CHEMICAL CHARACTERISATION OF AEROSOLS EMITTED FROM HOUSEHOLD BIOMASS BURNING OF MADHYA PRADESH, INDIA

A Dissertation report
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DEDICATED TO MY MOM

CERTIFICATE

This is to certify that the thesis entitled **"Chemical characterisation of aerosols emitted from household biomass burning of Madhya Pradesh, India"** being submitted by **Mr Gaurav Pandey** in partial fulfilment of the requirement for the award of degree for the **Master of Technology in Environmental Science and Technology** at the Department of Biotech and Environmental Sciences, Thapar University, Patiala is a bonafide work carried out under our guidance and supervision and that no part of this project has been submitted for the award of any other degree.

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DECLARATION

I, the undersigned hereby declare that the research work presented in the M.Tech project entitled **"Chemical characterisation of aerosols emitted from household biomass burning of Madhya Pradesh, India''** has been carried out under the guidance of Dr. S. K. Sharma, Scientist, National physical Laboratory, New Delhi.

Further, I declare that this is an authentic work carried out by me and no part of this thesis has been submitted for a degree or any other qualification of any other university or examining body in India/elsewhere.

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airborne particles smaller than 10 μm diameter. This fraction can be inhaled through the larynx and that can penetrate into the thoracic region. These particles are therefore are also termed 'inhalable' or 'thoracic'. $PM_{2.5}$, which is the particle fraction smaller than 2.5 μm diameter, can penetrate even deeper into the lungs, namely into the alveolar regions, where they are deposited for long periods. These particles are generally denoted as 'respirable'. Ultrafine particles (generally denoted as $PM_{0.1}$, i.e. particles smaller than 0.1 μm diameter) are likely to even pass through the lung into the bloodstream (Brunekreef and Holgate 2002). Note that the term 'coarse particle' is used commonly for both, the TPM and PM_{10}-fraction, respectively, minus the $PM_{2.5}$- fraction.

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ABSTRACT

Biomass burning started to attract attention since the last decade because of its impact on the atmosphere and the environmental air quality, as well as significant potential effects on human health and global climate change. Approximately 2500 million people are exposed daily to emissions from biomass burning sites. Biomass burning is a major source of trace gases and particles that have a profound impact on the atmosphere. Trace gases emitted by fires include the greenhouse gases CO_2 and CH_4, as well as CO and volatile organic compounds that affect air quality. Particle emissions affect climate, visibility, the hydrologic cycle, and human health. Knowledge of particle emission characteristics from biomass burning is crucially important for the quantitative assessment of the potential impacts.

This thesis present the results of study aimed towards comprehensive characterisation of particle emission from biomass burning. The study was conducted under controlled laboratory conditions, to quantify the particle size distribution and emission factors by taking into account various factors which may affect the particle characteristics. This work is an attempt to expand the knowledge of aerosol obtained from burning emission of biomass mainly used by the rural poor of Madhya Pradesh, India.

The present study deals with technological constraints in the characterization and utilization of rural biomass, water soluble ionic species and the estimation of the various parameters associated. For this purpose, an artificial burning setup was developed for characterisation of rural biomass. The aerosol particle were characterized in terms of size distribution and emission factors, such as PM2.5 particle mass emission factor and particle number emission factors, under various burning conditions. The characteristics of particles over a range of burning phase (e.g., ignition, flaming and smoldering) were also investigated.

The result showed that the particle characteristics depend on the burning rate and the type of biomass used (e.g., dung cake, fuel wood and crop residue).

Keywords: aerosol, trace gases, combustion, biomass burning, human health.

1.1 Background and Motivation

The Earth's atmosphere is an essential, omnipresent element of our environment, occupying a seemingly inexhaustible space. Even though the atmosphere extends more than 100 km above, its total mass is only equivalent to a minute water layer of just 10 m height. Nearly invisible and volatile, it often remains unnoticed. But it is indispensable for life on Earth - fulfilling most important functions e.g. delivering oxygen to animals and carbon dioxide to plants, transporting water, compensating global temperature differences, removing noxious exhaust fumes, protecting the Earth's surface from deadly impacts by meteorites and irradiation and providing a temperate climate.

There has always been a natural change of the atmosphere. But the anthropogenic influence on the atmospheric composition has increased so much, that since a few years it is clear that the anthropogenic activities are significantly shifting the physical properties which are controlling our climate and our environment. Although much has been achieved to decouple growth of economy and consumption of natural resources especially earth's biomass, the trend towards an increased usage of environment is unbroken - worldwide.

The study of atmospheric processes is an essential part of Earth system science. In order to understand the climate of our planet Earth and to understand and possibly predict the changes of the climate brought about by human activities, we must understand the complex systems contributing to the energy budget. The improved understanding and characterisation of aerosols emitted from household biomass burning is urgently needed. The reasons for initiating this study were based on the following:

i) Knowledge of characteristics of biomass burning particles (such as particle size distribution and emission factors) is still limited.

ii) The role of specific factors affecting the characteristics of biomass burning particles is not clear.

iii) $PM_{2.5}$ emission data is very limited for many type of biomass burning, in many states in India, particularly in central India, a part that frequently experiences biomass burning.

1.2 The extent of the problem

Global climate change is arguably the most severe problem that the World faces today. Our climate influences every aspect of life on this planet from our ability to produce food and therefore our future development, to the distribution of biomes and the level of biodiversity that exists in the World – much of which remains scientifically unclassified or unknown. The degree to which climate change affects our lives must not be taken lightly. If we continue to upset nature's various equilibrium these events will certainly become the norm for a majority of the World's population. While these events will themselves lead to severe ecological problems they will also illicit many equally dangerous socio-political situations such as disputes over water resources, air quality related issues and in the creation of 'environmental refugees'.

There are a limited study has been conducted previously on biomass burning, their chemical characteristics and impact on ambient air quality over Central India. To characterize the aerosol (obtained from household biomass burning) which causes climate and health issues, it is necessary to have a better understanding of its character, their emission budget at various regions, annual cycles, fine and coarse particle fractions, and their diversity. The results from this work can be useful at several levels. First, the baseline fine particle air quality characterization apportionment study of the rural area of Madhya Pradesh has documented. Second, the water soluble ionic species study has helped to define the chemical composition of household biomass fuel that contributes to pollution.

1.3 Specific aim of the Research

The effects of aerosols on atmospheric chemistry and physics, climate, and public health are among the central topics in current environmental research. Aerosol particles can scatter or absorb radiation, influence the formation of clouds and precipitation, and affect the abundance of trace gases via heterogeneous chemical reactions and other multiphase processes. Moreover, they can cause respiratory, cardiovascular, and allergic diseases. The primary parameters which determine these effects are particle size, structure, and composition. A large part of the uncertainty in predicting the future climate is due to atmospheric aerosols, as presented in the previous sections. The composition of the atmosphere and the large variety of

physical, chemical and biological processes taking place within it are components affecting a large complex system, and the focus of this thesis.

This on-going DST project was aimed at the experimental investigation and mechanistic description of the chemical characterisation and trace gas estimation, emitted by fuel particularly biomass used in India by rural sector and small scale industries.

1.4 Objectives and Outline of this Thesis

The overall objective with this project has been is to understand the emission pattern from burning biomass samples typically used in this region as well as to characterize their emission profiles and ultimately strengthen the research capabilities in India in the field of Atmospheric Sciences.

The main objectives of this thesis were the following:

i) To determine and analyze the emission factors of BC and OC from biomass burning using biomass samples over different parts of Madhya Pradesh

ii) To evaluate the budgets for Black Carbon and Organic Carbon for representative site-by-site scenario using the activity data available from literature

iii) Determination of chemical properties of ambient aerosols over different parts of Madhya Pradesh

iv) Attempt will be made to suggest some mitigation related to aerosol emission from household biomass fuel burning and try to implement some design modification for experimental setup

The continuous improvement of the system understanding helps to identify alert indicators at an early stage and is needed to find possible action options. Moreover, the ability to predict the impact reliably and with sufficient accuracy helps to avoid costly wrong decisions in environmental politics. The outline of this thesis is as follow:

The first chapter comprises the background and specific aim of the research, extent of the present problem associated, objective of the study with major research needs. The second chapter is literature review, which covers basic introduction of biomass burning followed by combustion process, air quality, aerosols and its impact on climate and health, particle size distribution, emission rate/ factors and finally air quality standards. Third chapter is focused towards methodology adopted for this

study. Chapter four covers all the results obtained and related discussion. Chapter fifth comprises Conclusion and Recommendations for future Research.

A discussion of the major research need "way forward" toward better constraints on aerosols i.e. Biomass burning, and hence climate sensitivity, is provided in the next section.

1.5 Major Research Needs - THE WAY FORWARD

The above sections of this chapter has emphasized that despite the increase in understanding aerosol forcing of the climate system, many important uncertainties remain. By way of perspective, concerted effort has been directed toward this issue for only about the past 20 years. In view of the variety of aerosol types and emissions, uncertain microphysical properties, great temporal and spatial variability, and the added complexity of aerosol cloud interactions, it is easy to understand why more work is required to define anthropogenic aerosol forcing with confidence comparable to that for other climate forcing agents.

The coming years will be an exciting time for Aerosol Studies and the atmospheric science community that it serves. Aerosols will augment the fleet of atmospheric research programmes with the communities, an experiment ideally suited to atmospheric chemistry studies. The present situation is not completely negative in so far as we have both the time and resources to avoid the worst apocalyptic scenarios.

Moreover, positive intervention in one area (i.e. climate change mitigation) may have positive ecological implications for others depending on the adopted course of action. Given that human development depends to a great extent on our general (environmental) well-being it is in our best interest to make our development (environmentally) sustainable. This philosophy does not hold that human beings should make 'irrational' sacrifices in order to preserve the environment. It does say, however, that we should take into consideration the long-term environmental impact of our actions. In doing so we could ensure equilibrium between human activities and our planet that allows and indeed *enhances* future human development. For many rural dwellers there is no possibility of changing to fuels other than Biomass.

The uncertainty in assessing total anthropogenic aerosol impacts on climate must be much reduced from its current level to allow meaningful predictions of future climate. This uncertainty is currently dominated by the aerosol component. In addition, evaluation of aerosol effects on climate must take into account high spatial

and temporal variation of aerosol amounts and properties. Thus, the way forward requires more certain estimates of aerosol related studies, which in turn requires better observations, improved models, and a synergistic approach.

2.1 Introduction

Biomass is anything that is alive. It is also anything that was alive a short time ago. Trees, crops, garbage, and animal waste are all biomass.

$$CO_2 + 2H_2O \longrightarrow CH_2O + H_2O + O_2 \quad (1)$$

Equation for Photosynthesis

Biomass gets its energy from the sun. The chemical energy that is stored in plants (as a result of the photosynthetic conversion process) and animals or in the wastes that they produce is called bioenergy. When we eat biomass, we use the energy to move and grow. When we burn biomass, we use the energy to make heat. We can also change the energy in biomass into gas and liquid fuels hence biomass is unique in its ability to provide solid, liquid and gaseous fuels which can be stored and transported. **[1]**

Presently, the biomass sources contribute 14% of global energy and 38% of energy in developing countries. Two notable components of biomass burning are the incineration of wood, charcoal and agricultural waste as household fuel, and the combustion of crop residue in open fields. Biomass is a major source of energy in developing countries particularly India where most of the energy requirement in the rural sector is met by bio-fuels. Although the per capita usage of the bio-fuels is declining as they are being substituted by more efficient commercial energy sources, but with the increase in population, the total consumption of biomass fuels is still showing an increasing trend. **[2]**

Rural areas of developing countries depend primarily on biomass for fuel. The amount of biomass fuel consumed varies as climate (higher consumption for colder climates). The choice of biomass fuel consumed depends on availability, local customs, and season. **[3]**

Asia is the largest contributor to the burning of biofuels and agricultural residue in the developing world, because of the dominance of China and India. Fuel wood includes firewood, brushwood, twigs, branches, and cut branches. On the other hand, billions of tons of agricultural wastes are generated each year in the developing and developed countries. Agricultural residue includes all leaves, straw and husks left in

the field after harvest, hulls and shells removed during processing of crop at the mills, as well as animal dung. **[4]**

Biomass burning has a significant impact on global atmospheric chemistry since it provides large sources of particulate matter as well as carbon monoxide, nitrogen oxides, and hydrocarbons, primarily in the tropics **[5]**.The amount of total biomass fuel burned in the developing world is distributed as 61% fuel wood, 30% crop residue, and about 7% dung.**[6]**

In India, biofuels accounted 93% of total biomass consumption (577MT/Yr), with forest fires contributing only 7%. According to NASA Earth Observatory, Scientists estimate that humans are responsible for about 90% of biomass burning with only a small percentage of natural fires contributing to the total amount of vegetation burned. This is in contrary to global patterns, where forest fires are the primary and biofuels a negligible contributor. The biomass fuel mix varied across different regions, with a national average of 56: 21: 23% for fuel wood, crop residue and dung-cake, respectively. **[7]**

In Madhya Pradesh, all types of biomass fuels like fuel-wood, agricultural residues and animal waste are used. Domestic biomass fuel burning accounts for 42% of the total biomass burnt in India **[8]**. Fuel wood is mostly used for cooking and heating purposes. **[9]**

Burning of biomass fuels, residential fuel and industrial fuel is a globally important source of aerosols, greenhouse gases, precursor gases and metallic species **[10]**.

Biomass burning has attracted the attention of people globally due to its contribution to air pollution issues and the effects of these emissions on human health. Biomass burning releases large amounts of particulates (solid carbon combustion particles), aerosols, un-burnt carbon and gases, including greenhouse gases, carbon dioxide, methane, and nitrous oxide. In addition, biomass burning is a source of chemically active gases, including carbon monoxide, non-methane hydrocarbons, and nitric oxide **[11]**. The biomass burning smoke contribute about three quarters of the aerosol burden in the regional haze while other sources like fossil fuel burning contribute the rest **[12]**.

Generally the aerosols contain carbonaceous aerosols, sulfate aerosols and metal species. About 70% of the mass of particulates related is fine carbon-containing

particles. Radiative interaction by both Black Carbon (BC) and Organic Carbon (OC) reduce visibility and surface irradiance, potentially affecting the sunlight available for agriculture. The dark component of these carbonaceous aerosols often referred to as soot or black carbon (BC) is actually a mixture of graphite-like particles and light-absorbing organic matter (OM) **[13]**.

Biomass burning is also a major source of ambient $PM_{2.5}$ (particulate matter with aerodynamic diameter less than 2.5 μm) and has significant impacts on human health **[14]**, regional and global air quality **[15]** and climate **[16 & 17]**. Water-soluble potassium (K^+) has been used extensively as an inorganic tracer to apportion biomass burning contributions to ambient aerosol **[18]**. Organic compounds are the largest component produced from fires and there are specific compounds found 20 to be exclusively emitted from biomass burning. The most commonly used organic tracer is levoglucosan, a sugar anhydride produced during the combustion of cellulose **[19]**.

Biomass burning has both short and long term impacts on the environment. Recognising the significance of bio-fuel combustion to green-house gas emissions is an important step in the development of a solution to the problem of traditional fuel use **[20]** and to the more general question of finding appropriate energy resources for a vast and rapidly changing world.

There is a limited study has been done in India to evaluate the impact of biomass fuel burning on ambient air quality and chemical characteristics of aerosol. The aim of this study is to provide an emission factor inventory for Madhya Pradesh that resolves the spatial and temporal variations. The present study emphasise only on the confined anthropogenic part of biomass burning and focuses on the air pollution caused by particulate matter emissions which are of primary relevance for public health and hence, contributing to Climate Change. Almost anywhere on the world, most fires are of anthropogenic origin. Fig. 2.1 gives a classification of the different types of burning according to the different biomass fuel types and purposes.

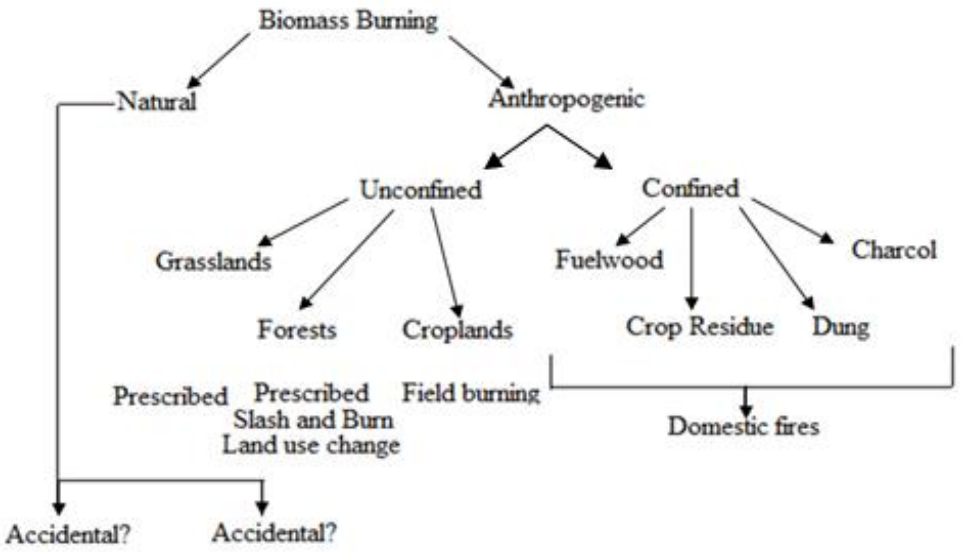

Fig. 2.1: Different types of biomass burning

Combustion Process:

The combustion process is a combination of physical and chemical processes, generally divided into three phases: ignition, flaming and smoldering **[21].**

Ignition occurs when biomass is set alight by adjacent ignited biomasses and the duration of the ignition phase depends greatly on the properties of the fuel, such as water content, density and size. During ignition, large quantities of highly, volatile organics are released.

Flaming occurs once the fuel is sufficiently dry. Hydrocarbons are volatilized through a char layer, containing less volatile solids of high carbon content, from thermally decomposing biomass that is rapidly oxidized in a flame when mixed with air. Reaction 2 shows the complete combustion process for a methane molecule, in this case:

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O + \text{heat} \qquad (2)$$

Incomplete combustion is far more common and occurs when not enough oxygen is present for combustion to occur completely and large amounts of by products are emitted, predominantly carbon monoxide and many organic compounds. The complex mixture of relatively reduced substances emitted during pyrolysis is converted to simple molecules, like CO_2, H_2O, NO, N_2O, N_2 and SO_2 **[22].**

Depending on the interaction between chemical kinetics and physical dynamics in the flame, intermediate products of flame radical chemistry, like CO, CH_4, H_2, C_2H_4, C_2H_2, PAH and soot particles are also released during this stage. During flaming,

most volatile organic carbon compounds (VOCs) and water is released from the near surface region of the fuel and the un-oxidized remainder is charcoal, consisting of approximately 90% carbon, 5% oxygen and 3% hydrogen.

The smoldering phase is characterized by flameless combustion or gas solid reaction between carbon and oxygen in the char layer of the charcoal and the predominant emission during smoldering is carbon monoxide and incompletely oxidized pyrolysis products. Not only do biomass burning emissions depend upon fuel type, moisture and structure, but also on the phase of combustion which varies spatially and temporally, and also on the movement of the flame front relative to wind direction or terrain slope.

2.2 Air Quality

During the times of Aristotle, it was thought that air was one of four fundamental substances (the other three: soil, fire, and water), none of which could be divided further into smaller components **[23]**. Today, of course, we know differently and the air that encircles our planet is a mixture of many discrete gases and aerosols, each with its own physical properties and quantity in the atmosphere. The most prominent constituents of the Earth's dry atmosphere are nitrogen (N_2, 78.1% volume mixing ratio), and oxygen (O_2, 20.9%), which together comprise 99% of the atmospheric composition on our planet. Although these gases are largely significant to planetary life, they have little importance on global and local environmental concerns. They have limited interaction with the incoming solar radiation and they do not interact with the infrared radiation emitted by the Earth. In addition to these gases, a small fraction of the atmospheric composition is attributed to inert (non-reactive) gases such as argon (Ar, 0.93%), neon (Ne, 0.0018%), helium (He, 0.00052%), and krypton (Kr, 0.00005%) **[24]**.

By absorbing and emitting infrared radiation, trace gases and particulate matter also play essential roles in the Earth's energy budget. The gases are called greenhouse gases, and include water vapour (H_20g), carbon dioxide (CO_2), and nitrous oxide (N_2O). When these greenhouse gases absorb the infrared radiation emitted by the Earth and/or solar short-wave radiation, they emit infrared radiation upward and downward and tend to raise the temperature near the Earth's surface **[25]**. The previously listed species and their effects on the Earth's radiative budget are

relatively well understood **[25],** but the remaining ~0.03% of the atmospheric constituents is not. These components include other trace gases and particles such as, ozone and aerosols, respectively. Although these components are minor to the overall atmospheric composition, they can potentially contribute greatly to the effects of local, regional and global climate and are concerns for environmental quality and human health **[24, 26 & 27]**.

The deterioration of air quality is a major source of concern and environmental problem not only in rural areas, but also on regional and global scales. Discussions of air quality generally centre on issues related to atmospheric oxidants and particulates. Biomass burning in rural areas is strong sources of pollutant gases and aerosols that can influence both regional and global environments. These pollutants include primary pollutants (e.g., VOC, SOx and NOx) released into the rural atmosphere, as well as secondary pollutants produced in the atmosphere by photochemical processing (e.g., ozone, inorganic and organic nitrates, acids, peroxides, carbonyls, and other partly oxidized organics). Many of these secondary pollutants play an important role in the atmosphere far from source regions, for example as sources of SOx and NOx in the remote atmosphere.

As previously discussed, tropospheric ozone and aerosols are pollutants of particular interest due to concerns for global warming, human health and environmental impacts. The greenhouse effect of ozone is relatively well understood hence this study is mainly focused on the influence of rural biomass burning emissions on the composition of airborne particles.

2.2.1 Airborne particles: general background and definitions

Atmospheric particles are constituted by solid and/or liquid particles that enter in the atmosphere from natural or anthropogenic sources. The term atmospheric aerosol is frequently used as a synonym of atmospheric particles.

2.2.2 Aerosols

"An aerosol is defined as a suspension of fine solid or liquid particles in a gas, in the case of atmospheric particles it is the ambient air."

This general definition, adapted from Seinfeld and Pandis, (2006), covers all types and sizes of atmospheric particles from numerous different sources. They can be

directly emitted as particles (primary aerosols) into the atmosphere by volcanoes, through the effect of wind lifting dust particles in arid regions, from combustion during biomass burning, from sea spray, from vegetation etc. They can also be formed in the atmosphere by nucleation and condensation of gaseous compounds (gas-aerosol system) (secondary aerosols). Table 2.1 summarizes the main sources of aerosols. It is estimated that 10% to 20% of the aerosols can be characterized as anthropogenic on the global scale.

Table 2.1: Main sources of aerosols

Natural	Anthropogenic
Primary Mineral aerosol Sea salt Volcanic dust Organic aerosols	***Primary*** Industrial dust Soot Biomass burning
Secondary Sulfates from biogenic gases Sulfates from volcanic SO_2 Organic aerosols from VOCs Nitrates from NO_x	***Secondary*** Sulfates from SO_2 Organic aerosols from VOCs Nitrates from NO_x

Aerosols are ubiquitous in air and are often observable as dust, smoke, and haze. Both natural and human processes contribute to aerosol concentrations.

The word aerosol derives from the fact that matter "floating" in air is a suspension (a mixture in which solid or liquid or combined solid-liquid particles are suspended in a fluid). To differentiate suspensions from true solutions, the term **sol** evolved originally meant to cover dispersions of tiny (sub-microscopic) particles in a liquid. With studies of dispersions in air, the term aerosol evolved and now embraces liquid droplets, solid particles, and combinations of these.

We are surrounded by aerosol particles in our daily life, and these are not only created from nature, as in the previous examples. When driving our car to work we generate particles from car exhaust **[28]**, in offices printers are known to be a source of aerosol particles **[29 a, b]**, and even during lunch cooking causes aerosols **[30]**. Other human activities such as the burning of fossil fuels and the alteration of natural surface cover also generate aerosols which are known as man-made, i.e. anthropogenic, aerosols. Averaged over the globe, aerosols made by human activities currently account for about 10 percent of the total amount of aerosols in our atmosphere.

2.2.2.1 Sources and fates of atmospheric aerosols

'In the following, major sources and fates of the tropospheric aerosols are discussed. If not otherwise stated, the information was taken or adapted from Seinfeld and Pandis (2006).

The most significant natural sources of particles include dust from soil and rock debris or volcanic action, sea spray, biomass burning, and reactions between natural gaseous emissions (see paragraph below on secondary aerosols). It has to be mentioned that oceans are the most important permanent producers of tropospheric aerosols in terms of emitted mass per year (sea spray, containing, among other constituents, sodium chloride, NaCl), also the oceans are the largest sinks for aerosols. Volcanoes can be temporarily much stronger sources of tropospheric aerosols than oceans; however occasional eruptions cannot be seen as a permanent source. A powerful source of aerosols is the deserts: Each year, thousands of tons of mineral dust is suspended from deserts and brought up to our latitudes by wind.

While directly emitted particles are termed as primary aerosol particles, gas-to-particle conversion processes occur as well, generating secondary aerosols. Combustion processes from industry and traffic, depending on the fuel, are also sources of sulphur and nitrogen compounds. SO_2 and NOx emissions are mainly converted to sulphuric acid (H_2SO_4) and nitric acid (HNO_3) in the atmosphere. The main basic compound in the atmosphere is ammonia (NH_3), originating mainly from agricultural activities. Atmospheric transport processes make these compounds, which are well soluble in water, available far from their source regions. A well characterized atmospherically relevant inorganic aerosol is ammonium sulphate, $(NH_4)_2SO_4$, which originates in the atmosphere from ammonium (derived from ammonia, see above) and from SO_2. Secondary organic aerosols (SOA) are subject of various current studies **[31, 32 & 9]**. Due to their volatility and fast reaction times, SOA are hard to characterize and quantify, however, SOA is a major constituent of the atmosphere **[33]**.

Aerosol emissions attributable to human activity arise primarily from (fossil) fuel combustion, industrial processes, "nonindustrial fugitive sources" (such as dust from paved and unpaved roads, wind erosion of cropland, construction, etc.), and transportation sources. Combustion of fossil fuel leads to carbonaceous particles

(containing organic and elemental carbon). The latter is solely produced by incomplete combustion (Fig. 2.2).

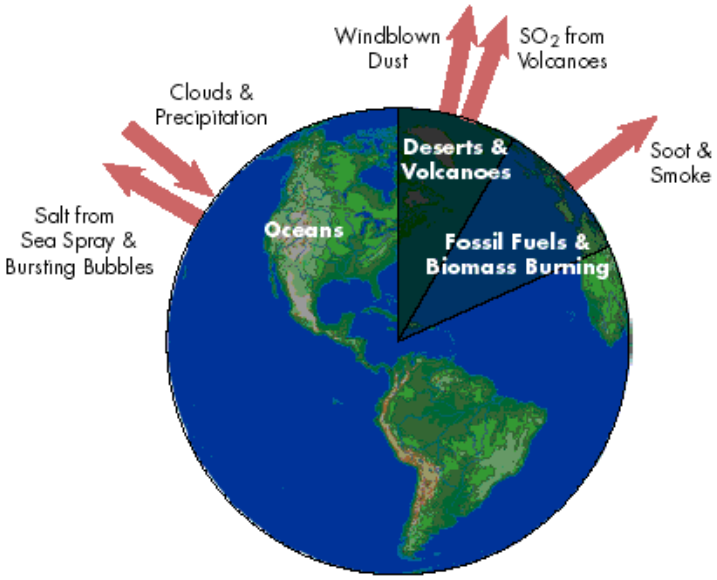

Fig. 2.2: Aerosol particles larger than about 1 micrometer in size are produced by windblown dust and sea salt from sea spray and bursting bubbles. Aerosols smaller than 1 micrometer are mostly formed by condensation processes such as conversion of sulfur dioxide (SO2) gas (released from volcanic eruptions) to sulfate particles and by formation of soot and smoke during burning processes. After formation, the aerosols are mixed and transported by atmospheric motions and are primarily removed by cloud and precipitation processes.

Aerosols undergo transformation processes in the atmosphere, termed aging. This involves (photo) chemical reactions changing the composition of the particles, but also coagulation (collision of two separate particles) or condensation of low-volatility material on existing particles. As a result, particles of an externally mixed aerosol (i.e. an aerosol consisting of particles with distinct composition) can be processed to an internally mixed aerosol (i.e. an aerosol consisting of particles with the same composition) in the atmosphere. The mixing state of a single particle can change in such a case: To give an example, a freshly emitted soot particle consisting of elemental and organic carbon can be coated and subsequently be mixed with other organic and inorganic compounds due to aging. Unravelling the history of such mixed ambient particles, in order to find sources of their compounds, is often a challenge.

2.2.2.2. Aerosols and Climate

Although Earth's atmosphere consists primarily of gases, aerosols and clouds play significant roles in shaping conditions at the surface and in the lower atmosphere. Predictions of future climate change are affected with large uncertainties. The main reason for these uncertainties is due to uncertainties in the aerosol effects.

Aerosols influence the climate in various ways, where most of the interactions still can only be described qualitatively, and quantitative numbers can be given with large uncertainty. An overview of selected aerosol effects on climate is schematically shown in Fig. 2.3. The effects of aerosols on climate are basically split into two classes: The direct effect and indirect effects. Note that most aerosol effects are connected to the interaction of particles with atmospheric water vapour (influencing the size and other properties of the particles).

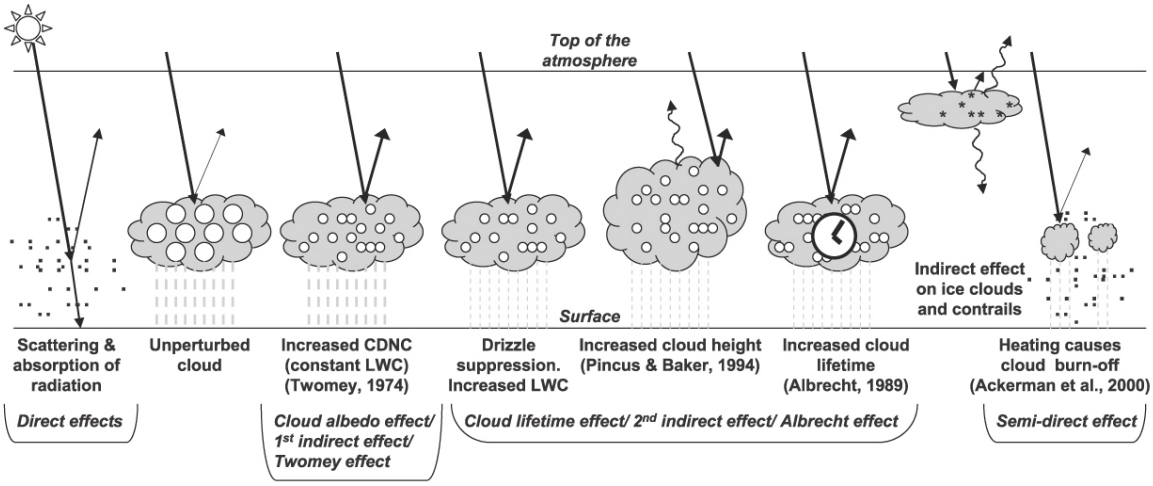

Fig. 2.3: Schematic diagram showing the various radiative mechanisms associated with cloud effects that have been identified as significant in relation to aerosols. The small black dots represent aerosol particles; the larger open circles cloud droplets. Straight lines represent the solar radiation, wavy lines represent terrestrial radiation. The filled white circles indicate the cloud droplet number concentration (CDNC). The unperturbed cloud contains larger cloud droplets as only natural aerosols are available as cloud condensation nuclei, while the perturbed cloud contains a greater number of smaller cloud droplets as both natural and anthropogenic aerosols are available as cloud condensation nuclei (CCN). The vertical grey dashes represent rainfall, and LWC refers to the liquid water content. Modified from Haywood and Boucher (2000), published in IPCC (2007).

Anthropogenic aerosols are believed to affect climate in several ways. These primarily scatter and cool the earth's surface and the dark absorbing component are

present they also may heat the air in which they are suspended. Role of aerosols in modifying the earth's climate has been known for many years. In recent years, the importance of carbonaceous aerosols to global radiative forcing has been stressed in a number of important papers and commentaries **[34]**.

Oxides of nitrogen (NO_x) in the atmosphere are a form of pollution which can give rise to smog and act as a greenhouse gas. Their persistence in the atmosphere is affected by aerosol droplets of water. In 1964 long chain fatty acids, either naturally produced from marine organisms dispersed into the atmosphere by wave action or man-made, were found to coat these droplets. In 2006 there was a study of the effect of the LCFA on the persistence of NO_x, but the long term implications, although thought to be significant, have yet to be determined.

Currently, the net effect of the most common short-lived aerosol pollutants on climate change is small, as the radiative forcing of different species nearly cancels. Reduced emissions of sulphur dioxide, leading to lower concentrations of cooling sulphates, combined with projected increases in emission of black carbon aerosols (assuming no worldwide shift to a green economy) will lead to a net warming effect from these species. In the long run, regional effects resulting from emissions patterns are projected to average out, with this warming following the geographic distribution of warming from well-mixed greenhouse gases.

2.2.2.3. Aerosols and health

Indoor air pollution caused by burning wood and other unprocessed solid biomass can be traced to prehistoric times when man first moved to temperate climates approximately 200,000 years ago. These cold climates necessitated the construction of shelters and the use of fire indoors for cooking, warmth and light. Ironically, fire, which allowed man to enjoy the benefits of living indoors, resulted in exposure to high levels of pollution as evidenced by the soot found in prehistoric caves **[35]**. Wood was the first fuel that man used and exposure to wood smoke is as old as humanity itself **[36]**.

This section will demonstrate a multitude of health problems especially in women who were chronically exposed to Aerosols suspended in biomass smoke during daily household cooking and their children who spend a lot of time with their mothers assisting them in the kitchen. They had higher prevalence of respiratory symptoms,

reduced lung function, bronchial hypersensitivity and airway inflammation when compared with LPG using women from similar neighbourhood. It is important to mention in this context that respiratory and cardiovascular effects of air pollution are primarily mediated by fine and ultrafine particles respectively, and the concentrations of PM_{10} and $PM_{2.5}$ in indoor air during cooking was 3 to 4 times higher in biomass-using homes than LPG-using households **[37]**.

Numerous recent epidemiological studies have shown consistent, statistically-significant associations between increased exposure to daily aerosol loadings at levels typical of modern cities and morbidity and mortality – with no apparent threshold **[38 - 41]**.

2.2.2.3.1 Excess mortality

The health impact of biomass smoke containing high concentrations of particulates and other pollutants can be devastating because for every 20 $\mu g/m^3$ rise of PM_{10} in ambient air over the standard, 1% increase in total daily mortality occurs **[42]**. Most people are aware that outdoor air pollution can damage their health. But fewer know indoor air pollution often cause greater harm.

Globally, indoor air pollution from biomass fuel use is responsible for 1.6 million deaths due to pneumonia, chronic respiratory disease and lung cancer. Biomass fuels accounts for 2.9 % of all deaths per year worldwide, and 3.7% of the overall disease burden in developing countries. In India, 400,000 to 2 million premature deaths occur per year due to indoor air pollution with a majority of deaths occurring in children under five due to acute respiratory infections **[43 - 46]** . There is also strong evidence of impact on women, up to 34,000 deaths resulting from chronic obstructive disorders **[47].** In contrast, mortality due to outdoor air pollution is 200,000 to 570,000 representing about 0.4 to 1.1 % of total annual deaths **[48] [49]**. In fact, indoor smoke from biomass burning is the most important health hazard after malnutrition and lack of safe water and sanitation.

2.2.2.3.2 Excess morbidity

Biomass smoke exposure increases the risk of common and serious diseases of both children and adults **[44].** It has been causally linked to acute respiratory infections (ARI), chronic obstructive pulmonary diseases (COPD), otitis media, tuberculosis, asthma, low birth weight, cataract and blindness, lung cancer, cancer of nasopharynx, larynx **[44, 47 & 50]** and uterine cervix **[51]**.

i) Acute respiratory infections (ARI)
ii) Tuberculosis
iii) Reduction in lung function
iv) Chronic Obstructive Pulmonary Disease (COPD)
v) Bronchial asthma
vi) Cardiovascular risk
vii) Change in immune defence
viii) Hormonal changes
ix) Eye irritation and cataract
x) Middle ear infection (Otitis media)
xi) Low birth weight and perinatal mortality
xii) Genotoxic effects
xiii) Increased risk of cancer
    a) Lung Cancer
    b) Cancer of the nasopharynx and larynx
    c) Cervical cancer

Prevalence of upper respiratory symptoms (URS)

Upper respiratory symptoms (URS) are represented by

xiv) Sinusitis
xv) Runny or stuffy nose
xvi) Sore throat
xvii) Common cold and fever

Prevalence of lower respiratory symptoms (LRS)

Lower respiratory symptoms (LRS) include

xviii) Dry cough
xix) Cough with phlegm (wet cough or sputum-producing cough)
xx) Chest discomfort or chest pain
xxi) Shortness of breath

xxii) Wheezing breath

Prevalence of other symptoms

xxiii) Recurrent headache

xxiv) Eye irritation and eye watering

xxv) Dizziness

xxvi) Muscle pain

xxvii) Tingling and numbness

2.2.3 Particle size distribution

Particle size is one of the most important parameters in determining atmospheric behaviour and impacts of particles. Airborne particles possess a multi-modal size spectrum ranging from a few nanometres to around 100 μm diameters. The total surface area and number of particles, chemical composition, atmospheric lifetime, health impact, visibility impairment and emission sources - all vary with particle size. Figure 2.4 shows an idealized schematic of principal modes, sources, and particle formation and removal mechanisms of atmospheric aerosols.

Based on particle size and formation mechanism, airborne particles can be classified into two fundamental modes: the fine and coarse (C) mode. The cut-off of these two modes is at particle diameters of around 2.5 μm. The finer mode, up to around 1 μm, generally originates from high temperature processes and/or gas-to-particle formation processes in the atmosphere; these particles carry inorganic compounds (such as sulphates, nitrates and elemental carbon) and organic compounds, including semi-volatile components. Mechanical processes such as erosion, corrosion and material abrasion give rise to coarser particles, usually larger than 1 μm. These particles carry *e.g.* soil components and sea spray. The fine mode can be further subdivided into an ultrafine mode (U) and an accumulation mode (A), the cut-off of these two fine modes is at around 0.1 μm **[52].** The ultrafine particles are better characterised by the number concentration (number of particles per cm3), because despite their large number they contribute only little to the particulate mass. Today, it has become common practice to denote the PM2.5 as the “fine fraction” and particles with diameters between 2.5 and 10 μm (PM2.5-10) as the “coarse fraction’’.

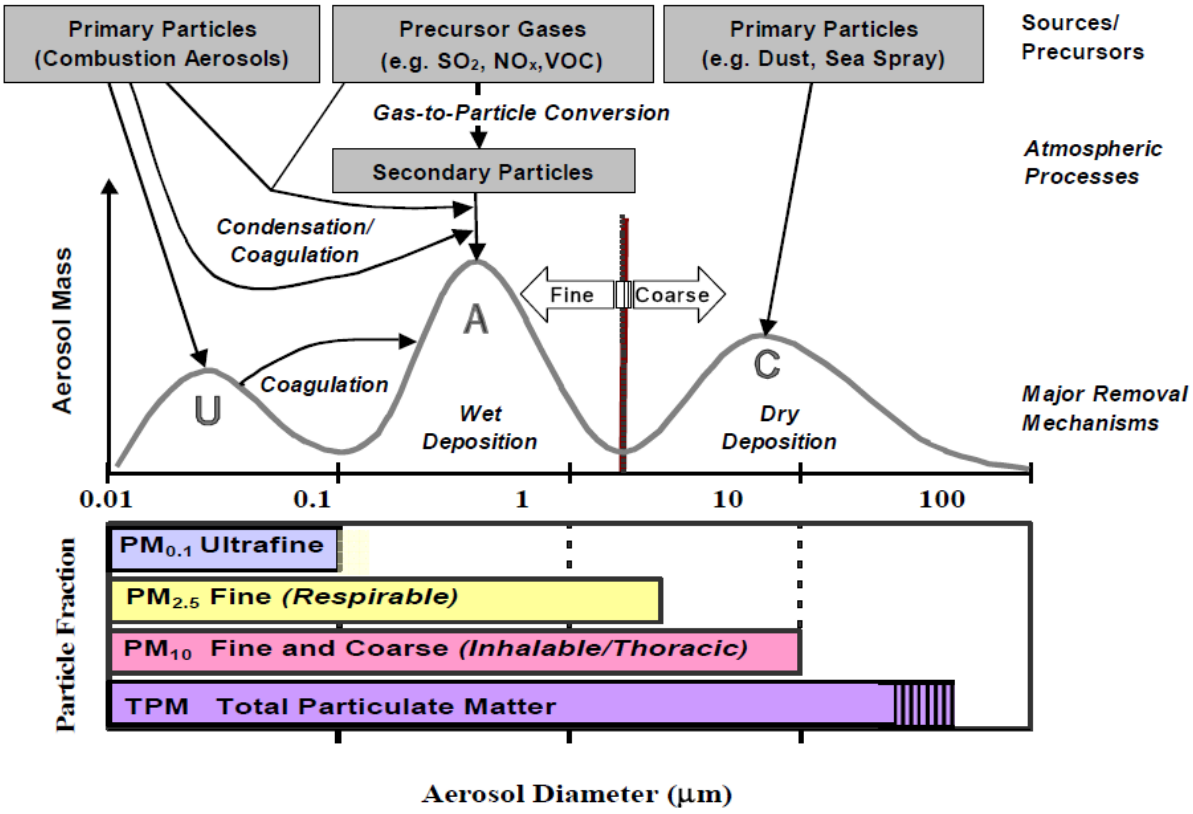

Fig. 2.4: Idealized schematic of principal modes, sources, and formation and removal mechanisms of atmospheric aerosols. The abscissa shows the aerosol diameter while the ordinate the size-dependent aerosol mass (based on Seinfeld and Pandis 1998). U stands for ultrafine particle mode, A for accumulation mode and C for coarse mode particles. In ambient air quality monitoring, the following particulate matter (PM) size fractions are typically measured: TPM, PM10, PM2.5 and PM0.1. Total Particulate Matter (TPM, frequently also referred to as Total Suspended Particles (TSP)) includes the entire size range of airborne particles, which may vary dependent on the environmental conditions. PM10 is the fraction of total airborne particles smaller than 10 µm diameter. This fraction can be inhaled through the larynx and that can penetrate into the thoracic region. These particles are therefore are also termed 'inhalable' or 'throracic'. PM2.5, which is the particle fraction smaller than 2.5 µm diameter, can penetrate even deeper into the lungs, namely into the alveolar regions, where they are deposited for long periods. These particles are generally denoted as 'respirable'. Ultrafine particles (generally denoted as PM0.1, i.e. particles smaller than 0.1 µm diameter) are likely to even pass through the lung into the bloodstream (Brunekreef and Holgate 2002). Note that the term 'coarse particle' is used commonly for both, the TPM and PM10-fraction, respectively, minus the PM2.5- fraction.

The PM10 concentration is the mass per volume unit (μg/m3) of particles with an aerodynamic diameter smaller than 10 micrometres (μm). The larger particles contained in the PM10 size fraction reach the upper part of the lung. The smaller particles of this size fraction (in particular PM2.5 and PM1.0, with diameters smaller than 2.5 and 1.0 μm) penetrate more deeply into the lung and reach the alveolar region. PM is often differentiated by chemical constituents (*e.g.* sulphates, heavy metals, organics), as well as by source-related constituents (*e.g.* diesel soot).

Large and very small particles have a limited atmospheric residence time due to deposition or coagulation. Particles in the size range between approximately 0.1 and a few μm remain much longer in the atmosphere (typically several days to a week) and can consequently be transported over long distances (1000 or more kilometres).

2.3.4 Emission Rate or Emission Factor

Sources produce pollutants in quantities presented using either emission factor or emission rate. Emission factor is defined as a unit based on a task **[53].** For example the task can be an amount of energy generated by a power plant in g/Mj **[54]**, the amount of energy used for cooking stoves **[55]**, or the amount of steam generated by a boiler in g/ton **[56]**. It may a task for certain distance driven by a motor vehicle that will be presented in g/km **[57 & 58]**. Emission rate is defined as the amount of the concerned pollutant as function of time. The unit of emission rate is expressed in g/s or Tg/year.

For biomass burning emission factor is defined as the amount of emission per kilogram of fuel burned on area burned (g/kg or Tons/ha): emission rate is associated with the amount of emission per unit time (Tons/year).
The emission factor of gases and aerosols is obtained as:

$$EF_{(X)} = M_{(X)}/M_{(biomass)} \qquad \text{(Eq. 1)}$$

Where $M_{(X)}$ is the mass of species (X) emitted and $M_{(biomass)}$ the mass of fuel actually burnt. It is important to note here that EF is not relative to biomass exposed to fires but to the burnt biomass. EF is expressed in gX/kgdm. The emission factor may also refer to the amount of carbon in the dry plant $M_{(C)}$:

$$EF_{C(X)} = M_{(X)} / M_{(C)} \qquad \text{(Eq. 2)}$$

The two equations are related by the carbon content of the fuel [C] ($EF_{(X)} = EF_{C(X)} \times [C]$). [C] is somewhat variable: typically 42 - 50% of the fuel dry matter is carbon. For a matter of clarity all the EF values presented in this study refer to the dry matter. The presence of two units for $EF_{(X)}$ (gX/kgdm and gX/kgC) may be a source of confusion and consequently lead to significant errors.

EF may be experimentally determined by:

$$EF_{(X)} = \Delta X / (\Delta \Sigma([CO_2], [CO], [CH_4], [C_{VOC}], [C_{aerosol}],\ldots) \times [C]biomass \quad \text{(Eq. 3)}$$

Where Δ denotes the difference between concentrations in the background and in smoke conditions, and (Σ ($[CO_2]$, $[CO]$, $[CH_4]$, $[C_{VOC}]$, $[C_{aerosol}]$,…) is the species concentration expressed as the amount of carbon. $EF_{(X)}$ is commonly referred to ($\Delta\Sigma$ ($[CO_2]$, $[CO]$) as these two species represent generally 95 - 99% of the carbon-containing emissions. When $EF_{(X)}$ corresponds to the ratio of the production of species X to the production of CO (or CO_2), it is called Emission Ratio (ER). **[59]**

$EF_{(X)}$ is highly dependent on the fire regime (see combustion process in section 2.1). In chronological order, fires begin with a drying phase (called ignition phase), followed by a 2nd phase including flaming, glowing and pyrolysis processes (called flaming phase), a 3rd phase with glowing and pyrolysis only (called smoldering phase) and a 4th phase with glowing and extinction. Emissions of different species are quantitatively and qualitatively governed by the relative importance of the different fire stages. The main emissions occur during phases 2nd and 3rd.

When specific data are missing, the values have been interpolated. It is important to note that for some types of burning, the uncertainty on EF is much lower than a few years ago, especially once they are normalised by expressing them as a function of the combustion efficiency. However, significant uncertainty still remains for some EF.

Above all factors, the uncertainty might be due to a lack of measurements, especially with respect to domestic and agricultural fires, which are important sources in developing countries, or for some specific compounds (such as oxygenated hydrocarbons). Some discrepancies may also be due to the sampling conditions: for example, aircraft and ground-based measurements do not sample the same air mass due to the rapid chemical aging of the biomass burning plume. Aircraft

measurements are also likely to exhibit a bias towards flaming fires whereas ground experiments can more easily characterize smoldering emissions.

2.3.5 Chemical Composition

In the troposphere, a significant portion of aerosols is anthropogenic in origin. Chemical composition of aerosols can be extremely variable, depending on the geographical region **[60]**. Nevertheless, typical compositions can be determined. Usually, rural aerosols are assumed to be composed of ammonium sulfate [$(NH_4)_2SO_4$] and insoluble mineral material **[61]**. The urban aerosol is assumed to be composed of 80% rural aerosols and 20% soot **[62]**. Small maritime aerosols are assumed to be 100% ammonium sulfate (gas-to-particle conversion of SO_2), while large particles are pure NaCl (sea spray evaporation) **[63]**.

Emissions from biomass burning include a wide range of gases and particles, in quantities that in some cases can be significant not only on the local scale but also on the global scale. This type of burning can have major effects seasonally on a regional scale, for example, during the months of rice straw burning in Southeast Asia. Reliable estimates of particle emissions from biomass burning depend not only on good estimates of the amount of matter burned, but also on good estimates of emission factors from burning of household fuels together with comprehensive assessments of the conditions of domestic fuel use throughout the developing world. The purpose of these experiments was to examine the emissions that occur when biomass are burned under conditions similar to a small chula typically used in many developing countries.

Generally the aerosols contain carbonaceous aerosols, sulfate aerosols and metal species. About 70% of the mass of particulates related is fine carbon-containing particles. Carbonaceous aerosols consist of fine particles, mostly less than 1 micrometer (μm) in diameter, which are usually classified as black carbon (BC), essentially but not identically the same as elemental carbon (EC) **[10]**, and organic carbon (OC), in which the carbon is bonded to other elements. BC has been proposed as possibly the second most important greenhouse species after CO_2 **[64]** with a positive net radiative forcing of as much as 0.5 W/m2.

A limited work has been done to determine the emission factors of black carbon and organic carbon from biomass fuels in the Indian subcontinent **[65 & 66]**. Despite

uncertainties in the magnitude of BC emissions, one thing is clear from the earlier work that China and India generates a sizeable proportion of global BC emissions, due to the widespread and often uncontrolled burning of coal biomass fuels. **[67].** It was estimated that Asian BC emissions in 2000 were 2.5 Tg, of which China generated 1.1 Tg and India 0.6 Tg. Streets estimated BC emissions in India to be 600 Gg **[68]**. Reddy and Venkataraman estimated Indian BC emissions to be 380 Gg for 1998 – 99 **[69 & 70]**. However, Dickerson expressed that BC emissions could be considerably higher, possibly as high as 2 – 3 Tg, based on atmospheric measurements, especially the observed BC/CO ratios **[71].** The primary carbonaceous emissions from coal-fired plants in India are largely controlled but there are lots of uncertainties in carbonaceous emissions from biofuel combustion in the residential sector.

2.3 Ambient air Quality Standard

Air quality standards for PM to protect public health, were introduced by the EPA in the 1971 and were revised in 1987 **[72 & 73]**. The revised standards included a 24-hour standard set at 150 micrograms per cubic meter (μg/m3) and annual standard set at 50 μg/ m3. This standard was attained when the expected number of exceedance days per year (averaged over 3 years) was less than or equal to 1. Since the establishment of the PM10 standards, a large number of important new studies on the health effects of particulate matter suggested that significant effects, such as premature mortality, hospital admissions, and respiratory illness, occurred at concentrations well below the previous standards. This led to another revision in the standards in 1997 **[74]**.

In December 1996, EPA published a proposal to revise the particulate matter standard. EPA solicited comments for a proposed $PM_{2.5}$ annual standard of 15 μg/ m3 and a PM10 24 hour standard of 50 μg/ m3. In 1997, based on the assessment of the health and other available information, EPA retained the annual PM10 standard of 50 μg/ m3 to protect against effects from both long and short-term exposure to coarse fraction particles **[74]**. With the addition of fine particle standards, EPA found that the original quantitative basis for the level of previous 24 hour PM10 standard was no longer appropriate. However, new health studies and information on coarse particles did not provide a basis for a lower standard level. Based on careful

review of public comments, many of which expressed concern that the 98th percentile might not provide adequate protection against larger particles; EPA changed the form of the PM_{10} 24 hour standard from the 98th percentile to the 99th percentile concentration-based form. Further studies and new results enforcing the health issue of fine particulates resulted in another NAAQS Revision Proposal for particle pollution in November 2009. The proposed revisions were aimed to strengthen the fine particle standard important for both health and visibility, and improve and refocus the coarse particle standards on the particles that are associated with public health concerns. The proposed revisions addressed two categories of particle pollution, fine particles ($PM_{2.5}$) and inhalable coarse particles (PM_{10} - $PM_{2.5}$), which are smaller than PM_{10} in diameter but larger than $PM_{2.5}$. Table 2.2 shows the proposed standards of November 2009 **[75]**.

NATIONAL AMBIENT AIR QUALITY STANDARDS

The finding as Notified on 16th November 2009 by the Central Pollution Control Board (CPCB) in exercise of its powers conferred under Section 6 and Section 25 of the Environment Protect Act, 1986 **[75]**.

Table 2.2: National Ambient Air Quality Standards

Pollutant	**Time-Weighted**	**Concentration in Ambient Air**	
	Average	**Industrial, Residential and other rural area**	**Ecologically Sensitive Area (Notified by C.G.)**
SO2 ug/m^3	Annual* 24 hours**	50 80	20 80
NOx ug/m^3	Annual* 24 hours**	40 80	30 80
PM10 ug/m^3	Annual* 24 hours**	60 100	60 100
PM2.5 ug/m3	Annual* 24 hours**	40 60	40 60
Lead ug/m^3	Annual* 24 hours**	0.50 1.0	0.50 1.0
CO ug/m^3	8 Hours** 1 Hour**	2000 4000	2000 4000
O3 ug/m^3	8 Hours** 1 Hour**	100 180	100 180
NH3 ug/m^3	Annual* 24 hours**	100 400	100 400

Source: Gazette of India, Part II-Section-3-Subsection (i) **[76]**

* Annual Arithmetic Mean of minimum 104

** 24-hourly / 8-hourly values or 0.1 hourly monitored values shall be complied with 98% of the time in the year. However, 2% of the time, it may exceed but not on two consecutive days.

In September 2006, the Agency revised the 1997 standards. The 2006 standards have tightened the 24-hour fine particle standard from 65 μg/ m3 to 35 μg/ m3, and retained the current annual fine particle standard at 15 μg/ m3. Due to a lack of evidence linking health problems to long-term exposure of coarse particles, the agency has revoked the annual PM_{10} standard.

2.4 Biomass Fuel Used: A Global and Indian scenario

BIOMASS FUEL USE: GLOBAL SCENARIO

Over the last 25 years, economic development and modernization has allowed households in wealthier parts of the world to switch to cleaner fuels such as petroleum products (e.g. kerosene, LPG) and electricity **[77]**. However, more than 2 billion people of the world, mostly in poor, developing countries of Asia, Africa and Latin America, still rely on solid unprocessed biomass fuels as the primary source of domestic energy **[47]**. Of these, 800 million people depend solely on crop residues and dung, although in more than 30 countries wood provides 70% of the energy needs, and in 13 countries it is over 90% **[78]**. It has been observed that people cook with biomass at least once a day in half of the world's households **[47]**. Although the proportion of global energy derived from biomass fuel has fallen from 50% in 1900 to around 13% currently, biomass use is increasing among the poor **[79]**.

About 50% of the gross energy consumption in most developing countries occurs in rural areas. The bulk of this energy is derived from locally available traditional energy resources like wood, dung, agricultural residues and charcoal. Modern energy sources such as electricity and petroleum-based fuels generally provide a small part (2 - 10%) of the energy consumed by rural people, mainly because of supply and affordability constraints. While the majority of people at risk of exposure to biomass smoke live in rural areas of the world's poorest countries, this is increasingly becoming a problem of poor urban dwellers. Half of the world's wood harvest is now being used as fuel. Poor families expend more than 20% of

disposable household income to purchase biomass, or devote more than 25% of total household labour to wood collection **[80]**.

BIOMASS FUEL USE: INDIAN SUBCONTINENT

Wood, agricultural residues and dung cake continue to be one of the major energy sources in India and many other developing countries. The agricultural wastes which have no particular use and lie in the field unutilized and cannot be composted easily end up as fuel. Hay, jute stick, paddy husk, wheat stalks, dried leaves of mango, jack-fruit, coconut, palm and sugarcane, bamboo leaves, branches and roots, cotton roots and stalks, root zone of millets, bajra, wheat husk, lops and tops of fruit trees which are annually pruned are used as fuel in rural areas.

Biomass contributes to one-fourth of the total energy consumed in India. About 33.6 million or 17.5% of all Indian homes use LPG as their primary cooking fuel whereas 78% homes rely on biomass fuels **[81]** and another 3% on coal [82]. Overall, three-quarters of the households of the country still use traditional biomass fuel for cooking and space heating **[83]**. The number of biomass users in the country is at present 585 million and it is expected to reach 632 million by 2030 **[84]**. Thus, biomass fuels will continue to be an important source of household energy in future. Biomass is extensively used in other south Asian countries also. For instance, 88% of Bangladeshis, 80% of Nepalese, 72% of Pakistanis and 67% of Sri Lankans are dependent on biomass as main household energy source **[85]**.

2.5 Conclusions from Literature Review

Despite the numerous regulatory approaches that have been promulgated to control airborne pollutants, $PM_{2.5}$ still remains a major problem in rural areas of India. Rural area of Madhya Pradesh faces severe fine particulate problem, with as many as 26 states in nonattainment of the fine particulate standards in India.

Literature provide that $PM_{2.5}$ emission data is very limited for many type of biomass burning, in many states in India, particularly in central India, a part that frequently experiences biomass burning. On the other hand knowledge of characteristics of biomass burning particles (such as particle size distribution and emission factors) is still limited and the role of specific factors affecting the characteristics of biomass burning particles is not clear. Against this backdrop, the findings can serve as an eye-opener. The need of the hour is proper understanding of the complex systems

contributing to the energy budget. The improved understanding and characterisation of aerosols emitted from household biomass burning is urgently needed.

Literature also provides strong evidence linking fine particulates to health issues, stressing the need to control the emissions. Millions of poor people of the country who cannot afford cleaner fuel have no other alternative but to use traditional biomass for cooking and room heating. In the process, their health becomes adversely affected, as demonstrated in the section 2.2.2.3 of chapter 2 of this study. The victims are generally women who cook with these fuels and their children who spend a long time with their mothers. The administrators, policy makers as well as the victims are largely unaware about the harm biomass fuels are causing on their health. In fact, air pollution and related health hazards are considered as a problem of urban life whiles the villages are treated as abode of peace, tranquillity and freshness. No wonder, there is no standard for indoor air quality in the country. Therefore, there is no question of maintaining the indoor emission level within standard. Moreover, since the victims are mainly women and children and that too from poor rural areas, they suffer in silence while everybody seems busy with so many 'important' issues.

In short, I could not find any extensive and comprehensive receptor source meteorology integrated $PM_{2.5}$ studies for this biggest state of India to the best of my knowledge. Understanding the aerosol behaviour and quantifying the relative contributions of various pollutant sources in a spatially specific air shed becomes critical in developing control and mitigation strategies to meet regulatory standards, improve public health, and safeguard the environment. The knowledge of characteristics of particle size distribution and emission factor from biomass burning is needed to get a better understanding of the impact assessment which lays out a framework that incorporates all the necessary steps to understand the pollutant thoroughly for the design of an effective and viable control by regulators and air pollution managers.

3.1 Introduction

This study was conducted in order to determine the chemical properties of aerosol emitted from biomass fuel burning and to evaluate the budgets for Black Carbon and Organic Carbon for representative site-by-site scenario using the activity data available from literature.

Biomass samples used for this study were already collected by Radio and Atmospheric Sciences Division of National Physical Laboratory, New Delhi-110012 for an on-going DST-project entitled "Evaluation of emission factors and budget of gases and particulate matter of relevance to climate change emitted by fuel particularly biomass used in India by rural sector and small scale industries".

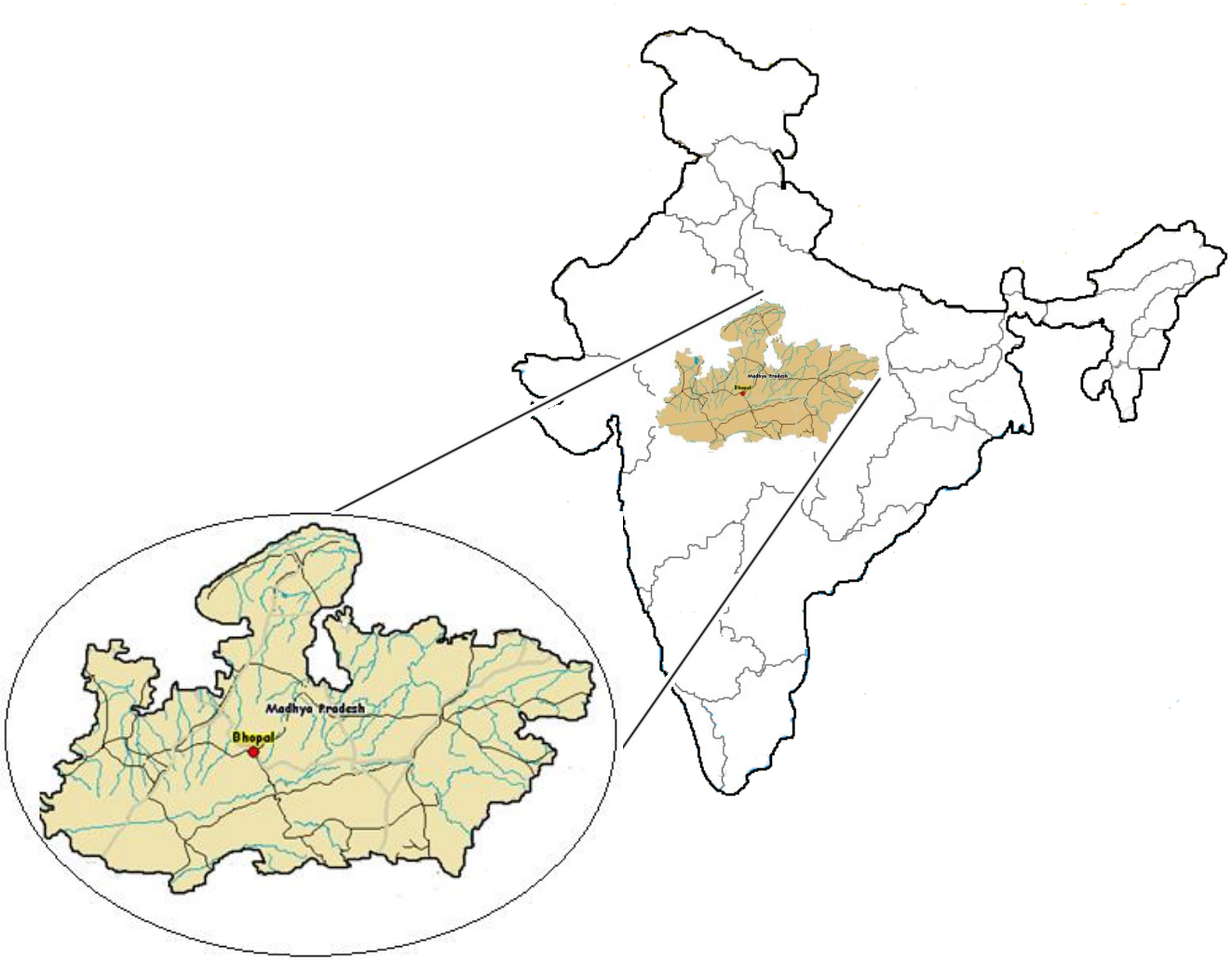

Fig. 3.1: Location map showing the study area

Biomass samples were collected at district level by visiting various rural places of the state Madhya Pradesh and got the biomasses used in these areas by asking the people of these localities. These samples were analyzed for the present study to determine the chemical properties of aerosol emitted from biomass burning. The collected biomass fuel samples are given in Table. Fig 3.1 and 3.2 shows the map of India with highlighted state and the representative sampling sites in Madhya Pradesh.

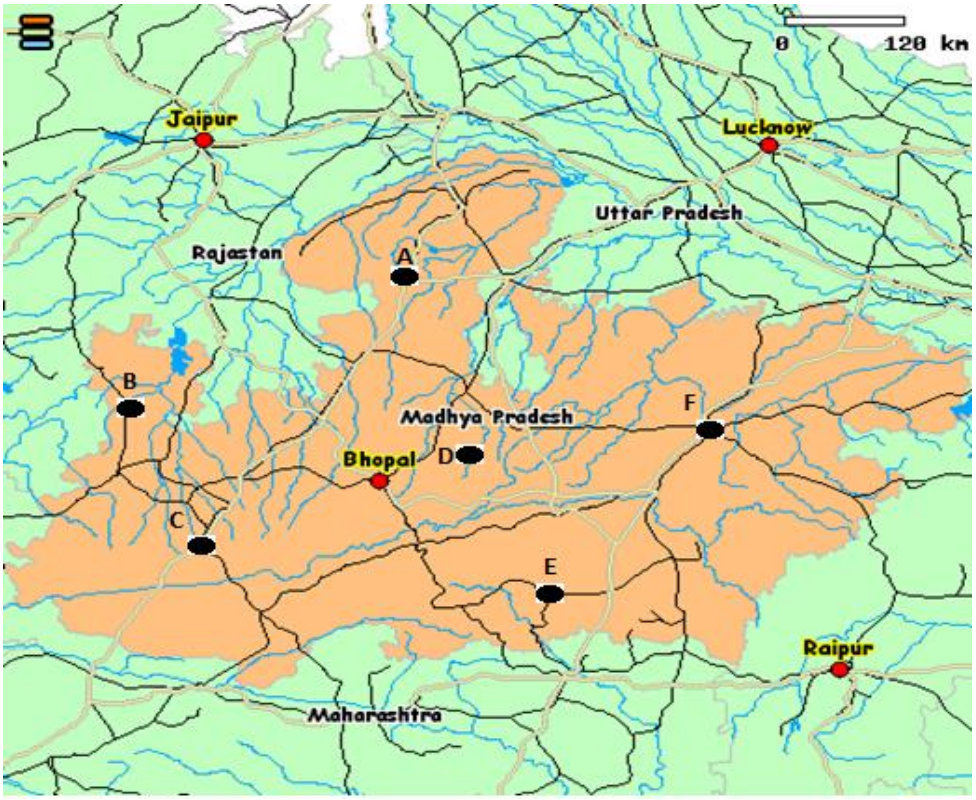

Fig. 3.2: Location of representative sites selected for Madhya Pradesh

For this study samples were collected from following representative locations of the Madhya Pradesh.

1. Shivpuri (25^{o} 48’ 861 N, 77^{o} 45’ 860 E).
2. Mandsaur (24^{o} 13’ 574 N, 74^{o} 59’ 634 E)
3. Indore (22^{o} 42’ 071 N, 75^{o} 43’ 709 E)
4. Raisen (22^{o} 54’ 501 N, 77^{o} 39’ 015 E)
5. Seoni (22^{o} 04’ 448 N, 79^{o} 37’ 783 E)
6. Katni (23^{o} 54’ 417 N, 80^{o} 06’ 391 E)

Madhya Pradesh: An Introduction

Madhya Pradesh (MP), in its present form, came into existence on November 1, 2000, following its bifurcation and the creation of the new state of Chhattisgarh. Spread across an area of 308,000 km^2, MP is the second largest state of the country, constituting 9.4 % of the total geographical area. It is bordered by Rajasthan, Uttar Pradesh, Chhattisgarh, Maharashtra and Gujarat.

The state straddles the Narmada River, which runs east to west between the Vindhya and Satpura ranges. The mountains and the Narmada are the traditional boundary between north and south India.

According to Census 2001, the state had a population of 60.33 million, which is about six per cent of the country's total population. Its density is around 196 per sq km. Sex ratio of Madhya Pradesh is 920/1000 males with a Literacy Rate of 64.1%. With a Net State Domestic Product (NSDP) of $9.8 billion, Madhya Pradesh is the ninth largest economy in India. The cost of basic infrastructure and skilled manpower is relatively low as compared to other states. Madhya Pradesh offers one of the lowest labour cost-to-sales ratios in the country. It has also successfully leveraged private investment in transport infrastructure.

The state government has initiated steps to strengthen and reinforce a conductive investment climate for potential investors through progressive policies, simplification of procedures and investment incentives. It is promoting a Greenfield Special Economic Zone (SEZ) at Indore.

The major crops of state are Soybeans, Gram, Pulses like Masoor, Arhar, etc. and major minerals are Copper ore, Lime stone, Manganese Ore, etc.

Key industry sectors in Madhya Pradesh are cement, textiles, mining and edible oil. The state is one of the largest producers of cement and a leading producer of edible oil. Many automobile and pharmaceutical companies have also shown interest to establish/ expand their production base in the state.

Key sectors include mineral and stores, forest-based industries, IT/ITeS sector, agriculture, cement, auto and auto components, textiles, tourism and power generation. These sectors present opportunities and form the core of investments flowing into the state.

Some of the leading companies having a presence in the state include ACC, Aditya Birla Group, Cadbury India Ltd, Coca Cola India, Nicholas Piramal India Ltd, Eicher Motors Ltd, Procter & Gamble (P&G), Hindustan Motors, and Bharat Heavy Electricals Ltd.

3.2 Sampling and Selection

Generally two sites were selected for biomass sampling in a district during experiment, but this study limit to the representative points selected in the state Madhya Pradesh and their characterization & analysis by the Dilution Sampler system.

3.3 Experimental Setup

The experimental setup (generally termed as Dilution Sampler), was designed by G. Uma Maheshwara Rao (1999) which later modified by C. Venkataraman in 2001 **[86]** and fabricated at Vayubodhan to carry out the burning of typical biomass fuels samples (100g).

The dilution sampler was designed to meet the considerations needed for accurate aerosol size-distribution measurements based on those identified for organic aerosols. The dilution source sampler possesses sufficient dilution, cooling of emissions to ambient temperature and enough residence time to allow condensation process to proceed to completion.

The features of the sampler include a rectangular hood (0.8m × 1.3 m), large enough to cover the largest stove and entrain the emissions without spillage since biomass fuel combustion is natural-convection driven. The rectangular hood is connected to a circular duct (D) of 0.163 m for collection of emission, dilution ratios needed for cooling post combustion gases (200 – 700°C) to 40°C is 46x (16x – 66x), residence time for 99% condensation of semi volatile organic species is 300 s. The source sampling system is constructed with stainless steel (SS-304) material to minimise the contamination and also to withstand through cleaning, heat treatment between uses, so that exhaust material deposited from one source will not contaminate the next set of samples. Teflon gaskets have been used in place of other rubber gasket to prevent further contamination. (Fig. 3.3)

The setup also consists of a low volume sampler (LVS), located just below the dilution chamber and connected to stack sampling ports. Their approximate locations are shown in Appendix IV. The LVS was placed on a table to keep the inlets of all the filter samplers at a uniform height (~0.5 m). The two cups of low volume sampler were separated by a T-tubing just below the dilution chamber. Air is drawn from the duct in a way that from the total pollutant sampling rate of 46.7 L min^{-1} (0.0477 m^3/ m), 30 L min^{-1} was allowed to pass through a Teflon filter paper placed over a quartz filter paper, whereas rest of 16 L min^{-1} was passed through a quartz filter paper. The pollutant sampling rate was determined by the particle collection instruments, and an average dilution ratio of 50 (residence time of 300 s) allowed sizing of the plenum (0.272 m^3) and the nozzle diameter (25.7 mm) required for isokinetic sampling emissions to the outside. A Velocity Monitor is used to record the pressure flow and combustion temperature. The setup also comprises a Stack Monitor so as to record upper stack temperature and lower stack temperature during biomass burning. These parameters will further help to generate emission factor inventory for different biomass samples.

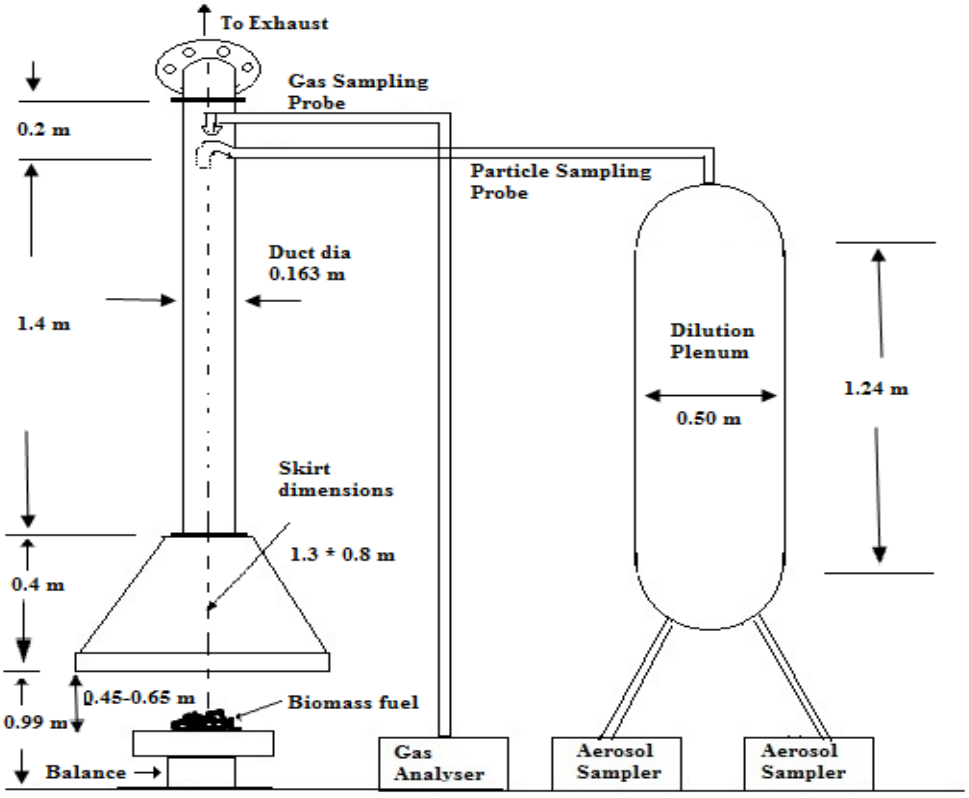

Fig. 3.3: Schematic diagram of lab scale simulated biomass burning setup

(Source: C. Venkataraman, 2001)

The entrainment of lab air into the duct along with the combustion emissions gave average dilution ratios of 40 - 60 (calculated from measured combustion and duct temperatures) and allowed cooling of the combustion gases to 2 - 3°C above ambient in the dilution plenum. A dilution plenum provides additional residence time for complete quenching. The extraction flow rate in the duct was adjusted by the fan rpm to provide this dilution, subject to a maximum of velocity of 1.5 ms^{-1}. The midpoint velocity was measured by a platinum hot-wire sensor, calibrated for total flow rate using a standard orifice calibrator. A duct diameter of 0.163 m was provided resulting in an average volume flow rate of 0.022 m3 s^{-1} and Reynolds number of 10:800 (at 50 °C).

3.3.1 Experimental Protocol

The experiments were performed during February to May 2011. Pre-desiccated and pre-weighed Whattmann Quartz micro fibre filters were used as collecting surfaces in the case of biomass burning sampling. The quartz (Whattmann grade QMA, Size 4.5cm) and Teflon (Whattmann PFTE 46.2mm) filter paper were weighed under controlled temperature and humidity conditions before and after the sampling in order to determine the concentrations of particulate matter with Sartorius microbalance (Fig. 3.6). Filters were conditioned in desiccators for 24 hour before and after sampling. The quartz filters were wrapped in aluminium foil and baked in an oven at temperatures > 600° C for 24 hours prior to sampling to remove organic contaminants. Each filter remained in its foil envelope until it was loaded on the sampler prior to the start of the burn.

During stack burns, the dilution sampler suction pump (attached with LVS) and suction pump for SOx - NOx estimation were turned on 30 seconds prior to ignition and turned off when the fire was considered extinguished based on visual observations. A double set of filters (one was quartz and another teflon) was used to remove the error in total carbonaceous aerosol obtained over single quartz filter paper as quartz has a properties to combine with volatile organic gases to form secondary aerosols. Filter sample times were typically 3 to 30 min, depending upon the sample type and properties.

Following the experiments, the exposed filters were removed from the sampler and folded into half face to face and again placed in a plastic bag and kept in a

Desiccators (Fig. 3.6) (Since airborne particulates and filters used in the impactor have hygroscopic characteristics) and the trace gas absorbed media stored in refrigerator before being analysed. Aerosol mass in each filter was measured using a gravimetric method by the mass difference before and after sampling. After PM collection, all filters were conditioned and re-weighed. The difference in weight before and after sampling gave the value of RSPM. Finally the concentration of PM_{10} ($\mu g/m^3$) and then emission factors (g/kg) in the designated size range is calculated by dividing the weight gain of the filter by the volume of air sampled.

For the extraction, half of the filter (0.0208 cm^2) was cut from Teflon filter and extracted with deionized water (20 ml) by using ultrasonic system (Oscar Ultrasonic Cleaner; Fig. 3.6) for 90 minute; finally the volume was made 25ml by adding deionized water. Then the samples were filtered into pre-cleaned polypropylene bottles. The filtered samples were preserved at 4ºC in a refrigerator until analysis. Extracts were analyzed for inorganic species (Cl^-, SO_4^{2-}, NO_3^-, Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+}) using Dionex DX-3000 series ion chromatography (IC) systems. The cation IC featured an IP 20 isocratic pump, CD 20 conductivity detector, CG12A guard column CS12A separation column and a CSRS-ULTRA1 suppressor. The anion IC featured a GP 40 gradient pump, CD 20 conductivity detector, AG4A-SC guard column, AS4A-SC separation column, and an ASRS-ULTRA suppressor. The ICs were calibrated by injection of aqueous standards prepared in the NPL at Centre for Global and Climate Change.

3.3.2 Analytical Methods

A) Characterization of water soluble ions

The Ions (cations and anions) present in water soluble aerosols samples were determined by using Ion Chromatograph (DIONEX, ICS-3000). The ion chromatograph is based on the separation of a mixture of compounds into its individual components i.e. ions based on their relative interactions with an inert matrix. A mobile phase, usually a liquid is used to transport the analytes through the stationary phase. Samples were analyzed for major anions (F^-, Cl^-, NO_3^-, SO_4^{2-}) and cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, NH_4^+). The anions were separated on Ionpac AS11-HC (4X250 mm) analytical column and AG11-HC (4x50 mm) guard column, in conjunction with an Anion Self-Regenerating Suppressor ASRS-300 (4 mm), using

100 mM NaOH as an eluent. Cations were separated on Ionpac CS17 analytical column and CG17 guard column, in conjunction with a cations Self-Regenerating Suppressor CSRS-300 (4mm), using 20 mM methanesulphonic acid as an eluent. The self–Regenerating suppressor is used for the post-column eluent suppression. Eluent used for the separation of anion and cation were 20 mM NaOH (50% w/w) and 5 mM MSA at the flow rate of 1.5 and 1ml/min respectively. The conductivity detector was CD-20 used for the detection of eluted analyst. The IC system was fitted with a 25µL sample loop that was used to introduce the sample manually. All of the standard solutions were filtered using 0.45-µm nylon membrane filters (Millipore) and degassed by ultra-sonication The glassware used in the extraction and analysis were washed several times with de-ionised water to remove any adhered impurities. Chromatographic data were collected at 5Hz and chromatograms were processed using the Chromeleon software. The chromatogram of anions is shown below for example.

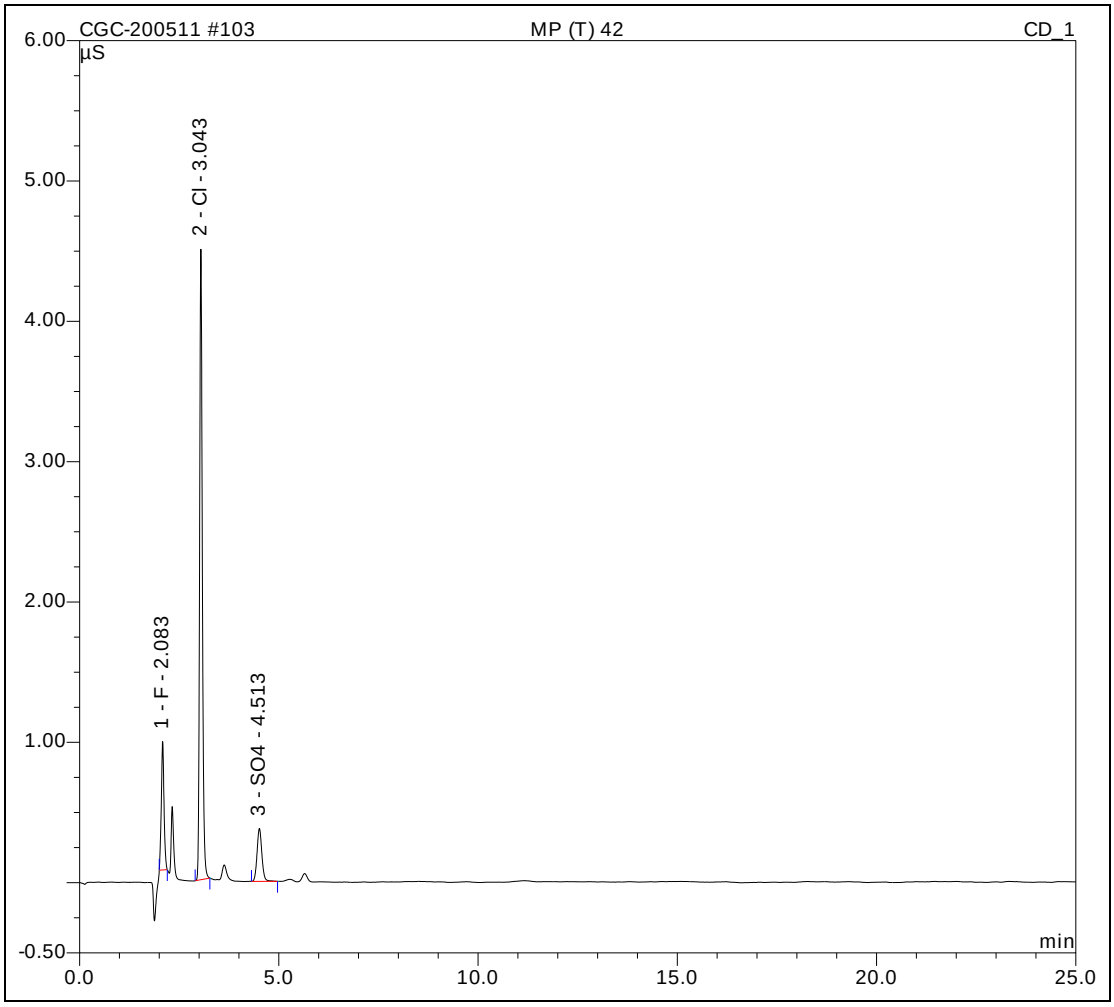

Fig. 3.4: The chromatogram of a crop residue named chola

B) Characterization of carbonaceous aerosol

The carbonaceous species i.e. TC, EC and OC present in aerosol sample were determined by using DRI Model 2001 Thermal/Optical Carbon Analyzer following the Interagency Monitoring of Protected Visual Environments (IMPROVE) thermal evolution protocol and assuming carbonate carbon in the samples to be negligible. The operation of this Analyzer is based on the preferential oxidation of organic and elemental carbon (OC and EC) compounds at different temperatures. Its function relies on the fact that organic compounds can be volatilized from the sample deposit in a non-oxidizing helium (He) atmosphere, while EC must be combusted with an oxidizer. The analyzer operates by:

1) Liberating carbon compounds under different temperature and oxidation environments from a small sample punch taken from a quartz-fibre filter;
2) Converting these compounds to carbon dioxide (CO_2) by passing the volatilized compounds through an oxidizer (heated manganese dioxide, MnO_2);
3) Reducing CO_2 to methane (CH_4) by passing the flow through a methanator (hydrogen-enriched nickel catalyst); and
4) Quantifying CH_4 equivalents with a flame ionization detector (FID).

The thermal/optical reflectance method of carbon analysis developed by Huntzicker *et al., (1982)* is studied at temperatures 120, 250, 450 and 550°C in a pure helium atmosphere, then to combustion at temperatures of 550, 700 and 800°C in 2% oxygen and 98% helium atmosphere. In this method a 0.5 cm^2 punch from micro QM/A filter paper was used for the analysis. The organic carbon was volatilized from the filter sample by heating in an atmosphere of pure helium at temperatures of 300, 400, and 600°C. Then elemental carbon was determined by heating the sample in an atmosphere 2% O_2, and 98% He. The CO_2, evolved at temperature of 400, 550, and 700°C was measured in the same manner as for organic carbon. To correct for pyrolytic conversion of organic carbon to elemental carbon (charring), which occurred during the organic analysis, the filter reflectance was continuously monitored with a He - Ne laser (633 nm). The correction was taken to be the amount of elemental carbon oxidation necessary to return the filter reflectance to its initial value (i.e., before pyrolytic conversion of organic to elemental carbon occurred).The thermo gram of OC and EC is shown on the next page for example.

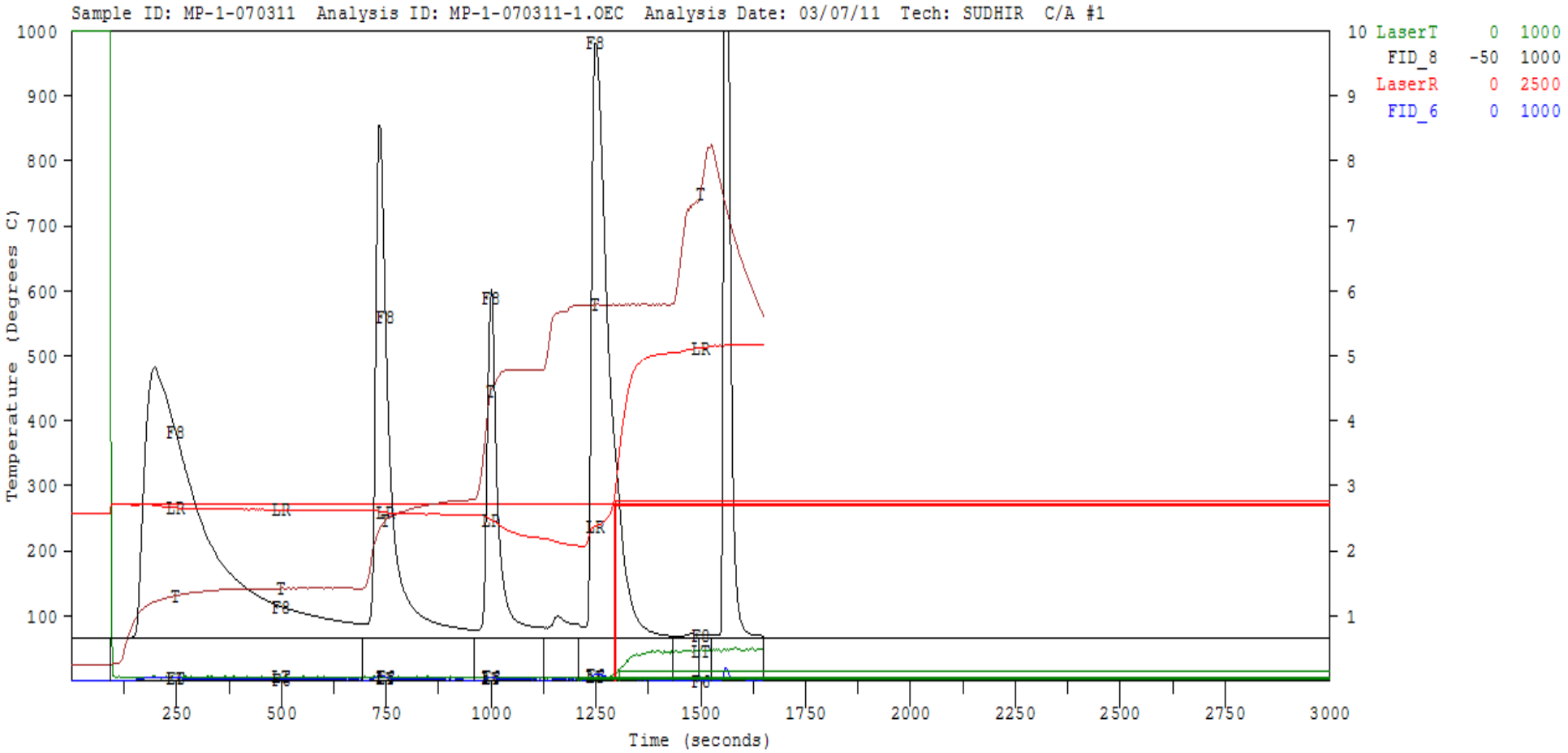

Fig. 3.5: The thermogram of fuel wood named khakra

3.3.3. Calibration

Calibrations of the Ion-Chromatograph (Anions and Cations) were carried out with standard solutions covering the desired concentration range of the analyte in the sample. Working standards were prepared from stock standard solutions procured from DIONEX, USA for calibration and these solutions were diluted up to working range.

3.4 Equipment/ Instrument used

The instrument and equipment used for the analysis of aerosols are listed in the table 3.1 and represented in Fig. 3.6

Table 3.1: Various Equipment/Instrument used

S.No.	Equipment/Instrument Name	Model and Remark
1	**Desiccators**	SECADOR Desiccators To remove moisture from filter papers
2	**Ion Chromatogram**	DIONEX ICS-3000 To determine concentration of ionic species in aerosol
3	**OC/EC Analyser**	DRI Thermal/optical carbon analyzer (MODEL 2001 A) To determine EC/OC in aerosol
4	**Deionised water system**	MILLIPORE ELIX Deionised water system
5	**Micro Balance**	SARTORIUS microbalance To determine weight of total particulate matter on filter paper
6	**Ultra Sonicator**	OSCAR ultrasonic cleaner To extract the ions from the aqueous solution.
7	**Syringe Filter**	STERLITECH Stainless Steel Syringe Filter To filter the sonicated extract

Fig.3.6: Equipment and instrument used: 1.SECADOR Desiccators; 2.DIONEX ICS-3000 Ion Chromatogram; 3. DRI Thermal/optical carbon analyzer (MODEL 2001 A); 4.MILLIPORE ELIX Deionised water system; 5.SARTORIUS microbalance; 6. OSCAR ultrasonic cleaner; 7.STERLITECH Stainless Steel Syringe Filter

The biomass samples were collected from six representative sites from Madhya Pradesh (Fig. 3.1 & 3.2), India (Shivpuri, Mandsaur, Indore, Raisen, Seoni and Katni) and burnt in natural condition by using the designed setup (Fig. 3.3 and appendix III) to study the chemical properties of aerosol emitted.

4.1 Biomass distribution over Madhya Pradesh

On the basis of all the samples (357), collected from 50 district of Madhya Pradesh (appendix I), dung cake is the most widely used biomass fuel in Madhya Pradesh (Fig. 4.1). During this study, it is also observed that there is a common practice of using Babool as Fuel wood. Fuel wood e.g., Mango (3.92%), Polas (3.36%), Neem (2.52%), Khakra (2.8%) and Ber (2.24%) are also used as basic fuel wood in Madhya Pradesh (Fig. 4.1). According to TEDDY, 2007 report, annual consumption of crop residue, fuel wood and dung cake for Madhya Pradesh are 5.7 Mt, 32.6 Mt and 6.2 Mt respectively.

Present analysis is based on survey at rural levels and each data are representative of at least two villages consisting of approximately 2000 – 20,000 households per village in a district (appendix I). Based on survey and results, it is observed that approximately 90% of rural households use biomass fuel as their main source of energy in Madhya Pradesh. It has been noticed that total biomass fuel usage pattern has not changed. Several factors including economic, technical, social and traditional constraints affect the household fuel usage. Along with fuel wood and agricultural residue, dung cake is mostly (80 - 90%) used as energy by rural households over Madhya Pradesh. This information may help to develop mitigation strategy to reduce atmospheric as well as indoor pollution.

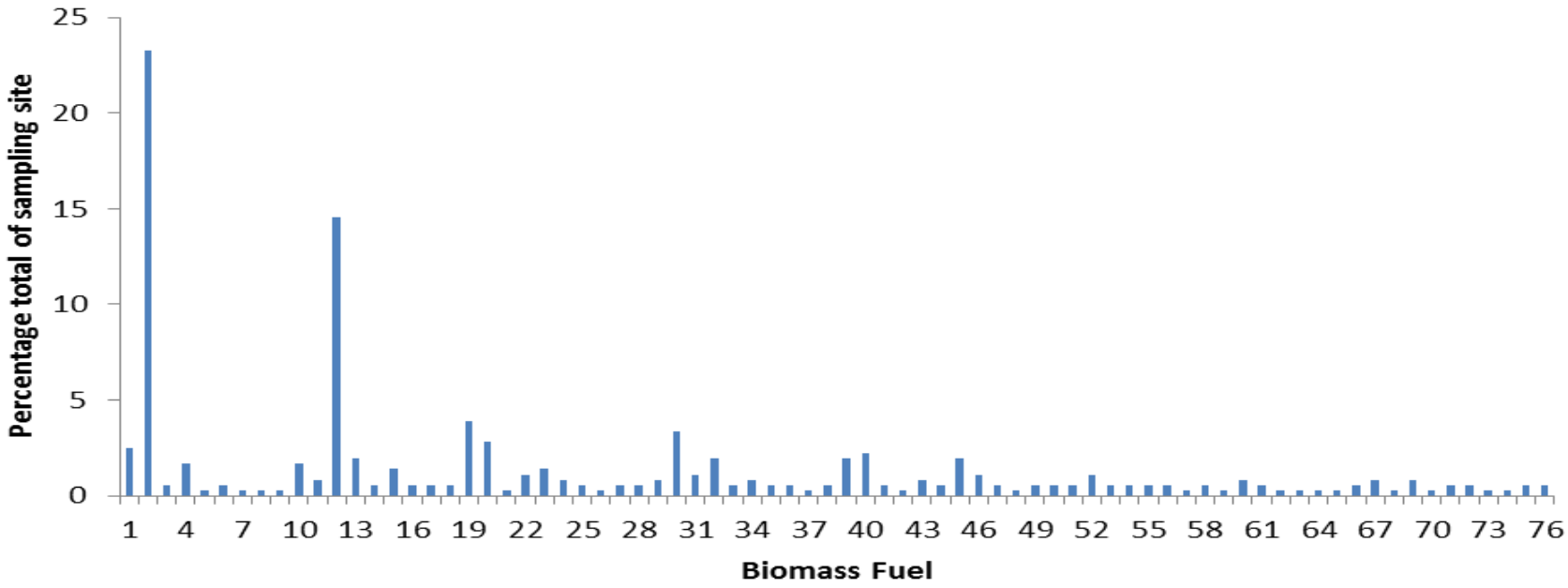

Fig. 4.1: Distribution of Biomass fuel uses in Madhya Pradesh: 1. Azadirachta indica (*Neem); 2.Cow Dung; 3.Dho; 4.*Acacia catechu (*Khair); 5.Jungal Jalebi; 6.*Zizyphus xylopyra (*Ghont); 7.Pakhi Babool; 8.Dhokri; 9.*Balanites roxburghii (*Hingot); 10.Chola; 11.Keekar; 12.*Acacia arabica (*Babool); 13.Basram; 14.Arhar; 15.* Prosopis juliflora (*Khejra); 16.Shymala; 17.Lakhuna; 18.* Phoenix sylvestris (*Khajur); 19.* Mangifera indica (*Mango); 20.Khakra; 21.Affeam; 22.Mustard; 23.Zea maize (Makai); 24.* Wendlandia exserta (*Til); 25.Dhaki Neem; 26.Sagon; 27.Hajera; 28.Bor; 29.* Woodfordia floribunda (*Dhawara); 30.Polas; 31.Mohua; 32.Cotton; 33.Mirch; 34.Tuhar; 35.Sitaphal; 36.Shiraali; 37.Bondaria; 38.Shiv Babool; 39.Su babool; 40.* Zizyphus jujuba (*Ber); 41.Kahu; 42.Landya; 43.Amla; 44.Sajara; 45.Tendu; 46.Saj; 47.Giria; 48.Gulsitara; 49.Sawla; 50.Kari; 51.Saja; 52.Renja; 53.Sal; 54.Bhilma; 55.Dhodra; 56.Kirkarh; 57.Gakhol; 58.Sathkatha; 59.Khansaru; 60.Gorah; 61.Kauwa; 62.Bhera; 63.Papru; 64.Kema; 65.Dudhi; 66.Rorue; 67.Tik; 68.Ramphul; 69.Clula; 70.Sarrai; 71.Umra; 72.Kathla; 73.Gulmahadi; 74.Latwa; 75.Khinna; 76.Eucaliptus; 77.Chiroal*

4.2 Aerosol emitted from different biomass

4.2.1 Emission Factor for PM

Fig. 4.1 shows the emission factor of particulate matter (PM) from simulated burning of biomass fuel sample i.e. crop residue, fuel wood and dung cake collected from Madhya Pradesh, India (Shivpuri, Mandsaur, Indore, Raisen, Seoni and Katni).

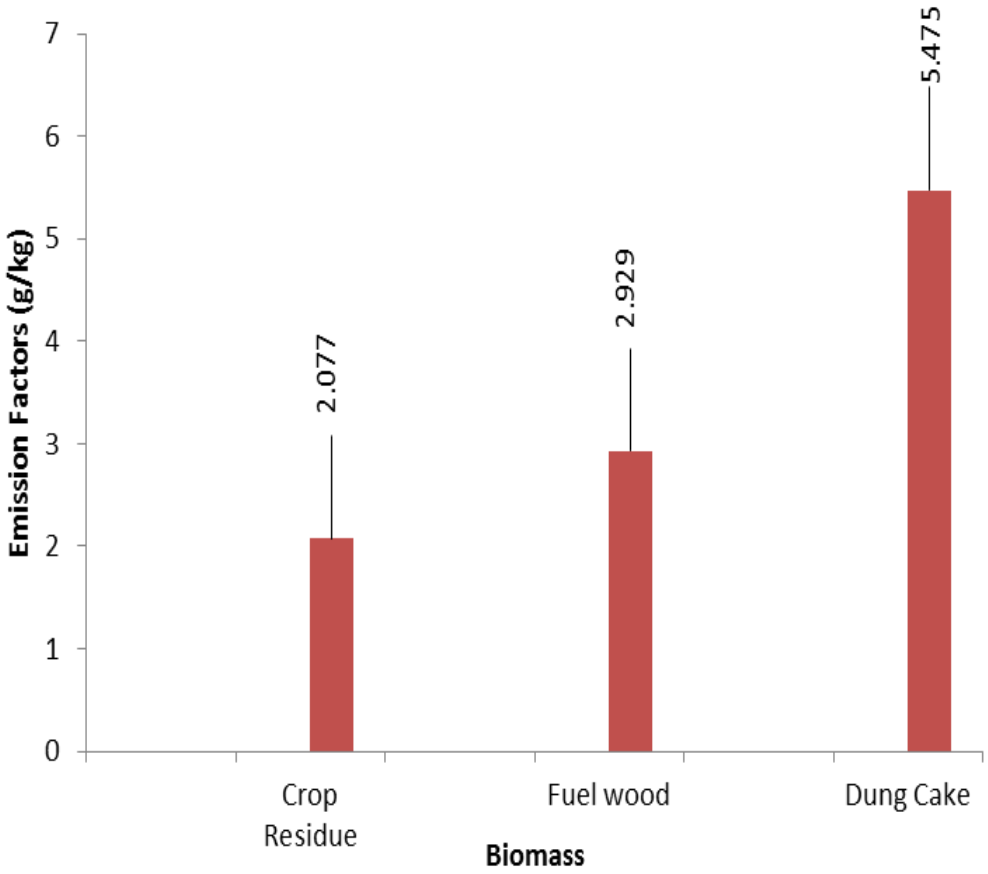

Fig. 4.2: Variation of emission factor (g/Kg) of PM in various biomass fuels

The average emission factors for PM emitted from Crop Residue, Fuel Wood and Dung-cake are 2.07 ± 1.85, 2.92 ± 3.90 and 5.47 ± 2.75 g/kg, respectively.

4.2.2 Characteristics of water soluble ions emitted from different biomass-fuels

Water soluble ionic concentration of PM analyzed using Ion Chromatographic technique to estimates the ionic species in aerosol emitted from burning of various crop residue, fuel wood and dung cake collected from rural area of Madhya Pradesh, India. Water soluble cations i.e., Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+} and anions i.e., F^-, Cl^-, SO_4^{2-}, NO_3^- are generally present in all the biomass samples (Appendix II).

4.2.2.1 Cations

Figure 4.3 shows the concentration of water soluble cations i.e., Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+} present in simulated burning of crop residue, fuel wood and dung cake collected from Madhya Pradesh. In the present study, the average concentration of Na^+ is observed highest in all the biomass samples collected from Madhya Pradesh as compare to other ions (Fig 4.2).

The Na^+ value ranges from 0.027 to 0.684 g/kg with an average value of 0.141 g/kg. The other cations i.e., NH_4^+, K^+, Mg^{2+} and Ca^{2+} ranges from 0.002 to 0.156 g/Kg. The average concentration of Na^+, K^+ and NH_4^+ are observed higher in dung-cake when compared with Mg^{2+} and Ca^{2+} whereas in fuel-wood the average concentration of K^+ are observed higher. The emission factor of magnesium (Mg^{2+}) is observed lowest in the entire biomass sample. The emission factor for Ca^{2+} in fuel wood and dung cake is almost equal. As expected the concentration of K^+ ions are present in all the biomass fuels **[87 & 88]**. The concentration of NH_4^+ observed higher in dung-cake when compared with Crop Residue and Fuel Wood and it might be due to nature of feeding material of animal.

Fig. 4.4 shows the percentage emission of cations of typical bio-fuels collected from Punjab and these are in order of $Na^+ > K^+ > NH_4^+ > Ca^{+2} > Mg^{+2}$. In these typical samples, result represent that the emission of Na^+ is higher and it might be due to higher sodium concentration present in soil, water and plant system.

4.2.2.2 Anions

Fig. 4.4 shows the concentration of water soluble anions i.e. F^-, Cl^-, NO_2^-, SO_4^{2-}, NO_3^- and PO_4^{2-} in aerosol sample obtained from simulated burning of Crop Residue, Fuel Wood and Dung-cake collected from Madhya Pradesh.

In the present study, average concentration of Cl^- is observed higher in all the bio-fuels samples collected from Madhya Pradesh and ranges from 0.011 to 0.729 g/kg with an average value of 0.182 g/Kg. The other anions i.e. F^-, SO_4^{2-}, NO_3^- and PO_4^{2-} ranged from 0.006 to 0.299 g/kg (Fig 4.5). The average concentration of Cl^- and F^- are observed higher in all the biomass samples when compared with NO_3^- and SO_4^{-2}. The highest concentration of Cl^- in dung cake may be due to the use of ammonium

chloride fertilizer in crop field to enhance production as rice husk and other crop residue are used in dung-cake making. Other reasons can be of higher salt concentration present in soil, water and plant system. Fig. 4.4 shows the percentage emission of anions of typical bio-fuels collected from Madhya Pradesh and these are in order of $Cl^- > PO_4^{2-} > F^- > NO_3^- > SO_4^{2-}$

Percentage of emission contribution of water soluble anions i.e. F^-, Cl^-, SO_4^{2-}, NO_3^- and PO_4^{2-} in different state are summarized in Table 4.3. The average of emission of F^-(0.012), Cl^-(0.060), SO_4^{2-}(0.005), NO_3^-(0.010) and PO_4^{2-}(0.054) % are estimated respectively from Madhya Pradesh. It is to be noted that the percentage of emission of Cl^- is higher in dung cake as compare to other biomass samples. The reason can be of presence of more hard water or chlorinated food type used for cattle in that region. On the other way, the percentage emission contribution of PO_4^{2-} is found only in the village Seola Kala of district Seoni from Madhya Pradesh. The reason can be of more use of ammonium phosphate as fertilizer which ultimately enters into the body of grazing animals.

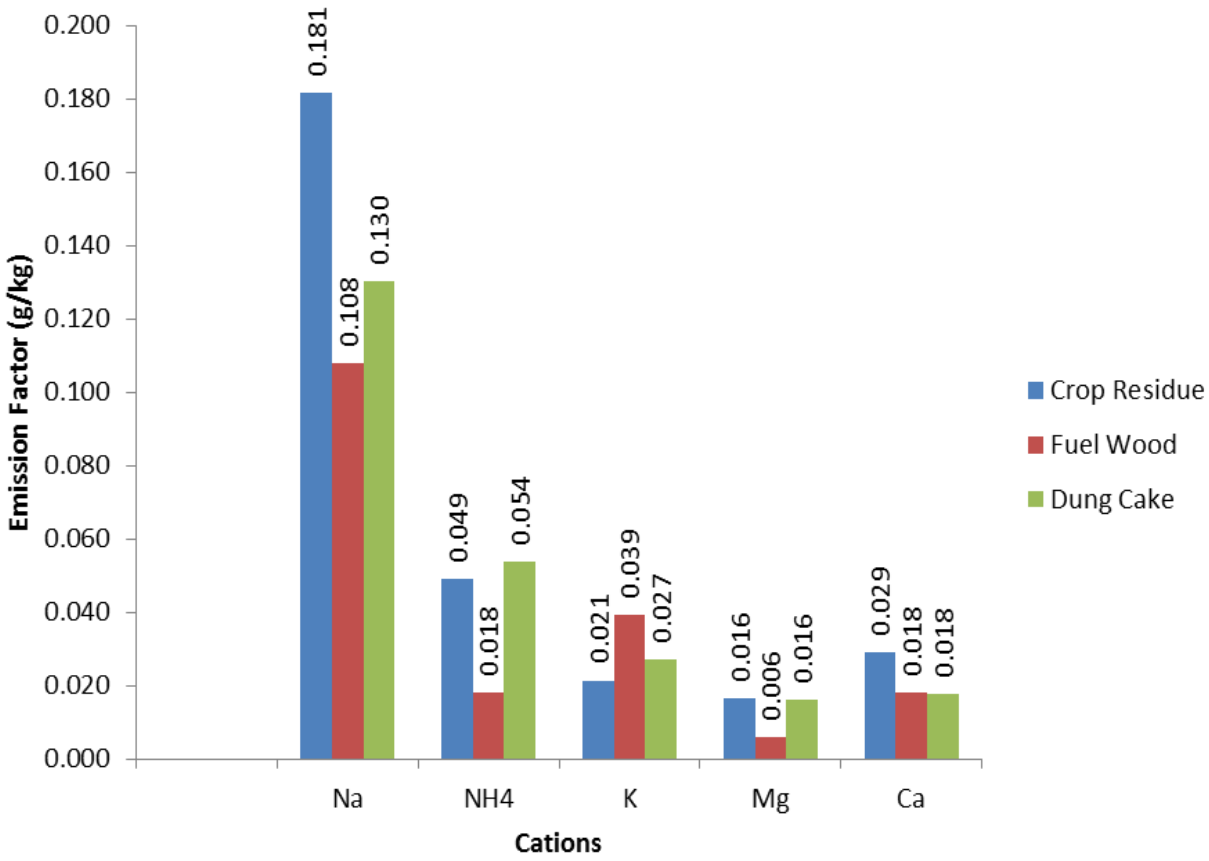

Fig. 4.3: Emission factor (g/Kg) of cations in various biomass fuels

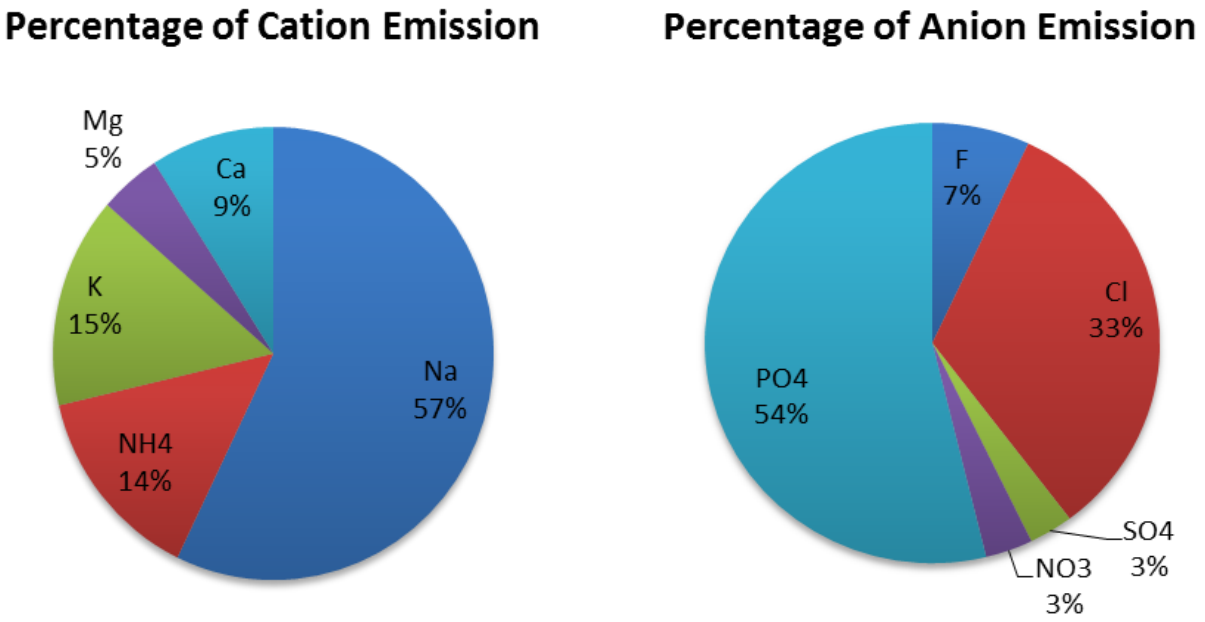

Fig. 4.4: Percentage emission of cations and anions in various biomass fuels

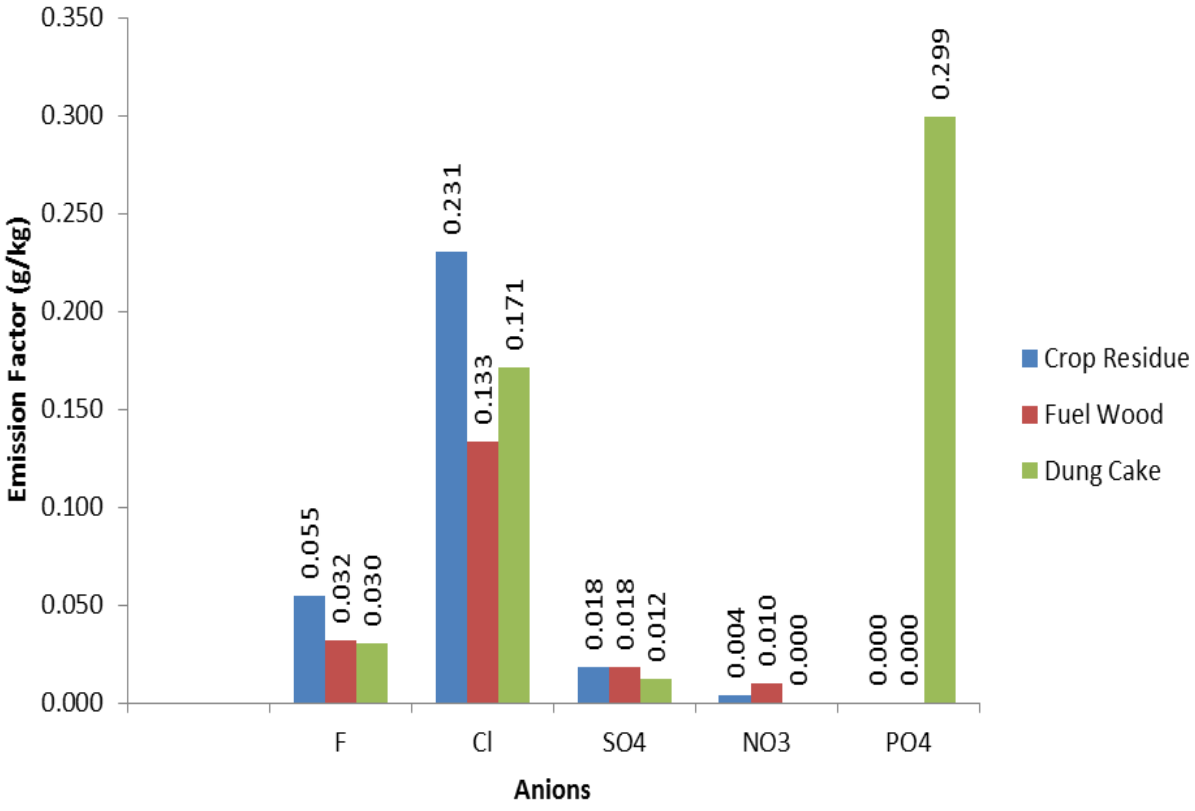

Fig. 4.5: Emission factor (g/Kg) of anions in various biomass fuels

4.2.3 Characteristics of carbonaceous aerosol emitted from different bio-fuels

The Concentration of organic carbon (OC), elemental carbon (EC) and total carbon (TC) of the collected aerosol samples of typical biomass fuels of Madhya Pradesh was analyzed using OC/EC Carbon Analyzer (DRI-2001).

Average emission factors of OC emitted from crop residue, fuel wood and dung cake collected from Madhya Pradesh are 0.74, 1.41 and 2.55 g/kg, respectively (Fig. 4.7). Similarly, average emission factors of EC are estimated as 0.27, 0.34 and 0.20 g/kg from crop residue, fuel wood and dung cake respectively. Higher concentration of OC is released from dung cake burning as compared to fuel wood.

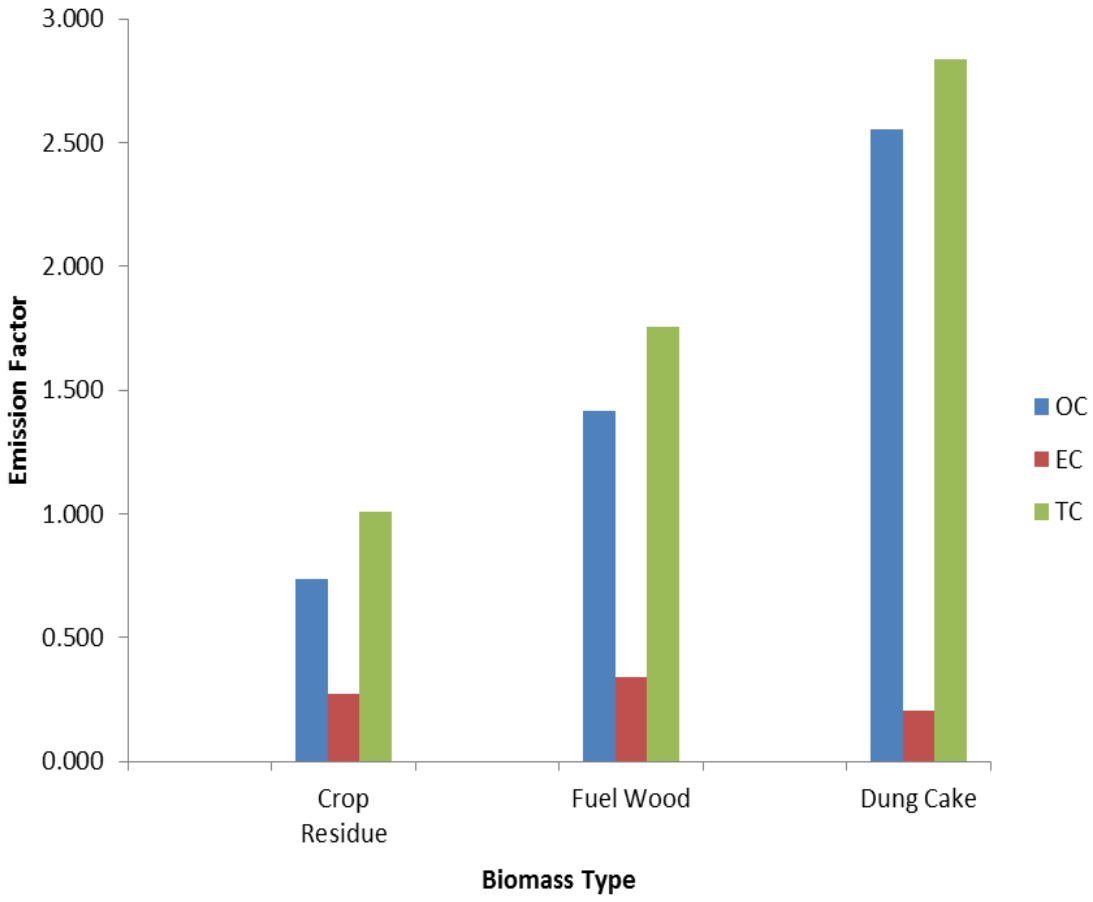

Fig. 4.7: Emission factor (g/Kg) of carbonaceous aerosols in various biomass fuels

4.3 Emission estimations

After the chemical analysis of PM collected from simulated burning of biomass fuel samples of Madhya Pradesh, emission factors are calculated for particulate matter, cations, anions and carbonaceous aerosols (OC and EC). State-wise aerosol emission budget were estimated using the data of annual consumption of various biomass fuels of Madhya Pradesh under study from Tata energy directory and data yearbook (TEDDY; 2007).

Table 4.4 Emission estimation (Gg/yr) of various biomass fuels used

	Types of Biomass		
Parameter	Crop Residue	Fuel wood	Dung Cake
PM	11.83 ± 10.59	95.48 ± 127.27	33.94 ± 17.07
OC	4.21 ± 3.43	46.13 ± 79.6	15.88 ± 4.17
EC	1.56 ± 0.76	11.18 ± 15.74	1.252 ± 0.39
Cations			
Na^+	1.03 ± 1.45	3.52 ± 3.73	0.81 ± 0.99
NH_4^+	0.28 ± 0.42	0.59 ± 1.02	0.33 ± 0.37
K^+	0.12 ± 0.11	1.28 ± 1.01	0.17 ± 0.14
Mg^{2+}	0.09 ± 0.16	0.19 ± 0.31	0.09 ± 0.13
Ca^{2+}	0.16 ± 0.16	0.59 ± 0.33	0.11 ± 0.07
Anions			
F^-	0.31 ± 0.31	3.52 ± 3.73	0.19 ± 0.21
Cl^-	1.31 ± 1.51	0.59 ± 1.02	1.06 ± 1.07
SO_4^{2-}	0.10 ± 0.11	1.28 ± 1.01	0.08 ± 0.06
NO_3^-	0.02 ± 0.03	0.19 ± 0.31	n.d.
PO_4^{2-}	n.d.	0.59 ± 0.33	n.d.

According to TEDDY (2007) annual consumption rates for crop residue, fuel wood and dung cake are 5.7 Mt, 32.6 Mt and 6.2 Mt respectively. Using this, emission factor budget inventory is developed for particulate matter emissions, cations, anions and carbonaceous aerosols (OC and EC) collected by burning of biomass fuels used in Madhya Pradesh. Table 4.4 shows the annual emissions (Gg/yr) of aerosols emitted from biomass burning. It is observed that fuel wood burning contributes higher emissions of PM (95.48 ± 127.27) Gg/yr and EC (1.56 ± 0.76) Gg/yr in crop residue compared to dung cake, whereas higher emission of OC is estimated from the burning of fuel wood (46.13 ± 79.6) Gg/yr. The emissions of almost all the cations and anions is observed to be highest from burning of fuel woods except Cl^- whose value is found more in crop residue and dung cake as compare to fuel wood.

5. CONCLUSIONS AND RECOMMENDATION FOR FUTURE RESEARCH

5.1 Conclusion and Recommendation

Aerosol particles can adversely affect human health and drive many key aspects of the atmospheric and climate systems. Aerosols contribute to the largest uncertainty in climate prediction and the mechanisms that lead to adverse health effects from aerosols have not been resolved **[89 & 87]**. Organic compounds constitute a large portion of aerosol mass, yet this fraction is poorly characterized. Burning and non-burning forest emissions are important contributors to global primary and secondary organic mass (OM) **[10 & 91].** In an effort to address the complexity of organic aerosols and in particular the impact of rural household emissions, biomass samples were collected from Madhya Pradesh, India, at some specefic sites in spring 2009.

Residential biomasses are still widely used as energy sources for home heating and cooking in the world. Such usage is particularly important in developing countries including India. The present study demonstrates that intensive domestic biomass (Corp Residue, fuel-wood and dung cake) burning can significantly contribute to anthropogenic aerosols and consequently has a great impact on the chemical composition of atmospheric particles and local air quality.

We have done study on chemical characterization of aerosol emitted from biomass burning since chemical composition of biomass play the important role. The composition of natural biomass depends on various factors namely:

1) Type of biomass, plant species or part of plants.

2) Growing conditions such as geographic location, climate, soil types , nutrients, edge of forest and near sea or polluted area.

3) Fertilizer and pesticide doses used which are highly important for some elements (Cl, K, N, P, S and certain trace elements).

4) Plant distance from sources of pollution such as highways, cities, factories and ore mines.

5) Pick-up of extraneous material like dust, dirt and entrained as during biomass harvesting transport and handling.

This study shown that burning of Corp Residue, fuel-wood and dung cake in Madhya Pradesh, India can be a source of some part of the ionic species and some part of other carbonaceous species of ambient aerosol. The other sources can be fossil fuel burning and soil dust. Based on this study, vehicular emissions together with biomass and refuse burning have significant contribution to ambient aerosol of Madhya Pradesh.

Abbreviations and acronyms:

ARI	Acute respiratory infections
BC	Black carbon
Ca^{2+}	Calcium ion
CCN	Cloud condensation nuclei
C.G.	Central government
Cl^-	Chloride ion
COPD	Chronic obstructive pulmonary diseases
CO	Carbon monoxide
CO2	Carbon dioxide
DST	Department of Science & Technology
EC	Elemental carbon
ER	Emission Ratio
F^-	Fluoride ion
GDP	Gross Domestic Product
GHG	Green House Gas
H_2	Hydrogen
IEA	International Energy Agency
INDOEX	Indian Ocean Experiment-Intensive Field Phase
K^+	Potassium ion
LPG	Liquid Petroleum Gas
LRS	Lower respiratory symptoms
LVS	Low volume sampler
Mg^{2+}	Magnesium ion
MNRE	Ministry of New and Renewable Energy
MoEF	Ministry of Environment and Forests
MW	Mega Watt
n.d.	Not determined
Na^+	Sodium ion
NH_4^+	Ammonium ion
NO_3^-	Nitrate ion
NSDP	Net State Domestic Product
NMHC	Non-methane hydrocarbons
OC	Organic carbon
PAHs	Polycyclic aromatic hydrocarbons
PM	Particulate Matter
RSPM	Respirable suspended particulate matter
SEZ	Greenfield Special Economic Zone
SOA	Secondary Organic Aerosol
SO_4^{2-}	Sulfate ion
TERI	The Energy and Resources Institute
TSP	Total suspended particulate
TWh	Tera Watt hour
UN	United Nations
URS	Upper respiratory symptoms
VOC	Volatile Organic Compound
UV	Ultraviolet Radiation
WHO	World Health Organization
WWF	World Wildlife Fund

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Appendix I:

Detail of various sites of Madhya Pradesh from where the samples were collected

S. No.	Latitude	Longitude	Act	District	Village (Site)
1	26° 26’ 252 N	78° 02’ 278 E	551 F	Morena	Jeruwa
	26° 10’ 112 N	77° 18’ 241 E	683 F		Tentra
2	26° 01’ 750 N	77° 54’ 129 E	1153 F	Gawlior	Sirsa
	26° 09’ 621 N	78° 27’ 033 E	666 F		Arouli
3	25° 48’ 861 N	77° 45’ 860 E	1050 F	Shivpuri	Bhangarh
	25° 08’ 282 N	77° 36’ 384 E	1513 F		Daherda
4	25° 50’ 73 N	77° 33’ 776 E	1128 F	Sheopur	Nerkhira
5	24° 49’ 443 N	77° 25’ 845 E	1547 F	Guna	Minakhyai
	24° 21’ 084 N	77° 07’ 859 E	1388 F		Barkhari
6	24° 00’ 807 N	76° 56’ 597 E	1138 F	Rajgarh	Kachri
	23° 45’ 557 N	77° 03’ 184 E	1452 F		Anchalpura
7	23° 27’ 072 N	77° 04’ 907 E	1529 F	Scheor	Beragarh Khuman
	23° 11’ 533 N	77° 06’ 492 E	1629 F		Sekda Kedi(Sharpur)
8	23° 19’ 629 N	77° 18’ 996 E	1575 F	Bhopal	Kurana
9	22° 59’ 362 N	76° 16’ 245 E	1630 F	Dewas	Arniya
	23° 03’ 027 N	76° 07’ 329 E	1759 F		Chota Malsapur
10	23° 28’ 246 N	76° 14’ 986 E	1496 F	Shajapur	Haran
	23° 39’ 509 N	75° 58’ 733 E	1728 F		Palkhari

11	23° 20’ 610 N	75° 51’ 184 E	1716 F	Ujjain	Nazarpur
	23° 18’ 214 N	75° 37’ 584 E	1719 F		Guda
12	23° 43’ 400 N	75° 06’ 730 E	1715 F	Ratlam	Richa Chanda
	23° 12’ 298 N	75° 08’ 899 E	1632 F		Ran
13	24° 13’ 574 N	74° 59’ 634 E	1592 F	Mandsaur	Barkhera panth
	23° 52’ 718 N	75° 06’ 235 E	1627 F		Akaiyd
14	24° 20’ 898 N	74° 56’ 931 E	1492 F	Nimach	Sakar gram
	24° 27’ 758 N	74° 55’ 575 E	1537 F		Janthpura
15	22° 53’ 758 N	75° 15’ 037 E	1707 F	Dhar	Ritodya
	22° 37’ 442 N	75° 02’ 654 E	1793 F		Kharali Khareli
16	22° 42’ 071 N	75° 43’ 709 E	1771 F	Indore	Jhalara
					Dharnavad
17	22° 45’ 253 N	74° 45’ 165 E	1310 F	Jhakua	Machaliya
	22° 41’ 727 N	22° 41’ 727 E	1202 F		Tekiri Moti
18	22° 33’ 806 N	74° 30’ 954 E	1294 F	Alirajpura	Jhambu Khera
	22° 24’ 429 N	74° 38’ 051 E	1208 F		Hardaspur
19	22° 04’ 508 N	74° 55’ 985 E	525 F	Barwani	Kasrawad
	21° 58’ 827 N	75° 04’ 498 E	695 F		Rajiv Gandhi Nagar(Bhamori)
20	21° 50’ 485 N	75° 46’ 703 E	795 F	Khargoan	Berung ghati
	21° 51’ 554 N	75° 56’ 361 E	926 F		Kodla Kholsa

21	$21^{o\,47'}$ 821 N	76^{o} 14’ 123 E	1097 F	Khandwa	Mokal Gaon
	21^{o} 41’ 529 N	76^{o} 31’ 022 E	1059 F		Piplod Balwada
22	21^{o} 32’ 104 N	76^{o} 18’ 619 E	1168 F	Burhanpur	Dahinala
	21^{o} 19’ 023 N	76^{o} 25’ 903 E	1170 F		Dalwada
23	22^{o} 20’ 983 N	77^{o} 13’ 468 E	1010 F	Harda	Bhaili Tappar
	22^{o} 17’ 899 N	77^{o} 18’ 970 E	1123 F		Tema gaon
24	22^{o} 07’ 695 N	77^{o} 29’ 987 E	1787 F	Betul	Alam garh
	22^{o} 02’ 876 N	77^{o} 49’ 664 E	1995 F		Jakhli
25	22^{o} 24’ 408 N	77^{o} 50’ 533 E	1138 F	Hoshangabad	Sukhtawa
	22^{o} 40’ 770 N	77^{o} 45’ 142 E	1135 F		Biaora
26	22^{o} 54’ 501 N	77^{o} 39’ 015 E	1536 F	Raisen	Barkheda
	23^{o} 15’ 959 N	77^{o} 39’ 798 E	1535 F		Kharwai
27	23^{o} 37’ 287 N	77^{o} 45’ 363 E	1419 F	Vidisha	Bamuria
	23^{o} 56’ 567 N	77^{o} 54’ 674 E	1358 F		Rojrua
28	22^{o} 14’ 979 N	77^{o} 56’ 871 E	1414 F	Ashok Nagar	Ghat Bamuria
29	24^{o} 09’ 229 N	78^{o} 13’ 961 E	1387 F	Sagar	Dhurwa
	23^{o} 35’ 672 N	78^{o} 51’ 590 E	1540 F		Umrali
30	22^{o} 56’ 434 N	79^{o} 02’ 255 E	1157 F	Narsimhaapur	Gogawali
	22^{o} 52’ 860 N	79^{o} 11’ 965 E	1207 F		Lokipar
31	22^{o} 44’ 891 N	79^{o} 13’ 181 E	1858 F	Chhindwara	Partapur
	22^{o} 15’ 013 N	79^{o} 14’ 575 E	2315 F		Khami

32	22° 04’ 448 N	79° 37’ 783 E	1925 F	Seoni	Selowa Kala
	22° 02’ 174 N	79° 47’ 685 E	1781 F		Konar Kala
33	21° 53’ 691 N	80° 04’ 894 E	1061 F	Balaghat	Dokar Bandi
	21° 52’ 563 N	80° 11’ 239 E	1062 F		Kumhari
34	22° 25’ 179 N	80° 12’ 047 E	1056 F	Mandla	Jamgaon
	22° 31’ 284 N	80° 20’ 482 E	1530 F		Limarua
35	23° 21’ 971 N	80° 01’ 989 E	1255 F	Jabalpur	Gandhigram, Rampur
	23° 13’ 762 N	80° 14’ 851 E	1395 F		Khandya
36	23° 32’ 730 N	79° 42’ 790 E	1319 F	Domoh	Purenhow Deatore
	23° 50’ 980 N	79° 34’ 550 E	1169 F		Bamori
37	23° 53’ 857 N	79° 53’ 823 E	1443 F	Panna	Kuwa Kaera
	24° 44’ 090 N	80° 00’ 907 E	707 F		Mandla
38	23° 54’ 417 N	80° 06’ 391 E	1373 F	Katni	Mohas
	23° 41’ 650 N	80° 18’ 185 E	1375 F		Nengwa
39	23° 12’ 012 N	80° 32’ 043 E	1874 F	Dindori	Sarwahi
40	23° 27’ 401 N	80° 44’ 259 E	1753 F	Umaria	Tawan Nara
	23° 26’ 181 N	80° 55’ 532 E	1495 F		Berhi
41	23° 17’ 492 N	81° 24’ 830 E	1634 F	Shahdol	Jammu
	23° 43’ 204 N	81° 22’ 282 E	1469 F		Kaavwa Sarai
42	23° 09’ 454 N	81° 39’ 947 E	1602 F	Anuppur	Chachisi Basti
43	24° 32’ 477 N	80° 59’ 940 E	1002 F	Satna	Mahurach

	24° 34’ 483 N	80° 39’ 880 E	999 F		Madi Khurd
44	24° 47’ 949 N	79° 54’ 464 E	679 F	Chattarpur	Tikhree
	24° 46’ 766 N	79° 27’ 444 E	977 F		Kheron
45	24° 07’ 971 N	81° 38’ 649 E	1148 F	Sidhi	Simarya
	22° 24’ 429 N	74° 38’ 051 E			Bhitri
	24° 26’ 506 N	82° 08’ 048 E	893 F		Matihani
46	24° 23’ 435 N	82° 14’ 500 E	889 F	Singrauli	Karthua
47	24° 45’ 841 N	82° 04’ 476 E	1174 F	Rewa	Massurha
	24° 12’ 878 N	81° 12’ 878 E	1031 F		Augdal
48	24° 42’ 619 N	79° 13’ 051 E	977 F	Tikamgarh	Kuriala
	24° 40’ 518 N	78° 47’ 188 E	978 F		Jarpoa
49	25° 42’ 690 N	78° 29’ 550 E	669 F	Datia	Jharia
	26° 02’ 803 N	78° 41’ 546 E	677 F		Chrokhra
50	26° 14’ 388 N	78° 42’ 785 E	675 F	Bhind	Rupawai

Appendix II: Spatial variation of ionic species of aerosol emitted from different types of biomass fuel used in Madhya Pradesh

District	Village	Biomass	Class of Biomass	Anions					Cations				
				F^-	Cl^-	SO_4^{2-}	NO_3^-	PO_4^{2-}	Na^+	NH_4^+	K^+	Mg^{2+}	Ca^{2+}
Raisen	Barkhera	Tilsa	CR	0.057	0.294	0.015	n.d.	n.d.	0.180	0.060	0.003	0.017	n.d.
		Bajar Battu	FW	0.023	0.164	0.015	n.d.	n.d.	0.058	0.021	0.030	0.003	0.011
		Shaaj	FW	0.080	0.340	0.044	0.029	n.d.	0.378	0.014	0.105	0.006	0.038
		Gheria	FW	0.035	0.200	n.d.	n.d.	n.d.	0.410	0.134	0.006	0.042	n.d.
		Dungcake	DC	0.088	0.389	0.017	n.d.	n.d.	0.425	0.156	0.010	0.049	n.d.
	Kharwai	Gulsitara	FW	0.022	0.104	n.d.	n.d.	n.d.	0.085	0.005	0.041	0.002	0.015
Katni	Nengwa	Nirbanshi	CR	0.144	0.729	0.056	0.007	n.d.	0.684	0.193	0.021	0.070	n.d.

		dharwa	FW	0.039	0.193	0.008	n.d.	n.d.	0.127	0.002	0.063	0.0025	0.014
		Seja	FW	0.019	0.064	0.007	n.d.	n.d.	0.045	0.005	0.024	0.001	0.012
Seoni	Konar Kala	Jamun	FW	0.064	0.382	0.018	n.d.	n.d.	0.172	0.004	0.069	0.007	0.035
		Polash	FW	0.043	0.168	0.021	n.d.	n.d.	0.125	0.004	0.076	0.003	0.024
		Mohwa	FW	0.066	0.250	0.036	n.d.	n.d.	0.124	0.010	0.081	0.005	0.025
	Selowa Kala	Dungcake	FW	0.009	0.024	0.006	n.d.	0.299	0.034	0.003	0.015	0.003	0.015
		Babool	FW	0.010	0.053	0.008	n.d.	n.d.	0.027	0.011	0.028	0.002	0.010
Shivpuri	Daherda	Kher	FW	0.038	0.147	0.007	n.d.	n.d.	0.094	0.009	0.050	0.003	0.024
		Babool	FW	0.042	0.154	0.010	n.d.	n.d.	0.119	0.005	0.066	0.004	0.025
		Dungcake	DC	0.018	0.152	0.014	n.d.	n.d.	0.076	0.022	0.031	0.004	0.022

	Bhangarh	Chola	CR	0.010	0.071	0.015	n.d.	n.d.	0.040	0.011	0.022	0.002	0.064
		Keekar	FW	0.028	0.011	n.d.	n.d.	n.d.	0.028	0.004	0.008	0.002	0.009
		Ghot	FW	n.d.	0.025	n.d.	n.d.	n.d.	0.050	0.007	0.002	0.011	n.d.
Mandsaur	Barkhera Panth	Dungcake	DC	0.055	0.375	0.023	n.d.	n.d.	0.201	0.058	0.056	0.005	0.026
		Babool	FW	0.005	0.121	0.010	n.d.	n.d.	0.041	0.052	0.021	0.002	0.012
		Affeam	FW	0.009	0.107	0.011	n.d.	n.d.	0.054	0.019	0.026	0.003	0.014
	Akaiyad	Maize	CR	0.053	0.181	0.010	n.d.	n.d.	0.127	0.010	0.054	0.004	0.036
Indore	Jhalara	Dungcake	DC	0.010	0.084	n.d.	n.d.	n.d.	0.043	0.080	0.048	0.033	0.024
		Babool	FW	0.013	0.065	0.009	n.d.	n.d.	0.025	0.016	0.015	0.001	0.012
	Dharmavad	Dhaki neem	FW	0.012	0.055	0.013	n.d.	n.d.	0.027	0.013	0.023	0.002	0.014

Note: CR: Crop Residue; FW: Fuel Wood; DC: Dung Cake; n.d.: not determined

Appendix III

District-wise Area, Population, Sex Ratio, and Growth Rate in Madhya Pradesh

S. No.	District	Area (In sq.km)	% age of Area	Population (1991) (In Lakhs)			Sex Ratio		Decadal growth Rate (Per cent) 1981-1991		
				Persons	Males	Females	1981	1991	Total	Rural	Urban
1.	Morena	11600	2.62	17.11	9.37	7.74	834	828	31.03	20.62	96.75
2.	Bhind	4500	1.02	12.19	6.71	5.48	827	822	24.71	19.38	51.81
3.	Gwalior	5200	1.17	14.13	7.71	6.42	845	831	27.72	16.55	36.85
4.	Datia	2000	0.50	3.96	2.14	1.82	853	853	27.53	22.66	47.55
5.	Shivpuri	10300	2.32	11.33	6.13	5.20	855	849	30.72	27.17	54.80
6.	Guna	11100	2.50	13.10	6.99	6.11	882	876	30.69	22.50	80.40
7.	Tikamgarh	5100	1.15	9.41	5.03	4.38	883	871	27.63	20.70	77.79
8.	Chhatarpur	8700	1.96	11.58	6.24	5.34	864	854	30.70	24.97	61.78
9.	Panna	7100	1.60	6.88	3.63	3.25	913	986	26.81	19.54	112.83
10.	Sagar	10200	2.30	16.48	8.76	7.72	891	881	24.42	22.06	30.52
11.	Damoh	7300	1.65	8.98	4.71	4.27	925	906	24.41	18.98	56.61
12.	Satna	7500	1.69	14.65	7.64	7.01	936	920	26.79	21.41	54.68
13.	Rewa	6300	1.42	15.66	8.05	7.50	969	936	28.37	25.10	50.14
14.	Shahdol	14000	3.16	17.44	8.99	8.45	940	941	29.58	24.37	53.64
15.	Sidhi	10500	2.37	13.73	7.15	6.58	951	923	38.51	32.17	351.68
16.	Mandsaur	10300	2.32	15.55	7.99	7.56	941	944	23.12	18.75	40.30
17.	Ratlam	4900	1.10	9.72	4.99	4.73	948	949	24.09	22.02	28376
18.	Ujjain	6100	1.38	13.83	7.17	6.66	926	932	24.12	19.65	31.59
19.	Shajapur	6200	1.40	10.33	5.39	4.94	929	919	22.88	18.77	46.45
20.	Dewas	7000	1.60	10.33	5.37	4.96	929	923	29.83	18.41	79.46
21.	Jhabua	6800	1.53	11.30	5.72	5.85	985	977	42.03	41.53	47.48
22.	Dhar	8100	1.83	13.67	7.00	6.67	966	952	29.24	28.41	35.01
23.	Indore	3900	0.88	18.36	9.63	8.73	978	908	29.90	17.03	36.54
24.	West Nimar	13400	3.02	20.28	10.40	9.88	954	951	24.24	23.84	26.56
25.	East Nimar	10700	2.41	14.32	7.39	6.93	939	941	24.21	33.01	27.48
26.	Rajgarh	6200	1.40	9.93	5.16	4.77	931	932	22.83	18.53	58.99
27.	Vidisha	7400	1.67	9.70	5.18	4.52	881	872	24.00	19.36	46.72
28.	Bhopal	2763	0.62	13.51	7.15	6.36	874	891	50.92	26.24	58.62
29.	Sehore	6272	1.41	8.40	4.43	3.98	907	896	27.84	20.92	72.94
30.	Raisen	8400	1.89	8.76	4.66	4.10	908	883	23.48	15.36	96.94
31.	Betul	10100	2.27	11.81	6.00	5.81	973	967	27.57	22.46	55.85
32.	Hoshangabad	10000	2.26	12.37	6.67	6.00	908	899	26.10	22.18	37.79
33.	Jabalpur	10200	2.30	26.50	13.84	12.66	914	916	20.31	19.25	21.60
34.	Narsinghpur	5100	1.15	7.85	4.11	3.74	930	913	20.61	18.76	32.46
35.	Mandla	13300	3.00	12.91	6.49	6.42	1003	988	24.48	23.65	35.32
36.	Chhindwara	11800	2.16	15.69	8.03	7.66	965	948	26.78	23.56	38.74
37.	Seoni	8800	1.98	10.01	5.07	4.94	982	974	23.47	21.17	50.83
38.	Balaghat	9200	2.07	13.66	6.82	6.84	1006	1003	18.72	17.65	30.00
39.	Sarguja	22300	5.03	20.82	10.64	10.18	962	955	27.52	22.84	76.67
40.	Bilaspur	19900	4.49	37.94	19.17	18.77	993	978	28.55	23.71	58.65
41.	Raigarh	12900	2.90	17.22	8.61	8.61	1006	998	19.49	17.93	36.51
42.	Rajnandgaon	10300	2.00	14.40	7.16	7.24	1020	1012	23.30	18.52	57.22
43.	Durg	19700	4.42	23.97	12.19	11.78	980	970	28.87	20.22	41.15
44.	Raipur	21251	4.30	39.08	19.61	19.47	1009	994	26.73	22.81	45.61
45.	Bastar	39100	7.82	22.71	11.34	11.37	1002	1002	23.20	21.81	44.88
	Madhya Pradesh	**442846**	**100.00**	**661.81**	**342.67**	**319.14**	**941**	**932**	**26.75**	**22.11**	**44.98**

Appendix IV: Pictorial presentation of simulated biomass burning setup