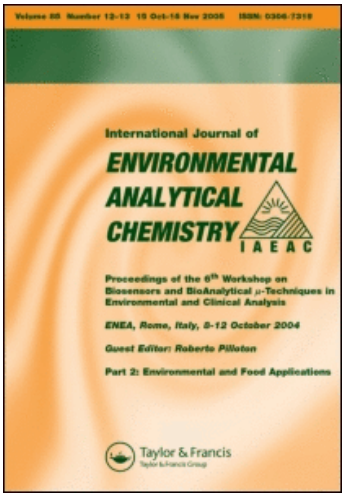

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Impact of rice crop residue burning on levels of SPM, SO_2 and NO_2 in the ambient air of Patiala (India)

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Ground-based ambient air monitoring was conducted at five different locations in and around Patiala city (29°49′–30°47′N Latitude, 75°58′–76°54′E Longitude) in Northern India in order to determine the impact of open burning of rice (*Oriza sativa*) crop residues on concentration levels of suspended particulate matter (SPM), sulphur dioxide (SO_2) and nitrogen dioxide (NO_2). Covering sensitive, residential, agricultural, commercial and urban areas, sampling of these pollutants was organised during August 2006 to January 2007 and August 2007 to January 2008 casing two rice crop residue burning periods (October–November) using a high volume sampling technique combined with gaseous sampling systems. Gravimetric analysis was used in the estimation of total suspended particulate matter (TSPM) whereas SO_2 and NO_2 concentration was determined using spectrophotometer (Specord205, Analytikjena). Monthly average concentrations of SPM, SO_2 and NO_2 have shown significant up and down features at all the selected sampling sites during the study period. Monthly average concentrations (24 hour) of SPM, SO_2 and NO_2 varied from $100 \pm 11\,\mu g\,m^{-3}$ to $547 \pm 152\,\mu g\,m^{-3}$, $5 \pm 4\,\mu g\,m^{-3}$ to $55 \pm 34\,\mu g\,m^{-3}$ and $9 \pm 5\,\mu g\,m^{-3}$ to $91 \pm 39\,\mu g\,m^{-3}$. Substantially higher concentrations were recorded at the commercial area site as compared to the other sampling sites for all the targeted air pollutants. Levels of SPM, SO_2 and NO_2 showed clear increase during the burning months (October–November) incorporated with the effect of meteorological parameters especially wind direction, precipitation and atmospheric temperature.

Keywords: ambient air quality; rice crop residue burning; TSPM; NO_2; SO_2

1. Introduction

Ambient air pollution has been the subject of growing concern for several decades due to its damaging effects on health and materials [1,2]. A number of health problems, starting from disorders in the respiratory system and cardiovascular system to mortality have been associated with air pollution [3–7]. Wheat straw field burning in several regions of Beijing has caused serious air pollution episodes [8]. It is important to know particulate matter concentration in the ambient air as it has severe adverse health effects [9,10].

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It has been postulated that ultra-fine particles have the ability to penetrate lung walls inducing inflammation in the pulmonary interstitum, which in turn stimulates the production of clotting factors in the blood and intensifies ischaemic heart disease [11,12]. Airborne particles remain suspended in the air for a very long time due to their small size and very light weight. Emissions of anthropogenic pollutants are increasing sharply with the modern agricultural practices, industrialisation and motorisation all over the world, which brings not only regional but also global effects through the use of long-range transport. Particulate pollution is now receiving worldwide attention, as it has potential impacts on health and climate change [13].

Biomass fires have been an imperative source of gaseous and particulate pollutants in the atmosphere and have considerable impact on global atmospheric chemistry and global climate change [14–16]. Crop residue burning is a common approach to eliminate waste after harvesting all over the world (Figure 1) [17–19]. Studies have estimated that 17–25% of the total agricultural residue production is burnt in the fields in China every year [20–24]. Modern crop harvesting practices using mechanical harvesters have become common in the rice–wheat system (RWS) in India. These practices leave behind large quantities of crop residue in the field. In India, rice is generally transplanted during June–July and harvested during October–November. Wheat is sown instantly after rice during November–December and harvested during April–May of the next year. Thus, there is hardly any turn-around time between the rice harvest and wheat sowing and farmers face considerable problems in managing the crop residues, especially from the rice crop. The

Figure 1. Rice crop residue burning in Sidhuwal Village (Patiala).

optimal time for sowing wheat is the middle of November but when grown after rice its sowing usually gets delayed by 30 to 45 days. Hence, farmers choose burning to remove crop residue from the fields as being perhaps the cheapest and least time consuming alternative than any other crop residue removal means [25].

Results of analysed IRS-P6 AWiFS satellite data of the Punjab state of India for two different crop harvesting seasons have shown that nearly 5504 sq. km area was under wheat crop residue burning and 12,685 sq. km under rice crop residue burning in 2005 [26,27]. Studies pertaining to the effects of crop residue burning on ambient air in Indian provinces are still inadequate. Existing scientific literature shows that the studies are focused on the contribution of vehicular and industrial emissions in the increment of air contamination in metropolitan cities. Studies on the concentration of suspended particulate matter with special reference to vehicular exhaust emission were carried out in the year 2004 by Mittal *et al*. [28] at some commercial and curbside locations in Patiala.

Particulate matter (PM), ozone (O_3), carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2) are the six criteria air pollutants decided by the United States Environmental Protection Agency (USEPA) as well as other Environmental Protection Agencies in the world [29,30]. The main objective of the present study was to determine the concentration of SPM, SO_2 and NO_2 in ambient air of Patiala city during rice crop residue burning episodes (i.e. during October–November) for the years 2006 and 2007 and to examine the effect of crop residue burning on the concentration levels of these pollutants.

2. Experimental

2.1 *Study area and sampling locations*

Patiala city (Figure 2) is located in the southeastern part of the Punjab state of northern India. It lies between the 29°49′–30°47′N latitude and 75°58′–76°54′E longitude. This district encompasses a total area of 3627 sq. km, having an entire population of more than 1.845 million (as per 2001 census) with overall 70% literacy. The district is predominantly a rural district in which 1.2 million (65%) people live in rural areas and only 0.645 million (35%) live in urban areas (population density = 509 sq. km/person). The main occupation of the people of this district is agriculture with 81% cultivable land. Wheat (*Triticum aestivum*) and rice (*Oriza sativa*) are the two major crops of the district with a combined cropping area of more than 86%. Although, very few industries are in the vicinity of the Patiala city there is a big problem of crop residue burning in and around the city during October and November every year. The climate here is typical of the Punjab plain i.e. very hot in summer and very cold in winter. The annual average rainfall is 688 mm with an average 61 rainy days. The variation in rainfall is appreciable. The month of May is the hottest with the mean monthly maximum temperature of 43 ± 2°C. January is the coldest month with mean monthly minimum temperature of 2 ± 2°C [31].

Five sampling sites (Table 1, Figure 2) were selected in and around Patiala city within a radius of 10 km according to the land use pattern covering sensitive, rural (agricultural), urban, semi-urban, commercial and residential areas. Site 1, Thapar University Site (TUS) is about 0.25 km away from the state highway (Patiala–Nabha) with a high proportion of three-wheelers, bikes, cars and buses. This site was considered as a sensitive site. The site is a broad open area with no side buildings. Site 2, Punjabi University (PUS) is situated

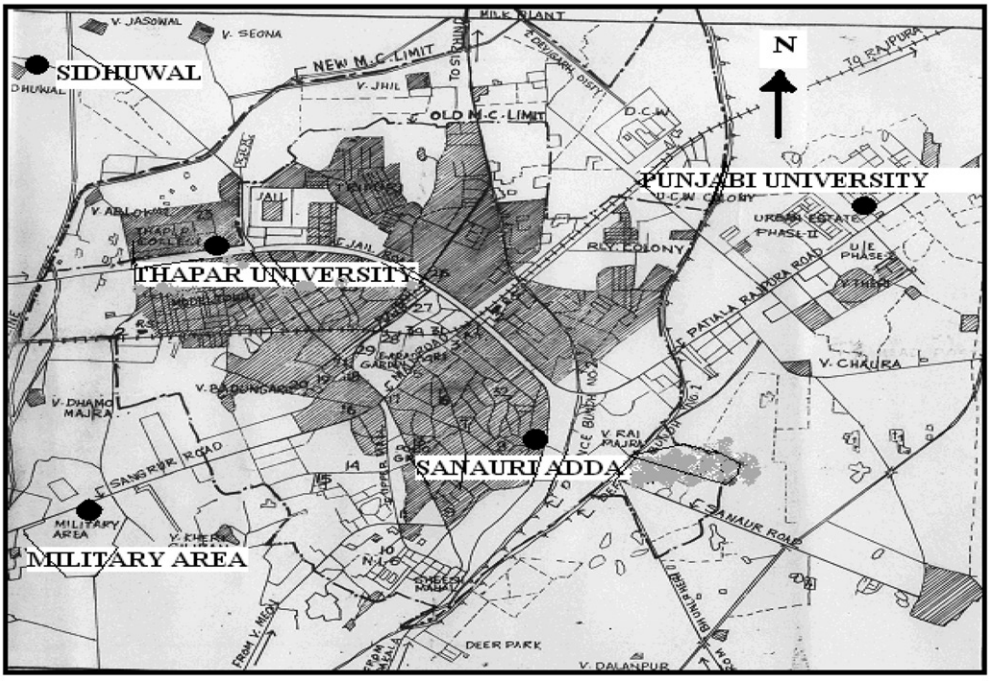

Figure 2. Location map of different observation sites in and around Patiala city.

Table 1. Different observation sites and their grid location.

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

about 6.0 km away towards the North-East (NE) of the main city. The site is about 0.5 km away from a very busy state highway with much movement of light and heavy vehicles as compared to Site 1 and was considered as a semi-urban site. Site 3, Sidhuwal Village Site (SVS) is located about 6.0 km towards the North-West (NW) of Patiala city, representing a rural area site with many agricultural fields all around it.

Site 4, Sanauri Adda Site (SAS), located in the market (Sanauri Adda) area in the South-East (SE) of Patiala city, with a dense population and a number of cottonseed oil mills, was considered as a commercial site. Site 5, Military Area Site (MAS), situated in the South-West (SW) of Patiala city was selected as a semi-urban site. It has a less populated

area as only military personnel are allowed to reside within its vicinity. It is 5.0 km from the city, having a large agriculture area all around.

2.2 *Materials and methods*

2.2.1 *Sampling and measurement of SPM, SO_2 and NO_2*

Sampling of Total Suspended Particulate Matter (TSPM) and gaseous pollutants (SO_2 and NO_2) was carried out from September 2006 to January 2007 and August 2007 to January 2008. Covering two rice harvesting periods, sampling was conducted at all the five selected locations in and around Patiala city using five High Volume Samplers (APM 430, Envirotech Instruments Pvt, India) [32–34] attached with thermoelectric gaseous sampling systems (Vayubodhan Upkaran Pvt, India). Although, during continuous sampling, day-to-day variations in the flow rate are expected due to varying meteorological conditions and changing atmospheric phenomena such as wind speed, wind direction and dispersion, etc. besides the impact of emission sources, the suspended particulate matter (SPM) was collected by passing ambient air at a high flow with an average rate of 1.0–1.3 $m^3 min^{-1}$. A high volume sampler was established at the rooftop of each individual sampling site at a height of about 8–10 metres from ground level. Weekly samples were collected simultaneously for equal sampling durations (24 hours) from all five sites with an increase of two samples at each site during crop residue burning months under natural conditions of temperature, and a pressure and gravimetric technique [35] was used for the estimation of SPM concentration. In case of rainfall, sampling was not accepted and it was performed again after two days [36–38].

Glass Micro Fibre sheets (GMF/A, Whatman) were used as a filter media for the collection of SPM. Prior to use, each new blank filter was exposed to a light source and inspected for pinholes, particles and other imperfections and then conditioned over dried silica gel (Loba Chemie) in a desiccator for 24 hours and weighed at room temperature (25°C) and humidity (50%) to reduce the probability of weighing errors due to differences in temperature and humidity. Pre-inspected and weighed new blank filters were placed into the sampling device for 24 hours' continuous sampling. After sampling each filter was removed from the sampler and carried into the laboratory for the final conditioning and weighing. Electronic balance (Sartorius BP 110, USA, accuracy ±0.1 mg) was used for pre- and post-weighing [39,40].

Sampling at Site-5 (MAS) could not be done in 2006 due to late establishment of HVS. Thus, 236 SPM samples (128 samples during non-burning months and 108 samples during burning months) were collected during September 2006 to January 2007 and August 2007 to January 2008. Similarly, 272 gaseous samples (140 for SO_2 and 132 for NO_2; including burning and non-burning months) were collected during August 2007 to January 2008. All the HVS were calibrated and standardised once within a period of six months to reduce the errors in the measurements.

Standard wet chemical methods [41,42] were applied for the determination of SO_2 and NO_2 concentration in ambient air. Sampling was done by passing ambient air at an average flow rate of 0.3 litre per minute (lpm) through the borosilicate glass impingers of 35 mL capacity having the specific absorbing media (Tetrachloromercurate for SO_2 and NaOH solution for NO_2). Impingers filled with specified absorbing solution were kept inside gaseous attachment and airflow rate was adjusted for individual impinger with the help of the manifold provided. Gaseous attachment was capable in maintaining a

temperature of 15–20°C, which improves the absorption efficiency of the system and prevents loss of absorbing solutions due to evaporation. All the collected gaseous samples were placed in a refrigerator (Samsung, India) maintained at 4°C for the subsequent analysis. Samples of SO_2 and NO_2 were collected from the ambient air simultaneously with the sampling of SPM at all the five sites and analysed in the laboratory using a UV–VIS spectrophotometer (Analytikjena, Specord205, Germany) at 560 nm and 540 nm, respectively.

2.2.2 *Measurement of meteorological parameters*

Concentration of SPM, SO_2 and NO_2 is not a constant value and depends on a number of factors including the sources and the ambient climate. Wind speed, wind direction, rainfall, humidity and temperature can play a crucial role in spatial and seasonal variations of air pollutants [43,44]. Meteorological parameters monitored during the sampling periods were wind direction, wind speed, relative humidity, temperature, atmospheric pressure and rainfall.

3. Results and discussion

Monthly average SPM concentration in Patiala city varied between $216 \pm 40\,\mu g\,m^{-3}$ to $470 \pm 101\,\mu g\,m^{-3}$ during September 2006 to January 2007 while in the next corresponding period starting from August 2007 to January 2008, the SPM concentration varied between $100 \pm 11\,\mu g\,m^{-3}$ to $547 \pm 152\,\mu g\,m^{-3}$. The monthly average data of SPM and the number of samples (n) averaged out in a particular sampling month for different monitoring sites is presented in Table 2 with their standard deviations (SD).

3.1 *Levels of SPM during burning and non-burning months*

SPM concentration has shown great variations at different monitoring sites during the study period incorporated with the effects of rice crop residue burnings and the meteorological parameters. The SPM concentration varied between $236 \pm 72\,\mu g\,m^{-3}$ and $348 \pm 81\,\mu g\,m^{-3}$ at TUS during September 2006 to January 2007 (Table 2, Figure 3) with the lowest concentration in September and the highest concentration in November 2006. During the next corresponding period starting from August 2007 to January 2008, the SPM concentration varied between $100 \pm 11\,\mu g\,m^{-3}$ and $386 \pm 101\,\mu g\,m^{-3}$ at this site (Figure 3), again with the highest level in October ($386 \pm 101\,\mu g\,m^{-3}$) and the lowest in September ($100 \pm 11\,\mu g\,m^{-3}$) 2007. A similar trend was observed with SPM concentration obtained at PUS during the corresponding sampling period, being the highest concentration in October and the lowest in September 2007.

At SVS, monthly average concentration of SPM during the sampling period from September 2006 to January 2007 varied between $216 \pm 40\,\mu g\,m^{-3}$ and $449 \pm 132\,\mu g\,m^{-3}$ (Figure 4) with the highest concentration in November 2006 and the lowest in December 2006. In 2007, monthly average SPM level varied between $146 \pm 50\,\mu g\,m^{-3}$ and $457 \pm 106\,\mu g\,m^{-3}$ with the highest concentration in October and the lowest in September (Figure 3) at the same site. Similarly, monthly average SPM concentration at SAS varied with the highest level in October ($470 \pm 101\,\mu g\,m^{-3}$) and the lowest in December ($266 \pm 6\,\mu g\,m^{-3}$) during September 2006 to January 2007 and from a value of $205 \pm 80\,\mu g\,m^{-3}$ to

Table 2. Monthly average concentration of SPM [($\mu g\,m^{-3}$) ± SD] from September 2006 to January 2008 at different monitoring sites in Patiala, India.

			SPM [$\mu g\,m^{-3}$]				
Year	Phase	Month	TUS	PUS	SVS	SAS	MAS
2006	Non-burning month	Sep	236 ± 72 ($n=4$)	276 ± 50 ($n=4$)	341 ± 60 ($n=4$)	340 ± 55 ($n=4$)	–
	Burning months	Oct	303 ± 13 ($n=6$)	345 ± 37 ($n=6$)	430 ± 98 ($n=6$)	470 ± 101($n=6$)	–
		Nov	348 ± 81 ($n=6$)	332 ± 112 ($n=6$)	449 ± 132 ($n=6$)	343 ± 176 ($n=6$)	–
	Non-burning month	Dec	284 ± 144 ($n=4$)	258 ± 64 ($n=4$)	216 ± 40 ($n=4$)	266 ± 6 ($n=4$)	–
2007	Non-burning months	Jan	266 ± 189 ($n=4$)	258 ± 67 ($n=4$)	257 ± 61 ($n=4$)	158 ± 12 ($n=4$)	–
		Aug	122 ± 14 ($n=4$)	122 ± 22 ($n=4$)	111 ± 22 ($n=4$)	209 ± 56 ($n=4$)	137 ± 14 ($n=4$)
		Sep	100 ± 11 ($n=4$)	100 ± 30 ($n=4$)	146 ± 50 ($n=4$)	205 ± 80 ($n=4$)	126 ± 37 ($n=4$)
	Burning months	Oct	386 ± 101($n=6$)	476 ± 86 ($n=6$)	457 ± 106 ($n=6$)	465 ± 91 ($n=6$)	427 ± 124 ($n=6$)
		Nov	381 ± 80 ($n=6$)	391 ± 110 ($n=6$)	417 ± 171 ($n=6$)	547 ± 152 ($n=6$)	414 ± 138 ($n=6$)
	Non-burning month	Dec	173 ± 103 ($n=4$)	210 ± 144 ($n=4$)	201 ± 46 ($n=4$)	258 ± 119 ($n=4$)	251 ± 164 ($n=4$)
2008	Non-burning month	Jan	166 ± 38 ($n=4$)	154 ± 67 ($n=4$)	160 ± 23 ($n=4$)	198 ± 13 ($n=4$)	201 ± 10 ($n=4$)

Notes: 'n' represents the number of samples averaged out.
– data not available.

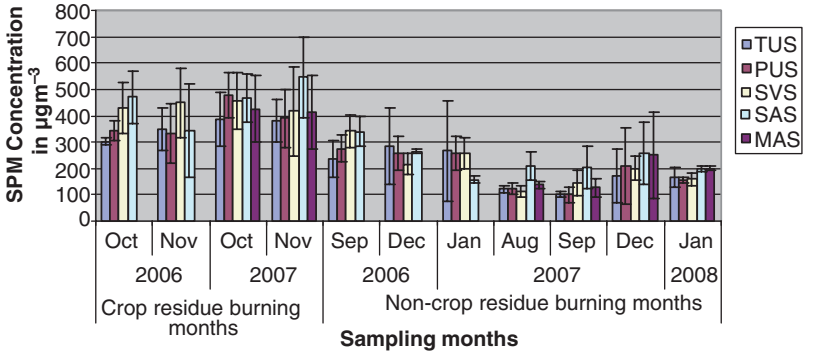

Figure 3. SPM concentration at different sampling sites in and around Patiala city during burning and non-burning months of the study period.

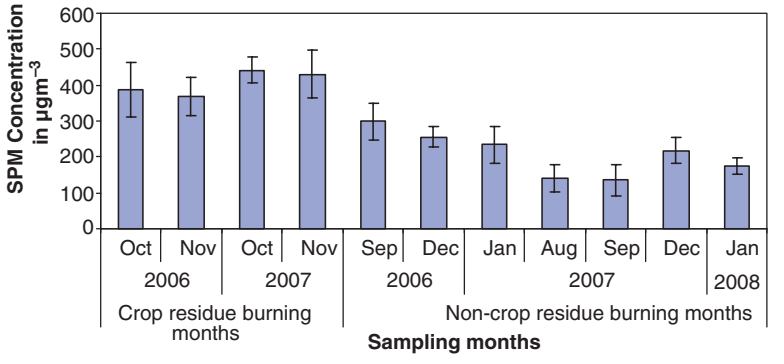

Figure 4. Average SPM concentration during different sampling months in and around Patiala city.

$547 \pm 152\,\mu g\,m^{-3}$ in the study period starting from August 2007 to January 2008 with the highest concentration in November and the lowest in September (Figure 3).

At MAS, monthly average SPM concentration varied between $126 \pm 37\,\mu g\,m^{-3}$ and $427 \pm 124\,\mu g\,m^{-3}$ during August 2007 to January 2007 with the highest concentration in October and the lowest in September (Table 2). SPM levels were higher at PUS as compared to TUS. This may be due to the higher population and vehicular density at the PUS as compared to TUS and also due to its location near the very busy state highway (about 0.5 km) connecting Patiala with Chandigarh (the state capital). Although, TUS was also close to another state highway (about 0.5 km) connecting Patiala with Malerkotla, but the frequency of vehicles travelling on this road is about 25% of Patiala–Chandigarh state highway. But this concentration was lower than that of the SAS because SAS is a densely populated residential-cum-commercial area with a number of cottonseed oil mills. It was observed that there was a quantum jump in the SPM levels during October–November (rice crop residue burning periods) at all the monitoring sites.

3.2 *Levels of SO_2 and NO_2 during burning and non-burning months*

Concentration levels of SO_2 and NO_2 were determined from August 2007 to January 2008 covering one rice crop residue burning period. The monthly average levels are presented

in Table 3. The monthly average SO_2 concentration in Patiala varied from a minimum value of $4 \pm 1\,\mu g\,m^{-3}$ in August 2007 to a maximum value of $21 \pm 19\,\mu g\,m^{-3}$ in November 2007. The concentration levels were almost similar during December ($17 \pm 9\,\mu g\,m^{-3}$) and October ($16 \pm 10\,\mu g\,m^{-3}$) in 2007 and during November 2007 ($21 \pm 19\,\mu g\,m^{-3}$) and January 2008 ($20 \pm 5\,\mu g\,m^{-3}$). Amongst all the five monitoring sites, SAS showed peak concentration of SO_2 with highest concentration in November 2007 ($55 \pm 34\,\mu g\,m^{-3}$) (Table 2).

It was observed that there was a significant increase in NO_2 levels during the months of October and November of 2007. SAS is located in densely populated area with much commercial activity. Remarkably high increase in NO_2 concentration was observed at SAS with $67 \pm 39\,\mu g\,m^{-3}$ in October and $91 \pm 39\,\mu g\,m^{-3}$ in November (Table 2), which may be attributed to vehicular emission integrated with the crop residue burnings effect. It is very difficult to correlate the increase in NO_2 levels with all sets of crop residue burning periods as the combustion of the rice crop straw takes place in October and November at a relatively low temperature due to greater moisture content but the results indicate an appreciable increase in NO_2 levels during this period. These observations become important in the absence of any other activity such as industrial or power generation in the area of about 20 km in the vicinity of the study area.

The increase in SO_2 levels at SAS can be associated with the reasons given above for the NO_2 levels. Since there is no possible source of emission such as iron smelting industries, coal fired units etc. in the vicinity, which could change the levels of SO_2 and NO_2, the variation in SO_2 and NO_2 can be safely attached with vehicular emissions and the crop residue burnings performed during rice harvesting seasons. An increased level of SO_2 concentration in the months of December 2007 and January 2008 may be because residence time of gaseous molecules in the ambient air is much longer (being lighter in weight) than that of particulate matter.

A similar trend in the variation of NO_2 levels at PUS, SVS and MAS can be seen from Table 3. Concentration levels increase almost linearly from September 2007 till November and drop down in December 2007. During the last week of September to the last week of October, harvesting of the rice crop is done by mechanical means that take place round the clock in vehicles dependent on fossil fuel, i.e. diesel. As a result of these activities much gaseous emissions from the crop harvesters enter into the ambient air and may also be responsible for the increase in the levels of SO_2 and NO_2 as observed in our study.

A comparison between the corresponding monitoring months of 2006, 2007 and 2008 has revealed significantly high SPM and NO_2 levels in October and November months as compared to the other sampling months. Although, SO_2 levels did not show considerable increase during October–November, the concentration was higher when compared with the concentrations obtained during August and September.

3.3 *Meteorological conditions and the variations in the levels of SPM, SO_2 and NO_2*

Daily Patiala weather data were obtained from a global weather-monitoring site [45]. Monthly averaged meteorological conditions during the sampling period are given in Table 4. Meteorological factors had significant effect on the concentration levels of SPM, SO_2 and NO_2 during different sampling phases in agreement with the earlier studies in other parts of the world [46]. Temperature and relative humidity ranged between $15 \pm 2^{\circ}C$ and $29 \pm 2^{\circ}C$ and $63 \pm 4\%$ and $83 \pm 4\%$, respectively, during the study period. The wind speed was low in December 2006, whereas the lowest surface pressure was obtained in the

Table 3. Concentration ($\mu g\,m^{-3} \pm SD$) of SO_2 and NO_2 from August 2007 to January 2008 at different monitoring sites in Patiala, India.

		TUS		PUS		SVS		SAS		MAS	
Phase	Months	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2	SO_2	NO_2
Non-burning months	Aug 07	5 ± 1 ($n=4$)	–	3 ± 0 ($n=4$)	10 ± 2 ($n=4$)	3 ± 2 ($n=4$)	14 ± 2 ($n=4$)	6 ± 1 ($n=4$)	–	3 ± 1 ($n=4$)	11 ± 5 ($n=4$)
	Sep 07	5 ± 4 ($n=4$)	22 ± 10 ($n=4$)	5 ± 4 ($n=4$)	9 ± 5 ($n=4$)	6 ± 3 ($n=4$)	10 ± 3 ($n=4$)	10 ± 3 ($n=4$)	15 ± 3 ($n=6$)	9 ± 1 ($n=4$)	3 ± 2 ($n=4$)
Burning months	Oct 07	9 ± 9 ($n=6$)	24 ± 14 ($n=6$)	13 ± 16 ($n=6$)	12 ± 4 ($n=6$)	12 ± 10 ($n=6$)	22 ± 11 ($n=6$)	33 ± 24 ($n=6$)	67 ± 39 ($n=6$)	14 ± 4 ($n=6$)	22 ± 12 ($n=6$)
	Nov 07	14 ± 10 ($n=6$)	19 ± 6 ($n=6$)	8 ± 7 ($n=6$)	19 ± 6 ($n=6$)	10 ± 3 ($n=6$)	27 ± 8 ($n=6$)	55 ± 34 ($n=6$)	91 ± 39 ($n=6$)	17 ± 5 ($n=6$)	44 ± 23 ($n=6$)
Non-burning months	Dec 07	7 ± 2 ($n=4$)	11 ± 4 ($n=4$)	18 ± 5 ($n=4$)	14 ± 2 ($n=4$)	8 ± 4 ($n=4$)	14 ± 9 ($n=4$)	24 ± 16 ($n=4$)	62 ± 15 ($n=4$)	26 ± 4 ($n=4$)	24 ± 3 ($n=4$)
	Jan 08	18 ± 1 ($n=4$)	21 ± 15 ($n=4$)	22 ± 9 ($n=4$)	16 ± 5 ($n=4$)	11 ± 0 ($n=4$)	13 ± 1 ($n=4$)	25 ± 22 ($n=4$)	23 ± 7 ($n=4$)	22 ± 1 ($n=4$)	22 ± 0 ($n=4$)

Notes: '*n*' represents the number of samples averaged out.
– data not available.

Table 4. Monthly averaged data of meteorological parameters during the study period in 2006–2008.

Year	Month	Temp (°C)	Humidity (%)	Wind speed ($Km\,h^{-1}$)	Wind direction	Pressure (hPa)	Physical conditions	Special event
2006	Sep	28	74	3	NW	1005	Clear	Rain ($n=2$), Fog ($n=1$), Thunder storm ($n=2$)
	Oct	25	63	1	NW, SE	1012	Haze, Mist, Cloudy	Rain ($n=1$), Fog ($n=2$), Thunder storm ($n=2$)
	Nov	20	65	2	NW, Calm	1015	Haze, Mist	Rain ($n=2$), Fog ($n=6$)
	Dec	15	70	3	NW	1017	Haze, Mist	Rain ($n=2$), Fog ($n=14$)
2007	Jan	13	69	3	NW, Calm	1019	Haze, Mist	Rain ($n=1$), Fog ($n=9$), Thunder storm ($n=1$)
	Aug	30	83	2	SE, Calm	1000	Haze, Clouds	Rain ($n=8$), Thunder storm ($n=2$)
	Sep	29	83	2	NW, Calm	1003	Haze, Mist	Rain ($n=4$), Thunder storm ($n=2$)
	Oct	24	64	1	NW, Calm	1010	Haze, Mist	Rain ($n=1$), Thunder storm ($n=1$)
	Nov	20	70	1	NW, Calm	1015	Haze, Mist	Rain ($n=1$), Thunder storm ($n=1$)
	Dec	15	70	3	NW	1017	Haze, Mist	Rain ($n=2$), Fog ($n=8$)
2008	Jan	12	70	3	NW, Calm	1017	Haze, Mist	Rain ($n=2$), Fog ($n=1$), Thunder storm ($n=1$)

Note: '*n*' represents the number of times the event occurred.

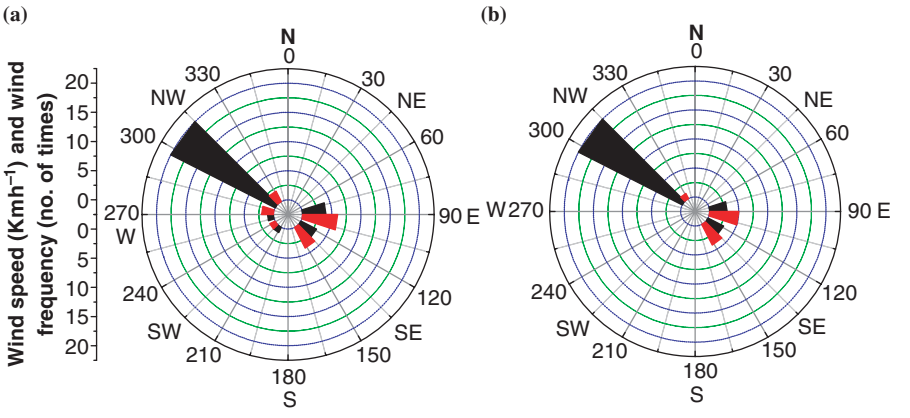

Figure 5. Wind rose plots showing wind direction and frequency in Patiala during September (A) and October (B) 2006. The length of each black 'spoke' around the circle represents the frequency of wind and the grey spokes represent wind speed.

month of September (1005 ± 2 hPa, 2006 and 1003 ± 3 hPa, 2007). Fine suspended particles in the accumulation mode have the tendency to coagulate and condense to form particles of larger sizes during more humid conditions and may settle down easily. In September 2006 higher SPM concentration was obtained as compared to September 2007 due to less rainfall ($n = 2$) in September 2006 as compared to September 2007 ($n = 4$) in the sampling months (Table 4).

Atmospheric pressure ranged from a minimum of 1003 hPa to a maximum of 1017 hPa during the study period of September 2006 to January 2008. A regular increase in the pressure was observed from September to December [47]. Most of the time, the wind direction remained North-West (NW) during the study period. Some times South-East (SE) and East (E) winds were also observed but the frequency was less. Wind roses plotted against the available data of wind frequencies and wind directions in October and November 2007 for the studied region have shown that the wind never blows from North (N) and North-East (NE) directions. Wind rose plots (Figure 5) were divided into eight sectors (N, NE, E, etc.) and it was determined that 90% of the time in September and October the wind was blowing from the North-West (NW) in Patiala with speeds between 1 and 3 km/h.

Except TUS, a clear association between temperature and SPM concentration was observed. In general, an increase in SPM concentration level was observed with decrease in atmospheric temperature. Ambient air temperature decreases from September till January and the SPM level is likely to rise with each degree decrease in temperature. Hence, relatively higher levels of SPM are observed in burning months. In other words, the observed increase in the levels of SPM is a result of a combination of lowering in temperature and contribution from crop residue burning. However, contribution from crop residue burning in the months of October and November more than compensate for the high value of the SPM due to low temperature. Effect of wind direction was seen prominently at the Sanauri Adda Site (SAS). Being located SE of the city, SAS has collected all the pollution emanating from the crop residue burning activities as well contribution from domestic, vehicular and commercial activities in the NW direction carried by the winds blowing towards the South-East (SE) (Figure 5). An opposite

relationship was observed between precipitation and the concentration of air pollutants. Low levels of the monitored air pollutants were observed during the months with higher rainy days supporting the theory that precipitation removes air pollutants from the air.

4. Conclusions

Results obtained have shown significant increase in SPM, SO_2 and NO_2 concentrations during rice crop residue burning periods (October and November) in 2006 and 2007 over Patiala, India. Although levels of SO_2 and NO_2 fluctuated at different monitoring sites, high concentrations were obtained in the months of October and November 2007. SPM levels during this sampling period were the lowest at TUS and highest at SAS due to its location in the SE side of the study area and a point most favoured by the wind direction (NW towards SE). It has also been observed that the background concentrations of pollutants were very high at sites SAS and PUS, where vehicular activities were higher. Nevertheless the background concentration of air pollutants during non-burning months was lower at SVS, where vehicular activities were less and industrial activities were absent, but during October and November this site has shown a high pollution level in both the years unlike other sampling sites, indicating the foremost impact of agricultural residue burning activities in its near vicinity.

Wind direction, precipitation and atmospheric temperature have also played significant impact on the levels of selected air pollutants. The higher levels obtained during December and January are also due to lower temperature in December (15°C) and January (12°C) as compared to August (30°C) and September (29°C) in 2007 incorporated with the long time effect of crop residue burnings performed during October–November. The increase in monthly average SPM levels from September to October and November and a fall thereafter may be due to the increase of crop residue burnings from October to November.

Results have supported that gaseous molecules stay in the ambient air for a longer duration than that of SPM. For the month of December the SPM levels fall back to the baseline value whereas the gaseous levels tend to sustain at higher concentration in December as well.

The background SPM concentration obtained at all the sites except SVS (rural site) was already well above to the National Ambient Air Quality Standards (NAAQS) set by the CPCB, New Delhi ($100\,\mu g\,m^{-3}$ for sensitive areas; $200\,\mu g\,m^{-3}$ for residential and commercial areas) but in the months of October and November it was increased due to the rice crop residue burnings performed by the farmers during these months. Thus, it can be concluded from the study carried out during September 2006 to January 2008 covering two rice burning episodes, that the crop residue burnings caused great deterioration in the quality of air of the study area during that period by an increase in the levels of SPM, NO_2 and SO_2 in the ambient air. Results obtained could be useful to air quality scientists, managers, planners and modellers in assessing the effectiveness of SPM, SO_2 and NO_2 pollution control strategies being implemented or being planned for the future.

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