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Ambient air quality during wheat and rice crop stubble burning episodes in Patiala

Susheel K. Mittal[a,*], Nirankar Singh[a], Ravinder Agarwal[b], Amit Awasthi[b], Prabhat K. Gupta[c]

[a] *School of Chemistry & Biochemistry, Thapar University, Patiala 147004, Punjab, India*
[b] *University Science Instrumentation Centre, Thapar University, Patiala 147004, Punjab, India*
[c] *Chemical Metrology Section, National Physical Laboratory, New Delhi 110012, India*

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ABSTRACT

Open crop stubble burning events were observed in and around Patiala city, India. A ground level study was deliberated to analyze the contribution of wheat (*Triticum aestivum*) and rice (*Oriza sativa*) crop stubble burning practices on concentration levels of aerosol, SO_2 and NO_2 in ambient air at five different sites in and around Patiala city covering agricultural, commercial and residential areas. Aerosols were collected on GMF/A and QMF/A (Whatman) sheets for a 24 h period throughout the year in 2007. Simultaneously, sampling of SO_2 and NO_2 was conducted and results obtained during stubble burning periods were compared to the non-stubble burning periods. Results clearly pointed out a distinct increase in aerosol, SO_2 and NO_2 levels during the crop stubble burning periods.

1. Introduction

Biomass burning is an important source of aerosol and gaseous pollution in the atmosphere, having potential impact on global air quality and climate chemistry (Andreae, 1991; Levine et al., 1995; Andreae and Merlet, 2001; Yang et al., 2008). Open biomass burning is a truly global practice to dispose of living and dead vegetation for land clearing and to change land-use patterns as well as natural, lightning-induced fires. It has been estimated that humans are responsible for about 90% of biomass burning with merely a small percentage of natural fires contributing to the total amount of vegetation burned. Studies show that biomass burning has increased on a global scale over the last 10 decades. Pollutants emanated from biomass burning can also affect properties, materials and moreover human health when they are inhaled, causing respiratory problems (Schwartz, 1993; Godish, 1997; Mohanraj and Azeez, 2004; Thaller et al., 2004; WHO, 2004; Pandey et al., 2005).

During harvesting periods, open burning of agricultural residues releases a large amount of pollutants to the atmosphere, including aerosols and hydrocarbons (Duan et al., 2004; Lemieux et al., 2004). Limited studies on emissions from open burning of agricultural residues have been conducted. An experiment (in situ) for wheat straw burning was undertaken in India for developing specific emission factors (EFs). Although these EFs were generated from a single field experiment yet they addressed an important information gap on field burning of crop residue in the region (Sahai et al., 2007).

Jenkins and Turn urbanized a wind channel to simulate agricultural burning and measured its particulate and gaseous emissions (Turn et al., 1997; CARB, 1996). Oppenheimer et al. (2004) reported NO_2 emissions from sugar cane field burning in Sao Paulo, Brazil. Hays et al. (2005) simulated agricultural fire in an enclosure and presented the physical and chemical characterization of aerosol emissions. Nguyen et al., 1994 conducted ground experiments and measured CO_2, CO, and CH_4 outcomes from rice straw burning in Vietnam. Li et al. (2007) reported particulate and trace gas emissions from open burning of wheat straw and corn stover in China. Dhammapala et al. (2006) performed wheat and bluegrass stubble burn experiments at the USEPA open burning test chamber and measured $PM_{2.5}$, CO_2, CO, and total hydrocarbon emissions.

In contrast to the wealth of data generated in industrialized countries, there have been few studies on air pollution in developing areas of the world. Moreover, data on crop stubble burning effects on ambient air are inadequate. The emission factors in the database for agricultural residues are mainly based on extrapolation, which may cause high uncertainty in emission estimates. In addition, air quality is significantly affected because of agricultural field burning during the harvest period. To determine its

* Corresponding author. Tel.: +91 175 239 3128; fax: +91 175 364498.
E-mail address: smittal2001@yahoo.com (S.K. Mittal).

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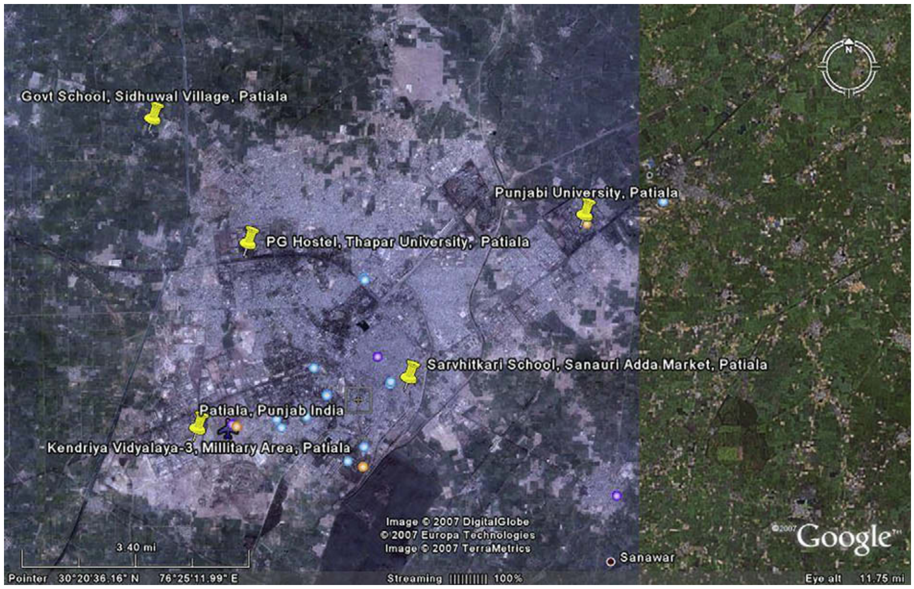

Fig. 1. Location map of different observation sites in and around Patiala.

contribution to ambient air quality, aerosol and gaseous pollutants source profiles from agricultural fire are needed. Therefore, field measurements were conducted to characterize the emissions of particulate and trace gases from open burning of typical agricultural residues in Patiala, India. Mittal and Goyal (2004) have studied suspended particulate levels of Patiala city in relation to automobile exhaust. In the present study, we report increments in the level of ambient air aerosol and gaseous pollution in and around Patiala city due to wheat and rice crop stubble burning practices. Patiala province was chosen for research because there is no industry in the vicinity of the city and thus no point source of air pollution in the city. But from the field survey it was estimated that there is a major problem of open burning of crop stubble in and around the city after wheat and rice crop harvesting during April–May and October–November every year. We examined the influence of stubble burning on the air quality of the city in addition to the effect of wind speed and wind direction on the pollutant concentration. The amounts and types of emissions change every year due to changes in the nation's economy, technology improvements, industrial activity, traffic and many other factors. Air pollution regulations and emission controls also have an effect. This study summarizes annual trends in emissions of air pollutants and gives an in-depth analysis of emissions for the year 2007.

2. Study area

Five locations (Fig. 1 from Google Earth Software) were selected in and around Patiala city for the monitoring of aerosol concentrations along with the sampling of SO_2 and NO_2. These locations were selected carefully, taking natural wind direction 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. These five locations covered residential areas, urban areas, agricultural areas (rural areas), commercial and sensitive areas to observe the effect of crop residue burning on these areas. No industrial area was covered, as there is no major industry in the vicinity of Patiala city. Patiala city is located in the southeastern part of the Punjab state of Northern India (latitude between 29°49′ and 30°47′ N, longitude between 75°58′ and 76°54′ E). The area around Patiala city is predominantly agricultural (rural) . Though farmers cultivate barley, maize and sugarcane crops in this region, wheat and rice (paddy) crops 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). The climate here is typical of the Punjab plain, i.e., very hot in summer (max. temp. 43 ± 2 °C) and very cold in winter (min. temp. 2 ± 2 °C). On an average there are 61 rainy days with annual average rainfall of 688 mm. The variation in rainfall is appreciable. May is the hottest month and January is the coldest month (TERI, 2003).

All the sampling sites were located within a radius of 10 km. A summary of the sampling sites is given in Table 1. A high volume sampler was placed on the rooftop of the PG Hostel building at Thapar University, about 25 m away from the state highway (Patiala–Nabha) with a high proportion of three wheelers, bikes, cars and buses and about 5 km away from agricultural fields to the North-West (NW). This site was considered as an urban area site. The site had a broad open area with no side buildings.

Another high volume sampler was placed on the rooftop of the Biotechnology Department building, Punjabi University, Patiala at the height of 12 m above ground level with no side buildings around and about 6 km away towards the North-East (NE) of the main city. It was located about 500 m away from a very busy state highway with a high concentration of heavy and light vehicles. Punjabi University Campus is very close to the agricultural fields (about 1 km) as compared to the Thapar University Campus. The fields are present to the NW of Punjabi University. Other land around the Punjabi University is covered with residential areas. The site is considered as a semi-urban area.

Table 1
Summary of sampling locations.

Site no.	Site name (Ellipsis)	Site details	Grid reference (Latitude/Longitude)
1.	Thapar University Site (TUS)	Urban site	30°21′05.42″ N, 76°21′57.93″ E
2.	Punjabi University Site (PUS)	Semi-urban site	30°21′28.10″ N, 76°27′02.57″ E
3.	Sidhuwal Village Site (SVS)	Rural	30°22′42.14″ N, 76°20′31.52″ E
4.	Sanauri Adda Site (SAS)	Commercial site	30°19′23.14″ N, 76°24′23.88″ E
5.	Military Area Site (MAS)	Semi-urban site	30°18′41.31″ N, 76°21′12.82″ E

A third high volume sampler was established at the Govt Elementary School of Sidhuwal Village, located at about 6 km towards the NW of Patiala city; this is a completely rural area around which a lot of agricultural fields are present. The sampler was placed on the first floor at the height of about 4.5 m from ground level.

A fourth sampler was placed on the second floor of Sarvhitkari School at Sanauri Adda site, located to the South-East (SE) of Patiala city. It is a densely populated area with a number of shops and cottonseed oil mills. This site was considered as a commercial site. The sampler was placed at about 8 m above ground level. The fifth high volume sampler was established at Kendriya Vidyalaya-3 in a military area, on the rooftop of the school. The military area is a much less populated area as only military personnel are allowed to reside here within its vicinity. It is about 5 km from the city and is covered with a number of agricultural fields.

3. Materials and methods

3.1. Sampling and measurement of aerosols in ambient air

Ambient air sampling was successfully completed at all five locations simultaneously in and around Patiala city using five high volume samplers (HVS) (APM-430, Envirotech Instruments Pvt. Ltd.) under natural conditions of temperature and pressure from January 2007 to December 2007. Glass Micro Fiber (GMF) and Quartz Micro Fiber (QMF) sheets (Whatman/A, 20×25 cm^2) were used as a filter media for the collection of aerosols. Filters were analyzed gravimetrically (IS: 5182 (Part XV), 1974) for the determination of mass as well as concentration of aerosols in ambient air. All the high volume samplers were calibrated and standardized once every 6 months.

Samplers were operated at a flow rate of 1.1–1.6 m^3 min^{-1} for a 24 h continuous period. Minimum two- times sampling was carried out during non-stubble burning months (pre- and post-burning months) and almost alternate day sampling was done consecutively during the stubble burning period from 15 April to 15 May (wheat harvesting period) and from 15 October to 15 November (rice harvesting period). Two- times sampling was carried out from 1 October to 15 October and from 15 November to 30 November at all the selected sampling locations. Thus, around 300 aerosol samples were collected during a 1-year study campaign covering one wheat crop stubble burning and one rice crop stubble burning period. Before and after the sampling, each blank unexposed filter sheet and exposed sampled filter sheet was conditioned for 24 h and then weighed at room temperature (25 °C) and humidity (40%). This was to reduce the weighing errors produced by differences in temperature and humidity between weighings. After 24 h continuous sampling each filter sheet was removed from the sampler, folded with the particulate matter inside, placed in a clean polythene bag and carried into the laboratory for conditioning and weighing. Silica gel (Loba Chemie) was used as a conditioning agent in desiccator and electronic balance (Sartorius BP 110) was used for pre- and post- weighings (IS: 5182 (Part XIV), 1974).

3.2. Sampling and measurement of NO_2 and SO_2 in ambient air

Samples of NO_2 and SO_2 were collected from the ambient air simultaneously with the sampling of aerosols from five sites in and around Patiala city using Thermoelectric Gaseous Attachments VTG1 (APM411). Ambient air was incessantly drawn into 25 ml of NaOH solution in borosilicate glass impingers for 24 h for the sampling of NO_2 and concentration was estimated by Jacob and Hochheiser (Modified Na-Arsenite) method (IS: 5182 (Part VI), 1974). For the sampling of SO_2, 25 ml of 0.04 M potassium tetrachloro-mercurate (TCM) solution was used as an absorber in the borosilicate glass impingers and concentration of SO_2 was determined by West– Gaeke method (West and Gaeke, 1956). Specified absorbing solution (TCM for SO_2 and NaOH for NO_2) was kept inside a Thermoelectric Gaseous Attachment and airflow rate was adjusted in individual impingers with the help of the manifold provided. Impingers had been placed in an ice tray to improve the absorption efficiency of the system and prevent loss of absorbing solutions by evaporation. Samples were brought to the laboratory and stored in a refrigerator in 60 ml size plastic bottles at 4 °C.

3.3. Measurement of meteorological parameters

Concentration of air pollutants is not a steady value and depends on a number of factors including the sources and the ambient climate. A high wind velocity and the frequency of the wind direction can play an essential role in spatial and seasonal variations of air pollutants. Humidity and temperature can also play a crucial role in seasonal and temporal variations in the concentration of air pollutants. Meteorological parameters like wind direction, wind speed, temperature, relative humidity, atmospheric pressure and rainfall were measured during the sampling periods (Gupta and Cheong, 2006).

4. Results and discussion

4.1. Periods of burning

Burning of crop stubble is a global problem and the period of burning depends upon the harvesting time, which further varies from region to region. Wheat stubble burning starts from the middle of April and continues up to mid- May every year in different regions of India, especially Punjab, Haryana and western Uttar Pradesh. After harvesting of these crops a large amount of stubble is left in the fields. Farmers burn this stubble to clear the fields for the next crop. The monthly average aerosol concentration ranged from a minimum of 100 μg m^{-3} to a maximum of 547 μg m^{-3} during January 2007 to December 2007. The monthly average data of aerosol mass concentration with standard deviation at different monitoring sites is presented in Table 2. During non-burning months the frequency of sampling was kept low as there was not much variation during these months, while it increased by 3–4 times during the stubble burning months. This was done so as to average out the variation in aerosol, SO_2 and NO_2 load.

4.1.1. Aerosol concentration during non-burning months

Average aerosol concentration level varied between 136 μg m^{-3} and 243 μg m^{-3} (Fig. 3) during non-burning months. In the month of January 2007, Site 2 (PUS) and Site 3 (SVS) showed almost similar concentration level (258 μg m^{-3}, 257 μg m^{-3}) while concentration was higher (266 μg m^{-3}) at Site 1 (TUS) and lower (158 μg m^{-3}) at Site 4 (SAS). During February and March, a high aerosol concentration (283 μg m^{-3}, 270 μg m^{-3}) was obtained at Site 3 (SVS) whereas the lowest concentrations (144 μg m^{-3}, 147 μg m^{-3}) was obtained at Site 5 (MAS) and Site 2 (PUS), respectively. Thus, results show that the aerosol level during the non-stubble burning months was higher than the National Ambient Air Quality Standards (NAAQS), India (100 μg m^{-3} for sensitive areas, 200 μg m^{-3} for residential and other mixed use areas).

4.1.2. Aerosol concentration during wheat stubble burning months

The aerosol load during the wheat stubble burning months (April and May) was very high. The level increased from 217 μg m^{-3} in March to 371 μg m^{-3} in April. Thus a 40% increase was observed in the ambient aerosol level from March to April. An almost similar increase (35%) in the concentration was observed from March to May. However, the concentration was higher (371 μg m^{-3}) in April as compared to that in May (346 μg m^{-3}).

Table 2
Monthly average concentrations of aerosol, SO_2 and NO_2 at five different locations in and around Patiala city during burning and non-burning months of 2007.

Period	Month	Concentrations [$\mu g\ m^{-3}$ ± standard deviation (number of samples, N)]														
		TUS			PUS			SVS			SAS			MAS		
		SPM	SO_2	NO_2	SPM	SO_2	NO_2	SPM	SO_2	NO_2	SPM	SO_2	NO_2	SPM	SO_2	NO_2
Non-burning months	Jan	266 ± 189 (2)	–	–	258 ± 67 (5)	–	–	257 ± 61 (7)	–	–	158 ± 12 (2)	–	–	–	–	–
	Feb	218 ± 50 (2)	–	–	261 ± 87 (6)	–	–	283 ± 103 (2)	–	–	231 ± 10 (2)	–	–	144 ± 19 (4)	–	–
	Mar	242 ± 13 (2)	–	–	147 ± 29 (8)	–	–	270 ± 18 (2)	–	–	244 ± 4 (2)	–	–	180 ± 36 (5)	–	–
Wheat crop stubble burning months	Apr	**316 ± 12 (5)**	**23 ± 2 (5)**	7 ± 4 (2)	**334 ± 103 (12)**	**16 ± 5 (7)**	**17 ± 5 (2)**	**454 ± 169 (8)**	**16 ± 7 (8)**	**10 ± 4 (5)**	**475 ± 89 (2)**	**28 ± 5 (2)**	**14 ± 1 (2)**	**278 ± 60 (12)**	**26 ± 15 (13)**	**20 ± 16 (13)**
	May	**302 ± 101 (6)**	**16 ± 5 (7)**	8 ± 3 (2)	**314 ± 89 (13)**	**32 ± 5 (11)**	**13 ± 2 (2)**	**417 ± 98 (10)**	**18 ± 2 (8)**	–	**393 ± 99 (11)**	**11 ± 3 (11)**	**68 ± 2 (2)**	**303 ± 70 (11)**	9 ± 10 (9)	**22 ± 18 (13)**
Non-burning months	Jun	135 ± 8 (4)	6 ± 5 (3)	**18 ± 8 (3)**	215 ± 136 (6)	4 ± 1 (6)	**15 ± 3 (4)**	179 ± 108 (4)	1 ± 1 (6)	**10 ± 5 (5)**	239 ± 120 (5)	4 ± 4 (6)	**14 ± 10 (5)**	303 ± 153 (3)	3 ± 2 (2)	**20 ± 13 (3)**
	Jul	238 ± 104 (2)	12 ± 3 (2)	–	293 ± 203 (2)	6 ± 1 (2)	12 ± 1 (2)	267 ± 139 (2)	5 ± 1 (2)	8 ± 8 (2)	176 ± 112 (2)	1 ± 0 (2)	34 ± 4 (2)	–	–	–
	Aug	122 ± 14 (2)	5 ± 1 (2)	–	122 ± 22 (2)	3 ± 0 (2)	10 ± 2 (2)	111 ± 22 (2)	3 ± 2 (2)	14 ± 2 (2)	209 ± 56 (2)	6 ± 1 (2)	–	137 ± 14 (2)	3 ± 1 (2)	11 ± 5 (2)
	Sep	100 ± 11 (2)	15 ± 4 (2)	22 ± 10 (2)	100 ± 30 (2)	5 ± 0 (2)	9 ± 1 (2)	146 ± 50 (4)	6 ± 3 (5)	10 ± 3 (2)	205 ± 80 (2)	10 ± 3 (2)	15 ± 3 (2)	126 ± 37 (2)	9 ± 1 (2)	3 ± 2 (2)
Rice crop stubble burning months	Oct	**386 ± 101 (11)**	9 ± 9 (9)	**24 ± 14 (9)**	**476 ± 86 (11)**	**13 ± 16 (10)**	**12 ± 4 (10)**	**457 ± 106 (13)**	**12 ± 10 (11)**	**22 ± 11 (11)**	**465 ± 91 (12)**	**33 ± 24 (9)**	**67 ± 39 (9)**	**427 ± 124 (12)**	**14 ± 4 (9)**	**22 ± 12 (10)**
	Nov	**381 ± 80 (8)**	**14 ± 10 (3)**	**19 ± 6 (5)**	**391 ± 110 (10)**	8 ± 7 (7)	**19 ± 6 (7)**	**417 ± 171 (10)**	**10 ± 3 (8)**	**27 ± 8 (8)**	**547 ± 152 (11)**	**55 ± 34 (8)**	**91 ± 39 (8)**	**414 ± 138 (11)**	**17 ± 5 (10)**	**44 ± 23 (12)**
Non-burning month	Dec	173 ± 103 (2)	7 ± 0 (2)	**11 ± 1 (2)**	210 ± 144 (2)	**18 ± 5 (2)**	**14 ± 2 (2)**	201 ± 46 (4)	8 ± 4 (4)	**14 ± 9 (4)**	258 ± 119 (2)	**24 ± 16 (2)**	**62 ± 15 (2)**	251 ± 164 (2)	**26 ± 4 (2)**	**24 ± 3 (2)**

Bold indicates high concentrations during crop residue burning months, –, data not available.

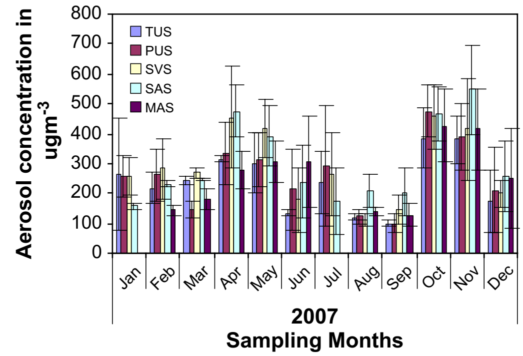

Fig. 2. Monthly variations in aerosol concentration at different locations in and around Patiala city.

4.1.3. Aerosol concentration during rice stubble burning months

During the rice harvesting period, i.e., in October and November, the monthly average aerosol concentration was 442 $\mu g\ m^{-3}$ and 430 $\mu g\ m^{-3}$, respectively (Fig. 3). These levels were much higher as compared to the levels in September (136 $\mu g\ m^{-3}$) and December (218 $\mu g\ m^{-3}$). From September to October, a 70% increase is observed. In December, levels fall to 50% of the value in November. The reason for this may be that after harvesting of the rice crop, a large mass of rice stubble left in the fields is burned by the farmers to clear the fields in time for sowing of the next crop.

Regression analysis ($R^2 = 0.7859$) shows that the trend of aerosol concentration in 2007 was the same, i.e. concentration was higher during crop stubble burning periods and lower during non-crop stubble burning periods. Though the aerosol level was found to be higher during April–May (the burning period of wheat stubble), the level of aerosol load was superior during the rice stubble burning period (October–November).

A certain quantity of wheat stubble is stocked for animal feed and extra material is burned by the farmers. In contrast, rice stubble can be bulky and is generally not used for animal feed. This may be the reason for higher aerosol concentration during the rice crop stubble burning period (Badrinath et al., 2006). From the above data it can be concluded that crop residue burning contributes to raising the level of aerosol and gaseous pollution in the ambient air, as there is no other point source such as industry or power plants in the vicinity of the city. This increase was observed at all the monitoring sites (Fig. 2).

4.2. Gaseous analysis

4.2.1. SO_2 and NO_2 concentration during the non-burning period

The phase from June to September and December to March is considered as the non-burning period. Concentration levels of SO_2 and

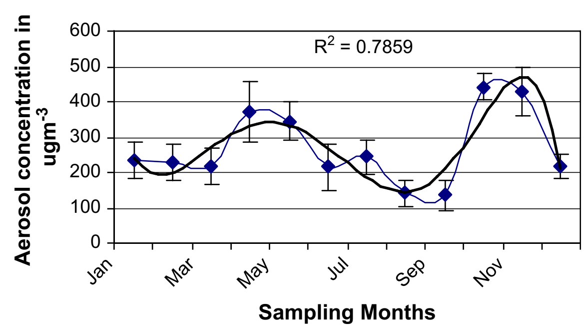

Fig. 3. Monthly average variations in aerosol concentration during the study campaign in 2007.

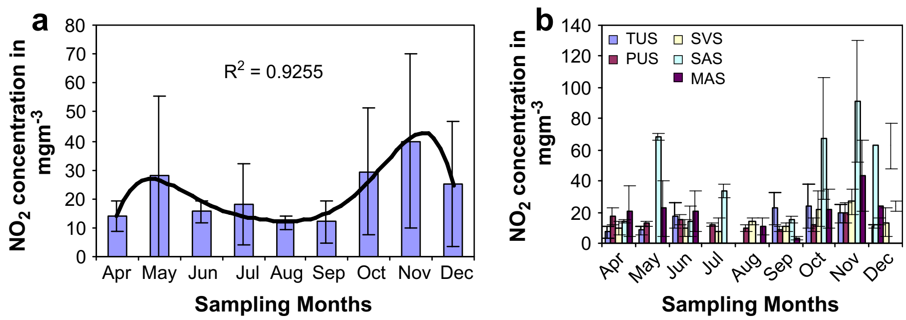

Fig. 4. (a) Monthly variation in NO_2 concentration at different locations in and around Patiala city. (b) Monthly average variations in NO_2 concentration during the study campaign in 2007.

NO_2 during these months varied from an average monthly concentration of 4 $\mu g\ m^{-3}$ to 17 $\mu g\ m^{-3}$ and 12 $\mu g\ m^{-3}$ to 18 $\mu g\ m^{-3}$, respectively. SO_2 concentration was much higher during December (17 $\mu g\ m^{-3}$) as compared to other non-burning months (June = 4 $\mu g\ m^{-3}$, July = 6 $\mu g\ m^{-3}$, August = 4 $\mu g\ m^{-3}$, September = 9 $\mu g\ m^{-3}$) while NO_2 concentration was found to be higher during July (18 $\mu g\ m^{-3}$). NO_2 concentration level remained at a similar level during August and September.

4.2.2. SO_2 and NO_2 concentration during stubble burning periods

April and May as well as October and November are the months considered as the crop stubble burning months. During April and May, wheat crop stubble is burned after harvesting where as rice crop stubble burning is performed during October and November. NO_2 concentration ranged from a minimum of 14 $\mu g\ m^{-3}$ to a maximum concentration of 40 $\mu g\ m^{-3}$ whereas SO_2 concentration varied from 16 $\mu g\ m^{-3}$ to 22 $\mu g\ m^{-3}$. A high NO_2 concentration was obtained during May (28 $\mu g\ m^{-3}$), the wheat stubble burning month and November (40 $\mu g\ m^{-3}$), the rice stubble burning month. A high SO_2 concentration was obtained during April (22 $\mu g\ m^{-3}$) and November (21 $\mu g\ m^{-3}$). Almost the same concentration of SO_2 was obtained during both burning periods but higher levels of NO_2 were observed during the rice stubble burning period. It was observed that there was a quantum jump in the SO_2 and NO_2 levels during burning months in 2007 (Fig. 4a and b).

Results of analyzed IRS-P6 AWiFS satellite data of Punjab state of India for two different crop harvesting seasons have shown that nearly 5504 km^2 was under wheat crop stubble burning and 12,685 km^2 under rice crop stubble burning in 2005 (Badrinath et al., 2006). In another study an attempt was made to identify biomass burning areas of agriculture residue for Punjab during May 2005 (wheat crop residue burning month) using satellite remote sensing data (Advanced Wide Field sensor, AWiFS) obtained from a knowledge-based classification approach using See5 algorithm showed a district- wise burned area distribution. The estimated total burnt area was found to be around 4315 km^2 during the wheat harvesting season (Punia et al., 2008). Emissions estimated from the rice field burning were 261 Gg of CO, 19.8 Gg of NO_X, 3 Gg of CH_4, 30 Gg of PM_{10} and 28.3 Gg of $PM_{2.5}$ during October 2005 (Badrinath et al., 2006). In Punjab, more than 90% of the rice and 80% of the wheat is harvested using combine harvesters, leaving loads of up to 9 tonnes per hectare of rice stubble in the fields, and 80% of farmers burn the stubble. More than 15 million tonnes of rice stubble and around 5 million tonnes of wheat stubble are burned each year in Punjab (Patel, 2008).

Although it is very difficult to correlate the increase in NO_2 level with the crop residue burning period as the combustion of the straw from the rice crop takes place in November at a relatively low temperature due to greater moisture content (as compared to the wheat crop residue), the results indicate an appreciable increase in NO_2 levels during this period. This can only be assigned to the outcome of rice crop residue burning as well as some contribution from the exploding of crackers during the festive season. The SO_2 levels do not increase proportionally because there is hardly any source of sulfur (S) in the crop residue stubble. The increase in NO_2 in both seasons is expected because of the use of nitrogen (N) based fertilizers in both crops. This observation becomes important in the absence of any other activity such as industrial or power generation in the near vicinity of about 20 km .

From the regression analysis of NO_2 and SO_2 levels ($R^2 = 0.9256$, $R^2 = 0.956$), it has been observed that the trend was same in the year 2007, i.e. concentrations of NO_2 and SO_2 were higher during the burning periods and lower during the non- burning periods Fig. 5.

4.3. Wind speed and direction during the study period

Wind direction during the study period in 2007 remained either NW or calm for most of the time. Windrose plots were made for the

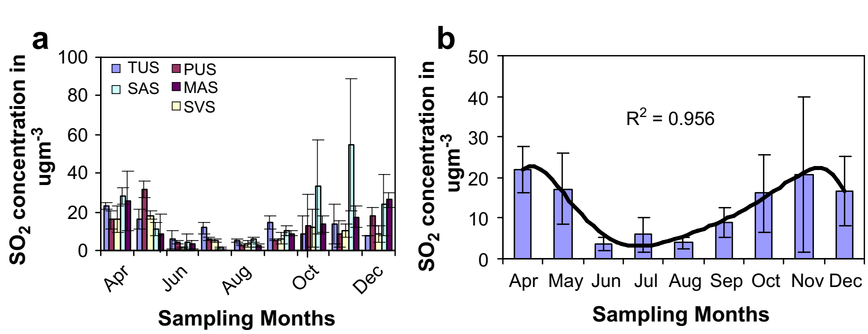

Fig. 5. (a) Monthly variation in SO_2 concentration at different locations in and around Patiala city. (b) Monthly average variations in SO_2 concentration during the study campaign in 2007.

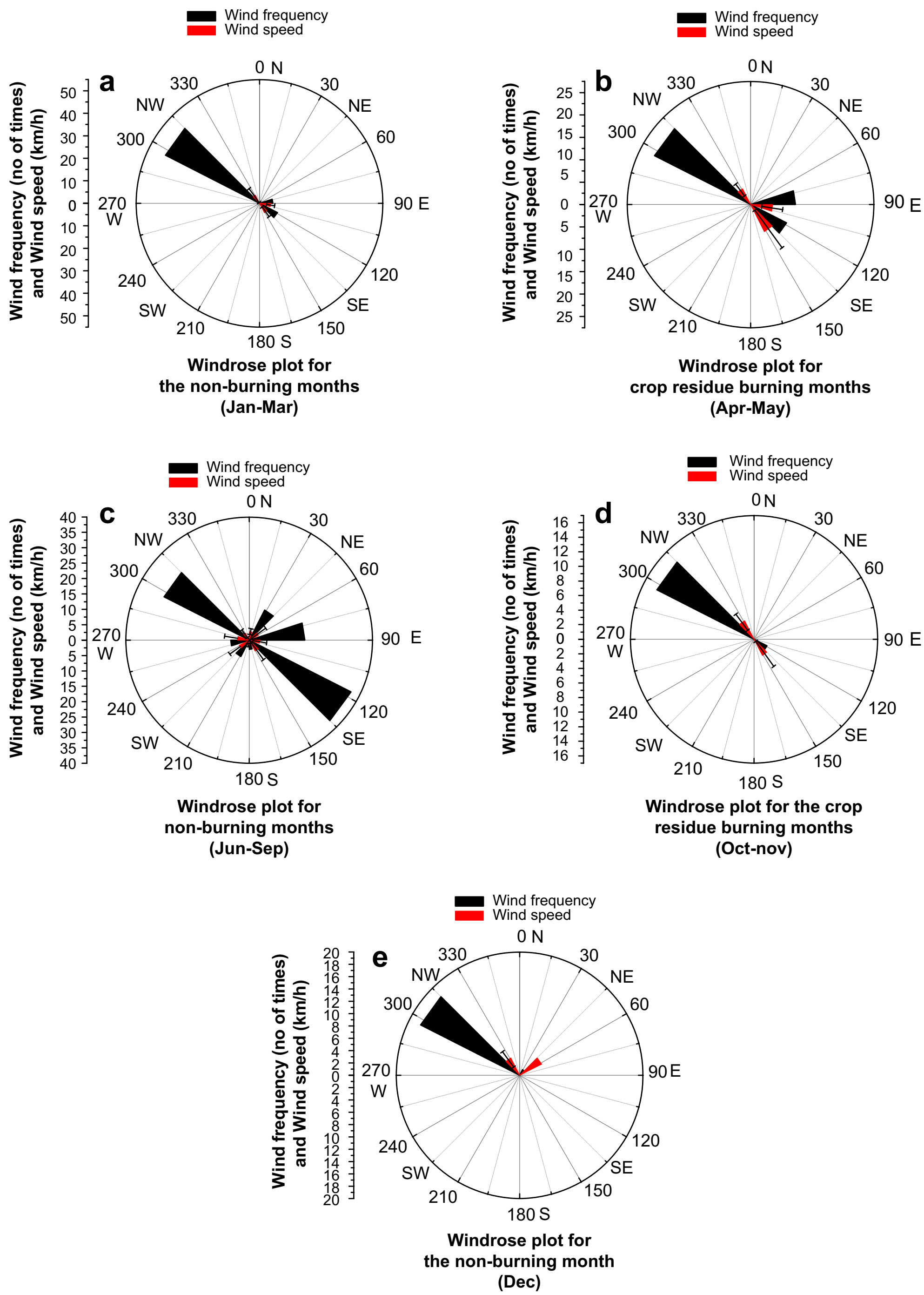

Fig. 6. (a–e) Windrose plots showing wind direction, wind speed and wind frequency in Patiala during burning and non-burning months of the study campaign in 2007.

burning and non-burning months of the year 2007. These windrose plots show the wind direction with wind frequency and wind speed during the study period. The windrose plot for the non-burning months (January–March) divided into eight sectors (Fig. 6a) shows that the winds at Patiala during January– March remained NW for most of the time. However, some times SE and E wind direction was observed, having wind speed between <1 and $8\ \mathrm{km\,h^{-1}}$. The windrose plot for January–March also shows that the wind never blows from the North or NE. Almost the same information is obtained from the windrose plot made for the wheat crop residue burning period (April–May) (Fig. 6b). The plot indicates that frequency of the wind blowing from the NW was still high and the wind speed varied similarly from 1 to $8\ \mathrm{km\,h^{-1}}$. During the non-burning months of June–September, the wind was blowing from the NW and SE with almost equal frequency (37 and 31, respectively) (Fig. 6c). On the contrary, winds were also blowing from NE, E and other directions during this period, but the frequency was negligibly small. Again it can bee seen from Fig. 6d and e that the wind was blowing from the NW for most of the time. Examining winds blowing from the NW (the longest spoke) it is found that approximately 90% of the time wind was blowing from the NW towards SE in Patiala at a speed between 1 and $8\ \mathrm{km\,h^{-1}}$. These wind roses are based on daily data from a global weather monitoring website (www.wunderground.com/global/stations/42101.html) and the Indian Meteorology Department website (www.imd.ernet.in/main_new.htm).

5. Conclusions

From the above results it can be concluded that the crop stubble burning performed after the wheat and rice crop harvesting had changed the chemistry of ambient air in Patiala in 2007 by increasing the concentration of aerosols, SO_2 and NO_2 in the province. Although levels of SO_2 and NO_2 were fluctuating at different monitoring sites, high concentrations were obtained in the months of April and May (wheat crop stubble burning months) as well as October and November (rice crop stubble burning months). Likewise, observations obtained from aerosol sampling resulted in high aerosol load during wheat and rice crop harvesting months. However, levels of these pollutants were high during both burning periods (April–May; wheat stubble burning period, October–November: rice stubble burning period), while aerosol and NO_2 concentration was high during the rice crop stubble burning period (October–November).

A very important inference can be drawn from the data that the gaseous molecules stay in the ambient air for a longer duration than those of aerosols. This can be confirmed from the monthly average levels of aerosol, NO_2 and SO_2 concentration. In the month of June and December the aerosol levels fall back to the baseline value whereas the gaseous levels tend to stay at higher concentrations in these months as well.

Though local aerosol concentration obtained at all sites during non- burning months was already higher than the NAAQS (India) of 200 $\mu g\, m^{-3}$ and World Health Organization standards for most of the sampling times, during crop residue burning months a very high increment was observed in aerosol level at all of the sites. The monthly average concentration of SO_2 and NO_2 remained below the NAAQS standards (80 $\mu g\, m^{-3}$); moreover, a higher concentration was obtained during the stubble burning period at all of the sampling locations.

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