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**Source apportionment studies to identify particulate matter
from crop residue burning affecting human health**

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Dedicated to my Parents and curiosity

Candidate's Declaration

I, hereby declare that the work presented in the thesis entitled “**Source apportionment studies to identify particulate matter from crop residue burning affecting human health**” in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy in the Department of Chemical Engineering, Thapar Institute of Engineering and Technology, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Susheel Mittal, Senior Professor, School of Chemistry and Biochemistry, Thapar Institute of Engineering and Technology, Patiala. The matter embodied in this thesis has not been submitted in part or full to any other university or institute for the award of any degree in India or Abroad.

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Gurpreet Singh Saggu

Abstract

Rice and wheat are the major crop in the North-Western part of the country, which generate a large amount of leftover crop residue, intensified with the usage of mechanical combine harvester technology, which is further, subjected to open field crop residue burning. It is a human initiated activity for the purpose of preparing the fields for the next crop quickly and inexpensively. The burning of agricultural residues leads to significant emissions of chemically and radioactively important trace gases such as methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), oxides of Nitrogen (NO_x) and Sulphur (SO_x) and particulate matter (PM) to the atmosphere. Size, concentration, composition, and toxicity of particulate matter are vital features that greatly affect the possible human health problems related to their exposure. This research provides insight on effects of particulate matter fractions (PM_{10} , $\text{PM}_{2.5}$ and PM_1) on lung efficiency of school children and was conducted from September 2014 to December 2015 covering one wheat and two rice crop seasons. The effects on children are more severe than other age groups due to their body structure and constraints. The children are unaware of their surrounding environment and their organs are in development phase. Due to comparatively weaker immune system, even short-term exposure could lead to harmful health effects on children. The study was undertaken at 3 rural sites in the districts of Patiala, Fatehgarh Sahib and Sangrur (Malwa region of Punjab) with no nearby another source except national highway at Fatehgarh Sahib. The monthly average values of PM_{10} , $\text{PM}_{2.5}$ and PM_1 were about 3–4 times higher than the National Ambient Air Quality Standards (NAAQS) given by Central Pollution Control Board during the crop residue burning periods. The MODIS data images of crop residue burning events confirmed the active fire operations over the region. The lung function parameters (Forced Vital Capacity, Forced Expiratory Volume in one second) of children (10–16 years) decreased with increase in particulate matter concentration while no significant effect was observed on Oxygen saturation level of children. The decrease in Forced Vital Capacity was slightly more in male subjects as compared to the female population. The sharp decrease in Pulmonary Function Test parameters during the crop residue burning period indicated the severity of the episodic burning events on the health of the children. The more decrease in lung efficiency was observed during rice crop residue burning periods as compared to wheat crop residue burning period, associated it with increased concentration levels of particulate matter during that time period.

The establishment of adverse health effects of increased particulate matter concentrations leads to the inquiry about the composition of the particulate matter. To determine the contribution of different particulate sources in PM₁₀ mass concentration at semi urban site of Thapar Institute of Engineering and Technology, Patiala, source apportionment study was carried out from 7 May 2015 to 9 June 2016. For source apportionment, particulate matter (PM₁₀) was collected on glass microfiber filter which was extracted and analysed for metals (Al, Ti, Ca, Mn, Fe, Mg, V, Cr, Ni, Cu, Zn, Ba and Pb) and ions (Na⁺, K⁺, SO₄²⁻, Cl⁻, NO₃⁻). To know the variability in sources, PM₁₀ was collected in daytime-nighttime paired samples for 24 hours. The study was specifically designed to apportion the sources of air pollution where main exposure is from crop residue burning. The particulate matter (PM₁₀) samples were analyzed for mass and chemical composition, with Potassium as biomarker for crop residue burning. Sulfate (SO₄²⁻) and potassium ion (K⁺) species dominated the concentration of characterized species. K⁺ and Cl⁻ were identified as reliable markers for crop residue burning while Zn, Pb, Al, Ni and Cu were identified as markers for vehicular exhaust. The results of Positive matrix factorization (PMF) model gives the five major sources as probable sources of PM₁₀ pollution. The highest contribution in PM₁₀ mass concentration was found to be sulfate (24.39±10.42), and potassium (24.02±09.56) and chloride (07.07±05.47), which combined accounts for nearly 60% of the total PM₁₀ mass fraction. The highest source contribution was from Industrial emission source (22.9%), with almost same contribution from biomass burning (21.2%), and resuspended dust (20.7%) and followed by vehicular emissions (19.0%) and least from secondary aerosols (16.2%). Nighttime concentrations were always higher than day time levels due to descend of the boundary layer height at night time period. The measured species mass concentration represents 65% mass fraction of the PM₁₀. The results of the study provide an approximate indication of which anthropogenic and natural sources of particulate pollution could be responsible for poor health quality in rural and semi urban areas in Punjab. Based on the results of the study, emissions cut off from industrial and biomass burning are required in the region as biomass burning and industrial emissions are the biggest contributor in PM concentrations (21.2% and 22.9%, respectively). Further, wide range of markers including trace gases, particulate matter and various Volatile organic compounds (VOCs) should be studied for better understanding of origin of the sources and GIS (Geographic Information System) should be used along with

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List of Abbreviations used:

1. AOD₅₀₀ = Aerosol Optical Depth at 500 meters
2. ART-2a = Adaptive Resonance Theory-2a
3. ARCRBP = After Rice Crop Residue Burning period
4. AWCRRBP = After Wheat Crop Residue Burning Period
5. ATS = American Thoracic Society
6. B(a)P = Benzo(a)pyrene
7. BB = Biomass Burning
8. BBOA = Biomass burning organic aerosol
9. BC= Black carbon
10. BDL = Below Detection Limit
11. BrC = Brown carbon
12. BRRCBP = Before Rice Crop Residue Burning Period
13. BWCRBP = Before Wheat Crop Residue Burning Period
14. CAFO = Concentrated animal feeding operations
15. CMB = Chemical mass balance
16. CMAQ = Community Multi-scale Air Quality
17. COPD = Chronic obstructive pulmonary disease
18. CWT = Concentration-Weighted Trajectory
19. DRRCBP = During Rice Crop Residue Burning Period
20. DR = Diagnostic ratio
21. DTT = DiThioThreitol
22. DWCRBP = During Wheat Crop Residue Burning Period
23. EC = Elemental Carbon
24. EDGAR = Emission Database for Global Atmospheric Research
25. EOS = Earth Observing System
26. FEV₁ = Forced Expiratory Volume in 1 Second
27. FRP = Fire Radiative Power
28. FTH = Fatehgarh Sahib Site
29. FVC = Forced Vital Capacity
30. GAN = Galactosan
31. GIS = Geographic Information System
32. GSTT1 = Glutathione S-Transferase genes
33. HYSPLIT = Hybrid Single-particle Lagrangian Integrated Trajectory
34. IARC = International Agency for Research on Cancer
35. IE = Industrial Emissions
36. IGP = Indo Gangetic Plain
37. ILA = Interstitial lung abnormalities
38. LPA = Local Planning Area
39. LVG = Levoglucosan
40. MAN = Mannosan
41. MDL = Method Detection Limit
42. ME-2 = Multilinear Engine-2

- 43. MLR = Multiple linear regression
- 44. MM5 = Mesoscale Modeling System Generation 5
- 45. MODIS = MODerate resolution Imaging Spectroradiometer
- 46. MPAES = Microwave Plasma Atomic Emission Spectroscopy
- 47. NAC = Nitro aromatic compounds
- 48. NH44 = National Highway 44
- 49. NMVOCs = Non methane volatile organic compounds
- 50. NOAA = National Oceanic and Atmospheric Administration
- 51. OC = Organic Carbon
- 52. OMI = Ozone Monitoring Instrument
- 53. PAH = Polyaromatic hydrocarbons
- 54. PCA = Principal component analysis
- 55. PEF = Peak expiratory flow
- 56. PM = Particulate matter
- 57. PMF = Positive matrix factorization
- 58. PSCF = Potential Source Contribution Function
- 59. PTA = Patiala Site
- 60. RM = Receptor model
- 61. ROS = Reactive Oxygen Species
- 62. RSSD = ReSuspended Soil Dust
- 63. SA = Secondary Aerosol
- 64. SALIA = Study on the influence of Air pollution on Lung function, Inflammation and Aging
- 65. SAN = Sangrur Site
- 66. SPAMS = Single particle aerosol mass spectrometry
- 67. SpO₂ = peripheral capillary oxygen saturation
- 68. TBH = Beijing- Tianjin- Hebei
- 69. VCP = Visuo-construction performance
- 70. VE = Vehicular Emissions
- 71. VOC = Volatile organic compounds
- 72. WHO = World health organization
- 73. WSOC = Water Soluble Organic Carbon
- 74. XRF = X-Ray fluorescence

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INTRODUCTION

CHAPTER- 1

Various studies have shown the effect of air pollutants on human health, still there is a lack of complete understanding about crop residue burning effect on school going children in rural areas. In recent years, most of the source apportionment studies were carried out in the big cities or majorly in urban areas. The novelty of the present work describes the sources of particulate matter in the semi urban site conducted during the biomass burning period carried over three crop seasons continuously. This chapter gives a brief introduction regarding air pollution, agricultural importance in the area, crop residue burning practices in the area, effects of particulate matter on human health and environment along with basics of receptor modeling and positive matrix factorization model.

Nearly 20,000 people die in a day over the globe, because of air pollution. The number of deaths attributed to air pollution is 6.5 million a year, with 4.2 million deaths from ambient air (outdoor) pollution, according to **World Health Organization**. That is more than the combined number of people killed by HIV/AIDS, tuberculosis and road injuries. As reported by **Health Effects Institute (2019)**¹, the fifth leading cause of deaths worldwide is the air pollution.

The major sources of air pollution are power generation, industry and vehicular emissions as well as fuels used for domestic purposes. It is a global problem, but some countries are more severely affected relative to others. Georgia, a country in Eurasia, tops the International Energy Agency's table, with nearly 300 deaths per 100,000 in 2012 due to air pollution. Bulgaria is fourth while China ranks sixth with over 150 deaths per 100,000 people.

Premature deaths resulting from air pollution have seen a decline in Europe, United States and few other countries, while an elevation is seen in other parts of the world. The countries having highest range of premature deaths caused by air pollution are mostly from Asian and

African continents. However, when adjusted to take account of the size of a country's population (i.e. deaths per 100,000 people), the highest rates of mortality from air pollution also span across other parts of the world, such as Eastern Europe (Schulz et al., 2018)².

Nearly 3 billion people still use solid fuel such as dung, wood, crop waste, coal and kerosene in open fires and inefficient stoves. Domestic air pollution is a recorded cause of approximately 3.8 million premature deaths in 2016, devastatingly in those areas where solid fuel or kerosene is used as a kitchen fuel as per fact sheets of Goldemberg et al., (2018)³.

For Indian scenario, air pollution is the third leading cause of mortality causing more than 12 lakh (1.2 million) deaths in 2017 alone (Figure 1.1), an increase of nearly 1.09 lakh from 2010, as per Health Effects Institute, 2019¹. In the last decade, loss of almost one and half year in life expectancy was attributed to outdoor air pollution whereas year and two months of life expectancy was reduced due to exposure to indoor air pollution (Gordon et al., 2014⁴; Brugha et al., 2014⁵; Balakrishnan et al., 2019⁶).

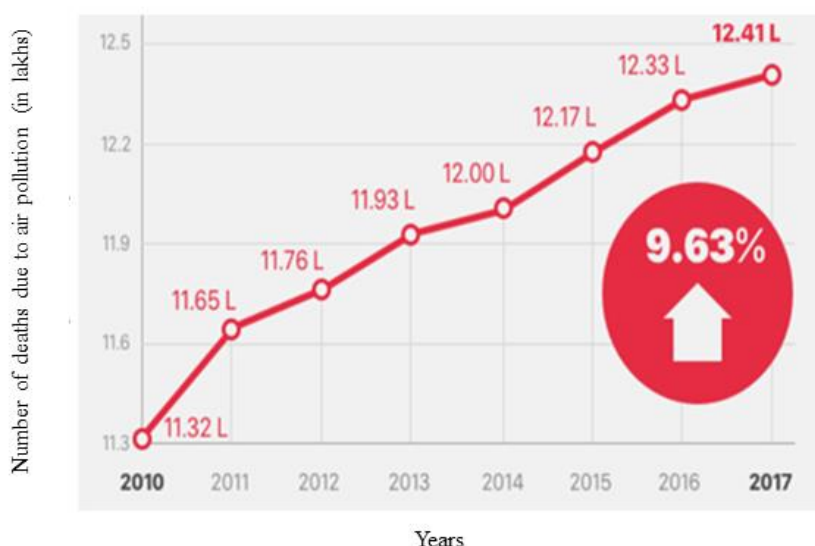


Figure 1.1 Increase in number of deaths due to air pollution in India (2010-2017)

High level exposure to ambient particulate matter (PM₁₀, PM_{2.5}), NO₂, O₃ has shown to be adversely associated with lung efficiency (Saggu et al., 2018)⁷, respiratory health (Neuberger et al., 2004⁸; Baldacci et al., 2015⁹), cardiovascular disease (Du et al., 2016)¹⁰, and depression and psychiatric problems (Gu et al., 2019)¹¹. There are only few sources of

air pollution which lead to majority of the pollutants (PM₁₀, PM_{2.5}, O₃, CO₂, CO, CH₄, TNMHC, organics, SO₂, NO_x, Black carbon, organic carbon) in Northern India and biomass burning is one of the major sources of air pollution in regions of Indo-Gangetic Plains (IGP) **(Bansal *et al.*, 2019¹²; Rana *et al.*, 2019¹³; Prabhu *et al.*, 2020¹⁴)**.

1.1 Agricultural importance in the area

South eastern Punjab lies in Indo-Gangetic Plains having large area under cereal crops which produces large amount of crop residue, majorly disposed off by open field burning. The number of combine harvesters in the Indo-Gangetic Plains has increased greatly from nearly 2000 in 1986 to over 10000 in 2010. The 75% of the cropped area in north-western part (Punjab, Haryana and Western Uttar Pradesh) has been harvested under combine harvesting, which produces more residue than manual harvesting **(Singh and Yadav, 2020)¹⁵**. Crop residues are considered waste products, but can be properly used and recycled to play a crucial role in satisfying nutrient demand in the crop system **(Kumar *et al.*, 2015)¹⁶**.

1.2 Agricultural crop residue and open field burning practices

Biomass is referred to as plant or plant based material which are not used for food or feed, such as wood, algae or bamboo. Biomass is made from living material which never runs out of energy and thus is considered as renewable source of energy. Biomass burning is the process of setting living and dead vegetation ablaze and is a major global health concern and indoor air pollutant **(Chen *et al.*, 2017¹⁷; Bhattraï *et al.*, 2019¹⁸)**. Crop residues are useful resources if not burnt in the field.

India is an agriculture dominant country and different estimates of residue generation varied from 620 million tons **(Jain *et al.*, 2014)¹⁹** to 686 million tons **(Hiloidhari *et al.*, 2014)²⁰**. Different states among the country produce different amount of crop residue depending upon the type of crops and there intensity. Uttar Pradesh (115.68 Mt) ranks the first in production of crop-residues followed by West Bengal (63.26Mt) and Andhra Pradesh (57.44 Mt). Punjab was at fourth number in crop residue generated/year with production of (56.74 Mt/year) **(Jain *et al.*, 2014)¹⁹**. In crops, cereals generate maximum residues (352 Mt), followed by fibers (66 Mt) and oilseeds (29 Mt). The cereal crops (rice, wheat, maize,

millets) contribute 54% (368 MT) followed by sugarcane 16% (111 MT) (**Hiloidhari *et al.*, 2014**)²⁰.

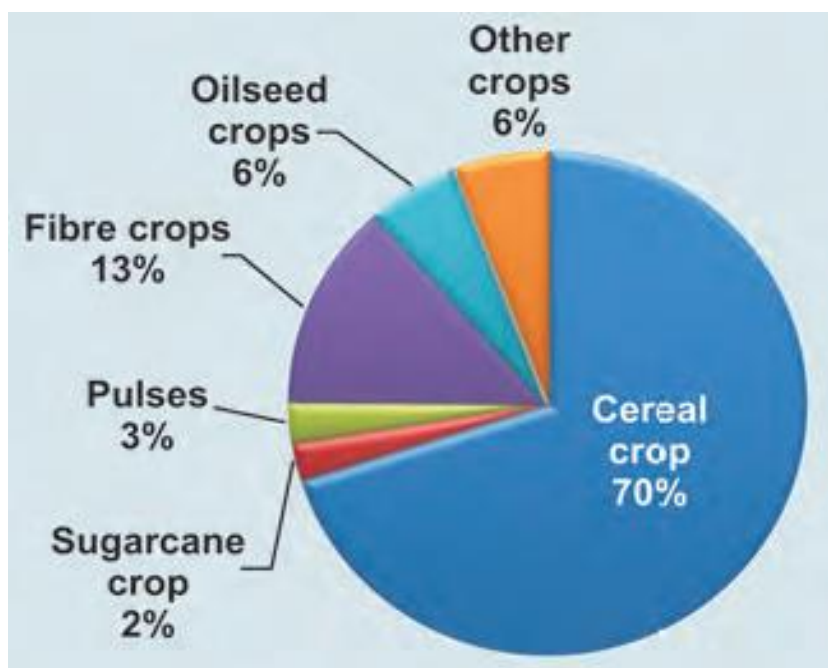


Figure 1.2 Crop residue contribution by different crops in India (Gupta and Dadlani, 2012)²¹

The open burning of crop residue is the prime source of the micron-sized aerosols and plays a major role in generating pollution for a definite period of time. It is a human initiated activity for the purpose of preparing the fields for the next crop quickly and inexpensively. Due to increased mechanization, particularly the use of combine harvesters, declining numbers of live-stocks, long period required for composting, unavailability of alternative economically viable solutions and to control weeds, diseases, and pests, farmers are compelled to burn the residues. Wheat straw to the extent of 75% is utilized as fodder for animals with the help of special cutting machine though this requires additional operation and investment, rice straw is considered poor feed for animal due to high silica content (**Sidhu *et al.*, 2015²²; Rafiq *et al.*, 2018²³**).

The burning of agricultural residues leads to significant emissions of chemically and radioactively important trace gases such as methane (CH₄), carbon monoxide (CO), nitrous oxide (N₂O), oxides of Nitrogen (NO_x) and Sulphur (SO_x) and other hydrocarbons to the atmosphere.



Figure 1.3 Open burning in the fields of Punjab (India)

Concentrations of the greenhouse gases have increased over the past 50 years as a result of anthropogenic activities including agriculture, and have accelerated the rise in average global temperature (Nda *et al.*, 2018²⁴; Letcher *et al.*, 2019²⁵). In Punjab, about 20 million tons of rice and wheat residues, out of a total of 50 million tons of total residues are being burned in situ annually. Burning of rice straw causes particulate matter and gaseous emission of 70% CO₂, 7% CO, 0.6% CH₄, and 2.09% N₂O. Many of the pollutants in biomass smoke found to be carcinogenic (Bhuvaneshwari *et al.*, 2019)²⁶.

1.3 Particulate matter and its classification (PM₁₀, PM_{2.5} and PM_{1.0})

Environmental Protection Agency (EPA) defined Particulate Matter (PM), “as a complex mixture of extremely small particles and liquid droplets”. Subtypes of atmospheric particle matter include Suspended Particulate Matter (SPM), Respirable Suspended Particle Matter (RSPM), fine particles, ultrafine particles and soot. An aerosol is a colloidal system of solid or liquid particles in a gas.

EPA groups particle pollution into following categories:

- a) **PM₁₀**: Particulate matter in which 50% of particles have an aerodynamic diameter of less than 10 μm . The main source of PM₁₀ is from materials typical of earth’s crust

(resuspended road dust and construction dust), agriculture residues, river beds, dust from construction sites or mines, grinding processes (metals) and other related activities. National Ambient air quality standard for PM₁₀ is 60 µgm⁻³ and 100 µgm⁻³ for annual and 24 hour duration, respectively.

- b) **Fine Particulate Matter (PM_{2.5}):** Particulate matter whose aerodynamic diameter is less than 2.5 µm in diameter. PM_{2.5} is a product of combustion, primarily caused by burning fuels. Sources include power plants, vehicles, wood burning stoves, and wild land fires. The fine fraction is characterized by constituents such as sulfate, nitrate, ammonium, metals, elemental carbon, and hundreds of different organic carbon compounds (**Valavanidis *et al.*, 2008**)²⁷. National Ambient air quality standard for PM_{2.5} is 40 µgm⁻³ and 60 µgm⁻³ for annual and 24 hour duration, respectively.

The field burning of crop residue is a major contributor to reduced air quality (particulates, greenhouse gases), and impacts human and animal health both medically, and by traumatic road accidents due to restricted visibility in North-West India during burning periods. The peak in asthmatic patients in hospitals in NW India coincides with the annual burning of rice residue in surrounding fields (**Singh *et al.*, 2014**)²⁸. It also elevates soil temperature causing death of active beneficial microbial population, though the effect is temporary, as the microbes regenerate after a few days. Frequent burning of the fields, vanishes the microbial population permanently and reduces soil fertility. Besides, burning of crop residues leads to a loss of organic matter and precious nutrients, especially Nitrogen and Sulphur.

Size, concentration, composition, and toxicity of particulate matter are vital features that greatly affect the possible human health problems related to their exposure (**Nihalani *et al.*, 2020**)²⁹.

1.4 Health effects of particulate matter

In India, the air pollution standards were first laid down in 1981 with the Air (Prevention & Control of Pollution) Act, 1981. These included measurement of Suspended Particulate Matter (SPM/PM_{>10}) only among various particulate fractions. The standards were prescribed in three categories- Industrial; Residential, Rural and other; Sensitive. In 2009, the standards were again amended and the SPM was removed stating that it has no health impacts. In addition to PM₁₀, standards were notified for PM_{2.5}. It is also evident from

literature that smaller the size of the particle, deeper it penetrates into the body (Yang *et al.*, 2016³⁰; Kim *et al.*, 2015³¹).

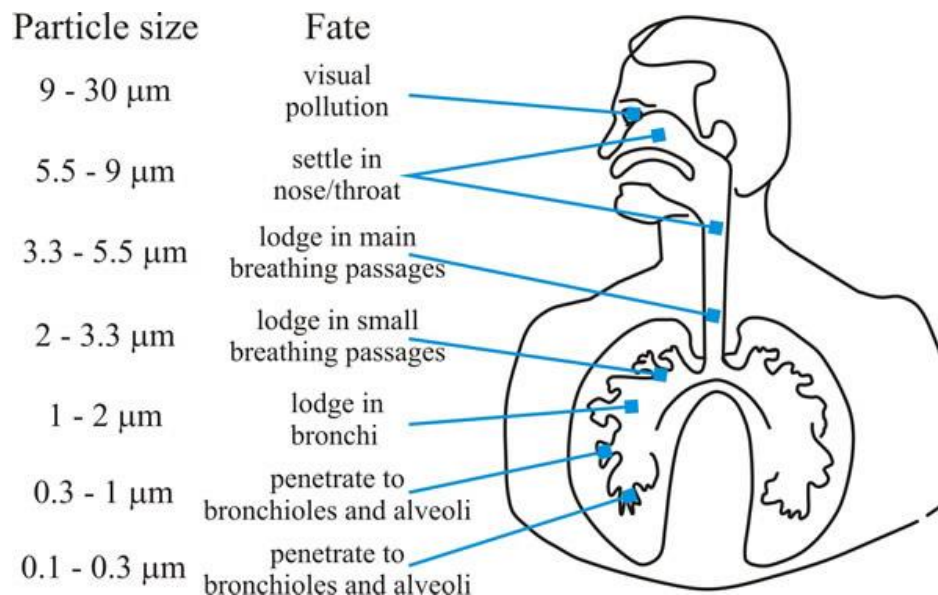


Figure 1.4 Penetration of different size particles in human body (Moore *et al.*, 2020)³²

The health impacts of air pollution depend on the pollutant type, its concentration in the air, length of exposure, other pollutants in the air, and individual susceptibility. Much of the adverse health impacts of particulate matter manifest themselves through diseases such as lung cancer, cardiovascular and respiratory conditions including infections (Gupta *et al.*, 2007³³; Lippmann *et al.*, 1969³⁴; Ohsaki *et al.*, 2019³⁵). The International Agency for Research on Cancer (IARC) and World Health Organization (WHO) designate airborne particulates a Group 1 carcinogen. Outdoor air pollution is a large-scale environmental issue that creates risks to the health of people in developed and developing countries alike. A report by WHO suggests that about 80% of the premature deaths caused by outdoor air pollution were caused by ischemic heart disease and strokes, while 14% of death toll was because of chronic obstructive pulmonary disease (COPD) or acute lower respiratory infections; and 6% of deaths were due to lung cancer.

While the health effects on adults cannot be neglected, children are more susceptible than young adults to air pollutants therefore; their exposure is a major health concern. Epidemiological studies strongly suggest that air pollution damages child health (pacitto *et*

al., 2020³⁶; Saggu *et al.*, 2018⁷). Toxic effects occur mainly on the air-tissue interface of the lung, but effects on other organs may also be important. Published reviews on the effects of air pollutants in children's health indicated that air pollutants alone and in combination with other environmental factors have adverse effects on children and adolescents regardless of their current health status (Guo *et al.*, 2020³⁷; Zhang *et al.*, 2020³⁸). Outdoor particulate air pollution has been associated with substantial mortality and morbidity. Particulates are the most fatal version of air pollution attributed to their tendency to penetrate deep into the lungs and blood streams unfiltered, and have the tendency to cause permanent DNA mutations, heart strokes and even death (Feretti *et al.*, 2019)³⁹.

1.5 Environmental effects of particulate matter

Along with human health, increased concentration of particulate matter also affects the environment. Secondary particles such as sulphate and atmospheric ammonia can lead to acid rain and climate change (Liu *et al.*, 2019⁴⁰; Grennfelt *et al.*, 2020⁴¹). This can further lead to destruction of vegetation and transboundary pollution (Siddqi *et al.*, 2019⁴²). Particulate matter can directly and indirectly contribute to global warming. They can provide cloud condensation nuclei for cloud formation and change the radiative balance of the earth (Seinfeld *et al.*, 2016⁴³) or absorbing black carbon heat the atmosphere, altering the regional vertical movement and atmospheric stability (Menon *et al.*, 2002⁴⁴). Also, the visibility gets greatly affected with the particulate matter emission in the regional area (Badarinath *et al.*, 2009⁴⁵).

1.6 Residence time of particles in the atmosphere

The most common ways by which particles gets removed from the atmosphere are wet and dry deposition. For particles responsible for most of the PM_{2.5} mass concentration, the lifetime is estimated to be around a week on average. For individual particles the actual lifetime can vary from seconds to several weeks or months. During the period of frequent rains, the lifetime of these particles is expected to be shorter while during the warmer season, the particles can spend longer periods in the atmosphere. Particles larger than a few micrometers have shorter residence times in the atmosphere as a result of their larger settling velocities and inertial properties (Jaenicke, 1993⁴⁶).

1.7 Sources of particulate matter

Particulate matter can be originated from natural sources such as dust storms, wind erosion, volcanic eruption, resuspension of dust, or it can be from various anthropogenic activities such as transport or vehicular emissions, industries, agricultural waste burning, fossil fuel burning and indoor sources, as shown in Figure 1.5 (Yatkin *et al.*, 2008⁴⁷; Mazzei *et al.*, 2008⁴⁸; Stanek *et al.*, 2011⁴⁹). Sources may vary with temporal and seasonal variation, along with geographical location.

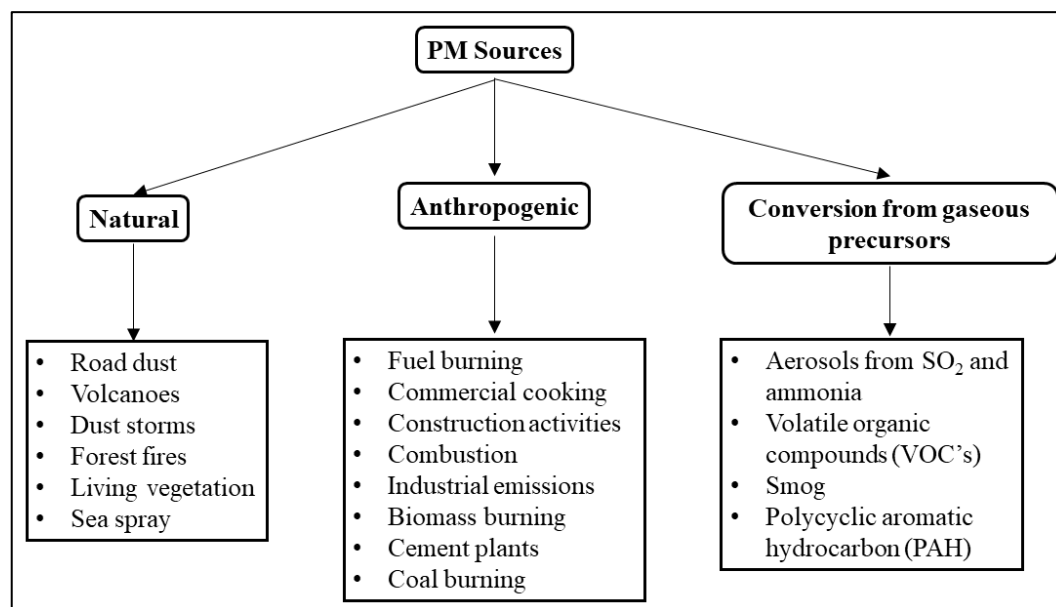


Figure 1.5 Different sources of particulate matter

1.8 Air modelling and source apportionment

Air pollution modeling is a numerical analysis method utilized to describe the informal relationship between emissions, meteorology, composition of the atmosphere, deposition, and other related aspects (Hopke *et al.*, 1985⁵⁰). Air pollution analysis imparts significant, quantitative information about ambient concentrations and deposition, but they are able to specify the air quality at particular locations and durations, without providing any identification of the source of the air quality problem. Air pollution modeling, on the other hand, provides a more descriptive analysis of the air quality problem that involves the investigation of factors and sources (emission sources, meteorological processes, and physical and chemical changes), and other guidance related to the implementation of mitigation measures (Hopke *et al.*, 2003⁵¹).

1.8.1 Receptor modeling

It is a method for determining the sources of air pollution based on air monitoring data. Receptor-based models employ chemical measurement techniques at a specified monitoring site (the receptor) to estimate the relative contributions from major sources towards the pollution at the chosen site. Receptor-based modeling is also referred to as source apportionment. These models can be applied to investigate the sources of individual air pollution “episodes” or, as with the emission inventory, to create effective control strategies (Reff *et al.*, 2007⁵²). They are most commonly used to investigate the sources of particulate air pollution, using speciated chemical data of the sampled particulate matter. However, more advanced techniques that incorporate wind trajectory data can be applied to the gaseous pollutants.

1.9 Source Apportionment

The four primary steps of source apportionment are ambient sampling, source profiling, chemical analysis and receptor modelling as shown in Figure 1.6. Ambient sampling involves the quantitative measurement of the aerosols in the ambient air. Measurements provide fundamental information for evaluating and managing the impacts of aerosols on air quality. In order to mitigate the PM pollution problem, the data obtained through measurement form is the foundation of all approaches used for qualitative and quantitative analysis. For quantitative analysis, source profiles must include chemical abundances for a range of compounds that can be distinguished appreciably between source and receptor and that are fairly constant among different items of the same type and operating conditions. Example of source profiling includes abundance of potassium (K) for biomass source, aluminium (Al) and silicon (Si) for fugitive dust source, sulfate ion for coal and diesel combustion, which can further be differentiated with other ion and metal fractions in the source profiles. Receptor modelling is done in order to assess quantitatively, the source contribution to the measured ambient samples based on the degree to which source profiles can be combined to reproduce ambient concentration. The output of the model provides groupings of chemical species which are then be interpolated as emission sources. The outcome of the modelling techniques can be considered as a "recipe" of air pollutant sources, and their respective contribution towards the overall air quality at the chosen site.

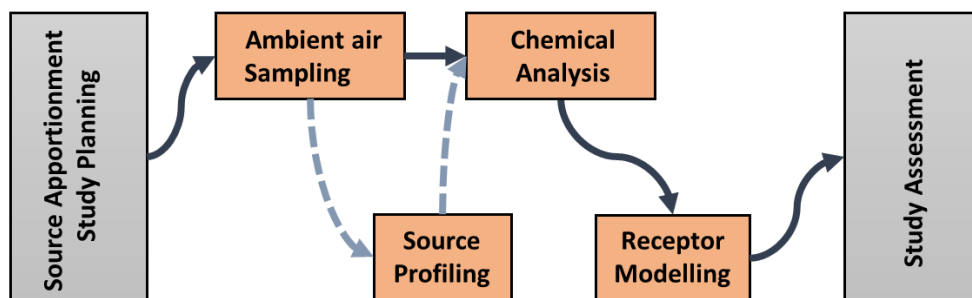


Figure 1.6 Layout of Source Apportionment Study

1.10 Positive Matrix Factorization (PMF) model

The Environmental Protection Agency (EPA) has developed a number of receptor models like Chemical Mass Balance (CMB), UNMIX models and Positive Matrix Factorization (PMF) models. CMB apportions completely concentrations of the receptors to chemically distinguishable source-types depending upon the source profile database, while UNMIX and PMF internally create source profiles from the ambient data. The main inputs for these models are individual chemical measurements at a receptor site. These are usually obtained by collecting particulate matter on a filter and analyzing the filter for the elements and organic carbon. The Chemical Mass Balance (CMB) model, which is endorsed by EPA, requires the additional inputs of the error associated with each chemical measurement and the source emission profile. A source profile is the chemical composition of the emissions, with each chemical species expressed as a mass fraction of the total (for example, resuspended dust might contain 20% aluminum, 20% calcium, 50% silicon, and 10% elemental carbon). Some more advanced models, such as Positive Matrix Factorization (PMF), do not require source profiles as an input, as this is part of the solution. The main output from these models is an estimate of the contributions from each source to the air pollution at that site (**Guttikunda, 2009⁵³**).

1.11 Chemical Analysis

Source signature or marker signifies a blend of follow markers or species components that are used for source identification. A broad array of source markers are used by the various groups, across India for source classification (**Jain et al., 2018⁵⁴**; **Keerthi et al., 2018⁵⁵**; **Bano et al., 2018⁵⁶**; **Pervez et al., 2018⁵⁷**). The PM₁₀ was further characterized into ionic and elemental species for the source apportionment studies.

1.11.1 Secondary species

Secondary particles are formed through photochemical processes, night time radical chemistry (such as NO_3^- , via the nitrate radical), and aqueous mechanisms (for example, during foggy conditions where SO_2 can be absorbed into water droplets and oxidized efficiently by H_2O_2 or metal catalysts). Sulfate, NO_3^- and NH_4^+ concentrations are very less in primary emission profiles as most of these are formed in the atmosphere from primary emissions of gaseous SO_2 , NO_x and NH_3 . Primary SO_4^{2-} is often part of a much complex molecule such as FeSO_4 , NiSO_4 , or organic sulfur. However, more than 90% of the fine sulphate particle are formed in the atmosphere and usually associated with NH_4^+ .

Sulfates can be formed by three different pathways:

1. The oxidation of SO_2 in the gas phase by the hydroxyl radical, $\text{OH}^\cdot$
2. The dissolution of SO_2 in the cloud, fog or rain water and subsequent aqueous phase oxidation.
3. The oxidation of SO_2 in reactions in the water of the aerosol particles themselves. This process takes place continuously, but only produces considerable SO_4^{2-} in alkaline (dust, sea salt) coarse particles (**Sievering *et al.*, 1992⁵⁸**).

Nitrates are formed from the oxidation of NO and NO_2 (NO_x) either during the daytime (reaction with $\text{OH}^\cdot$) or during the night (reaction with ozone and water) (**Wayne *et al.*, 1991⁵⁹**).

1.11.2 Ionic species

Ionic components (NO_3^- , SO_4^{2-} , Cl^- , Na^+ , K^+) of particulate matter is generally major fraction of the total particulate mass. Na^+ and Cl^- are most obvious markers for sea salt for coastal areas. K^+ is an important component of PM and has been used widely as tracer of biomass burning around the world (**Yu *et al.*, 2018⁶⁰; Artaxo *et al.*, 1998⁶¹; Cheng *et al.*, 2013⁶²**).

1.11.3 Elemental species

Various elemental markers are eliminated or reduced due to pollution control, such as Pb in gasoline, so species could become a limiting factor for apportioning sources. For this purpose, we had considered these many elemental markers (Al, Ti, Mn, Fe, Mg, V, Ni, Cu, Zn, Ba, Pb, Cr, Ca). These were selected on the basis of common sources and profiles from studies conducted in similar areas. Some of the markers for major source type are

- Traffic related emissions: Al, Si, Fe, Cu, Sb, Ba
- Fossil fuel combustion (Residual oil combustion): Ni and V
- Fossil fuel combustion (coal combustion): Zn, As, Se, Cd, Hg, Pb, S, SO_4^{2-}

Since many of the trace elements are emitted from a range of sources (e.g. Zn is emitted from tyre wear as well as refuse burning), it is necessary to consider large set of species to apportion the PM to its sources with high degree of confidence.

1.12 Receptor Model

Various studies have compared different source apportionment models applied to the same dataset (Song *et al.*, 2008⁶³; Shi *et al.*, 2014⁶⁴; Jain *et al.*, 2019¹⁹). PMF model have more refined (or aging) characteristics which result in atmospheric mixing and oxidized compound condensation, while the source profiles used in CMB are derived from emission sources measurements with minimal atmospheric processing volumes. PMF profiles are different for different sites and relate to variability of local sources. In contrast, even though they are regional representative, CMB profiles may not be locally representative (Lee *et al.*, 2008⁶⁵). For fewer chosen species in CMB, the mass was decreased and the amount of wood burning was estimated to be unrealistically high (Bullock *et al.*, 2008⁶⁶). Combined models such as PCA/MLR-CMB and the PMF-CMB models (F_{peaks} from 0 to 1.0) predictions are satisfactory, and the Unmix-CMB model is unstable (Shi *et al.*, 2014⁶⁴). Miller *et al.*, (2002)⁶⁷ evaluated four models, chemical mass balance, principal component analysis/absolute principal component scores, positive matrix factorization (PMF), and graphical ratio analysis for composition estimates/source apportionment by factors with explicit restriction, incorporated in the UNMIX model. PMF generated source profiles most accurately represented the significant sources of simulated generated data. Thus, for the present study, EPA PMF 5.0 model was used for source apportionment.

To conclude, in this chapter, introduction to air pollution and its mortality rate through various sources and in different countries is mentioned. Importance of agriculture in the area and crop residue burning is discussed next. Data for crop residue generated in country and in state is mentioned. Types of particulate matter, their health effects and role in environmental phenomena are briefly discussed as they are main pollutants determined in the following research. Residence time of particles and their sources are described in brief.

Source apportionment, receptor modelling, and basic introduction to positive matrix factorization (PMF) model is mentioned in the above chapter. Various methods for chemical characterization of the PM samples are mentioned.

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REVIEW OF LITERATURE

CHAPTER- 2

Particulate matter pollution, in any concentration, is harmful to health and is increasing cause of worldwide mortality. The point of this review of literature is to legitimize the study's objectives, taking into consideration the past particulate matter studies and their impacts and deciding where the work is required in future. This section presents an account of writing that is covering different viewpoints of particulate matter and their noteworthiness in connection to lung capacities of human subjects. In the literature survey, different episodes of surrounding particulate matter and health impacts are examined who raised the consideration of research communities to explore this area. Various studies are discussed here, which demonstrated the response of human subjects under clinical trials, hospital entries or controlled experiments of particulate matter pollution. There is still a need of investigation in context to agriculture crop residue burning in relation with ambient particulate matter concentration level. The effect of these increased concentration levels on human subjects who are less susceptible, particularly the school going children residing in the vicinity of crop residue burning prone areas. Biomass burning is one of the prominent sources of pollution throughout the world. Second subsection of the literature shows it's Characterisation, collection, and effects on various aspects of environment and health. Next section of the literature presents the various studies regarding different sources of air pollution at both urban and rural areas. Source apportionment studies are carried out using different models globally. PMF is one of the most commonly used receptor model. Next section describes work done using mixed models and last section of this chapter gives the broad idea of studies correlating various sources with different health aspects. Though few studies were carried out at Patiala region of Punjab by one or two groups, still almost no study has used source apportionment model to identify the different sources of PM at semi urban site of Malwa region in Punjab.

2.1 Effect of particulate matter concentration on human health

To measure the health effects of different pollutants, large number of participants are required. Based on the suspicion of lung cancer due to ambient air pollution, **Raaschou et al., (2013)**¹ took the huge dataset of 17 cohort studies in 9 European countries. The 312994 cohort member study showed no association among lung cancer and nitrogen oxide concentration but indicated affiliation between particulate matter contamination and frequency of Lung cancer in Europe. **Liu et al., (2014)**² concluded that the ultra-fine particles, SO₂, NO₂ and CO were 50–100% higher in concentration at the site near the steel plant as compared to the college site. The male subjects were found to have the highest pulse rate elevation. Less variation was observed in systolic and diastolic blood pressure and pulse pressure at both the sites. Exposure studies have shown the linkage between exposure sites and health effects on exposed population. **Sigsgaard et al., (2015)**³ investigated the negative cardiovascular and respiratory health with increased biomass combustion. **Veras et al., (2016)**⁴ investigated the way lung development is affected by air pollution during pre-gestational and gestational period. The study concluded that early life air pollutants exposure are connected to modification in lung improvement and function and respiratory childhood conditions that may last into adulthood. Conceivable mechanisms include changes in maternal physiology which includes hypoxia, oxidative stress and DNA changes of the fetus. **Panis et al., (2017)**⁵ measured the pulmonary function tests of the cohort of 2499 employees and correlated these with daily measurements of PM₁₀, NO₂ and ozone in Belgium. The average PM₁₀ concentration was 24.9 µg m⁻³ on the day of tests. A large decrease in Forced Vital Capacity (FVC) was associated with 10µg PM₁₀/m³ increase. Decrement in Peak Expiratory Flow (PEF) was also associated with increase in NO₂ concentration. **Bowatte et al., (2017)**⁶ used the regression models for the affiliations between Traffic-related air pollution and unfavorably susceptible sensitization, lung efficiency, cough and asthma (N=1405) as the continuation of Tasmanian Longitudinal health study. Carriers of Glutathione S-Transferase genes (GSTT1) might be at a more noteworthy hazard for these results. **Liu et al., (2017)**⁷ assessed the spatial and temporal impacts of air pollutants on human health in China from 2004 to 2012. The increment in deaths due to PM_{2.5} from 800,000 deaths in 2004 to 12,00,000 deaths in 2012 related to stroke, heart diseases and lung cancer were reported. Health effects have shown spatial variability with more number of

deaths concentrated in regions of high air pollution, or more population density, such as Henan, Anhui, Sichuan Basin, Yangtze river delta, Pearl River Delta and Wuhan Metropolitan Region.

Milanzi *et al.*, (2018)⁸ conducted longitudinal (N = 915) and cross-sectional investigations (N = 721) of correlation between air pollution with Forced Expiratory Volume in 1 second (FEV₁) and Forced Vital Capacity (FVC) in age group of 8-16 years in Netherlands. Greater air pollution susceptibility was related with diminished FEV₁ growth. FEV₁ associations shown stronger correlation with boys than girls, unaffected by asthma status. **Huls *et al.*, (2018)⁹** used the data from the Study on the influence of Air pollution on Lung function, Inflammation and Aging (SALIA) cohort. An increment of one interquartile range in Forced expiratory volume in 1 s (FEV₁) and forced vital capacity (FVC) was positively associated with visuo-construction performance (VCP) ($\beta=0.18$ and 0.23 , respectively). The study concludes that air pollution linked VCP was partially interfered by lung functions. **Parascandola, (2018)¹⁰** discussed the challenges in finding the extent of ambient air pollution causing lung cancer. The lag between the time period of exposure of disease and its occurrence, the individual exposure and restricted historical pollution data are some of the main challenges. Isolation of the impact from air pollution gets compromised as high dependence of lung cancer trends on tobacco smoking in Poland. Though some case control studies and secondary data analyses have documented the pollution exposure correlation with lung cancer in Poland there is still requirement of exhaustive air pollution monitoring and health impacts.

Isiugo *et al.*, (2019)¹¹ collected the data related to PM_{2.5} from 44 asthmatic children between 10 to 16 age group. The lung efficiency of children with asthma was more strongly correlated with indoor PM than the outdoor particulates. A decrement of 4.1% in FEV₁/FVC ratio was related to one unit increment in indoor particulate matter. Indoor fungal spores and black carbon along with outdoor particulate matter was not significantly correlated with lung efficiency. **Rice *et al.*, (2019)¹²** determined interstitial lung abnormalities (ILA) and its progression of 2618 participants. Out of total 2618 participants, 176 participants had interstitial lung abnormalities, while 1361 had no ILA and rest were non determinant. ILA or its progression were not related to PM_{2.5} and Ozone. Though elemental carbon

(Constituent of PM_{2.5} from vehicular emission) exposure was associated with increased risk of progressive ILA. **Zhang et al., (2019)**¹³ have assessed the air pollution and breast feeding with children's lung capacity in a 5 month study done during November, 2018. Results shown that younger children who were less than 12 years of age were linked with lower lung function deterioration in the cohort of children who were breastfed. Forced vital capacity (FVC) and forced expiratory volume in the 1st second were linked with air pollution and poor lung efficiency among children who were not breastfed as compared to those who were fed. Disabilities in prevalence of lung function ranged from 6.8% for Peak expiratory flow (PEF) and 11.3% for Forced vital capacity (FVC).

Schultz et al., (2019)¹⁴ measured respiratory and allergic health of people living in rural areas near concentrated animal feeding operations (CAFO) at upper mid-west of United States. The increase in allergies, including nasal and lung, and asthma and uncontrolled asthma (reported as asthma incident within last 1 year) was correlated with people living with the 1.5 miles from CAFO. Also, the decrement of 7.72% was reported with in predicted forced expiratory volume in the 1st second for residents within 1.5 miles from CAFO compared to living in 3 miles from the facility. **Oliveira et al., (2019)**¹⁵ reviewed various studies which measured effect of particulate matter (PM) and Polyaromatic hydrocarbons (PAH) on the respiratory health of children in school micro-environment. School indoor PM₁₀ concentration levels at European schools were 7.5-229 µgm⁻³ and for PM_{2.5} were 4-100 µgm⁻³. For outdoors, the PM₁₀ concentration levels were 21-166 µgm⁻³ and for PM_{2.5} were 6.1-115 µgm⁻³. Several studies have demonstrated the compelling correlation between particulate matter and PAHs with asthma, skin diseases, pulmonary lung functions and allergies. **Morakinyo et al., (2019)**¹⁶ demonstrated the concentration of bacterial and fungus aerosols in PM_{2.5} and their impact on human health in South Africa. The fungus concentration varied between 58-155 CFU/m³ which was lower than bacterial concentration in samples, which ranged between 168-378 CFU/m³. Their concentration was higher in summer than in winter season in PM_{2.5}. Children were exposed to greater dose of bio aerosols than adults. **Deng et al., (2019)**¹⁷ forecasted the deposition of particles from various sources into human lungs. The particles greater than 2.5 µm gets accumulated in tracheobronchial (TB) area whereas particles less than 2.5 µm get collected in pulmonary area of the lungs through processes of sedimentation and diffusion. The modeling results have shown that

coarse particles ($>2.5\ \mu\text{m}$) originated from crustal origin might have more detrimental effects on human health comparative to those occurring due to deposition of fine particles ($<2.5\ \mu\text{m}$) originated from combustion source.

Lopes *et al.*, (2019)¹⁸ have shown that the personal exposure of $\text{PM}_{2.5}$ ($19\ \mu\text{gm}^{-3}$) was comparatively more than the closest background station ($11\ \mu\text{gm}^{-3}$). Time tracked actions showed that greater than 80 % of the time was spent by children in indoors, where they received 44% of the daily black carbon exposure. Though they only spent 5% of their time in travel, they were exposed to 23% of daily black carbon exposure while travelling during peak hours. The results have shown the need of urban planning to decrease the traffic related exposure of children along with awareness regarding the exposure of indoor sources. **Idavain *et al.*, (2019)¹⁹** measured the association between asthma and respiratory health with pollution from industrial origin for children residing in vicinity of oil shale factories in Idu-Viru County, Estonia. Individual level exposure was determined by dispersion modelling from industrial source to individual subject's home address. 2 to 4 times more respiratory symptoms were recorded for children residing in near vicinity of oil shale site ($> 5\ \text{km}$) than in children living in reference site of Tartu County. Exposure of $1\ \mu\text{gm}^{-3}$ higher levels of benzene, formaldehyde, phenol and non- methane hydrocarbons had a greater odds ratio of having high FeNO levels ($\geq 30\ \text{ppb}$) in children. The 2008 economic crisis in European Union has led to increased use of household biomass burning.

2.2 Biomass Burning

There are many reasons for burning of crop residues in the fields. **Grover *et al.*, (2015)²⁰** inquired about the probable reasons for crop residue burning based on farmer's awareness levels in Kurukshetra district of Haryana. The major reason was short time period to prepare land for next crop and weed removal along with low availability of manpower for removal and its high cost. Biomass burning also interacts with the daytime atmospheric chemistry of $\text{OH}\cdot$ and night time chemistry of $\cdot\text{NO}_3$. **Nie *et al.*, (2015)²¹** have checked the influence of nitrous acid (HONO) from biomass burning emissions at western Yangtze River delta, eastern China. Their finding suggested higher conversion rates of NO_2 to HONO during biomass burning periods as compared to non-burning period. Aqueous secondary organic aerosols enhances the brown carbon budget.

Gilardoni *et al.*, (2016)²² have estimated the aqueous secondary organic aerosol emissions from biomass burning contributes about 4 to 20 % of total organic aerosol emissions in Europe. Similarly, **Lin *et al.*, (2016)**²³ have observed biomass fuel based brown carbon absorption and the chemical composition of light absorbing compounds. Biomass burning organic aerosol (BBOA) samples contain few strong brown carbon (BrC) chromophores responsible for light absorption. On similar terms, **Lin *et al.*, (2017)**²⁴ observed a significant rise in brown carbon (BrC) light absorption coefficient at Lag Ba'Omer, the night long biomass burning event in Israel. Nitro aromatic compounds (NAC), specifically nitro phenols, were responsible for 50 – 80% of the visible light absorption, suggesting the important role of nighttime chemistry of $\cdot\text{NO}_3$ and N_2O_5 in brown carbon transformations.

Kaulfus *et al.*, (2017)²⁵ utilized National Oceanic and Atmospheric Administration (NOAA) Fire and Smoke product to establish that mostly smoke is found over Great Plains and western states in summer period. Smoke presence was associated with 20% exceedance of 24 hour PM pollution in Continental United States. **Vaishya *et al.*, (2017)**²⁶ have shown that in central Indo Gangetic Plain (IGP), during winter and post monsoon seasons, local sources are more dominant than long range transport of aerosols, due to calm wind conditions and lower boundary layer height.

Black carbon is a good indicator of incomplete combustion. **Sharma *et al.*, (2017)**²⁷ measured seasonal variability in aerosol optical depth (AOD_{500}) at 500 meters with increase in post monsoon and decrease during winter season. Study highlighted the black carbon interaction from biomass burning during post monsoon in warming of atmosphere at Patiala. **Chen *et al.*, (2017)**²⁸ have reviewed research conducted in China on biomass burning. The open crop residue burning was major biomass burned in China. The recommendations included to carry out research in various regions along with measurement of optical properties of the smoke produced. The health effects of fresh indoor pollutants and aged biomass burning smoke were emphasized. The review also highlighted the importance of atmospheric effect of black carbon and brown carbon from biomass burning. Research on biomass burning is also limited due to lack of biomarkers. **Yu *et al.*, (2018)**²⁹ investigated whether K can be used as sole indicator of biomass burning in Beijing, China. Coal

combustion was the major source of K followed by biomass burning and dust. Ratio of K/Ca and K/Pb were used to signify dust and coal combustion.

Winiger *et al.*, (2019)³⁰ determined isotope constrained sources of black carbon responsible for Arctic's warming. Biomass burning in the summer season and fossil fuel combustion during winter responsible were found as major sources of Black carbon. **Bikkina *et al.*, (2019)³¹** used the dual carbon isotope fingerprint ($\delta^{13}\text{C}/\Delta^{14}\text{C}$) to conclude that in summers most of the lower layer black carbon (BC) is from fossil fuel sources ($\sim 83\%$), in Delhi region. The crop residue burning in nearby rural areas contributed in winter and autumn ($\sim 42 \pm 17\%$). **Andreaea *et al.*, (2019)³²** have compiled the data from over 370 published studies and emission factors from different types of biomass burning activities. The results presented the need for improvement in accuracy of activity estimates and measurements. Suggestions included to use fire radiative power (FRP) and burnt area based remote sensing approaches with coordinated regional CO studies for decreasing the uncertainties. Regional and seasonal differences should be calculated for better geographically based modelling.

Xu *et al.*, (2019)³³ found levoglucosan as most abundant biomarker for biomass burning while arabitol and mannitol were found to be fungal spore tracers. **Bhattarai *et al.*, (2019)³⁴** discussed various methods of measurement and analysis of unique marker of biomass burning, levoglucosan. Levoglucosan is used as marker of biomass burning throughout the world because of its unique origin from pyrolysis of cellulose and hemicellulose. **Pastor *et al.*, (2020)³⁵** measured the organic constituents from biomass burning at rural site in Southern Spain. Out of measured 77 organic markers, tracers such as B(a)P and levoglucosan show increased daily concentrations and anhydrosaccharides and xylitol were major emitted compounds.

2.3 Source Apportionment

An increase in the number of fire counts was observed by MODerate resolution Imaging Spectroradiometer (MODIS) as well as raised tropospheric columnar NO_2 concentrations, as measured by Ozone Monitoring Instrument (OMI). This helped **Mishra *et al.*, (2012)³⁶** to suggest that agriculture crop residue burning as the major source of aerosol loading over the Indo-Gangetic Basin (IGB) during the months of October and November. Particles in air pollution has become the foremost problem in the world, resulted in 7 million deaths

globally. **Rastogi et al., (2014)**³⁷ have studied the systematics of the chemical characteristics of ambient PM_{2.5}, from a region having biomass burning as the major source. The results presented an elevated diurnal variability in mass concentrations of PM_{2.5}, NO₃⁻, NH₄⁺, K⁺, organic carbon and elemental carbon having concentration increment from 30 to 300% during night time.

Guo et al., (2017)³⁸ used the source oriented type of community Multi-scale Air Quality (CMAQ) along with database from Global Atmospheric Research (EDGAR) for analyzing eight sources of PM_{2.5}. Industry and residential sources contributed 60% of primary particulate matter whereas secondary inorganic aerosols were originated from different sources at different areas. **Healy et al., (2017)**³⁹ measured black carbon (BC) at mixed background and near road locations in Ontario, Canada. Vehicular traffic was major dominating source at highway site. The study suggested that black carbon is not exclusively local pollutant. **Singh et al., (2019)**⁴⁰ determined the contribution of biomass burning in ambient organic carbon (OC). The potassium from biomass burning (K_{BB}⁺) was major fraction (77±24%) as compared to ambient fine K⁺. **Gao et al., (2018)**⁴¹ have shown the severity of PM_{2.5} pollution in Beijing- Tianjin- Hebei (TBH) region in China with more than 95% samples with concentrations above the annual standards. PMF resolved factors were vehicular pollution, coal combustion and biomass burning.

Blumberger et al., (2019)⁴² determined the mass size distributions in the range of 0.053 µm to 9.9 µm with median concentrations as 0.36 µgm⁻³, 37 ngm⁻³, 10.9 ngm⁻³ and 0.32 µgm⁻³ for levoglucosan (LVG), mannosan (MAN), galactosan (GAN), and K, respectively. **Bukowiecki et al., (2019)**⁴³ inferred that during high biomass burning activities, majority of the air masses arrived from southwest (northern Thailand, Laos and Myanmar). Meteorological conditions such as increased temperature > 20°C and ambient relative humidity 60 – 70% were similar to aerosol optical properties like lower single scattering albedo of 0.8 – 0.9 with increased absorption Angstrom Exponent 1.6 – 2.0 during high biomass burning periods. Wet season (June to September) was of least pollution.

Etchie et al., (2019)⁴⁴ have found dangerous organic compounds in PM₁₀ in urban, peri urban and rural areas of Nagpur, India. Polyaromatic hydrocarbons (PAHs), Dioxins, furans, phthalates, esters, ethers, aldehydes, ketones, phenols, chlorinated hydrocarbons and organic

acids were detected in PM₁₀. PAH concentrations exceeded greatly health based guidelines. **Shahid et al., (2019)**⁴⁵ calculated the contribution of biomass burning into organic carbon (OC) and particulate matter (PM) at residential site in Islamabad, Pakistan. Both OC and PM contained about 90 % of anhydrosacharides (levoglucosan, mannosan and galactosan). **Sulliavn et al., (2019)**⁴⁶ collected the samples on aircraft using particle into liquid sampler under the WINTER campaign. High Levoglucosan and organic carbon concentrations showed the great extent of biomass burning contribution during the campaign.

2.3.1 Source apportionment using Positive Matrix Factorization (PMF) model

The effects of open burning of wheat straw residues on PM_{2.5} during the harvesting time were studied by **Song et al., (2014)**⁴⁷. The sampling site was kilometer away from the wheat field in the regions of eastern China. Wheat residue burning alone contributed 51.3% of PM_{2.5} during the Phase-2(the local burning) which was higher in comparison with Phase-1(the pre-local burning) and 3(post local burning). **Saeaw and Thepanondh, (2015)**⁴⁸ analysed the total of eleven factors for airborne volatile organic compounds (VOCs) in the urban and industrial regions of Thailand. The mobile sources contributed about 42% to 52% in industrial areas while the industrial processes contributed 15-44% along with a 3 to 10% contribution from the household chemical usage. Background concentration in ambient air contains Freon 11, Freon 114 and carbon tetrachloride which are categorized as the ozone depleting VOCs.

Various study groups in India have conducted source apportionment studies using the Positive Matrix Factorization (PMF) model. **Sharma et al., (2016)**⁴⁹ conducted the source apportionment of PM₁₀ in upper (Delhi), middle (Varanasi) and lower (Kolkata) parts of Indo Gangetic Plain (IGP). Average mass concentration decreases from middle to upper to lower IGP. Organic carbon (OC) have shown significant variation between upper (23.57 μgm^{-3}) and lower (12.74 μgm^{-3}) IGP whereas elemental carbon (EC) was almost consistent. Another study by same group of **Sharma et al., (2016)**⁵⁰ have shown strong seasonal variance in PM_{2.5} in Delhi with maximum during winters and minimum during monsoon. PMF resolved highest contributing source of PM_{2.5} as secondary aerosols (21.3%) and least as sea salt (4.3%). **Jeong et al., (2016)**⁵¹ did more robust source apportionment of PM sources, by applying PMF modeling separately on trace metals only (PMF_{metal}) and organics

only (PMF_{org}) and compared them with full results (PMF_{Full}). Comparison of three PMF analyses provided many advantages in analyzing local and regional sources. **Nayebare et al., (2017)**⁵² have done first type of study in area of Rabigh, Saudi Arabia by delineating the sources of fine particulate matter (PM_{2.5}) by utilizing enrichment factors (EF), PMF model and backward trajectories. Soil, industrial dust, fossil fuel combustion, vehicular emissions and sea sprays were main contributors in PM_{2.5}. **Tao et al., (2017)**⁵³ have determined ship emissions an important source of PM_{2.5} using PMF model at urban and sub urban areas of Pearl River delta, South China. Ship emissions contributed more than 17% of PM_{2.5} mass contributions were previously ignored in making emission control policies in the area.

Amarillo et al., (2017)⁵⁴ used diagnostic ratio (DR) and PMF model to determine the concentration of polycyclic aromatic hydrocarbons (PAH) on PM₁₀. Particulate matter concentration remained almost constant throughout the year whereas PAH were higher in winters than summers from main sources of diesel vehicular emissions and gasoline. **Ciarelli et al., (2017)**⁵⁵ studied the measurements during summer giving the real time concentration from sources using the high time resolution. PMF shows the dominance of regional sources at road side site and urban background site in New York. Long term variability of emission sources of PM₁₀ and PM_{2.5} were assessed by **Diapouli et al., (2017)**⁵⁶ in first of its type study in metropolitan areas of Athens and Thessaloniki in Greece. Previous datasets and PMF model results verified the biomass burning as the largest source in both size fractions. China being one of the major pollution causing country, conducted large number of source apportionment studies. **Li et al., (2017)**⁵⁷ measured trace elements using PMF modeling of online X-Ray fluorescence (XRF) which can greatly enhance precision in source apportionment calculations. **Huang et al., (2017)**⁵⁸ found similar type of composition at urban and background sites comprised of organic matter, sulfate, nitrate, ammonium and mineral dust using PMF model in China. The results implied that the control strategies for haze formation should reduce fossil fuel combustion, specifically from motor vehicles. **Landis et al., (2017)**⁵⁹ measured the particulate matter in coarse and fine fraction at the same site where oil sands upgrading, fugitive dust and biomass burning were found to be major contributors of PM_{2.5} using PMF. **Gupta et al., (2018)**⁶⁰ determined the traffic related pollution as major source at Delhi, India. PMF resolved samples into 7 sources as compared to 5 factors resolved by Principal component analysis (PCA). **Campa et al., (2018)**⁶¹ utilized

the PMF model to investigate the organic and inorganic aerosol data major olive grove area in Southwest Europe. The major sources were biomass burning, mineral dust including secondary inorganic compounds and marine aerosols. In addition to this, for the winter months, the primary source was the use of biomass for olive oil production which has significant residential and industrial uses.

Zhao *et al.*, (2019)⁶² analyzed the PM_{2.5} samples collected during the day and night hours from the urban and suburban localities in the region of Tianjin using PMF model. Higher concentrations of PM_{2.5} were found in suburban area during day time in winters. Also, the primary source of PM_{2.5} in urban areas is coal combustion and vehicle emissions while in the suburbs, secondary aerosols were the major pollutants during night hours in winters. **Zhao *et al.*, (2019)⁶³** observed the high concentrations of PM_{2.5} during winters and their contribution decreased in spring and autumn and became minimum in summer. The ratio of $\text{NO}_3^- / \text{SO}_4^{2-}$ was greater than one which represents the major contribution from mobile sources rather than stationary. The Positive Matrix Factorization (PMF) model identifies the secondary nitrates (26.95%), secondary sulfates (15.49%), secondary organic aerosols (SOA) (19.64%), vehicle exhaust (15.67%), coal combustion (8.6%), fugitive dust (7.7%), ships and heavy oil (5.23%), biomass burning as the major contributors.

Galvao *et al.*, (2019)⁶⁴ proposed new PMF approach using chemical species (organic and inorganic) and directionality of pollutants using wind roses at the site of Great Vitoria, located southeast of Brazil. They determined the following consolidated markers: elemental carbon (EC) and organic carbon (OC) for vehicular sources; chloride (Cl) and sodium (Na) for sea salt; iron (Fe) for industrial sources. Cl was used in the sintering of industrial products. Only the assessment of pollutant roses allowed the identification of the most relevant sources for these factors. **Petit *et al.*, (2019)⁶⁵** used PMF model on atmospheric particles (PM₁₀) in Metz, Eastern France. Nine factors were identified with major contributions from anthropogenic sources of primary PM (19.2% and 16.1% for traffic and biomass burning, respectively) and secondary aerosols (12.3%, 14.5%, and 21.8% for sulfate-, nitrate-, and oxalate-rich factors, respectively). Wood-burning contributed up to 30% of the PM mass fraction during winter, while relatively constant source was identified

as traffic emissions. Concentration-Weighted Trajectory (CWT) showed the main transport of nitrate-rich and sulfate-rich factors from Northeastern Europe and from the Balkan region.

In another study, the same group, **Landis et al., (2019)**⁶⁶ conducted the filter based source apportionment study of Polyaromatic hydrocarbons (PAH) from 2014 to 2015. 24 hour sampling was conducted at the monitoring station, which was located near to various surface oil sand mining sites. PM_{2.5} average concentration during the sampling period was $8.6 \pm 11.8 \mu\text{gm}^{-3}$ while PM_{10-2.5} average concentration was $8.5 \pm 9.5 \mu\text{gm}^{-3}$. The PMF model resolved the data into six factors, which account for 95% of PM_{2.5} and explained measured 78% of PAH. Highest contributor was biomass combustion (40%) among the various sources. **Wang et al., (2019)**⁶⁷ used PMF model for source apportionment of PM_{2.5} at two different sites namely, TG (a general station) and PE (city's ferry terminal). 8 sources were identified with secondary sulfate and secondary nitrate as major contributors, contributing 33% and 23%, respectively. 12% was contributed by vehicular emissions along with helicopter followed by 10% contribution from industrial sources.

Saraga et al., (2019)⁶⁸ collected PM_{2.5} for the period of one year at two different sites in Thessaloniki port city, namely, city center and the port. Five sources at the city center and six sources at the port of PM_{2.5}. The combined effect of two major sources (Biomass burning and traffic) contributed around 70% of PM_{2.5} for city center in winter season. Road dust presents different contribution at both the sites with greater contribution of 19.7% at the port site while its contribution in the city was meagre 7.4%. Spain was struck by serious economic crisis 10 years ago (2009-2013), but the economy improved in 2014. **Hao et al., (2019)**⁶⁹ used the Positive Matrix Factorization (PMF) model to determine the source changes before and after the economy grew. PM₁₀ samples were collected in 2014 for knowing the sources at 6 different locations in Andalusia, situated in the Southern Spain. Seven sources were identified out of which the soil dust had the greatest impact on all the sites, followed by the road traffic source. Contributions from industries showed an increase in pattern from periods of financial crisis to economic recovery. After the financial crisis, the heavy metal concentration in the ambient air increased and simultaneously the health risk factor increased for people. **Lucarelli et al., (2019)**⁷⁰ measured fine (<2.5 μm) and coarse fraction (2.5-10 μm) of particulate matter in Tuscany district of Italy. With the use of Positive Matrix

Factorization (PMF), they measured 10 sources of particulate pollution, out of which only two were natural and six anthropogenic sources. The major source which contributed 30% annual mass fraction of PM₁₀ was biomass burning. The study was conducted near a waste incinerator but it contributes only 2% of PM₁₀ mass on average.

Yu et al., (2019)⁷¹ determined dithiothreitol (DTT) as Reactive oxygen species (ROS) in PM_{2.5} samples over Beijing, China. PMF results shows vehicular activity as most prominent source of DTT. **Ding et al., (2019)**⁷² conducted source apportionment in Wuhan, China using PMF model. NH₄⁺, SO₄²⁻ and NO₃⁻ make up the 97% of the total ions concentration. Secondary nitrate, coal combustion and biomass burning were the top three contributors with 23%, 18% and 15% contribution, respectively. Winds from NW and N lead to dispersion of the pollutant. **Liao and Wu, (2020)**⁷³ conducted source apportionment using the PMF model in the urban area of Taipei city of Taiwan. Seven potential sources were conducted including ammonium sulphate related sources as the most dominating source (33%), followed by coal/marine with 18% contribution and industrial/vehicular (16%) in PM_{2.5}. Through trajectory analysis data, contribution of ammonium sulfate from various distant sources were determined. **Li et al., (2020)**⁷⁴ analysed PM_{2.5} using Positive matrix factorization (PMF) model in Linfen, China. Six factors were identified as vehicular sources (26.5%), secondary nitrate (16.5%), coal combustion and industrial emissions (25.7%). **Jain et al., (2020)**⁷⁵ have used Positive matrix factorization (PMF) at Delhi for characterizing 8 sources of PM₁₀ and PM_{2.5}. Total carbon contributed around 28% of the PM_{2.5} concentration and biomass burning was one of the major source especially during winter and post monsoon season.

Garaga et al., (2020)⁷⁶ have shown vehicular exhaust and dust emissions as the dominant sources in urban and rural regions using the Positive Matrix factorization (PMF) model. 5 to 8 sources were identified at three different locations. **Wu et al., (2020)**⁷⁷ found the wood/biomass burning as highest contributor (31.02%) of PAH (Poly aromatic hydrocarbons) followed by vehicular emissions (27.17%), petroleum and coal combustion (20.53%). The largest share in mutagenicity and carcinogenicity was from vehicular exhaust as 41.46% and 36.61%, respectively. **Sun et al., (2020)**⁷⁸ compared the source categories based on literature from 2008 to 2018 specially poly aromatic hydrocarbons (PAH). Coal

combustion and vehicular emissions were most common sources of PAH whereas agricultural, vehicular and industrial contributed heavy metals.

2.3.2 Source apportionment using various models

Various research groups in India have used different models for analyzing the sources of pollution and their impacts. **Singhai *et al.*, (2017)**⁷⁹ highlighted the role of aerosol precursors in production of secondary aerosols and fog-smog-fog rotation. PMF and PSCF have shown the role of geographical locations of Punjab, Haryana and East Pakistan in secondary sulfate and nitrate formation in Delhi. **Bhuyan *et al.*, (2018)**⁸⁰ made use of Principal Component Analysis-Multi Linear regression (PCA-MLR) which demonstrates 42% aerosols from combustion sources whereas, 24% from secondary formation. Those originating as road and crustal dust had a contribution around 26%. The utilization of Chemical Mass Balance (CMB) model revealed that the contribution from combustion sources is about 47% of aerosol concentration and this result was in agreement with PCA-MLR.

Dai *et al.*, (2019)⁸¹ used the size profiles of various chemical species as tracers for different sources using the SR-CMB (Size resolved chemical mass balance) model for source apportionment. The biggest source contribution was from other sources (22.22%), followed by dust (20.5%), vehicular sources (19.6%) in PM_{0.006-9.8}. **Wei *et al.*, (2019)**⁸² used the Positive Matrix Factorization (PMF) model along with chemical transport models i.e., Mesoscale modeling system generation 5 (MM5) and Community multiscale Air Quality (CMAQ) model, for the source apportionment of PM_{2.5} in one of the most polluted parts of China, Hundan city. Results indicated 36% of PM_{2.5} from local sources, with maximum contribution from coal (22.3%) and industrial sources (18.5%). **Taghvaei *et al.*, (2019)**⁸³ used the Principal component analysis (PCA), multi linear regression (MLR) and spearman correlation method for tracking sources for oxidative potential of PM_{2.5}. Vehicular emissions, indicated by Elemental carbon (EC) were indicated as major source by MLR method, whereas water soluble organic carbon (WSOC) and levoglucosan were used as biomarkers for secondary organic aerosol and biomass burning, respectively in urban area in Athens, Greece.

Peng *et al.*, (2019)⁸⁴ developed a new method, Single particle aerosol mass spectrometry (SPAMS-RM) that occupied the receptor model (RM) on an MS dataset from SPAMS to

identify particle sources. Multilinear Engine-2 (ME2) and adaptive resonance theory-based neural networks-2a (ART-2a) were separately used to analyze the single particle MS dataset. Source apportionment was done using two receptor models, Positive Matrix Factorization (PMF) and ME2, based on the 1 h resolution chemical dataset. ART-2a obtained 19 clusters that merged into five major classes: carbon species, rich-K, sea salt, crustal dust, and industrial metals. SPAMS-RM identified eight sources by interpreting the MS characteristic of factors and investigating the relationship of the temporal trends of factor contributions, chemical species, gaseous pollutants, and particle clusters.

Liuh *et al.*, (2019)⁸⁵ developed a receptor model, consisting of four non-negative matrix factorization algorithms: the multiplicative update process; the optimal gradient process; the highly efficient, monotonic, fixed-point method; and the conjugate gradient process. The receptor model used was Positive Matrix Factorization (PMF) 5.0 model for feasibility and performance of the developed model, using both synthetic dataset and PM_{2.5} air samples. Comparisons between the modeled organic carbon, and the elemental carbon source apportionments and radiocarbon measurements, suggested that combined application of multiple algorithms could satisfactorily apportion emission source contributions for one, or a few, specified samples among a receptor dataset, thus validating the accuracy of model. **Stracquadanio *et al.*, (2019)⁸⁶** measured the wood burning's contribution to PM₁₀ using Positive Matrix Factorization (BB_{PMF}) and levoglucosan concentration as macro tracer (BB_{levo}). Samples were collected for 24 hours and 8 hours for PM₁₀ and PM_{2.5}, respectively. Contributions from woody biomass towards PM₁₀ were highest in winters (nearly 30% of total mass). **Liang *et al.*, (2019)⁸⁷** used the PMF and ISORROPIA II thermodynamic equilibrium model for identifying different sources in two fine fractions, PM₁ and PM_{2.5}. The sum of carbonaceous particulate and secondary aerosols accounted for up to 40% of PM_{2.5} mass fraction. Another model WRF-Chem was used for knowing the origins and carbonaceous mass concentrations. The modeled values were consistent for carbonaceous species with sampled values, but particulate mass was lowered than measured.

Jain *et al.*, (2019)⁸⁸ used various receptor models such as UNMIX and Positive Matrix Factorization (PMF) model for source apportionment of PM₁₀ over Indo Gangetic Plain of India (IGP). The average PM₁₀ concentration measured were 206.2±77.4 µgm⁻³ at Varanasi,

followed by $202.3 \pm 74.3 \mu\text{gm}^{-3}$ at Delhi, and $171.5 \pm 38.5 \mu\text{gm}^{-3}$ at Kolkata, during 2011. The PMF model determined 7 major sources at all the three sites with little variation in the sources. Other receptor models such as UNMIX and principal component analysis with absolute principal component scores (PCA-APCS) determined less number of sources for the three sites. The major output of all the receptor models was that Vehicular exhaust, Biomass burning, secondary aerosols and soil dust are the dominant sources of PM_{10} in IGP. **Gadi *et al.*, (2019)⁸⁹** used Positive Matrix factorization (PMF) and Principal Component Analysis (PCA) for source apportionment at three different sampling sites in India, namely at Delhi, Haryana and Uttar Pradesh. 3-day backward trajectories were also used for assessing the transport pathways of air masses which effect the PAH concentrations. Both the models resolve 5 sources of $\text{PM}_{2.5}$ with highest contribution from vehicular emission (32.2%) and biomass burning (30%). Transport sector is the main area where emissions need to be curbed. **Kumar *et al.*, (2020)⁹⁰** used the Conditional Bivariate Probability Function (CBPF) for identifying local and potential source contribution function (PSCF) for regional sources at forested location in Bihar. Regional contribution to $\text{PM}_{2.5}$ was most dominant from surrounding areas of Chhattisgarh, northern and south eastern parts of Madhya Pradesh, Delhi, Haryana and Rajasthan.

2.3.3 Health related studies and source apportionment

Andersen *et al.*, (2007)⁹¹ found the strongest positive association between PM_{10} and asthma. The strongest correlation was found between crustal and secondary sources with cardiovascular. Biomass was correlated with respiratory problems and asthma was associated with vehicular source. No single source of PM_{10} was attributed to all morbidity. **Lurie *et al.*, (2019)⁹²** identified five different sources at two sites with highest contributions from oil combustion and soil and resuspended dust, at Korangi site (industrial/residential site). At Tibet center (commercial and residential), sea spray (26%) and soil and urban dust resuspension (25%) were major contributors. The maximum concentration of $\text{PM}_{2.5}$ was $269 \mu\text{gm}^{-3}$ and $279 \mu\text{gm}^{-3}$ at Tibet Center and Korangi site, respectively. Lifetime risk assessment of arsenic and lead also surpassed the WHO (2000) limit.

Rojas *et al.*, (2019)⁹³ measured the metal concentration such as Cr, Fe, Mn, Ni, and Si from exhaust and Zn, Pb, Zr, Ca, Cu, K, Cr, and Cd from other sources by using X-ray

spectroscopy (EDS) in school areas in Rio Grande do Sul (Brazil).. Road traffic was the main source for nanoparticles in school surrounding areas, leading to pollution exposure. Non exhaust emissions includes Ca, Fe and Cu from the resuspensions road dust and Cu, Fe and Mn from wearing of brakes. Other sources such as maintenance and condition of classroom and building were also considered as sources for nanoparticles in classrooms. **Akther et al., (2019)⁹⁴** have shown the decline in lung efficiency due to penetration of ultra-fine particles (PM₁) as shown by negative correlation between the two. For traffic, construction and industry, higher enrichment factor for Pb, Zn and Ni were found. The greater concentrations of NO₂ (0.076±0.007ppm) and TVOC (90.0±46.0ppm) were found as compared to other studies.

*Many studies were conducted in different set of environmental conditions of air pollution. **Singh et al., (2017)⁹⁵** have reviewed 51 source apportionment studies over South Asia out of which more than half of the studies (55%) were only concentrated in few urban locations (Delhi, Dhaka, Mumbai, Agra and Lahore). The literature shows the lack of source apportionment studies in small cities and especially rural and semi urban sites. For this reason, the study sites were chosen in rural backgrounds. More detail is given in the next chapter of the thesis. 62% of the studies have used positive matrix factorization (PMF) and principal component analysis (PCA) due to lack of local source profiles and emission inventories (**Singh et al., 2017)⁹⁵**. Hence, in present study, positive matrix factorization (PMF) model 5.0 was used for source apportionment purposes. Next chapter describes the methodology of choosing sites, samples and processes carried out in detail.*

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MATERIALS AND METHODOLOGY

CHAPTER- 3

This chapter describes the methods, techniques and principle of operation of various instruments employed for the research work. Sample collection includes the data on particulate matter and pulmonary function tests of school going children, along with oxygen saturation levels. Respirable dust samplers and various instruments were used for measuring respirable particulate matter concentration and its various components. Modelling was done by Positive Matrix Factorization model, which was freely provided by US EPA. National and International standards and protocols, were followed for sample selection and collection. Study area and its surroundings are briefly described in section 3.1. Section 3.2 describes the procedures followed for sample collection and instrumentation used and their principles are described in Section 3.3. Section 3.4 explains the metrology and atmospheric conditions of the study area. Section 3.5 give details about source apportionment studies. It includes its site description, instrumentation and various procedures followed for collection, transportation and storage of filters, along with characterization of various elements. For secondary dataset, air mass backward trajectories and satellite data using MODIS are discussed for presenting more realistic view of air masses and their transport pathways.

The study was designed into two parts with the first part as finding the association between particulate matter and respiratory parameters of school children which follows the steps as selection of sampling sites, selection of human subjects with collection of samples.

Second part aims at knowing the sources of particulate matter in the selected area, for which collection of particulate matter and chemical characterization of particulate samples are the preceding steps.

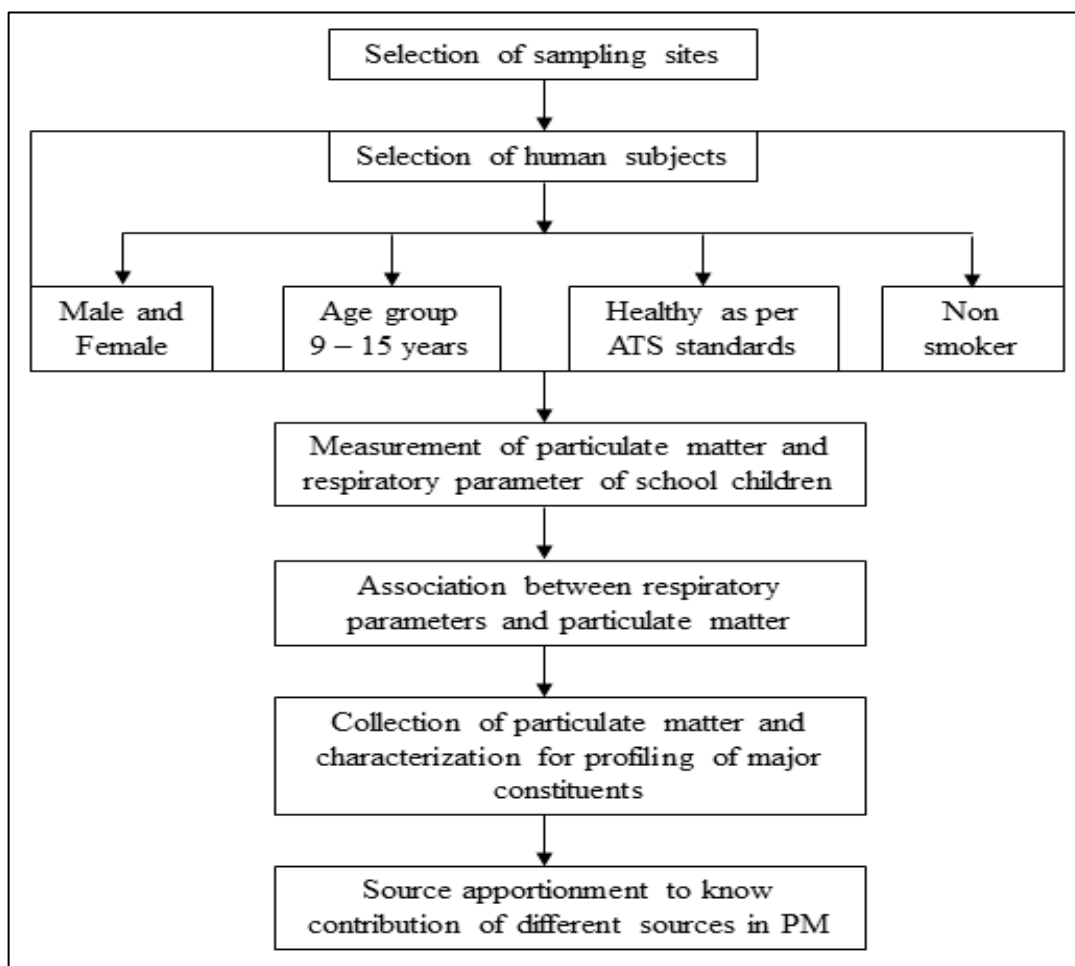


Figure 3.1 Flow chart of the study (Methodology)

3.1 Study location

Three agriculture active sites were selected in Punjab region of India. Figure 3.2 represents location map of study area. The distance between Patiala (PTA) site and Sangrur (SAN) site is nearly 70 km and between Fatehgarh Sahib (FTH) site and Sangrur (SAN) site is 100 km. All the selected sites were located from 0 to 1 km from nearest crop residue burning activity.

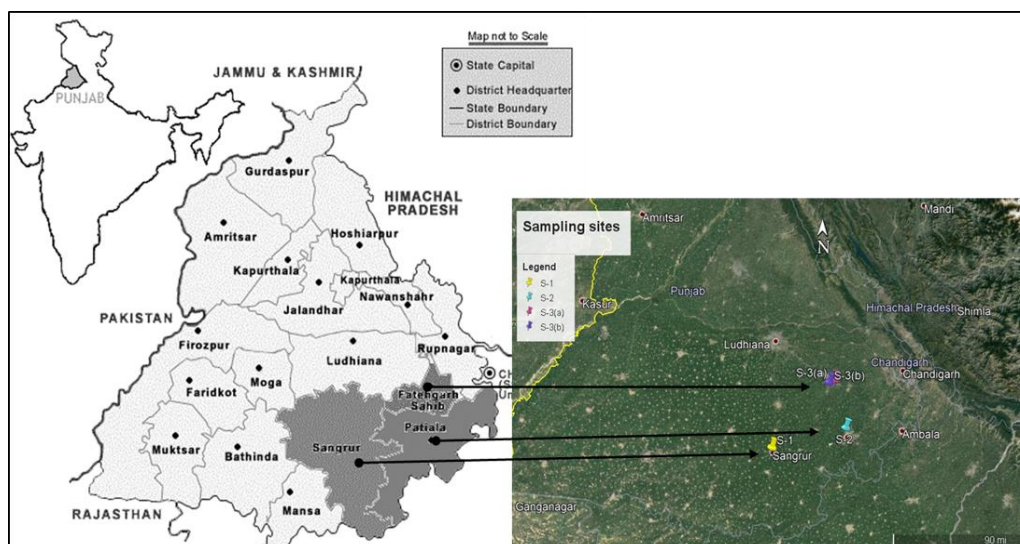


Figure 3.2 Location map of study districts. S1 Patiala site (PTA), S2 Sangrur site (SAN), S3(a) Nabipur village, Fatehgarh Sahib, S3(b) Jalvehra village, Fatehgarh Sahib

3.1.1 Site 1 (S1): Sidhuwal village in Patiala (PTA): Patiala city is located in south eastern Punjab, in northern India. It is the fourth largest city in the state. Rice and wheat are the two major crops of this region with a combined cropping area of more than 86%. The total biomass generated in Patiala from all sources like agriculture crop residues, forest and other wastelands and agro-industry is 3,792,252 MT/year, out of which, crop residue contributes 90.4% (**Teri report. 2003SF62**). With over 65% of the population living in rural areas, 38% the population depends on agriculture either as laborers (17%) or cultivators (21%). Sidhuwal is a rural/agricultural area located 6 km North-west (NW) of Patiala. Government Senior School, located in Sidhuwal village was selected for the study. The area around the school is majorly covered with agriculture fields, and no other major source of pollution is present within 10 km radius.

3.1.2 Site 2 (S2): Upli village in Sangrur (SAN): Sangrur is located at 30°15'N, 75°50'E. It has an average elevation of 232 meters (761 feet). This region is generally referred to as the land of agriculture and cattle. The total area of Local Planning Area (L.P.A.) Sangrur is 221.96 km² (22,196 hectares) out of which 21.58 km² is urban area (9.72%) and 200.38 km² is rural area (90.28%). Longitude and Latitude of Upli village are 30°19'N and 75°79'E. The selected school in the area of Upli was Rishi Public School, which is surrounded by agricultural fields in the near vicinity.

3.1.3 Site 3 (S3): Nabipur and Jalvehra villages in Fatehgarh Sahib (FTH): Fatehgarh Sahib is historically important city located in the north of Patiala city. Two Schools were selected from this location to make the total number of students to 61. Sacred Heart Public School, Nabipur and Shaheed Lalit Kumar Govt. Public School, Jalwera were only 500 m apart and ambient conditions were similar at both the schools. Health parameters and air samples were measured for both the sites and combined values were considered for final results. Henceforth, the human subjects from both schools were considered as one unit of sampling site. National Highway 44 (NH44) is the only major source other than crop residue burning in the near vicinity of the selected sites.

3.2 Selection of School and human subjects

School children were selected as human subjects on the basis of questionnaire. Questionnaires were distributed to every children of class 6 and 7 and requested to get duly signed by the parents. Only after the parent's consent, children were allowed to participate in the sampling procedures. Height and weights were noted at the start of the study and were regularly checked on monthly basis.

To collect the physiological parameters of human subjects, 162 students (94 males and 68 female) were selected from three sampling sites. The average age was 12 years of the children in the age group 9–15 years. None of the subjects had a history of asthma respiratory or any other illness and were not on medication. All subjects were students studying in 6–7 standards. Preliminary questionnaire according to American Thoracic Society and European Respiratory Society were used for selection of subjects. Prior to testing all subjects were questioned for their habits like smoking, health status, occupational and medical history. All the subjects selected were non-smokers (active and passive, both are excluded) and none of the subjects had any medical problem, respiratory illness or symptoms and are of North Indian ethnicity. Consent form for voluntary participation in the sampling activity for their pulmonary function tests were obtained from each subject (duly signed by guardians and school authorities).

3.3 Sample collection and analytical methods

The data was collected for respirable dust samples and health parameters for the period September 2014 to December 2015. Health related samples were collected according to the American thoracic society standards. Same conditions and procedures were followed through the study period. Sample size was maintained constant for the study duration. School children were given demonstrations on sampling procedure multiple times before starting the sampling. Children with asthma or any severe cardiovascular problem were not considered in the study. All the samples were collected on assigned time except for the month of June, when all the schools were closed due to summer vacations. PFT data is missing during that time period while PM data was still collected inside the schools but outside classrooms, while otherwise PM samples were collected inside the classrooms at the same height as subjects. PFT samples were collected in separate classrooms where students came in the group of pairs and after giving samples returned to their respective classrooms. Resting time period of 5 minutes was maintained throughout the sampling period before taking the samples. SpO₂ was always checked on the index finger of the right hand. Three samples were collected for health related sampling throughout the study period and average of three samples were considered as final value.

3.4 Instrumentation

Various instruments were used for collecting data related to health and air monitoring. The working and measuring principles of the instruments are described below.

3.4.1 Measurement of particulate matter concentration

Air monitoring was done using a portable aerosol spectrometer (GRIMM Model 1.108), which was specifically designed for indoor air quality monitoring. It displays real time data in as little as six seconds in 15 different size channels from 0.30 µm to 20 µm but environmental data mode (in PM₁, PM_{2.5} and PM₁₀ fractions) was used. Instrument was once calibrated during the sampling period (Grimm Envirotech Solutions) in Feb, 2015 with less than 2% deviation from measured mean mass value. Indoor air quality monitoring was conducted for 6 hour/day throughout the study. The air sampling was conducted during the school working hours, which represents the true exposure period of the subjects. The air monitoring was done on the same day on which the health survey was conducted. Sampling

was done two times per month during the non-burning months and 3 times per month during the burning months.



Figure 3.3 Grimm's Aerosol Spectrometer (model 1.108)

The instrument measured the dust particles based on principle of orthogonal light scattering. The incident light beam is set at 90 degree angle to the detector. Thus, the incoming particles are illuminated by a laser at 90 degrees. A light pulse is created when laser beam is crossed by any particle. By calculating the dust mass, the size distribution of particles is measured. Through the means of an internal volume flow controller pump, the sample air is sucked through the measuring cell and gravimetric filter. The filter is a dust collector that can be used for gravimetric control of the optically gained measurement results. The pump also transmits the rinsing air collected from it. The exhaust air of the pump is kept constant via a zero filter through a rinsing air control. Like other components of the optical cell, the rinsing air protects the laser optics against pollution and acts as particle independent reference air during the self-test. Upon a subsequent signal amplification, the signal of the detector diode is divided into different size channels in the range of 0.23 μm to 20 μm .

The instrument can be operated in four different modes: Environment, occupational health, particle count and mass concentration. In this study, the mass concentration mode was used throughout the study, which provides the PM concentration in three size fractions (PM₁₀, PM_{2.5} and PM₁).

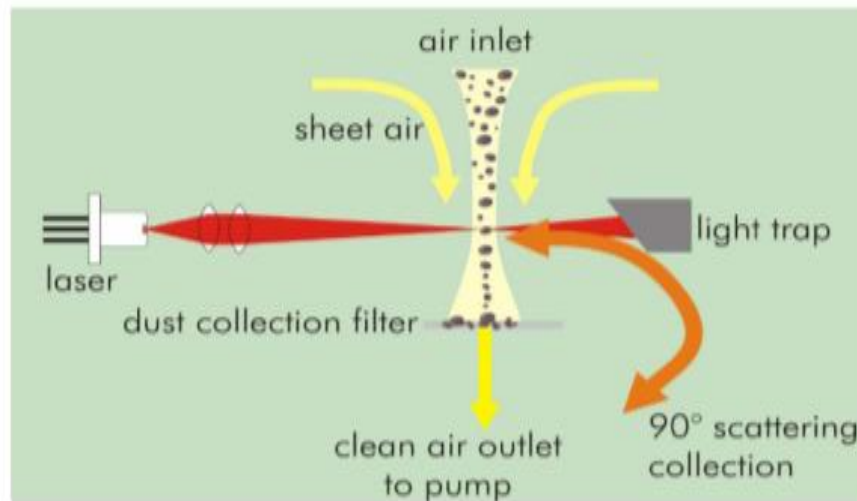


Figure 3.4 Working principle of Grimm's Aerosol spectrometer

3.4.2 Measurement of health related data

Health related measurements included Pulmonary function tests like Forced vital capacity (FVC) and Forced expiratory volume in the first second (FEV₁) and pulse oximetry parameters, such as oxygen saturation levels (SpO₂) were measured using SPIRODOC (Medical International Research, Italy). It is a portable instrument with both modes for spirometer as well pulse oximetry measurements. Spirometric tests of children were performed in an empty classroom during the school hours, according to the American Thoracic Society (ATS) standards. Each subject was told to perform each test 3 times, and the best of three attempts was recorded making sure the tests are conducted as per standards (Miller *et al.*, 2005¹; Redlich *et al.*, 2014²).

Pulmonary function tests were repeated to obtain at least three reproducible forced expiratory flow curves, with subjects standing and wearing nose clips during tests. These tests are based on American Thoracic Society recommendations, updated in 2005, modified for children. While measuring oxygen saturation levels (SpO₂), continuous reading was taken for almost 3 min for each subject and the average value was considered. The subjects were instructed to stay still during the test and left index finger was used every time for maintaining uniformity and to avoid the presence of bright light sources. As part of the pulmonary function evaluation, the children's height and weight were measured using standard methods, and a questionnaire was dispensed out asking about respiratory symptoms.



Figure 3.5 SPIRODOC (Medical International Research, Italy)

3.5 Basic meteorology of the study site

3.5.1 Classification of Weather Seasons

The three well defined seasons in Punjab are: Hot Season (from mid-April to the end of June). Rainy Season from early July to the end of September. Cold Season starts at early December to the end of February.

The transitional seasons are: Post-monsoon (September to end of November). It is transitional period between the rainy and cold seasons. Pre-hot season (March to mid-April). It is a transitional period between the cold and hot seasons.

The temperature begins to rise from February onwards. Though the real hot seasons begin in mid-April, the increasing temperature breaks the high pressure belt in the north-west of the Indian peninsula. Rainy season is of utmost importance as the agricultural year starts with its advent. Monsoon winds usually enter the area within the first weeks of July. The Bay of Bengal branch of the monsoon current is the primary source of rainfall. The temperature decrease is minimal in January, when the mean temperature decreases to 12°C during day time and nighttime to 5°C.

3.5.2 Temperature

The crop residue burning activity extends from April 15 to May 15 during wheat crop season while in rice crop season the stubble burning takes place from October 15 to November 15

every year. The average temperature and relative humidity during wheat crop residue burning period were 27.3 °C and 53.6% in 2015. During rice crop residue burning period, the average temperature and relative humidity were 21.3 °C and 70% with winds in North-Western direction. During 2016, 30.1°C and 45% were the average temperature and relative humidity for wheat crop residue burning period. The meteorological data was retrieved from Continuous Air Monitoring station at Thapar Institute of Engineering and technology, Patiala.

3.5.3 Rainfall

In the Punjab rainfall ranges from 250 mm and 1000 mm. During the three months of south-west monsoon winds, 70-80 % of overall rainfall is distributed and the remaining happens during the winter months. The amount of rainfall received in east and west Punjab is significantly different. Gurdaspur, Hoshiarpur, Ropar district and eastern areas of Patiala receive more than 750 mm of annual rainfall.

3.5.3.1 Monsoon Rainfall

The major part of annual rainfall is experienced during the monsoon period, when the monsoon current in the Bay of Bengal enters from the south-east. The usual advent of the Punjab monsoon is in July 1st week.

3.5.3.2 Winter Rainfall

Weather in Punjab is usually cold and dry during the winter season. The passing of western disturbances through the area is related with this weather. The role of Punjab's winter rainfall is significant largely due to its period and efficiency. Winter crops in the region depend upon this rainfall.

Meteorology of all selected sites are similar. The climate of the PTA city is very hot in the summer (with a maximum temperature of 43° C during May) and very cold in the winter (minimum temperature of 2° C during January). This region is also affected by the prominent synoptic meteorological phenomenon (western disturbances), that is dominant during pre-monsoon and winter seasons (**Agarwal *et al.*, 2012³; Rastogi *et al.*, 2015⁴**).

3.6 Source apportionment

The second part of the section includes methodology used to conduct source apportionment study. Source apportionment study was conducted to identify the sources of particulate matter which was measured using above describes methodology. School sampling sites were not feasible for this study due to instrument noise. So, nearest possible site was selected for conducting this study which was representative of the three selected sites. Particulate matter were collected in this study, pre and post weighed to measure PM mass. Chemical characterization was done using various methods, described in detail below followed by receptor modeling using positive matrix factorization (PMF) model.

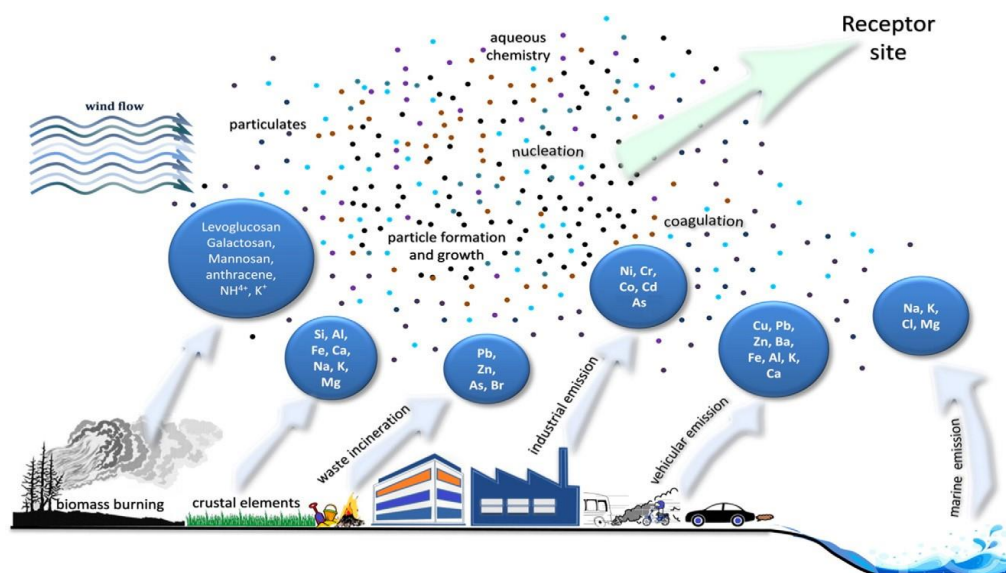


Figure 3.6 Various organic and elementary signature molecule markers from different sources (Banerjee et al., 2015⁵)

3.7 Sampling site

Samples were collected at roof top of a three storey building (about 35 feet from ground level) of Thapar Institute of Engineering and Technology, which is 250 acre campus located in Patiala (30.3 N, 76.36 E; 258 m amsl) in the Malwa region of the Punjab province in the Indo Gangetic Plain (Figure 3.4).

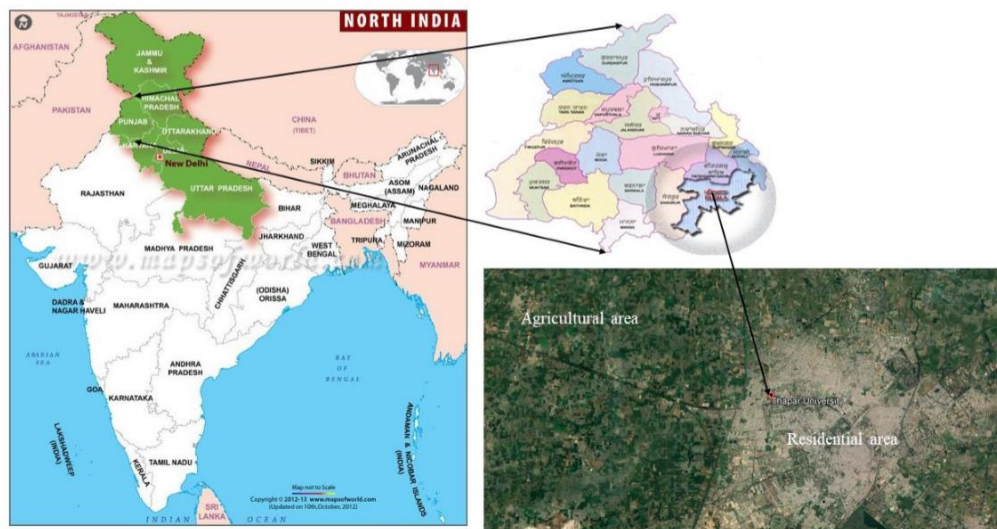


Figure 3.7 Site description of the study site for source apportionment

Sampling site is in area surrounded mainly by agricultural fields. It is situated in the South West part of the Indo Gangetic Plain. Large scale steel industries and power plants are located in and around Mandi Gobindgarh, Ludhiana, Amritsar and Lahore (Pakistan) in the North West direction within a distance from 50 to 200 km.

Patiala district is an agricultural district with total geographical area of 332445 Ha and 81.5% of this area is under cultivation with 65% population lived in rural areas and engaged in agriculture as in present data available. As per 2011 census, population of Patiala district is 18,95,689. Vehicle number increased averagely at 7.5% per annum and the nearby highway (NH64) connecting Patiala and Sangrur carries more than 7500 Passenger Car Unit (PCU)/hr, whereas nearest road from sampling location (Bhupindra road) carries 4555 PCU.

3.8 Filter preparation

Filter preparation was done by storing the filters in air desiccator over fused calcium chloride for 24 h period before sampling to remove the moisture content before weighing on electronic balance (Shimadzu, AY 220, with accuracy up to 4 decimal value and 0.1 mg detection limit) and mounting these on respirable dust sampler. After the sampling, filters were directly transferred to desiccator to remove any gained moisture during sampling and respective weights were taken. Average value of three weighing measurements were considered as final value.

3.9 PM₁₀ sample collection and analytical methods

The respirable dust sampler (Envirotech, APM460) was placed on the terrace of a B-Block building of the site. Sampling of PM₁₀ was conducted at the sampling site in Patiala from May 2015 to June 2016. The sampling frequency was increased during crop residue burning period as compared to rest of the crop season.

PM₁₀ samples were collected on glass microfiber filters (8x10 inch) using Respirable Dust Sampler (Envirotech, APM 460) for 12 h sampling period, with day time sampling from 7 a.m. to 7 p.m. and night sampling period from 7 p.m. to 7 a.m. Flow rate varied between 0.9 and 1.1 m³/min. A total of 148 samples were collected during the study period using Microglass Fiber filters GF/1 (Millipore Micro Products). The particulate matter (PM₁₀) on glass micro fiber filter was collected using Respirable dust sampler APM 550 from May 2015 to July 2016.

The collection of particulate matter was done using PM₁₀ samples were collected on glass microfiber filters (8x10 inch) using Respirable Dust Sampler (Envirotech, APM460) for 12 hour sampling period, with day time sampling from 7 am to 7 pm and night sampling period from 7 pm to 7 am. Flow rate varied between 0.9 and 1.1 m³/min. A total of 148 samples were collected during the study period using Microglass Fiber filters GF/1 (Millipore Micro Products). Filters were stored in air desiccator over fused calcium chloride for 24 hour period before sampling to remove the moisture content before weighing on electronic balance (Shimadzu, AY 220, with accuracy up to 4 decimal value and 0.1 mg detection limit) and mounting these on respirable dust sampler.

After the sampling, filters were directly transferred to desiccator to remove any gained moisture during sampling and respective weights were taken, after they were stored in constant temperature and humidity for overnight. Average value of three weighing measurements were considered as final value. The final filter weight minus the tare weight is calculated. The Indian standard methods for measurement of air pollution were followed for calculating PM₁₀ mass concentration **(5182 (Part 23): 2006)**.



Figure 3.8 Envirotech APM 450 Respirable Dust Sampler installed at PTA site

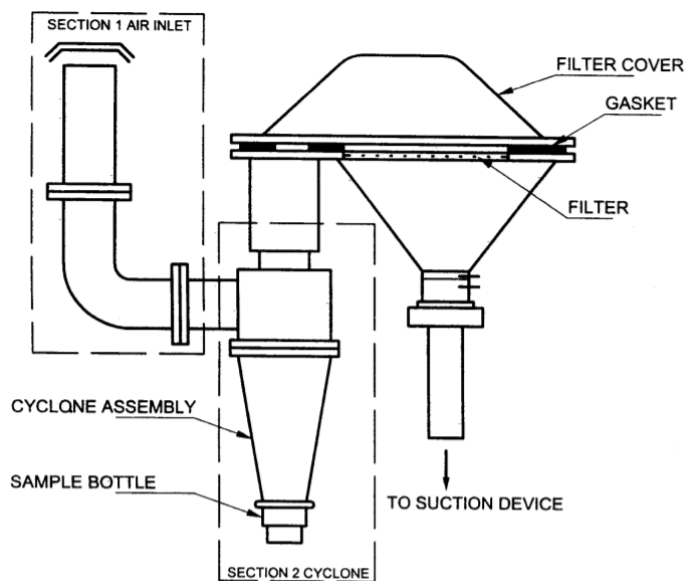


Figure 3.9 Schematic diagram of respirable dust sampler

3.10 Chemical analysis

After the collection of PM₁₀ particulates on glass microfiber filter, filters were extracted into clear particle free aqueous solutions for measurement of different elements present in PM₁₀. Depending upon the type of instrument and method used, filters were acid digested and water digested.

3.10.1 Acid digestion

Filters were digested weekly (samples collected in a one week) for chemical analysis. All exposed glass microfiber filters were cut into two equal portions. The one half portion was digested for metal analysis by hot plate digestion method, as per recommended in method 3010A of EPA of acid digestion of aqueous samples and extracts for total metal analysis. Total volume make up was 250 ml for metal detection of Al, Ti, Ca, Mn, Fe, Mg, V, Cr, Ni, Cu, Zn, Ba and Pb.

3.10.2 Water digestion

Water digestion was carried out for ions (Na⁺, K⁺, SO₄²⁻, Cl⁻, NO₃⁻). Final volume was make upto 250 ml. The 250 ml total volume was required for: 50 ml for Na⁺, 50 ml for K⁺, 50 ml for Cl⁻, 50 ml for NO₃⁻, and 50 ml for SO₄²⁻. Blanks with empty filters were checked for every 20 samples.

3.10.3 Analysis of elements

Following processes were adopted for analyses of different species. Metals in the ambient air were analyzed by Microwave Plasma Atomic Emission Spectrophotometer (Agilent technologies 4100 MP-AES). This instrument is present in Sophisticated Instrumentation Analysis Lab, Thapar Institute of Engineering and Technology, Patiala.

3.10.4 Analysis of ions

Sodium ion (Na⁺) and potassium ions (K⁺) were measured using Flame photometer (Esico Microprocessor Flame photometer, model: 1382E). Filters were acid digested under fume hood before measuring for metal concentrations. Nitrate (NO₃⁻) concentration in digested solution was measured using Ultraviolet Spectrophotometric Screening method (IS: APHA 4500- NO₃⁻). Gravimetric method with Ignition of Residue (IS: APHA 4500- SO₄²⁻ C) was used for measuring concentration of sulfate (SO₄²⁻) and chloride (Cl⁻) was measured using

argentometric method (IS: 3025 (Part 32)-1998). One blank filter was analyzed for every 20 samples. The 3% analytical error (repeatability) was estimated based on triplicate (n = 3) analysis.

3.11 Method detection limit

The EPA defines the Method detection limit (MDL) as the "minimum concentration of substance that can be measured and reported with 99% confidence that the analyte concentration is greater than zero, and is determined from analysis of a sample in a given matrix containing the analyte". The method detection limit for different elements detected by various methods is given below in Table 3.1. The method detection limit for electronic weighing balance (Shimadzu, AY 220) is 0.1 mg. Filters were pre weighed and post weighed after collecting PM₁₀ samples.

Table 3.1 Method detection limit for various species

Species	Instrumentation	MDL
Aluminium (Al)	MP-AES	2.5
Titanium (Ti)	MP-AES	0.1
Calcium (Ca)	MP-AES	0.1
Manganese (Mn)	MP-AES	0.1
Iron (Fe)	MP-AES	0.2
Potassium (K ⁺)	Flame photometry	0.5
Sodium (Na ⁺)	Flame photometry	0.5
Magnesium (Mg)	MP-AES	0.01
Vanadium (V)	MP-AES	0.1
Chromium (Cr)	MP-AES	0.05
Nickel (Ni)	MP-AES	0.1
Copper (Cu)	MP-AES	0.05
Zinc (Zn)	MP-AES	0.05
Barium (Ba)	MP-AES	0.1
Lead (Pb)	MP-AES	0.05
Sulphate (SO ₄ ²⁻)	Ignition of Residue (IS: APHA 4500- SO ₄ ²⁻ C)	10
Chloride (Cl ⁻)	Argentometric method (IS: 3025 (Part 32)-1998)	0.15
Nitrate (NO ₃ ⁻)	Ultraviolet Spectrophotometric method (IS:APHA 4500-NO ₃ ⁻)	0.885

3.12 Positive matrix factorization (PMF) model

Positive matrix factorization is a receptor model used for PM source identification and apportionment. It was developed by Paatero in 1997. Receptor models are mathematical approaches for quantifying the contribution of sources to samples based on the composition or fingerprints of the sources. The aim of receptor models is to solve the chemical mass balance (CMB) between measured species concentrations and source profiles, with number of factors p , the species profile f of each source, and the amount of mass g contributed each individual sample.

$$x_{ij} = \sum_{k=1}^p g_{ik} f_{kj} + e_{ij}$$

Where i is the number of samples and j is chemical species, k is the source, p is the number of sources, x_{ij} is the concentration of j_{th} element in the i_{th} sample; g_{ik} is the source contribution from the k_{th} source to the i_{th} sample, f_{kj} is the element fraction of the j_{th} element in the k_{th} source, and e_{ij} is the residual for each sample/species.

PMF is a multivariate factor analysis tool that decomposes a matrix of speciated sample data into 2 matrices: factor contributions (G) and factor profiles (F) (**Paatero and Tapper, 1994⁶; Paatero, 1997⁷**). The PMF model minimize the objective function Q to obtain factor contributions and profiles as:

$$Q = \sum_{i=1}^n \sum_{j=1}^m \left[\frac{x_{ij} - \sum_{k=1}^p g_{ik} f_{kj}}{u_{ij}} \right]^2$$

Q is a crucial parameter and two types of Q are obtained:

- Q_{true} : It is a goodness of fit parameter including all points.
- Q_{robust} : It is a goodness of fit parameter excluding points not fit by the model, for which uncertainty scaled residual is greater than 4.

3.12.1 Working principle

Multilinear engine – 2 solves the Positive Matrix Factorization equation in the PMF model by doing iterations, minimizing the sum-of-squares object function, Q , over a series of steps. When additional iterations to minimize the value of Q start providing diminishing returns, it means a stable solution to the equation has been reached. ME-2 typically requires a few hundred iterations for small data sets (500 runs were used for the study) (**Paatero, 2000⁸**).

The two main advantages of PMF compared to other receptor modeling tools are its intrinsic non negative constraints and its way to measure specific data points and include uncertainties, which allows it to include less stable species and provide real world sources **(Hopke, 2016⁹)**. PMF uses two input files, concentration and user provided uncertainty associated with sample data to weight individual points.

Some constraints are applied while obtaining the results that no source can have negative source contributions. Data below detection limit are still utilized by the model but with associated uncertainty adjusted so as to have less impact than data points above the detection limit.

3.12.2 Concentration file

Pretreatment of measured concentration was done before the concentration file was input into the model. The units used for concentration of various metals, ions and PM₁₀ concentration in the concentration file were in μgm^{-3} . The measured values of ions and metals were in mg/l which were converted to μgm^{-3} according to following steps:

- a. Firstly, the results were corrected for blank (units = mg/l).
- b. Converted the mg/l into $\mu\text{g/ml}$.
- c. Then multiplied by makeup volume, i.e., $250 \text{ ml} \left(\frac{\mu\text{g}}{\text{mL}} \times \text{mL} \right) = \mu\text{g}$.
- d. Results were corrected for full length filter (μg), i.e., multiplied by 2.
- e. Then obtained values were divided by volume of air used for sampling (m^3) = μgm^{-3}

Missing values can be replaced by geometric mean but there were no missing values in the data. Below detection limit (BDL) were replaced by MDL/2. Method detection limit (MDL) values for different species are given in Table 3.1.

Time period for day and night samples were input in first column with dates in second column and species as first row. A data matrix of 148 samples (columns) and 17 species (rows) was created.

3.12.3 Uncertainty file

Two types of uncertainty files were measured, namely equation based and observation based. The uncertainty files have same dimensions and first column have time, second column have date and species in first row as in concentration file. Negative values and zeros were not permitted in the uncertainty file. EPA PMF does not run if negative or zeros are included in the uncertainty data.

As for most of the samples, the concentration is greater than the Method detection limit (MDL), so the following equation was used to calculate uncertainty:

$$\text{Uncertainty} = \sqrt{(\text{Error fraction} \times \text{concentration})^2 + (0.5 \times \text{MDL})^2}$$

The missing value in the dataset was specified as “-999” value, although any negative value can be chosen to indicate the missing value.

For samples where the concentration was less than or equal to MDL, the uncertainty was calculated using the following equation (**Polissar *et al.*, 1998; Kim and hoopke, 2004**):

$$\text{Uncertainty} = \frac{5}{6} \times \text{MDL}$$

3.13 Satellite Data: Moderate Resolution Imaging Spectroradiometer (MODIS)

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument onboard the earth observing system (EOS) Terra and Aqua satellites for observing the atmosphere, sea and ground surface with a range of Visible, NIR, MIR and thermal channels. It can provide the images for any location of morning (Terra) and afternoon (Aqua). MODIS Active fire detection is based on the AVHRR and TRMM VIRS heritage algorithms (**Justice *et al.*, 2002¹⁰**). Various studies have used MODIS data for determining the extent of spatial burning of rice and wheat crops, changes in fire patterns, smoke produced, aerosols produced and cloud properties (**Gunaseelan and Bhaskar, 2020¹¹; Jiang *et al.*, 2020¹²; Hieu *et al.*, 2020¹³; Lu *et al.*, 2019¹⁴**).

3.14 Back air trajectory simulations using HYSPLIT

HYSPLIT (Hybrid Single-particle Lagrangian Integrated Trajectory) is used for track down the large scale air mass transit routes to a sampling site (**Kong *et al.*, 2010¹⁵**). Back

trajectories give advanced understanding of air flow patterns and long-range modes of transport.

The model trajectories, on the basis of equations of horizontal and vertical advection (wind speed and direction) predict the course of a single particle (**Kim et al., 2009**)¹⁶. This method is used in the thesis to identify the sources on larger scales, which were otherwise difficult to track (**Lowenthal et al., 2010**)¹⁷.

In this chapter, various Instruments, techniques, methods and working principles of instruments are described. The instruments were calibrated at regular intervals for reliability of the data. Brief introduction for online instruments such as MODIS and Hysplit are given. This chapter describes the methodology followed for obtaining results, which are describes in next chapter.

3.15 References

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RESULTS AND DISCUSSION

CHAPTER- 4

In rural areas, biomass burning is considered as the only major source of air pollution. The study was designed to first check the prominence of different sized particulate matter on lung efficiency of less immune age group of school children. To validate the contribution of different sources in particulate matter concentration, the later part of the work includes the source apportionment study. The results and interpretation of the source apportionment study, done using Positive Matrix Factorization (PMF) model are shown in CHAPTER 5. The section 5.4 and section 5.5 includes the backward trajectory data and fire spot data to verify the biomass burning and origin of particulate matter from different sources. The results of this study have shown some unexpected results and will be helpful to shed new light on the contribution of various sources in the air pollution at sensitive sites in the area. The outcomes presented here can also give guiding factor to the controlling agencies at the later stage to curb down the air pollution at the emission source.

The initial study inquires the impacts of particulate matter on lung efficiency of school children. The particulate matter were measured in three different size fractions (PM_{10} , $PM_{2.5}$ and PM_1) using Grimm Portable Aerosol Spectrometer (Model 1.108) and pulmonary function tests were performed using the spirometer (MIR's spiro doc) and the results are shown in CHAPTER 4.

This section describes the results of 16 month study carried out in three cities of the Punjab state from September 2014 to December 2015. Lung efficiency of the school children were checked for different parameters using the spirometer (MIR's spiropod) and simultaneous particulate matter indoor concentrations were recorded in different size fractions (PM_{10} , $PM_{2.5}$ and PM_1) using Grimm Portable Aerosol Spectrometer (Model 1.108). Although the Punjab state covers less than 2% of India's land surface, it produces about two-thirds of the country's food grains. Farmers burn the crop residues into the fields after harvesting of the crops. Agriculture crop residue burning (ACRB) is an episodic event which occurs in the month of October-November and April-May for Rice crop residue burning and Wheat crop residue burning, respectively. Site selection and instrumentation used were mentioned in chapter 3 in detail.

4.1 Particulate concentration levels at different sampling sites of PTA, FTH and SAN

Patterns of PM levels (PM_{10} , $PM_{2.5}$ and PM_1) are same (as seen in Figures 4.1, 4.2 and 4.3) that sources of these pollutants are also consistent with the sampling duration. Bar heights can be seen rising during the crop residue burning periods like October and November in rice crop season and April and May during the Wheat crop season. Since all the three sampling sites at PTA, FTH and SAN are equally covered with agricultural activities (81.50%, 87.45% and 90.28%, respectively), the extent of release of PM in the ambient air due to crop residue burning is also the same.

Fortnightly averaged levels at PTA, FTH and SAN of PM_{10} , $PM_{2.5}$ and PM_1 sites are shown in Figure 4.1, Figure 4.2 and Figure 4.3, respectively from September 2014 to December 2015. PM_{10} levels increase from October to November due to extensive burning of rice crop residue. The PM (PM_{10} , $PM_{2.5}$ and $PM_{1.0}$) were higher in FTH as compared to SAN and PTA. The Higher levels of PM during rice crop season, as compared to, wheat crop season are well accepted (Sidhu *et al.*, 1998)¹. The rice crop residue burning is much more hazardous than wheat crop residue burning on two counts: one, the content of burning is more wide spread at relatively low temperature and secondly, the meteorological conditions being more stable prevents mixing with the upper layer of the ambient air (Kothai *et al.*, 2011)². In the absence of possible dispersion the PM levels keep on rising as the crop residue burning activities pick up.

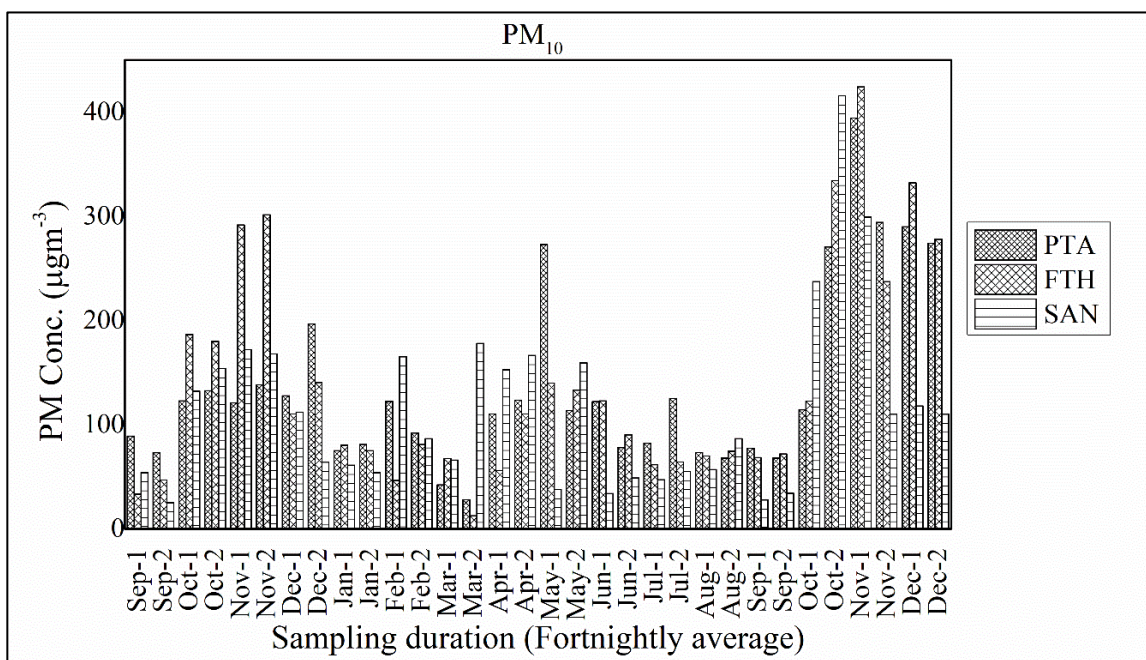


Figure 4.1 Particulate matter (PM₁₀) levels (Fortnightly averaged) at different sampling sites of PTA, FTH and SAN from September 2014 to December 2015

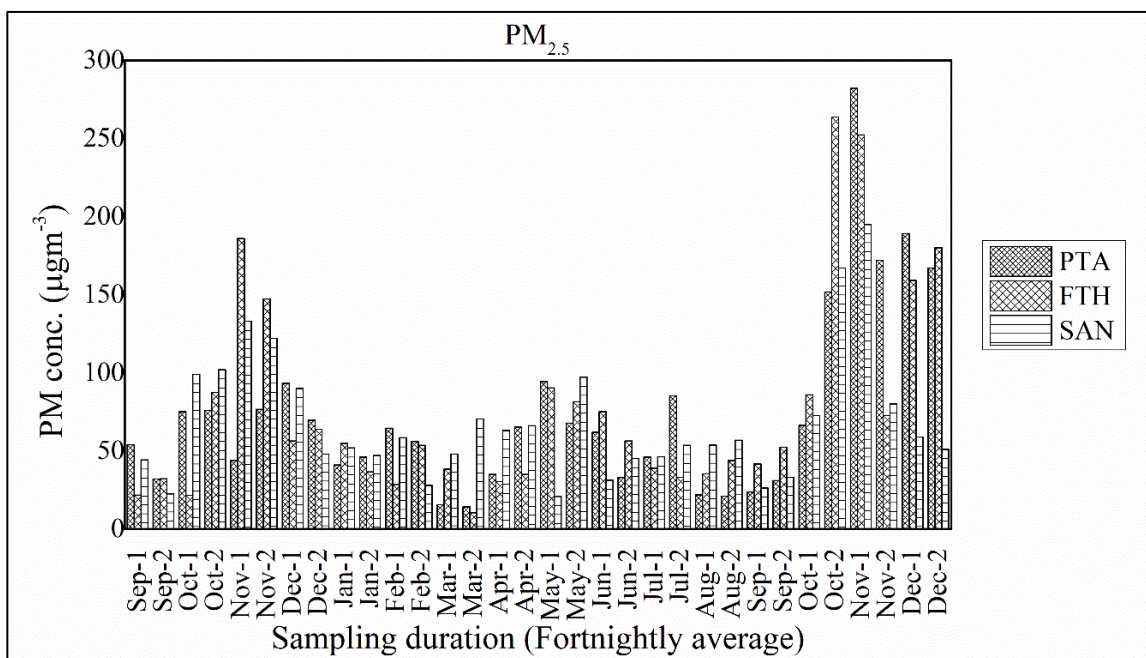


Figure 4.2 Particulate matter (PM_{2.5}) levels (Fortnightly averaged) at different sampling sites of PTA, FTH and SAN from September 2014 to December 2015

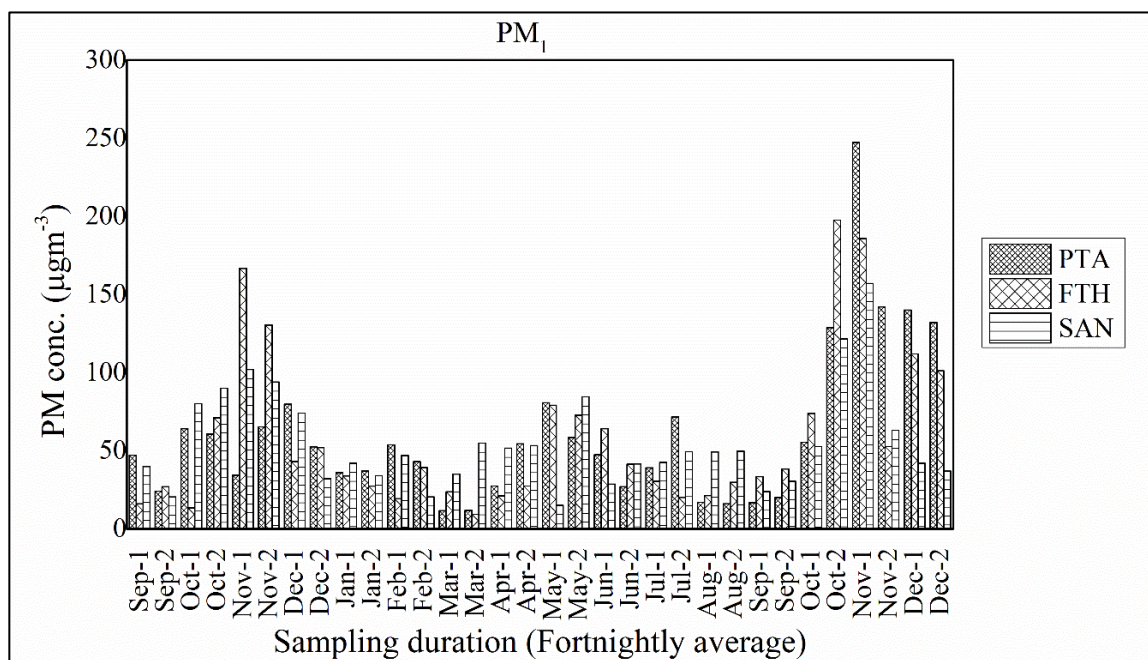


Figure 4.3 Particulate matter (PM₁) levels (Fortnightly averaged) at different sampling sites of PTA, FTH and SAN from September 2014 to December 2015

- * PTA = Patiala site
- * FTH = Fatehgarh Sahib site
- * SAN = Sangrur site

4.2 Particulate matter concentration levels at PTA, FTH and SAN sampling sites

Fortnightly averaged levels of PM₁₀, PM_{2.5} and PM₁ at PTA, FTH and SAN sites are shown in Figure 4.4, Figure 4.5 and Figure 4.6, respectively from September 2014 to December 2015. During Oct-Nov 2014, the mass fraction of PM₁₀ at PTA and SAN site is mostly made up of smaller size mass fraction indicating the major contribution from organics and carbonaceous sources, pointing towards local crop residue burning sources. At FTH site, the PM₁₀ mass fraction predominates over PM₁ and PM_{2.5} indicating resuspended road dust particles, which can be due to nearby highway, National Highway 1 (NH-1).

For 2015, only at PTA site the smaller size fraction predominates the PM₁₀ mass concentration indicative of crop residue burning. At FTH and SAN site, major coarse fraction particles contributes in PM mass. It is interesting to notice the concentration levels of PM₁₀ during the wheat crop residue burning period (April and May) at all the

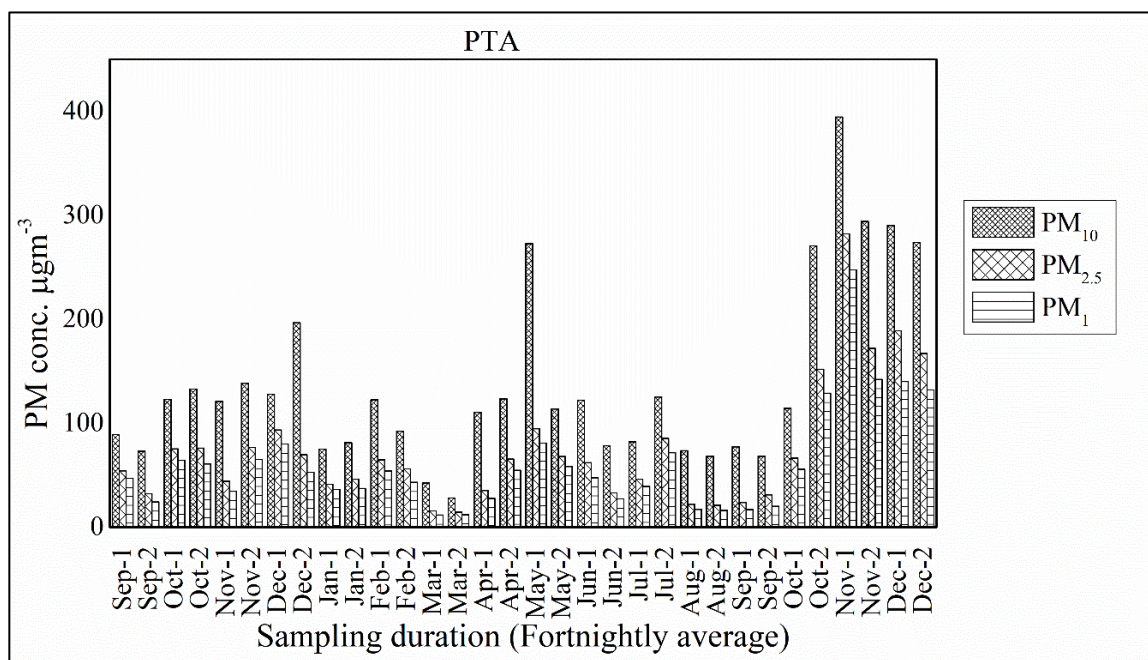


Figure 4.4 Particulate matter (PM₁₀, PM_{2.5}, PM₁) levels (Fortnightly averaged) at PTA site from Sep 2014 to Dec 2015

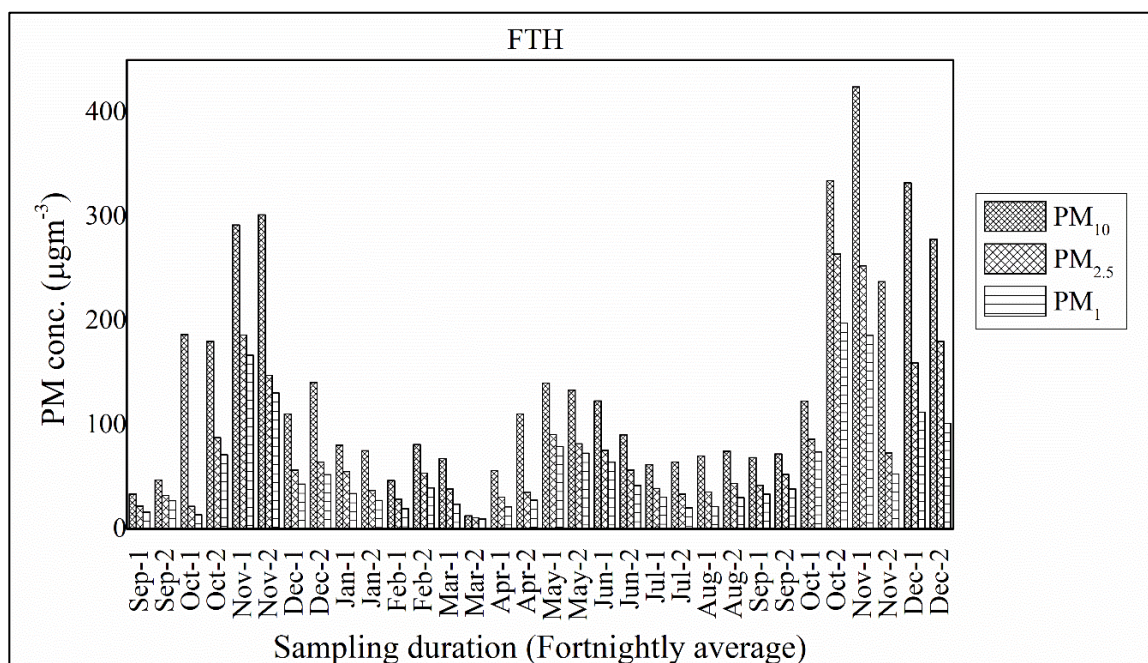


Figure 4.5 Particulate matter (PM₁₀, PM_{2.5}, PM₁) levels (Fortnightly averaged) at FTH site from Sep 2014 to Dec 2015

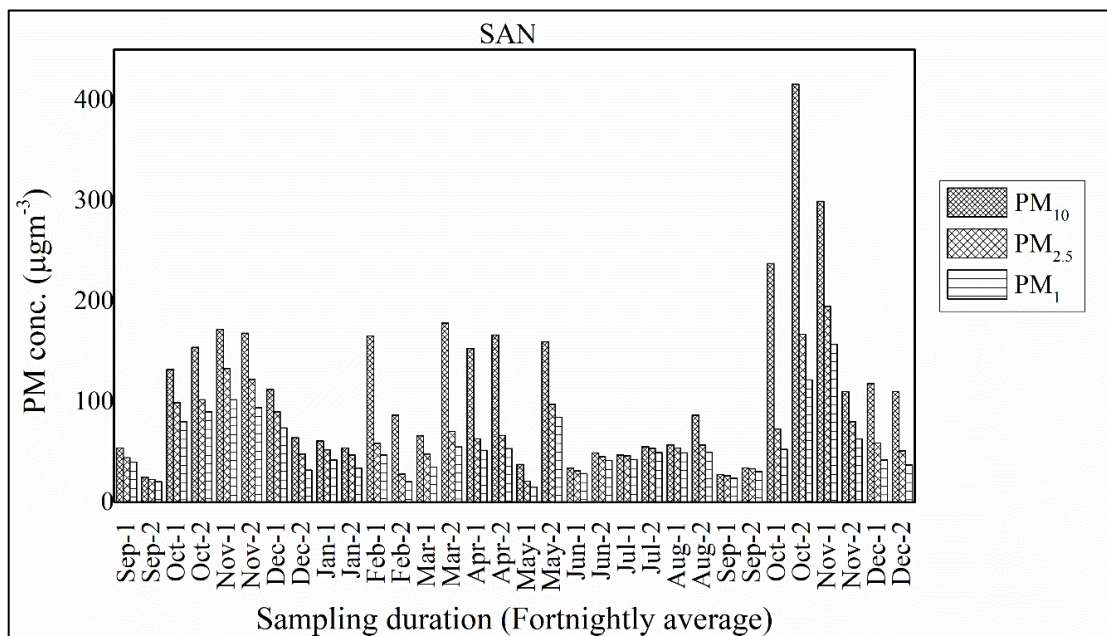


Figure 4.6 Particulate matter (PM₁₀, PM_{2.5}, PM₁) levels (fortnightly averaged) at SAN site from Sep 2014 to Dec 2015

three sites as compared to the rice crop residue burning (October and November). The higher bars indicate generation of bigger particles (PM₁₀) with respect to PM_{2.5} and PM₁ due to crop residue burning taking place at higher ambient temperature in the range of 35-40°C as compared to the rice crop residue burning happening at ambient temperature of 20 - 25°C.

4.3 Concentration levels of particulate matter

Table 4.1 shows the monthly average values for PM₁₀, PM_{2.5} and PM_{1.0} levels in ambient air of sampling sites in Malwa region. The overall monthly average concentration levels of PM₁₀, PM_{2.5} and PM₁ during the study period were 138 ± 31 , 86 ± 18 and 67 ± 17.2 (FTH site), 127 ± 30 , 76 ± 18 and 62 ± 16 (SAN site), 138 ± 44 , 73 ± 25 and 61 ± 23 (PTA site). The background concentration (Monthly average particulate matter levels for the period immediately before the onset of burning events) of PM₁₀, PM_{2.5} and PM₁ during the study period were 70 ± 20 , 41 ± 13 , 31 ± 11 (FTH site), 67 ± 28 , 46 ± 16 , 39 ± 14 (SAN site) and 85 ± 23 , 42 ± 36 and 33 ± 14 (PTA site).

Table 4.1 Particulate matter (PM₁₀, PM_{2.5} and PM_{1.0}) levels (monthly averaged) of in ambient air of three sampling sites of FTH, SAN and PTA

Sampling Site	Period of sampling	PM ₁₀	PM _{2.5}	PM ₁
FTH	BRCRBP 2014	40.1±9.4	27.0±7.4	21.5±7.8
	DRCRBP 2014	235.7±78.9	136.7±69.7	118.9±67.7
	ARCRBP 2014	101.4±30.3	53.0±11.6	39.0±10.8
	BWCRBP 2015	51.8±29.8	32.7±18.0	22.9±12.5
	DWCRBP 2015	136.6±4.9	85.9±6.3	75.8±4.5
	AWCRBP 2015	84.6±28.5	50.9±19.0	39.0±18.8
	BRCRBP 2015	71.1±2.5	43.2±7.0	30.6±7.2
	DRCRBP 2015	379.3±63.6	258.1±8.1	191.6±8.4
	ARCRBP 2015	305.0±38.2	169.6±14.7	106.6±7.6
SAN	BRCRBP 2014	39.4±20.5	33.4±15.4	30.1±13.7
	DRCRBP 2014	163.1±12.7	117.5±21.9	96.0±8.6
	ARCRBP 2014	72.8±26.5	59.3±20.6	45.5±19.5
	BWCRBP 2015	123.9±56.0	51.2±18.1	39.3±15.0
	DWCRBP 2015	162.8±4.9	81.8±21.9	68.9±22.1
	AWCRBP 2015	46.2±9.7	44.0±9.4	40.4±8.6
	BRCRBP 2015	51.3±26.6	42.5±15.1	38.3±13.1
	DRCRBP 2015	357.5±82.3	181.0±19.6	139.3±25.1
	ARCRBP 2015	114±5.6	55±5.6	39.5±3.5
PTA	BRCRBP 2014	81.2±11.3	43.1±15.6	35.0±16.3
	DRCRBP 2014	154.2±37.1	79.8±12.1	65.8±13.6
	ARCRBP 2014	92.6±21.1	51.9±10.5	42.4±8.2
	BWCRBP 2015	75.9±47.9	32.5±23.8	26.3±20.2
	DWCRBP 2015	193.1±112.5	81.2±18.8	69.5±15.9
	AWCRBP 2015	101.8±25.2	56.6±22.5	46.2±18.8
	BRCRBP 2015	71.6±11.2	24.4±8.6	17.4±4.5
	DRCRBP 2015	332.5±87.7	216.9±92.1	188.0±83.8
	ARCRBP 2015	282±11	178±16	136±6

*The values after ± indicate Standard Deviation;

Bold values indicate Particulate matter levels during both crop residue burning episodes.

* BRCRBP = Before Rice Crop Residue Burning Period

* DRCRBP = During Rice Crop Residue Burning Period

* ARCRBP = After Rice Crop Residue Burning period

* BWCRBP = Before Wheat Crop Residue Burning Period

* DWCRBP = During Wheat Crop Residue Burning Period

* AWCRBP = After Wheat Crop Residue Burning Period

As observed from the values, the average particulate matter concentration increased by 2 to 3 times as compared to the background values at almost all sites. It was observed that PM concentration (PM_{10} , $PM_{2.5}$ and PM_{10}) was much higher during rice crop residue burning periods as compared to the corresponding wheat crop residue burning periods.

The highest value of PM_{10} observed during the study period was $379 \mu g m^{-3}$ at FTH site during rice crop residue burning period in 2015. It was higher at the other two sites, $358 \mu g m^{-3}$ (at SAN site) and $333 \mu g m^{-3}$ (at PTA site), during same period probably due to relatively close proximity (about 1 km) from the national highway (NH-1) whereas, the sampling sites SAN and PTA were located deep in the rural areas, about 5-6 km and 10 km, respectively away from the state highway 10 (SH10).

The main reason for higher concentration of particulate matter during rice crop residue burning as compared to the wheat crop residue burning period was due to more quantity of rice crop residue offered to the burning events, as the wheat crop residues are also used as fodder for the cattle. A study done by National Remote Sensing Agency in Punjab reported that 13 Gg of PM_{10} and 12 Gg of $PM_{2.5}$ were produced by wheat crop residue burning during May 2005. Paddy straw/ stubble burning was estimated to contribute 30 Gg of PM_{10} and 28.3 Gg of $PM_{2.5}$ during October 2005 (**Badrinath et al., 2006**)³. Emissions from wheat crop residues in Punjab were also reported lower as compared to those from rice crop residue burning (**Mittal et al., 2009**)⁴. The contribution of episodic events of crop residue burning is likely to enhance respirable suspended particulate matter in indoor air also.

For the quantification of loading of particulate fractions, MODIS derived active fire counts have been analyzed for the Punjab region.

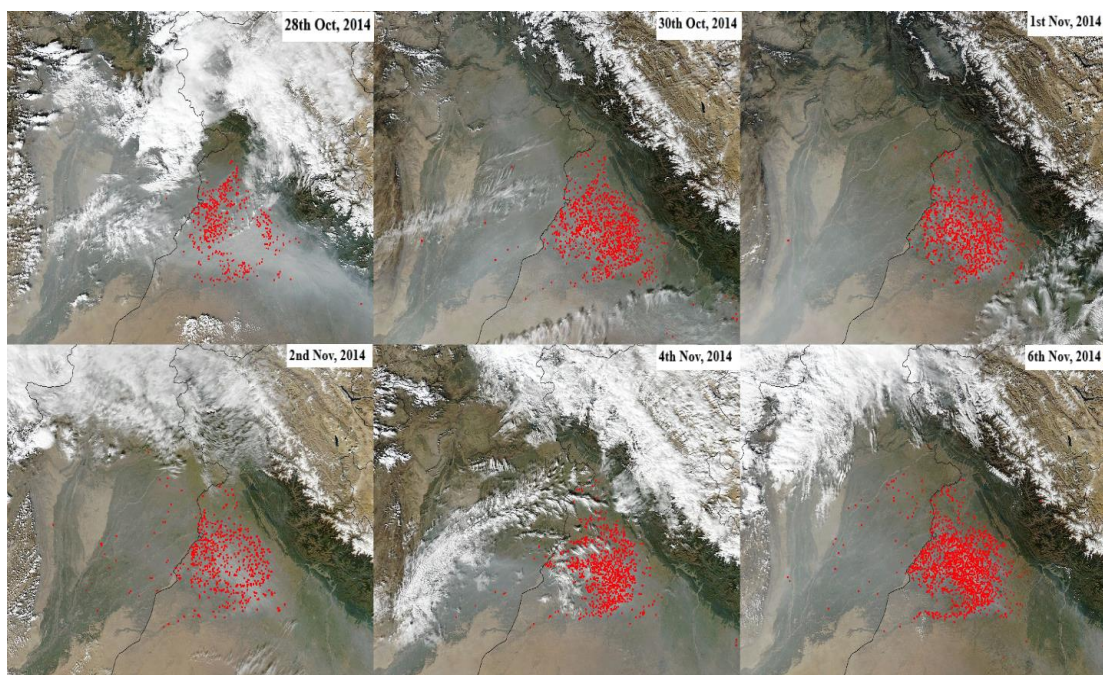


Figure 4.7(a) Terra MODIS true color composites showing intense agriculture crop residue burning (red color) and smoke over Punjab state, India during October and November, 2014

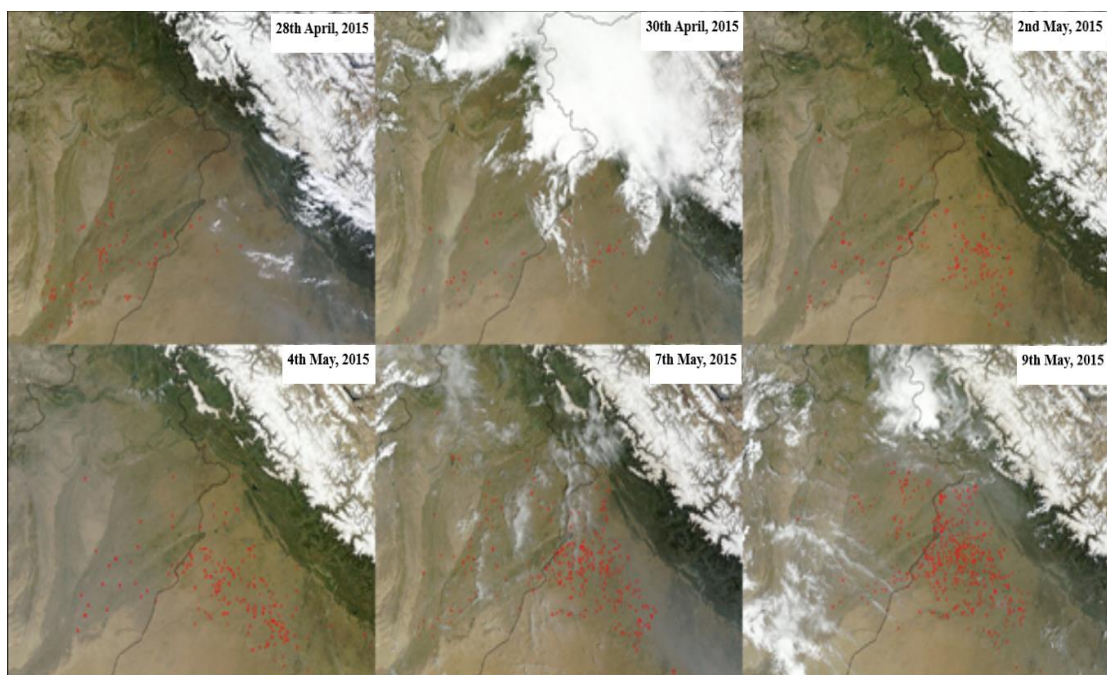


Figure 4.7(b) Terra MODIS true color composites showing agriculture crop residue burning (red color) and smoke over Punjab state, India during April and May, 2015

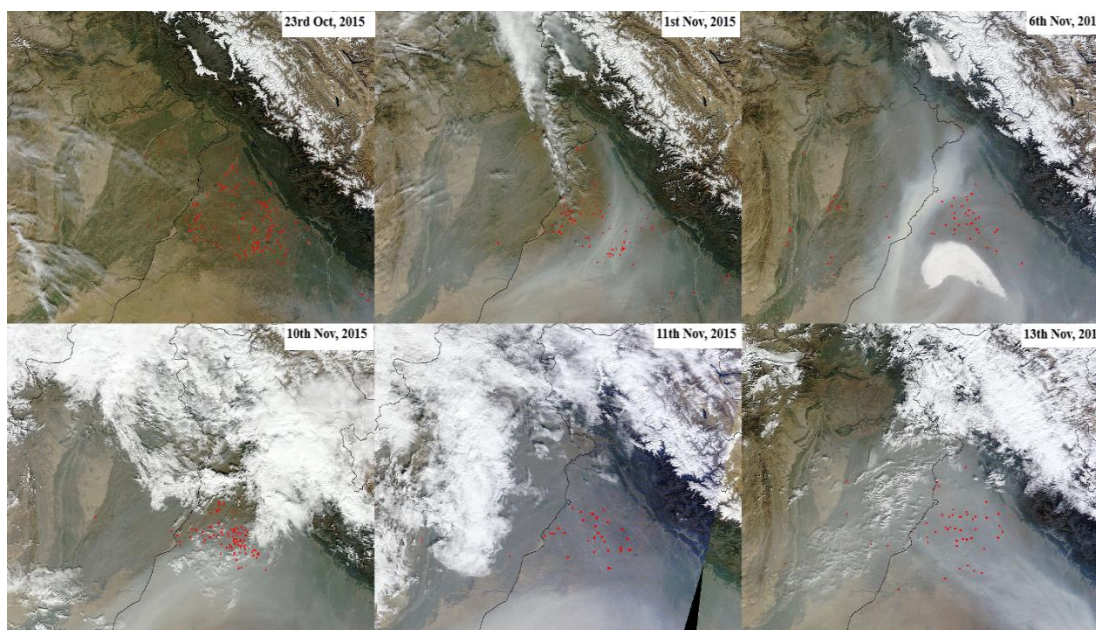


Figure 4.7(c) Terra MODIS true color composites showing intense agriculture crop residue burning (red color) and smoke over Punjab state, India during October and November, 2015

Figure 4.7 (a) shows the Terra-MODIS derived true color composite images on 28th, 30th October, 2014 and 01st, 02nd, 4th, 6th November, 2014 all over the Punjab region, India. For 2015, Figure 4.7 (b) represents the fire counts for wheat residue burning on 28th, 30th April, 2015 and 2nd, 4th, 7th, 9th May, 2015. Figure 4.7 (c) represents the fire count for rice crop residue burning period on 23rd October, 2015 and 1st, 6th, 10th, 11th, 13th November, 2015. Large number of fire counts and the smoke can be clearly seen from the images over Punjab due to rice residue burning in the fields during October and November, in 2015. The less smoke in 2014 represents the effect of rain as the images are clear. The less red spots in the month of May represents less burning in comparison to October and November months.

4.4 Descriptive analysis of school children from the sampling sites at PTA, FTH and SAN

Table 4.2 represents characteristics of the subjects from three different sites Patiala (PTA), Fatehgarh Sahib (FTH) and Sangrur (SAN). To collect the physiological parameters of human subjects for the present study, 162 students (94 males and 68 female) were selected from three schools. The average age of the children was 12 years varying between 9 to 15 years with average height and weight as 145 cm and 34 kg,

respectively. None of the children had a history of asthma respiratory or any other illness and were not on medication.

Table 4.2 Some important parameters of school children from the three sampling sites

Parameters	Sampling Sites		
	PTA	FTH	SAN
Male (Number)	20	36	38
Female (Number)	25	25	18
Average age (Years)	12	12	11
Mean Height (cm)	144	143	148
Mean Weight (Kg)	34	34	35
Mean BMI index	16.3	15.8	16.1
Symptoms of Asthma	Nil	Nil	Nil

All the subjects were students studying in 6-7 standards in schools. Preliminary questionnaire according to American Thoracic Society and European Respiratory Society were used for selection of subjects. Prior to testing, all subjects were questioned for their habits like smoking, health status, occupational and medical history. All the subjects selected were non-smokers (active and passive, both are excluded) and none of the subjects had any medical problem, respiratory illness or symptoms and are of North Indian ethnicity (Miller *et al.*, 2005)⁵. A significant decrease in Pulmonary Functions is observed during the crop residue burning periods.

4.5 Variations in FVC of male and female students at PTA, FTH and SAN sites due to crop residue burning events

As shown in Table 4.3, Forced Vital Capacity (FVC) shows noteworthy decrease at all the three sites during both the rice and wheat crop residue burning periods, which bring out the impact of the crop residue burning on the respiratory health of children. The male and female subjects were separately tested for forced vital capacity (FVC) test to check their lungs efficiency. In male subjects, (Figure 4.8 (a)), the value of FVC, decreases in the months of October and November, recovering back in the months of January and February.

Table 4.3 Forced vital capacity (FVC, percent predicted) values of male and female subjects from BRCRBP to DRCRBP, DRCRBP to ARCRBP and BWCRBP to DWCRBP, DWCRBP to AWCRRBP during the period of study (by using paired t-test) at rural sites SAN, PTA and FTH

Difference between Periods	Change in FVC (% predicted)					
	FVC (M)			FVC (F)		
	SAN	PTA	FTH	SAN	PTA	FTH
BRCRBP-DRCRBP	-9.2	-8.5	-6.5	-9.1	-5.9	-4.1
DRCRBP-ARCRBP	7.8	6.3	4.2	5.1	3.5	0.8
BWCRBP-DWCRBP	-7.5	-7.2	-3.8	-8.4	-4.5	-3.8
DWCRBP-AWCRBP	6.4	8.6	1.8	0.25	7.3	2.5
BRCRBP-DRCRBP	-12.2	-13.4	-9.2	-12	-13.7	-11.9
DRCRBP-ARCRBP	3.0	4.5	0.2	3.5	2.0	1.0

The values start decreasing in the second fortnight of April till first fortnight of May, which is wheat crop residue burning period. There is a gradual decrease in the FVC value, at all the three sites from first fortnight of September to second fortnight period of October. Although the rice crop residue burning was done in the second fortnight of October and first fortnight of November, the effect stayed till first fortnight of December at the PTA site, as the fine particulate matter remained suspended for much longer time period in the atmosphere. PTA site is a semi urban site with contribution from vehicular and industrial sources also.

The FVC of students at SAN site started increasing or recovered immediately after the burning period, as crop residue burning was the major source of particulate matter in the nearby area. At FTH site, there was a regular decrease in FVC of male subjects till second fortnight of October, which might be due to Rice crop residue burning in the nearby fields. Then there was a slight increase in the value of FVC, after which it increased sharply. However, it cannot be compared with other sites due to the prolonged effect till December.

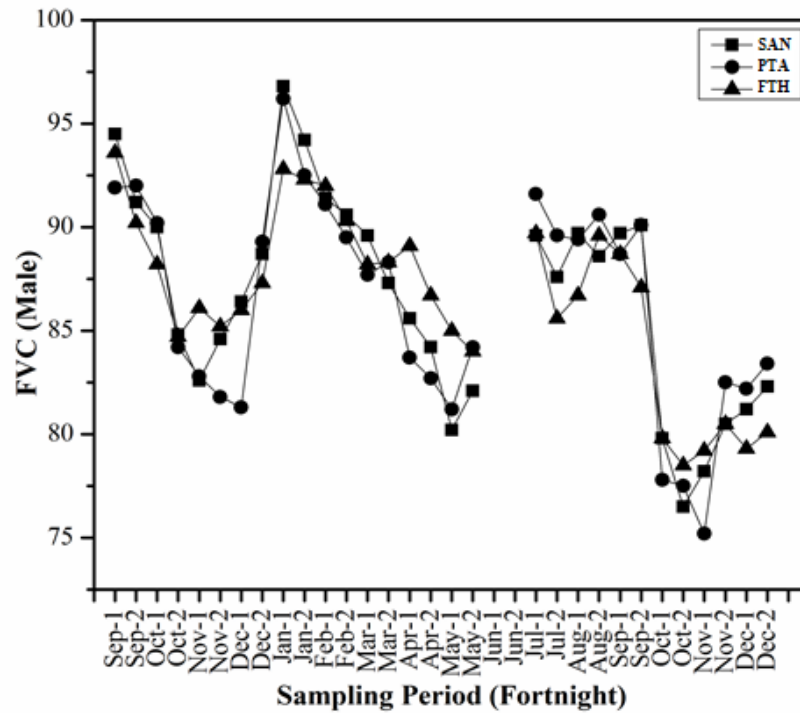


Figure 4.8(a) Forced Vital Capacity (FVC) values (fortnightly averaged) of male students at the three sampling sites

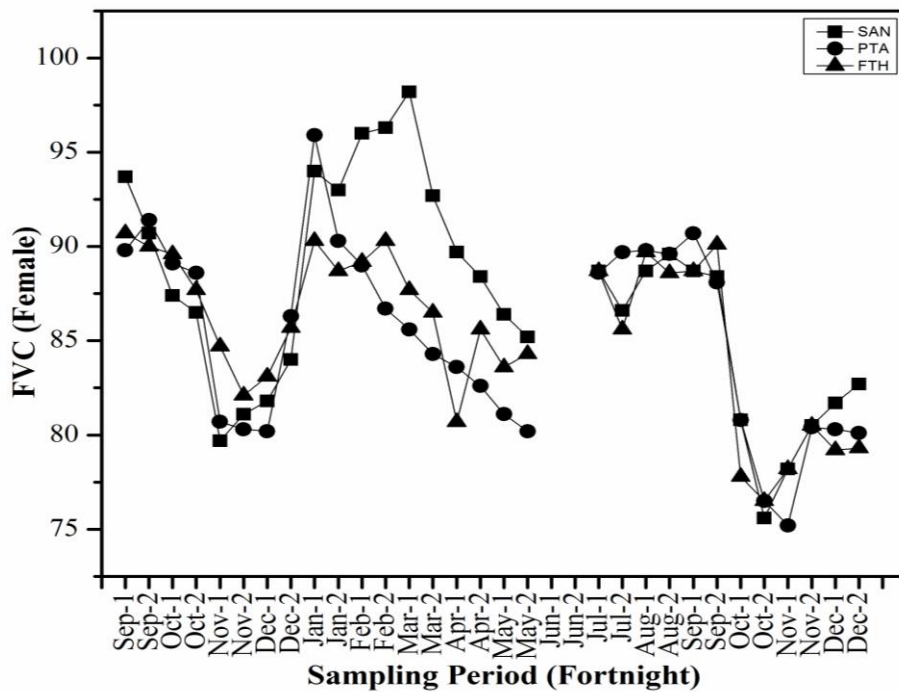


Figure 4.8(b) Forced Vital Capacity (FVC) values (fortnightly averaged) of female students at the three sampling sites

Then again, the FVC values decreased till May, which is wheat crop residue burning period. Fatehgarh sahib (FTH) site is located near the National Highway (NH1) due to which vehicular pollution also contributes to decreased lung efficiency along with seasonal biomass burning episodes. The PFT parameters for the month of June could not be recorded due to summer holidays in the schools.

The fall in FVC (male students) during RCBP in 2015 was greater by 9.2%, 8.8% and 7.4% more as compared to that in 2014 at SAN and PTA and FTH sites, respectively. This was directly related to PM_{2.5} levels that increased in 2015 as compared to that in 2014 by 54% in SAN, 171% in PTA and 88% in FTH sites. The decrease in particulate matter concentration during RCRBP in 2014 was due to washout of the pollutants from atmosphere by the rainfall (The days of rainfall were 1,2,3,4,5,6,8,9,12 in September and 8, 14 and 23 in October 2014). The data was retrieved from continuous ambient air quality monitoring station, installed at Thapar University, Patiala. FVC values of female students showed same pattern with a little decreased intensities, as depicted in Figure 4.8 (b).

4.6 Variations in FEV₁ of male and female students at SAN, PTA and FTH sites

Significant decrease in Forced Expiratory volume in 1 second (FEV₁) was observed during both the rice and wheat crop residue burning periods, as shown in Table 4.4. As the subjects in the study were school going children, who were in their growing phase of body, the early lung function deficits might increase the risk of acquiring chronic obstructive lung function diseases at later stage in life, as well as, increased cardiovascular morbidity (**Parsons *et al.*, 2013**)⁶.

The first row represents the change in percentage predicted of FEV₁ from before crop residue burning period to during crop residue burning period. Similarly, the second row represents the change in percentage predicted value of FEV₁ between during crop residue burning period and after crop residue burning period. The negative values of the FEV₁ indicate a decreased lung capacity to exhale as compared to the value of lung capacity during the preceding period. It can be seen that during the rice crop season, the respiratory health of school children (both male and female) is affected to a greater extent as compared to that during the wheat crop season. Male children are seen to be

affected to a relatively greater extent than the female students especially during rice crop season, probably due to their more exposure to outdoor environment.

Table 4.4 Changes in FEV₁ (percent predicted values) from BRCRBP to DRCRBP, DRCRBP to ARCRBP and BWCRBP to DWCRBP, DWCRBP to AWCRBP during 15 months of study (by using paired t-test) at rural sites SAN, PTA and FTH

Study periods	Change in FEV ₁ (% predicted)					
	FEV ₁ (M)			FEV ₁ (F)		
	SAN	PTA	FTH	SAN	PTA	FTH
BRCRBP-DRCRBP	-7.3	-4.8	-3.1	-9.0	-5.7	-2.9
DRCRBP-ARCRBP	9.2	4.6	2.4	5.8	2.8	1.8
BWCRBP-DWCRBP	-7.9	-4.5	-5.7	-6.5	-5.7	-5.4
DWCRBP-AWCRBP	5.7	5.2	7.3	5.8	9.1	5.6
BRCRBP-DRCRBP	-8.1	-7.3	-8.6	-9.6	-9.2	-6.7
DRCRBP-ARCRBP	1.3	1.0	1.7	2.7	1.7	3.0

The positive values of FEV₁ indicate improvement in the respiratory health as compared to that in the preceding period. Although the human body shows self-recovery of respiratory organs, yet the extent of recovery is always less than the damage. Hence, the cumulative effect of particulate pollution season after season result in a permanent damage of the respiratory health.

4.7 Ratio of FEV₁/FVC

Ratio of FEV₁/FVC < 70%, signifies an obstructive defect. Common examples of obstructive defects include chronic obstructive pulmonary disease (COPD) and asthma (Dijk *et al.*, 2015⁷; Bhatt *et al.*, 2019⁸). The FEV₁ can be expressed as a percentage of the predictive value which allows classification of the severity of the impairment. An FEV₁/FVC > 70%, is seen in restrictive defects such as interstitial lung diseases (e.g., idiopathic pulmonary fibrosis) and chest wall deformities. In our study, the value of FEV₁/FVC is always greater than 70%.

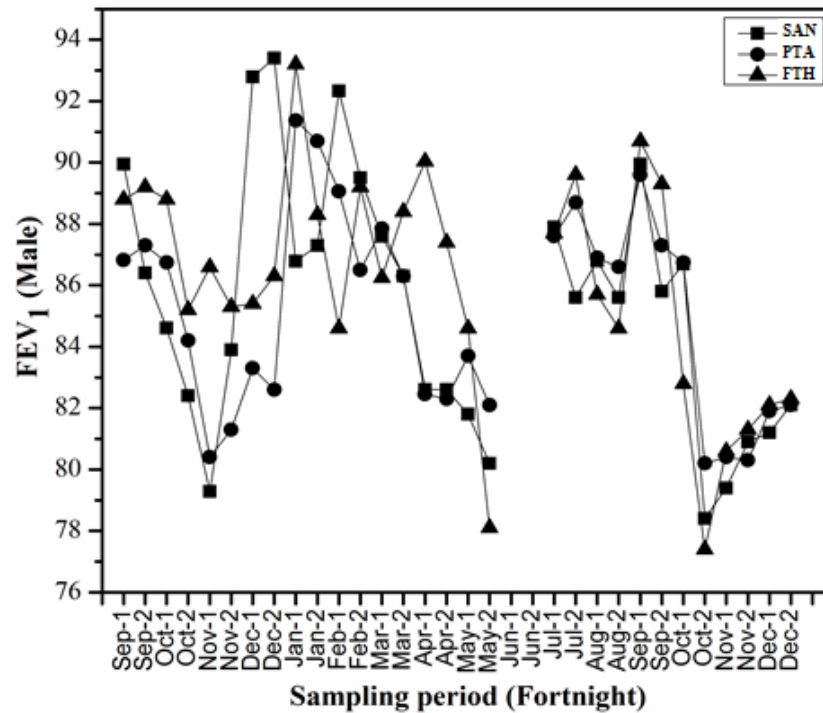


Figure 4.9(a) Forced expiratory volume-one second (FEV₁) value of male students at three sampling sites

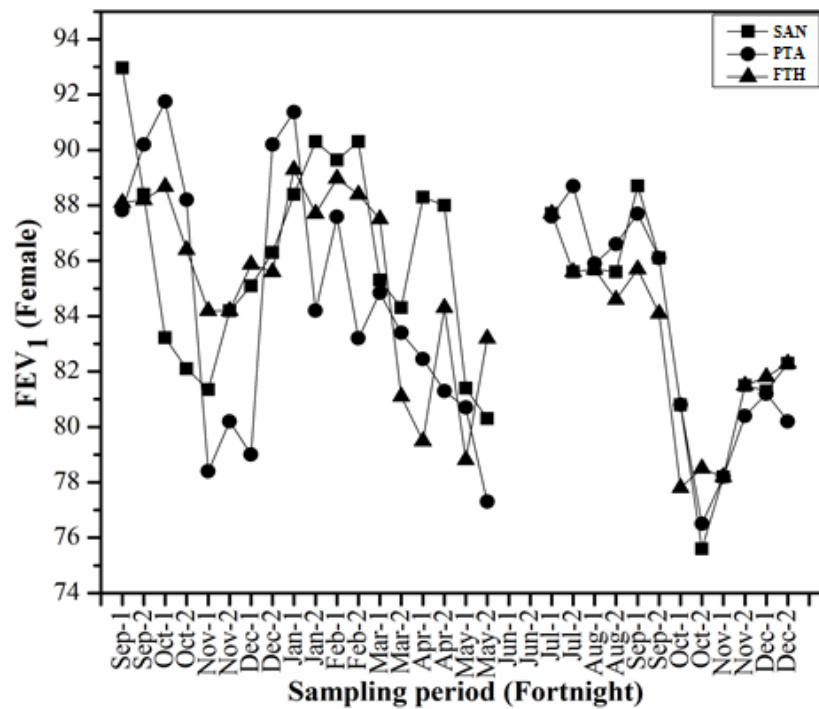


Figure 4.9(b) Forced expiratory volume-one second (FEV₁) value of female students at three sampling sites

rice crop residue burning period and indicating restrictive defects in the study population. The main reasons for restrictive lung diseases could be intrinsic (that occur due to the restriction in the lungs), extrinsic (that originate outside of the lungs), and neurological (central nervous system hinders the flow crucial to provide air into lungs).

4.8 Oxygen Saturation Level

Oxygen saturation (SpO_2) is defined as the ratio of oxyhemoglobin to the total concentration of hemoglobin present in the blood (i.e., oxyhemoglobin + reduced hemoglobin). Arterial oxyhemoglobin saturation measured non-invasively by pulse oximetry is called SpO_2 . Some studies have observed that pulse rate is associated with hypertension, coronary heart disease, and mortality (Gillman *et al.*, 1993⁹; Hjalmarson *et al.*, 1990¹⁰; Julius *et al.*, 1998¹¹), but associations with fine particulate matter were not documented.

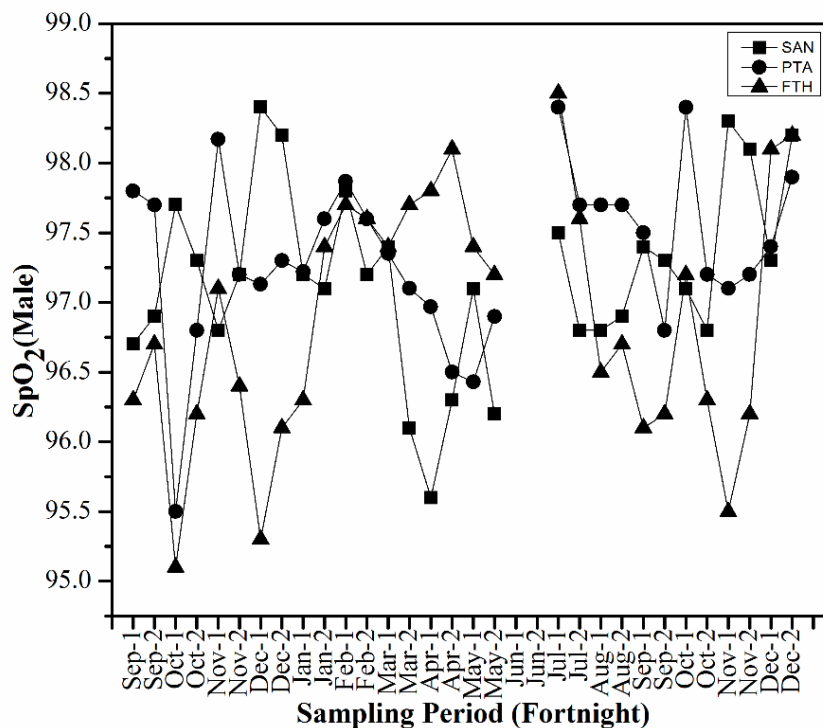


Figure 4.10(a) SpO_2 levels (fortnightly averaged) of male children recorded at sampling sites of SAN, PTA and FTH

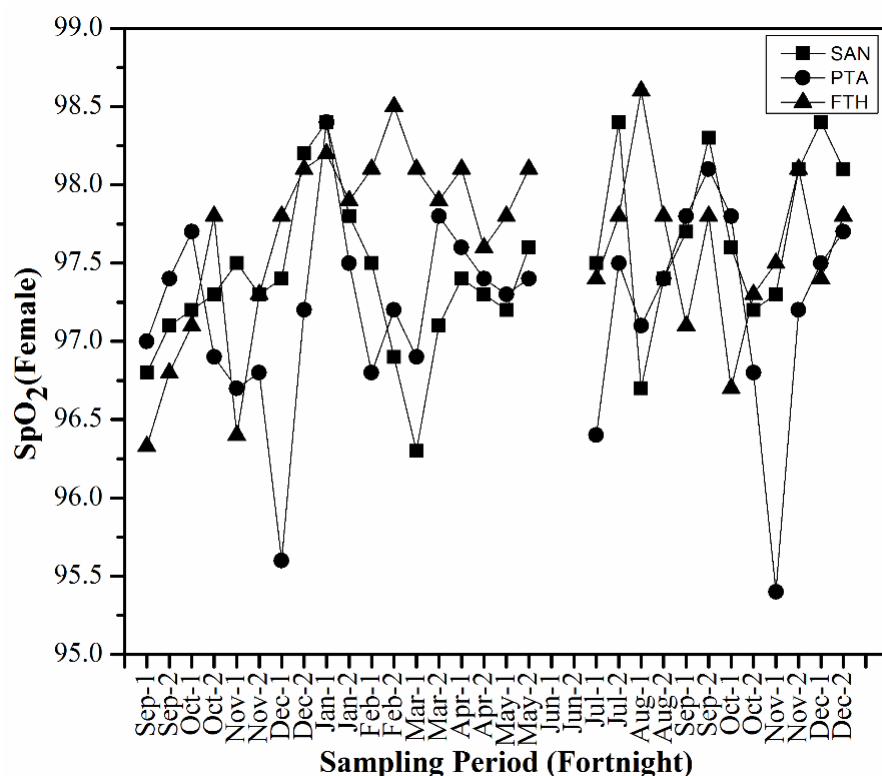


Figure 4.10(b) SpO₂ levels (fortnightly averaged) of female children recorded at sampling sites of SAN, PTA and FTH

No significant correlation have been observed between PM₁₀ and oxygen saturation level, however, SpO₂ of male students of PTA site and FTH site are found to be somehow correlated with PM₁₀ values only. Exposure to CO from crop residue burning could falsely raise the SpO₂ as oximeter cannot read carboxyhemoglobin (**Pope et al., 1999**)¹². Oxygen saturation of female students from all three sites were not found to be correlated with any of the particulate matter concentration value i.e., SpO₂ does not have any effect on girl population whose exposure time is less than the boys.

The SpO₂ value of not a single student was found to be lower than 90% during the sampling duration, thus no indication of pollution related hypoxemia. The average of all the students was always in the safe limit, i.e., above 95% limit.

4.9 Statistical correlation between PFT and Ambient Particulate Matter Levels

Associations between respiratory health parameters and particulate matter concentrations were analyzed by IBM SPSS Statistics 20. The results of pulmonary

functions and oxygen saturation levels in 162 children (94 male and 68 female) were analyzed, and correlated with different particulate matter concentrations at three different sites. As shown in Table 4.5, the physiological parameters like FVC (male), FVC (female), FEV₁ (male), FEV₁ (female) and SpO₂ (female) were all statistically negatively related to PM₁₀ with r value of -0.679, -0.663, -0.658, -0.468 and -0.484, respectively. Inferences have been drawn separately for each sampling site and are summarized in following points.

4.9.1 Correlation coefficient matrix for health parameters and particulate matter at PTA site

Table 4.5 Correlation coefficient matrix for health parameters and particulate matter concentration for PTA site from Sep, 2014 to Dec, 2015

	PM ₁₀	PM _{2.5}	PM ₁	FVC male	FVC female	FEV ₁ Male	FEV ₁ Female	SpO ₂ Male	SpO ₂ Female
PM ₁₀	1								
PM _{2.5}	.933**	1							
PM ₁	.925**	.999**	1						
FVC male	-.679**	-.654**	-.653**	1					
FVC female	-.663**	-.640**	-.640**	.932**	1				
FEV ₁ Male	-.658**	-.576**	-.565**	.794**	.855**	1			
FEV ₁ female	-.468*	-.463*	-.467*	.827**	.905**	.715**	1		
SpO ₂ Male	-.244	-.200	-.200	.155	.147	.254	.004	1	
SpO ₂ female	-.484**	-.573**	-.580**	.483**	.528**	.485**	.430*	-.158	1

**Correlation is significant at the p < 0.01 level (2-tailed).

*Correlation is significant at the p < 0.05 level (2-tailed).

†FVC = Forced Vital Capacity

‡ FEV₁ = Forced Expiratory Volume in 1 second

§ SpO₂ = Oxygen Saturation Level

Inferences

1. PM₁ is highly correlated with PM_{2.5} (r = 0.9) and PM₁₀ (r = 0.9) indicating the major fraction of the particulate matter is fine particulate matter. This could be explained as around 80% of particulate matter in biomass burning are < 0.1 µm.
2. Forced Vital Capacity (FVC) of male students shows negative correlation (r = -0.68) with PM₁₀ with slightly less correlation with lower size fraction, i.e. with

PM_{2.5} and PM₁ supporting the hypothesis that increased PM levels leads to fall in FVC.

3. Forced Vital Capacity (FVC) of female student's show almost same trend as with male subjects ($r = -0.66$) with PM₁₀. A little higher value indicate better resilience towards particulate matter pollution in comparison to male population, probably due to their longer stay indoors and less exposure to particulate pollution.
4. Forced Expiratory Volume in 1 second (FEV₁) of male students shows negative correlation ($r = -0.65$) with PM₁₀ and ($r = -0.57$) with PM_{2.5} and PM₁.
5. FEV₁ of female students is again less affected with particulate matter correlation ($r = -0.46$), due to the same reason.
6. SpO₂ on the other hand, showed more negative correlation with PM_{2.5} ($r = -0.57$) and PM₁ ($r = -0.58$) in comparison to its correlation with PM₁₀ ($r = -0.48$).
7. SpO₂ of both male and female students is not significantly dependent on particulate matter values, neither does it correlated to SpO₂ or FVC or FEV₁, significantly.

4.9.2 Correlation coefficient matrix for health parameters and particulate matter at FTH site

Respiratory health parameters like Forced vital capacity (FVC), Forced Expiratory volume in one second and oxygen saturation pressure recorded on human subjects of Fatehgarh site have been correlated separately for male and female human subjects with PM levels (PM₁₀, PM_{2.5} and PM₁) and presented in Table 4.6. PM pollutants in the range PM₁₀ deposit in the head airways while PM_{2.5} are likely to penetrate and deposit deeper in tracheobronchial and alveolar regions (**Brook *et al.*, 2004**)¹³.

The health parameter values were better correlated with PM_{2.5} as compared to PM₁₀. The correlations shown in Table 4.6, depicted the physiological parameters, FVC (male), FVC (female), FEV₁ (male), FEV₁ (female) and SpO₂ (female) were all statistically negatively related to PM₁₀ with r value of -0.726, -0.665, -0.608, -0.477 and -0.443, respectively.

Table 4.6 Correlation coefficient matrix for health parameters and particulate matter concentration for FTH site

	PM ₁₀	PM _{2.5}	PM ₁	FVC male	FVC female	FEV ₁ male	FEV ₁ Female	SpO ₂ Male	SpO ₂ female
PM ₁₀	1								
PM _{2.5}	.910**	1							
PM ₁	.905**	.990**	1						
FVC male	-.726**	-.701**	-.691**	1					
FVC female	-.665**	.687**	-.683**	.884**	1				
FEV ₁ Male	-.608**	.632**	-.625**	.762**	.674**	1			
FEV ₁ female	-.477**	.554**	-.554**	.773**	.858**	.571**	1		
SpO ₂ Male	-.443*	-.295	-.262	.255	.089	.139	-.016	1	
SpO ₂ female	-.240	-.262	-.314	.086	.131	-.015	.084	.172	1

**Correlation is significant at the $p < 0.01$ level (2-tailed).

*Correlation is significant at the $p < 0.05$ level (2-tailed).

Forced Vital Capacity (FVC) of male students was found to be more negatively correlated with PM₁₀ at FTH site as compared to other 2 sites indicating better respiratory health of the human subjects at Fatehgarh site as compared to those at other two sites as indicated from their respective BMI data (Table 4.2). As the particulate matter values were highest at the FTH site (might be due to combined effect of crop residue burning in the near fields and vehicular pollution effect from National Highway 1, in the near vicinity of the schools), the decrease in FVC and FEV₁ values of school children were more as compared to other two sites.

Following inferences can be drawn from the correlation data presented in Table 4.6

1. In general, the FVC of any human subject is expected to fall with increase in PM levels in the ambient air. Hence, related negatively with each other. Forced Vital Capacity (FVC) of male students is negatively correlated ($r = -0.72$) with PM₁₀ and also with both PM_{2.5} and PM₁ ($r = -.70$) while of female students is $r = -0.66$ with PM₁₀ and $r = -0.68$ with both PM_{2.5} and PM₁. FVC of female students is positively correlated ($r = 0.88$) to FVC of male students. This indicates greater

effect of PM pollution on male students as compared to the female students due to greater outdoor activities of boys than girls. The best correlation of FVC with PM is at FTH site.

2. Forced Expiratory Volume in 1 second (FEV₁) of male students show negative correlation ($r = -0.60$) with PM₁₀ and -0.63 with PM_{2.5} and PM₁.
3. FEV₁ of female students is poorly correlated ($r = -0.48$) with PM₁₀ and more -0.55 with both PM_{2.5} and PM₁ for the same reason as that for FEV values.
4. SpO₂ of female students is not significantly dependent on particulate matter values, neither does it correlated to SpO₂ or FVC or FEV₁. Hence, SpO₂ is very little related to PM levels for both male and female subjects.

4.9.3 Correlation coefficient matrix for health parameter and particulate matter for SAN site

Table 4.7 Correlation coefficient matrix for health parameters and particulate matter concentration for SAN site

	PM ₁₀	PM _{2.5}	PM ₁	FVC male	FVC female	FEV ₁ male	FEV ₁ Female	SpO ₂ Male	SpO ₂ female
PM ₁₀	1								
PM _{2.5}	.855**	1							
PM ₁	.812**	.991**	1						
FVC male	-.709**	-.650**	-.623**	1					
FVC female	-.595**	-.715**	-.696**	.805**	1				
FEV ₁ Male	-.537**	-.608**	-.613**	.696**	.536**	1			
FEV ₁ female	-.691**	-.736**	-.715**	.865**	.784**	.705**	1		
SpO ₂ Male	-.069	.146	.136	.007	-.227	.344	-.117	1	
SpO ₂ female	-.147	-.075	-.070	.053	-.246	.026	-.004	.197	1

**Correlation is significant at the $p < 0.01$ level (2-tailed).

*Correlation is significant at the $p < 0.05$ level (2-tailed).

The correlations show that FVC (male), FVC (female), FEV₁ (male), FEV₁ (female) and SpO₂ (female) were all statistically negatively related to PM₁₀ with r value of -0.709 , -0.595 , -0.537 , -0.691 and -0.484 , respectively (Table 4.7). FVC of male students was

slightly better correlated with PM_{10} concentration at PTA site than FVC of female students. Thus, pollution has more effect on male candidates of SAN site as compared to PTA site. FEV_1 of female students was higher as compared to PTA site. SpO_2 are not significantly correlated with any Particulate matter value. Thus, they does not depend significantly on particulate matter concentrations.

Inferences

1. PM_{10} shows correlation of 0.81 with PM_1 at SAN site, which is less than the PTA site. This indicates the higher fraction of particulate matter in PM_{10} in comparison to PTA site.
2. Forced Vital Capacity (FVC) of male students shows better correlation ($r = -0.70$) with PM_{10} at SAN site as compared to PTA site ($r = -0.68$).
3. Forced Vital Capacity (FVC) of female students shows negative correlation ($r = -0.60$) with PM_{10} , -0.71 with $PM_{2.5}$ and -0.69 with PM_1 , respectively. Thus, $PM_{2.5}$ and PM_1 affecting more as compared to coarse particulates. Exposure time of female population is more at SAN site in comparison to PTA site, accounting for slightly better correlation with fine fraction of PM.
4. Forced Expiratory Volume in 1 second (FEV_1) of male students show negative association ($r = -0.53$) with PM_{10} .
5. FEV_1 of male students show positive association ($r = 0.69$) with FVC of males.
6. FEV_1 of female students shows better correlation ($r = -0.69$) with PM_{10} than male population and ($r = -.73$) with $PM_{2.5}$ and ($r = -.71$) with PM_1 , respectively. This can be accounted by more exposure time of female population.
7. SpO_2 of both female and male students didn't correlated significantly with particulate matter concentrations.

Effectiveness of the study includes the supervised lung function tests, with many repeated observations per subject. It also decreases the within-subject variability, and the overall representative sample size with specific selection criteria of subjects (non-smokers, exclusion of respiratory disease subjects, subjects residing in same agricultural area). The harmful effect of Agriculture Crop Residue Burning on PFT of young and children have also been reported earlier (**Awasthi et al., 2011**)¹⁴. The fortnightly variation in values of PFTs of children from September 2014 to November 2015 are

shown in the Figure 4.8 and 4.9. Minimum of 2 samples per fortnight have been collected in non-burning season and three samples per fortnight during burning period. Fortnight average includes average of all the samples in first 15 days and 2nd fortnight includes average of next 15 days of the month. The pulmonary function tests were missing for the June month due to the summer holidays at all the three sites. So no samples were collected for the June months.

Figure 4.9(a) and 4.9(b) showed similar trend of decrease in FEV₁ values during wheat and rice crop residue burning period. Figure 4.10(a) and 4.10(b) represent the fortnightly averaged SpO₂ values of male and female subjects at the selected sampling sites, respectively. Concluding, these data show that pulmonary function of school going children, both male and female, are very sensitive to harmful effects of living in close vicinity of rural areas with crop residue burning in the fields.

The decrease in FVC of female students is nearly 6% less than FVC of male students with PM₁₀. In addition to the better health care by the females, this may be due to less exposure time of female students to the outdoor activities as compared to male students, throughout the day. Similarly, the decrease in FEV₁ of female students is around 12% less in comparison to male population. This was observed that boys have more extensive exposures because they are relatively active and spend more time outdoors and, therefore, are more affected by air pollutants. This finding is in accordance with a previous global studies indicating that chronic exposure to ambient air pollution was significantly associated with lower FVC and FEV₁ only among children with more outdoor activities (**Peters *et al.*, 1999**)¹⁵. Similarly, **Lee *et al.*, (2011)**¹⁶ reported greater effects of ambient air pollutants on pulmonary function for boys than for girls, whereas another study done on respiratory health of children examined the effect of motor vehicle exhaust from freeways showed more pronounced effect in girls than in boys (**Vliet *et al.*, 1997**)¹⁷. So overall, the pulmonary functions of females are more resistant to particulate matter concentrations as compared to male students.

4.10 Discussion

This study has served the purpose by identifying the problem of respiratory health linked to fine particulate matter levels in the ambient air, although pointed to a small

susceptible sample population at risk, school children. Early life environment appears to have more long lasting effects. Decrement in pulmonary function in childhood is serious health problem and should not be underestimated (**Holland *et al.*, 1969**)¹⁸, as small decrease in lung function parameters may have long term implications on the development of the chronic diseases later in life (**Bates, 1992**)¹⁹.

The reduction in lung functions (FVC and FEV₁) can be attributed to the higher particulate matter concentration in ambient air. Furthermore, there is a need for large scale observational epidemiological studies to identify the role of ambient air pollutants and its effect on respiratory health. For better understanding of effects of air pollution on lung function status, long term studies are required.

4.11 References

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CHAPTER 5

5. Source Apportionment

5.1 Concentration of PM₁₀ and its various components

For source apportionment, particulate matter (PM₁₀) was collected on glass microfiber filter which was extracted and analysed for metals (Al, Ti, Ca, Mn, Fe, Mg, V, Cr, Ni, Cu, Zn, Ba and Pb) and ions (Na⁺, K⁺, SO₄²⁻, Cl⁻, NO₃⁻). Table 5.1 represents the (average ± standard deviation) concentration of the chemical constituents of PM₁₀ mass fraction during different crop residue burning periods.

Table 5.1 Concentration of metals and ions (annual average) with respect to crop residue burning periods for PM₁₀ (µgm⁻³) at Patiala

Species (µgm ⁻³)	Average	Range	BRCRP	DRCRBP	ARCRBP	BWCRBP	DWCRBP	AWCRBP
PM ₁₀	126.02 ±38.96	56.30 ±320.32	145.75 ±31.92	131.00 ±49.84	106.29 ±28.89	116.76 ±25.72	125.83 ±32.42	97.45 ±39.89
NO ₃ ⁻	09.10 ±07.28	00.44 - 38.37	22.30 ±10.33	08.19 ±06.68	06.99 ±06.61	09.04 ±03.42	05.51 ±04.04	08.15 ±02.23
SO ₄ ²⁻	24.39 ±10.42	05.00- 55.98	29.55 ±14.78	24.97 ±10.80	21.80 ±10.70	23.19 ±07.72	26.58 ±07.44	21.64 ±14.52
Cl ⁻	07.07 ±05.47	00.08- 36.22	03.11 ±02.85	07.40 ±04.58	09.59 ±05.88	07.12 ±04.78	10.92 ±10.68	02.83 ±03.08
Al	02.00 ±02.26	01.25- 15.74	01.25± 00.00	01.44 ±00.63	01.25 ±00.00	01.25 ±00.00	01.25 ±00.00	01.25 ±00.00
Ti	00.06 ±00.03	00.05- 00.36	00.05± 00.00	00.05 ±00.00	00.05 ±00.00	00.05 ±00.00	00.05± 00.00	00.05± 00.00
Ca	01.57 ±01.44	00.05- 07.52	01.91± 00.69	01.25 ±00.80	00.83 ±01.53	01.01 ±00.66	01.45 ±01.23	01.15 ±00.47
Mn	00.05 ±00.02	00.05- 00.19	00.06 ±00.02	00.05 ±00.01	00.05 ±00.01	00.05 ±00.00	00.06 ±00.02	00.05 ±00.00

Fe	00.81 ±00.88	00.10- 05.46	00.91 ±00.47	00.50 ±00.33	00.34 ±00.43	00.59 ±00.41	00.76 ±00.62	00.35 ±00.29
Mg	00.67 ±01.10	00.00- 05.23	00.39 ±00.20	00.33 ±00.21	00.15 ±00.31	00.23 ±00.17	00.41 ±00.31	00.26 ±00.16
V	00.32 ±00.78	00.05- 04.81	00.06 ±00.03	00.11 ±00.12	00.06 ±00.02	00.05 ±00.00	00.07 ±00.04	00.05 ±00.00
Ni	00.21 ±00.44	00.05- 02.75	00.05 ±00.00	00.25 ±00.50	00.17 ±00.11	00.07 ±00.03	00.27 ±00.43	00.07 ±00.03
Cu	00.21 ±00.44	00.02- 02.75	00.04± 00.02	00.26± 00.49	00.17± 00.11	00.06± 00.04	00.27± 00.44	00.05± 00.04
Zn	01.23 ±01.65	00.02- 08.74	00.35± 00.29	01.18± 00.88	00.19± 00.37	00.66± 00.78	00.74± 00.94	00.71± 00.39
Ba	00.65 ±01.78	00.02- 09.78	00.05± 00.00	00.10± 00.15	00.07± 00.05	00.08± 00.08	00.04± 00.01	00.04± 00.02
Pb	00.14 ±00.11	00.05- 00.49	00.16± 00.10	00.22± 00.10	00.11± 00.11	00.10± 00.07	00.15± 00.13	00.06± 00.03
Na ⁺	10.16 ±07.15	00.20- 41.77	09.52± 07.90	07.96± 02.86	06.06± 02.68	07.21± 04.00	08.41± 04.59	10.05± 06.41
K ⁺	24.02 ±09.56	02.03- 59.29	27.11± 06.58	26.42± 08.99	25.23± 08.11	27.85± 05.70	24.26± 05.67	18.53± 09.26

5.2 PM₁₀ and K⁺

Figure 5.1 shows the temporal variation of PM₁₀ and K⁺ mass concentration for the complete sampling duration. The varying concentration of PM₁₀ shows the highest peaks for the month of November, starting from 12 November till 5 December. This period coincides with the rice crop residue burning period. The chemical composition of PM₁₀ in different phases are listed in Table 5.1. PM₁₀ mass concentration varied from 56.3 µgm⁻³ to 320.3 µgm⁻³, with an average concentration of 126.1 µgm⁻³ with standard deviation as 39.0 µgm⁻³ (Figure 5.1a). Mostly, the nighttime concentrations were greater than the corresponding daytime PM₁₀ mass concentration values.

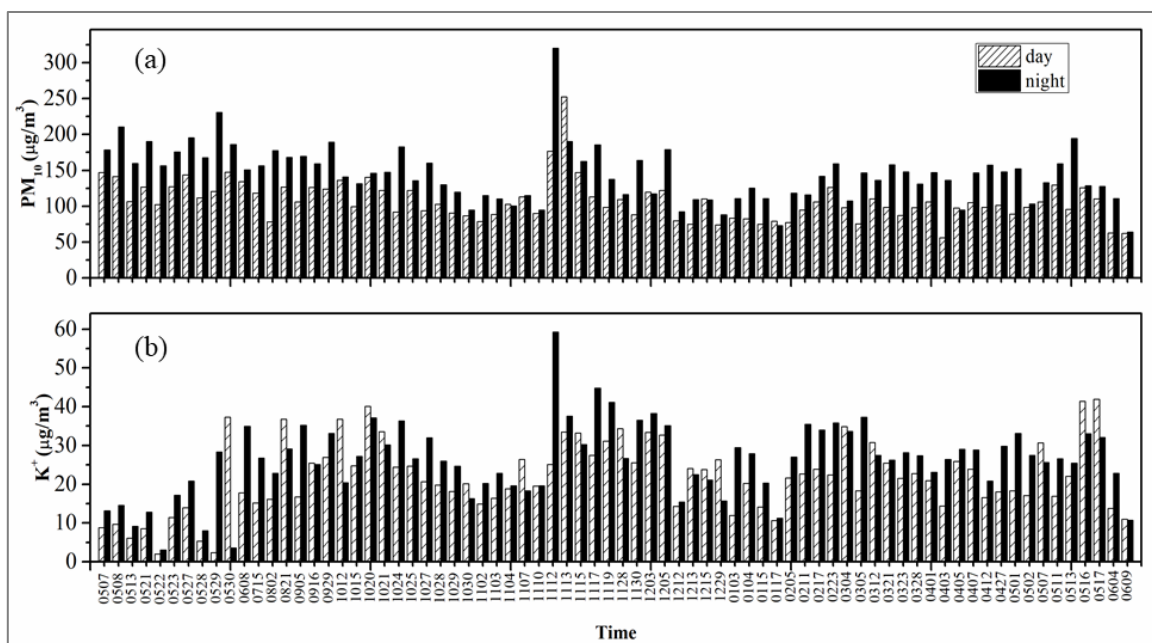


Figure 5.1 Daily variation (day and night) of (a) PM_{10} and (b) K^+ from May, 2015 to June, 2016

The lower boundary layer and nighttime burning events could be the main reason for overall increased night time concentration values. At present, crop residue burning is banned in many areas of Punjab, including Patiala city. Potassium ion (K^+) concentration levels were higher during the rice crop residue burning period indicating the clear source of potassium as rice crop residue burning (Figure 5b). Similar but less intense peaks were observed for wheat residue burning period. In India, K^+ has been used extensively as key elemental marker for biomass burning (**Khare and Baruah, 2010¹; Park *et al.*, 2013²; Thepnuan *et al.*, 2019³**). The reason for using K^+ concentrations as biomarker for crop residue burning activities lies with the application of fertilizers containing potassium chloride (KCl) as the most widely used source of potassium for wheat and rice crops (**Kafkafi *et al.*, 2001⁴**).

5.3 Factor profiles

Positive Matrix Factorization (PMF) model was run numerous times randomly on the data collected for PM_{10} samples, with varying number of factors, bootstrap and F_{peak} to obtain optimum factor resolution and factor composition. The final model results were obtained with 500 number of runs and F_{peak} of -0.1. Five factors were recognized as outcome of the model. The samples to species ratio was 1:8.2 which far exceeds the minimum variable.

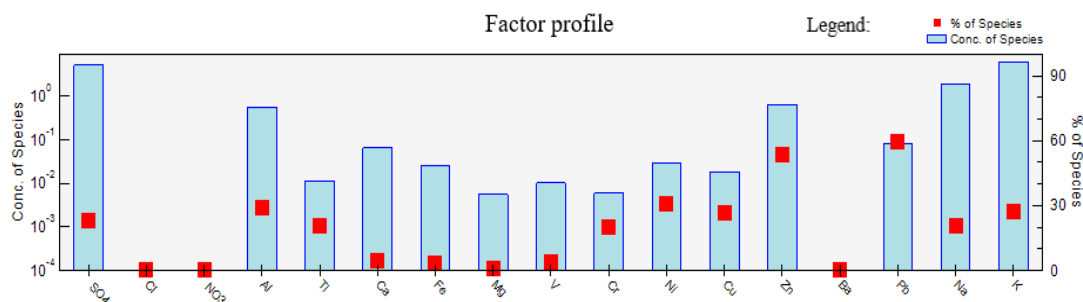


Figure 5.2(a) PMF extracted source profile for Vehicular emissions (Pb, Zn, Ni, Cu) as Factor 1 and temporal variation to PM₁₀ (Concentration in $\mu\text{g m}^{-3}$)

Factor analysis results have shown that factor 1, designated as vehicular emissions (Figure 5.2 (a)) by observation of major contributors (Pb, Zn, Cu, and Ni) with highest contribution from lead and zinc, combined contribution of 35% concentration at receptor site. Same species were identified as elemental markers for vehicular emissions by **Almeida *et al.*, (2006)⁵**; **Begum *et al.*, (2011)⁶** and **Crawford *et al.*, (2007)⁷**. Aluminium, titanium and chromium have also shown significant share in factor 1 (vehicular emission origin) (**Gadkari and Pervez, 2007⁸**). Trace metals like Cu and Zn are most likely derived from brake and clutch linings and tyre wear (**Thorpe and Harrison, 2008⁹**). Non exhaust emissions (from brake wear, tyre wear, road wear and resuspension) were 6 times higher than exhaust emissions in Delhi (**Singh *et al.*, 2020¹⁰**).

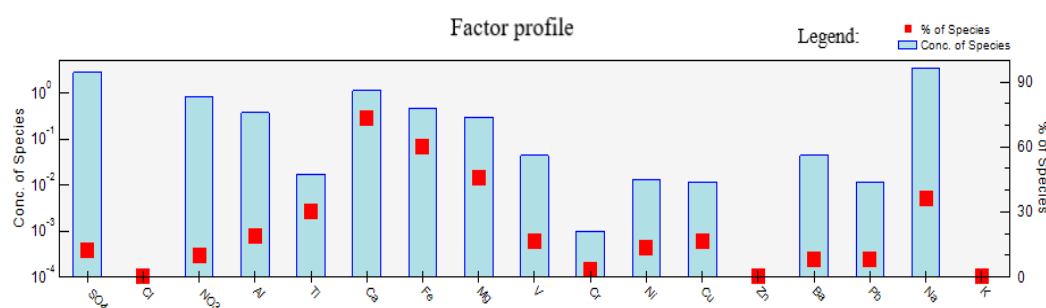


Figure 5.2(b) PMF extracted source profile for Resuspended road dust (Ca, Fe, Mg, Ti) as Factor 2 and temporal variation to PM₁₀ (Concentration in $\mu\text{g m}^{-3}$)

Figure 5.2 (b) represents the second factor which was identified as resuspended road dust. The major crustal elements that represents soil dust were Ca, Fe, Mg, Ti. The studies conducted by **Chakraborty and Gupta, (2009)¹¹**; **Shridhar *et al.*, (2010)¹²**; and **Srimuruganandam and Nagendra, (2011)¹³** have identified a whole array of elements including Al, Si, Ca, Ti, Fe, Pb, Cu, Mg and V as tracers for resuspended road dust. Calcium

can be from the cement dust, which gets settled on the ground over the period of time as construction work was going on near the sampling site that could be the single largest source of calcium. High abundance of iron might be from the wearing of brake discs and drums from high abrasion of particles generated by road traffic (Gietl et al., 2010)¹⁴.

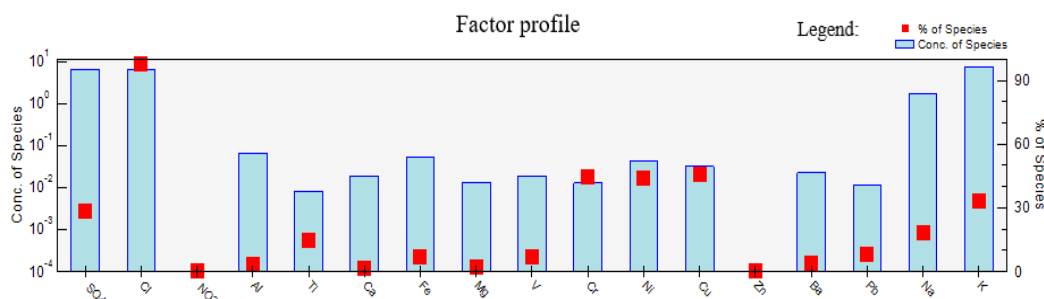


Figure 5.2(c) PMF extracted source profile for Biomass burning (K^+ , Cl^-) as Factor 3 and temporal variation to PM_{10} (Concentration in $\mu g m^{-3}$)

Third factor was identified as the biomass burning (Figure 5.2(c)). Soluble K^+ has been used as key elemental marker for biomass burning/wood combustion in India for TSP, PM_{10} and $PM_{2.5}$ (Khare and Baruah 2010¹; Park et al., 2013²; Rastogi et al., 2014¹⁵). Biomass burning contributed around 21.2 % in PM_{10} contribution, which is comparable to many source apportionment studies in various regions (Dumka et al., 2018¹⁶; Bikkina et al., 2019¹⁷; Jain et al., 2018¹⁸). Molar ratio of K/Na from 0.6 to 2.9 was reported for burning of different types of crop residues (Le Canut et al., 1996¹⁹). The molar ratio of potassium to sodium for the third factor (1.79) indicates presence of the sodium and potassium at receptor site from same source of crop residue burning which is comparable to another study (Singhai et al., 2017)²⁰.

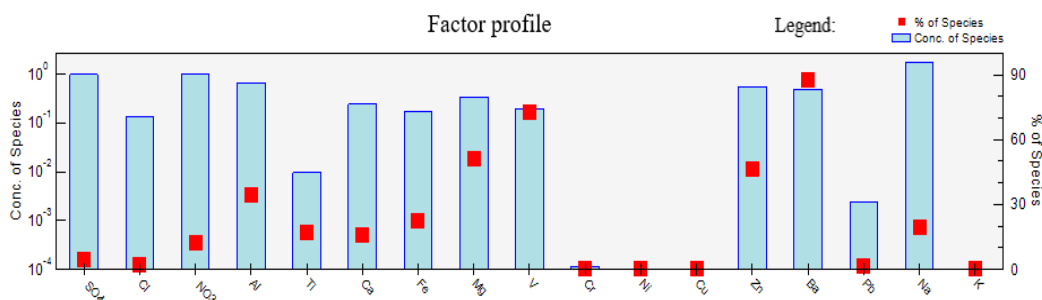


Figure 5.2(d) PMF extracted source profile for Industrial emission (V, Mg, Ba, Zn) as Factor 4 and temporal variation to PM_{10} (Concentration in $\mu g m^{-3}$)

Figure 5.2 (d) shows the fourth factor profile which was identified as industrial emission. Mg may be from coal combustion. Vanadium (V) might be from textile industry emission (Negi *et al.*, 1987)²¹ or from lead acid/nonferrous industry (Mouli *et al.*, 2006)²². Ba was most probably from brake parts of vehicles or construction activity (Wei *et al.* 2019). Zn and Fe were identified as markers for steel industry (Lestari and Mauliadi, 2009²³; Tauler *et al.*, 2009²⁴).

The species associated with fifth source are NO_3^- , SO_4^{2-} , K^+ which were characterized as secondary aerosols, including secondary nitrate and secondary sulfate (Figure 5.2(e)). This source accounts for almost 16 % to PM_{10} mass. Sulfate (SO_4^{2-}) and nitrate (NO_3^-) particles come from their primary precursor gases SO_2 and NO_x . Secondary aerosols can be formed anthropogenic or natural sources. Some studies have shown combustion as major source for sulfate aerosols (Kumar *et al.*, 2001)²⁵. Lead (Pb) could be from construction activities going on in campus.

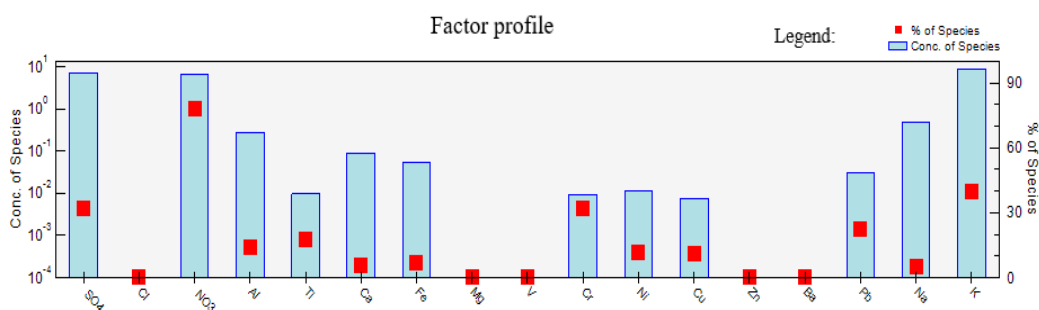


Figure 5.2(e) PMF extracted source profile for Secondary aerosol (NO_3^- , SO_4^{2-}) as Factor 5 and temporal variation to PM_{10} (Concentration in $\mu\text{g m}^{-3}$)

5.4 Source contribution in daytime and nighttime

Investigation of daily factor contribution from PMF showed difference in magnitude in daytime and nighttime observations as shown in Figure 5.3 (a) and (b). Daytime samples were collected from 7 am in the morning to 7 pm in the evening at roof top of three story building. Night time samples were collected from 7 pm in the evening to 7 am in the morning at the same location using same instrument.

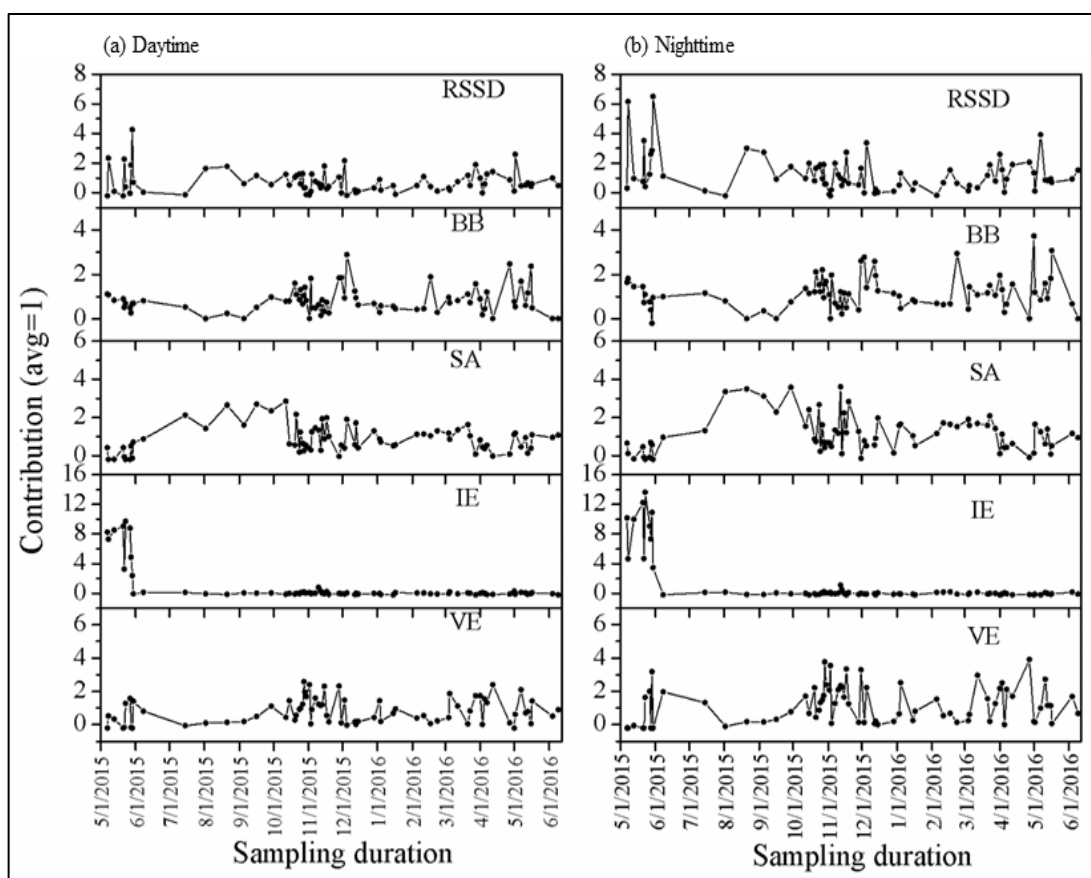


Figure 5.3 Monthly source contribution analyzed from the PMF analysis of PM₁₀ in (a) Daytime and (b) Nighttime time period

The difference in magnitude clearly shows night time values to be more aggravated than day time contributions as boundary layer drops to almost 500 meters at night. As the day advances, solar heating causes a convection that increases the height of the mixed layer and thus reduces the species levels (**Rastogi et al., 2014¹⁵; Singh et al., 2014²⁶**). All atmospheric particles have shown effect of compression or expansion of mixing layer height irrespective of their primary or secondary origin in the atmosphere.

It was observed that concentration from vehicular source was particularly high in winter season as compared to other seasons. Biomass burning also contributed during this period and calm winds and low mixing height creates an atmosphere for less dispersion and emissions from various vehicles get entrapped in the atmosphere. Industrial emissions were almost constant throughout the year except the sudden increase during summer months of May 2015. Higher boundary layer during this period along with strong winds might be the

contributing factors. Secondary aerosols shown high values during July, August and November months (monsoon season). Table 5.2 summarizes the percentage contribution of different variables in identified five different sources.

Table 5.2 Contribution of species in different source profiles for PMF

Species	RSSD	BB	SA	IE	VE
SO₄²⁻	12.3	28.7	31.9	4.3	22.8
Cl⁻	0.0	98.0	0.0	2.0	0.0
NO₃⁻	9.7	0.0	78.0	12.3	0.0
Al	18.8	3.4	14.0	34.7	29.1
Ti	30.0	14.7	17.5	17.1	20.7
Ca	73.1	1.2	5.8	15.7	4.2
Fe	60.4	6.8	7.0	22.4	3.4
Mg	45.8	2.0	0.0	51.4	0.8
V	16.2	7.0	0.0	73.0	3.8
Cr	3.3	44.3	31.8	0.4	20.2
Ni	13.3	43.9	11.9	0.0	30.8
Cu	16.6	45.9	11.0	0.0	26.5
Zn	0.0	0.0	0.0	46.4	53.6
Ba	8.0	4.0	0.0	87.9	0.0
Pb	8.3	8.2	22.5	1.8	59.2
Na⁺	36.5	18.3	5.1	19.3	20.9
K⁺	0.0	32.9	40.0	0.0	27.1

5.5 Backward air trajectories (HYSPLIT)

The 7 day backward air trajectories were produced using Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model from National Oceanic and Atmospheric Administration (NOAA) Air Resource Laboratory (ARL) (**Draxler and Hess, 1998**), shown in Figure 5 (a, b, c and d). The starting point of the trajectories is continuous ambient air monitoring station (30.35 N, 76.37 E) at Thapar Institute of Engineering and Technology,

Patiala. Each trajectory was computed for 168 hour back in time with a starting height of 500 meters, i.e., the minimum starting height for air mass was set up as 500 meters. The previous studies in India used lower starting height for biomass burning, mostly below ~2 km (Badarinath *et al.*, 2009²⁷; Kaskaoutis *et al.*, 2014²⁸; Mishra and Shibata, 2012²⁹). So, with reference to that, two heights were selected as 500 meters and 1000 meters. Backward trajectories show the long range transport from higher elevation than 5000 meters from west Asia across Afghanistan and Pakistan and local transport of air mass for 500 meters from Pakistan.

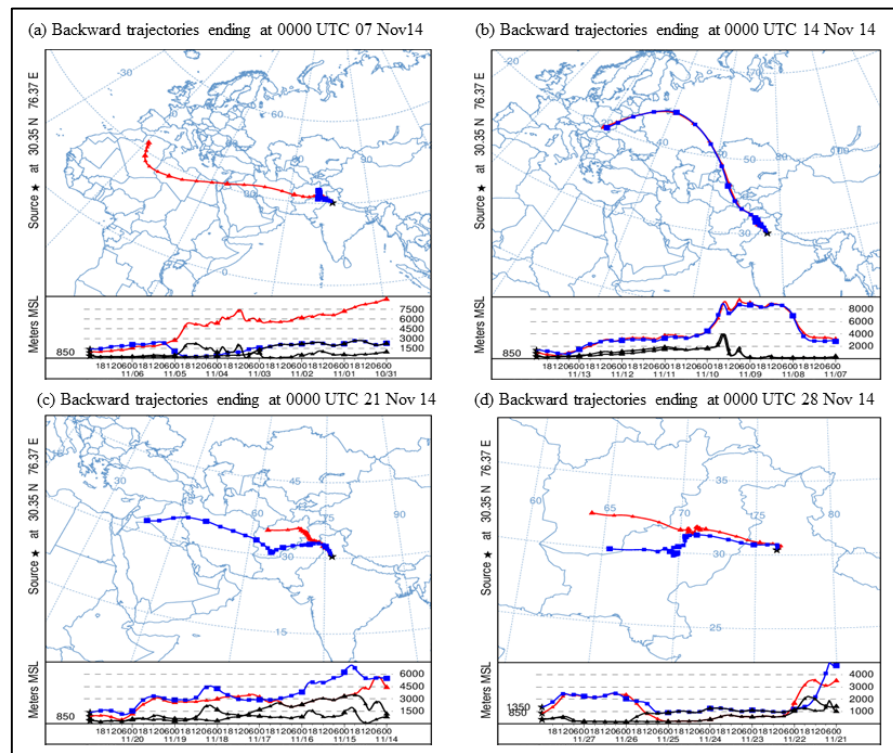


Figure 5.4(a) 168 hour backward trajectories for the month of November, 2014 using HYSPLIT model from NOAA ARL

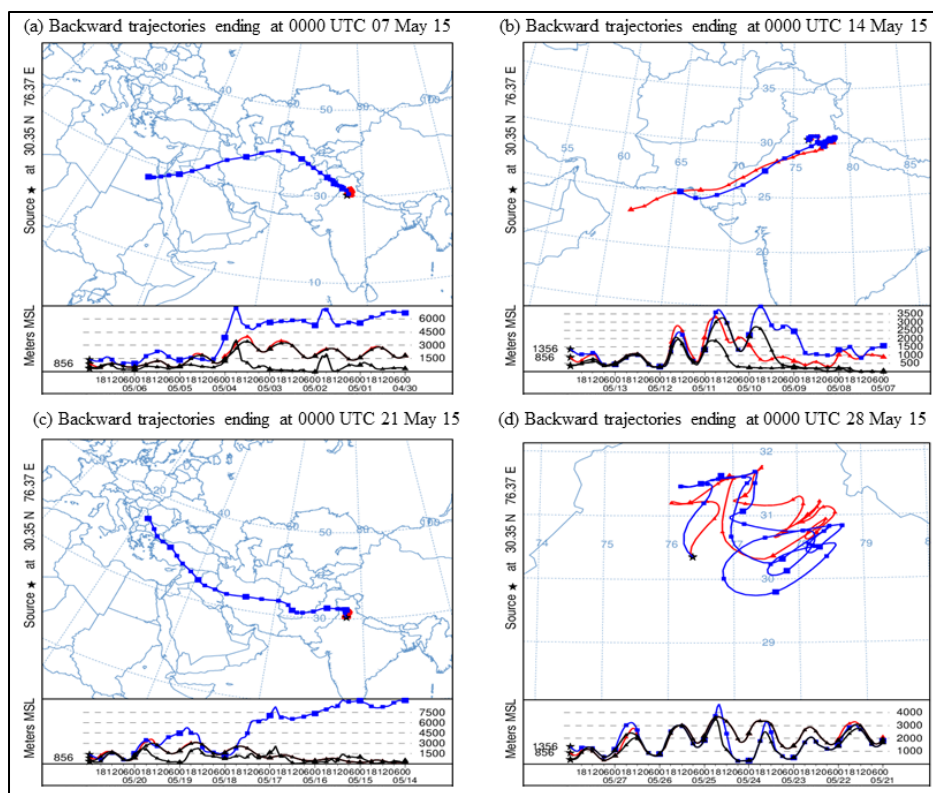


Figure 5.4(b) 168 hour backward trajectories for the month of May, 2015 using HYSPLIT model from NOAA ARL

During the wheat crop residue burning period, the temperatures are generally high during April and May month in India, which leads to higher boundary layer and Figure 5.4(b) and Figure 5.4(d) represents the backward trajectories for the period of May, 2015 and May, 2016, respectively. This period majorly represents localized or regional transport of air masses. This could also be reason for decreased levels of PM emissions during wheat crop residue burning period as compared to rice crop residue burning period. Similar localization of air masses during this period was observed during May, 2016 (Figure 5.4(d)) except for last week of May, 2016. Backward trajectories indicated that PM₁₀ concentrations during the wheat crop residue burning period were majorly from local sources whereas air masses from north western direction during rice crop residue burning period show contribution from neighboring countries.

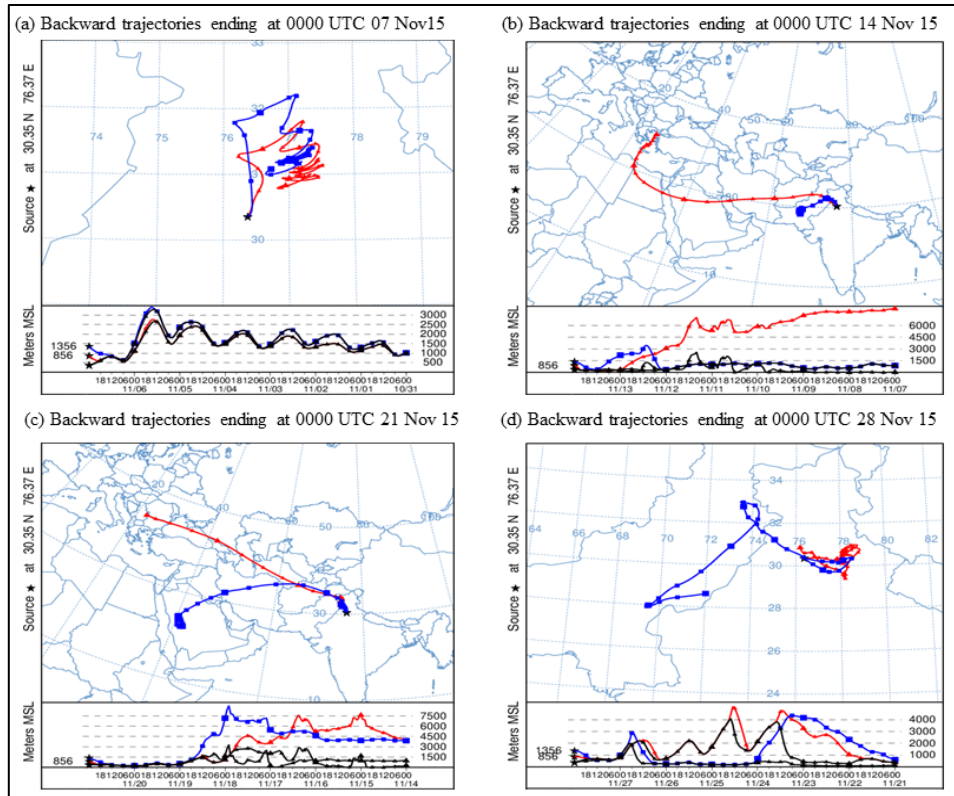


Figure 5.4 (c) 168 hour backward trajectories for the month of Nov, 2015 produced using HYSPLIT model from NOAA ARL

Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Aqua satellite shows haze and red spots indicating fires over the IGP region every year. Most of the red spots (fires) indicated burning near the sampling sites. Images for different biomass burning periods were shown in Figure 4.7(a), 4.7(b) and 4.7(c) in section 4.3 of Chapter 4. MODIS satellite data for both TERRA and AQUA satellites were obtained from NSIDC (National Snow and Ice Data Center).

5.6 Fire count

Figure 5.5 represents the area under fires by fire counts data (at >50% confidence interval) during wheat and rice crop residue burning period in the proximity of the study area (28°N -32°N latitude and 72°E- 78°E longitude). Sharp rise in peaks were observed during the rice crop residue burning period i.e., from 15 October to 15 November with smaller peaks during wheat crop residue burning period (15 April to 15 May). Emissions during this time period contributed to the Second largest source of PM₁₀, i.e., biomass burning.

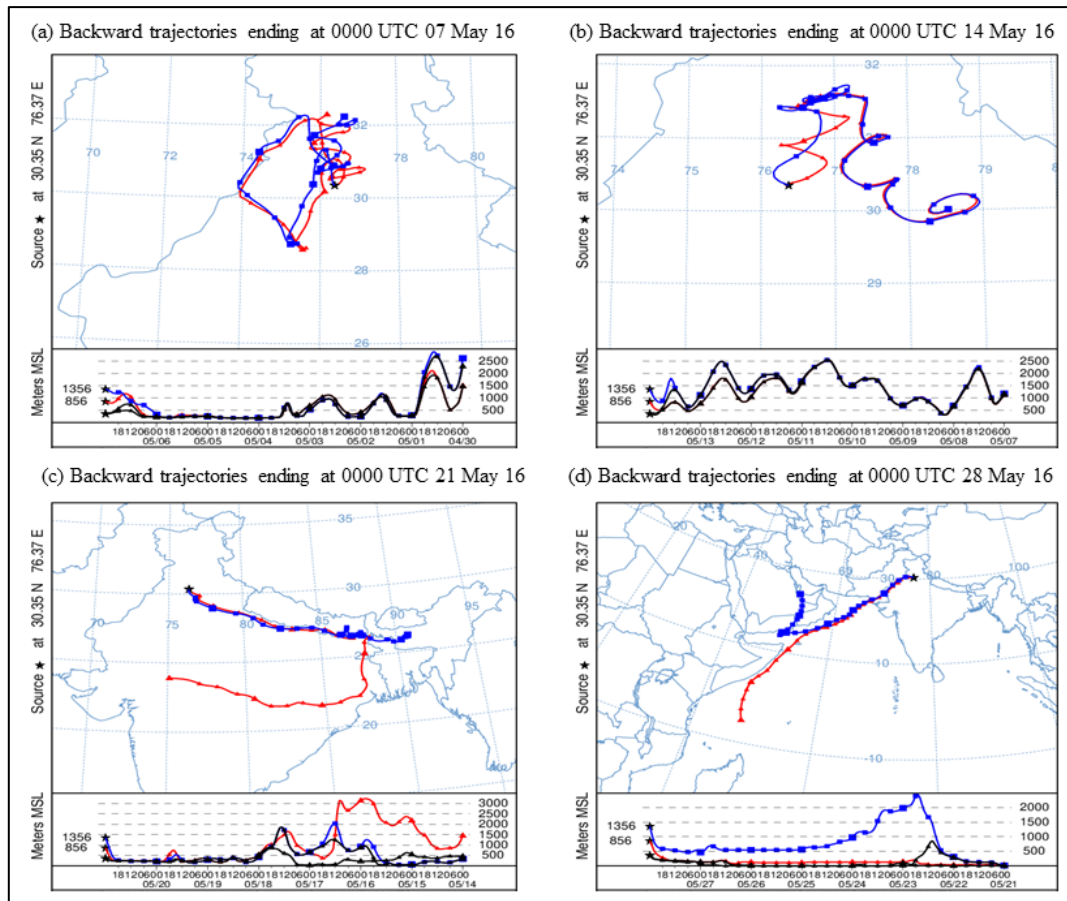


Figure 5.4(d) 168 hour backward trajectories for the month of May, 2016 produced using HYSPLIT model from NOAA ARL

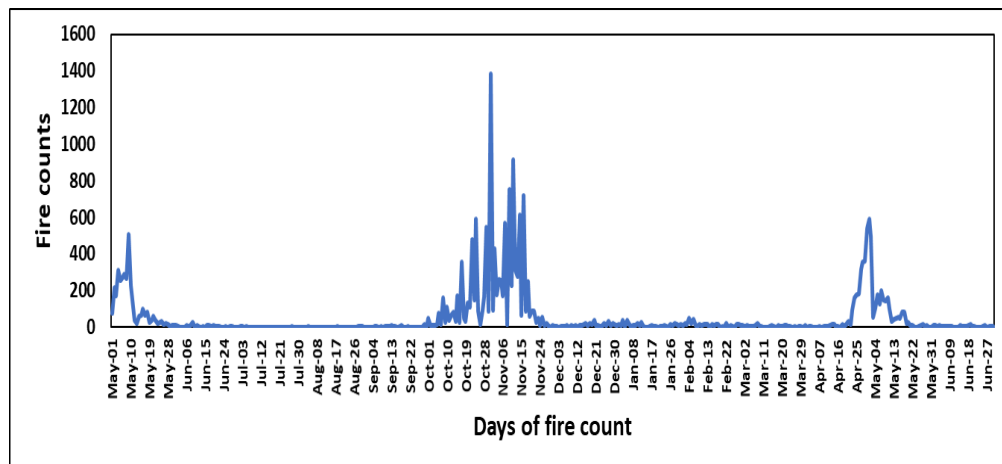


Figure 5.5 Daily fire count in the area grid of 28°N - 32°N latitude and 72°E- 78°E longitude

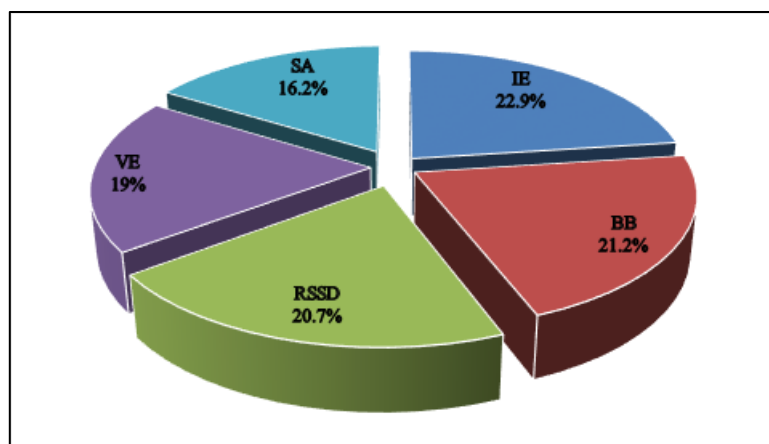


Figure 5.6 Source apportionment of PM₁₀ mass (IE = Industrial emissions; BB = Biomass burning; RSSD = Resuspended soil dust; VE = Vehicular emissions; SA = Secondary aerosols) at Patiala estimated by PMF

5.7 Conclusion and Future recommendation

To know the contribution of various sources of PM₁₀, at the sensitive receptor location, Positive Matrix Factorization (PMF) has been applied. The major results of the source apportionment study are summarized as follows:

- The measured species mass concentration represents 65% mass fraction of the PM₁₀. This is justifiable as the organics (OC and EC) were not included in the PMF study. It has been found that Industrial Emissions (22.9%), Biomass Burning (21.2%), and Re Suspended Soil Dust (20.7%) are the major sources as they total account for around 65% of the PM₁₀, followed by Vehicular Exhaust (19.0%) and least from Secondary Aerosols (16.2%) (Figure 5.6).
- Species concentration in all the factors were greater during night time period than the corresponding day time values. Thus, the boundary layer descend and ascend have shown equal effect on the particles, irrespective of their primary or secondary source origin.
- The results of the study provide an approximate indication of which anthropogenic and natural sources of particulate pollution could be responsible for poor health quality in rural and semi urban areas in Punjab. Based on the results of the study, emissions cut off from industrial and biomass burning are required in the region as biomass burning and industrial emissions are the biggest contributor in PM concentrations (21.2% and 22.9%, respectively). Also, natural source of resuspended dust is one of the major pollution source which is also enhanced by increased vehicular density.

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- d) Further, wide range of markers including trace gases, particulate matter and various Volatile organic compounds (VOCs) should be studied for better understanding of origin of the sources and GIS (Geographic Information System) should be used along with modeling and satellite data for representing real picture of the pollutants origin and their transport.

5.8 References

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Summary

The number of deaths attributed to air pollution is 6.5 million a year, with 4.2 million deaths from ambient air (outdoor) pollution, according to World Health Organization. That is more than the combined number of people killed by HIV/AIDS, tuberculosis and road injuries. As reported in State of Global Air, (2019), the fifth leading cause of deaths worldwide is the air pollution. Power generation, industrial processes, biomass burning, vehicular emissions and fossil fuel burnt are the major sources of air pollution. It is a global problem, but developing countries such as India and China are more severely affected by it. There are only few sources of air pollution which lead to majority of the pollutants (PM_{10} , $PM_{2.5}$, O_3 , CO_2 , CO , CH_4 , TNMHC, organics, SO_2 , NO_x , Black carbon, Organic carbon) in Northern India and biomass burning is one the major source of air pollution in regions of Indo-Gangetic Plains (IGP). Respirable particulate matter (PM_{10}) causes morbidity and mortality by penetrating deep into the lungs. While the health effects on adults cannot be neglected, children are more susceptible than young adults to air pollutants therefore; their exposure is a major health concern.

With the approval of Indian Council of Medical Research (ICMR) ethical committee, the study was carried out from September 2014 to December 2015. The data was collected for respirable dust samples and health parameters of school children. Health related samples were collected according to the American thoracic society standards. Health related measurements included Pulmonary function tests like Forced vital capacity (FVC) and Forced expiratory volume in the first second (FEV_1) and pulse oximetry parameters such as oxygen saturation levels (SpO_2), were measured using SPIRODOC (Medical International Research, Italy). It is a portable instrument with both modes for spirometer as well pulse oximetry measurements. Particulate matter concentration measurement was done using a portable aerosol spectrometer (GRIMM Model 1.108). It displays real time data in as little as six seconds in 15 different size channels from $0.30\ \mu m$ to $20\ \mu m$ but environmental data mode (in PM_1 , $PM_{2.5}$ and PM_{10} fractions) was used.

The study was designed to determine the effects of particulate matter size fractions (PM_{10} , $PM_{2.5}$ and PM_1) on health of school children from September 2014 to December

2015 covering one wheat and two rice crop seasons. Different schools were selected at 3 rural sites in the districts of Patiala, Fatehgarh Sahib and Sangrur (Malwa region of Punjab). The daily average values of PM_{10} and $PM_{2.5}$ were about 3-4 times higher than the National Ambient Air Quality Standards (NAAQS) of $100 \mu g m^{-3}$ and $60 \mu g m^{-3}$, respectively during the crop residue burning periods. The MODIS data images of crop residue burning events confirmed the active fire operations over the region. The lung function parameters (Forced Vital Capacity, Forced Expiratory Volume in one second) of children (10-16 years) decreased with increase in particulate matter concentration while no significant effect was observed on Oxygen saturation level of children. The decrease in Forced Vital Capacity was slightly more in male subjects as compared to the female population. The sharp decrease in Pulmonary Function Test parameters during the crop residue burning period indicated the severity of the episodic burning events on the health of the children.

After analyzing the rise in trends of particulate matter during crop residue burning period, source apportionment study was carried out for analyzing different sources of particulate matter (PM_{10}) concentration from 7 May 2015 to 9 June 2016. PM_{10} samples were collected at roof top of a three storey building (about 35 feet from ground level) of Thapar Institute of Engineering and Technology, Patiala. PM_{10} samples were analyzed for 18 species (SO_4^{2-} , NO_3^- , Cl^- , Na^+ , K^+ , Al, Ti, Mn, Fe, Mg, V, Ni, Cu, Zn, Ba, Pb, Cr, Ca). The study was specifically designed to apportion the sources of air pollution where main exposure is from crop residue burning. The particulate matter (PM_{10}) samples were analyzed for mass and chemical composition, with Potassium as biomarker for crop residue burning. Sulfate (SO_4^{2-}) and potassium ion (K^+) species dominated the concentration of characterized species. K^+ and Cl^- were identified as reliable markers for crop residue burning while Zn, Pb, Al, Ni and Cu were identified as markers for vehicular exhaust.

The results of Positive matrix factorization (PMF) model gives the five major sources as probable sources of PM_{10} pollution. The highest contribution in PM_{10} mass concentration was found to be sulfate (24.39 ± 10.42), and potassium (24.02 ± 09.56) and chloride (07.07 ± 05.47), which combined accounts for nearly 60% of the total PM_{10} mass fraction. The highest source contribution was from Industrial emission source

(22.9%), with almost same contribution from biomass burning (21.2%), and resuspended dust (20.7%) and followed by vehicular emissions (19.0%) and least from secondary aerosols (16.2%). Future recommendations include detailed emission inventories for particulates and its constituents. Use of Geographic Information System (GIS) and satellite data in comparison to ground based observations for better accuracy of the data. Assessment of wide range of markers of sources, specially representing local sources.

List of Publications

1. Gurpreet Singh Saggu and Susheel Kumar Mittal, 2020. **“Source apportionment of PM₁₀ by positive matrix factorization model at a source region of biomass burning”** Journal of Environmental Management 266: 110545 (IF = 4.865)
2. Gurpreet Singh Saggu, Susheel Kumar Mittal, Ravinder Agarwal, and Gufran Beig, 2018. **“Epidemiological Study on Respiratory Health of School Children of Rural Sites of Malwa Region (India) During Post-harvest Stubble Burning Events”**, MAPAN-Journal of Metrology Society of India 33: 281-295 (IF=1.00)

Papers/Posters in Conferences

1. Received second prize in Poster presentation Conference award category at the 2nd Indian International Conference on Air Quality Management: Health and Exposure (IICAQM 2017), jointly organized by the Department of Civil Engineering, IIT Madras, Department of Civil Engineering, IIT Delhi and Newcastle University, UK on June 1-2, 2017, at IIT Delhi.
2. Poster presentation on “Source apportionment in Semi urban site of Punjab” in Phonics Group of Institutions, Roorkee from 29-30 April, 2017.
3. Presented poster in International Conference on Emerging Areas of Environmental Science and Engineering (EAESE-2017) Organized by Department of Environmental Science and Engineering, Guru Jambheshwar University of Science and Technology, Hisar on February, 16-18, 2017.
4. Attended Pre-AdMet Workshop on “Best Practices in Measurements and Evaluation of Uncertainty” from February, 22-23, 2016 organized at CSIR-National Physical Laboratory, New Delhi -110012.
5. Presented Research Paper titled “Effect of burning crop residue around Patiala on lung functioning of school children” at National Symposium on Contribution of Metrology & Measurement Standards in Social and Industrial Development (MAPIKI 2014) held at National Physical Laboratory, New Delhi on 8th and 9th December, 2014.