season, while Si, S, Cl, Fe, Ca, K and Na were most dominating chemical constituents in ambient PM_{10} concentration across monitoring locations during winter season.
- NH_4^+, Ca^{2+}, Cl^-, SO_4^{2-} and NO_3^- were the most dominating ionic species in ambient PM_{10} across different monitoring locations during summer and winter seasons.
- Ions were most dominating chemical constituents in ambient $PM_{2.5}$ samples across the monitoring locations during both summer and winter seasons.
- Across all monitoring locations, Ca, Fe, K, Na, Si, Zn, S and Cl were the most dominating chemical constituents in ambient $PM_{2.5}$ during the summer and winter seasons, respectively.
- NH_4^+, SO_4^{2-} and Cl^- were also the most dominating ionic species in $PM_{2.5}$ samples across all monitoring locations during both summer and winter seasons.
- The proportion of EC ranged between 19% and 31% and 14 and 30% of total carbon in PM_{10} and $PM_{2.5}$ respectively, across different monitoring locations during summer and winter seasons.

Characterization of ambient particulate matters poses major challenges depending upon the size, composition, polluting sources, and meteorological conditions including temperature, humidity, rainfall and wind speed. Chemical composition of particulate matter could provide useful information about the formation, ageing, reaction mechanism, and the source they originate from. The ambient particulate matter collected on different filter media at seven different locations during both the seasons were analyzed for their chemical characteristics. Composition of different ions, elements, and carbon in ambient PM_{10} and $PM_{2.5}$ samples collected at different locations was analysed following the methods described in Table 3.1. Detailed methodology of chemical characterization of ions, elements, and carbon is provided in Annexure II.

Table 3.1: Details of chemical characterization of different element, ions, and carbon content in ambient PM_{10} and $PM_{2.5}$

Component	Filter media	Analytical method
Elements Na, Mg, Al, Si, P, S, Cl, Ca, Br, V, Mn, Fe, Co, Ni, Cu, Zn, As, Ti, Ga, Rb, Y, Zr, Pd, Ag, In, Sn, La Se, Sr, Mo, Cr, Cd, Sb, Ba, Hg, and Pb	Teflon filter	Energy Dispersive X-Ray Fluorescence (ED-XRF) spectrometry (EDX 7000, Shimadzu, Japan)
Ions F^-, Cl^-, Br^-, NO_2^-, NO_3^-, SO_4^{-2}, K^+, NH_4^+, Na^+, Ca^{++}, Mg^{++}	Teflon filter	Ion chromatography (IC) system (ICSAquion, ThermoFischer Scientific)
Carbon Analysis (OC, EC & Total Carbon)	Quartz filter	Thermal/Optical Carbon Analyzer (DRI Model 2001A; Desert Research Institute, USA)

3.1 Chemical Characterization of Ambient PM_{10}

Elements were the most abundant chemical constituents across all the monitoring locations. Elemental proportion of ambient PM_{10} at different monitoring locations during summer season followed the order: Commercial (57%) › Industrial (48%) › Residential Location–3 (46%) = Kerbside (46%) › Residential Location–2 (43%) › Residential Location–1 (42%) › Background (36%) (Figure 3.1). Further, the fraction of Al, Ca, Si, K, and S was recorded higher at the commercial and residential locations compared to other monitoring sites. Therefore, the presence of such elements at these locations could be attributed to road dust, ongoing construction activities, and biomass burning near the vicinity of monitoring site. On the other hand, carbon was the most abundant chemical constituents in ambient PM_{10} at different monitoring locations during winter season. The carbon proportion of ambient PM_{10} samples were recorded highest at the background location (57%) among different monitoring locations in the Patna city during winter season (Figure 3.1). Ions were the second most dominating chemical species in ambient PM_{10} during summer and winter seasons across different monitoring locations. Highest fraction of ions was recorded at Kerbside location (36%) probably because of road dust and ongoing construction activities near the vicinity of the sampling area, tail pipe emissions from vehicles, and secondary aerosol formation. During winter season highest ionic fraction was recorded at industrial location (34%) (Figure 3.1).The carbon fraction of ambient PM_{10} varied between 5% and 31% during summer season, with highest fraction (31%) observed at the background location probably because of combustion of fuels in households, vehicular movements, coal combustion in brick kilns, and DG sets used in agricultural fields. On the other hand, during winter season, the carbon fraction of ambient PM_{10} varied between 25% and 57%.

3.1.1 Elements

Si, Al, Fe, and Ca were identified as the most dominating species in ambient PM_{10} across respective monitoring locations during summer season, while Si, S, Cl, Fe, Ca, K and Na were recorded as the most dominating chemical species amongst the elements in ambient PM_{10} across monitoring locations during winter season

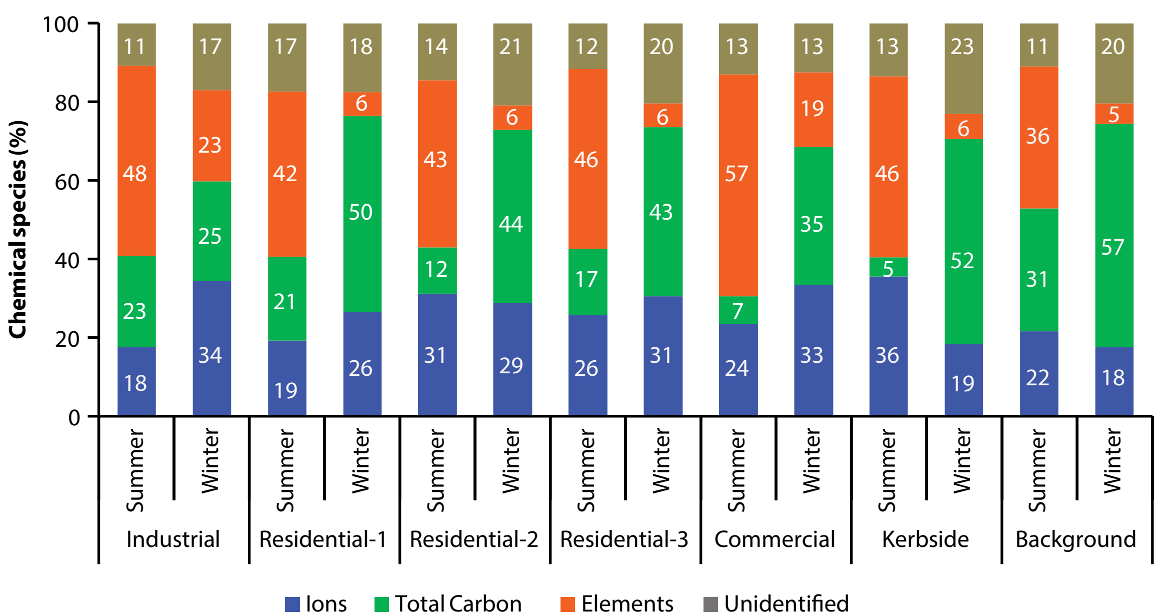


Figure 3.1 Seasonal variations in chemical characterization of ambient PM_{10} at different monitoring locations

*The unidentified portion includes organic matter associated with organic carbon, oxygen associated with the oxides of metals and other unidentified species which are not analysed. This discrepancy could also be attributed to some loss of organic compounds due to volatilization.

(Figure 3.2). Presence of several other elemental species was detected in trace amounts during both the seasons. Irrespective of monitoring locations, Al and Si were identified as the most abundant elemental component in ambient PM_{10} during both summer and winter seasons which could be attributed to the dust generated from soil, road dust, and construction activities. The proportion of Al in ambient PM_{10} at different sampling locations followed the order: Commercial (47%) › Residential Location–1 (31%) › Background (29%) › Residential Location–3 (24%) › Residential Location–2 (23%) › Industrial (17%) › Kerbside (10%) during summer season. Higher Al levels at the commercial location may be attributed to combustion of coal in *tandoors* (restaurants and *dhabas*) and small eateries surrounding the location. Presence of Al at this location can also be attributed to the dust generated from soil and road dust re-suspension. The proportion of Si in ambient PM_{10} at different sampling locations followed the order: Kerbside (37%) › Residential Location–3 (35%) › Industrial (30%) › Background (29%) › Commercial (27%) ›Residential Location–2 (20%) › Residential Location–1 (19%) during winter season. High silica at Kerbside can be attributed to road dust near the monitoring location. Further, Ca and Fe were identified as the second most abundant elemental components in ambient PM_{10} during both summer and winter seasons which can be attributed to the presence of dust generated from soil, road and construction activities near this location. The proportion of Ca in ambient PM_{10} at different sampling locations followed the order: Residential-2 (22%) › Kerbside (20%) › Residential Location–1 (16%) = Residential Location–3 (16%) › Background (12%) › Industrial (11%) › Commercial (9%). Highest proportion of Ca at Residential Location–2 location could be attributed to ongoing construction activities, soil and road dust near the monitoring site. The proportion of Fe in ambient PM_{10} at different sampling locations followed

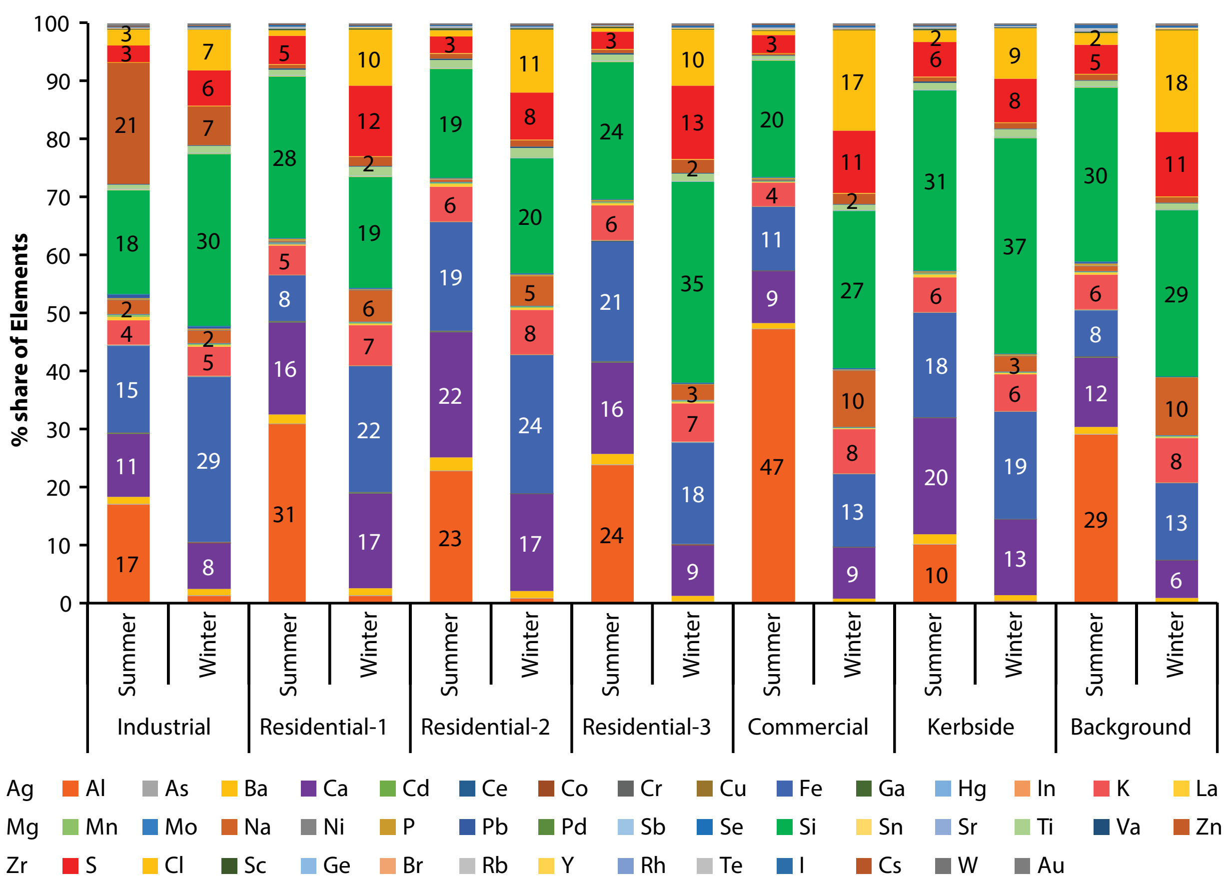


Figure 3.2 Seasonal variations in speciation of elements in ambient PM_{10} at different monitoring locations

the order: Industrial (29%) › Residential Location–2 (24%) › Residential Location–1 (22%) ›Kerbside (19%) › Residential Location–3 (18%) › Commercial (13%) = Background (13%). Presence of highest fraction of Fe at the industrial site could be attributed to release of Fe containing particles due to industrial activities, combustion of oil in industries, and also from soil and road dust.

3.1.2 Ions

NH_4^+, Ca^{2+}, Cl^-, SO_4^{2-} and NO_3^- were the most dominating ionic species in ambient PM_{10} across different monitoring locations during summer and winter seasons. The highest proportion of NH_4^+ in ambient PM_{10} was recorded at Residential Location–3 during summer (38%) and winter (52%) seasons, which may be attributed to secondary particulate formation. The highest proportion of SO_4^{2-} in ambient PM_{10} was recorded at the commercial location (22%) and Residential Location–3 (18%) during summer and winter seasons, respectively. This can be attributed to the secondary particulate formation due to combustion of coal in restaurants, *dhabas*, and small eateries and also because of gasoline and diesel combustion in automobiles. Proportion of Ca^{2+} in ambient PM_{10} varied between 9–18% and 1–3% during summer and winter seasons, respectively. On the other hand, the proportion of Cl^- in ambient PM_{10} was between 7–21% and 5–19% during summer and winter seasons, respectively.

In winter, the molar ratio of NH_4^+ and SO_4^{2-} was ›1. This suggests that in addition to $(NH_4)_2SO_4$, NH_4NO_3 is also formed due to low temperature and excess amount of atmospheric NH_4^+. However, the molar ratio in summers was ‹1, indicating lesser possibility of NH_4NO_3 formation in the atmosphere compared to the winter season. Ambient NH_3 concentrations play an important role in the formation of secondary particles in and around Patna city.

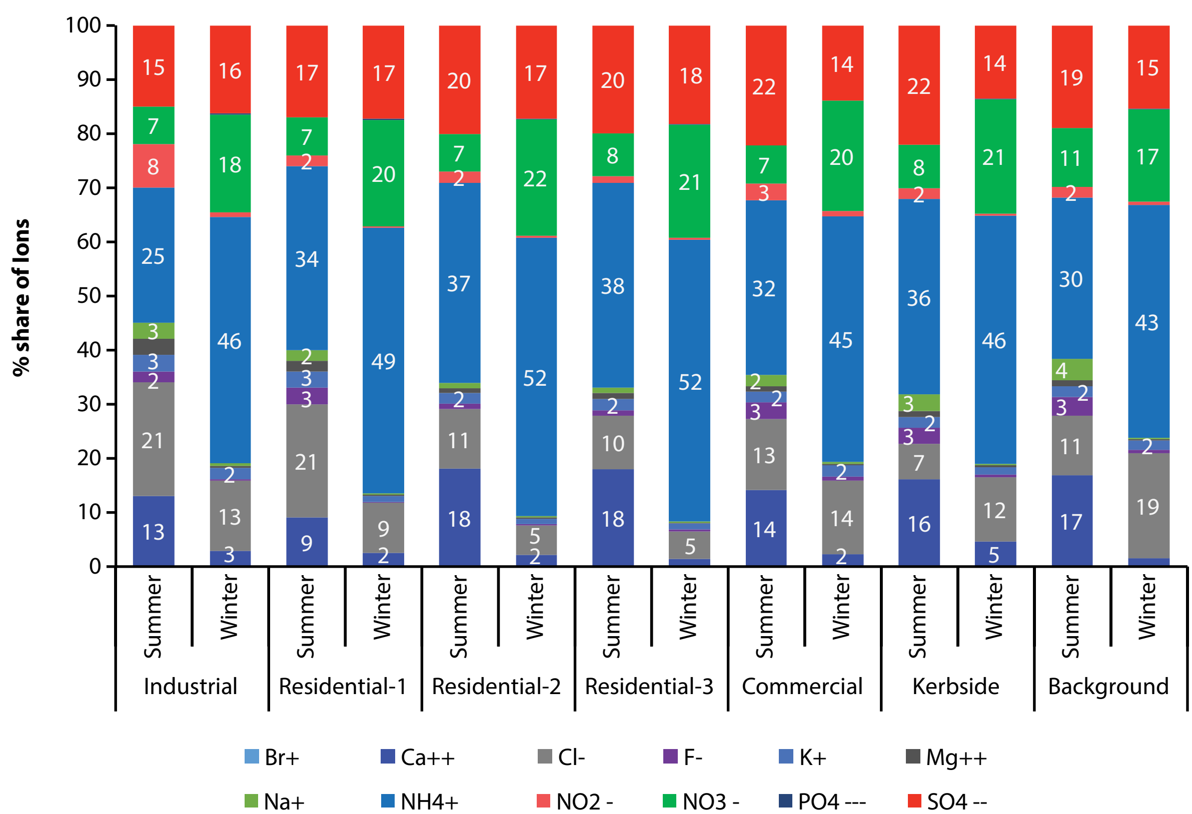


Figure 3.3 Seasonal variations in ionic composition of ambient PM_{10} at different monitoring locations

3.1.3 Carbon (Elemental and Organic)

The proportion of elemental carbon (EC) ranged between 20% and 30% of total carbon in PM_{10} amongst different monitoring locations during summer and winter seasons (Figure 3.4). Lowest proportion (69%) of organic carbon (OC) in ambient PM_{10} was recorded at Residential Location–3 and Residential Location–1 during summer and winter seasons, respectively.

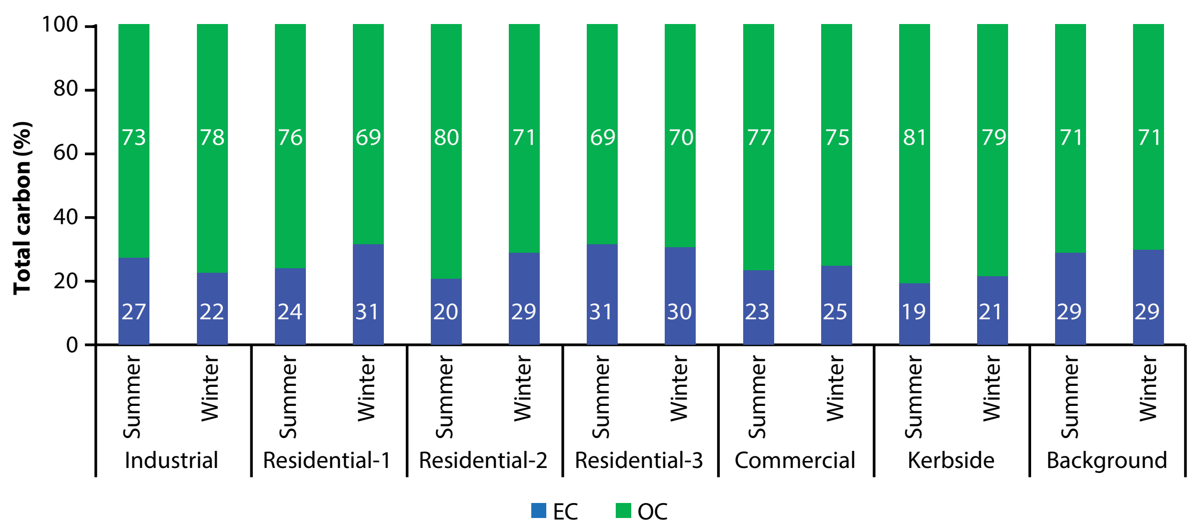


Figure 3.4 Seasonal variations of different fractions of carbon in ambient PM_{10} at different monitoring locations

3.2 Chemical characterization of ambient $PM_{2.5}$

Ions were the most dominating chemical constituents in ambient $PM_{2.5}$ samples across the monitoring locations during both summer and winter seasons. The proportion of ions in the ambient $PM_{2.5}$ concentration at different monitoring locations followed the order: Residential Location–2 (49%) › Residential Location–3 (42%) › Residential Location–1 (41%) = Commercial (41%) › Kerbside (40%) › Industrial (36%) › Background (28%) during summer season and Residential Location–1 (48%) › Kerbside (47%) › Residential Location–3 (39%) › Industrial (38%) › Residential Location–2 (35%) › Commercial (32%) › Background (34%) during winter season (Figure 3.5). Elements were the second most dominating chemical species in ambient $PM_{2.5}$ among different monitoring locations during the summer season, while carbon was the second most dominating chemical species in ambient $PM_{2.5}$ during the winter season.

The proportion of elements in ambient $PM_{2.5}$ amongst different monitoring locations followed the order: Residential Location–1 (31%) › Background (29%) › Commercial (26%) › Industrial (23%) = Residential Location–3 (23%) › Residential Location–2 (21%) › Kerbside (19%) during summer season. Further, highest proportion of carbon fraction in ambient $PM_{2.5}$ was recorded at the Background location (22%) and Commercial location (36%) during summer season and winter season, respectively (Figure 3.5).

3.2.1 Elements

Across all monitoring locations, Ca, Fe, Si, Al, K, Se, Ce, Zr, Va, S, and Te were the most dominating chemical constituents in ambient $PM_{2.5}$ during the summer season and Ca, Fe, Si, K, Se, Zr, Va, and S were the most dominating chemical constituents in ambient $PM_{2.5}$ during winter season. Highest proportion of S was recorded at the commercial location (32%) and Residential Location–3 (34%) during the summer and winter seasons, respectively. High sulphur can be attributed to use of high sulphur-based fuels e.g. coal in restaurants and hotels surrounding these locations and also combustion of diesel in automobiles. High

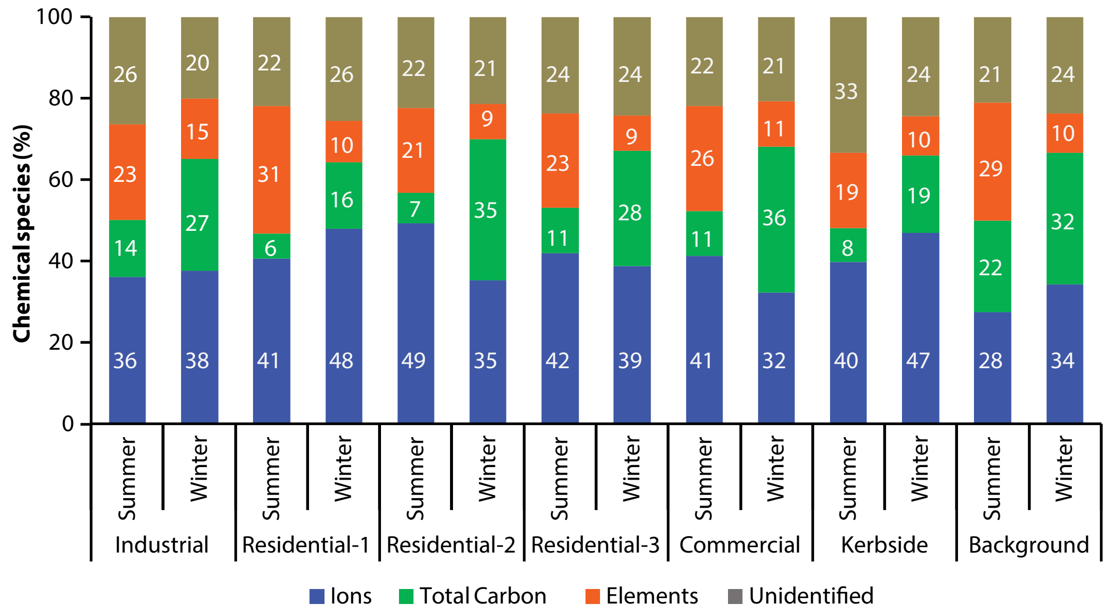


Figure 3.5 Seasonal variations in chemical characterization of ambient $PM_{2.5}$ at different monitoring locations

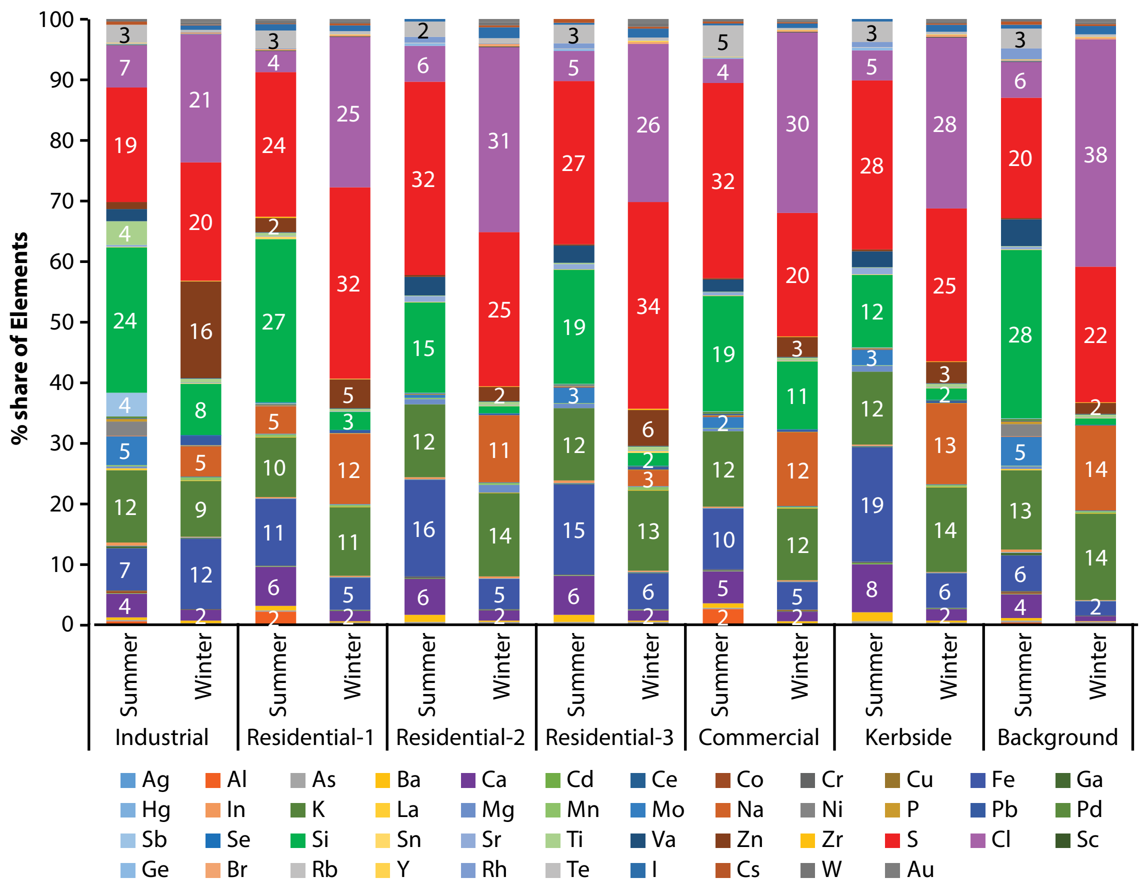


Figure 3.6 Seasonal variations in speciation of elements in ambient $PM_{2.5}$ at different monitoring locations

proportion of Fe (19%) and Cl (38%) were recorded at Kerbside and background site during the summer and winter seasons, respectively. Chloride is an indicator of waste burning, and along with 'K' becomes a good indicator of biomass burning too.

3.2.2 Ions

Like PM_{10}, NH_4^+, SO_4^{2-} and Cl^- were also the most dominating ionic species in $PM_{2.5}$ samples across all monitoring locations during both summer and winter seasons. NH_4^+ was identified as the most abundant cationic species in ambient $PM_{2.5}$ during summer and winter seasons. The highest proportion of NH_4^+ was recorded at Residential Location–3 (38%) and Residential Location–1 (51%) during summer and winter seasons, respectively. The highest proportion of SO_4^{2-} was recorded at Residential Location–1 (25%) during summer season, whereas, highest proportion of Cl^- was recorded at Industrial location (24%) and Background location (17%) during summer and winter seasons, respectively.

3.2.3 Carbon (Elemental and Organic)

The proportion of EC ranged between 14% and 30% of total carbon in $PM_{2.5}$ amongst different monitoring locations during summer and winter seasons (Figure 3.8). Highest proportion of OC in ambient $PM_{2.5}$ was recorded at the Residential Location–2 (86%) monitoring site during summer season. Among different monitoring sites, the highest EC/OC ratio in ambient $PM_{2.5}$ was recorded at Industrial location, indicating use of diesel vehicles or generators, which show high EC to OC ratios in their emissions.

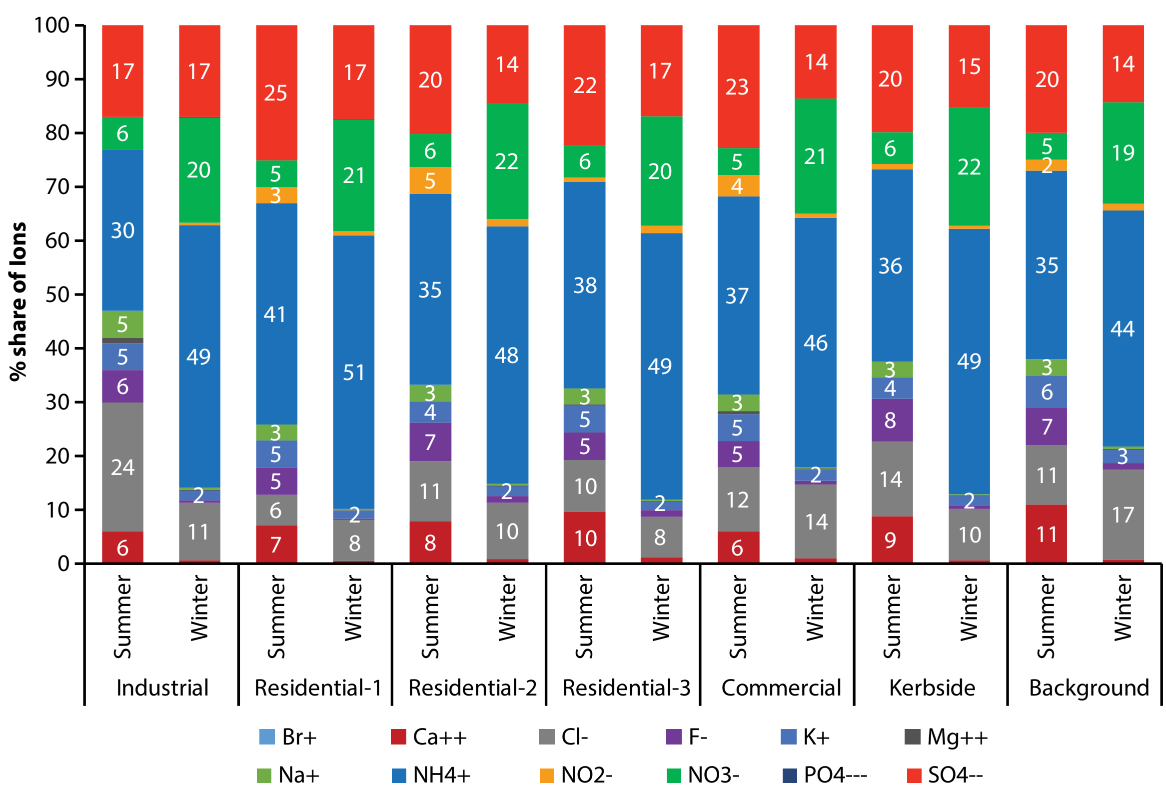


Figure 3.7 Seasonal variations in ionic composition of ambient $PM_{2.5}$ at different monitoring locations

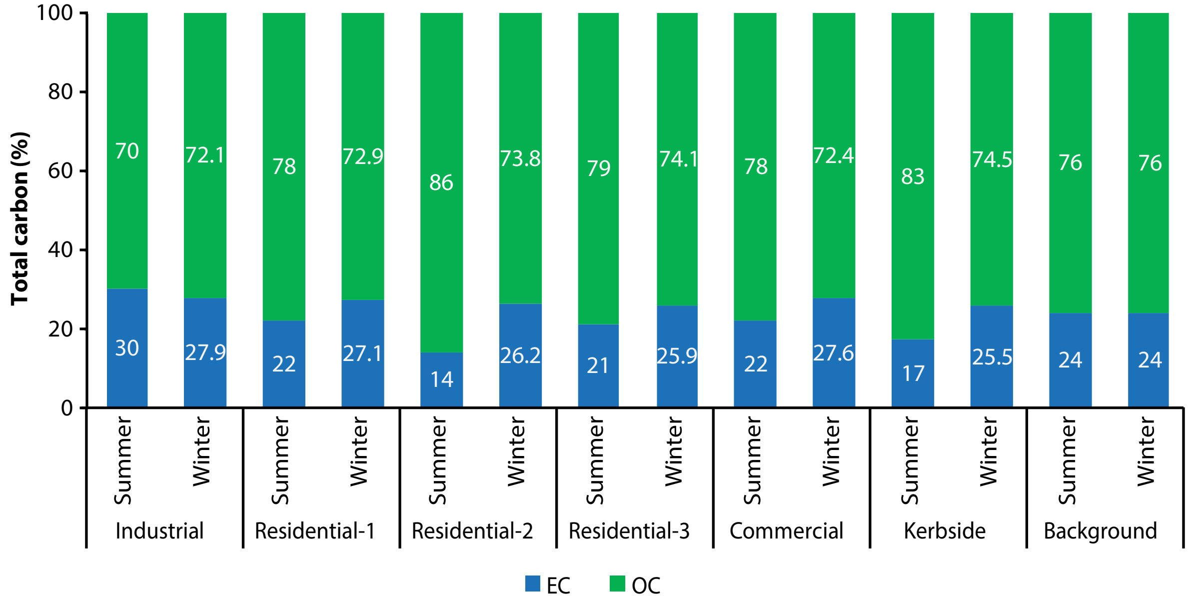


Figure 3.8 Seasonal variations of different fractions of carbon in ambient $PM_{2.5}$ at different monitoring locations

4 SOURCE APPORTIONMENT OF AMBIENT PARTICULATE MATTER USING RECEPTOR MODEL

Key Observations

- Road dust and construction were estimated as the major sources of ambient PM_{10} at different monitoring locations in the city during both the seasons.
- Biomass burning was estimated as the most important source of ambient PM_{10} at the background location during both summer and winter seasons. This suggests possible contribution of biomass burning in PM concentrations in the Patna city due to atmospheric transport from upwind regions.
- Secondary inorganic particulates were estimated as the major contributor to ambient $PM_{2.5}$ during the winter season at most of the monitoring locations in Patna city. This indicates significant regional scale contributions to the city.
- The source contributions of transport, industry and residential sectors were found similar to as reported earlier by CCAAP (2019), with some variations.

In this study, receptor modelling technique was used for source apportionment of ambient particulate matters. The framework for using receptor models consists of the following:

a. Formulating a conceptual model
b. Identifying potential sources
c. Characterizing source emissions
d. Obtaining and analysing samples for major components and source markers
e. Confirming source types with multivariate receptor models
f. Quantifying source contributions with the chemical mass balance
g. Estimating profile changes and the limiting precursor gases for secondary aerosols

Receptor modelling approaches have also been termed as 'top–down approach'. These are statistical protocols that compare the profiles of gases and particles (chemical and physical characteristics) at sources (known as source profiles) and receptors (location of monitoring) in a given area to estimate the source contributions at receptor locations. The fundamental principle of receptor models is based on mass conservation. Thus, a mass balance analysis is carried out to identify and apportion sources of airborne particulate matter in the atmosphere. This approach infers source contributions by determining the best fit linear combination of emission source chemical composition profiles needed to reconstruct the measured chemical composition of ambient samples (Watson et al., 1984). However, receptor models like CMB have some limitations:

i. They cannot identify the contribution of individual sources if several sources of the same type and emission characteristics are located in the area considered
ii. They require individual source profile of elements, ions, etc.
iii. Receptor models do not use pollutant emissions from different sources, meteorological data and atmospheric chemical transformation to simulate the contribution of different sources to receptor concentration of pollutants, unlike dispersion air quality models (USEPA, 2007). CMB model (ver 8.2) was used in this study to determine different source contributions at individual monitoring locations.

4.1 Chemical Mass Balance Model

TCMB model is based on the mass conservation of individual chemical species: ions, elements, and organic compounds, which are commonly referred to as markers. The basic equation (Eq. 1) of the CMB model as a statement of species conservation has been given by Watson *et al.* (1984):

$$Ci = \Sigma_{j=1}^{m} f_{ij} S_j + ei \qquad \text{eq. 1}$$

where, C_i is the ambient concentration of species *i*; *f* is the fraction of species *i* in source *j*; S_j is the source contribution of source *j*; and, e_i is for errors.

Various diagnostic checks are performed for each model run, such as t-statistics (source contribution divided by error of source contribution), chi-square test, regression coefficient, and percentage mass explained by the model. USEPA has set a standard range for each of these diagnostic measures. Along with these, the ratio of computed and measured concentration of each element (C/M ratio), and the ratio of residuals to uncertainty (R/U ratio) are checked, which are considered for each species while running the model. The CMB model quantifies the contributions from chemically distinct source types (i.e. sources with similar chemical and physical properties cannot be distinguished from each other by CMB). CMB requires speciated profiles of potentially contributing sources and the corresponding ambient data from analysed samples collected at receptor sites (USEPA, 2006). In this study, soil dust profiles for both $PM_{2.5}$ and PM_{10} have been created for Patna. Other sources' profiles such as coal burning, brick kilns, diesel and gasoline vehicles, construction, coal and wood chulah burning, construction, etc. have been used from CPCB (2012), ARAI (2017), etc.

4.2 Background of the Modelling Framework

Receptor models work on the principle of mass conservation which can be used to identify and apportion sources of airborne particulate matter in the atmosphere. The input dataset for receptor modelling are the large number of chemical constituents of PM concentrations in a number of samples. Receptor models use monitored pollutant concentration and their chemical composition, along with source profiles of the local air pollution sources to estimate the relative contributions of these sources on pollutant concentrations at any single monitoring location. Receptor models are retrospective, that is, they can only assess the impacts of air pollution source categories on pollutant concentrations that have already been monitored. CMB is a USEPA approved model which uses source profiles and speciated ambient data to quantify source contributions. Contributions are quantified from chemically distinct source types rather than from individual emitters.

The CMB receptor model consists of a solution to linear equations that express each receptor chemical concentration as a linear sum of products of source profile abundances and source contributions.

The major assumptions applicable in the case of the CMB model are as follows:

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

The key steps followed to carry out CMB modelling are as follows:

- Daily average concentrations of different species of PM at monitoring sites
- Details of source profiles selected and used for CMB analysis, which are as follows:

  a. Non-vehicular sources:

- A road dust study-specific profile was developed under this project and used.
- Refuse burning and soil (Source Apportionment of $PM_{2.5}$ & PM_{10} of Delhi NCR, 2018: TERI & ARAI).
- Profiles developed by IIT-Bombay (CPCB, 2009, Stationary Source Profiling report)
  - » Biomass burning
  - » Construction
  - » Industry

b. Vehicular source profiles:

- New composite profiles of different fuel types developed for newer technology vehicles (post-2005) (Source Apportionment of $PM_{2.5}$ and PM_{10} of Delhi NCR, 2018: TERI & ARAI).
- Earlier profiles of pre-2005 vehicle technology (CPCB, 2009, Vehicle Source Profiling report)

- Solution of the chemical mass balance equations was obtained through CMB-8.2 receptor model.
- Contributing sources were identified by averaging the contribution from sources observed based on daily samples across the monitoring period.

Source contribution estimates (SCE) are the main output of the CMB model. The sum of these concentrations approximates the total mass concentrations. When the SCE is less than its standard error, the source contribution is undetectable. The reduced chi square (x^2), coefficient of determination (R^2), and percent mass are goodness of fit measures for the least-square calculation. The x^2 is the weighted sum of squares of the differences between calculated and measured fitting species concentrations divided by the effective variance and the degrees of freedom. A value of less than one indicates a very good fit to the data. Values greater than 4 indicate that one or more of the fitting species concentrations are not well-explained by the source contribution estimates. x^2 values less than 4 were considered acceptable. R^2 is determined by the linear regression of the measured versus model-calculated values for the fitting species. R^2 ranges from 0 to 1. The closer the value is to 1.0, the better the SCEs explain the measured concentrations. When R^2 is less than 0.8, the SCEs do not explain the observations very well with the given source profiles. Value of $R^2 \geq 0.8$ was considered acceptable. Percent mass is the percent ratio of the sum of model-calculated SCEs to the measured mass concentration. Values ranging from 80% to 120% were considered acceptable. While the receptor modelling is carried out, the results were finalized only after the assurance that all the performance criteria are being met.

The SCE estimation of ambient particulate matter using the CMB model at different monitoring locations during the two seasons are presented in the following sections:

4.3 Estimation of Seasonal Variations of Sources Contributions to Ambient Particulate Matter

A comparative analysis of source contribution results for different monitoring sites have been discussed for each season. It is to be noted that the receptor model shows the shares of different sectors in primary PM and the un-apportioned secondary particulates separately.

4.3.1 Seasonal Variations of Sources of Ambient PM_{10} at Different Monitoring Locations

Summers and winters show differences in PM_{10} contributions from existing regional and local sources in the Patna region. Summers show a dominance of dusty sources, while vehicular combustion-based sources show higher contributions in winters (Figure 4.1). This is because of higher wind speeds in summers which cause increased suspension of soil dust, and dust from construction activities. Higher wind speeds also lead to reduced contribution of local sources (e.g. vehicles) and more influence of regional scale sources such as biomass burning, industries, and secondary particulates. In addition, higher nitrate formation during winter leads to enhanced contribution of secondary particulates in the season.

Dust (soil, road dust, and construction) was estimated as the major source of ambient PM_{10} at different monitoring locations in the city during both the seasons (summer: 43% to 73% and winter: 22% to 34%). Dust contribution was observed to be maximum at residential location-3 because of construction activities in the vicinity. This was followed by commercial location which also showed high dust contributions attributable to the frequent vehicular movements on poorly maintained roads surrounding the location. At the background location, dust was estimated to contribute only 11% and 16% of ambient PM_{10} during summer and winter seasons, owing to the presence of more dominant source of biomass burning. Secondary particulates were found to contribute between 4% and 14% in summer and 15% and 22% in winters. Contribution of secondary particulates were estimated at residential location-3 (29%) followed by commercial location (28%) and residential location-1 (27%) during winter season. Higher contribution of secondary particulates in winter is due to higher nitrate formation at lower temperatures. Highest contribution of industry/brick kiln to ambient PM_{10} was estimated at the background (35%) and industrial locations (24%) during the summer and winter seasons, respectively. This indicates considerable contributions of industries from outside of city limits. Biomass burning was estimated as the major source of ambient PM_{10} at the background location during both the summer (37%) and the winter (41%) seasons. This is attributed to use of solid biomass fuel for residential cooking purposes in the surroundings and burning of agriculture refuse materials in the villages outside Patna city. About 9–17% of PM_{10} contributions have been observed at the 6 stations within the city indicating regional scale effect . As expected among different monitoring locations, highest contribution to ambient PM_{10} from the transport sector was estimated at kerbside location (22%), followed by residential location-3 (20%) and commercial location (12%) during the winter season. At most locations, contributions of transport sector are found to be higher in winter due to slower wind speeds, which leads to enhanced contributions from the local sources within the city and lesser from regional scale sources. Higher nitrate formation from the NOx released by vehicular

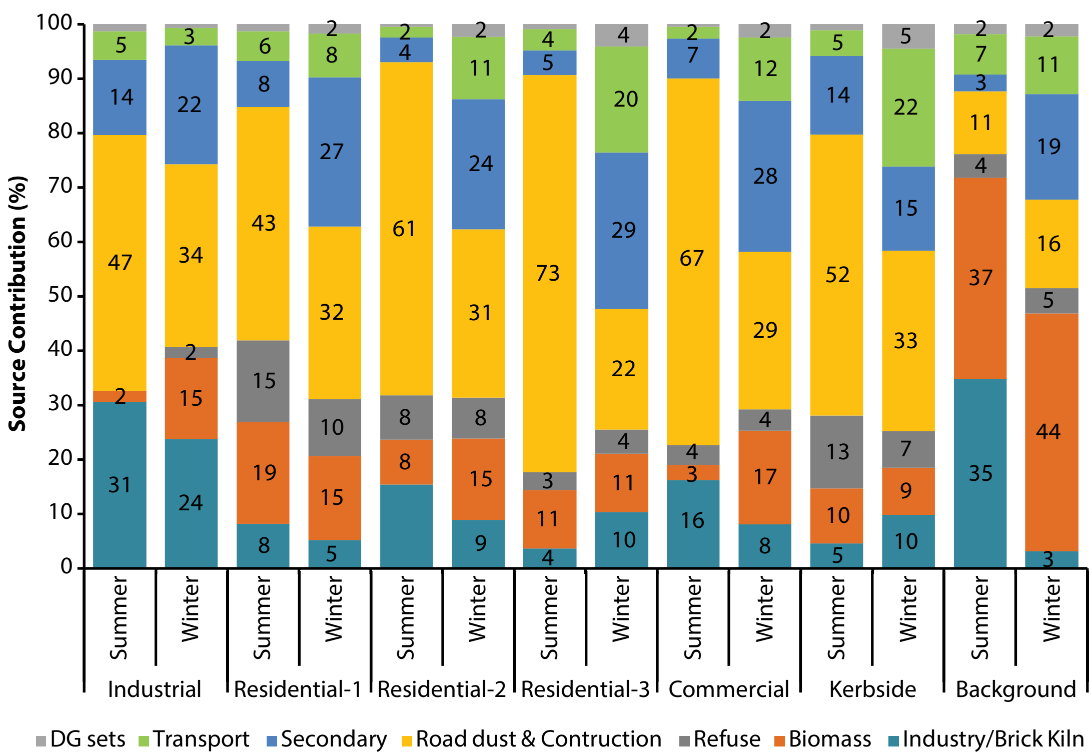


Figure 4.1 Estimated contributions of different sources to ambient PM_{10} at different monitoring locations during the two seasons

sources contributes more to secondary particulates during winter.

This is because the pollutants emitted from this local source are not dispersed completely owing to unfavorable meteorological conditions such as low wind speed and mixing height and get trapped in air and remain in the city for much longer time than in summer.

As expected, dust contributions (soil, construction and road dust) are more in summer than in winters due to drier conditions and higher wind speeds leading to dust suspension from far off sources. Similarly, at all the locations, the contribution of secondary particulates was found to be higher in winter than in summer due to higher nitrate formation in winter.

4.3.2 Seasonal Variations of Sources of Ambient $PM_{2.5}$ at Different Monitoring Locations

Like PM_{10}, seasonal variations are observed in source contributions of existing sources towards prevailing $PM_{2.5}$ concentrations. Other than local sources such as transport, construction and road dust, waste burning, etc. regional sources like biomass burning, industries also contribute significantly to $PM_{2.5}$ concentrations in Patna city.

Dust (soil, road dust and construction) (21% to 38%) was estimated as the major source of ambient $PM_{2.5}$ during summer season; whereas, inorganic secondary particulates (29% to 48%) were estimated as the major contributor to ambient $PM_{2.5}$ during the winter season at most of the monitoring locations in Patna. Biomass burning was estimated as the major source (41%) of ambient $PM_{2.5}$ at the background location during the winter season. Biomass burning was also estimated as the major source of ambient $PM_{2.5}$ at the industrial (31%) and commercial (34%) locations during the winter season. This is mainly from transported contributions from outside the city. Estimated contributions of the industry/brick kiln at different monitoring locations followed the order: Industry (45%) › Residential Location–2 (34%) › Commercial (22%) › Residential Location-3 (21%) › Residential Location–1 (19%) › Kerbside (18%) › Background (11%) during the summer season. The share of diesel from DG sets and the transport sector cannot be distinguished by the CMB model due to the presence of co-linearity in the source profiles. Therefore, to apportion the contribution of transport and DG set sector, we have used results of dispersion model from CCAAP (2019). The contribution of DG set to ambient $PM_{2.5}$ at different monitoring locations was estimated between 1% and 5% during the monitoring period.

It is also clear from Figure 4.2 that the share of local sources such as transport sector to the $PM_{2.5}$ concentrations at all the locations during winter season was observed to be higher than in summer. This is because the pollutants emitted from this local source are not dispersed completely due to unfavorable meteorological conditions such as low wind speed and mixing height and get trapped in air and remain in place for much longer time.

As expected, dust contributions (soil, construction and road dust) are more in summer than in winter due to drier conditions and higher wind speeds leading to dust suspension from far off sources. At all the locations, the contribution of secondary particulates was found to be higher in winters than in summers due to higher nitrate formation in winters.

4.3.3 Average Sources Contributions to Ambient Particulate Matter in Patna in Two Seasons

Figure 4.3 shows the contributions of different sources towards prevailing PM_{10} and $PM_{2.5}$ concentrations in Patna (average of 6 locations) during summers and winter seasons.

Dust (soil, road dust and construction) were estimated as the major sources of atmospheric PM_{10} during the summer (57%) and winter (30%) seasons in Patna city. In the summer season, major contribution of ambient $PM_{2.5}$ was also estimated from dust (soil, road dust and construction at 29%); however, secondary particulates were estimated as the major source of ambient $PM_{2.5}$ (38%) during the winter season. Contribution of biomass burning was estimated as 10% and 21% to ambient $PM_{2.5}$ during the summer and winter seasons, respectively. Higher biomass contributions in winters can be attributed to enhanced heating requirements

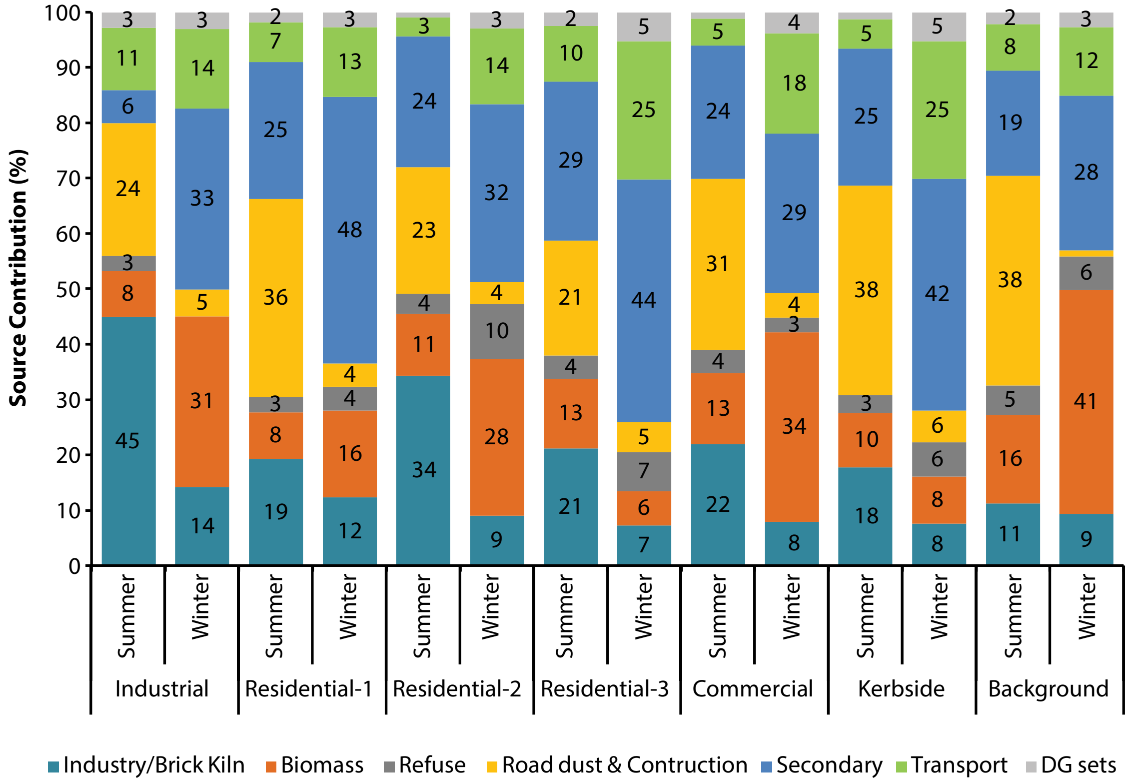


Figure 4.2 Estimated contributions of different sources to ambient $PM_{2.5}$ at different monitoring locations

within and outside of the city. About 11% and 10% of ambient PM_{10} and $PM_{2.5}$ were estimated to be contributed from the industry/brick kilns during the winter season. Industries contribute 10–27% $PM_{2.5}$ in the two seasons. DG sets contribute 4% $PM_{2.5}$ in winter and 2% $PM_{2.5}$ in summer. Refuse burning contribute 5% $PM_{2.5}$ in winter and 3% $PM_{2.5}$ in summer.

As expected, dust originating from soil, road, and construction activities contributed more in summer than in winter for both PM_{10} and $PM_{2.5}$ owing to drier conditions and higher wind speeds in summer leading to dust re-suspension and transport from far off sources.

On the contrary, the contribution of secondary particulates to the PM_{10} and $PM_{2.5}$ levels were found to be higher in winter than in summer as lower temperatures provide favorable conditions for formations of ammonium nitrate through reactions of nitric acids (formed by NOx) with ammonia. Moreover, for both the seasons, the contribution of secondary particulates to the ambient $PM_{2.5}$ levels were found to be higher than in PM_{10}, as secondary particles generally lie in fine range of particles. Also, irrespective of size fraction, the contribution of tail pipe emissions from transport sector is found to be higher in winters than in summers because the pollutants emitted from this local source are slowly dispersed due to calmer conditions in winters which leads to trapping of the pollutants and, hence, higher contributions from the transport sector is observed. Additionally, irrespective of the season, contribution of tail pipe emissions from vehicles was found to be higher in the ambient $PM_{2.5}$ fraction than in PM_{10} fraction. This is because emissions from tail pipe of vehicles contribute majorly to fine finer fraction of PM ($PM_{2.5}$) than coarse fraction of PM_{10}.

Various diagnostic checks were performed for each model run, such as chi-square value, regression coefficient, and percentage mass explained by the model. The chi-square value for 60% of the samples

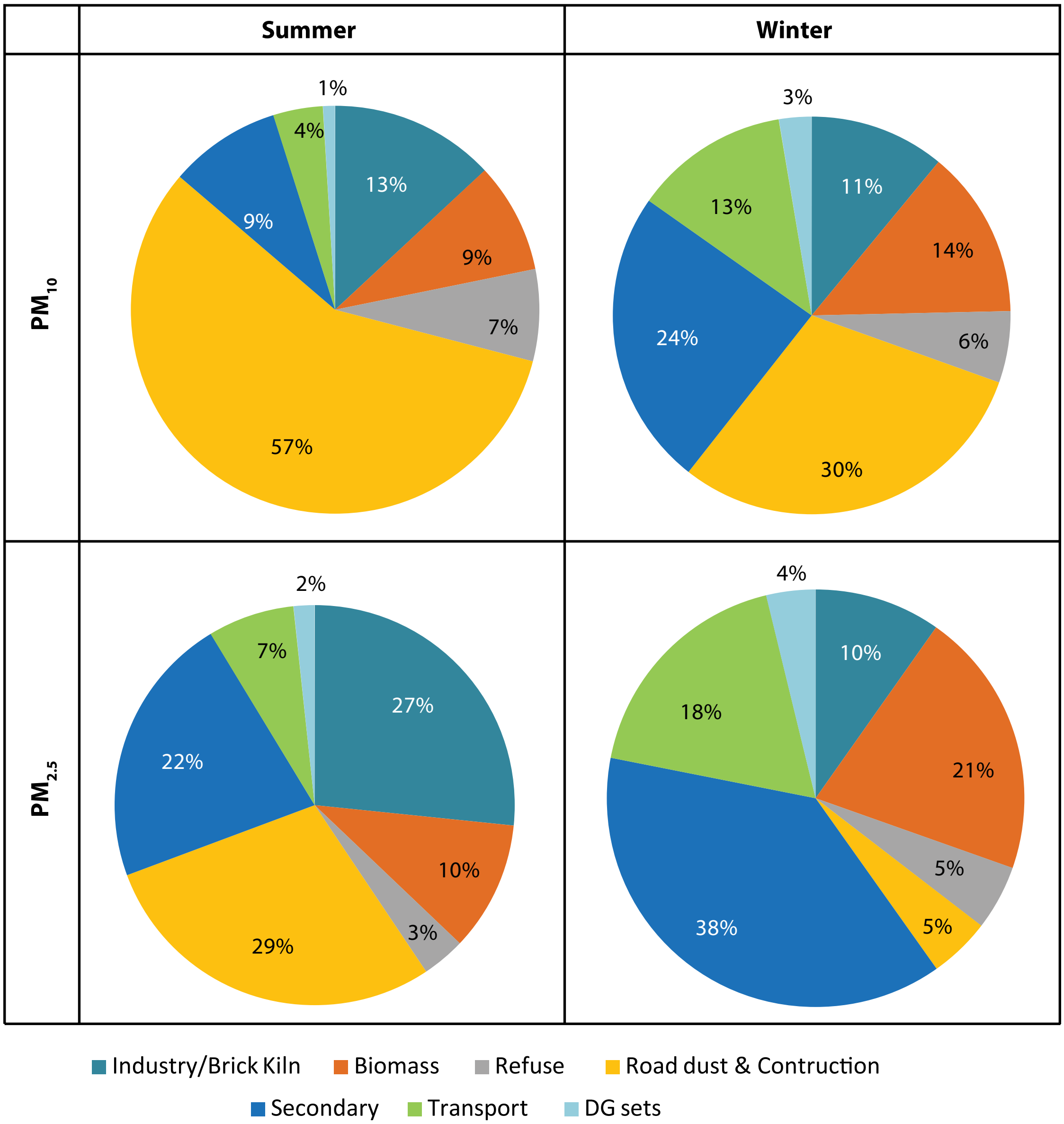
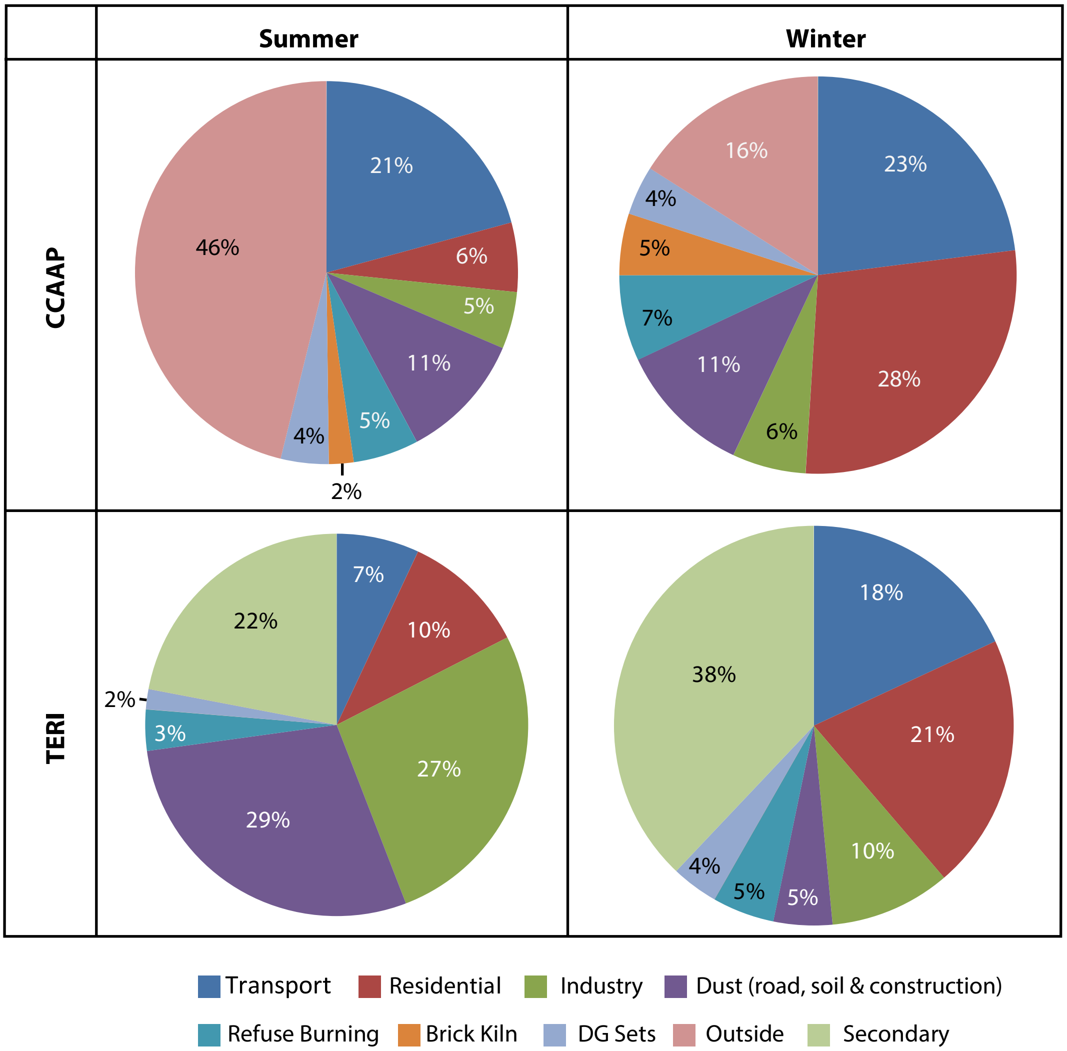


Figure 4.3 Estimated seasonal contributions of different sources to ambient PM_{10} and $PM_{2.5}$ in Patna city

were less than 4 and for nearly 35% samples were in the range of 4 to 8. R^2 is determined by the linear regression of the measured versus model-calculated values for the fitting species. R^2 ranges from 0 to 1. The closer the value is to 1.0, the better the SCEs explain the measured concentrations. It was observed that R^2 arranged from 0.75 to 0.98 for the samples. Percent mass is the percent ratio of the sum of model-calculated SCEs to the measured mass concentration. Values for the samples were ranging from 75% to 110% and were considered acceptable.

4.4 Comparative Analysis of Receptor modeling (TERI) study and Dispersion model (CCAAP, 2019) study

A similar air quality modelling study for Patna city determined the contribution of potential sources towards the total ambient $PM_{2.5}$ concentration



* the comparative analysis has been done for the two monitoring season (May-June 2019) for summers and (December 2019-January 2020) for winters for both the TERI and CCAAP, 2019 study

** This is to be noted that dispersion model results show source contribution from Patna city only and outside contributions are not distributed in the sectors. However, in receptor model results sectors show sectoral contributions of both city and outside sources; additionally it shows secondary particulates separately.

Figure 4.4 Comparative analysis of Receptor Modelling (TERI) and Dispersion Modelling (CCAAP) estimates of sources of ambient $PM_{2.5}$ concentrations in Patna

using dispersion modelling tool. In this section, a comparative analysis of the estimated source contributions using dispersion modelling tool (CCAAP, 2019) and the results of the present receptor modelling study have been done (Figure 4.4).

It is evident from the CCAAP (2019) results that the trans-boundary pollution is the major contributor in summers, while residential sector is the major contributor in winters to ambient $PM_{2.5}$ concentration in Patna city. The contribution from outside the Patna city is 46% in summers and 16% in winters, whereas residential sector contributes 28% in winters and 6% in summers. Transport sector is the second major contributor and contributes 23% in winters and 21% in summers.

On the other hand, this present report using receptor modelling shows that dust from soil, road and construction activities are the major contributors in summers and contribute 29% to the total $PM_{2.5}$ concentration while secondary particulates from various sources are the major contributors during winter's season and contribute 38% to the total $PM_{2.5}$ concentration. The second major contributor is industries/brick kilns sector which contributes to 27% of $PM_{2.5}$ concentration during summers. However, residential sector is the second major contributor during winter season and contributes 21% to the total $PM_{2.5}$ concentration.

CCAAP, 2019 report has shown significant contribution from outside sources, the present study shows significant secondary particulate contributions separately. The results of the two studies are not directly comparable on a one-to-one basis and need to be interpreted carefully. For example, industrial and residential biomass contributions in CCAAP study are seen low as they get eclipsed due to outside contributions. These sources are not present in plenty within the city and are mainly from outside the city limits. Similarly, in contrast to the CCAAP study, current study shows secondary particulates separately, which if allocated to the sectors will increase contributions of transport (mainly nitrates) and industrial (both nitrates and sulfates) sectors. In light of these observations, it can be seen that both the studies show high contributions of transport, residential biomass burning in winters. However, in summers, due to high wind speeds dust and industrial contributions are dominant.

4.5 Comparative Analysis of Chemical Mass Balance (CMB) model results with Positive Matrix Factorization (PMF)

In this section, a comparative analysis of the estimated source contributions, using two different receptor modeling approaches i.e. Positive Matrix Factorization (PMF) and Chemical Mass Balance (CMB) has been performed for the city of Patna. In PMF, source profiles are identified from the input data unlike CMB, in which source profiles are externally fed into the model.

In PMF, a solution to the mass balance equations is sought. The model automatically carries out multiple iterations to finalize the best possible factor contributions and source profiles from the chemically characterized PM data of different locations. The equation used for mass balance in the PMF model is

$$Xij=\Sigma k=1\ p\ Gik\ .\ Fkj + eij \qquad eq2$$

Where Xij is the concentration of species j measured on sample i, p is the number of factors contributing to the samples, Fkj is the concentration of species j in factor profile k, Gik is the relative contribution of factor k to sample i, and eij is the residual of the PMF model for the j species measured on sample i.

For running the PMF model with statistically valid sample size, all the samples of the 6 locations within the city were clubbed to ascertain source contributions of $PM_{2.5}$ in the city of Patna. The samples clubbed are on the basis that all of them are part of the city of Patna and represent the city providing some local variations in their characteristics. Comparative analysis of two different receptor modeling approaches to estimates the sources of ambient $PM_{2.5}$ concentrations in Patna is presented Figure 4.5.

As analyzed, city average source contribution estimated using both the approaches seems to be in consensus with small differences for most sectors as shown in Figure 4.5.

Both the approaches indicate that industrial (along with power plants) and dust (road, soil & construction) are the major contributor to $PM_{2.5}$ concentrations in summer season. Contributions from different sectors to the summer-time $PM_{2.5}$ concentrations in Patna city using the two approaches (CMB and PMF) are: a) 29% and 24% from dust (road, soil & construction), b) 27% $PM_{2.5}$ contribution from both the approaches from industries, c) 22% and 25% $PM_{2.5}$ contribution from secondary contribution, d) 10% and 18% $PM_{2.5}$ contribution from biomass and 7% and 6% $PM_{2.5}$ contribution from transport. Since, the chemical composition for biomass and refuse is similar; it's difficult to distinguish between the two sources in PMF.

In winters, secondary particles have the major contribution to $PM_{2.5}$ concentrations with a

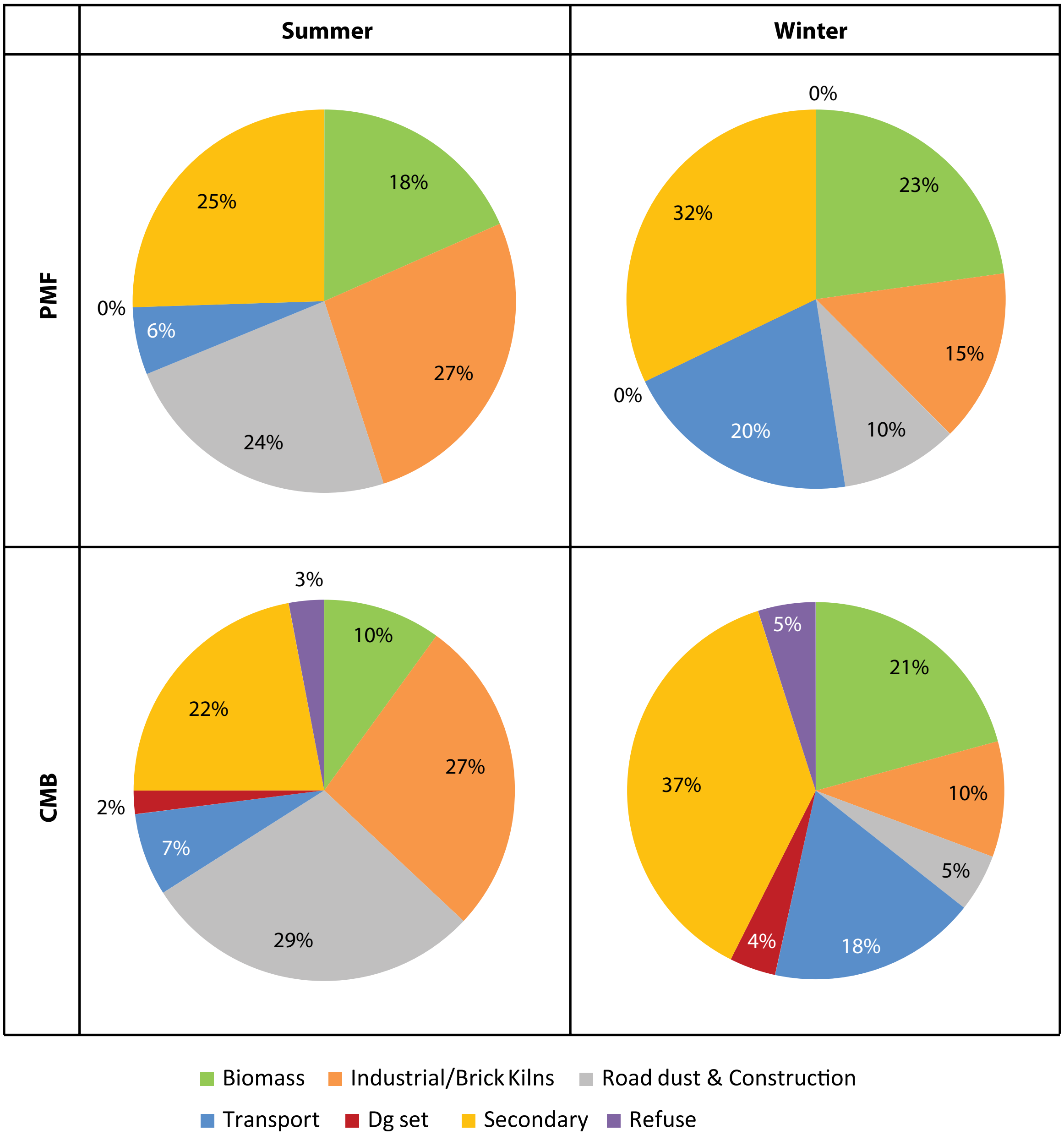


Figure 4.5 Comparative analysis of average estimates of sources of ambient $PM_{2.5}$ concentrations estimated by PMF and CMB models for the city of Patna

contribution of 37% and 32% from CMB and PMF approaches respectively, followed by 21% and 23% $PM_{2.5}$ contribution from residential, 18% and 20% $PM_{2.5}$ contribution from transport and 5% and 10% $PM_{2.5}$ contribution from dust(road, soil & construction).

Evidently, the source apportionment results of two receptor models are aligned to each other and hence provide more confidence in the datasets. Using these result, important policy decisions can be taken and air quality management plan needs to be strengthened.

5 SUMMARY AND CONCLUSION

This study analysed and quantified contribution of sources and identified key air pollution sources in Patna which need to be controlled for improvement of air quality. The report finds that ambient particulate concentrations in Patna city were much higher (especially in winter season) than the NAAQS. Ambient PM_{10} and $PM_{2.5}$ concentrations were lower in summer season than in winter season due to meteorological reasons. PM_{10} and $PM_{2.5}$ concentrations for summer season were 152±43 µg/m³ and 43±13 µg/m³, whereas PM_{10} and $PM_{2.5}$ concentration for winter season were 241±60 µg/m³and 130±37µg/m³, respectively. Concentration of PM_{10} varied from 103 µg/m³ to 271 µg/m³ in summer season and 198 µg/m³ to 277 µg/m³ in winter season across six different monitoring stations in the city. The average concentration of $PM_{2.5}$ in summer season ranged between 32 and 64 µg/m³ and 82 to 197 µg/m³ during winter season.

The assessment of sources contributing to ambient PM_{10} concentrations using the receptor model technique reveals that dust (soil, road and construction) is the major contributor of PM_{10} in both winter (30%) and summer (57%). Dust contributes in the range of 22%–34% to PM_{10} concentrations at six different locations in winter season. Secondary inorganic particulates, which are formed by reactions of gases such as ammonia, SO_2 and NO_x, contribute to 24% in PM_{10} concentrations in winter and 9% in summer. Secondary particulate contributes in the range of 15% to 29% at the six locations in PM_{10} concentrations in winter. In summer, another important source is the industrial sector which contributes to an average of 13% of PM_{10} concentration in Patna city. Vehicles and biomass burning contribute to 4–13% and 9–14% in the PM_{10} concentrations during the two seasons, respectively.

$PM_{2.5}$ source contributions are somewhat different than PM_{10}. Sources that emit particles more in fine range (e.g. biomass burning and vehicles) show more contributions in $PM_{2.5}$ than in PM_{10}. In winter, secondary particulates contribute to about 38% in the $PM_{2.5}$ concentration which is the highest contribution from any source in the season; ranging from 29% to 48% at different locations in the city. $PM_{2.5}$ contribution in winter from biomass (21%) and transport (18%) is found to be more than the PM_{10}, depicting dominance of fine particulates from these sectors. The average industrial contributions to $PM_{2.5}$ range between 10% and 27% during the two seasons. CCAAP's earlier study based on a dispersion model also showed that residential (6–28%), transportation (21–23%), and industry (5–6%) are the major sources contributing to $PM_{2.5}$ concentrations in the city during the two seasons. However, it is to be noted that these sectoral estimates in the CCAAP study do not include contributions from outside of city. Open waste burning and road and construction dust account for 5–7% and 11% of the total $PM_{2.5}$ concentration respectively, during the two seasons. Source contributions estimated by the two studies cannot be compared directly as CCAAP study does not show distribution of outside sources, while this study could not apportion the secondary particulates. However, it is evident from both the studies that biomass burning and transport are the major contributors to $PM_{2.5}$ in winters, while industries (through atmospheric transport from outside of city) and dust are the major contributors in summers.

5.1 Control Strategies for Pollution Management in Patna City

It is evident from this study and the study carried out by CCAAP that air pollution is a regional issue and, hence, cannot be controlled just by taking measures within the city of Patna. More, wider scale regional approach, covering at least the district of Patna and preferably whole of Bihar, needs to be developed and followed. A regional scale air quality management plan for Bihar needs to be developed and implemented, along with the city level action plan of Patna for most-effective results. Sectoral measures are listed here.

a. Dust (road, soil & construction) was estimated as the major sources of ambient PM_{10} concentrations during both summer (57%) and winter (30%) seasons. They were also estimated as the major sources of average ambient $PM_{2.5}$ in the city during summer season (29%). The city is located on the alluvium plain of river Ganga and heavy silt deposit in the river near Patna contributes to windblown dust. In order to avoid the windblown dust from the river, a green belt should be created with the local varieties of trees such as pipal, neem, kikar, on the river bank towards the city side. In addition, large number of construction activities are being carried out in the city related to road construction, building construction, and other infrastructure development. It is important to undertake actions to reduce the dust blown out of these construction sites. Being on the bank of river Ganga, the city has good source of water which can be sprinkled at each construction site regularly at least during morning and in the evening to suppress the dust to the ground. All loose material at construction sites need to be covered properly to reduce the wind spray of dust from these sites. All construction vehicles need to be cleaned at the site itself before operating on the roads. Fog guns can be used at major construction sites to suspend the airborne particulate matter. During episodic high pollution events, highly polluting construction activities can be halted. In order to control road dust re-suspension, all major roads need to be regularly cleaned with cost-effective road sweeping machines and the collected dusts can be used at the construction development sites as filling material. Kerbs of the roads need to be properly landscaped to reduce silt loadings on the roads.

b. Industry/Brick kilns sector is estimated as one of the largest sources of atmospheric PM_{10} during both summer (13%) and winter (11%) seasons. Industry/Brick kilns sectors were also estimated as the second largest source of atmospheric $PM_{2.5}$ in the city during summer season. Measure should be taken to shift the technology of all the brick kilns in the Patna district (preferably in the whole Bihar) to zig-zag technology, which will reduce not just pollution but also coal consumption. Biomass/coal used in these industries need to be either switched over to gas/electric modes or need to be fitted with real-time stack monitoring equipment along with adequate control devices. The PM control standards need to be made more stringent with the prescription of more advanced devices for control such as cyclones, wet scrubbers, bag filters. Solid fuel burning within the city limits need to be prohibited and replaced by electricity or gas. High sulphur fuels such as furnace oil/pet coke, etc. should only be permitted with installation of adequate SO_2 control devices such as flue gas desulphurization or at least a wet scrubber. Finally, the capacities of state pollution control board need to be strengthened in terms of manpower, equipment, skillsets, finances, and laboratories. This is essential for an effective law enforcement regime for air quality control.

c. Residential fuel wood burning is the major source of atmospheric $PM_{2.5}$ (21%) in the city during winter season The CMB model has estimated significantly higher contributions from residential fuel wood burning towards the ambient PM_{10} concentrations compared to other sources, especially at the background monitoring stations during both summer (37%) and winter (44%) seasons. This suggests that residential fuel wood burning outside the Patna Municipal Corporation is quite prevalent and, hence, contributes towards the ambient PM_{10} concentration of the city during both summer and winter seasons. Somewhat lesser but still very significant contributions of biomass burning are seen in Patna city, which can be attributed to contributions from outside. Residential fuel wood burning outside the Patna city boundary must be gradually reduced by faster penetration of LPG/PNG. While Patna city has higher percentage of LPG users, the number is relatively less outside the city limits. As a limited time strategy two cylinders can be given free during the winter season to people below poverty line (who cannot afford LPG) . Additionally, biomass is also burnt in winter for heating purposes. In order to curtail this, temporary shelter homes with heating facilities need to be provided to homeless during winter. Night-time security guards need to be provided with electric heaters.

d. Transport sector has been estimated as one of the largest contributors towards the ambient $PM_{2.5}$ in the city. The sectoral contribution can be reduced through tailpipe emissions via improving the quality of fuel with regular inspection and maintenance of vehicles. Further, it is important to reduce the vehicular load inside the city to reduce congestion and tailpipe emissions. For this, nation-wide adoption of BS-VI standards has started which will slowly turn over the fleet of old vehicles to new low polluting BS-VI vehicles. Plans need to be framed to replace the old government vehicles with new technology BS-VI vehicles. Awareness programmes need to be launched to encourage people to modernize their fleets. Additional fiscal incentives need to be planned for early turnover of the fleet. Electric charging infrastructure needs to be installed with assurance to the Discoms that recoveries can be made later when a decent electric vehicle-based electricity demand is generated. Future, public transport vehicles need to be on electric modes preferably with safe, reliable, and comfortable approach in order to attract private vehicle owners. Congestion is a very important factor responsible for real–world emissions from vehicles, and use of advanced traffic management techniques may reduce congestion, time of travel, fuel consumption, and pollution. Odd-even scheme can be employed during air pollution emergency; however, congestion pricing scheme needs to be developed as a long-term solution. The current vehicle PUC system needs to be upgraded; an experiment with remote sensing-based inspection system needs to be carried out.

In brief, the following actions may be undertaken to reduce the ambient PM_{10} and $PM_{2.5}$ concentrations in the city:

- Development of a regional scale plan for control of pollution in Bihar with Patna and other important cities as hotspots.
- A green belt with local dense canopy tree species needs to be developed on the bank of river Ganga to stop the windblown dust sediments reaching the city.
- Dust has to be controlled at major construction sites in the city through barriers, cleaning, and dust suppressants.
- Regular mechanical sweeping of city roads (including minor roads) particularly near the construction sites and dumping the collected waste at major construction sites as filling material.
- Legislation on use of cleaner fuels (gas/electricity) instead of biomass and coal in industries/brick kilns in and around Patna city, else real-time monitoring of stacks and mandatory use of high efficiency control devices with standards made more stringent
- Capacity building of SPCB with more budgetary allocations, staff, skill sets, and equipment.
- Penetration of LPG in district in a time bound manner and distribution of two free cylinders, in winter, to people below poverty line.
- Improvement of vehicular inspection and maintenance programme (experiment with remote sensing technology) in and around Patna city to reduce the contribution of particulates from the tailpipe emission of the vehicle.
- Enhancement of public transport system preferably on electric modes which can prove exemplary for others to move to electric modes. Installation of electric charging infrastructure.
- State-level fleet modernization plan with concessions on registration fees to old vehicle owners for early fleet modernization; heavy

penalties on unregistered, visibility polluting vehicles.

- Traffic congestion management actions for free flow of traffic.
- Awareness programme to encourage people for non-motorized transportation within 5 to 6 km in the city and introduction of non-motorized lanes wherever possible within the city.
- Increase plantation in open spaces within the city, wherever possible.
- Development of graded response plan, emergency response plan, and forecasting system for early warnings.

We understand that there is considerable growth in sectoral activities and the state has also implemented several control measures to control air pollution post 2019, however, the current study is not able to capture all of those. We would like to state that receptor model based studies are retrospective in nature and provide information about a point in time. We also believe that air quality management is a dynamic process, which is expected to change very quickly in a growing city like Patna. We, therefore, recommend regular updation of source apportionment results either on a real-time basis or atleast at an interval of 3 years to take into account the growth patterns and the impact of the measures taken.

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ANNEXURE

Annexure I: Daily Ambient Particulate Matter Concentration Data

I. Background: Nizampur (Summer) & Danapur (Winter)

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
5/12/2019	152	89	12/19/2019	176	120
5/13/2019	123	56	12/20/2019	281	105
5/14/2019	108	49	12/21/2019	280	239
5/15/2019	82	36	12/22/2019	331	166
5/16/2019	123	36	12/23/2019	282	123
5/17/2019	138	65	12/24/2019	259	129
5/18/2019	107	38	12/25/2019	162	110
5/19/2019	108	42	12/26/2019	222	92
5/20/2019	155	75	12/27/2019	162	99
5/22/2019	111	37	12/28/2019	278	96
5/25/2019	102	47	12/29/2019	270	86
5/26/2019	83	29	12/30/2019	288	161
5/27/2019	167	39	12/31/2019	327	178
5/28/2019	111	39	01/01/2020	303	223
5/29/2019	88	49	01/02/2020	270	125
5/30/2019	97	34	01/03/2020	169	59
5/31/2019	37	44	01/04/2020	176	81
06/01/2019	41	33	01/05/2020	135	66
06/02/2019	36	12	01/06/2020	248	106
06/03/2019	50	18	01/07/2020	260	75
06/11/2019	139	31	01/08/2020	192	109
06/12/2019	91	21	01/09/2020	164	76
6/13/2019	115	20	01/10/2020	141	102
6/14/2019	202	55	01/11/2020	199	107
6/15/2019	147	20	01/2/2020	176	82
6/16/2019	200	47	1/13/2020	190	98
6/17/2019	145	12	1/14/2020	163	94

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
6/18/2019	120	19	1/15/2020	230	97
6/19/2019	160	37	1/16/2020	254	115
6/20/2019	87	17	1/17/2020	210	99
6/21/2019	43	14	1/18/2020	155	81
6/22/2019	47	19	1/19/2020	170	52
6/23/2019	40	15	1/20/2020	164	91
Minimum	36	12	**Minimum**	135	52
Maximum	202	89	**Maximum**	331	239
Mean	108	36	**Mean**	221	110
Std. deviation	±46	±18	**Std. deviation**	±58	±42

II. Residential Location-1: Revenue colony

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
5/12/2019	139	74	12/19/2019	301	171
5/13/2019	127	50	12/20/2019	247	141
5/14/2019	119	35	12/21/2019	153	110
5/15/2019	106	46	12/22/2019	206	84
5/16/2019	109	56	12/23/2019	169	84
5/17/2019	174	46	12/24/2019	148	125
5/18/2019	119	42	12/25/2019	198	108
5/19/2019	61	45	12/26/2019	201	143
5/20/2019	129	45	12/27/2019	304	140
5/22/2019	107	46	12/28/2019	315	146
5/25/2019	149	47	12/29/2019	256	114
5/26/2019	106	24	12/30/2019	264	107
5/27/2019	108	35	12/31/2019	308	83
5/28/2019	100	47	01-01-2020	319	134
5/29/2019	210	51	01-02-2020	359	159
5/30/2019	92	31	01-03-2020		
5/31/2019	133	29	01-04-2020		
6/01/2019	94	28	01-05-2020		
Minimum	61	24	**Minimum**	148	83
Maximum	210	74	**Maximum**	359	171
Mean	121	43	**Mean**	250	123
Std. deviation	±33	±12	**Std. deviation**	±67	±28

III. Residential Location-2: Phulwari Sharif

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
5/12/2019	101	32	12/19/2019	301	154
5/13/2019	122	40	12/20/2019	256	162
5/14/2019	97	32	12/21/2019	312	100
5/15/2019	128	33	12/22/2019	255	96
5/16/2019	118	37	12/23/2019	242	75
5/17/2019	137	45	12/24/2019	252	79
5/18/2019	219	38	12/25/2019	188	85
5/19/2019	248	38	12/26/2019	253	102
5/20/2019	183	30	12/27/2019	214	129
5/22/2019	252	44	12/28/2019	233	153
5/25/2019	131	24	12/29/2019	250	150
5/26/2019	93	23	12/30/2019	247	140
5/27/2019	127	30	12/31/2019	142	59
5/28/2019	123	23	01/01/2020	146	48
5/29/2019	97	25	01/02/2020	158	52
Minimum	93	23	**Minimum**	142	48
Maximum	252	45	**Maximum**	312	162
Mean	145	33	**Mean**	230	106
Std. deviation	±54	±7	**Std. deviation**	±51	±40

IV. Residential Location-3: East Gola Road

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
5/12/2019	87	32	12/19/2019	234	122
5/13/2019	83	32	12/20/2019	174	123
5/14/2019	70	33	12/21/2019	187	82
5/15/2019	86	28	12/22/2019	177	65
5/16/2019	87	30	12/23/2019	173	91
5/17/2019	95	39	12/24/2019	211	76
5/18/2019	130	21	12/25/2019	205	43
5/19/2019	79	31	12/26/2019	180	82
5/20/2019	108	33	12/27/2019	165	61
5/22/2019	125	33	12/28/2019	190	90
5/25/2019	220	50	12/29/2019	156	35
5/26/2019	152	27	12/30/2019	226	76

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
5/27/2019	171	35	12/31/2019	236	127
5/28/2019	127	24	01-01-2020	254	94
5/29/2019	111	31	01-02-2020	196	67
Minimum	70	21	**Minimum**	156	35
Maximum	220	50	**Maximum**	254	127
Mean	115	32	**Mean**	198	82
Std. deviation	±41	±7	**Std. deviation**	±29	±27

V. Commercial location: S.D.A. Mission School

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
5/12/2019	180	70	12/19/2019	415	332
5/13/2019	139	50	12/20/2019	337	267
5/14/2019	211	45	12/21/2019	279	206
5/15/2019	165	44	12/22/2019	189	176
5/16/2019	142	61	12/23/2019	179	164
5/17/2019	167	54	12/24/2019	226	170
5/18/2019	139	42	12/25/2019	228	155
5/19/2019	163	52	12/26/2019	233	204
5/20/2019	107	42	12/27/2019	196	138
5/22/2019	109	47	12/28/2019	341	246
5/25/2019	136	53	12/29/2019	318	249
5/26/2019	184	44	12/30/2019	326	220
5/27/2019	146	42	12/31/2019	291	210
5/28/2019	157	50	01-01-2020	95	83
5/29/2019	126	39	01-02-2020	156	128
5/30/2019	190	50	01-03-2020		
Minimum	107	39	**Minimum**	95	83
Maximum	211	70	**Maximum**	415	332
Mean	154	49	**Mean**	254	197
Std. deviation	±29	±8	**Std. deviation**	±85	±62

VI. Kerbside location: Boring Canal Road

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
5/12/2019	76	42	12/19/2019	286	151
5/13/2019	76	35	12/20/2019	207	187
5/14/2019	73	42	12/21/2019	225	136
5/15/2019	158	85	12/22/2019	265	107
5/16/2019	116	84	12/23/2019	223	129
5/17/2019	76	30	12/24/2019	243	132
5/18/2019	69	39	12/25/2019	242	154
5/19/2019	119	38	12/26/2019	221	124
5/20/2019	130	34	12/27/2019	272	149
5/22/2019	76	25	12/28/2019	249	153
5/25/2019	95	22	12/29/2019	254	137
5/26/2019	104	26	12/30/2019	230	130
5/27/2019	135	34	12/31/2019	236	125
5/28/2019	120	28	01-01-2020	181	95
5/29/2019	128	23	01-02-2020	202	92
Minimum	69	22	**Minimum**	181	92
Maximum	158	85	**Maximum**	286	187
Mean	103	39	**Mean**	236	133
Std. deviation	±28	±20	**Std. deviation**	±28	±24

VII. Industrial location: Didarganj

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
5/12/2019	303	112	12/19/2019	459	221
5/13/2019	335	126	12/20/2019	370	146
5/14/2019	360	72	12/21/2019	396	125
5/15/2019	269	52	12/22/2019	110	100
5/16/2019	245	50	12/23/2019	195	118
5/17/2019	189	50	12/24/2019	284	90
5/18/2019	129	41	12/25/2019	187	128
5/19/2019	144	50	12/26/2019	326	146

Summer	Concentration (µg/m³)		Winters	Concentration (µg/m³)	
	PM_{10}	$PM_{2.5}$		PM_{10}	$PM_{2.5}$
5/20/2019	318	76	12/27/2019	376	225
5/22/2019	218	66	12/28/2019	224	153
5/25/2019	325	57	12/29/2019	219	113
5/26/2019	306	47	12/30/2019	166	89
5/27/2019	292	52	12/31/2019	225	117
5/28/2019	359	48	01/01/2020	328	152
5/29/2019	271	56	01/02/2020	295	121
Minimum	129	41	**Minimum**	110	89
Maximum	360	126	**Maximum**	459	225
Mean	271	64	**Mean**	277	136
Std. deviation	±73	±25	**Std. deviation**	±98	±41

Annexure –II- Methodology for chemical analysis of PM samples

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

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

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

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

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A unique developing country institution, TERI is deeply committed to every aspect of sustainable development. From providing environment-friendly solutions to rural energy problems to helping shape the development of the Indian oil and gas sector; from tackling global climate change issues across many continents to enhancing forest conservation efforts among local communities; from advancing solutions to growing urban transport and air pollution problems to promoting energy efficiency in the Indian industry, the emphasis has always been on finding innovative solutions to make the world a better place to live in. However, while TERI's vision is global, its roots are firmly entrenched in Indian soil. All activities in TERI move from formulating local- and national-level strategies to suggesting global solutions to critical energy and environment-related issues. TERI has grown to establish a presence in not only different corners and regions of India, but is perhaps the only developing country institution to have established a presence in North America and Europe and on the Asian continent in Japan, Malaysia, and the Gulf.

TERI possesses rich and varied experience in the electricity/energy sector in India and abroad, and has been providing assistance on a range of activities to public, private, and international clients. It offers invaluable expertise in the fields of power, coal and hydrocarbons and has extensive experience on regulatory and tariff issues, policy and institutional issues. TERI has been at the forefront in providing expertise and professional services to national and international clients. TERI has been closely working with utilities, regulatory commissions, government, bilateral and multilateral organizations (The World Bank, ADB, JBIC, DFID, and USAID, among many others) in the past. This has been possible since TERI has multidisciplinary expertise comprising of economist, technical, social, environmental, and management.

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