

Characterization of atmospheric aerosols for organic tarry matter and combustible matter during crop residue burning and non-crop residue burning months in Northwestern region of India

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A B S T R A C T

Aerosol (total suspended particulate) samples collected at three diverse locations (urban-commercial, semi-urban and rural-agricultural) in Patiala, India were analyzed for loss on ignition (LOI) and organic tarry matter (OTM) content in ambient air during crop residue burning (CRB) episodes and non-crop residue burning (NCRB) months in 2006–2007. Results showed high levels of LOI and OTM during wheat and rice crop residue-burning periods at all the sites. Higher levels were obtained during rice crop residue-burning period as compared to the wheat residue-burning period. At semi-urban site, LOI varied between $53 \pm 36 \mu\text{g m}^{-3}$ and $257 \pm 14 \mu\text{g m}^{-3}$ constituting 38–78% (w/w) part of the aerosols whereas levels of OTM varied between $0.98 \pm 0.11 \mu\text{g m}^{-3}$ and $7.93 \pm 2.76 \mu\text{g m}^{-3}$ comprising 0.42–3.28% (w/w) fraction. At rural-agricultural area site, levels of LOI varied between $86 \pm 40 \mu\text{g m}^{-3}$ and $293 \pm 70 \mu\text{g m}^{-3}$ comprising 27–84% (w/w), whereas OTM levels varied between $1.31 \pm 0.64 \mu\text{g m}^{-3}$ and $10.09 \pm 6.56 \mu\text{g m}^{-3}$ constituting 0.83–2.42% (w/w) fraction of the aerosols. At urban-cum-commercial site, levels of LOI and OTM varied between $48 \pm 23 \mu\text{g m}^{-3}$ and $281 \pm 152 \mu\text{g m}^{-3}$ and $2.53 \pm 1.23 \mu\text{g m}^{-3}$ and $17.40 \pm 8.50 \mu\text{g m}^{-3}$, constituting 24–62% (w/w) part of the aerosols, respectively. Results also indicated that OTM and LOI were integral parts of aerosols and their concentrations were influenced by the crop residue burning practices with incorporated effect of vehicular activities in Patiala.

1. Introduction

Open burning of wheat and rice crop residue after harvesting is a common practice performed by farmers in Punjab, India as well as other northwest regions of the country. Though straw burnings are banned by the local administration still farmers find these practices economical and convenient for the removal of residue and readying land for the next crop. Crop residue burning (CRB) practices generate a huge amount of smoke containing particulate matter and gaseous species which deteriorate quality of ambient air and affect public health (Dennisa et al., 2002; Wiedinmyer et al., 2006). These activities involve the incomplete burning of organic materials under sub-optimum combustion conditions. Aerosol is one of the criteria pollutants emitted during crop residue burnings (Handa et al., 1980). It acts as a carrier of pollutants such as polycyclic aromatic hydrocarbons (PAH), toxic gases, metal particles, etc.

which have deleterious effects on human health (Freeman and Cattell, 1990; Godoi et al., 2004). The aerosol PAHs emissions during sugarcane burning were studied in Brazil and Indonesia and the levels were found to be comparable with some urban centers (Fang et al., 1999; Godoi et al., 2004). Larkin et al. (1986) estimated that 1.26 million ha of land was burnt in UK during 1884, resulting in emission of 18,000 tonnes of black smoke. Based on this and the Freeman and Cattell (1990) study, approximately 6.3 tonnes of total particulates containing PAHs were released (Wild and Jones, 1995).

Measurement of aerosol levels in ambient air has always been important, as it is one of the true indices of ambient air quality (Baek et al., 1997, 1991). Organic compounds are the major components of aerosol in urban environments and the second most abundant fraction after sulphates at background and rural sites. The necessity to study the chemical composition of organic aerosols is well described in the literature (Jacobson et al., 2000; Jacobson, 2001). Various organic markers have been identified in organic extracts of biomass smoke samples collected worldwide (Wang et al., 2009; Fartas et al., 2009; Mazzoleni et al., 2007; Simoneit, 2002). The composition data of smoke particulate matter is

important for understanding the organic component contribution of biomass burning emissions to atmospheric chemistry and complements existing work on the characterization of direct organic emissions from biomass sources (Abas et al., 1995; Simoneit et al., 1983, 1988, 1991, 1990, 1993).

In India, studies were carried out mainly in the central (Pandey et al., 1999; Samal and Santra, 2002) and southern parts of the country. Very few studies (Sandhu and Gehlan, 1991, 1992) are reported on aerosols in the Northwestern region of India. Air pollution due to wheat and rice crop residue fires is a serious environmental problem in this northwest region, especially Punjab and Haryana provinces of India. In 1999, an international team of scientists conducted an intensive field campaign called the Indian Ocean Experiment (INDOEX) to study the air pollution and its possible impacts on regional and global climate. The observations provided that the aerosol (particulate) pollution existed in a layer as thick as 3 km (1.86 miles) and spread thousands of kilometers away from the source. In addition to the impact on public health, the “brown cloud” may be diminishing the monsoon-related rainfall in southern Asia and reducing crop yields through the filtering of sunlight (<http://earthobservatory.nasa.gov>).

While searching for the origins of atmospheric aerosols, the organic fraction may be further divided into “primary” and “secondary” materials (Stern, 1968). The carbonaceous material present in atmospheric aerosols is a combination of elemental carbon, organic (including polymeric) and inorganic compounds (e.g., carbonate salts). Considerable research efforts have been made to characterize the nature and origins of organic particulate constituents known to be hazardous (e.g., PAHs) and some studies of carbonaceous matter have primarily examined organic solvent-soluble fractions of aerosols (Mader et al., 1952; Ciaccio et al., 1974). A large carbonaceous (84%, w/w) content has been reported from the solvent extraction of PM samples from simulated rice crop residue burnings (Hays et al., 2005). Numerous techniques have been explored, including column chromatography, high resolution mass spectroscopy, thermal analysis, and multiple solvent extractions with total carbon analyses of the various solvent extracts (Williamson, 1973). After conducting studies on different solvents, Grosjean concluded that solvent extraction could be used for the extraction of organic compounds in atmospheric particulate matter (Grosjean, 1975). Availability of detailed organic aerosol data greatly enhances the ability of receptor models to identify the emission sources (Schauer et al., 1996; Schauer and Cass, 2000).

Ignitable matter is a representative of combustible or unburnt hydrocarbons and is a measure of non-volatile compounds in the atmospheric aerosols. Organic tarry matter (OTM) represents the total organic matter (volatile and non-volatile, viz., aliphatic hydrocarbons, polycyclic aromatic hydrocarbons, fatty acids and alkanols) in ambient carbonaceous aerosols (Lighty et al., 2000; Johansson et al., 2003). A study conducted in Beijing to identify and estimate the contribution of biomass burning to the urban aerosol organic carbon concentration indicated a high aerosol organic carbon concentration during wheat straw open fires (Duan et al., 2004). Present study was aimed at determining the levels of combustible matter and organic tarry matter in aerosol (total suspended particulate) samples collected during crop residue burning episodes to determine the contribution of crop residue burning which may be helpful in source apportionment. In this manuscript, we have presented results of solvent extraction and thermal heating of atmospheric aerosols collected at three different locations in Patiala for the determination of soluble organic fraction and ignitable fraction. Correlation between combustible matter (LOI) and organic tarry matter (OTM) was also studied. Sampling locations for the study include rural-cum-agricultural, semi-urban and urban-cum-commercial sites.

2. Experimental

2.1. Study area and selection of sampling sites

Patiala district (Latitude between 29°49' and 30°47'N, Longitude between 75°58' and 76°54'E) is one of the famous princely states of former undivided Punjab forming the southeastern part of the province. Patiala having a population of 1.845 million is the 6th most populated district of Punjab as per 2001 census. The climate here is very hot in summer ($43 \pm 2^\circ\text{C}$) and very cold in winter ($2 \pm 2^\circ\text{C}$). The district is generally arid and hot, with monsoon enduring three months. The annual average precipitation (rainfall) is 688 mm with appreciable variation. During winter, days are sunny and mornings and evenings may be foggy. May is the hottest month and January is the coldest month. The wind direction is North-West (NW) (blowing from the NW towards SE) for most of the time (TERI, 2003; Mittal et al., 2009). The area around Patiala city is predominantly agricultural (rural). Though farmers also cultivate barley, maize and sugarcane crops in this region, wheat and rice (paddy) are the two major crops of the district with a combined cropping area of more than 86%. Farmers usually burn crop residue after crop harvesting during April–May (wheat crop harvesting period) and October–November (rice crop harvesting period).

Patiala was selected for the study because there is no major industry in and around the city and crop residue burning practices (Figs. 1–4) can be seen easily in the fields during wheat and rice harvesting months. Three different locations (Table 1) were selected for the aerosol sampling covering agricultural (rural), semi-urban, urban-cum-commercial areas and samples were collected from September 2006 to December 2007. Sampling locations were selected carefully, taking natural wind direction (NW) and land use patterns into consideration. Accessibility of logistics like security of sampling instruments and electricity supply during air sampling was also taken into account. There is no major industry in the vicinity of Patiala city hence; results are not affected by industrial emissions. All the sampling sites were located within a radius of 10 km. A summary of the sampling sites is given in Table 1.

The Punjabi University site (PUS, Site-1) was situated in the north-east (NE) of the city about 6 km away from the main city. This site was considered as semi-urban area site. Due to its vicinity near the state highway (SH), ambient air aerosol composition is likely to contain vehicle emissions. The site-3, Sidhuwal village site (SVS) was located 6 km away and NW to the main city having agricultural fields all around it. Being situated in NW direction and upwind from the city, it may collect aerosols generated due to the agricultural



Fig. 1. Location of Patiala (India) in Asian context.



Fig. 2. Residue burning in Sidhuwal Village site during wheat harvesting month (May) in 2007.

fires during harvesting periods and hence considered as a rural area (agricultural area) site. The site-3, Sanauri adda site (SAS) was situated in south-east (SE) of the city and was a densely populated area with a lot of commercial activities. This site was considered as urban-cum-commercial site. The predominant wind direction of Patiala is Northwest. Detailed windrose plots have been provided elsewhere (Mittal et al., 2009), and all these sampling sites were selected in the downwind direction.

2.2. Sampling of aerosols

Aerosol samples were collected during the months of September 2006–December 2007 using high volume samplers (HVS) (Envirotech, India) equipped with Glass fiber filters (Whatman, Schleicher & Schuell, GF/A, Made in England) as a filtration media at selected sites (IS: 5182 (Part XIV) IS Standard, 1979). Each filter was exposed to a light source to detect any holes or any other imperfections and was conditioned over silica gel in a desiccator for 24-h duration for constant weight. Glass fiber filter was then positioned in the HVS with its rough side up. Each aerosol sample was collected for 24 h by passing air through the filter with an average rate of 1.5 cubic meters per minute. After sampling, filters were again conditioned in the desiccator for 24 h and weighed to a constant weight. From the difference in the initial and final weights, and the total volume of the air sampled, aerosol concentration in the ambient air was calculated. The collected samples



Fig. 3. Residue burning in Sidhuwal Village site during rice harvesting month (November) in 2007.



Fig. 4. Physical appearance of GMF/A (Whatman) filters before and after aerosol sampling. Filters become black after 24 h.

were stored in refrigerator at 4 °C temperature with protection from atmospheric moisture, and brought to room temperature just prior to analysis.

2.3. Determination of organic tarry matter (OTM)

2.3.1. Solvent extraction

Soxhlet technique has been widely used for extracting a variety of organic compounds from solid matrices. Organic solvents like Benzene, Cyclohexane, Dichloromethane, Methanol–chloroform etc are commonly used for extraction (Bowyer and Pleil, 1997; Appel et al., 1976, 1979). In the present study, soxhlet extraction was applied to determine organic tarry matter concentration. A fraction soluble in organic solvents represents the organic tarry matter (OTM) present in samples. Samples were extracted with dichloromethane (DCM) using a customized procedure based on various used practices (Shannigrahi et al., 2005; Stephanou and Stratigakis, 1993; Gogou et al., 1998; Alves and Duarte, 1999; Oros and Simoneit, 2001).

A quadrant of each aerosol sample was extracted with 150 mL DCM (Merck, India) for a period of 8 h using a soxhlet extractor. Solvent was reduced to 5 mL at steam bath temperature (steam bath treatment of organic extracts is not expected to produce significant loss of organic aerosol constituents). The extracts were then filtered through Whatman filter thimbles and transferred to pre-weighed chromatographic amber vials. The filtrates were dried at room temperature and the weight of the extracts was determined with a microbalance (Sartorius, BT224S, Made in Germany) having precision of 0.1 µg.

2.4. Determination of loss on ignition (LOI)

Loss on ignition (LOI) test has been widely used as a screening tool to estimate the organic and carbonate contents of sediments as an indicator of non-volatile organic matter in the sample. (Dean, 1974; Bengtsson and Enell, 1986; Heiri et al., 2001; Boyle, 2004;

Table 1

Sites selected for aerosol sampling in Patiala.

Site no.	Sampling site name (abbreviation)	Land use pattern	Location	Wind direction
1	Punjabi University Site (PUS)	Semi-urban	East	NW
2	Sidhuwal Village Site (SVS)	Rural-cum-agricultural	NW	NW
3	Sanauri Adda Site (SAS)	Urban-cum-commercial	SE	NW

Folliard et al., 2006). Despite the importance and relevance of the LOI test, the LOI test results are sensitive to practical variations that are within the requirements of the ASTM C 311 test standard. When thermal treatment is applied to any particulate sample, in the first reaction organic matter is oxidized at 500–550 °C to carbon dioxide (CO₂) and ash. In the second reaction, CO₂ is evolved from carbonate leaving oxide.

LOI tests on ambient aerosol samples were performed considering cooling time, sample size, ignition duration, and ignition temperature. An electrically heated temperature controlled Muffle Furnace (Sciential, India) capable of maintaining a high temperature of 800 ± 10 °C was used for the determination of loss on ignition in aerosol samples. A quadrant of each exposed filter was placed in a pre-weighed silica crucible and ignited at 600 ± 10 °C in a muffle furnace for 3 h. The crucibles were removed from the furnace (at 50 °C), placed in the desiccator for cooling and weighed to a constant weight using a microbalance (Sartorius, BT224S, made in Germany). A few blank glass micro fiber filters were also ignited under the same conditions and the weight of the residue was subtracted from the observed weights (Marr et al., 1999; Rukmangad, 1991).

3. Results and discussion

3.1. Aerosols in the ambient air

At PUS, SVS and SAS, aerosol levels varied between 100 ± 29 µg m⁻³ and 458 ± 79 µg m⁻³, 86 ± 40 µg m⁻³ and 496 ± 73 µg m⁻³ and 144 ± 85 µg m⁻³ and 623 ± 172 µg m⁻³, respectively during different sampling periods showing higher levels in the months of October–November and April–May at all the sites. During the period of study, 95% of the samples exceed the standard level of aerosols (200 µg m⁻³ for residential areas) recommended by the Central Pollution Control Board (CPCB), India. Aerosol levels were significantly higher in the months of October–November and April–May, indicating a clear contribution of agricultural activities, like the dust released during the process of shredding of wheat and rice grain from their spikes and crop residue burning activities after harvesting of these crops. CRB activities remain at its peak during these periods in this region of the country (Mittal and Goyal, 2004). Since biomass combustion particles include particulates in the accumulation mode (100–1000 nm) as well, it is likely to increase the total suspended particulate concentration during crop residue burnings.

3.2. Organic tarry matter in ambient aerosols

Organic carbon (OC) and water-soluble potassium (K⁺) are the typical components of biomass burning aerosol. Close to fires, OC has accounted for about two-thirds of biomass burning aerosol mass (Cachier et al., 1995). In a source profile study conducted in North Carolina, USA, the biomass burning contribution was found to be 30–50% of the annual OC concentration (Sheesley et al., 2007). K⁺ has been used as a tracer element for the qualitative identification of biomass burning in many source apportionment studies (Cachier et al., 1991; Chow, 1995).

In the present study, OTM concentrations of aerosols were analyzed and found to be associated with agricultural waste fires. Variations in the levels of OTM of aerosols are shown in Figs. 5–7. Monthly average absolute amounts of OTM are plotted for each site. Results have indicated that the OTM content is dependent on the concentration of aerosols and is an essential component of it. OTM levels are known to depend on vehicular exhaust (Li et al., 2009; Zheng et al., 1997), but CRB practices have greatly influenced the OTM levels in and around Patiala city indicating a great

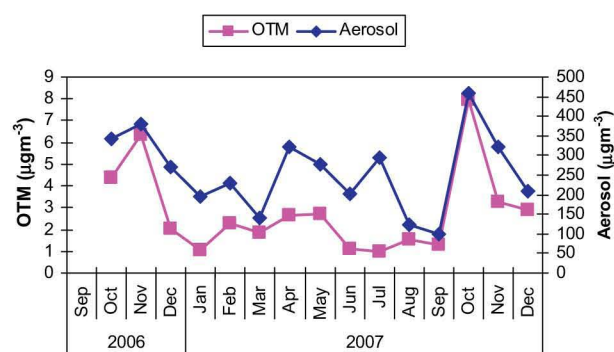


Fig. 5. Variation in Organic Tarry Matter (OTM) levels with respect to aerosol levels at Punjabi University Site (semi-urban area site).

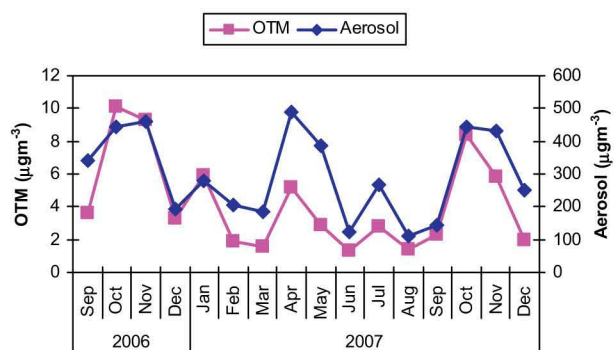


Fig. 6. Variation in Organic Tarry Matter (OTM) levels with respect to aerosol levels at Sidhuwal Village Site (rural area site).

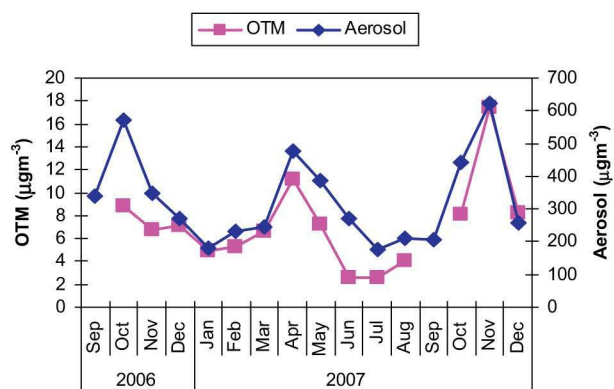


Fig. 7. Variation in Organic Tarry Matter (OTM) levels with respect to SPM levels at Sanauri Adda Site (commercial area site).

association with aerosol levels except observations in July 2007 at PUS. Sandhu and Gehlan (1991) have reported similar results in a study conducted in Amritsar, India.

During the study period, OTM concentration varied between 0.98 ± 0.11 µg m⁻³ (lowest) and 17.40 ± 8.5 µg m⁻³ (highest). Higher concentration was obtained in October–November and April–May as these were the months during which farmers burn rice and wheat crop residues after harvesting of the crops. Average levels of OTM during CRB months [8 µg m⁻³ (rice season, 2006); 5 µg m⁻³ (wheat, 2007); 8 µg m⁻³ (rice, 2007)] were found higher as compared to that of the average OTM levels during NCRB (4 µg m⁻³ 2006; 3 µg m⁻³ 2007) (Fig. 8). However, levels were higher during rice CRB periods (8 µg m⁻³) as compared to that of

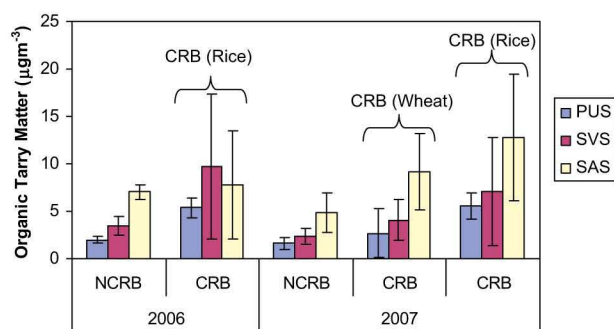


Fig. 8. Variation in Organic Tarry Matter (OTM) levels during crop residue burning (CRB) and non-crop residue burning (NCRB) episodes.

wheat CRB. At PUS, levels of OTM varied between $0.98 \pm 0.11 \mu\text{g m}^{-3}$ and $7.93 \pm 2.76 \mu\text{g m}^{-3}$ with highest concentration in the month of October 2007 ($7.93 \pm 2.76 \mu\text{g m}^{-3}$) and lowest in the month of July 2007 ($0.98 \pm 0.11 \mu\text{g m}^{-3}$). Concentration of OTM was found dependent on the levels of aerosols, in these months and helps in retaining the PM in the lower ambient environment i.e., OTM concentration was higher during high aerosol load. In terms of percentage of aerosols, OTM constituted only 0.42–3.28% (w/w) fraction at this site (Fig. 9, Table 2).

At SVS, OTM levels (Table 2) varied between $1.31 \pm 0.64 \mu\text{g m}^{-3}$ and $10.09 \pm 6.56 \mu\text{g m}^{-3}$ showing the highest concentration in October 2006 ($10.09 \pm 6.56 \mu\text{g m}^{-3}$) and lowest in June 2007 ($1.31 \pm 0.64 \mu\text{g m}^{-3}$). Concentration levels of OTM varied in association with the concentration of aerosols. OTM in aerosol samples varied between 0.83% and 2.42% (Fig. 9). Similarly, OTM concentration varied at SAS and the levels were found higher during October–November and April–May in 2007. Peak concentration was obtained in November 2007 ($17.40 \pm 8.50 \mu\text{g m}^{-3}$) whereas, the lowest concentration was observed in July 2007 ($2.53 \pm 1.23 \mu\text{g m}^{-3}$). Higher levels during October–November and April–May again indicated the effect of CRB on OTM levels being higher in the rice CRB events in October than in wheat CRB months (April–May) as the former events occur at lower temperature (Mittal et al., 2009) than the later events and eventually resulting in generation of particulates rich in carbon contents. Higher concentration of OTM is a clear result of the proposed hypothesis. This effect is compounded due to lower ambient temperatures. Although OTM levels were higher at all the sites during CRB, but

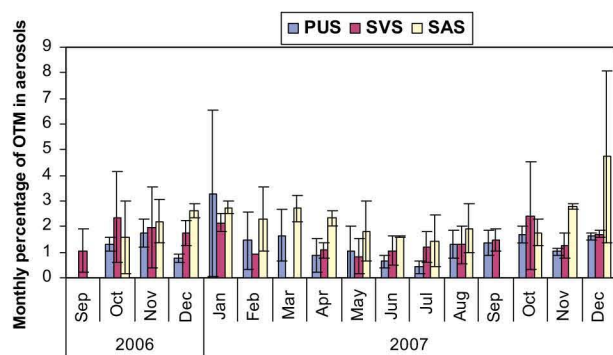


Fig. 9. Percent variation in organic tarry matter (OTM) levels with respect to aerosol levels at different monitoring locations during the study.

peak concentration was obtained at SAS. In terms of total mass of aerosols, OTM ranged between 4.74% and 1.44% (w/w) at this site. Meteorological parameters like wind speed, wind direction, temperature and rainfall play important role on the levels of ambient air particulates or aerosol concentration. Trends of monthly variation in OTM concentration were observed similar to the trends of variation in aerosol concentration being higher, when aerosol concentration was high and lower during low aerosol levels. Effect of meteorological parameters on aerosol concentration has been discussed in earlier study (Mittal et al., 2009) and the effect of meteorological parameters on OTM shall also be similar to that on aerosol levels.

3.3. Loss on ignition in aerosols

To introduce composition of aerosol likely to be lost on ignition at 600 °C, aerosol samples collected during September 2006–December 2007 were analyzed to determine the combustible matter in the form of LOI levels. LOI in the aerosol samples collected at PUS varied between $53 \pm 36 \mu\text{g m}^{-3}$ and $257 \pm 14 \mu\text{g m}^{-3}$ (Fig. 10). Higher LOI was obtained during October–November and April–May. LOI in aerosol samples varied between 38% and 78% (w/w) at this location (Fig. 14). At SVS, LOI concentration in aerosol samples varied between $86 \pm 40 \mu\text{g m}^{-3}$ and $293 \pm 70 \mu\text{g m}^{-3}$ indicating higher levels in April–May and October–November (Fig. 11). In terms of percent weight, LOI at SVS varied between 27% and 84% (w/w) of the aerosol mass. Likewise,

Table 2
Levels of organic tarry matter in aerosol samples during CRB and NCRB months.

Year	Episode	Month	Concentration in $\mu\text{g m}^{-3} \pm$ standard deviation (number of samples, N)					
			PUS		SVS		SAS	
			OTM	SPM	OTM	SPM	OTM	SPM
2006	NCRB	Sep	–	–	3.59 ± 1.36	341 ± 143	–	340 ± 186
	CRB (Rice)	Oct	4.40 ± 0.42	344 ± 45	10.09 ± 6.56	445 ± 105	8.88 ± 7.73	571 ± 127
		Nov	6.35 ± 1.68	381 ± 120	9.27 ± 8.77	460 ± 165	6.74 ± 3.61	348 ± 232
		Dec	2.00 ± 0.38	269 ± 73	3.31 ± 0.67	192 ± 16	7.06 ± 0.76	269 ± 10
2007	NCRB	Jan	1.02 ± 0.89	193 ± 184	5.90 ± 1.12	277 ± 54	4.91 ± 0.44	179 ± 31
		Feb	2.30 ± 0.95	230 ± 112	1.89 ± 1.45	206 ± 103	5.25 ± 2.63	231 ± 108
		Mar	1.87 ± 1.37	139 ± 34	1.56 ± 1.2	186 ± 72	6.61 ± 1.15	144 ± 85
	CRB (Wheat)	Apr	2.67 ± 2.23	321 ± 98	5.20 ± 2.0	488 ± 168	11.16 ± 3.58	474 ± 88
		May	2.73 ± 2.95	277 ± 74	2.89 ± 2.27	387 ± 72	7.20 ± 4.48	386 ± 139
	NCRB	Jun	1.12 ± 0.36	200 ± 142	1.31 ± 0.64	125 ± 4	2.62 ± 1.48	272 ± 239
		Jul	0.98 ± 0.11	293 ± 202	2.75 ± 0.06	266 ± 138	2.53 ± 1.23	175 ± 40
		Aug	1.56 ± 0.38	122 ± 22	1.36 ± 0.54	111 ± 22	4.03 ± 1.60	209 ± 89
		Sep	1.31 ± 0.07	100 ± 29	2.32 ± 0.73	141 ± 18	–	205 ± 73
	CRB (Rice)	Oct	7.93 ± 2.76	458 ± 79	8.42 ± 7.20	442 ± 112	8.05 ± 4.79	441 ± 91
		Nov	3.24 ± 0.02	320 ± 39	5.83 ± 4.16	432 ± 170	17.40 ± 8.50	623 ± 172
		Dec	2.87 ± 0.80	210 ± 143	1.99 ± 0.62	248 ± 45	8.21 ± 5.81	257 ± 118

N.B. Values in bold indicates levels of OTM and SPM during crop residue burning episodes, – data not available.

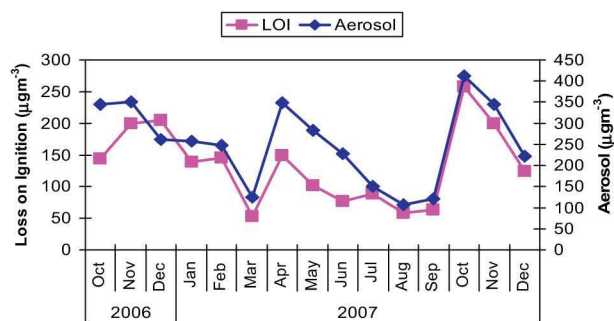


Fig. 10. Variation in loss on ignition (LOI) with respect to aerosol levels at Punjabi University Site (semi-urban area site).

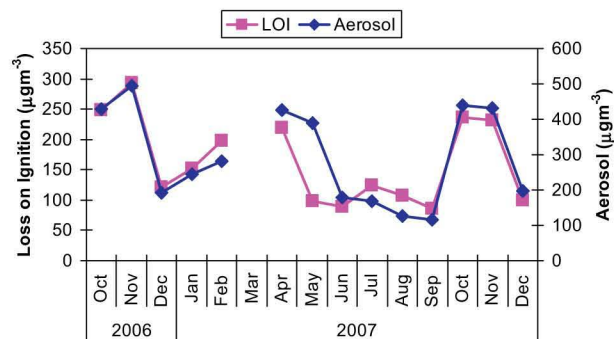


Fig. 11. Variation in loss on ignition (LOI) with respect to aerosol levels at Sidhuwal Village Site (rural area site).

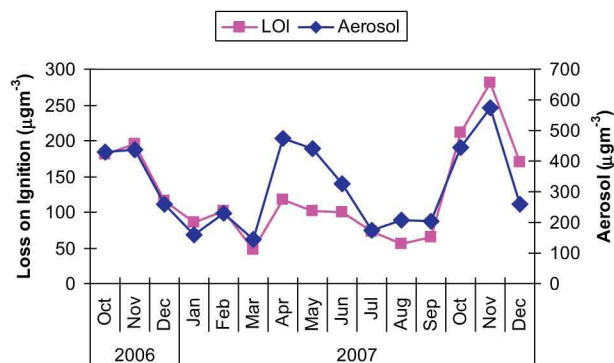


Fig. 12. Variation in loss on ignition (LOI) with respect to aerosol levels at Sanauri Adda Site (urban-cum-commercial area site).

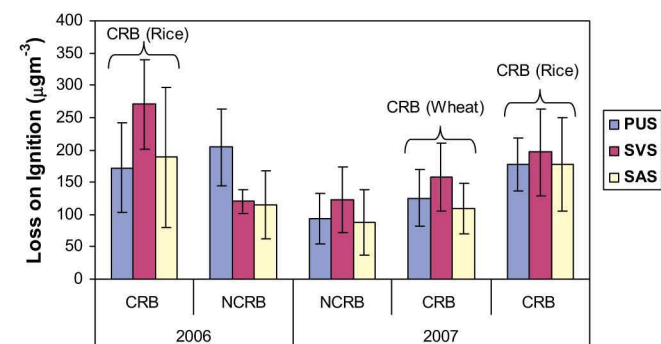


Fig. 13. Variation in LOI during crop residue burning (CRB) and non-crop residue burning (NCRB) episodes at different monitoring locations.

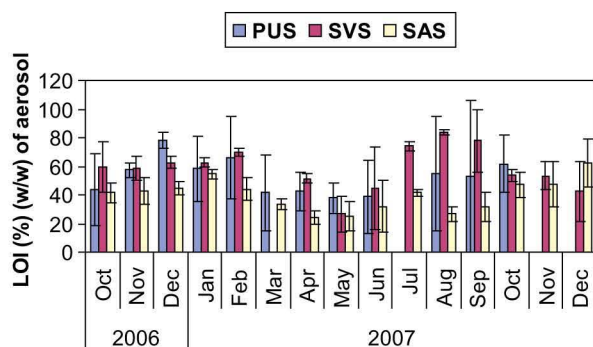


Fig. 14. Percent variation in LOI with respect to aerosol levels at different monitoring locations.

LOI varied between $48 \pm 23 \mu\text{g m}^{-3}$ and $281 \pm 152 \mu\text{g m}^{-3}$ and 24–62% (w/w) at SAS.

At all the sites, LOI levels increased with increase in aerosol levels. Figs. 10–12 represent a clear association between LOI and aerosol levels, indicating possibility of a similar source for aerosols and combustible matter at the selected locations (Sharma and Patil, 1992; Sillanpaa et al., 2005). LOI levels were higher at all the sites during CRB (October–November and April–May) but the highest value was obtained at SVS ($293 \pm 70 \mu\text{g m}^{-3}$). In terms of parentage,

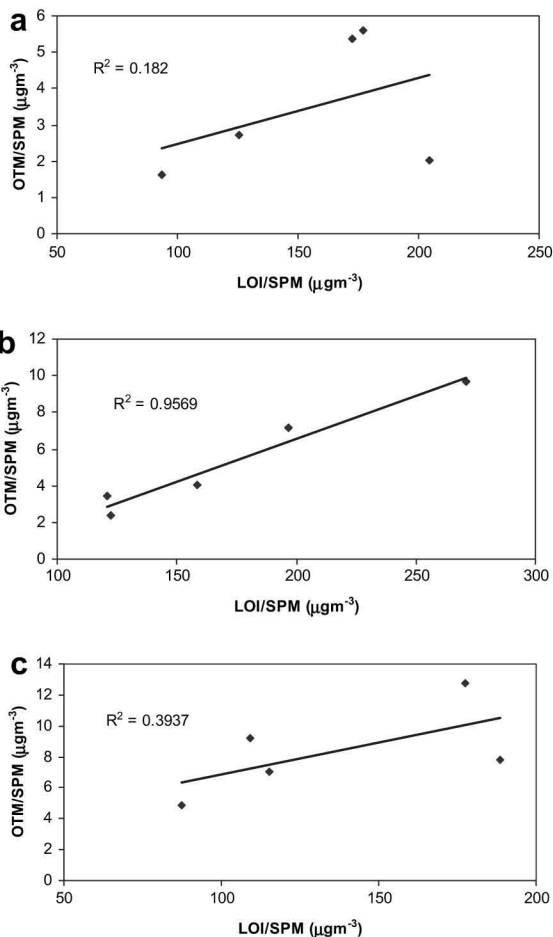


Fig. 15. Relationship between OTM and LOI in aerosols at three different sites viz. (a) semi-urban, (b) rural-agricultural, and (c) urban-commercial. Average monthly levels of OTM and LOI obtained during crop residue burning and non-crop residue burning months were used for the linear regression analysis.

Table 3
Concentration of ignitable matter in terms of loss on ignition (LOI) in aerosols at three different locations in Patiala during 2006–2007.

Year	Period	Month	PUS		SVS		SAS	
			LOI	SPM	LOI	SPM	LOI	SPM
2006	CRB (Rice)	Oct	145 ± 74	345 ± 37	249 ± 68	430 ± 98	181 ± 78	429 ± 127
		Nov	200 ± 64	350 ± 115	293 ± 70	496 ± 73	196 ± 139	436 ± 232
	NCRB	Dec	205 ± 59	262 ± 78	121 ± 18	192 ± 17	115 ± 53	258 ± 96
2007	NCRB	Jan	139 ± 18	258 ± 67	152 ± 33	245 ± 55	86 ± 48	158 ± 112
		Feb	146 ± 50	248 ± 91	198 ± 78	283 ± 103	102 ± 41	231 ± 108
		Mar	53 ± 36	126 ± 23	—	—	48 ± 23	144 ± 85
	CRB (Wheat)	Apr	150 ± 64	349 ± 95	219 ± 68	426 ± 128	117 ± 45	475 ± 89
		May	101 ± 24	283 ± 83	98 ± 36	390 ± 86	101 ± 33	440 ± 177
	NCRB	Jun	76 ± 41	227 ± 162	89 ± 89	179 ± 108	99 ± 96	327 ± 239
		Jul	89 ± 32	150 ± 60	125 ± 20	168 ± 74	73 ± 36	176 ± 56
		Aug	58 ± 40	107 ± 56	107 ± 16	127 ± 62	56 ± 27	209 ± 119
		Sep	64 ± 51	121 ± 74	86 ± 40	115 ± 48	65 ± 19	205 ± 157
	CRB (Rice)	Oct	257 ± 14	413 ± 47	237 ± 69	441 ± 110	211 ± 58	443 ± 88
		Nov	200 ± 74	345 ± 53	232 ± 96	430 ± 140	281 ± 152	575 ± 182
	NCRB	Dec	124 ± 42	223 ± 89	99 ± 77	198 ± 126	170 ± 117	258 ± 119

N.B. Values in bold indicates levels of organic tarry matter and suspended particulate matter during crop residue burning episodes, — data not available.

LOI levels varied between 24% and 62% (w/w) of the aerosol weight at SAS. Due to agricultural fields all around the SVS sampling site, peak LOI concentration was obtained at this location (SVS), indicating a greater impact of CRB. Average concentration of combustible matter (LOI) during CRB months [$211 \mu\text{g m}^{-3}$ (rice 2006); $131 \mu\text{g m}^{-3}$ (wheat 2007); $184 \mu\text{g m}^{-3}$ (rice 2007)] was found higher when compared with the average concentration level of NCRB months ($147 \mu\text{g m}^{-3}$ 2006; $101 \mu\text{g m}^{-3}$ 2007). This clearly indicates the influence of CRB on the levels of ignitable matter in atmospheric aerosols (Fig. 13).

3.4. Relationship between OTM and LOI of aerosols at three different locations

Linear regression analysis was performed to find out the correlation between OTM and LOI using average monthly levels of OTM and LOI obtained during crop residue burning and non-crop residue burning months. Regression coefficients were calculated for all the sites. Results from linear regression analysis showed good correlation between OTM and LOI ($R^2 = 0.956$, Fig. 15b) at rural-agricultural area site as compared to the semi-urban ($R^2 = 0.182$, Fig. 15a) and urban-commercial ($R^2 = 0.393$, Fig. 15c) sites. This

indicated that there is a similar source of Organic Tarry Matter and combustible matter at rural-agricultural site (SVS). At, semi-urban and urban-commercial sites, greater deviation in the values of OTM and LOI indicate different sources of OTM and combustible matter, the former more likely coming from automobile exhaust as well (Tables 3 and 4).

Higher levels of LOI were observed in the samples of rural-agricultural (SVS) site as compared to those of semi-urban site (PUS) and urban-commercial site (SAS). Levels were higher in the aerosol samples collected during CRB months in 2006 and 2007, which may once again be due to the corresponding harvesting seasons. Similar sources of LOI were reported by Sandhu and Gehlan (1991) for the studies carried out at Amritsar, Punjab (India). The overall average LOI in the present study was about 50% of the aerosol content as compared to 43% found in Amritsar.

4. Conclusions

Average level of loss on ignition (LOI) was 50% of the aerosol indicating the presence of a high content of combustible matter. Study indicated that levels of combustible matter content were associated with the levels of aerosols in the ambient air of the

Table 4
Percentage of ignitable matter in terms of loss on ignition LOI and organic tarry matter (OTM) in aerosol samples at three different sites in Patiala during 2006–2007 study period.

Year	Month	PUS		SVS		SAS	
		LOI (%)	DCM soluble organic fraction (%)	LOI (%)	DCM soluble organic fraction (%)	LOI (%)	DCM soluble organic fraction (%)
2006	Sep	—	—	—	1.05 ± 0.83	—	—
	Oct	44 ± 25	1.30 ± 0.27	59 ± 18	2.37 ± 1.76	41 ± 7	1.58 ± 1.42
	Nov	57 ± 5	1.76 ± 0.55	59 ± 8	1.95 ± 1.58	43 ± 9	2.21 ± 0.82
	Dec	78 ± 6	0.76 ± 0.14	63 ± 4	1.75 ± 0.50	45 ± 5	2.62 ± 0.29
2007	Jan	58 ± 23	3.28 ± 3.25	62 ± 3	2.15 ± 0.34	54 ± 3	2.75 ± 0.23
	Feb	66 ± 29	1.45 ± 1.13	70 ± 2	0.92 ± 0.46	44 ± 8	2.30 ± 1.24
	Mar	42 ± 26	1.65 ± 1.01	—	—	33 ± 4	2.71 ± 0.52
	Apr	43 ± 13	0.87 ± 0.66	51 ± 3	1.06 ± 0.28	24 ± 5	2.32 ± 0.32
	May	38 ± 11	1.02 ± 1.00	27 ± 13	0.83 ± 0.69	25 ± 10	1.82 ± 1.17
	Jun	39 ± 26	0.65 ± 0.25	44 ± 29	1.06 ± 0.56	32 ± 18	1.61 ± 0.04
	Jul	—	0.42 ± 0.25	74 ± 3	1.19 ± 0.60	41 ± 2	1.44 ± 1.02
	Aug	54 ± 40	1.33 ± 0.55	84 ± 2	1.30 ± 0.75	27 ± 5	1.93 ± 0.94
	Sep	53 ± 53	1.38 ± 0.48	78 ± 22	1.47 ± 0.44	32 ± 10	—
	Oct	62 ± 20	1.69 ± 0.32	54 ± 5	2.42 ± 2.12	47 ± 9	1.77 ± 0.53
	Nov	—	1.02 ± 0.13	53 ± 10	1.25 ± 0.49	47 ± 16	2.79 ± 0.11
	Dec	—	1.61 ± 0.11	42 ± 21	1.71 ± 0.15	62 ± 17	4.74 ± 3.35

NB. — Data not available.

selected locations incorporated with the effect of crop residue burning practices in the region. Organic tarry matter (OTM) was found only 2% of the total aerosol concentration. Levels of LOI and OTM were also associated with the crop residue burning episodes during 2006–2007, indicating a sizable contribution in the increase of levels of aerosols as well as OTM and combustible matter. Aerosol concentration level was above the $200 \mu\text{g m}^{-3}$ (National Ambient Air Quality Standards (NAAQS) for residential areas set by the Central Pollution Control Board, CPCB) that may be harmful itself for the living beings especially for children and elderly people. Higher levels of combustible particulate matter and OTM increase the possibility of the presence of polycyclic aromatic hydrocarbons (PAH) in the ambient air. Determination of these components can be helpful in the study of biomass burning influences and source apportionment, as concentration of these constituents increase with the increase in the levels of aerosol concentration, as well as, crop residue burning events. Residue burning practices should be stopped for a clean environment in the region. Hopefully, conducting such analyses with better time resolutions will provide more information on sources, formation mechanisms, and transport patterns for suspended carbonaceous material associated with aerosols. Such information is a necessary prerequisite to a successful control strategy.

Acknowledgement

The authors thank to the Science and Engineering Research Council (SERC), Department of Science and Technology (DST), Government of India, for providing funds to carry out this study and award of fellowships at Thapar University, Patiala. The authors are also thankful to the Director, Thapar University, for providing research facilities.

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