Deposition Of Size Distributed Atmospheric Aerosol In Human Respiratory System In An Urban Atmosphere

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ABSTRACT

Several epidemiological studies have reported the association of atmospheric particulate matter ($PM_{2.5}$) with daily and cardiovascular mortality specifically during wintertime and a higher risk of acute cardiovascular diseases, with systemic oxidative stress induced by air pollution as a potential underlying mechanism. The risk that the inhaled particles pose depends on their chemical composition and where they deposit in the respiratory system. Therefore, to adequately assess the health risks of aerosols, it is vital to understand the deposition of particles in the lungs. The efficient inhalation of pharmaceutical aerosols also depends on this kind of comprehension. This project attempts to understand the size distributed deposition in three major regions of the respiratory system. The multi-modal nature of urban aerosol mass distribution for Bhopal using log-normal distribution curves and the empirical equations using the International Commission on Radiological Protection (ICRP) model are utilized to estimate the regional and total deposition in the human lungs. The annual averages indicated a total deposition of 42 µg m^{-3} with highest values observed during the summer month of April and lowest during September. Even though the overall deposition in the month of April is the highest (124.61 µg m^{-3}), most of the deposition in the month of April is in the head airways region (137.7 µg m^{-3}) which is protected by a mucociliary layer while the deposition in the alveolar region is low (4.43 µg m^{-3}). Generally, the deposition in head airways region is the highest followed by alveolar region. The amount of deposition in alveolar region dominates over deposition in other regions in the winter season (December, January, February) implying higher risk to lung capacity during these months.

1. INTRODUCTION

Air pollution is a major environmental health hazard affecting majority of population worldwide, caused by the presence of unwanted harmful substances into the atmosphere, including gases, particulate matter, and biological molecules. These pollutants have a wide spectrum of health related issues, including respiratory and cardiovascular diseases, cancer, and premature death. Elevation of blood pressure and aggravation in pre-existing heart condition due to an inflammatory effect of air pollution on human heart can be some of the detrimental effects. The primary course exposing people to air pollution is through the respiratory system. Immune suppression, mutagenicity, oxidative stress, and inflammation in the body's cells are some of the effects caused by inhalation of particulate matter, which further can affect the brain, heart and lungs resulting in diseases of various kind. Numerous literature is available connecting air pollution to a spectrum of health issues, including the escalation of cardiovascular and respiratory diseases, decreased lung function, coughing and difficulty breathing among others. It is important to take measures to reduce air pollution levels in order to protect human health. This can be achieved through a combination of individual actions such as reducing car usage or using public transport, as well as collective actions such as implementing policies that reduce emissions from factories and power plants.

According to the WHO reports, almost seven million people die every year due to air pollution and out of 10 people in the world, 9 breathe air that exceeds WHO guideline limits. Developing countries like India and China have the highest exposure to air pollution. In India, the air quality status is very severe. 37 Indian cities are listed among the top 100 cities in the world with the worst particulate matter (PM10) pollution, according to WHO. Due to acute and chronic health hazards, particulate matter may induce health issues. The International Agency for Research on Cancer (IARC) in October 2013 categorized outdoor particulate matter as a Group 1 carcinogen. The impact of pollution can be varying, depending on the amount of time a person is exposed and the concentration and size of the pollutants [Buiarelli et al., 2019]. Studies have suggested that regular exposure to air pollution affects children and may worsen or make difficult medical conditions in adults. Urban areas with their industries, vehicle emissions and garbage burning have created significant changes in the environment and human health. Due to this, the air quality status of urban cities and its impact on health is of greater interest.

Aerosols, tiny floating particles in a gaseous medium, are a part of air pollution and cause harmful effects on human health and the environment. In past years the concentration of anthropogenic aerosols has increased which has led to climate change [IPCC, 2013]. Fine aerosol particles play an important role in reducing visibility and climate change; as lifetime of these particles is higher than coarse particles [Priyadharshini et al., 2019]. Hence, it is essential to estimate the ambient concentration and physio-chemical properties of fine aerosols. Several types of aerosols are there in the atmosphere that result in atmospheric phenomena such as smoke, haze, fog and smog. Anthropogenic aerosols exert a direct (-0.9 and -0.1 Wm^{-2}) and an indirect (-1.8 and -0.3 Wm^{-2}) cooling effect causing an imbalance in the earth's energy balance (Solomon et al., 2007).

There is evidence of fine (aerodynamic diameter less than 2.5 μm) particles' relation with respiratory and cardiovascular diseases. Moreover, depending on the size of the particulate matter, it can penetrate deeply into the human lungs, for example, PM_{10} can be trapped in the nasopharyngeal tract, while $PM_{2.5}$ can reach up to alveoli. The particle size of about 50 micrometres can be captured by the nasal cavity and easily filtered by cilia or mucus. A study in Delhi (India) reported that for kerbside locations up to 52% of the particles belong to that size range which can reach up to the lower respiratory tract and 47% of the particles can reach up to the upper respiratory tract, while these value for residential and industrial sites are up to 40% and 31% for the lower and upper respiratory tract. Exposure to these particles can cause asthma, pulmonary fibrosis, cancer, cardiovascular, pulmonary diseases and immune-related diseases, because of the dynamic and complex chemical composition of ambient aerosol. The chemical composition of ambient particulate matter normally depends on the source of its generation and also absorb some toxic element in the atmosphere like volatile organic compound (VOC), polycyclic aromatic hydrocarbons (PAHs) and heavy metals, which are likely to be more toxic because they generate reactive oxygen species in biological tissue and if the concentration of these increases beyond the critical threshold limit it may pose serious health hazards. The chemical composition of different size range aerosol particles is different, but no adequate research is available and there is a big research gap to justify this hypothesis. There is a lack of knowledge regarding ambient aerosol oxidation potential, which closely mimics the actual interaction between the chemical composition of ambient aerosol and the human cell. This value can be used to estimate the health risk that an ambient aerosol particle poses.

Hence in the present study estimation of deposition of size segregated aerosol distribution for various months and the dominance during each month for lung deposition calculations is done. The accumulation of particles in various regions of the human respiratory system in different months of the year using the International Commission on Radiological Protection (ICRP) model equations is also estimated.

2. MEHTODOLOGY

2.1 Study Region

The study was carried out in Bhopal (23.26 °N, 77.41 °E), the capital of the Indian state of Madhya Pradesh. There were 1.7 million people living in the urban agglomeration, which includes the city and its suburbs, as of 2011. Bhopal faces a large urban population, heavy traffic, extreme poverty, overpopulation, and other logistical and social issues as a burgeoning metropolis in a developing nation.

A scorching summer, cool, dry winter, and a humid monsoon season are all characteristics of Bhopal's humid subtropical climate. The annual average temperature is 25.8 ^{0}C; monthly mean temperatures are in the range of 16-30 ^{0}C. Summers (March- mid June) are hot with the average temperatures around 32^{0}C with highest temperatures generally exceeding 40^{0}C in May and June. Winter begins in November, with seasonal lows in December and January falling to 9 to 110^{0}C. With daily temperatures ranging from 26 to 410^{0}C, May is the warmest month. In July and August, the city frequently experiences hailstorms or thunderstorms that are followed by heavy rain or dust storms. Between June and September, Bhopal is flooded by rains delivered by the Bay of Bengal branch of the south-west summer monsoon.

The measurements were carried out for 12 months from April 2022 to March 2023. An aerosol size spectrometer (model 1.108, Grimm Aerosol Technik, Germany) is utilized to measure the size distribution of ambient aerosols. It provides a particle count for aerosols in the 0.23μm to 20μm size range by dividing into 16 separate size bins.

2.2 HUMAN RESPIRATORY SYSTEM

The respiratory system is divided into three zones (the **conducting zone**, the **transitional zone**, and the **respiratory zone**.), each of which contains several anatomical units. These locations differ significantly in terms of structure, airflow patterns, function, retention time, and susceptibility to deposited particles. The conducting zone includes the nasal cavity, pharynx, larynx, trachea, bronchi, and bronchioles. The transitional zone includes the terminal bronchioles and respiratory bronchioles. The respiratory zone includes the alveolar ducts, alveolar sacs, and alveoli.

2.3 LUNG DEPOSITION MECHANISMS

Lung deposition mechanisms refer to the various ways in which aerosolized particles, such as airborne pollutants or medications in aerosol form, can be deposited within the human respiratory system. These mechanisms are crucial to understanding how inhaled substances are distributed within the lungs and can have significant implications for both health and therapeutic applications. The mechanisms taken into consideration were:

2.3.1 Inertial Impaction:

Inertial impaction is a lung deposition mechanism driven by the inertia of relatively large aerosol particles. These particles have enough mass and momentum to resist changes in airflow direction and may collide with the walls of the airways instead of following the curving path of the airflow.

2.3.2 Gravitational sedimentation:

The mechanism of the gravitational sedimentation refers to the mechanism driven by the force of gravity acting on relatively large and denser aerosol particles. These particles tend to settle out of the airstream as it moves through the respiratory system, depositing in areas where the airflow velocity decreases.

2.3.3 Brownian diffusion:

Brownian motion is a random, chaotic movement of small particles caused by the thermal energy of the surrounding gas molecules. This motion increases the likelihood of these particles colliding with airway surfaces.

2.3.4 Electrostatic Precipitation:

Electrostatic precipitation is a mechanism of particle deposition in the lungs that occurs when charged particles are attracted to oppositely charged surfaces. The charged particles cause opposite sign image charges to form on the typically uncharged surfaces of the airways, which are electrically conductive.

2.3.5 Interception:

Interception is a mechanism of particle deposition in the lungs that occurs when particles come into contact with the airway walls. It is a process by which particles are intercepted by the airway walls due to their size and shape. Interception is most effective for particles larger than 5 μm in diameter.

2. DEPOSITION MODEL:

There are many mathematical models that can quantify and locate particles deposited in the respiratory system. The two most advanced and widely used models are from the International Commission on Radiological Protection (ICRP, 1994) and the National Council on Radiation Protection (NCRP, 1997). The model was designed to estimate the radiation dose to different organs and tissues from the inhalation of radioactive particles in different men and women. This model is based on empirical data, theories and prior versions of ICRP models from the 1960s. They can estimate deposition in different regions and throughout the respiratory system for different particle sizes and breathing conditions. The two models have similar predictions for total and head airways depositions. However, they differ in estimating the distribution of particles smaller than 0.1 μm between the tracheobronchial region and the alveolar region. However, the difference is negligible compared to the variation of deposits among normal individuals.

The ICRP model was fitted using the following condensed equations for mono-disperse spheres with standard densities under standard conditions. The average of the data for both sexes for the three exercise intensities of sitting, light exercise, and heavy exercise was calculated. Over the size range of 0.001 to 100 μm, the fractions predicted by these equations are within ±0.03 of the ICRP model's predictions.

$$\mathrm{DFHA} = \mathrm{IF}\left(1/\left(1 + \exp\,(6.84 + 1.183\ln d)\right) + 1/\left(1 + \exp\,(0.924 - 1.885\ln d)\right)\right)$$

$$\mathrm{DFTB} = 0.00352/d\left(\exp\,(-0.234(\ln d + 3.40)^2) + 63.9\exp\,(-0.819(\ln d - 1.61)^2)\right)$$

$$\mathrm{DFAL} = 0.0155/d\left(\exp\,(-0.416(\ln d + 2.84)^2) + 19.11\exp\,(-0.482(\ln d - 1.362)^2)\right)$$

$$\mathrm{DF} = \mathrm{IF}\left(0.0587 + 0.911/\left(1 + \exp\,(4.77 + 1.485\ln d)\right) + 0.943/\left(1 + \exp\,(0.508 - 2.58\ln d)\right)\right)$$

$$\mathrm{IF} = 1 - 0.5\left(1 - 1/\left(1 + 0.00076 * (d^{2.8})\right)\right)$$

where, DFHA= Deposition Fraction in the Head Airways Region
DFTB= Deposition Fraction in the Tracheobronchial Region
DFAL= Deposition Fraction in the Alveolar Region
DF = Total Deposition Fraction
IF = Inhalable Fraction
d= Diameter of the Particle

3. RESULTS AND DISCUSSION

It is important to understand the aerosol mass distribution in various size ranges to understand the deposition in various respiratory regions.

3.1 AEROSOL MASS DISTRIBUTION

Mass concentrations will be measured in 16 size bins. We will limit our study only to the particles with a diameter < 10 μm. The sizes have been divided into two different modes, namely fine mode for particles of diameter < 1 μm (PM_1) and Coarse mode for particles with diameter between 1 and 10 μm. Usually, from the literature, it has been observed that there are two major modes in the distribution, one in the fine mode region and the other in the coarse mode region.

Several authors [Devini et al., 2023, Ganguly et al., 2005a] have demonstrated that multiple modes, which represent various production sources, combine to form the tropospheric aerosols. We also found that the log-normal distributions are multi-modal with one mode in the region of 0.23 to 1 micron and another in the region of 1 to 10 micron. All the curves had at least two modes, one in the finer region and the other in the coarser region. The peak in the finer mode shifts right as we move from December to March and also the peak value of both fine and coarse mode decreases. The peak is located at the diameter of 0.3 micron for December and then it changes to the value of 0.4 micron for January, February and March. Particles of diameter 2 μm and 7.5 μm dominate during April and May respectively. June, July and August show a similar pattern with the peak in the coarse mode around 2.8 to 3 μm. September shows the highest concentration for the coarse particles occurring at 3 μm diameter. We observe an unexpected result in November because the data available for November was recorded only for three hours in the afternoon. We do not have nighttime data for this month and hence we get less concentration in November.

Table 1: Mass median diameter (MMD) and geometric standard deviation (GSD) values for various months

Month	Fine Mode			Coarse Mode		
	MMD	GSD	Max. dm/dlogd	MMD	GSD	Max. dm/dlogd
April 2022	0.35	1.66	9.39	4.8	1.88	17.49
May 2022	0.4	1.63	2.31	3.8	2.16	11.04
June 2022	0.32	1.72	6.19	2.5	1.92	6.12
July 2022	0.38	1.63	1.75	2.4	1.83	11.7
August 2022	0.38	1.63	8.83	2.4	1.58	24.9
September 2022	0.39	1.64	57.88	2.5	1.76	45.89
October 2022	0.37	1.84	2.76	2.8	1.75	14.02
November 2022	0.38	1.53	10.61	2.5	1.8	5.06
December 2022	0.33	1.5	205.77	2.1	1.71	36.44
January 2023	0.3	2	92.34	2	1.8	21.64
February 2023	0.31	1.61	84.81	2	1.85	23.07
March 2023	0.32	1.63	53.16	2	1.75	27.12

3.2 Regional and total Deposition

Deposition of particles in the upper airways varies greatly and is influenced by a number of variables, such as breathing through the mouth or nose, flow rate, and particle size. Through contact with the nasal hairs and airflow path bends, larger particles are expelled. Particles that have accumulated on the ciliated nasal cavity surfaces are removed to the pharynx and swallowed. 90% of breathed 10 μm particles and 80% of inhaled 5 μm particles enter the nose while engaging in modest activity. Head area depression increases as the average inspiratory flow rate for combined mouth and nose breathing rises. Due to their high diffusion coefficient, ultrafine particles smaller than 0.01 μm are significantly deposited in the upper airways.

In the tracheobronchial area, if the average inspiratory flow rate is greater than or equal to 1.2 m3/h, it is the dominant mechanism for the deposition of particles larger than 3 μm. Under mild exercise conditions, efficiencies of approximately 35% and 90% were estimated for particles with aerodynamic diameters of 5 and 10 μm reaching the tracheobronchial region. The results improved significantly as the breathing rate increased. Sedimentation is the primary deposition mechanism for particles with an aerodynamic diameter of 0.5-3 μm or a flow rate of 1.2 m3/hour, but the total tracheobronchial deposition for these particles is very small. Due to their rapid Brownian motion, ultrafine particles, particularly those smaller than 0.01 μm, cause more deposition in the tracheobronchial area.

The size of the particles, the pace of breathing, and the tidal volume all affect alveolar deposition. Alveolar deposition is the portion of inhaled particles that deposit in the alveolar region after passing through the upper respiratory tract. Particles bigger than 10 m cannot reach the alveolar region due to the deposition of size-selective particles in the tracheobronchial region, but particles in the range of 2–10 m reach the alveolar region in lesser quantity. When the tracheobronchial and cephalic airways are expanded, the amount of deposition in the alveolar region reduces. As a result, the quickly cleansed area contributes to the protection of the more sensitive alveolar area.

Table 2: Deposition fraction for peak particle diameters during various months

Month	Peak Particle Diameter(μm)	IF	DFHA	DFTB	DFAL	DF
April	7.5	0.911766	0.863123	0.026223	0.032159	0.904943
May	2	0.997367	0.593401	0.05653	0.119419	0.796468
June	3	0.991897	0.753081	0.060531	0.095496	0.910969
July	3	0.991897	0.753081	0.060531	0.095496	0.910969
August	2.8	0.993302	0.729751	0.060977	0.100313	0.897897
September	0.3	0.999987	0.043837	0.00494	0.058292	0.127355
October	3	0.991897	0.753081	0.060531	0.095496	0.910969
November	3	0.991897	0.753081	0.060531	0.095496	0.910969
December	0.3	0.999987	0.043837	0.00494	0.058292	0.127355
January	0.4	0.999971	0.069066	0.005097	0.068983	0.138301
February	0.4	0.999971	0.069066	0.005097	0.068983	0.138301
March	0.4	0.999971	0.069066	0.005097	0.068983	0.138301

Where
IF = Inhalable Fraction
DFHA = Deposition fraction in head airways region

DFTB = Deposition fraction in tracheobronchial region
DFAL = Deposition fraction in alveolar region
DF = Total deposition fraction

Table 3: Concentration of aerosol deposition for various months

Month	Total Concentration	HA	TB	AL	Total
April	137.7	118.852	3.610907	4.428294	124.6107
May	77.5	45.98858	4.381083	9.254973	61.72627
June	32.56	24.52032	1.970889	3.10935	29.66115
July	33.85	25.49179	2.048974	3.23254	30.8363
August	43.55	31.78066	2.655548	4.368631	39.10341
September	148.71	6.519	0.734627	8.668603	18.93896
October	37.04	27.89412	2.242068	3.537172	33.74229
November	41.18	31.01188	2.492667	3.932525	37.5137
December	326.04	14.29262	1.610638	19.00552	41.52282
January	295.78	20.42834	1.507591	20.40379	40.90667
February	188.26	13.00237	0.959561	12.98674	26.03655
March	145.01	10.01526	0.739116	10.00322	20.05503

Where
HA= Deposition in the head airways region in µg/m^3
TB= Deposition in the Tracheobronchial region in µg/m^3
AL= Deposition in the Alveolar region in µg/m^3
Total = Total Deposition in µg/m^3

The deposition fractions for both regional and total deposition are calculated using the equations of the ICRP model corresponding to the peak particle diameter as indicated in tables 2 and 3. Multiplying these deposition fractions with the total concentration of the particle gives total and regional deposition. The deposition in the head airways region ranges from 6.52µg/m^3 (September) to 118.85 µg/m^3 (April). The deposition in Tracheobronchial region ranges from 0.73 µg/m^3 (September) to 4.38 µg/m^3 (May). This shows the deposition in both Head airways and tracheobronchial regions are highest during the during the April-May months which happens to be the summer. The above tables also indicate that the amount of deposition in alveolar region dominates the deposition in other regions especially in the winter season (December, January, February) which implies that these are the months in which the lung deposition is going to most harmful. The deposition reaches to a value of 20.40 in January and 19.00 in December and concentrations of this magnitude in the vulnerable alveolar region are very harmful.

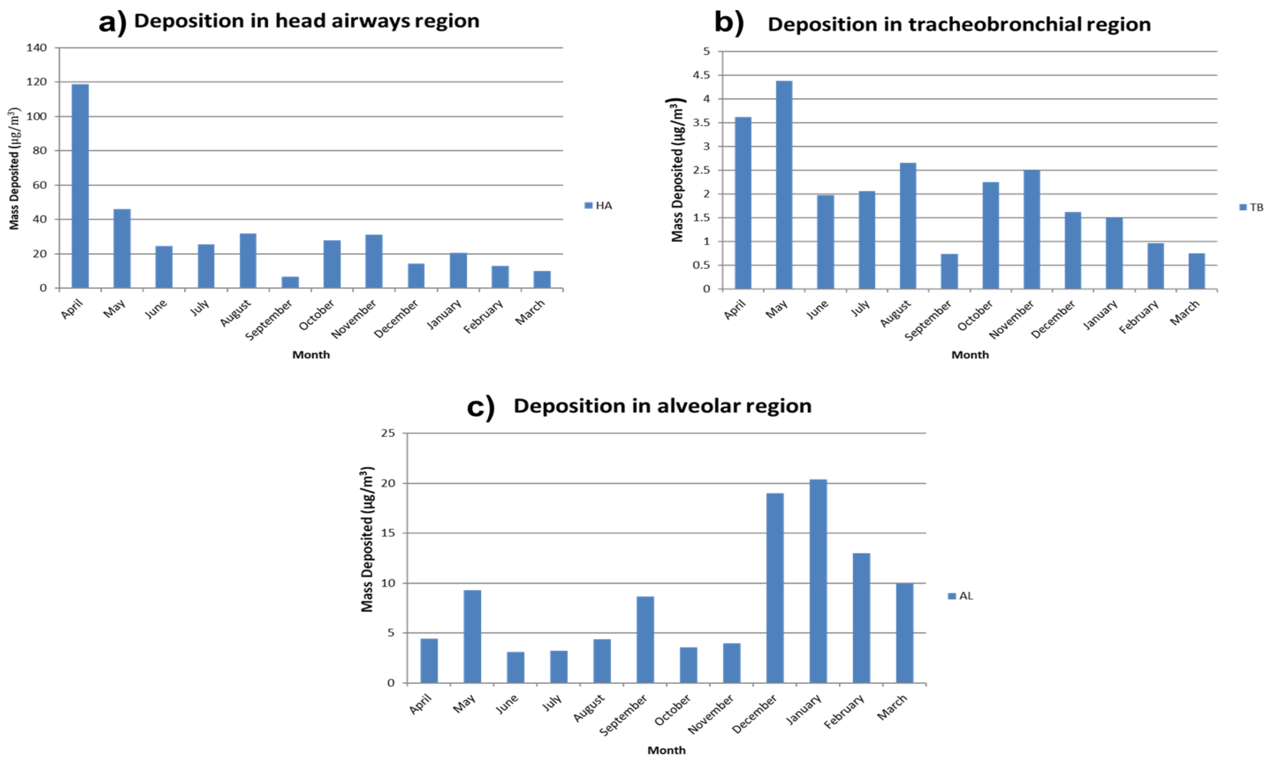

Figure 1. Deposition in the head airways (a), tracheobronchial (b) and alveolar region (c)

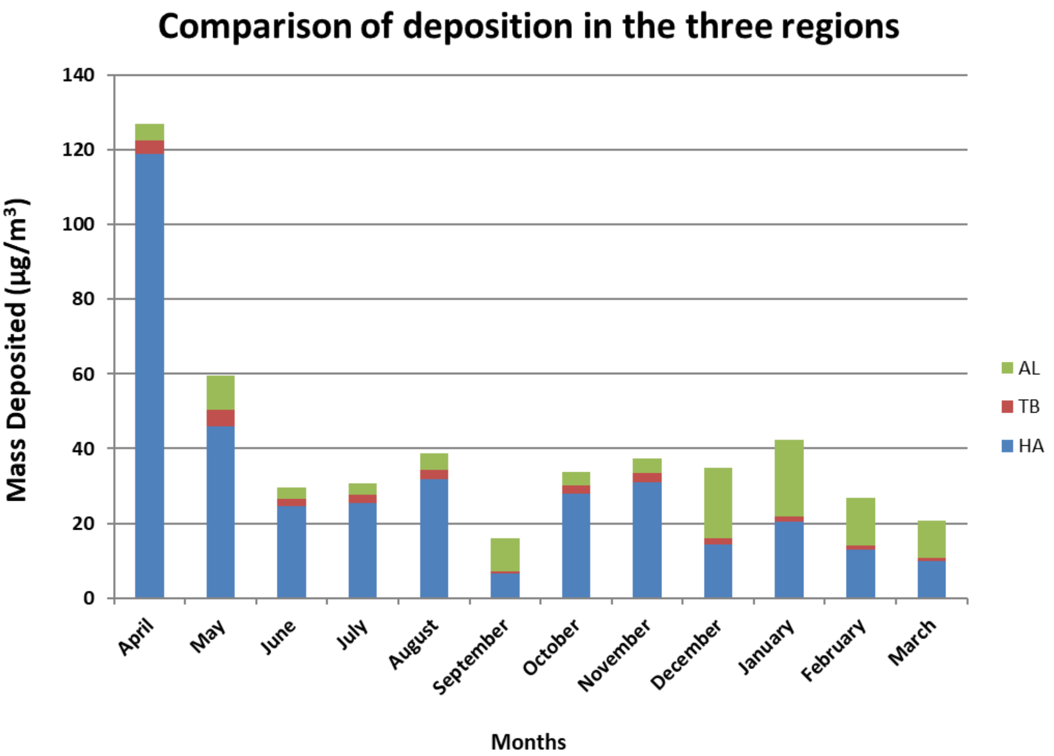

Figure 2. Comparison between the depositions in the three regions

4. CONCLUSION

We find that the aerosol mass distribution in Bhopal follows a multi-modal distribution with one mode in the fine region (PM_1) and other in the coarse region (1 to 10 micron). The mass mean diameter for the fine mode comes to be around 0.4 micron for most part of the year except the dry season where it is little lower (0.3 micron). The mass mean diameter of the coarse mode is also around 2.5 micron for monsoon and post-monsoon season but drops to 2.1 micron (similar to fine mode) during dry season and raises to 4.3 for the pre-monsoon season.

Using the equations given by International Commission on Radiological Protection (ICRP) model, the regional deposition and total deposition were estimated. Deposition in the head airways region is highest throughout the study period as most of the particles are entrapped in this region, followed by alveolar and tracheobronchial region. Even though the overall deposition in the month of April is the highest (124.6 µg m^{-3}), most of the deposition in the month of April is in the head airways region (137.7 µg m^{-3}) which is protected by a mucociliary layer while the deposition in the alveolar region is low (4.4 µg m^{-3}). The alarming part is the amount of alveolar deposition in the months of December (19.1 µg m^{-3}), January (20.4 µg m^{-3}) and February (12.9 µg m^{-3}) where the mass of particles deposited in the alveolar region is very high and hence it is more viable for causing lung diseases. Deposition being higher in alveolar than tracheobronchial region brings attention to the detrimental effects particulate deposition can cause at the lungs.

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