

Chemical mass balance source apportionment of PM₁₀ and TSP in residential and industrial sites of an urban region of Kolkata, India

A.K. Gupta^{a,*}, Kakoli Karar^a, Anjali Srivastava^b

^a Environmental Engineering Division, Department of Civil Engineering, Indian Institute of Technology, Kharagpur 721302, India

^b NEERI, Mumbai Zonal Laboratory, 89/B, Dr. A.B. Road, Worli, Mumbai 400 018, India

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Abstract

Daily average PM₁₀ (particulate matter which passes through a size selective impactor inlet with a 50% efficiency cut-off at 10 μm aerodynamic diameter), TSP (total suspended particulate matter) and their chemical species mass concentrations were measured at residential and industrial sites of an urban region of Kolkata during November 2003–November 2004. Source apportionment using chemical mass balance model revealed that the most dominant source throughout the study period at residential site was coal combustion (42%), while vehicular emission (47%) dominates at industrial site to PM₁₀. Paved road, field burning and wood combustion contributed 21%, 7% and 1% at residential site, while coal combustion, metal industry and soil dust contributed 34%, 1% and 1% at industrial site, respectively, to PM₁₀ during the study period. The contributors to TSP included coal combustion (37%), soil dust (19%), road dust (17%) and diesel combustion (15%) at residential site, while soil dust (36%), coal combustion (17%), solid waste (17%), road dust (16%) and tyre wear (7%) at industrial site. Significant seasonal variations of the particulate matters have been observed during the study period. In the monitoring sites total carbon, organic carbon and iron were found to be the marker species of road dust, while organic carbon, total carbon, chloride and sulfate have been observed as the marker species of soil dust in TSP.

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1. Introduction

Urban air quality in developing countries has deteriorated gradually because of rapid urbanization, population growth, lack of sufficient public facilities and industrialization. The PM₁₀ (particulate matter which passes through a size selective impactor inlet with a 50% efficiency cut-off at 10 μm aerodynamic diameter) is the respirable fraction of TSP (total suspended particulate matter) that deeply embedded in human lung tissue and cause respiratory problems and exacerbates other cardiovascular diseases [1]. In developing countries such as India the problem of particulate air pollution continues to worsen [2].

Several epidemiological studies have indicated a strong association between elevated concentrations of inhalable aerosol particles (PM₁₀), and increased mortality and morbidity [3–8]. PM₁₀ is settles very slowly and stay suspended in the air for long

periods. In addition to negative health effects, particulate matter reduces visibility and accelerates the deterioration of buildings [1,9]. PM₁₀ also influences many atmospheric processes including cloud formation, visibility, solar radiation and precipitation, and play a major role in acidification of clouds, rain and fog [10–12]. Ambient particulate matter may be the carriers of acidic or toxic species and may have detrimental effects on human health and ecosystems [13].

Particulate matter with aerodynamic diameter less than 2.5 μm (PM_{2.5}) is associated with increase in mortality [14,15], asthma [16] and visibility degradation [17]. The particles those are less than 1–2 μm in an aerodynamic diameter are mostly deposited in the alveolar region of the lung where the adsorption efficiency for trace elements is 60–80% [18] and can affect lung physiology, especially if the particles contain biologically available toxic metals. Very small particulates are of great concern due to their adverse health effects [19]. The fine and ultrafine particles can be deposited deep in the lungs and the residence time will be very long, up to several months [20]. The fine particles (PM_{2.5}), or those less than or equal to 2.5 μm, are comprised

* Corresponding author. Tel.: +91 3222 283428; fax: +91 3222 255303.
E-mail address: akgupta@iitkgp.ac.in (A.K. Gupta).

of both primary and secondary materials. The most prevalent fine materials are sulfates, organic carbon, nitrates, and ammonium. These generally account for approximately 80% of fine mass. The remaining part of the fine mass is comprised of small amounts of elemental carbon, water, crustal material, and trace amounts of metals [21,22].

Total suspended particulate matter (TSP) includes all airborne solid and liquid substances [23]. In India, the air pollution has become a great topic of debate at all levels because of the enhanced anthropogenic activities [24].

Receptor models use the chemical and physical characteristics of aerosol particles measured at source and receptor to both identify the presence of and to quantify source contributions to the receptor [25–27]. Receptor models commonly used are chemical mass balance (CMB), principal component analysis (PCA) and multiple linear regression analysis (MLR). Chemical mass balance is the fundamental receptor model based on the use of mass balance concept. As Kolkata experiences high concentrations of PM_{10} and TSP, particularly when the concentrations are in exceedance of an air quality standard, it is important to identify the contributing emissions sources. Source apportionment techniques for airborne particulate matter are defined as the method that quantifies the contribution of different sources to airborne particulate matter concentrations at receptor locations in the atmosphere. Source apportionment techniques are valuable tools that aid in the design of effective emissions control programs to reduce particulate air pollution.

The present study uses the measurements of particulate air quality level in an urban region of Kolkata to evaluate the importance of different sources and processes responsible for the high degree of particulate atmospheric level observed frequently in urban areas of large urban conurbations. It is important to understand the contribution of each emission source of air pollutants to ambient concentrations to establish effective measures for risk reduction.

The aim of the study was to quantitatively apportion the sources leading to high PM_{10} and TSP aerosol mass concentrations at residential and industrial sites of an urban region of Kolkata using chemical mass balance, a receptor model.

2. Methodology

2.1. Study area

Kolkata ($22^{\circ}32'N$, $88^{\circ}22'E$) is the second most populous city of India after Mumbai according to 2001 census report. It is the second largest metropolis in south Asia and is one of the worst polluted cities in the world [23]. Rapid and unplanned urbanization, uncontrolled vehicular density on insufficient badly cared road space and higher use of leaded petrol fuel increased the air pollution in Kolkata [28].

The city is bounded to the west and north-west by the Hugly river spread along 80 km, which divides it from Howrah on the western bank. The city has a tropical savannah climate with a marked monsoon season. Average relative humidity (RH) is 66% and 69% in winter and summer, respectively. Mean monthly temperature ranges from 20 to 31 °C, and the maximum tem-

peratures often exceed 42 °C. The pre-monsoon and monsoon seasons are dominated by strong southwesterly winds with greatest air ventilation potential [29]. Moderate northwesterly winds prevail for most of the year. Being located in a coastal area and influenced by sea-based disturbances include higher concentrations of ambient atmospheric chloride and sulfate aerosols. It has an average wind speed of 7 km/h blowing throughout the year. The monitoring locations of study area are shown in Fig. 1.

The residential and industrial monitoring stations were set up based on importance of emission sources, sensitivity of receptors, wind directions and predominant activities of the local areas. Residential location (Kasba) is typically residential area and air quality is mainly influenced by domestic activities, vehicular movement, solid waste dumping and open burning of leaves and garbage. Industrial location (Cossipore) has mainly thermal power generation plant, ordnance factory, railway yard for loading and unloading materials, heavy vehicular traffic, electroplating industry and dyeing industry.

2.2. Monitoring instruments

At each monitoring site, concentrations of both PM_{10} and TSP were measured. Respirable dust sampler (Envirotech) was deployed for the monitoring of ambient PM_{10} . Ambient air laden with suspended particulate matter enters the respirable dust sampler through inlet pipe. As the air enters the cyclone, coarse, non-respirable dust is separated from the air by centrifugal forces acting on the solid particles. The air stream deposited to the quartz microfibre filter paper, clamped between the top cover and filter adopter assembly, carries the fine dust forming the respirable fraction of TSP. The filter paper retains the respirable dust and the blower exhausts the carrier air from the system. High volume sampler (Envirotech) measured TSP. Both these instruments were operated at flow rates of 0.80–1.40 m^3/min . Monitoring of both the pollutants was carried out once a week at each monitoring site for a period of 24 h.

2.3. Sample analysis

PM_{10} and TSP were collected on 20.3 cm \times 25.4 cm Whatman quartz microfibre filters. The particulate concentrations were measured gravimetrically by weighing the particulate mass collected and knowing the total volume of air sampled. Filter papers were kept in desiccators for 24 h before and after the sample collection. Field and laboratory blank filter samples were routinely analyzed for PM_{10} and TSP to evaluate analytical bias and precision.

After gravimetric analysis, the quartz microfibre filters were digested in HNO_3 (nitric acid) and used for trace metal analysis. The digested solutions were then analyzed by using inductively coupled plasma-atomic emission spectroscopy (Jobin Yvon JY-24) for chromium (Cr), zinc (Zn), lead (Pb), cadmium (Cd), nickel (Ni), manganese (Mn) and iron (Fe).

The aliquot of PAHs samples and blanks were taken by punching out small circular portion of the exposed filter papers with a stainless steel punch and ultrasonicated with cyclohexane. The PAHs compounds (fluoranthene (Fl), pyrene (Py),

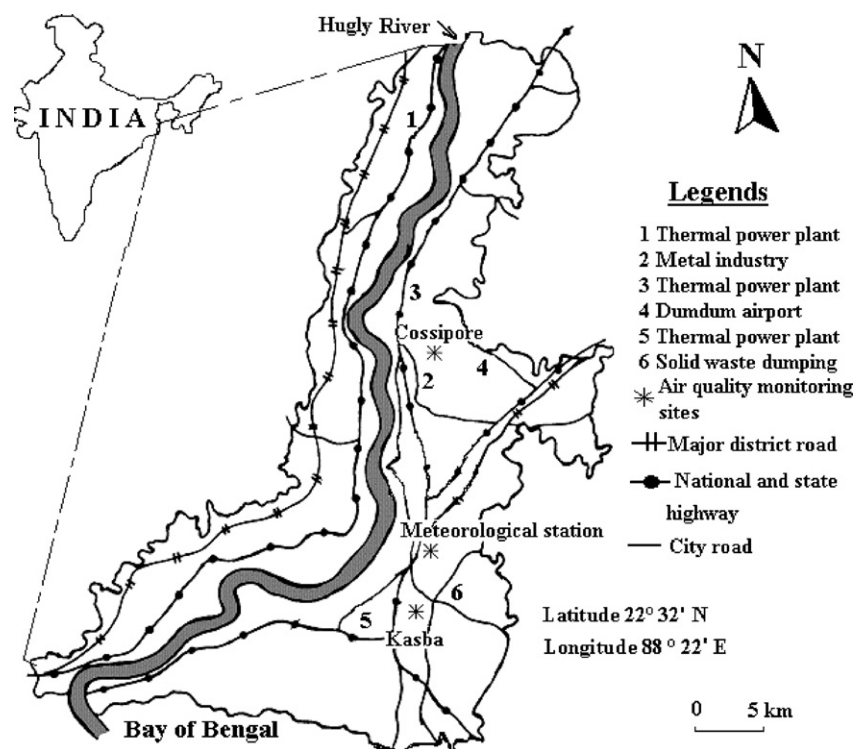


Fig. 1. Map of Kolkata with ambient air quality monitoring sites and major source locations.

benzo(*a*)anthracene (BaA), benzo(*b*)fluoranthene (BbF) and benzo(*a*)pyrene (BaP) have been analyzed using gas chromatography (Perkin-Elmer, auto system XL, GC-FID).

Total carbon (TC), inorganic carbon (IC) and organic carbon (OC) of PM₁₀ and TSP were analyzed using Carbon analyzer (SSM-5000A).

A part of exposed quartz microfibre filter papers were extracted in water and analyzed for water-soluble ions of fluoride (F⁻), chloride (Cl⁻), nitrate (NO₃⁻), phosphate (PO₄³⁻) and sulfate (SO₄²⁻) using ion chromatography (IC-Dionex DX-100).

2.4. Quality assurance and quality control

An intensive quality control program was implemented to maintain the accuracy and precision throughout the study. The present sampling and analysis ensured the following quality assurance procedures:

- Maintenance and service was done at frequent periods of the equipments used for monitoring and analysis.
- Collection of representative samples with proper labeling (e.g. sample type, location, time and date of collection, environmental characteristics, etc.) was ensured.
- The expendable material, e.g., glassware, solvents, etc. were used with suitable quality.
- Acceptance tests for the instruments and apparatus being used.
- Quality control during field operation and chemical reagent handling.

- The flow rate of the pump was calibrated using a rotametre and monitored at an interval of 1 h.
- Routine calibration to ensure that the flow rates were maintained in an acceptable range.
- Filter handling was cautious, using clean forceps.
- Ultimate care was taken during the sampling, sample handling, processing and analysis to avoid any contamination.
- Data quality control by means of collocated sampling, flow audit, spot check and duplicate analysis.
- Competence tests of field operators and laboratory analysts.

2.5. Data analysis

Chemical mass balance (version 8.0) modeling approach using multiple linear least squares regression has been used to identify the probable sources of PM₁₀ and TSP in the study area. Assumption of CMB model [30] in the present study was examined with regard to source compositions being constant over a period of sampling. According to assumption that chemical species do not react with each other, it is necessary to measure source profiles or modify them by some objective method to account for changes in the character between source and receptor [31]. The CMB receptor model is well documented and tested [32]. Ref. [33] summarizes the results of several CMB source apportionment studies performed throughout the world.

A total of 20 particulate chemical species were selected for inclusion in the present modeling study. The fundamental principle of CMB is the mass conservation that can be used to identify and apportion sources of airborne particulate matter in the atmosphere [32,34]. A mass balance equation for all *m* chem-

ical species in the n samples as contributed from p independent sources is given by the following equation:

$$X_{ij} = \sum_{k=1}^p c_{ik} S_{kj} \quad (1)$$

where X_{ij} is the i th elemental concentration measured in the j th sample at the receptor site, $i = 1, 2, \dots, m$ and $j = 1, 2, \dots, n$; c_{ik} the fractional composition for the i th element from the k th source, and S_{kj} is the airborne mass concentration of species from the k th source contributing to the j th sample.

With the knowledge of the number and nature of the sources in the receptor region, the mass contribution of each source to each sample can be calculated [35–37]. Ref. [37] modified Eq. (1) to explicitly include changes in composition of the source material while in transit to the receptor as given by the following equation:

$$X_{ij} = \sum_{p=1}^k \alpha_{ik} c'_{ik} S_{kj} \quad (2)$$

where α_{ik} is the coefficient of fractionation so that if c'_{ik} were the composition of the particles as emitted by the source and c_{ik} is the composition of the particles at the receptor site

$$c_{ik} = \alpha_{ik} c'_{ik} \quad (3)$$

In practice, it is generally impossible to determine the α_{ik} values and they are assumed to be unity:

$$c_{ik} = c'_{ik} \quad (4)$$

Initially, ordinary least squares were given by Ref. [38]. Since different elements have quite different scales for their values (major elements at $\mu\text{g}/\text{m}^3$ concentrations, minor elements at concentrations of hundreds of ng/m^3 and trace elements at ng/m^3 values), a weighted least squares regression analysis has been used to fit different sources with various constituents of ambient particulate matter samples [39]. It was recognized that there is uncertainty in the source profile values. A mathematical formulation called effective variance weighting was independently suggested that included the uncertainty in the measurement of the source composition profiles as well as the uncertainties in the ambient concentrations [36]. The effective variance weights are given by the following equation:

$$(w_c)_{ii} = \frac{1}{\sigma_i^2 + \sum_{k=1}^p \sigma_{ik}^2 \sigma_k^2} \quad (5)$$

where σ_i is the measured uncertainty in the ambient concentration x_i and σ_{ik} is the measured uncertainty for element i emitted by source k .

3. Results and discussion

Source apportionment study using CMB model has been performed at residential and industrial sites of the study area. The purposes of this apportionment study were to identify possible emissions sources of ambient PM_{10} and TSP, and to quantify the contributions of the sources to measured particulate pollutants.

Seasonal variations seemed to be largely affected by atmospheric conditions. The PM_{10} and TSP data showed regular seasonal variations, with higher concentrations during winter and lower concentrations during monsoon.

The daily average concentrations of PM_{10} and TSP were found in the range 68.2–280.6 and 139.3–580.3 $\mu\text{g}/\text{m}^3$ for residential (Kasba) site, while 62.4–401.2 and 125.7–732.1 $\mu\text{g}/\text{m}^3$ for industrial (Cossipore) site, respectively. Higher concentrations were found in winter months. It indicates a longer residence time of particulate matter in the atmosphere during winter due to low winds and low mixing height. Approximately 85% of the monitored PM_{10} data at residential (Kasba) site and 70% at industrial (Cossipore) site exceeded national ambient air quality standard (NAAQS) as specified by central pollution control board, India. At residential site 80% of the monitored TSP data exceeded NAAQS, while 20% at industrial site. Table 1 statistically summarizes the various concentrations of chemical species of PM_{10} and TSP.

3.1. CMB model performance measures

The absolute accuracy of CMB source contribution estimates is difficult to establish. Because these estimates are based on least squares linear regression, they are not unique [40]. Ref. [41] described several CMB performance measures and statistics, which may be used to evaluate the validity of CMB source apportionments. The coefficient of determination (r^2) values of the source contribution estimate along with ratio R/U , chi-square (χ^2), percent mass and degree of freedom are the different performance measures that are used to evaluate the validity of source contribution measures. Table 2 summarizes the performance measures of CMB model in the present study.

The r^2 is the fraction of the variance in the measured concentrations that is explained by the variance in the calculated species concentrations [30]. The r^2 value ranges from 0 to 1.0. The closer the value of r^2 towards 1.0, the better the source contribution estimates explain the measured concentrations. The R/U is a signed difference of measured and calculated concentration of species (residual), divided by the uncertainty of that residual. Acceptable values of R/U range from 0.5 to 2. Positive values of R/U indicate that one or more profiles are contributing significantly to that species. Negative value of R/U is indicative of insufficient contribution to that species and a source may be missing [26,30].

The chi-square value (χ^2) is a weighted sum of squares of the difference between calculated and measured fitting species concentrations and should be equal to 1 for a very good fit. Values between 1 and 2 are acceptable and values greater than 4 indicate that one or more species concentrations are not well explained by source contribution estimates. Percent mass is the percent ratio of the sum of the model-calculated source contribution estimates to the measured mass concentration. Percent mass ranging from 80% to 120% represent good fit to the data. Degree of freedom equals the number of fitting species minus the number of fitting sources. Degree of freedom must be greater than 5 as per EPA (environmental protection agency) target [42].

Table 1
Statistical analysis of chemical species of PM₁₀ and TSP during the study period

Species	Unit	Residential site		Industrial site	
		Species of PM ₁₀ (average ± S.D.)	Species of TSP (average ± S.D.)	Species of PM ₁₀ (average ± S.D.)	Species of TSP (average ± S.D.)
Fl	ng/m ³	15.9 ± 9.9	21.3 ± 8.3	22.7 ± 14.8	22.7 ± 14.8
Py	ng/m ³	15.1 ± 8.1	20.5 ± 7.5	18.2 ± 9.8	18.2 ± 9.8
BaA	ng/m ³	17.9 ± 10.4	14.8 ± 4.1	22.9 ± 15.2	22.9 ± 15.2
BbF	ng/m ³	29.8 ± 18.9	18.5 ± 5.9	23.7 ± 17.9	23.7 ± 17.9
BaP	ng/m ³	12.9 ± 8.4	21.4 ± 3.6	14.3 ± 9.6	14.3 ± 9.6
TC	ng/m ³	2061.6 ± 1343.1	12650.3 ± 3700.1	3021.9 ± 1178.4	30029.0 ± 1209.0
IC	ng/m ³	159.3 ± 71.7	1150.1 ± 394.3	228.7 ± 136.3	1228.7 ± 136.3
OC	ng/m ³	1902.3 ± 1611.2	11500.2 ± 3600.1	2793.2 ± 1772.1	28800.3 ± 1800.4
Cr	ng/m ³	7.1 ± 6.2	56.0 ± 19.1	6.3 ± 4.2	36.3 ± 4.2
Zn	ng/m ³	489.5 ± 297.8	607.3 ± 201.4	534.5 ± 301.9	508.1 ± 307.2
Pb	ng/m ³	40.4 ± 29.1	158.8 ± 49.1	118.6 ± 94.4	168.6 ± 94.4
Cd	ng/m ³	2.2 ± 2.1	39.6 ± 13.5	5.2 ± 3.8	45.2 ± 3.8
Ni	ng/m ³	6.8 ± 4.3	27.5 ± 8.9	8.3 ± 4.2	38.3 ± 4.2
Mn	ng/m ³	2.0 ± 1.3	28.1 ± 10.2	2.1 ± 1.5	29.1 ± 1.5
Fe	ng/m ³	87.2 ± 69.2	1100.2 ± 513.1	123.2 ± 90.1	2107.6 ± 108.4
F ⁻	ng/m ³	93.5 ± 60.7	62.6 ± 34.9	124.9 ± 92.3	124.9 ± 92.3
Cl ⁻	ng/m ³	711.5 ± 610.3	1803.4 ± 607.1	1213.2 ± 890.9	1902.6 ± 902.3
NO ₃ ⁻	ng/m ³	181.9 ± 107.2	402.3 ± 112.8	158.5 ± 108.2	209.3 ± 107.6
PO ₄ ³⁻	ng/m ³	198.3 ± 132.3	52.9 ± 18.9	18.3 ± 4.2	78.3 ± 4.2
SO ₄ ²⁻	ng/m ³	1186.3 ± 601.9	5901.4 ± 2701.0	1671.3 ± 401.9	6706.8 ± 428.6

3.2. CMB source profiles

Source profiles for road dust and soil dust contributing to TSP have been prepared for residential and industrial sites of an urban region of Kolkata. Other source profiles used in the present CMB model study were selected from USEPA Speciate 3.2 database [43]. The emission sources considered are coal combustion, field burning, paved road, vehicle, wood combustion, diesel combustion, soil dust, metal and tyre wear.

3.2.1. Development of source profiles

Chemical mass balance model for source apportionment requires information about the chemical characteristics of the sources that are likely to affect pollutant concentrations at receptor. Road dust and soil dust profiles were prepared that represented the selected receptor sites. Dust from road and soil near monitoring sites were collected by sweeping an area of 10 m × 1 m. These dust particles were dried in an oven at 50 °C and sieved for TSP. The sieved dusts were then further analyzed for various chemical species. Concentrations of these species are presented in terms of the percent of total TSP mass concentrations as summarized in Table 3. It is evident from source

profiles that the major components of road dust are OC, TC, Fe and SO₄²⁻, while soil dust are OC, TC, Cl⁻ and SO₄²⁻ at residential site. Chloride and sulfate in the soil dust represents the presence of marine aerosol. Each profile results from the average of six samples taken around each measurement location. At industrial site OC, IC, TC, Fe and Zn have dominance in road dust and soil dust.

Iron, organic carbon and total carbon are most abundant species in road dust profiles at both the monitoring sites. Dust on a paved road surface builds up by being tracked out from unpaved areas, wear of vehicle components, wear of pavement surface, deposition of suspended particles from nearby emission sources and wind erosion from adjacent areas.

When the fractional composition for a species is several times larger than its uncertainty, that species is a good marker for that source type. In this study, TC, OC, and Fe contributing to TSP were found to be marker species of road dust at the monitoring sites. At the monitoring sites OC, TC, Cl⁻ and SO₄²⁻ have been observed as the marker species of TSP in soil dust.

3.3. CMB source apportionment at residential site

The CMB model was applied to each sample at each site. Result of the model study summarized that there was a dominance of emission from coal combustion at residential (Kasba) site to both PM₁₀ and TSP as shown in Fig. 2. Thermal power plant is located southwest of the monitoring site at residential area as shown in Fig. 1. Also nearby small restaurants using coal emit PM₁₀. The wind is blowing from southwest direction most of the time as shown in Fig. 3. Hence coal combustion is a major source of PM₁₀ and TSP aerosol at residential site. Percentage contribution by coal combustion is highest in winter, may be due to temperature inversion and lowest during summer. Paved road

Table 2
Chemical mass balance model performance test during the study period

Parameter	Residential site		Industrial site	
	PM ₁₀	TSP	PM ₁₀	TSP
r ²	0.98	0.97	0.89	0.95
χ ²	1.61	0.95	0.23	0.93
R/U	-2.9	1.4	0.5	2.9
Percent mass	68.0	116.7	110.3	181.4
Degree of freedom	8	30	38	27

Table 3
Source profiles for TSP at the monitoring sites

Species	Residential site		Industrial site	
	Road dust (Conc. \pm Unc.)	Soil dust (Conc. \pm Unc.)	Road dust (Conc. \pm Unc.)	Soil dust (Conc. \pm Unc.)
Fl	0 \pm 0	0.01 \pm 0.00	0.015 \pm 0.001	0.01 \pm 0.00
Py	0.010 \pm 0.001	0.020 \pm 0.003	0.009 \pm 0.000	0.0083 \pm 0.002
BaA	0.015 \pm 0.001	0.001 \pm 0.000	0.0172 \pm 0.026	0.008 \pm 0.001
BbF	0.006 \pm 0.000	0 \pm 0	0.003 \pm 0.000	0.004 \pm 0.000
BaP	0.01 \pm 0.00	0.011 \pm 0.002	0.0085 \pm 0.004	0 \pm 0
TC	4.82 \pm 0.22	4.4 \pm 0.45	2.8 \pm 0.21	2.97 \pm 0.31
IC	0.7 \pm 0.1	0.5 \pm 0.2	1.2 \pm 0.3	1.07 \pm 0.12
OC	4.12 \pm 0.40	3.9 \pm 0.2	1.6 \pm 0.2	1.9 \pm 0.2
Cr	0.001 \pm 0.000	0.00001 \pm 0.00000	0.005 \pm 0.002	0.0002 \pm 0.001
Zn	0.0002 \pm 0.000	0.001 \pm 0.000	0.7 \pm 0.3	6.6 \pm 0.4
Pb	0.055 \pm 0.006	0.005 \pm 0.001	0.205 \pm 0.016	0.08 \pm 0.02
Cd	0.001 \pm 0.000	0.001 \pm 0.000	0.0006 \pm 0.002	0.0009 \pm 0.0003
Ni	0.01 \pm 0.00	0.001 \pm 0.000	0.0014 \pm 0.004	0.001 \pm 0.000
Mn	0.011 \pm 0.002	0.0031 \pm 0.0004	0.0061 \pm 0.007	0.00015 \pm 0.00003
Fe	5.512 \pm 0.439	0.076 \pm 0.034	6.7 \pm 0.8	7.5 \pm 3.9
F ⁻	0 \pm 0	0 \pm 0	0 \pm 0	0 \pm 0
Cl ⁻	0 \pm 0	6.5 \pm 0.7	0.005 \pm 0.002	0.25 \pm 0.03
NO ₃ ⁻	0.141 \pm 0.022	0 \pm 0	0.0014 \pm 0.002	0.001 \pm 0.000
PO ₄ ³⁻	0 \pm 0	0.02 \pm 0.00	0.0007 \pm 0.003	0.003 \pm 0.001
SO ₄ ²⁻	5.1 \pm 0.4	6.102 \pm 0.712	0.15 \pm 0.04	0.15 \pm 0.04

Conc. is the average abundance (percent of total mass) from same source type. Unc. is the standard deviation of the abundances for samples.

is the second largest contributor to PM₁₀ aerosol at residential site. These road dusts are in the ambient air by the resuspension of dust particulates. It is comparatively higher in summer than other season because of the effect of wind turbulence. Con-

tribution of PM₁₀ aerosol mass by paved road being minimum during monsoon because of the washout of dust particulates by rain (Fig. 4). Paved road dust contributed an average of 21% to PM₁₀ and 17% to TSP at Kasba during the study period.

Field burning also influences the emission of PM₁₀ aerosol and is contributed higher in winter. It contributed an average of 7% to PM₁₀ during the study period. Monitoring site at residential area has small open restaurants using wood and coal as fuel. These small open restaurants emit PM₁₀ aerosol in minor fraction from wood combustion. Wood combustion contributed an annual average of 1% to PM₁₀.

The TSP concentration has been found maximum during winter and minimum during monsoon but the maximum percentage contribution by diesel combustion has been found highest in monsoon. Particles emitted by diesel combustion are in finer fraction and remain suspended in air inspite of pluvial rain. Emissions from diesel combustion contributed an average of 15% of TSP measured at residential site. These diesel combustion emissions were mostly emitted from diesel-operated vehicles such as diesel internal combustion engines. Soil dust and road dust are also the major contributors to TSP aerosol at residential site with comparatively higher percentage during summer and lower during monsoon. These particulates by road dust and soil dust were resuspended and remain in the ambient air.

Soil dust mainly included emissions from nearby solid waste dumping site, construction activities, wind blown dust and resuspension of soil particles and contributed an average of 19% to TSP. Unexplained source at residential site contributed 29% to PM₁₀ and 12% to TSP. This unidentified source may be the combination of solid waste dumping, vehicular emissions, auto repair, tyre wear and constructional activities.

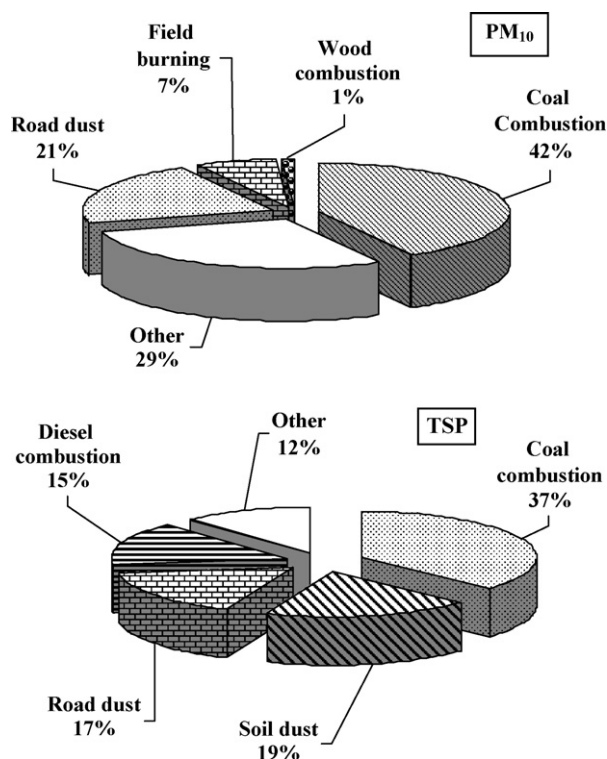


Fig. 2. Contribution of sources to PM₁₀ and TSP aerosol by CMB model at Kasba (residential site).

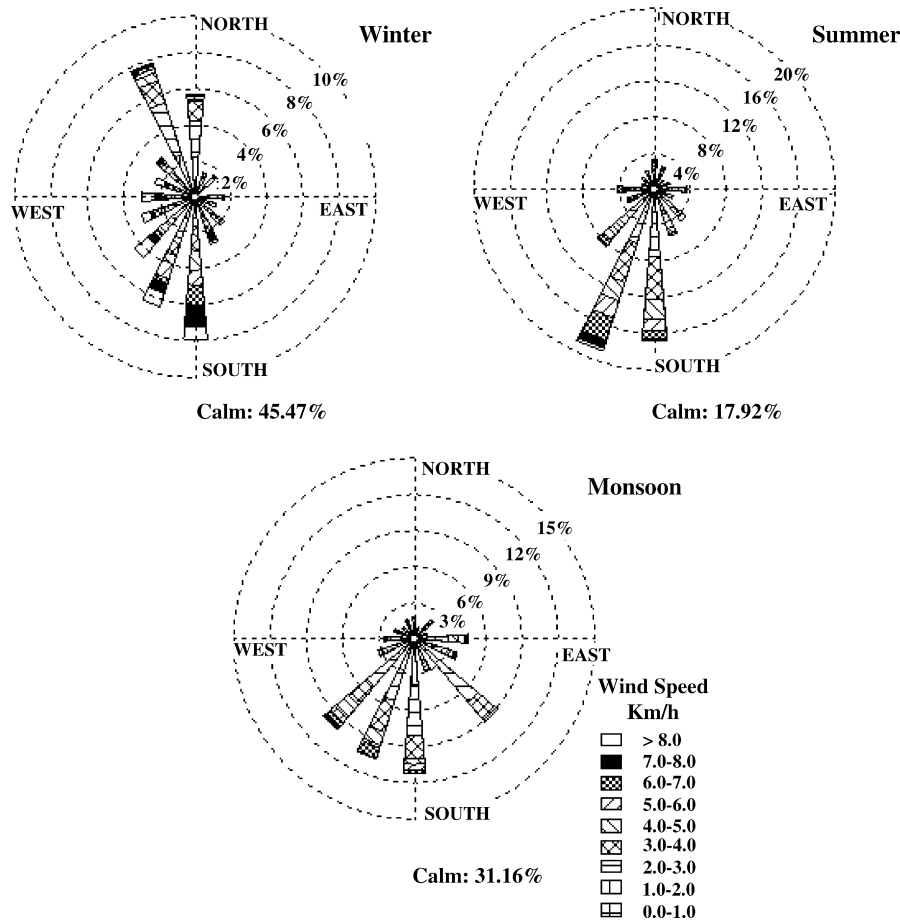


Fig. 3. Seasonal wind rose plot of the study area.

3.4. CMB source apportionment at industrial site

The CMB model result showed that particulate emission from vehicle (47%) dominated the source contribution estimate of PM_{10} at industrial (Cossipore) site as shown in Fig. 5. Monitoring site at industrial area has nearby roads with moderate to heavy traffic flow. Vehicular emission has been found to be major aerosol contributor to PM_{10} aerosol at industrial site (Cossipore), as compared to residential site. Industrial area was more influenced by traffic than the residential area. Vehicular emission including diesel exhaust has higher percentage of fine particles. Particulate matters generated from the diesel exhaust are less than $1 \mu m$ in size.

Coal combustion was the second largest source of both PM_{10} and TSP at industrial (Cossipore) site. Cossipore has thermal power plant that uses coal-fired boiler. There is considerable amount of emissions from the stack throughout the firing cycle, particularly during coal charging and coal churning in the firing gates of the boilers. It contributed 34% to PM_{10} and 17% to TSP on average data of the study period as shown in Fig. 5, while comparatively higher during winter and lower during monsoon as shown in Fig. 6. A few small-scale metal industries including galvanization and electroplating industries are located in the southwest direction of the monitoring location as shown in Fig. 3 and contributed 4% during winter, while 1% during summer and

monsoon. Soil dust contributed an average of 1% of the measured PM_{10} during monsoon (Fig. 6).

The CMB model identified soil dust and road dust as the major contributor to TSP aerosol at industrial site (Cossipore). They mainly emit due to resuspension of dust particles in the atmosphere. Soil dust contributed an average of 36% of TSP during the study period as shown in Fig. 5, while road dust contributed 16% of TSP. These soil dust and road dust profiles have been developed in the present study. Model result showed that solid waste and tyre wear contributed 17% and 7% to TSP, respectively, on the average data during the study period with comparatively higher value during winter. Tyre wear included the emissions from wear and tear of brake pads, tyres and other parts of vehicles. Other sources (17% to PM_{10} and 7% to TSP) included transportation, auto repair, ordnance factory, and loading and unloading of materials in railway yard.

Several CMB model studies have been performed on particulate matter. Ref. [44] observed that based on CMB receptor modeling, fugitive dust accounted for 80–90% of the PM_{10} , and motor vehicle exhaust accounted for 3–9% of the PM_{10} in the Las Vegas Valley. Ref. [45] found at Bakersfield that 45% of PM_{10} was contributed by geological material, 14% by vegetative burning, 8% by motor vehicle primary emissions, 6% by secondary sulfate, 1% by primary residual oil combustion emissions and 26% remained unexplained.

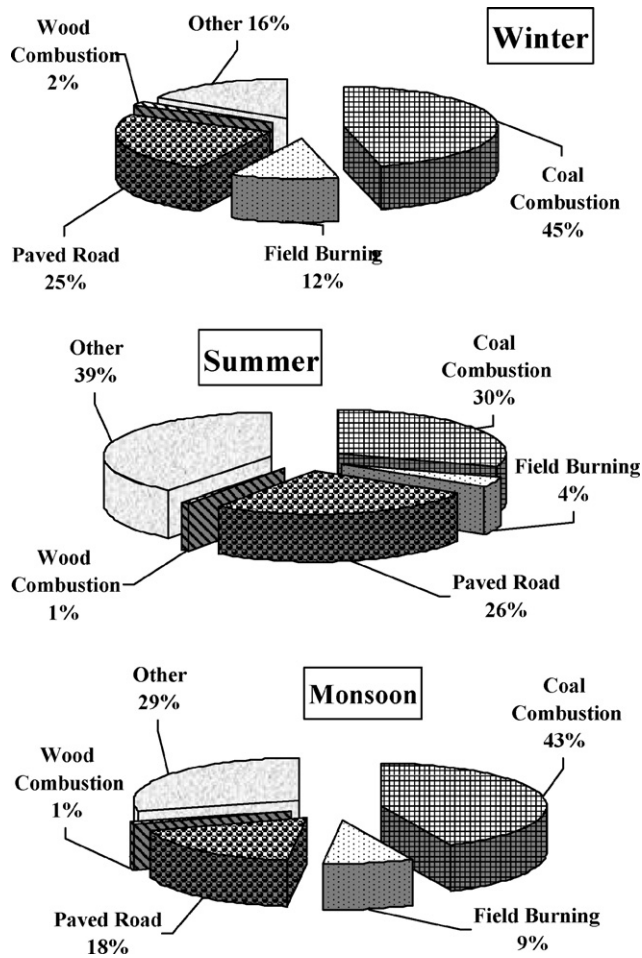


Fig. 4. Seasonal contribution of sources to PM₁₀ aerosol Kasba (residential area).

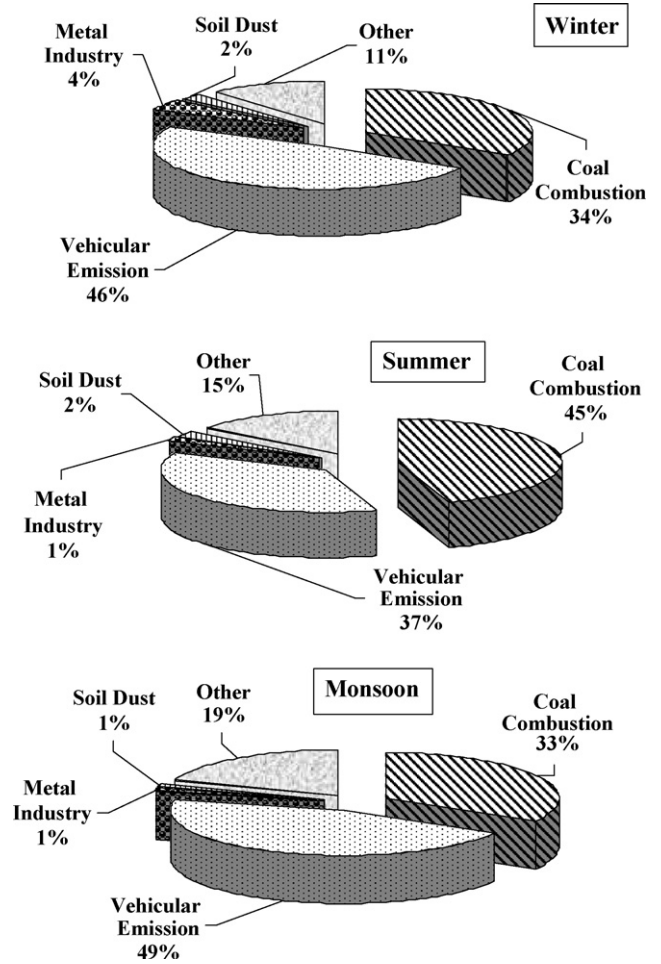


Fig. 6. Seasonal contribution of sources to PM₁₀ aerosol Cossipore (industrial area).

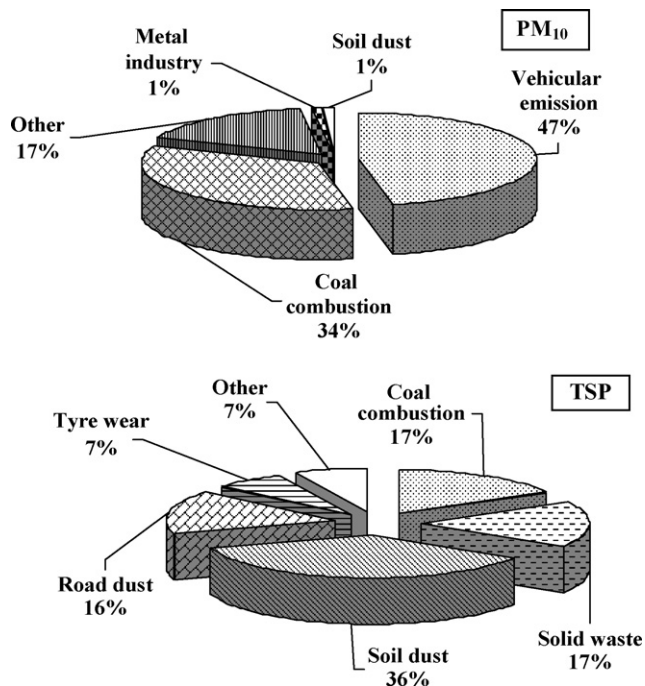


Fig. 5. Contribution of sources to PM₁₀ and TSP aerosol by CMB model at Cossipore (industrial site).

4. Conclusions

This study investigated the contributions of different emission sources to PM₁₀ and TSP aerosol mass in Kolkata using CMB model. Result of CMB model showed that the major source throughout the study period was coal combustion to both PM₁₀ and TSP at residential site, contributing an average of 42% and 37%, respectively. At industrial site vehicular emission (47%) has significant contribution to PM₁₀ and soil dust (36%) to TSP aerosol mass concentrations. Coal combustion has also significant influence on particulate emission at industrial site, accounting for 34% to PM₁₀ and 17% to TSP. Other major identified sources of particulate emission were field burning, wood combustion, diesel combustion, soil dust and road dust at residential site, while metal industry, solid waste, tyre wear, road dust and soil dust at industrial site.

Source profiles for road dust and soil dust contributing to TSP and representing the selected receptor sites were prepared during the study period. In this study, total carbon, organic carbon, and iron were found to be the marker species of road dust, while organic carbon, total carbon, chloride and sulfate have been observed as the marker species of soil dust in TSP.

A quantitative understanding of source contributions to ambient particulate levels is needed to develop emission control strategies. The results of this study will be very useful for the environmental management of particulate concentrations that violated the standards in the study area.

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