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Fine particulate pollution and ambient air quality: A case study over an urban site in Delhi, India

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The current study discourses the impact of variation in $PM_{2.5}$ concentration on the ambient air quality of Delhi. The 24-hourly $PM_{2.5}$ concentration dataset was obtained from air quality measurement site (Anand Vihar) of Delhi Pollution Control Committee (DPCC) for the duration of April 2015 to December 2018. The annual and seasonal variability in the trend of ambient $PM_{2.5}$ along with cumulative impact of meteorological parameters have been analyzed. The overall percentage increase in annual $PM_{2.5}$ concentration, compared to National Ambient Air Quality Standards (NAAQS) guidelines, is observed to be 286.09%. The maximum concentration of fine particulate matter was recorded to be 788.6 $\mu g/m^3$ during post-monsoon season and it was found to be associated with lower ambient temperature of 21.34°C and wind speed of 0.33 m/sec. Further, $PM_{2.5}$ concentration was found to be correlated with CO ($R = 0.6515$) and NH_3 ($R = 0.6396$) indicating similar sources of emission. Further, backward trajectory analysis revealed contribution in $PM_{2.5}$ concentration from the states of Punjab and Haryana. The results indicated that particulate pollution is likely to occur in urban atmospheric environments with low temperatures and low wind speeds.

Keywords. Particulate matter; vehicular emission; exceedance factor; carbon monoxide; backward trajectory.

1. Introduction

Air pollution is an intricate blend of injurious gases and particulate matter, both exhibiting spatial as well as temporal variations in their source and composition (Monks *et al.* 2009; Seinfeld and Pandis 2016). It is a principal global health threat and Indian megacities (Delhi, Mumbai and Kolkata) are estimated to have some of the worst levels of air pollution globally (Kumar *et al.* 2013; Gurjar *et al.* 2016). As per World Health Organization, 13 cities of India are listed in the world's top 20 cities with the highest annual levels of $PM_{2.5}$ (particulate matter with aerodynamic diameter below 2.5 µm), with New Delhi holding the leading position (Gordon *et al.* 2018). Further, the Delhi Pollution Control Committee measured elevated levels of pollutants (Nitrogen dioxide (NO_2) as high as 540 $\mu g\ m^{-3}$, PM_{10} as high as 989 $\mu g\ m^{-3}$, and $PM_{2.5}$ as high as 585 $\mu g\ m^{-3}$) all over Delhi during the smog episode of November 2012 (Sati and Mohan 2014). In urban areas, maximum pollutant emissions can be attributed to vehicles and industry. Apart from these, another major contribution comes from construction activities. In winter and post-monsoon seasons, extensive biomass burning in agricultural fields – a low priced substitution of mechanical tilling – is a dominant contributor to ambient smoke, smog and particle pollution (Badarinath *et al.* 2009). This increased particulate loading predominantly throughout winter season causes haze, dense fog and smog formation, which further results in bad weather conditions, reduced visibility, and threat for human health (Prakash *et al.* 2013; Verma *et al.* 2013; Sharma *et al.* 2014; Zheng *et al.* 2014). In the year 2017, 1.24 (1.09–1.39) million deaths were caused by air pollution in India including 0.67 million deaths from exposure to hazardous levels of ambient particle concentration (Balakrishnan *et al.* 2019).

Particle pollution (a subset of air pollution) is a combination of solid particles that can be either fine or coarse particles and liquid droplets. According to the particle size, there are mainly two categories of ambient particulate matter: PM_{10} and $PM_{2.5}$. These particulate matter are minute in size and therefore, are measured in micrometres (µm). $PM_{2.5}$ particles generally designated as fine particulate matter having aerodynamic diameter below 2.5 micrometres (0.0025 mm) and the mass concentration of these particles is a major threat to worldwide air quality. $PM_{2.5}$ can be both primary pollutants as well as secondary pollutants. In developing countries, rapid urbanization has led to heightened emissions of particulate matter attributable to growing energy demand, change in land use, and other anthropogenic activities (Mayer 1999; Fenger 1999; Laakso *et al.* 2006; Dang and Unger 2015; Kumar *et al.* 2015). The dominant sources contributing to overall particulate emissions in India are residential energy usage, industrial emissions, transportation and biomass burning (Guttikunda *et al.* 2014; Sharma *et al.* 2018). Other emission sources include coal-based power plants (Goyal 2002; Prasad *et al.* 2006) and biofuel burning (Venkataraman *et al.* 2005). These particles exhibit both spatial and temporal variability (Mayer 1999; Mallik *et al.* 2014). These variations in $PM_{2.5}$ concentration are mainly driven by atmospheric chemical reactions, atmospheric dynamics, photochemistry and meteorological parameters prevailing over the region (Mallik *et al.* 2014; Zoran *et al.* 2019). Various processes such as condensation, nucleation and coagulation of atmospheric gaseous constituents also affect the quantity and composition of the particulate matter in the atmosphere.

Higher levels of atmospheric particulate matter exert a broad spectrum of negative impacts on human health (Pope and Dockery 2006) and on the atmosphere, including their direct and indirect effects on weather and climatic system (Satheesh and Ramanathan 2000; Stocker *et al.* 2013; Field *et al.* 2014; Wang *et al.* 2014). Based on their residence time, hygroscopicity, and the ability to act as condensation nuclei, these particles are directly associated with smog episodes (Lin *et al.* 2018). Particulate matter plays significant role in altering radiative budget, cloud formation and precipitation (Ramanathan *et al.* 2007). Due to its smaller size, $PM_{2.5}$ particles can be inhaled easily and are capable of penetrating deep into the respiratory tract up to the alveolar level, thus creating an array of health issues (WHO 2006). Therefore, impact analysis and control of particulate matter is essential at global as well as regional levels.

Delhi is currently facing serious air pollution problems along with extremely high concentrations of suspended particulate matter in the atmosphere. The particulate air pollution shows an ever-increasing trend over Delhi due to increase in vehicular emissions, industrial activities, emissions, coal-fired thermal power plants and construction activities. Delhi is one of the world's most polluted cities with $PM_{2.5}$ annual average of 143.0 ± 17.8 micrograms per cubic metre (Cheng *et al.* 2016). As of 2011, the population of Delhi reached almost 16.3 million; thus making it the one of the most populated urban agglomeration in India (ENVIS CPCB 2016). Further, the highest annual population-weighted mean $PM_{2.5}$ in India, i.e., 209.0 $\mu g/m^3$ was in Delhi in 2017 (Balakrishnan *et al.* 2019). Therefore, Delhi requires a close study of air pollution, which will serve the importance of controlling the poisonous atmosphere.

During the last 10 years, numerous strategies are implemented over Delhi to de-escalate the increasing levels of air pollution. To control the increased emissions of greenhouse gases 'clean air act' along with strict air quality regulations and continuous air quality monitoring is (Zheng *et al.* 2017) sustained. However, even with the implementation of various pollution control strategies and vehicles running on diesel (e.g., odd–even rule) during the past decade, the particulate pollution has not shown any significant reduction and thus need continuous monitoring and analysis for effective control and policy planning. Therefore, more concerted efforts, continuous monitoring and analysis of air quality is of utmost importance over Delhi, which can aid in further reduction in pollution level. To mitigate the problem of particulate pollution, we need to have detailed understanding of major determinants of the pollutant in the atmosphere.

For aforementioned reasons, the aim of the present study is to understand and determine the role of meteorological parameters on ambient mean concentration of major pollutant, i.e., particulate matter concentration ($PM_{2.5}$) over an urban site in Delhi region. The study also examines the annual and seasonal trend in concentration of particulate matter and its correlation with trace gases, i.e., oxides of nitrogen (NO_X), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3) and ammonia (NH_3) for a recent duration (2015–2018) to understand the pollutant dynamics pertaining to an urban site over Delhi, India. Further, backward air mass trajectory analysis helped to identify probable regional and local sources of pollutant.

2. Site description

Delhi (28.7041°N, 77.1025°E, 216 m altitude above mean sea level) is the national capital of India with a population density of 11,312 persons/km^2 according to 2011 Census of India. It covers an area of 1484 km^2, which encircled vastly by industrialized National Capital Region. The National Capital Region (NCR) covers rapidly developing commercial and industrial satellite townships such as Faridabad, Ghaziabad, Gurgaon, and Noida (Guttikunda and Gurjar 2012). The number of vehicles in the national capital surged to 10.9 million by March 2018, including over 7 million two wheelers showing growth percent of 5.81 to the previous year, according to Delhi's Economic Survey 2018–2019 report (New Delhi (India), Planning Department, Government of National Capital Territory of Delhi 2019). Delhi is situated in the sub-tropical belt of northern temperate geographical area with immensely scorching summers, average precipitation, and chilling winters. Out of 38 air-monitoring stations in Delhi, Anand Vihar was selected for the present study (figure 1). The location is surrounded by heavy major roadside traffic due to presence of Inter-State Bus Terminus (ISBT) in close proximity. Further, this area is encircled by Sahibabad and Patparganj industrial areas.

3. Material and methodology

3.1 *Instruments for measurement*

The air quality datasets utilized in the current study includes ambient mean concentration of six criteria pollutants, which includes $PM_{2.5}$ and trace gases (NO_X, SO_2, CO, O_3 and NH_3) at the selected monitoring station. The instruments available at the monitoring site for the measurement of $PM_{2.5}$ and trace gases have been discussed in detail by Hama *et al.* (2020). At the sampling site, the $PM_{2.5}$ is measured by the BAM 1020 that works on the principle of Beta ray attenuation and automatically measures and records airborne particulate matter concentration levels (in milligrams or micrograms per cubic meter). Non-Dispersive Infrared (NDIR) spectroscopy is used to measure ambient levels of carbon monoxide (CO), while UV photometric 49i (Thermo Fischer Scientific Inc., USA) is used for ambient levels of O_3. The principle of work behind both the instruments is absorption of radiation by the gas component for pollutant concentration measurement (infra-red beam for CO and ultra-violet light for O_3). For SO_2 measurement, a well-proven technique of ultraviolet fluorescence is employed. Lastly, for measuring ambient levels of oxides of nitrogen (NO_X) and ammonia (NH_3) chemiluminescence method is applied. NO_X analyser (Thermo 42i NO-NO_2-NO_X monitor, Thermo Fischer Scientific Inc., USA) is used to measure the pollutant concentration by measuring the light intensity of the chemiluminescent gas phase reaction of NO and O_3.

3.2 *$PM_{2.5}$ and trace gases dataset*

The 24-hourly ambient air quality dataset of $PM_{2.5}$ and trace gases (NO_X, SO_2, CO, O_3 and NH_3) has been acquired for the selected monitoring station of Anand Vihar run by the Delhi Pollution Control Committee (DPCC). Daily concentrations $PM_{2.5}$ and trace gases were downloaded from the CPCB (Central Pollution Control Board) database (source: http://www.cpcb.gov.in/CAAQM/frmUser

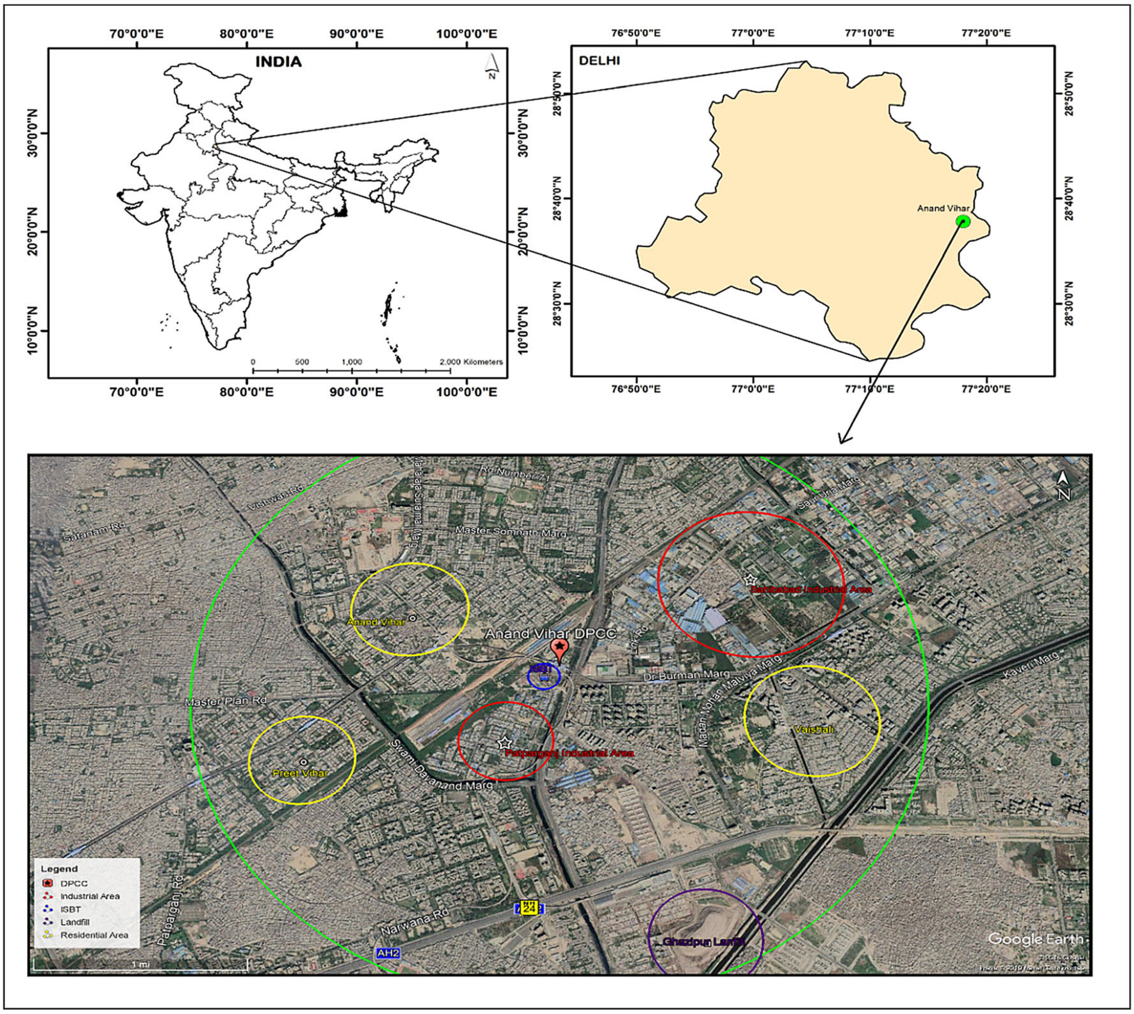

Figure 1. Study area map representing the monitoring station location. The circles in the map indicate the span of different areas. The green circle encircles the area falling within 5 km radius from the monitoring station. Red circles indicate industrial area, yellow circles indicate the residential area, purple circle is indicating the landfill site and blue circle is for ISBT (Bus Stand).

AvgReportCriteria.aspx) and covers the duration of April, 2015–December, 2018. Monthly average concentration data is first developed from diurnal information. Further, monthly datasets have been averaged to obtain seasonal and annual concentration data. Percentage upsurge in yearly averaged concentrations of $PM_{2.5}$ with respect to National Ambient Air Quality Standards (NAAQS) was calculated by employing the following equation (Khanum *et al.* 2017):

$$\text{Annual increase in PM}_{2.5}\text{ concentration (\%)} = \{[C_O - C_S]/C_S\} \times 100, \quad (1)$$

where C_O is the observed annual mean pollutant concentration and C_S is the standard annual mean pollutant concentration.

Interrelationship between particulate matter concentration and trace gases have been analyzed. Various statistical methods were implemented for trend analysis along with computation of exceedance factor. Exceedance factor (EF) is defined as the ratio of the annual mean concentration of a pollutant with that of the respective standard value (Ganguly and Thapa 2016) (table 1). It was calculated by using the formula:

$$\text{Annual EF} = C_O/C_S. \quad (2)$$

Backward trajectories for the identification of regional sources contributing to fine particle pollution over the study area were calculated and analyzed for high pollution days ($PM_{2.5}$ concentration exceeding 500 $\mu g/m^3$) in post-monsoon and winter seasons. The hourly 5-day backward air mass trajectories were calculated by using Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model developed by National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) (Stein

Table 1. *National ambient air quality monitoring (NAMP) network categorization of air quality based on the exceedance factor.*

Exceedance factor	Pollution level	Remarks
>1.5	Critical	Violation of the prescribed pollutant standards with varying magnitude
1.0–1.5	High	
0.5–1.0	Moderate	The present prescribed standards of the pollutant are being met but violation of the limits may occur in future
<0.5	Low	The pollutant concentrations are maintained below the prescribed standards

**Source*: New Delhi, India, Central Pollution Control Board (CPCB) 2008.

Table 2. *Mean annual concentration and exceedance factor of* $PM_{2.5}$ *at Anand Vihar.*

Year	$PM_{2.5}$ concentration	Exceedance factor	Pollution level	$PM_{2.5}/PM_{10}$ ratio
2015	157.10 ± 93.49	3.93	Critical	0.3169
2016	163.56 ± 104.36	4.09	Critical	0.3799
2017	147.59 ± 93.74	3.69	Critical	0.3732
2018	149.50 ± 81.45	3.74	Critical	0.4368

et al. 2015; Rolph *et al.* 2017). These backward trajectories started at 100 m above the ground level with a time resolution of 1 hr.

3.3 *Meteorological data*

To study the impact of local meteorological conditions on particulate matter concentration over the monitoring station, daily meteorological data for ambient temperature, wind speed and direction and relative humidity were collected from CPCB database (source: http://www.cpcb.gov.in/CAAQM/frmUserAvgReportCriteria.aspx) for the duration (April, 2015–December, 2018). We have investigated the $PM_{2.5}$ and meteorological dataset according to four seasons designated by India Meteorological Department (IMD) – winter (December–February), summer (March–May), monsoon (June–September) and post-monsoon (October–November). The effect of relative humidity, temperature and wind speed are discussed in section 4.2.

4. Results and discussion

For the determination of characteristic trend in particulate matter concentration monitored dataset obtained from the Central Pollution Control Board (CPCB) database are used. Annual, seasonal and monthly variations in $PM_{2.5}$ along with cumulative effects of meteorological parameters on pollutant concentration are discussed and analyzed. Correlation between trace gases and $PM_{2.5}$ has also been presented. Lastly, backward air mass trajectory analysis has been performed for the identification of probable sources.

4.1 *Annual variation in concentration of particulate matter*

Table 2 presents the annual variations in $PM_{2.5}$ concentration and exceedance factor at Anand Vihar for the entire study period. The annual exceedance factors determined for $PM_{2.5}$, summarized in table 2 revealed that the particulate pollution level over the monitoring station is critical, exceeding 1.5 value throughout the entire study period. Further, the overall percentage increase in yearly averaged concentrations of $PM_{2.5}$ with respect to NAAQS guidelines were observed to be 286.09% for Anand Vihar. The percentage increase in annual mean concentration of $PM_{2.5}$ determined at Anand Vihar as per NAAQS standards (40 μg/m^3) is predominantly due to the presence of large number of vehicles in the zone and 'start–stop' action of buses (Ganguly *et al.* 2019). Besides this, other anthropogenic activities such as agricultural residue burning (Kanawade *et al.* 2020) and enhanced pollutant emissions during and after Diwali festival (Mukherjee *et al.* 2018) are probable reasons for increasing percentage of $PM_{2.5}$ concentration over the monitoring site.

To ascertain the contribution of fine particles in degradation of Delhi's air quality, annual concentrations of $PM_{2.5}$ are plotted. Further, annual $PM_{2.5}$ concentrations were compared with the prescribed pollutant standards (NAAQS standards) established by Central Pollution Control Board (CPCB) (figure 2A). It is clearly indicated in figure 2(A) that particulate matter concentration at the monitoring station exceeded prescribed limits as per NAAQS standards (40 $\mu g/m^3$) for the entire study period. The highest value of annual $PM_{2.5}$ concentration was 163.56 ± 104.36 $\mu g/m^3$ in 2016.

Another significant observation made from figure 2(A), is that there was no definite trend exhibited by $PM_{2.5}$ over the study years at the monitoring station. This could be a resultant of sources contributing to particulate matter concentration over the study area such as 'start–stop' action of buses and vehicular congestion (Ganguly *et al.* 2019). No particular trend was observed at the monitoring station because the above-mentioned sources are primarily mobile sources and therefore, the emission of particulate matter from such sources remains inconsistent throughout the year.

The $PM_{2.5}/PM_{10}$ ratios can help provide vital information relating to the sources of particulate matter origin over a region (Sugimoto *et al.* 2016). The annual $PM_{2.5}/PM_{10}$ ratio ranged from 0.32 in 2015 to 0.44 in 2018 (figure 2A and table 2), which is typical of urban site (Saliba *et al.* 2010).

The monthly $PM_{2.5}/PM_{10}$ ratios are shown in figure 2(B) over the study region. The $PM_{2.5}/PM_{10}$ ratio depicts progressive increase during winter months that peaks in January (0.54) followed by a significant decrease with lowest ratios found during the monsoon season, i.e., July (0.27) and August (0.24) months over the location. The monthly $PM_{2.5}/PM_{10}$ ratio in figure 2(B) showed minimum in the summer monsoon season, as there is decrease in both $PM_{2.5}$ and PM_{10} due to monsoon rainfall. While the $PM_{2.5}/PM_{10}$ ratios exhibit maximum during winter season in the months of November, December and January (figure 2B), possibly due to increment in anthropogenic activities such as transportation, re-suspended roadside dust (Sugimoto *et al.* 2016) and smog that can enhance PM contribution in more stable atmosphere (Sati and Mohan 2014). Previous studies also show that the variation of $PM_{2.5}/PM_{10}$ ratio happens due to busy traffic hours and in consequence of re-suspended coarse road dust (Querol *et al.* 2001; Evagelopoulos *et al.* 2006). Higher levels of pollutant concentration are a resultant of heavy vehicular congestion because of Inter-State Bus Terminus (ISBT) that is in close proximity to the monitoring station and as majority of the buses use diesel as the primary source of fuel. The problem is further exacerbated by the close proximity of the monitoring site to Sahibabad and Patparganj industrial areas.

4.2 *Seasonal variations of $PM_{2.5}$ and impact of meteorological parameters*

The maximum, minimum and mean concentrations of $PM_{2.5}$ for four different seasons (winter, summer, monsoon and post-monsoon) along with meteorological parameters have been summarized in table 3. The obtained results show a strong seasonality in $PM_{2.5}$ which changes with the prevailing meteorological conditions. The concentration of $PM_{2.5}$ were observed to be the lowest (72.49 ± 12.46 $\mu g/m^3$) during the monsoon seasons and highest (247.28 ± 26.09 $\mu g/m^3$) during the post-monsoon seasons. The primary reason behind lower concentration of particulate matter during monsoon season is the process of wet deposition of particulate matter due to precipitation events (Murari *et al.* 2017). On the other hand, decrease in ambient temperature and wind speed creates stagnant meteorological conditions and prevents dispersion of pollutants (Tiwari *et al.* 2013), thereby resulting in higher values of particulate matter concentration during post-monsoon season.

In the atmosphere, the pollutant concentration gets altered due to the variation in meteorological factors. Therefore, the variation in $PM_{2.5}$ concentration along with varying ambient temperature, wind speed and relative humidity is presented in figure 3 and the cumulative effect of meteorological parameters (ambient temperature, wind speed and relative humidity) on concentration of $PM_{2.5}$ have been analyzed and discussed below.

The impact of ambient temperature and wind speed on $PM_{2.5}$ concentration is shown in figure 3(A and B), respectively. In summer and monsoon seasons, relatively higher values of mean ambient temperatures (31.43° in summer and 31.65°C in monsoon) and wind speed (1.73 m/sec

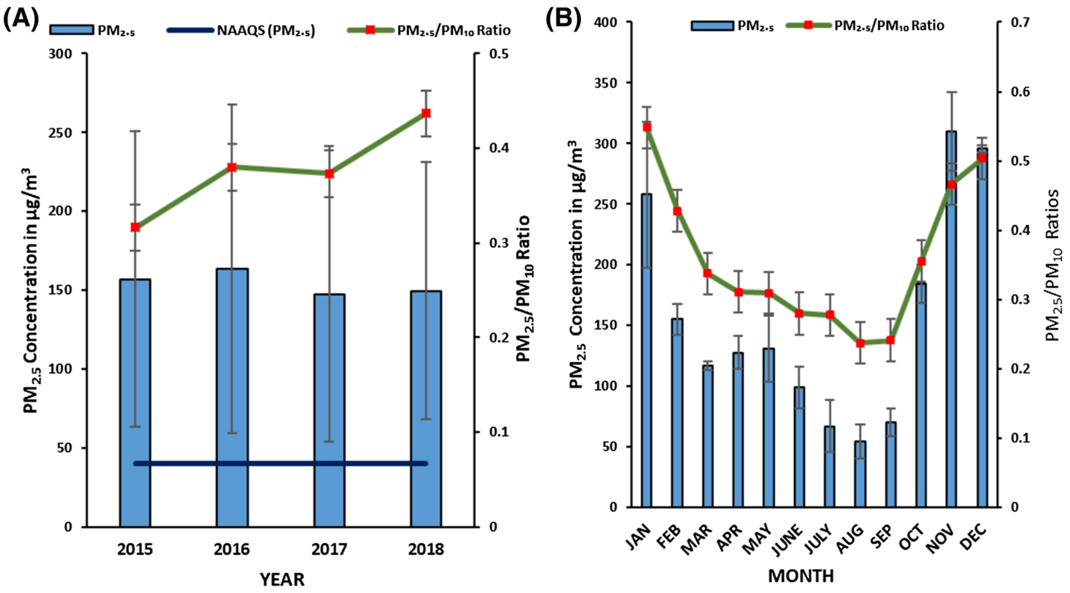

Figure 2. (**A**) Annual and (**B**) monthly variations in $PM_{2.5}$ concentration and $PM_{2.5}/PM_{10}$ ratio.

Table 3. *Maximum, minimum and mean concentration* ($\mu g/m^3$) *of* $PM_{2.5}$ *and mean values of meteorological parameters for four seasons.*

Season	Average	Maximum	Minimum	Ambient temperature (°C)	Wind speed (m/sec)	Relative humidity (%)
Summer	126.93 ± 11.11	355.76	36.64	31.43	1.73	34.48
Monsoon	72.49 ± 12.46	330.46	15.29	31.65	1.74	60.97
Post-monsoon	247.28 ± 26.09	788.60	58.48	25.46	0.74	48.24
Winter	235.93 ± 29.14	566.00	61.34	17.50	0.94	55.33

in summer and 1.74 m/sec in monsoon) were recorded, which favour good pollutant dispersion conditions consequently resulting in lower concentrations of $PM_{2.5}$. However, this situation is reversed during post-monsoon and winter months. The average ambient temperature (25.46°C in post-monsoon and 17.50°C in winter) as well as wind speed (0.74 m/sec in post-monsoon and 0.94 m/sec in winter) decreases, thereby decreasing the rate of pollutant dispersion during post-monsoon and winter season. As a result, accumulation process of fine particulate matter is accelerated leading to increased concentration of $PM_{2.5}$ over the monitoring station. The highest value of fine particulate matter was recorded to be 788.6 $\mu g/m^3$ at Anand Vihar during post-monsoon season and it was found to be associated with an ambient temperature of 21.34°C and wind speed of 0.33 m/sec.

Inverse relationship between surface-level air temperature and wind speed with $PM_{2.5}$ concentration could be consistent with importance of temperature inversion. Temperature inversion is a thin layer of the atmosphere, where the normal decrease of temperature with altitude switches to increase of temperature with altitude (Trinh *et al.* 2019). Lower temperatures and wind speed during winters and post-monsoon create inversion conditions. Raising thermals are reduced when temperature reduces, lowering PBL (Planetary Boundary Layer) during colder periods. Further, reduced wind speed weakens the convective mixing system of the atmosphere. Decreased PBL height and stagnant meteorological conditions (i.e., lower ambient temperature and lower wind speed or formation of inversion layer) combined together prevent the diffusion of pollutants (Mohan and Bhati 2009; Tiwari *et al.* 2013; Payra *et al.* 2016; Kanawade *et al.* 2020). On the other hand, increase in ambient temperature and wind speed were recorded for summer and monsoon months which lead to stronger thermally-induced convections and thereby favouring pollutant diffusion.

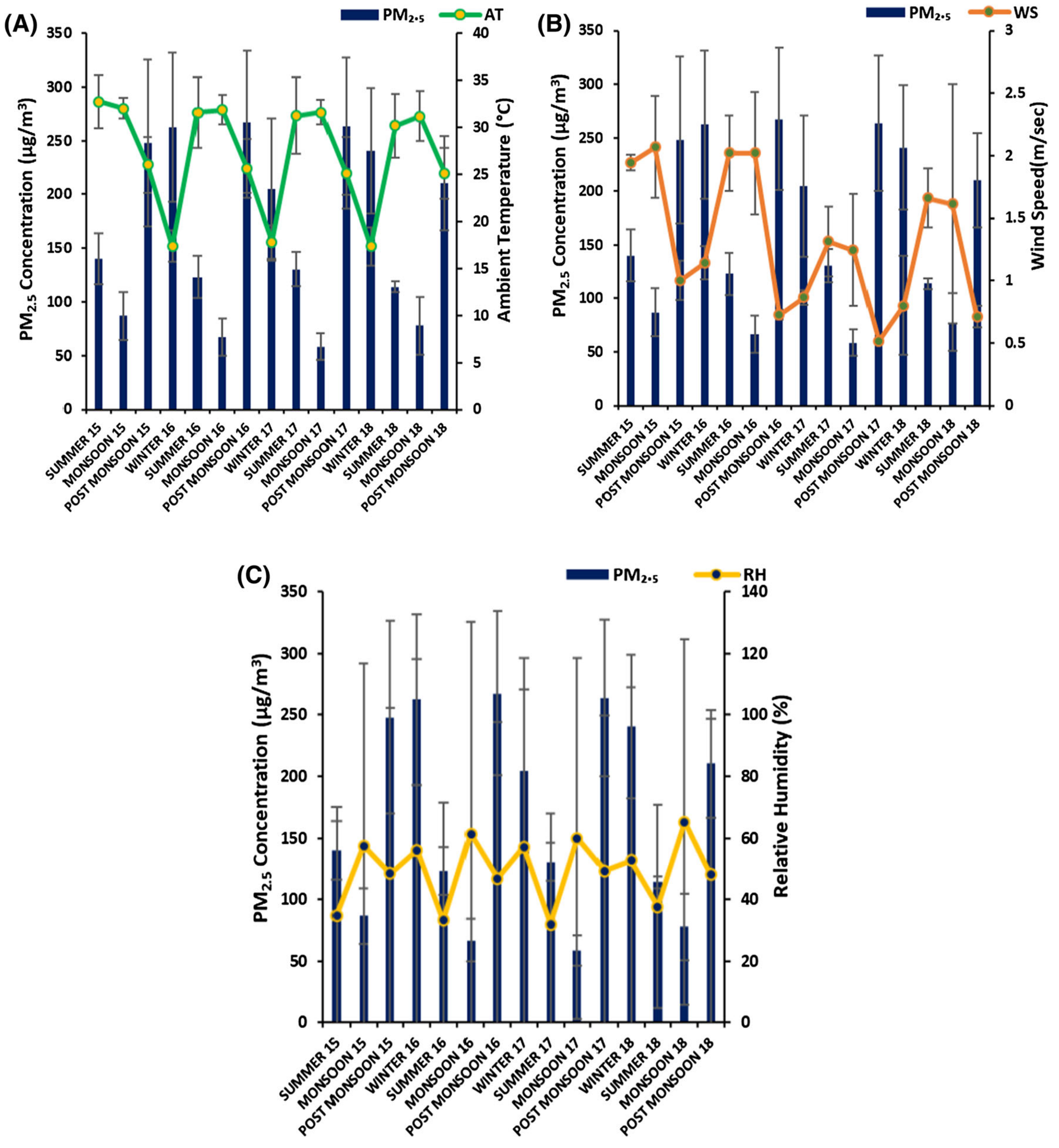

Figure 3. Interrelationship between $PM_{2.5}$ and meteorological parameters.

Humidity has a direct relationship with pollutant concentration as the presence of high amount of water vapour supports prolonged suspension of particles, mostly within the PBL (Patidar and Afghan 2019). Therefore, an increase in particulate matter concentration is expected to be associated with higher levels of relative humidity. However, such justification does not always stand valid; an exception can be observed during monsoon season when increased levels of relative humidity were associated with precipitation, which further facilitates wet deposition of particulate matter (Pillai *et al.* 2002; Murari *et al.* 2017). The effect of relative humidity on $PM_{2.5}$ is presented in figure 3(C). In summers, fall in relative humidity levels is accompanied by lower levels of fine particulate matter, while in monsoon season the $PM_{2.5}$ concentration tends to decrease with increase in humidity. The lowest concentration of $PM_{2.5}$ was 15.29 $\mu g/m^3$ at Anand Vihar during monsoon season. This decrease in particulate matter concentration in monsoon can be attributed to wet deposition process. For post-monsoon and winter, relative humidity is recorded to be in the range of 46–62%. During post-monsoon season, particulate matter concentration was recorded to be 267.45

µg/m^3 in 2016, 263.48 µg/m^3 in 2017 and 210.23 µg/m^3 in 2018, while the relative humidity was recorded to be 46.88%, 49.37% and 48.18% for 2016, 2017 and 2018, respectively. On the contrary, during extreme winter period, the particulate matter concentration was recorded to be 317.68, 242.56 and 308.71 µg/m^3 in 2016, 2017 and 2018, respectively, with relative humidity values of 54.98%, 58.71% and 55.71% for these three consecutive years, respectively. This shows that slight increase in relative humidity values is concurrent with the increase in $PM_{2.5}$ concentration values during extreme winter period.

In general, these results indicate that ambient air temperature, wind speed and relative humidity play a significant role in determining $PM_{2.5}$ concentration over a region. Particulate pollution is likely to occur in urban atmospheric environments with low temperatures and low wind speeds.

Wind direction also plays a significant part in the transport as well as the magnitude of the concentration of pollutants (Soni *et al.* 2018). So, wind rose has been plotted for all the four seasons, i.e., winter, summer, monsoon and post-monsoon throughout the study period. Figure 4 depicts the seasonal variation of average wind speed along at ground-level with the wind directions at Anand Vihar (an AQMS site of Delhi). In winter season, the wind mainly comes from the west and south-west directions and the most common wind speed falls in the range of 0.5–1 m/sec. It indicates that particulate matter concentration during winter season is coming from the nearby regions of Punjab and Haryana present on the western side of Delhi. The prevalent wind direction in summer season was south-west, while monsoon season is characterized by lowest concentration particulate matter and winds predominantly coming in from southeast direction. In monsoon season, we can see that the wind speeds between 1.5 and 3.7 m/sec are most common. Lastly, the post-monsoon season exhibits large variability in the prevailing wind directions and the wind speeds between 0 and 0.5 m/sec are most common. It can also be observed that the

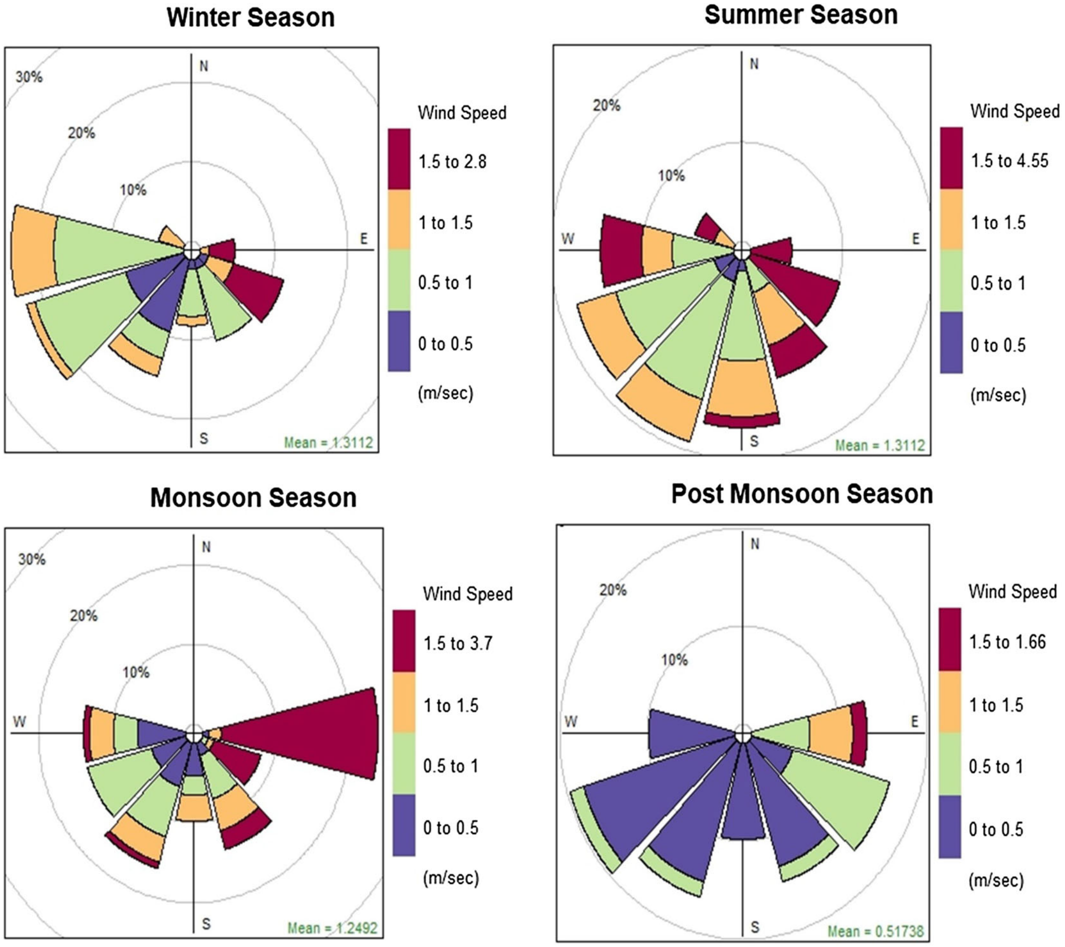

Figure 4. Annual wind rose plot for the monitoring station (Anand Vihar).

prevailing wind speeds in winter and post-monsoon are lower, thus favouring stagnant atmospheric conditions and higher levels of particulate matter.

4.3 *Relationship between trace gases and particulate matter ($PM_{2.5}$)*

The bivariate correlation analysis was performed using daily measured data from April 2015 to December 2018. The correlation plot between $PM_{2.5}$ and trace gases have been presented in figure 5. The concentration of $PM_{2.5}$ shows significant correlation with CO ($R = 0.6515$; $R^2 = 0.4244$) – the traffic related pollutant and NH_3 ($R = 0.6396$; $R^2 = 0.4088$) which is primarily associated with biomass burning (Khan *et al.* 2020). This indicates that the above-mentioned trace gases (CO and NH_3) and $PM_{2.5}$ were probably originated from similar anthropogenic sources, i.e., vehicular emissions and biomass burning. On the contrary, $PM_{2.5}$ concentration shows weak correlation with NO_X ($R^2 = 0.2730$), SO_2 ($R^2 = 0.0936$) and O_3 ($R^2 = 0.0192$) probably due to different sources of origination of $PM_{2.5}$ with that of trace gases (NO_X, SO_2 and O_3) in the atmosphere over the study site. Furthermore, Kannan and Kapoor (2004) described that the conversion of SO_2 to sulfate occurs via multiple pathways, including gas phase oxidation to sulfuric acid followed by condensation into the particulate phase. Aqueous phase oxidation also happens in the

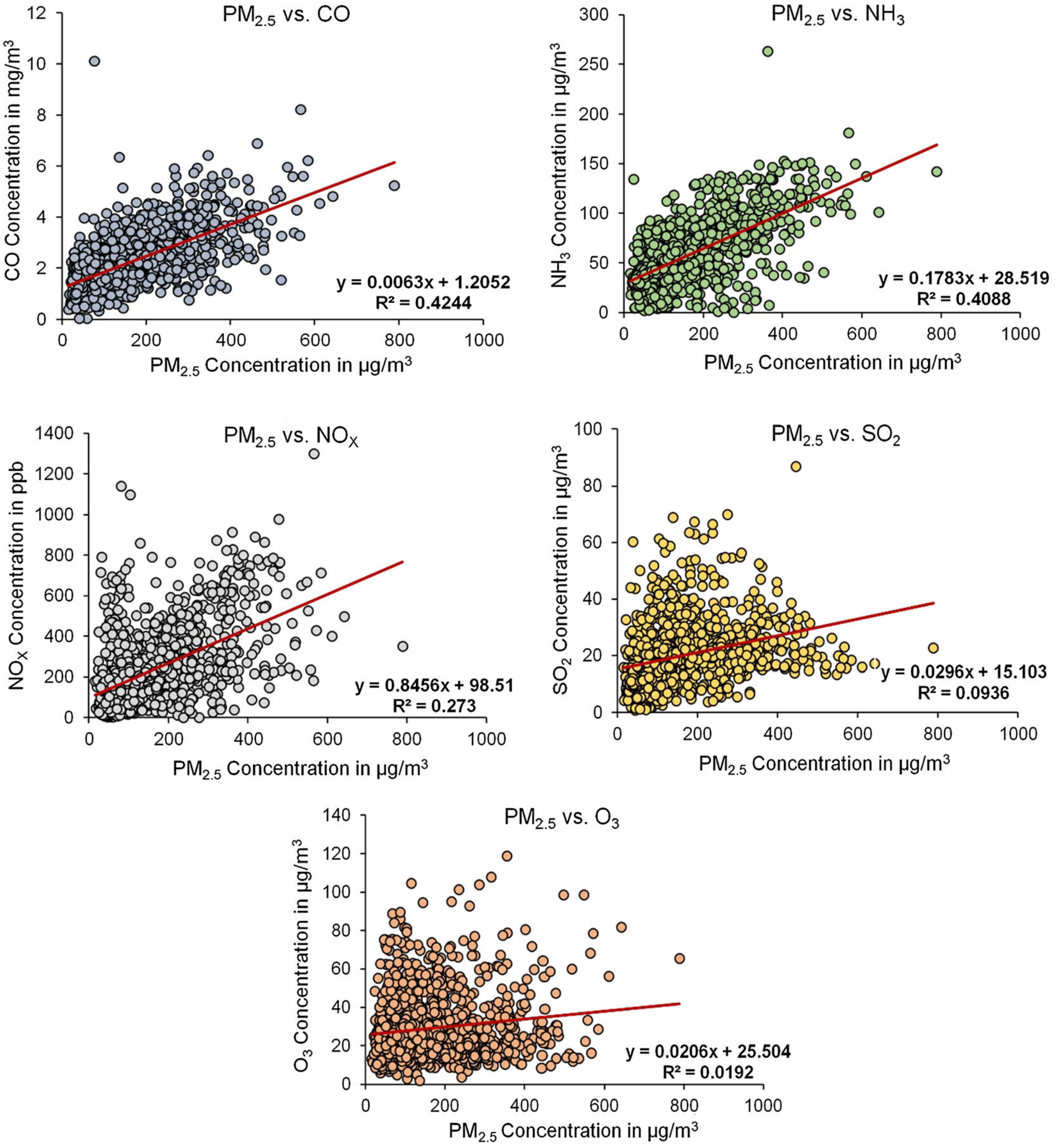

Figure 5. Correlation between $PM_{2.5}$ and trace gases for the monitoring station.

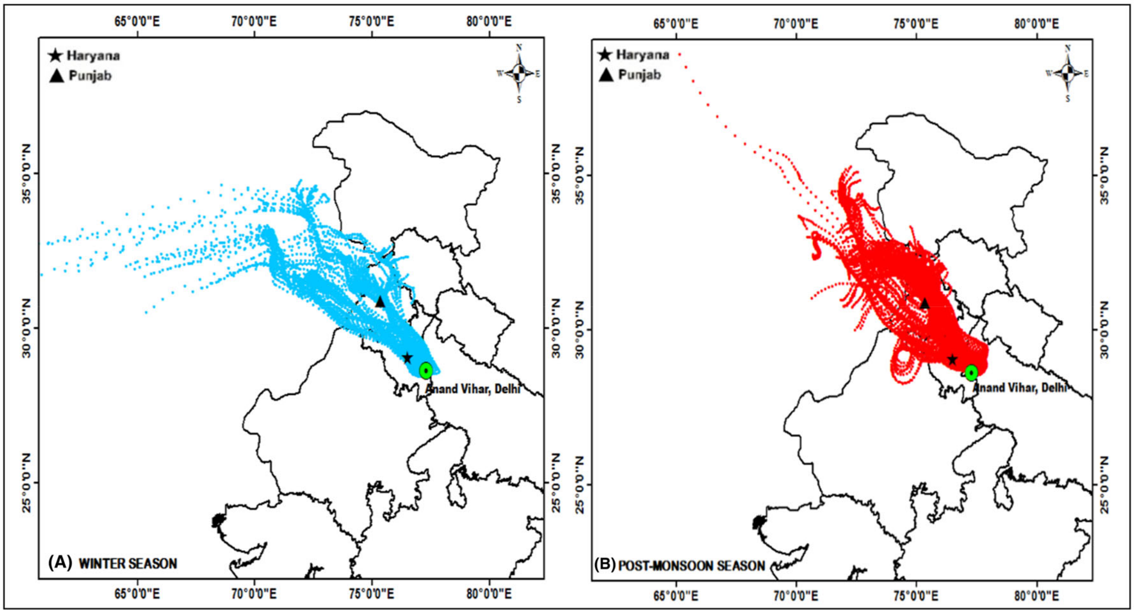

Figure 6. Backward air mass trajectory for two seasons (**A**: winter season; **B**: post-monsoon season) over the monitoring station.

presence of high relative humidity and it is quicker than previous one (Mohan and Payra 2009). Similarly, nitrogen dioxide also forms nitrite and nitrate ions. NO_2 can also react with a number of species in aqueous solution (Littlejohn *et al.* 1993). Literature supports the fact that the sulfate formed due to various reactions falls in the range of particles having size 0.1–10 μm (Seinfeld and Pandis 1998) as well as nitrate (Mohan and Payra 2009), which can contribute to an increase in the amount of fine particulate matter. Contrary to sulfur and nitrogen dioxide trends, CO being non-reactive does not show similar trends. Due to the atmospheric conversion of SO_2 and NO_2 to fine particulate matter, the ambient concentration of these trace gases decreases, which ultimately leads to weak correlation between trace gases (NO_X and SO_2) and $PM_{2.5}$ concentration. These results indicate that vehicular emissions and biomass burning are the predominant sources contributing to particulate matter concentration over the monitoring station.

In our analysis, we have checked the seasonal dependence in the relationship between trace gases and $PM_{2.5}$. The value of CO and $PM_{2.5}$ does not show any changes in two distinct seasons, as CO is a non-reactive pollutant, whereas SO_2 converts to sulphate in a stable atmosphere and higher relativity, which is very common over Delhi during winter. Therefore, decreasing SO_2 and increasing $PM_{2.5}$ is possible and the correlation of summer and winter agrees well with the trend.

4.4 *Backward air mass trajectory analysis*

For the identification, probable regional sources contributing to fine particle concentration over Anand Vihar 5-day backward air mass trajectory analysis have been presented for winter season (figure 6A) and post-monsoon season (figure 6B). We have selected the post-monsoon and winter season for backward trajectory analysis because $PM_{2.5}$ pollution was observed to be more severe in these two seasons with higher $PM_{2.5}$ concentration (as discussed in section 4.2). These back trajectories also help to understand the contribution of air pollution due to crop fires. The backward trajectories for single air parcel coming towards the receptor location (Anand Vihar, Delhi) are computed for episodic days ($PM_{2.5}$ concentration exceeding 500 $\mu g/m^3$) during both seasons. During winter season, as shown in figure 6(A), there is a sparse dispersion in the backward trajectories with majority of trajectories coming from the regional states of Punjab and Haryana, while a fewer trajectories extending as far as Pakistan. Similar observations can be made from figure 6(B) for the post-monsoon season. Therefore, it can be concluded from figure 6(A and B) that majority of the fine particulate matter advecting towards the monitoring station comes from the states of Haryana and Punjab and this could be a potential contributor to pollutant concentration over the region. The emissions can be apportioned to the large-scale agricultural biomass burning occurring in these two states (Haryana and Punjab). Previous studies have also emphasized that the air quality of Indo-Gangetic Plains (IGP), primarily central IGP to south-eastern IGP region have been profoundly impacted by the agricultural residue burning in Haryana and Punjab during post-monsoon season (Sharma *et al.* 2010; Mishra and Shibata 2012; Vijayakumar *et al.* 2016; Cusworth *et al.* 2018; Sarkar *et al.* 2018). Additionally, localized emissions during festival can also be a contributing factor to increased levels of pollutant species during post-monsoon (Mukherjee *et al.* 2018).

The overall results indicate that the potential sources for particulate matter over the monitoring location are heavy vehicular emissions throughout the year and biomass burning during post-monsoon and winter months.

5. Conclusions

A detailed analysis of $PM_{2.5}$ concentration for a recent period of 4 years (2015–2018) over Anand Vihar, Delhi has been conducted in present study. The results of our study depict consistent very high PM values due to the heavy roadside traffic of Inter-State Bus Terminus (ISBT) in close proximity over study location.

We can broadly make the following conclusions.

1. Determination of exceedance factor revealed that the particulate pollution levels over the monitoring station is critical, exceeding 1.5 value throughout the entire study period.
2. The $PM_{2.5}/PM_{10}$ ratio was observed to be minimum in the summer monsoon season, as there is decrease in both $PM_{2.5}$ and PM_{10} due to monsoon rainfall. While the $PM_{2.5}/PM_{10}$ ratios exhibit maximum during winter season in the months of November, December and January, thereby attributing aggravated levels of particle pollution to anthropogenic sources.
3. Seasonal analysis of $PM_{2.5}$ concentration indicated that particulate pollution was severe during post-monsoon and winter months. Further, the analysis of association between $PM_{2.5}$ and meteorological factors revealed that low wind speed and low ambient temperature combined together created stable atmospheric conditions, consequently enhancing the accumulation of fine particulate matter over the region during both the seasons. On the contrary, monsoon season experienced the lowest levels of particulate pollution probably attributing to the wet removal of airborne particles during precipitation.
4. Carbon monoxide ($R = 0.6515$; $R^2 = 0.4244$) and Ammonia ($R = 0.6396$; $R^2 = 0.4088$) were found to be correlated with $PM_{2.5}$ indicating that both the trace gases (CO and NH_3) and $PM_{2.5}$ probably originated from similar anthropogenic sources, i.e., vehicular emissions and biomass burning.
5. Backward air mass trajectory analysis clearly depicted that air mass direction was coming to the receptor site (Anand Vihar) from the states of Haryana and Punjab and this could be a significant contributor to particulate pollution over the region. The emissions could be apportioned to large-scale agricultural residue burning in the above-mentioned regions (Haryana and Punjab).

For air quality assessment on local to regional scale, a continuous long-term dataset is extremely essential for the formulation of control strategies. These strategies could appropriately curb emissions at local levels and consider air pollution from nearby regional sources.

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Author statement

Janhavi Singh and Priyanshu Gupta did write-up and statistical analysis of paper. Data collection was done by Deepak Gupta. Dr. Swagata Payra and Dr. Divya Prakash carried review of the manuscript. Overall, paper supervised and conceptualised by Dr. Sunita Verma. Each author had participated sufficiently in the work to take public responsibility for appropriate portions of the content. All the authors read and approved the final manuscript.

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