Quantifying sources of particulate matter pollution at different categories of landuse in an urban setting using receptor modelling

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ABSTRACT

Urban areas need to deal with the problem of deteriorating air quality due to the presence of various contributing sources. This paper quantifies the contribution of various sources towards prevailing ambient particulate matter (PM) concentrations at different landuse categories in an urban setting. PM_{10} and $PM_{2.5}$ were monitored at seven locations representing different area categories in Bangalore. PM samples were analysed for its constituents including ions, organic carbon, elemental carbon, elements, and molecular markers. The chemically speciated data of PM samples were fed into a receptor model (Chemical Mass Balance) along with indigenously developed source profiles to undertake apportionment of the sources. Performance of the model was adjudged with an average r^2 value of 0.83 and χ^2 of 5. Results of receptor modelling show the variation in source contributions across different landuse categories. While transport had the highest contribution at the kerbside locations, diesel generator sets used as alternative power supply emerged as an important source in the residential areas. In the coarser fraction (PM_{10}), the contribution of re-suspended dust was found to be high. At city level, on an average, transport sector contributed significantly (19%) in PM_{10} and dominantly (50%) in $PM_{2.5}$. The study clearly highlights the variety of sources to be controlled in different areas of a city. The methodology followed can be replicated to understand and control the sources of air pollution in an urban area. The approach could also lead to more informed and effective decision making for air pollution control.

INTRODUCTION

Particulate matter (PM) is now well known to have significant impacts on human health. The problem is more evident in urban areas due to more and more intense sources. The major sources which could be linked to high activity levels in a city are transport, industries, power generation units, diesel generator (DG) sets, domestic fuel burning, re-suspended dust, etc. $PM_{2.5}$ not only impacts the human health but also known to cause visibility degradation [1-4]. Wilson and Suh [5] state that the ambient fine PM is not a single pollutant but a mixture of many chemical species that are dominated in urban environments by primary and secondary aerosols from combustion-based emissions. The mix of different species is dependent on the type and intensity of emission sources, which vary considerably in different land uses. Hence, it is relevant to understand the constituents of PM and the relative contribution from sources towards its concentrations for various locations within an urban area. This not only helps in correct decision making but also in optimization of resource allocation for air pollution control.

Emission of pollutants from particular sources and their concentrations in ambient air can be simulated using modelling techniques. The two widely used modelling techniques are receptor and dispersion modelling. While dispersion modelling tracks the path of the pollutant from its source to the receptor based on the meteorology, topography and chemical transformations; receptor models interpret the quantity and quality of the constituents of the pollutant both at the sources and the receptor.

There have been a few studies in past on the use of receptor models for apportionment of sources of PM in Indian cities. World Bank [6] identified diesel

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combustion (7-61%), road dust re-suspension (4-41%) and biomass burning (9-32%) as the major sources in Delhi, Kolkata, Mumbai and Chandigarh. USEPA [7] concluded that in Hyderabad city vehicles contribute 48% to PM_{10}, followed by road dust (33%), secondary pollutants 8% and industries 6%. Pervez et al. [8] investigated the source contribution estimates of mercury in urban dust fallout in Raipur using the chemical mass balance (CMB8) receptor model. Chelani et al. [9] carried out source apportionment of PM_{10} in Mumbai, India using the CMB Model and observed vehicular, industrial and soil dust to be the dominant sources. Kushwaha et al. [10] have also attempted source apportionment and exposure of PM_{10} in Delhi. In addition to PM, receptor models have also been used for ascertaining the sources of volatile organic compounds [11]. The current study for quantifying the sources of particulate matter (PM_{10} and $PM_{2.5}$) is based on extensive sampling done for all the three seasons at various landuse categories in an urban region.

MATERIALS AND METHODS

1. Study Region

Bangalore City (India) was selected as the region to apply the receptor modelling technique and devise air pollution control strategies for specific landuse based area categories. The selection of Bangalore City for the study was based on its very high activity levels - rapid population growth, energy demands, and mobility demands, resulting in high emissions of air pollutants, extensive violation of ambient air quality standards and limited infrastructure for control. The whole city was divided into the grids of 2 x 2 km and seven representative grids were selected depicting different landuse categories. The landuse and locations chosen for conducting air quality monitoring are shown in Fig. 1.

Preliminary surveys were carried out and significant sources of air pollutant emissions were identified and quantified in the seven grids. It was observed that Domlur (R1), a residential location, had limited vehicular activity, but significant DG set usage and liquefied petroleum gas (LPG) use for cooking. On the other hand, Kammanahalli (R2) is another residential location but with higher vehicular activity and significant firewood use for cooking. Two kerbside locations, namely Victoria Road (K1) and Central Silk Board (CSB) (K2), were chosen to represent a congested commercial area and a busy traffic intersection, respectively. IGICH (S) is chosen as a sensitive location because of hospital and other institutions in its vicinity. Peenya (I), the largest industrial area towards the western outskirts of the city, is taken as another landuse category. The background location (BG) is chosen outside the eastern city limits to avoid influence from city emissions.

2. Methodology

Ambient air quality monitoring was carried out at the selected seven locations in Bangalore during three seasons (winter (Dec-Feb), summer (Apr-Jun), and pre-monsoon (Jul-Sep)) of 2007. PM_{10} was measured for 20 d (with each sampling run of 24 h) in three seasons using a multichannel (3 channel) speciation sampler. $PM_{2.5}$ concentrations were measured for 1 wk in each season using a Federal Reference Method Partisol sampler. The samples were simultaneously collected on different types of filters (Teflon/Nylon) using multiple channels that were later used for detection of various constituents of PM such as elements, ions, carbon and molecular markers. A carbon analyser, ion chromatograph, atomic absorption spectrophotometer, induced coupled plasma mass spectroscopy and gas chromatography were used for analyzing different constituents of the collected PM samples (Table 1). Molecular markers were analysed in the ambient fractions of PM_{10} and $PM_{2.5}$ to resolve the issue of co-linearity between few sources such as DG sets and diesel driven vehicles. The shares of some of the molecular markers (such as hopanes, hexa-decanamide and picene) were found to be distinctively different in the two sources.

Air quality data monitored at all seven locations were analysed to understand their statistical behavior. The daily data of chemically speciated PM_{10} and $PM_{2.5}$ concentrations were eventually fed into a receptor model (CMB) to compute the contribution of different sources. Indigenous source profiles developed by the Indian Institute of Technology Bombay (IITB) [12] were used as another input to the model. The source profiles were developed specifically for many of the sources existing in Bangalore city e.g. soil dust, paved road dust, DG sets, wood combustion, etc. Sethi and Patil [12] further details out the procedures followed for the development of profiles, its comparison with other source profile datasets and its validity in Indian context. Receptor model runs were carried out for all monitoring days and the results were obtained after satisfying performance criteria for statistical fit, i.e., % mass, r^2, and χ^2 and t-statistics. The results of receptor modelling were also validated with the outcomes of dispersion modelling carried out using the USEPA's approved ISCST3 model.

3. Software

The USEPA approved CMB receptor model [13-17] was used to compute the share of different sources towards prevailing PM concentrations. The fundamental principle of CMB receptor model is based

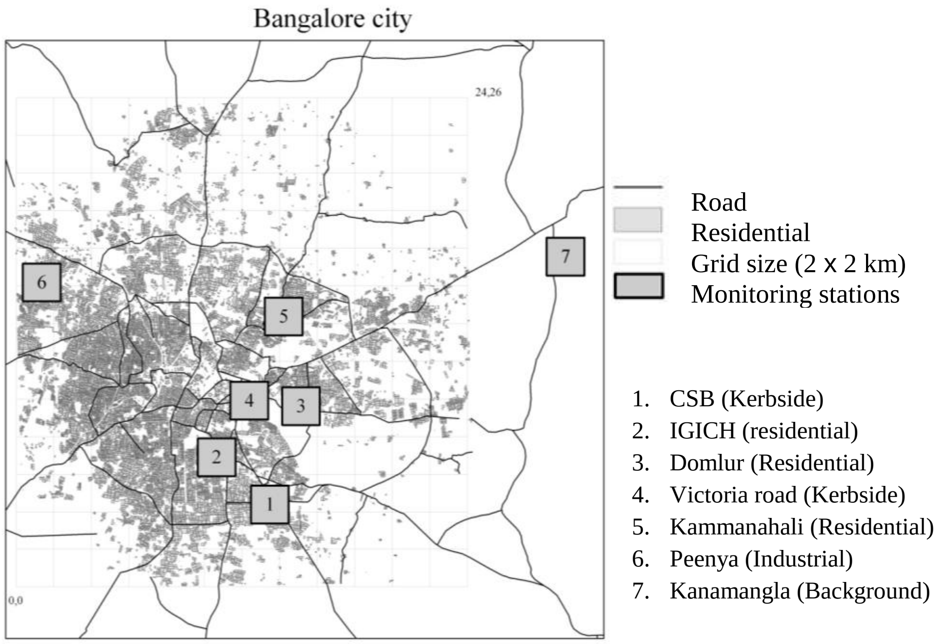

Fig. 1. Landuse and locations chosen for conducting air quality monitoring in Bangalore city.

Table 1. Sampling and analytical protocol for the study

Parameters	Sampling	Analysis
PM_{10} and $PM_{2.5}$	Speciation sampler using teflon filter	Gravimetric
Elements (Na, Mg, Al, Si, P, S, Cl, Ca, Br, V, Mn, Fe, Co, Ni, Cu, Zn, As, Ti, Ga, Rb, Y, Zr, Pd, Ag, In, Sn, La Se, Sr, Mo, Cr, Cd, Sb, Ba, Hg, and Pb)	Teflon filter	Flame AAS and GT-AAS and Hydride generation for As and Hg, ICP-MS
Ions (F^-, Cl^-, Br^-, NO_2^-, NO_3^-, SO_4^{-2}, K^+, NH_4^+, Na^+, Ca^{++}, Mg^{++})	Teflon filter	Ion chromatography with conductivity detector
Carbon analysis (OC, EC and Total Carbon)	Quartz filter	Carbon analyser using IMPROVE protocol
Molecular markers: n-Hentriacontane, n-Tritriacontane, n-Pentatriacontane, 22, 29, 30 – Trisnorneohopane, 17α(H), 21β(H)-29 Norhopane, 17α(H), 21β(H) Norhopane, Hexadecanamide, Octadecanamide, Benzo[b]fluoranthene, Benzo[k]fluoranthene, Benzo[e]pyrene, Indeno[1,2,3-cd]fluoranthene, Indeno[1,2,3-cd]pyrene Phenylenepyrene, Picene, Coronene, Stigmasterol, Levoglucosan	Quartz filter	Extraction, followed by GC-MS/ GC-FID analysis with and without derivatization

on the principle of mass conservation, which can be used to identify and apportion the sources of airborne PM in the atmosphere [18]. It consists of a solution to linear equations that express each receptor chemical concentration as a linear sum of products of source profile abundances and source contributions.

$$C_i = \sum_{j=1}^{J} F_{ij} \times S_j$$

where i = 1 to I, C_i is concentration of elemental component I, S_j is the source contribution, and F_{ij} is the fraction of source contribution S_j composed of element i.

The model uses the chemical and physical characteristics of particles measured at the source and receptor to identify and quantify the source contributions to receptor concentrations [19]. The source profile abundances (i.e., the mass fraction of a chemical from each source type) and the receptor concentrations, with appropriate uncertainty estimates, served as input to the CMB. The output consists of the amount contributed by each source type represented by a profile relative to the total mass, as well as to each chemical species.

RESULTS AND DISCUSSION

1. Air Quality Analysis

The results of air quality monitoring of PM_{10} at the seven monitoring sites are presented in Fig. 2. The background location, being outside the city limits, shows the minimum concentrations. Residential locations R1 and R2 show variation in the measured PM_{10} concentrations, mainly due to differences in their population profiles. While Domlur (R1) is an area belonging to high income population, Kammanhali (R2) also accommodates lower-income people using biomass for cooking. Kerbside and industrial locations show very high PM_{10} concentrations mainly due to vehicular and industrial sources.

The 24-h PM_{10} and $PM_{2.5}$ samples were analysed for their constituent fractions of ions, carbon and elements. Tables 2 and 3 show the three-season average results of chemically speciated PM_{10} and $PM_{2.5}$ samples, respectively. The relative share of carbon in the total PM_{10} and $PM_{2.5}$ mass was found to be highest at kerbside locations (K1 and K2) and lowest at background and residential (R1) location. Moreover, the kerbside locations showed a significant increase in the carbon content in $PM_{2.5}$ samples when compared to PM_{10}, indicating enhanced contribution in the finer particle range by the combustion sources such as vehicles. The relative share of ions in the total mass was found to be higher at the locations in the outskirts (Background and Peenya), indicating secondary particulate formation. The relative share of elements was found to be less for $PM_{2.5}$ relative to PM_{10}, depicting less influence of coarser elements in the finer fractions.

2. Receptor Modelling

Monitored ambient PM concentrations speciated into different components along with speciation profiles of different sources [12] acted as the two inputs to the receptor model. CMB 8.2 compatible files were prepared using speciated PM_{10} and $PM_{2.5}$ data for each of the seven sites. Based on the indigenous source profiles developed by IITB [12], a CMB compatible source profile data file was prepared. This included emission profiles of various sources including wood burning, fuel oil burning, DG sets (diesel and kerosene), LPG combustion, road dust, soil dust, petrol vehicles, diesel vehicles, and secondary particulates (sodium nitrate, ammonium sulphate ammonium nitrate).

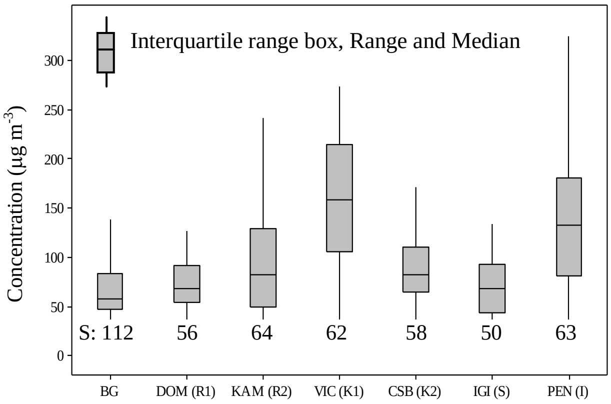

Fig. 2. Results of air quality monitoring of particulate matter (PM_{10}) at the seven monitoring sites in Bangalore. S: Number of samples.

Using the two inputs, CMB8.2 model was run for all days during which the monitoring was carried out in the three seasons. The results of receptor modelling for PM_{10} and $PM_{2.5}$ for different locations in Bangalore are presented in Table 4 which shows relative shares of different sources contributing to PM_{10} and $PM_{2.5}$ fractions. The unidentified mass was found to be varying between 28-41% in PM_{10} and 6-24% in $PM_{2.5}$ modelling results across different seasons. Results were analysed keeping in mind the area categories of various monitoring stations.

2.1. Domlur (R1)

Source apportionment at Domlur suggested significant contribution from diesel burning in DG sets and to some degree from the transport sector. DG sets contributed 21-38% in PM_{10} fractions which further increases to 37-49% in $PM_{2.5}$. Transport sector (both diesel and petrol) contributes 6-8% in PM_{10} and 13-48% in $PM_{2.5}$ fractions. Secondary particulates also had a significant relative share of 9-19% in the PM_{10} concentrations and 4-39% in $PM_{2.5}$. Dust (originating from road dust re-suspension and crustal sources) had a significant relative share of 35-62% in PM_{10} fractions during different seasons. The source profile of road dust in Bangalore has shown significant quantities of carbon and ionic material, other than elemental components. This is probably due to settling of these species on the road surface and further re-suspension during the movement of vehicles. Very high relative share of road dusts at Domlur (despite low relative shares of elements in the monitored PM) could be explained through this. Dust, however, being coarse, did not feature much in the $PM_{2.5}$ distribution.

2.2. Kammanahalli (R2)

Source apportionment at Kammanahalli indicated substantial contribution from the transport sector.

Table 2. Average contributions (μg m^{-3}) of different species in ambient PM_{10} concentrations across various seasons at different locations

Marker	Specie	Background	Domlur	Kammanhalli	Victoria road	CSB	IGICH	Peenya
Crustal signature	Al	1.23	1.59	2.32	2.64	4.12	1.19	2.84
	Ca	0.98	1.77	2.54	4.51	0.88	0.41	0.73
	Si	1.22	1.89	1.93	2.43	1.18	1.01	2.34
	Fe	1.59	2.02	2.16	3.11	5.45	1.70	3.96
Salt	Cl^-	1.94	1.62	2.28	1.83	1.79	2.76	2.98
	Na^+	1.21	1.87	0.93	1.05	0.97	1.47	1.74
Elements	Mn	0.07	0.10	0.07	0.06	0.14	0.08	0.12
	Zn	0.65	0.75	0.99	0.79	2.66	0.38	1.08
	V	0.01	0.02	0.01	0.01	0.02	0.01	0.08
	Ni	0.04	0.09	0.02	0.02	0.02	0.05	0.02
	Co	0.03	0.03	0.04	0.03	0.25	0.00	0.01
	As	0.02	0.05	0.02	0.08	0.03	0.04	0.06
	Se	0.30	1.51	0.75	0.00	0.00	0.00	0.00
	Ti	0.02	0.05	0.03	0.03	0.04	0.02	0.06
	Others	3.36	4.17	5.21	6.01	6.04	3.75	6.35
Organic carbon	OC	9.8	12.5	18.1	27.6	41.1	11.4	21.4
Elemental carbon	EC	5.2	4.9	7.3	14.8	13.7	4.6	8.1
Secondary ions	Nitrates	1.5	1.6	1.4	1.8	1.8	1.2	2.1
	Sulfates	6.4	6.4	4.0	5.7	6.5	4.2	6.7
	Ammonium	1.6	1.2	0.4	0.8	0.4	0.5	0.4
Other ions	Others	0.86	1.90	0.87	1.15	1.00	1.21	1.84

Table 3. Average contributions (μg m^{-3}) of different species in ambient $PM_{2.5}$ concentrations measured across various seasons at different locations

Category	Specie	Background	Domlur	Kammanahalli	Victoria road	CSB	IGICH	Peenya
Crustal	Al	0.23	0.77	1.17	0.51	0.12	0.22	0.17
	Ca	1.93	7.70	13.88	3.57	0.07	1.18	0.42
	Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Fe	0.45	1.24	1.49	1.04	0.26	0.39	0.42
Salt	Cl-	1.00	1.65	0.71	1.27	1.22	1.45	1.13
	Na+	0.69	0.96	0.60	0.94	0.78	0.97	1.18
Elements	Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Zn	0.08	0.23	0.15	0.06	0.00	0.01	0.21
	V	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Co	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	As	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Se	0.00	0.03	0.00	0.00	0.00	0.00	0.00
	Ti	0.02	0.07	0.05	0.05	0.02	0.03	0.02
	Others	1.00	2.73	2.16	2.21	0.61	0.65	1.32
Organic carbon	OC	6.8	8.0	17.2	22.5	23.5	10.8	13.5
Elemental carbon	EC	3.1	4.2	8.2	11.8	16.3	4.3	7.5
Secondary ions	Nitrates	0.4	0.3	0.5	0.5	0.7	0.4	0.7
	Sulfates	5.0	4.4	3.6	3.9	5.9	3.3	4.3
	Ammonium	1.4	1.3	1.0	1.2	1.8	0.9	0.6
Ions	Others	0.6	0.5	0.6	0.7	1.2	1.1	1.0

Table 4. Results (%) of CMB8.2 receptor modelling for PM_{10} and $PM_{2.5}$ for different seasons and locations in Bangalore

Location	Season	PM_{10} Transport	$PM_{2.5}$ Transport	PM_{10} DG set	$PM_{2.5}$ DG set	PM_{10} Industrial	$PM_{2.5}$ Industrial	PM_{10} Domestic	$PM_{2.5}$ Domestic	PM_{10} Paved road & Soil dust	$PM_{2.5}$ Paved road & Soil dust	PM_{10} Secondary	$PM_{2.5}$ Secondary
Domlur (R1)	I	6	13	38	37	0	0	1	11	35	1	19	39
	II	6	34	20	45	0	0	0	1	62	5	11	15
	III	8	47	35	49	0	0	2	0	45	0	9	4
Kammanhalli (R2)	I	38	57	5	7	0	0	4	2	38	10	15	23
	II	41	80	5	9	0	0	7	3	40	2	7	7
	III	26	80	3	9	0	0	8	3	62	0	1	8
CSB (K2)	I	54	40	3	47	0	0	4	0	26	1	13	13
	II	30	55	2	35	0	0	0	3	52	3	17	3
	III	14	49	1	45	0	0	7	1	72	1	7	5
Victoria road (K1)	I	16	76	15	5	0	0	2	3	52	5	16	12
	II	14	59	19	3	0	0	1	8	60	1	6	28
	III	8	84	8	4	0	0	3	0	73	6	9	5
IGICH (S)	I	7	37	9	37	0	0	7	12	64	4	14	10
	II	20	38	17	24	0	0	9	13	48	18	6	7
	III	22	43	32	38	0	0	2	11	44	0	1	9
Peenya (I)	I	18	20	12	16	17	25	16	15	31	0	6	23
	II	11	41	8	13	23	23	2	7	56	7	0	8
	III	4	44	2	22	42	14	1	10	50	0	1	9
Kanamangala (BG)	I	25	51	0	0	0	0	11	14	24	2	40	33
	II	15	58	0	0	0	0	11	10	55	2	19	30
	III	25	70	0	0	0	0	5	2	57	19	13	9

I: Winter, II: Summer, III: Pre-monsoon

Transport sector (petrol & diesel) had a significant relative share of 26-41% in PM_{10} and 57-80% in $PM_{2.5}$ samples. Dust contributed about 38-62% to PM_{10} samples but is almost non-existent in $PM_{2.5}$ fractions. Domestic firewood burning also appeared to be significant (4-8%) at this location. The relative share of secondary particulates varied in between 1-15% in PM_{10} and 7-23% in $PM_{2.5}$ samples.

2.3. Victoria Road (K1)

Victoria road is a kerbside location and clearly showed higher contributions from transport sector (8-15% in PM_{10} and 40-55% in $PM_{2.5}$). Being a commercial area too, DG sets contributed 8-19% in PM_{10} and 35-47% in $PM_{2.5}$ samples. In PM_{10}, dust had the highest relative share of 52-73%, however, it is insignificant in $PM_{2.5}$ fractions. Secondary particles contribute 6-16% in PM_{10} and 4-13% in $PM_{2.5}$ fractions.

2.4. CSB (K2)

CSB is another kerbside location and, as could be expected, showed high contribution from transport sector. Transport sector contributes 14-54% in PM_{10} concentrations and 60-84% in $PM_{2.5}$. Like other locations, dust contributed mainly in PM_{10} fractions (26-72%). DG sets contribute minimally (less than 5%) to concentrations of both sizes. The relative share of secondary particulate varies from 7- 17% in PM_{10} and from 5-38% in $PM_{2.5}$ fractions.

2.5. IGICH (S)

Though IGICH is a hospital location, it is also in the heart of the city. The CMB8.2 model suggests a significant contribution from the transport sector (7-22% in PM_{10} and 37-43% in $PM_{2.5}$). There had also been observations of wood burning in vicinity of the hospital and particles from this source were detected, varying from 2-9% in PM_{10} and 9-13% in $PM_{2.5}$ samples. In PM_{10} samples, the relative share of dust eclipsed the share of other sectors and contributed 44-64%, however the contribution went down to less than 18% in $PM_{2.5}$ fractions.

2.6. Peenya (I)

We expected Peenya, an industrial location, to show some fuel oil (FO) burning and hence displaying a contribution from industrial sector. FO burning contributed 17-42% in PM_{10} samples and 14-25% in $PM_{2.5}$. However, transport sector (diesel & petrol) also had a substantial relative share: 4-18% in PM_{10} and 20-44% in $PM_{2.5}$ samples. Wood burning was detected varying from 1-16% in PM_{10} and 7-15% in $PM_{2.5}$ fractions depicting the usage of wood in industries. The fact that many industries in the area have DG sets as secondary power source, is reflected in their contribution of 3-12% in PM_{10} and 13-23% in $PM_{2.5}$ fractions. Dust again had the highest relative share of 31-56% in PM_{10} samples; however it is very low in case of finer fraction of $PM_{2.5.}$

2.7. Kanamangla (Background)

The background location was a village outside the city limits with limited sources of pollution. Understandably, the CMB8.2 model suggested major contribution from secondary particulates and soil dust,

Table 5. Dominance of sources in PM fractions monitored at different landuse categories of the city

Location	PM_{10}	$PM_{2.5}$
Domlur (R1)	Road dust, DG sets, Secondary	DG sets, Transport, Secondary
Kammanhalli (R2)	Road dust, Transport, Domestic	Transport, DG set, Domestic
Victoria Road (K1)	Road dust, Transport, DG sets	Transport, Secondary, DG sets
CSB (K2)	Road dust, Transport, Secondary	Transport, DG sets, Secondary
IGICH (S)	Road dust, Transport, Domestic	Transport, DG sets, Domestic
Peenya (I)	Road dust, Industries Transport	Industries, Transport, Secondary
Kanamangala (BG)	Secondary, Road dust, Transport	Secondary, Transport, Domestic

a general feature of a background location. Secondary particulates contributed 13-40% in PM_{10} and 9-33% in $PM_{2.5}$ samples. Dust contributed 24-55% in PM_{10} and 2-19% in $PM_{2.5}$ samples. The transport sector also had a relative share of 16-25% in PM_{10} and 51-70% in $PM_{2.5}$ samples, which we attributed to a highway passing nearby. In keeping with its character as a rural site, wood burning was detected varying from 5-11% in PM_{10} and 2-14% in $PM_{2.5}$ samples across different seasons.

Based on the receptor modeling results, Table 5 presents the dominance of sources in different PM fractions monitored at different landuse categories of the city.

3. Discussion

Receptor modelling of PM_{10} and $PM_{2.5}$ at the seven locations based on landuse based area categories suggests that there is a wide variation in contribution of sources to PM_{10} concentrations.

3.1. PM_{10}

The major contributors to the PM_{10} concentrations observed at the seven locations in Bangalore were dust from paved road and soil, transport, and DG sets (Fig. 3). Domestic and industrial sectors have small and site-specific

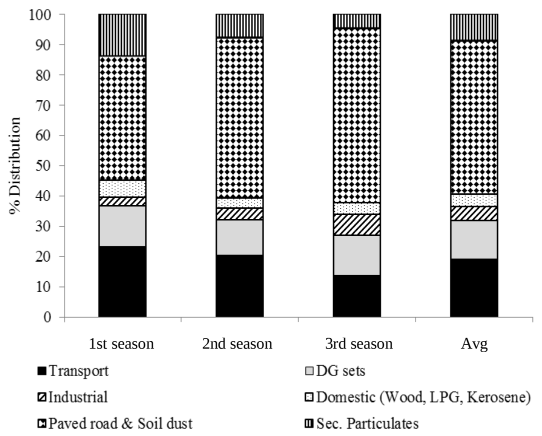

Fig. 3. Relative sectoral contributions to PM_{10} concentration in Bangalore city.

contributions. Average relative share of transport sector in PM_{10} concentrations observed in Bangalore across various seasons varies from 14-23%. DG sets contribute 12-14% with industries 3-7%. Paved road and soil dust are the major contributors having a relative share of 41-58%, while secondary particulates contribute 5-14% in the PM_{10} concentrations. The contribution of paved road dust re-suspension and soil dust is significant at all the seven sites and it eclipses the share of other combustion based sources. Vehicular sources are predominant at the kerbside locations (K1 and K2), while higher share of FO combustion is observed at industrial location (Peenya). Background location (Kanamangala) shows higher contribution from secondary particulates depicting formation of these particles during transport of gaseous pollutants.

3.2. $PM_{2.5}$

It emerged out that the transport sector contributed significantly to the $PM_{2.5}$ concentrations, followed by other sectors like DG sets, and secondary particulates (Fig. 4). However, domestic sector, and industries had smaller contributions. Contribution of transport sector is significant at all seven sites, with kerbside locations showing the highest shares. The average relative share of transport sector in $PM_{2.5}$ concentrations varied from 41-58%, during different seasons. Secondary particulates being finer in size showed substantial relative share (7-20%) in the $PM_{2.5}$ concentrations with Background location showing the highest contribution. Domestic sectors had a small relative share of 4-7%, followed by industries 2-4%. Dust being coarse, did not contribute much to the $PM_{2.5}$ concentrations observed in Bangalore.

3.3. Validation of results of receptor modelling

Dispersion modelling was carried out to estimate the share of different sources at the locations where actual monitorings were carried out. Traffic counts were carried out at 25 locations in Bangalore city to assess variations of traffic patterns and corresponding emissions at different types of roads. Each road segment in the city was sub-divided into innumerous

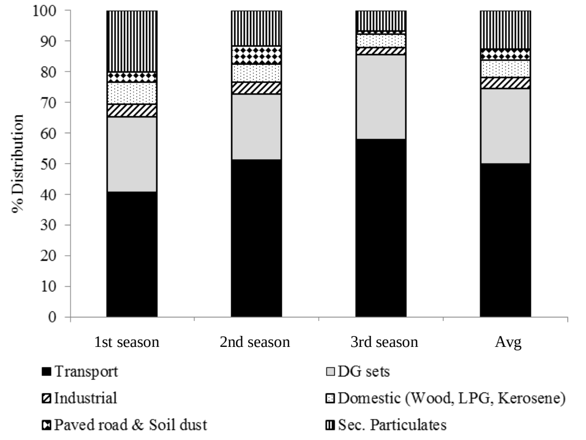

Fig. 4. Relative sectoral contributions to $PM_{2.5}$ concentration in Bangalore city.

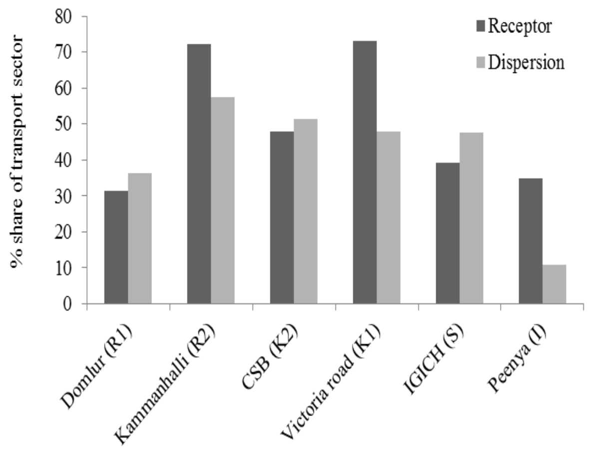

Fig. 5. Share of transport sector in $PM_{2.5}$ concentrations estimated by the receptor and dispersion modelling approaches.

small sources and survey findings were used to assess their emissions. The emission from all the sources including transport sector were fed into the ISCST3 model for prediction of PM concentrations. Sensitivity runs were performed to assess the share of different sources. For validation, the results of receptor modelling were compared with the outcomes of dispersion model (ISCST3) at the six locations within the city. The relative share of the transport sector estimated by the receptor and dispersion models is shown in Fig. 5.

The two modelling approaches show reasonably similar results for R1, R2, K2, and S locations. This overlap suggests that a combination of the two approaches can deliver reliable insights for improved decision-making for air pollution control.

On the other hand, K1 and I locations show higher share of transport sector than the dispersion modelling approach. This could be attributed to lower accounting for transport emissions at these locations in the dispersion modelling approach. The K1 location in particular deals with heavy congested traffic, which sometimes gets unaccounted while estimating the emissions using average speed emission factor approach. More research is required to understand the variations observed at these two sites, and no immediate action could be taken on the basis of current work.

3.4. Comparison with other studies

The results of the current work were compared with the outcomes of other studies of source apportionment of PM across different cities in Asia. Table 6 lists the results of various studies and shows that our results are within the overall observed ranges. Across different studies, the share of transport in $PM_{2.5}$ fractions varies between 7-68% and the current work estimates it to be 50% in Bangalore. Similarly, the share of road dust is also in between the overall range of 2-18%. The current work is also consistent with other studies on the higher shares of dust (road dust/soil dust) in the PM_{10} fractions.

CONCLUSIONS

The study focuses on estimating the contributions of different sources toward prevailing PM concentrations at different landuse based area categories of an urban centre. This helped in understanding the fact that the share of sources varies across different landuse categories. There is a clear dominance of finer particles ($PM_{2.5}$) in the vehicular exhaust. Road and soil dust has been identified as a major contributor to the ambient PM_{10} concentrations. On the other hand, $PM_{2.5}$ depicts significant contribution from combustion based anthropogenic sources. The approach also identifies DG sets' contribution in PM levels, mainly due to frequent power cuts in the city. The contribution of industries is found to be generally low except in specific industrial areas of Bangalore. Similarly, the domestic sector has a small contribution only at the sites where firewood burning takes place. The study shows the presence of secondary particulates mainly in $PM_{2.5}$ fractions, which demands control of gaseous pollutants like NO_x and SO_2.

The study also highlights certain limitations that require further research in the future. These include the issue of co-linearity amongst the source profiles, and limited distinction between fuel usage in different sectors such as diesel usage in transport and DG sets. It has also been re-emphasised that the results of receptor modelling should be used complementarily with the results of dispersion modelling. The results of this study will certainly be useful in highlighting the use of receptor modelling approach for drafting air quality management strategies for urban centres.

Table 6. Results (%) of various source apportionment studies carried out in different cities

City	Year	Transport	Dust	Industries	Secondary	Source
			$PM_{2.5}$			
Bangalore	2007	50	4	4	13	Current study
Shanghai	2004	22	11	29	-	[20]
Beijing	2000	7	12	7	34	[21]
Bangkok	2003	35	2	-	18	[22]
Dhaka	2001-05	54	18	19	-	[23]
Hanoi	2001-08	40	3	36	8	[24]
Pune	2007	27	4	-	49	[25]
Kanpur	2007	28	7	8	22	[25]
Kuala Lumpur	2004-08	68	8	17	-	[26]
Hongkong	2001	23	10	19	28	[27]
			PM_{10}			
Bangalore	2007	19	51	5	9	Current study
Dhaka	2001-05	39	46	5	-	[23]
Kuala Lumpur	2004-08	42	18	17	-	[26]
Kanpur	2007	16	8	8	17	[25]
Pune	2007	7	57	17	-	[25]

*Industries includes coal combustions and power plants also
** Values are averaged for various stations/seasons for the city

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Discussions of this paper may appear in the discussion section of a future issue. All discussions should be submitted to the Editor-in-Chief within six months of publication.

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