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DOI
10.1007/s10661-023-11635-6

Publication date
2023

Document Version
Final published version

Published in
Environmental Monitoring and Assessment

Citation (APA)
Khan, A. A., Garsa, K., Jindal, P., & Devara, P. C. S. (2023). Effects of stubble burning and firecrackers on the air quality of Delhi. *Environmental Monitoring and Assessment*, *195*(10), Article 1170. https://doi.org/10.1007/s10661-023-11635-6

Environ Monit Assess (2023) 195:1170
https://doi.org/10.1007/s10661-023-11635-6

RESEARCH

Effects of stubble burning and firecrackers on the air quality of Delhi

**Abul Amir Khan · Kalpana Garsa ·
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Received: 30 April 2023 / Accepted: 24 July 2023

Abstract Every year at the onset of winter season (October–November), crop residue/parali/stubble burning starts in Punjab and Haryana, leading to heavy air pollution in Delhi, and adversely affecting human and environmental health. During this time, the combination of unfavourable meteorological conditions, additional emissions from stubble burning, and firework activities in this area causes the air quality to further deteriorate. In this study, we have attempted to understand the influence of parali and firecracker incidents on air pollutants' variability over Delhi during the last three years (2020 to 2022). For this purpose, daily average particulate matter and gaseous pollutants data were fetched from the Central Pollution Control Board (CPCB), and daily total fire counts and fire radiative power (FRP) data were retrieved from NASA's Fire Information for Resource Management System (FIRMS). A bigger area of severe burning is suggested by higher FRP values and higher fire counts in the middle of November in all the years considered. Three years satellite-based FIRMS data over Punjab and Haryana show the highest number of active fire counts in 2021 ($n = 80{,}505$) followed by 2020 ($n = 75{,}428$), and 2022 ($n = 49{,}194$). More than 90% parali burning incidents were observed in Punjab state only despite the considerable variability in numbers among the years. The significant effect of parali burning was seen on pollutant concentration variability. As the number of fire count increases or decreases in Punjab and Haryana, there is a corresponding increase or decrease in the particulate matter concentration with a time lag of few days (1 to 2 days). The trend in backward air mass trajectories suggests that the variable response time of pollutants' concentration is due to local and distant sources with different air mass speeds. Our estimates suggest that stubble burning contributes 50–75% increment in $PM_{2.5}$ and 40 to 45% increase in PM_{10} concentration between October and November. A good positive correlation between $PM_{2.5}$, PM_{10}, NO_X, and CO and fire counts (up to 0.8) suggests a strong influence of stubble burning on air quality over Delhi. Furthermore, the firecracker activities significantly increase the concentration of particulate matter with ~100% increment in $PM_{2.5}$ and ~55% increment in PM_{10} mass concentrations for a relatively shorter period (1 to 2 days).

Keywords Particulate matter · Firecrackers · Stubble burning · Fire counts · Gaseous pollutants

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Introduction

Stubble or parali burning can be defined as the intentional incineration of stubbles (crop residue) by farmers after crop harvest (Abdurrahman et al., 2020). It was estimated that about 80% of the total global biomass burning is contributed by tropical regions (Southeast Asia, Southern Africa, Australia, and South America) (Sahu et al., 2015). About one-fourth of worldwide biomass burning events are due to stubble burning alone. India is at the second rank in terms of stubble burning contribution (33%) after China (44%) (Jain et al., 2014; Kant et al., 2022; Streets et al., 2003). Biomass burning, including forest fires and crop residue burning, depletes ~500–1000 million hectares of open forest and savannas, approximately 1 million hectare of northern latitude, and 4 million hectares of tropical and sub-tropical forests every year (Yadav & Devi, 2018). Biomass burning poses serious threats to human health, environmental health, agriculture and food productivity, weather, and climate (Abdurrahman et al., 2020). India being an agriculture-dominant country produces more than 500 million tonnes of crop residues annually.

Numerous studies have proven the adverse effects of air quality on environment and human health, ranging from skin and eye irritation to severe neurological, cardiovascular, respiratory diseases (asthma, chronic obstructive pulmonary disease (COPD), bronchitis, emphysema), cancer, etc. (Kulshrestha et al., 2004; Wang et al., 2007; Barman et al., 2008; Singh et al., 2010; Sarkar et al., 2010; Kumar et al., 2010; Chatterjee et al., 2013; Lave & Seskin, 2013; Pachauri et al., 2013; Gurung & Bell, 2013; Ghorani-Azam et al., 2016; Ghei & Sane, 2018; Ambade, 2018; Tao et al., 2017; Arora et al., 2018; Gupta et al., 2018; Singh, 2018; Ganguly et al., 2019; Ravindra et al., 2019a; Garg & Gupta, 2020; Manisalidis et al., 2020; Devara et al., 2020a, b; Roberts, 2021 and several others). Combustion of crop residue contributes to the emission of major pollutants like CO_2, N_2O, CH_4, CO, NH_3, NO_X, SO_2, non-methyl hydrocarbons (NMHC), volatile organic compounds (VOCs), black carbon, and particulate matter into the atmosphere (Jain et al., 2014). Indian Agriculture Research Institute (IARI) estimated that stubble burning contributes nearly 150 million tonnes of carbon dioxide, more than 9 million tonnes of carbon monoxide, a quarter-million tons of sulphur oxides, 1.25 million tonnes of particulate matter, and ~0.07 million tonnes of black carbon into the atmosphere (Porichha et al., 2021). Stubble burning not only leads to atmospheric pollution but also results in loss of nutrients present in the residues. Stubble burning affects soil productivity by burning the essential nutrients inside the soil (Jain et al., 2014; Singh et al., 2018). Straw burning elevates soil temperature to 42 °C which in turn displaces or kills the important microorganism in the soil and has the potential to disturb the C:N (ratio) equilibrium of the soil (Singh & Verma, 2021; Singh et al., 2018). Almost all the carbon and nitrogen, large amounts of phosphorus, potassium, sulphur, and other micro-nutrients are lost from the soil due to stubble burning (Koul et al., 2022). The soil loses moisture and helpful bacteria because of the heat created by burning the stubble. Dense smoke resulting from the stubble burning is also contributing towards the increased vehicular accidents due to poor or reduced visibility. The pollutants and smoke produced due to stubble burning adversely affect the food productivity by damaging plant tissues, acid rain and plant mortality, chlorosis, or bifacial necrosis, etc. (Augustaitis et al., 2010; Ghosh et al., 2019). Also, emissions from stubble fire affects the global radiation budget by release of greenhouse gases (carbon dioxide and methane) into the atmosphere which may potentially lead to global warming (Bellarby et al., 2008; Maraseni et al., 2018; Ravindra et al., 2019b).

Most of the regions in North India have very high concentration of air pollutants during burning episodes (Kant et al., 2022), however, the influence is significantly higher in Delhi-NCR (Kumar et al., 2015; Nair et al., 2020; Singh et al., 2021). Every year at the onset of winters (October–November), stubble burning begins in Punjab, Haryana, Rajasthan, and Western Uttar Pradesh leading to heavy air pollution in Delhi and adversely affecting the human and environment. It is estimated that Punjab accounts for 21.32 million tons stubble burnt every year (out of 51 million ton of crop residue), while Haryana burns 9.18 million tons (out of 28 mt crop residue) (Jain et al., 2014).The World Bank conducted the first study of its kind on source apportionment for $PM_{2.5}$ in 2001 for numerous Indian cities, including Delhi. They found that biomass burning causes a 9-28 % increment in $PM_{2.5}$ concentration in Delhi (Abdurrahman et al., 2020). Awasthi et al. (2011) recorded increases in $PM_{2.5}$ concentrations of 78% and 43%, respectively, during the periods when rice and wheat stubble were burned in Delhi. According to SAFAR (MoES), stubble burning's contribution was 25% in 2021, 32% in 2020, and 19% in 2019. Other study stated that stubble burning contributed about 50–75% of total $PM_{2.5}$ concentration during post-monsoon seasons (October and November) in Delhi from the upwind regions (Kulkarni et al., 2020). Depending on the year and inventory, a different study that employed a combination of observed and modeled variables during each post-monsoon burning season from 2012 to 2016 indicated a 7 to 78% increase in $PM_{2.5}$ owing to fires (Cusworth et a., 2018). Beig et al. (2020) reported that the stubble burning contribution in Delhi ranges from 1 to 58% as it is highly dependent on transportation pathway of air mass, controlled by source to target region meteorological parameters. Despite several efforts and strict policies implemented by the government, the practice of stubble burning in India continues to be a threat to human and environmental health. It was observed that stubble burning incidents have increased in recent years at a rate of 250 per year over Punjab and Haryana between 2003 and 2017 (Balwinder et al., 2015).

Diwali is an important Hindu religious festival celebrated throughout India. The main day of Diwali is called "Lakshmi Puja". In the past, Diwali has been celebrated eco-friendly through using earthen lamps. With the passage of time and modernization, firecrackers were introduced in the market (Saha et al., 2021). Nowadays, use of firecrackers is a common tradition that has become the festival's main attraction and source of excitement. The deterioration of air quality is a new normal in India during Diwali festival causing a major concern for the environment and human health. Numerous studies reported that the burning of firecrackers significantly increases the concentration of various atmospheric pollutants, such as sulphur dioxide (SO_2), potassium nitrate (KNO_3), charcoal, nitrogen dioxide (NO_2), carbon monoxide (CO), particulate matters ($PM_{2.5}$ and PM_{10}), volatile organic compounds, and several other harmful chemical compounds during Diwali festival (Pandey et al., 2016; Ravindra et al., 2003; Wang et al., 2007). Diwali does not fall on the same date or month every year because it follows the Hindu lunar calendar but falls between the months of October and November. During this time, firecrackers coupled with parali burning activities make Delhi and adjacent region as gas chamber every year. All these anthropogenic activities along with vehicular (major source) and industrial pollution designate Delhi as one of the most polluted cities on the earth. Some of the chemicals produces smoke during fire cracking are more harmful than smoke produced by factories and heavy vehicles (Mandal et al., 2012; Singh et al., 2010; Garg & Gupta, 2020; Murty, 2000).

Diwali falls during the period of stubble burning (October-November), is an unfortunate coincidence for Delhi's air quality. The aftermath of Diwali is not particularly pleasant during this period. Ghei and Sane (2018) reported that the burning of firecrackers during the Diwali celebrations results in a quantitatively small (an increase of about 40 μg/m^3 $PM_{2.5}$ concentration) and statistically significant rise in air pollution in Delhi by comparing the stubble burning periods with and without Diwali in year 2018. According to Mukherjee et al. (2018), firecracker activities during Diwali festival in Delhi may result in approximately 25% increase in $PM_{2.5}$ concentration every year.

The adverse effect of stubble burning and firecrackers on environment and human health is well reported in the literature; however, the reported contribution of pollutant due to stubble burning or firecracking activities is highly variable in Delhi NCR. Considering this a major gap in knowledge, an attempt has been made in the present work to obtain reliable estimates on the contribution of pollutants from stubble burning and Diwali firecrackers in Delhi.

Methodology and study area

In this work, two different (real-time ground monitoring and satellite-based remote sensing) datasets were used. For air quality analysis, we fetched daily (24-h) concentrations of seven pollutants, namely, $PM_{2.5}$, PM_{10}, NO_X, CO, SO_2, NH_3, and O_3, from the Central Pollution Control Board (CPCB) online portal (https://app.cpcbccr.com/ccr/#/caaqm-dashboard-all/caaqm-landing/caaqm-comparison-data) during 3 years period from 2020 to 2022. Air quality data were collected from all stations in Delhi (Anand Vihar, Bawana, Burari Crossing, East Arjun Nagar, IGI Airport, RK Puram, Lodhi Road, Chandni Chowk, ITO, Vivek Vihar, Nehru Nagar, Jahangirpuri, Mandir Marg, Dilshad garden, North Campus DU, DTU, Alipur, Ashok Vihar, Aya Nagar, Dr. Karni Singh, Dwarka Sector-8, NSIT-Dwarka, IGI Airport, Major

Dhayan Chand stadium, CRRI-Mathura Road, Narela, Patparganj, Okhla Vihar-Phase II, Punjabi Bagh, Pusa IMD Road, Rohini, Sonia Vihar, Wazirpur, Shadipur, Najafgarh, Jawahar Lal Nehru Stadium, Mundka, Siri fort, Sri-Aurobindo Marg) (Fig.1).

The data used for detecting fires are received from NASA's Visible Infrared Imaging Radiometer Suite (VIIRS) (VIIRS NOAA-20 375m). The VIIRS sensor aboard the Suomi National Polar-Orbiting Partnership (SNPP) satellite has a resolution of 375 m^2, and the data is available from 1 January 2020 onwards (Wang & Cao, 2021). Active fire detections and thermal anomalies are displayed in the VIIRS fire layer (Schroeder et al., 2014). The fire layer is helpful for analysing the spatial and temporal distributions of fire, identifying hotspots that persist over time, and identifying where smoke and gas flares are causing air pollution (Csiszar et al., 2014). Due to the 375-m data's enhanced spatial resolution, which enables for a greater response over relatively small fires as well as improved mapping of large fire perimeters, VIIRS NOAA- (375 I band) complements MODIS fire detections. Additionally, the 375-m data has better performance at night. As a result, this data has been extensively used for enhanced fire mapping quality and fire management (Meyer et al., 2020; Yan et al., 2021). Fire radiative power (FRP) is one of the most crucial factors in defining wildfires. In MW (megawatts), FRP represents the pixel-integrated fire radiative power. The variable is retrieved from the radiance at the 4-μm band of satellite sensors and represents the instantaneous radiative energy that is released from actively burning fires (Roberts et al., 2005; Li et al., 2018). It is related to the rate of biomass combustion and rate of emissions. FRP has been widely used as a proxy for fire intensity to characterize fire types, fire behaviours, and fire regimes, as well as the dynamics of land cover and the hydrological cycle (Kaufman et al., 1998; Wooster et al., 2005; Freeborn et al., 2009; Kumar et al., 2017). We obtained daily fire count and Fire radioactive power (FRP) data from VIIRS-NOAA product, Fire Information for Resource Management System (FIRMS, NASA (https://firms.modaps.eosdis.nasa.gov/download).

Fig. 1 Map of the study area

To understand the potential source sectors of pollutants and its transport towards the study location, backward air mass trajectories were obtained from HYSPLIT (the Hybrid Single-Particle Lagrangian Integrated Trajectory model). HYSPLIT is a Lagrangian particle/puff model that was first developed by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (ARL) in the 1980s (Draxler, 1982). The method for computing the pollutants concentration in the HYSPLIT model combines Eulerian (which calculates concentrations for each grid cell by integrating pollutant fluxes at each grid cell interface due to advection and diffusion) and Lagrangian (which calculates concentrations by adding the contributions of each pollutant "puff" that is advected through the grid cell as represented by its trajectory) approaches (Draxler & Hess, 1998; Ashrafi et al., 2014). HYSPLIT is one of the most widely used models for calculating air parcel trajectories, dispersion, chemical transformation, deposition simulations with scales ranging from 1 to 1000 km, and construct source-receptor associations (Anastassopoulos et al., 2004; Safi et al., 2007; Shan et al., 2009; Badrinath et al., 2009; Draxler & Rolph, 2010; Miller et al., 2011; Atwod et al., 2013; Rolph et al., 2017; Sentian et al., 2019; Ma et al., 2021; Bilal et al., 2022). Backward air mass trajectories were extracted for the months of October and November for the Delhi region in the years 2020, 2021, and 2022 (https://www.ready.noaa.gov/HYSPLIT_traj.php).

Delhi, India's capital territory, is a massive metropolitan city which lies in the landlocked Northern plains of the country. Due to its proximity to the Himalayas in the north and Thar Desert in the west, Delhi experiences annual weather extremes. Delhi has semi-arid weather with four distinct seasons: summer/pre-monsoon (March to June), monsoon (July to mid-September), short post-monsoon (October to November), and winter (December to February). The temperature in Delhi ranged between 4 and 10 °C in the winter season and 42 to 48 °C in the summer season (Kumar et al., 2017). December and January are the two coldest months of the year, and May and June are the two hottest months of the year. Although some minor spatial variations, the southwest monsoon season, which typically begins in the last week of June and lasts until mid-September, brings most of the rainfall to Delhi (between 80 and 85%) (Perrino et al., 2011). The climate in the research area is characterized by low humidity, hot summers, and mild, foggy winters, except for the monsoon season (Malik et al., 2010). Dust storms and thunderstorms are frequent before or during the rainy season. Through the Thar Desert, dust pollution is carried long distances to the study areas.

Results and discussion

Parali burning

In this section, we investigated the influence of parali burning on air pollutants' variability during post-monsoon seasons (October and November) over Delhi for the last 3 years (2020 to 2022). For this purpose, active fire counts and fire radiative power (FRP) values were retrieved and analysed during parali burning time (Fig. 2) (in this study, from late September to November). Significant variability and one to one correlation in terms of number of fire counts and FRP values were seen in all the years considered. The daily variation in fire counts and corresponding changes in FRP values are depicted in Fig. 2. In all of the years taken into account, relatively lower FRP values were seen towards the start of the parali burning time. Early to mid-November, when parali activity is at its greatest, is when FRP values reach their maximum concentration. Later in November, when there are fewer fires, FRP values gradually decline. Higher FRP values coupled with greater number of fire counts around mid of the November suggest intense burning covering a larger area.

Three years satellite-based fire counts' data over Punjab and Haryana show the highest number of parali burning incidents in 2021 followed by 2020 and 2022 (Fig. 3a–f). We observed 75,428 fire counts in 2020, 80,505 in 2021, and 49,194 in 2022. In all these years, the highest number of stubble burning incidents were noticed in Punjab. The total count of active fires in Punjab was estimated to be 44,401 (90% of total fire counts in Punjab and Haryana) in 2022, 70,430 (> 90% of total fire counts in Punjab and Haryana) in 2021, and 69,505 in 2020 (~92% of total fire counts in Punjab and in Haryana). Compared to Punjab, there were 5,923 in 2020, 10,075 in 2021, and 4,793 fire counts in 2022 in Haryana. In the monthly fire counts, the highest number of fire counts were observed in November (45,215 in 2020, 63,722 in 2021, and 32,284 in 2022) followed by October (29,283 in 2020, 16,534 in 2021, and 16,660 in 2022) (Figs. 2 and 3). Our fire count estimates suggest an increase of 5,077 (~7%) fire counts in 2021 compared to 2020 in Punjab and Haryana. We also noted a significant reduction of 31,311 (~38%) fire counts in 2022 compared to previous year (2021).

To identify the influence of these parali burning activities on air quality over Delhi, daily average particulate matter and gaseous pollutants were studied during the pre-parali, parali, and post-parali burning time from 2020 to 2022. Time series of daily average particulate matter concentration (Figs. 4 and 5) and gaseous pollutants (Figs. 7, 8, 9, 10 and 11) in Delhi were plotted with respect to daily fire counts in Punjab and Haryana. The effect of parali burning was clearly seen on pollutant concentration in all the years studied. All the pollutants showed highest concentration in November, which coincided with highest number of fire count incidents in all the years (Figs. 2-11). The average concentration of $PM_{2.5}$ over Delhi in November comes out to be 215.7 ± 20.7 $\mu g/m^3$, 240.8 ± 12.0 $\mu g/m^3$, and 240.7 ± 12.0 $\mu g/m^3$ in 2020, 2021, and 2022, respectively. In terms of PM_{10}, the average concentration in the month of November works out to be 351.2 ± 13.8 $\mu g/m^3$, 393.5 ± 26.0 $\mu g/m^3$, and 393.5 ± 16.2 $\mu g/m^3$ in 2020, 2021, and 2022, respectively. Likewise, all the gaseous pollutants have the highest monthly average concentrations in the month of November (Figs. 7, 8, 9, 10 and 11).

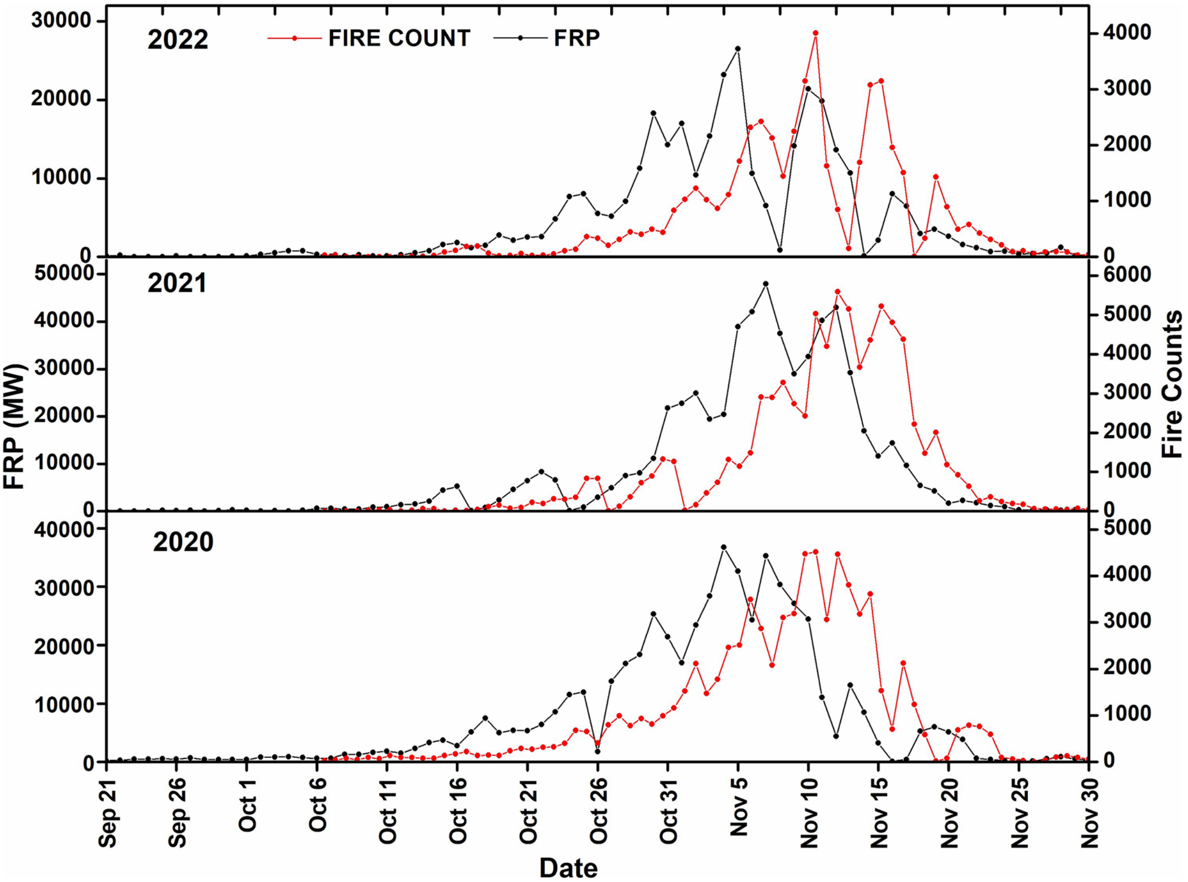

Fig. 2 Graph showing day-to-day variability in number of active fire counts and corresponding changes in fire radiative power (FRP)

As is evident from Figs. 4 and 5, particulate matter concentration was very low in early October with relatively lesser or no fire count incidents. As the number of fire count increases or decreases in Punjab and Haryana, there is a corresponding increase or decrease in the particulate matter concentration with a time lag of few days (1 to 2 days). The variable response time of pollutant concentration is possibly due to variable speed of air masses reaching over the study area.

To analyse potential sources and transmission paths of atmospheric pollutants towards the study area during 2020 to 2022 (Fig. 6a–c), 48-h backward air mass trajectories were computed at 00:00 hours using the HYSPLIT model at an altitude of 500 meters above ground level (m.a.g.l) on selected dates representing monthly direction of air mass.

The air mass speed is calculated using air mass trajectories with the help of Arc GIS software. The estimated speed of air mass ranged from 3 to 27 km/h. The results from back air mass trajectories suggest a uniform direction of air masses coming from local as well as distant source from the west or north-western regions of India, Pakistan, and Afghanistan. This trend suggests mixed (local/slow moving trajectories

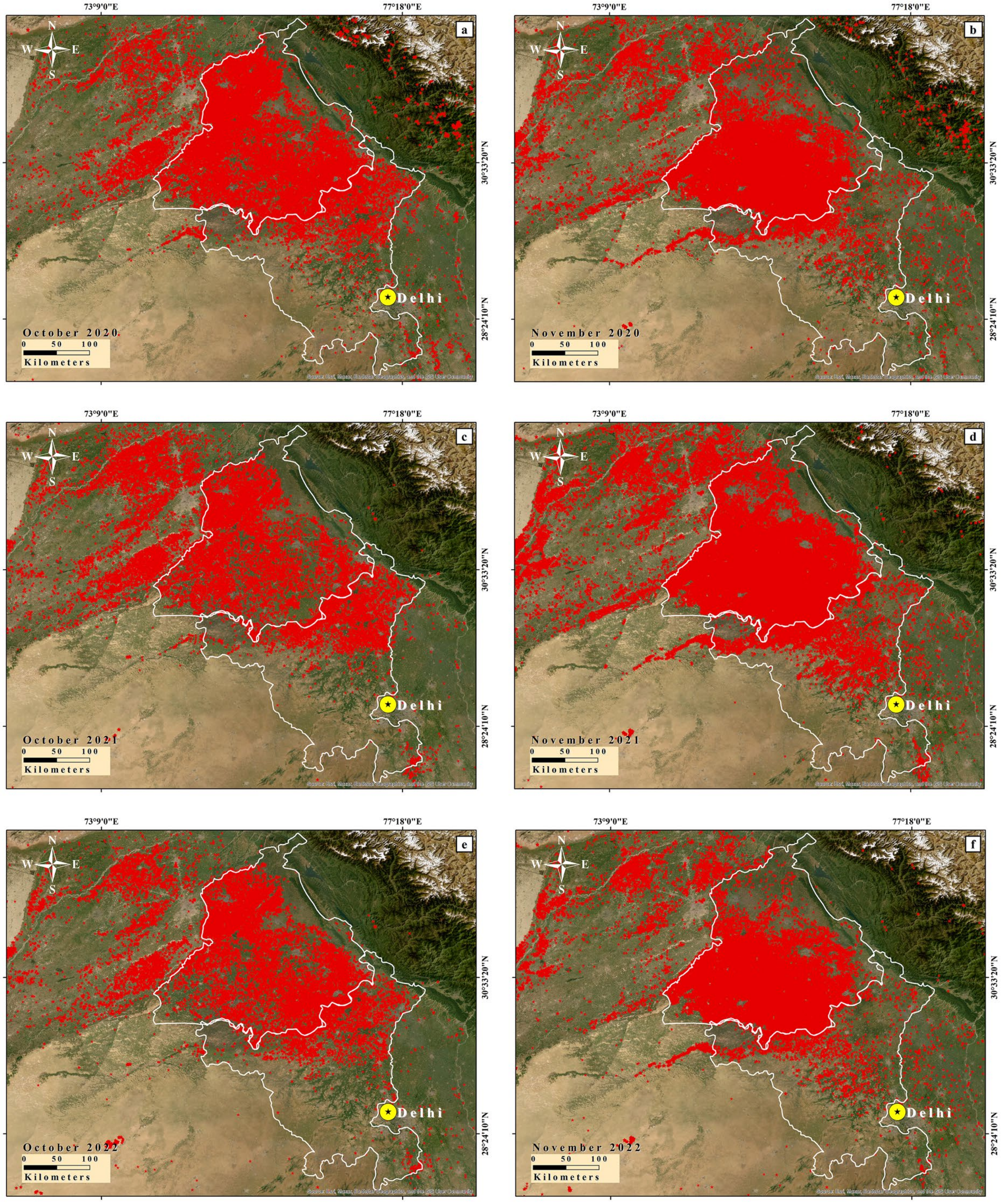

Fig. 3 FIRMS retrieved fire counts (red colours) superimposed on the geographical boundaries of Punjab, Haryana, and Delhi during October and November from 2020 to 2022. **a** October 2020, **b** November 2020, **c** October 2021, **d** November 2021, **e** October 2022, and **f** November 2022

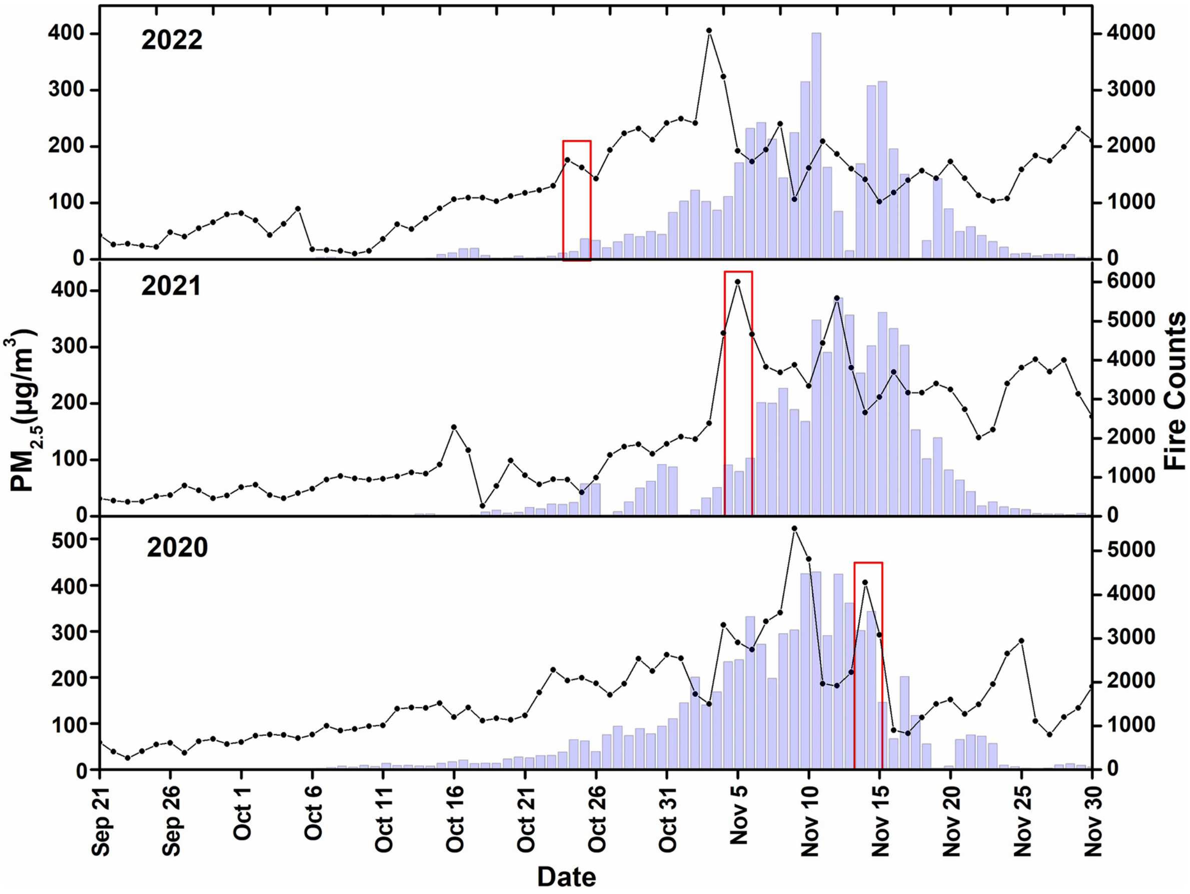

Fig. 4 Graph showing day-to-day variation in number of fire count and corresponding changes in of $PM_{2.5}$ concentration. Red-coloured rectangle represents the Diwali time in respective years

and relatively fast moving/distant source trajectories) with different air mass speed causes variable response (1 to 2 days) of pollutant concentration.

We also estimated the contribution of parali burning on air pollutant concentration. For this purpose, parali burning time was divided in to three periods: pre-parali, parali, and post-parali. Since, low air pollutants level in September was due to monsoonal rainfall, we have not considered September as pre-parali burning time. Due to more or less linear increasing trend in fire counts and increase in pollutants level in 2020 (Figs. 4-11), we have considered the early October (1 to 15) as pre-parali burning time with relatively lower fire counts (less than 500), and 16 Oct to 15 Nov as parali burning time with higher/highest fire counts, and 16 Nov to 30 Nov as post-parali burning (fire count number decrease to less than 500). In 2020, the average $PM_{2.5}$ concentration during pre-parali, parali, and post-parali burning was found to be 95 μg/m^3 (1 to 15 Oct 2020), 169 μg/m^3 (15 to 30 Oct 2020) to 287 μg/m^3 (1 Nov to 15 Nov 2020), and 143 μg/m^3 (16 to 30 Nov 2020). During the same time period, the average PM_{10} concentration varies from 231 μg/m^3, 332 to 455 μg/m^3, and 247 μg/m^3 representing pre-, parali, and post-parali periods, respectively. However, in 2021 and

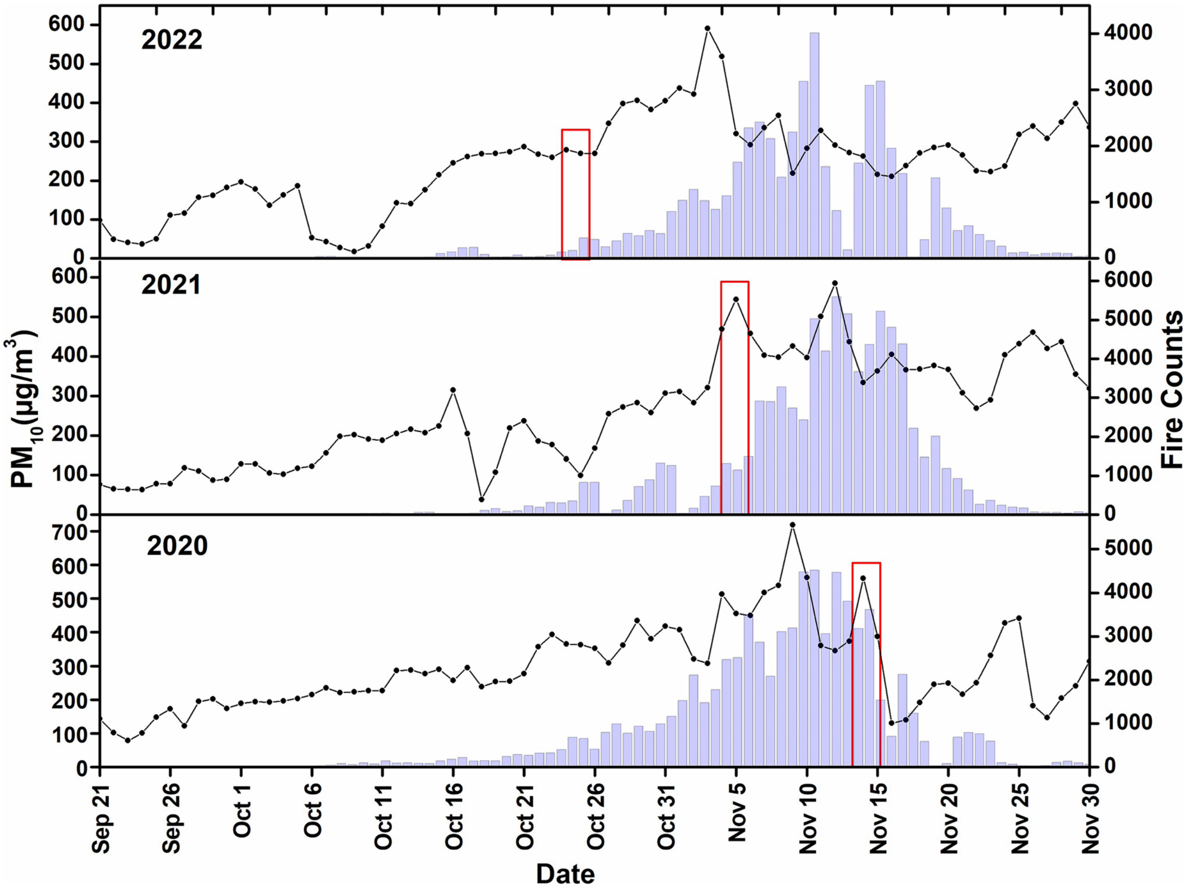

Fig. 5 Graph showing day-to-day variation in number of fire count and corresponding changes in of PM_{10} concentration. Red-coloured rectangle represents the Diwali time in respective years

2022, there is a marked variation in daily average fire count data and corresponding changes in pollutant level. Hence, in these 2 years, we estimated the changes by taking the average concentration during high fire counts and low fire counts. We have also considered the changes in meteorological parameters between October and November (slight decrease in temperature and planetary boundary layer height from October to November) (Guttikunda & Gurjar, 2012). Therefore, we have estimated the month-wise changes in particulate matter and gaseous pollutants. After due consideration, we found that parali burning contributes 50–75% increase in $PM_{2.5}$ concentration (75% in 2020, ~50% in 2021, and 2022), 40 to 45% increase in PM_{10} concentration in Delhi. A variable response in gaseous pollutant concentration with respect to fire count was seen. Among the gaseous, NOx showed the highest increment of more than 70% (Fig. 7), followed by CO (Fig. 8) with > 50%, and SO_2 (Fig. 9) with less than 20% increment due to parali burning. NH_3 and surface ozone (O_3) have not shown any variability in their concentration during the parali burning periods (Figs. 10 and 11). Our estimates on the contribution of particulate matter due to parali burning over Delhi closely matches with Awasthi et al. (2011) and Kulkarni et al. (2020)

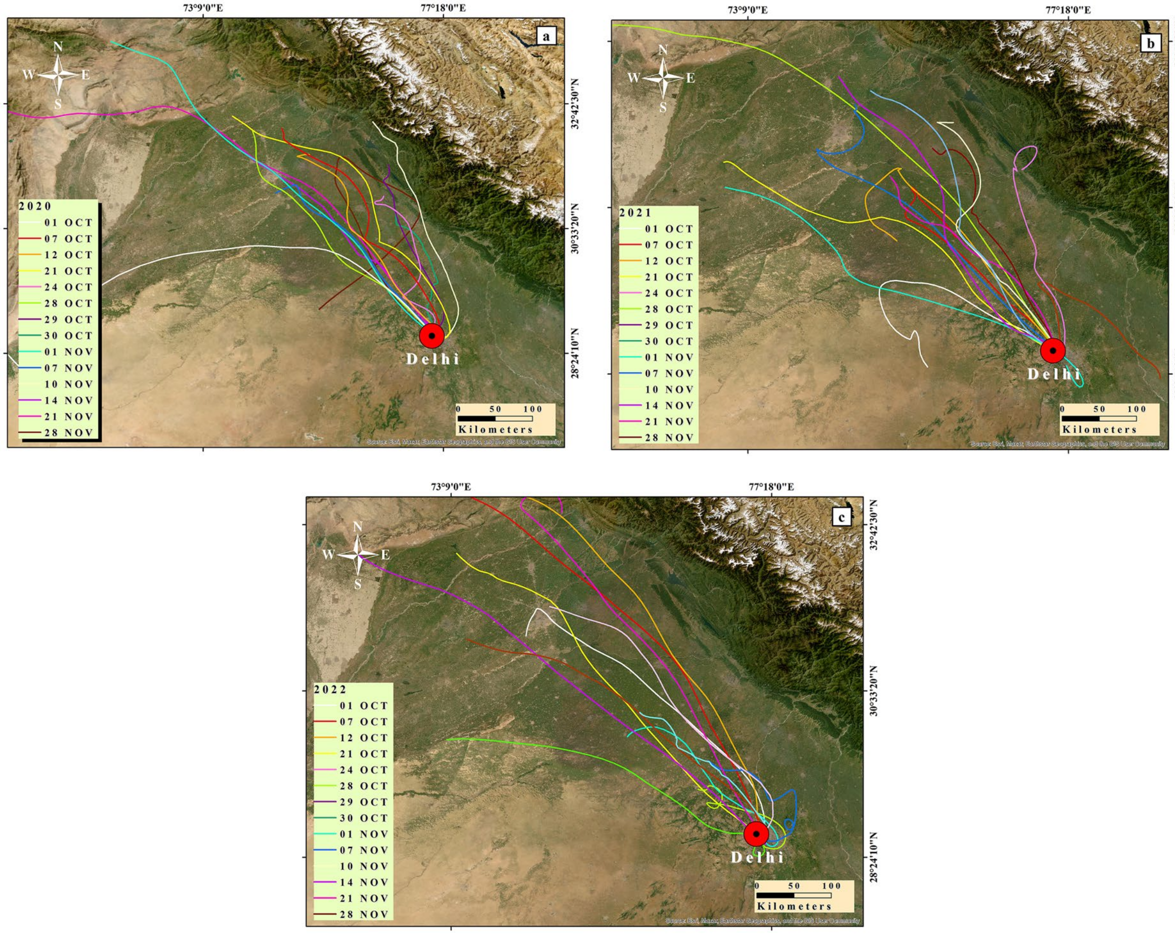

Fig. 6 Maps showing the back air mass trajectories during the parali burning time (October–November) of the year 2020 (**a**), 2021 (**b**), and 2022 (**c**)

Correlation

In this section, we examined the correlation among particulate matters, gaseous pollutants, number of fire counts, and fire radiative power (FRP) during the parali burning period (Table 1). The results of Pearson coefficient revealed an excellent (for particulate matter) to good/moderate (gaseous pollutants) correlation between atmospheric pollutants, number of fire counts, and FRP from 2020 to 2022 (Table 1). Here, $PM_{2.5}$ concentration was found to possess a very strong positive correlation with PM_{10} ($r = 0.97$) followed by CO and NH_3 ($r = > 0.8$) in all the years. Despite slight variability among the years, $PM_{2.5}$ also showed a good positive correlation with NO_X and SO_2. As is evident from Table 1, CO possessed an excellent positive correlation with NO_X ($r = > 0.9$), NH_3, and SO_2 ($r = > 0.8$). In terms of fire count and FRP, particulate matter concentration was found to possess a good positive correlation with $r = > 0.70$ in 2020, and $r = > 0.6$ in 2021 and 2022. In terms of gaseous concentration, a good positive correlation with fire counts and FRP was observed only in 2020 with $r = \sim 0.6$ for NOx, CO and NH_3 (Table 1).

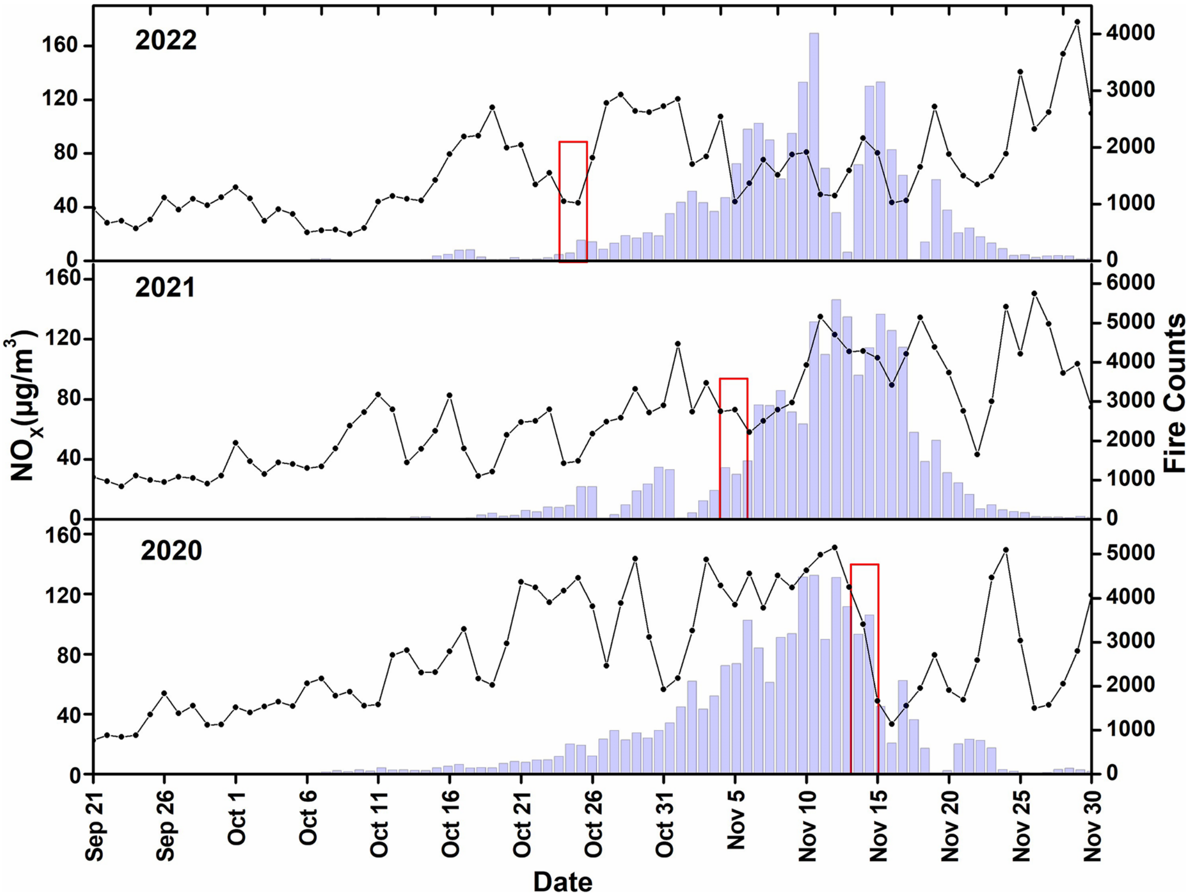

Fig. 7 Graph showing day-to-day variation in number of fire count and corresponding changes in NOx concentration. Red-coloured rectangle represents the Diwali time in respective years

A strong positive correlation between particulate matters in all the years and gaseous pollutants in 2022 with fire counts suggest a strong effect of parali burning on air quality over Delhi. The correlation was lower for particulate matter as well as for gaseous pollutants in 2021 and 2022 than in 2020 (Table 1). However, compared to particulate matter during this time, the correlation for gaseous pollutants was substantially lower. The decreasing or waning correlation of gaseous pollutants over the study area could be due to (i) unusually higher precipitation in October 2021 (~101 mm) and 2022 (~128 mm) compared to October 2020 (~3 mm), (ii) a significant decrease in the number of fires due to stringent state policies in 2022 (49,194 in 2022 compared to 75,428 and 80.505 in 2020 and 2021, respectively), (iii) other anthropogenic activities outside of excessive parali burning were at their lowest levels in 2020 due to the restrictions of COVID -19, and (iv) the process of removing particulate matter and gaseous pollutants from the atmosphere during rainfall is not the same. The removal of gaseous pollutant takes place by the process of absorption by raindrops falling on the ground while the removal of particulate matters by the processes of impaction and entrapment by falling raindrops (Shukla et al., 2008). The correlation between

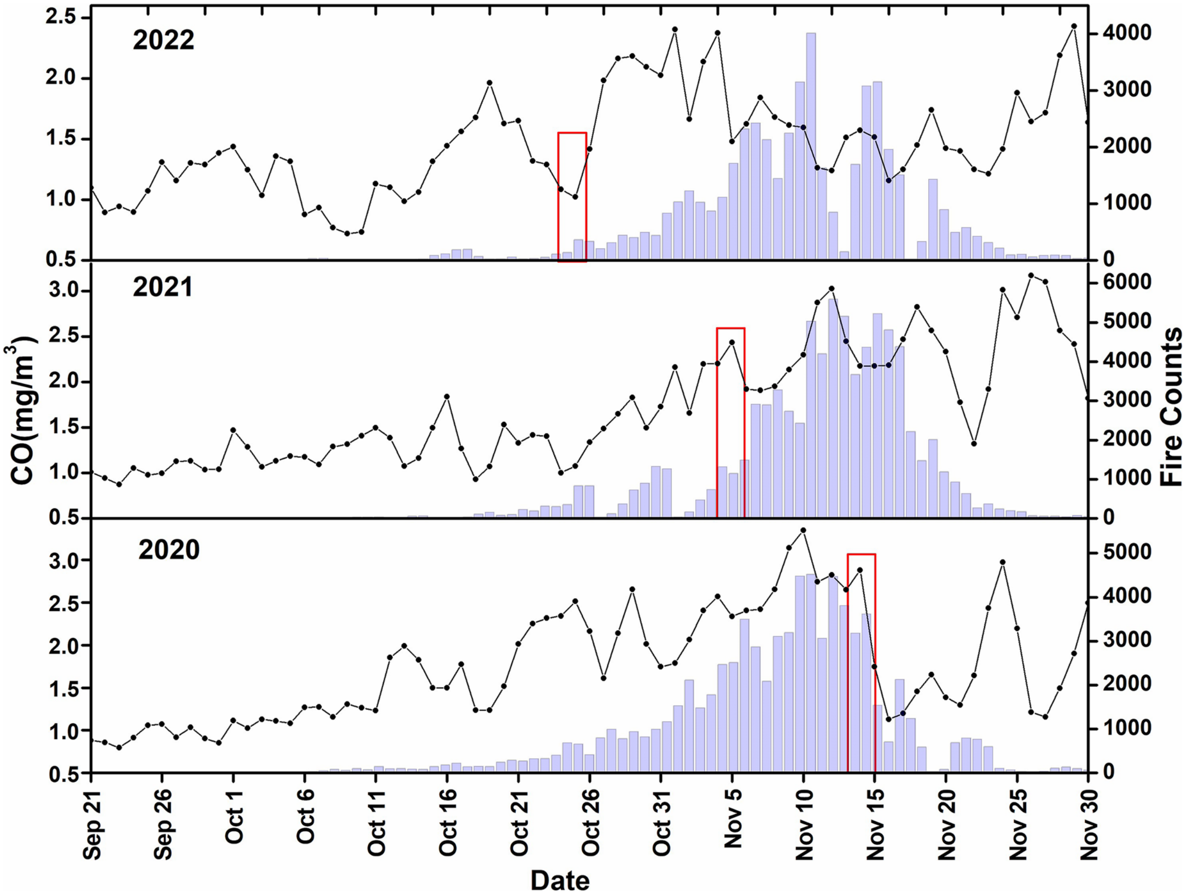

Fig. 8 Graph showing day-to-day variation in number of fire count and corresponding changes in CO concentration. Red-coloured rectangle represents the Diwali time in respective years

pollutant concentration and parali burning events is impacted by all of these parameters.

Diwali

As mentioned earlier, the dates of Diwali festival are not fixed every year, but it occurs in the month of October or November. During the considered 3 years, Diwali held on 14 November 2020, 4 November 2021, and 24 October 2022. During this time in Delhi and adjacent regions, the air pollution becomes more worse and complex than other parts of the country. In this region, the time of Diwali celebration coincides with already poor air quality due to parali burning activities in Punjab and Haryana. In this section, we estimated the contribution of firecracker activities during Diwali celebrations to particulate matter and gaseous pollutants. The analysis was performed to observe any increase in pollutants level during Diwali days with respect to pre-Diwali time (2 days before the Diwali dates) in respective years. The analysis revealed a short term but significant increase in particulate matters (Figs. 3 and 4) and most of the gaseous concentrations (Figs. 7, 8, 9, 10 and 11) during Diwali days in all the years, but for a relatively shorter period (1 to 2 days). A sharp increment in particulate matter level was clearly seen on the Diwali days in all the years considered (Figs. 3 and 4). However, the gaseous pollutants showed a variable trend (increase or decrease) during Diwali days (Figs. 6, 7, 8, 9 and 10). The average $PM_{2.5}$ concentration during pre-Diwali period (2 days average before Diwali day) over Delhi was found to be ($PM_{2.5}$: 196.0 μg/m^3 in 2020, 150.5 μg/m^3 in 2021, and 126.52 μg/m^3 in

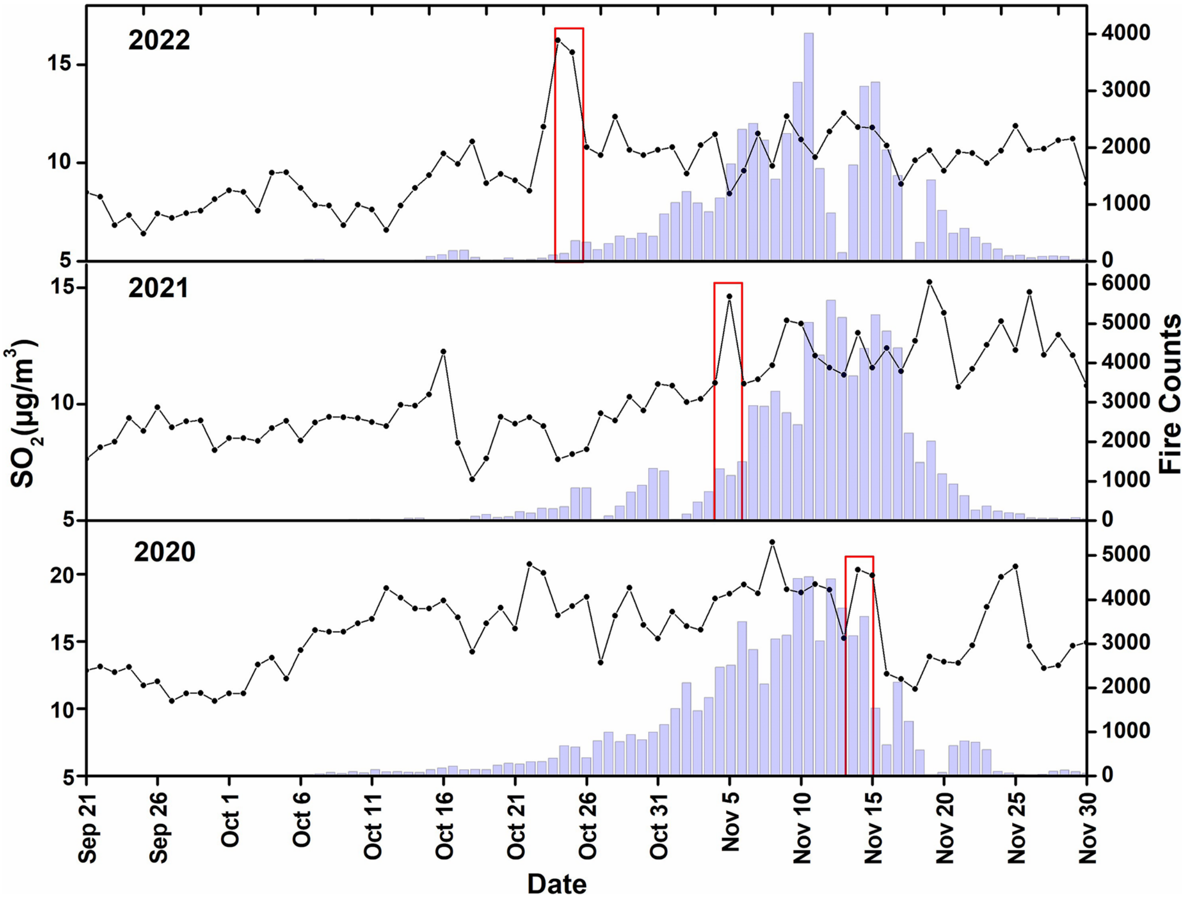

Fig. 9 Graph showing day-to-day variation in number of fire count and corresponding changes in SO_2 concentration. Red-coloured rectangle represents the Diwali time in respective years

2022, and PM_{10}: 360.0 µg/m^3 in 2020, 301.6 µg/m^3 in 2021, and 263.37 µg/m^3 in 2022), which rose to average concentration ($PM_{2.5}$: 406.0 µg/m^3 in 2020, 324.8 µg/m^3 in 2021, and 176.16 µg/m^3 in 2022, and PM_{10}: 560.6 µg/m^3 in 2020, 469.0 µg/m^3 in 2021, and 279.04 µg/m^3 in 2022) during respective Diwali days. This trend suggests a ~100% increment in $PM_{2.5}$ and ~55% increment in PM_{10} mass concentration in 2020 and 2021 due to firecracker activities on Diwali in Delhi. However, in 2022, significantly lower increase in particulate matter was seen. This year, only 40% in $PM_{2.5}$ and 6% increment in PM_{10} average mass concentration was noted. Our observation reveals that the contribution of particulate matter due to firecrackers depends when Diwali date falls, which in turn depends on meteorological conditions and intensity of stubble burring activities in Punjab and Haryana. For example, in 2020 and 2021, Diwali falls in the month of November, which causes a significant increment in particulate matter concentration (~100% in $PM_{2.5}$ and ~55% in PM_{10}). In November 2020 and 2021, the meteorological conditions for pollution dispersion were not favourable, i.e. lower monthly average temperature (~19 °C) and lower mean monthly planetary boundary layer height (~750 m above ground level), and the number of fire counts were significantly higher compared to October. But in 2022, Diwali celebrated in the month of October with only a minor contribution of 40% and 6% in $PM_{2.5}$ and PM_{10} levels, respectively. This time period which coincided with no or very less number of fire counts and better favourable conditions for pollution dispersion, i.e.,

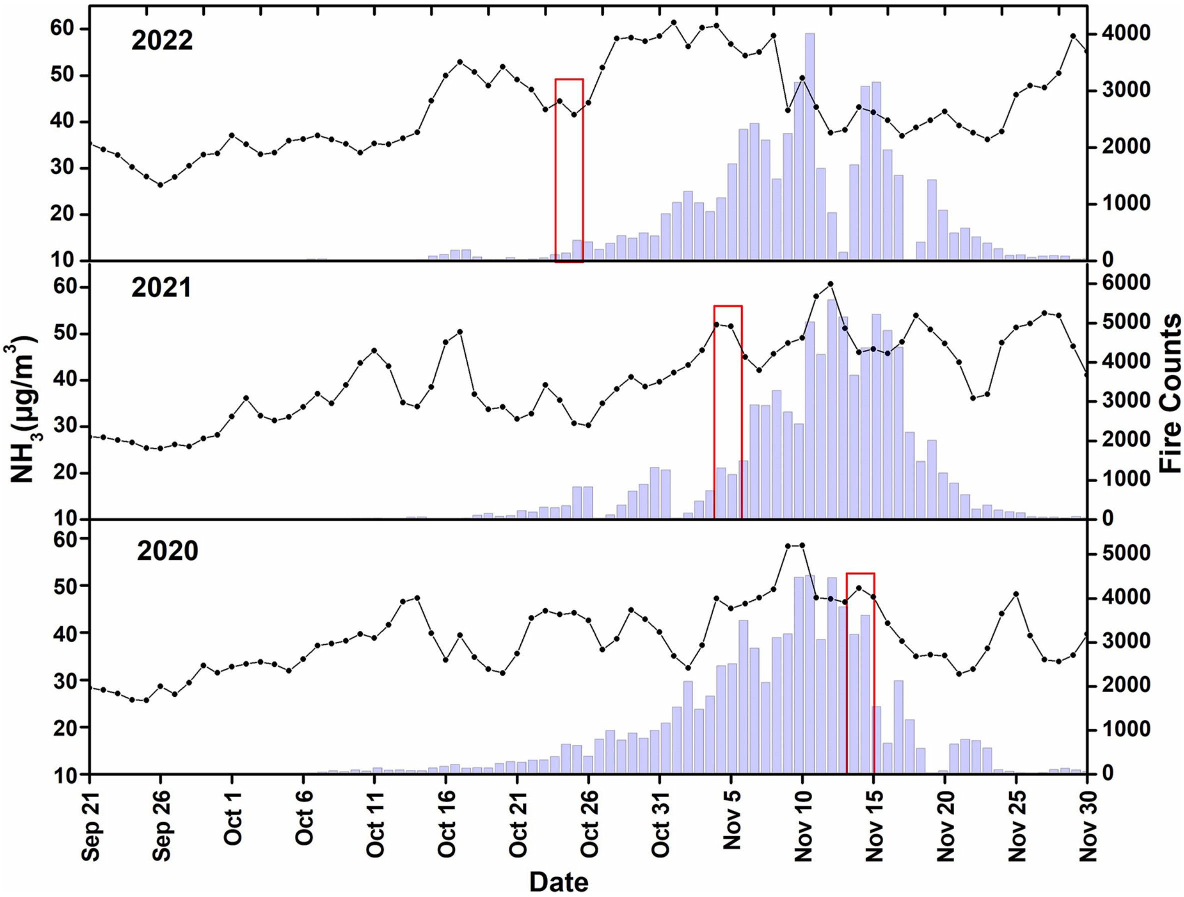

Fig. 10 Graph showing day-to-day variation in number of fire count and corresponding changes in NH_3 concentration. Red-coloured rectangle represents the Diwali time in respective years

higher monthly average temperature (~25 °C) and higher mean monthly planetary boundary layer height condition (~1000 m above ground level) compared to November. A variable response of gaseous pollutants was seen in Diwali days. A sharp increase was observed in SO_2 (Fig. 9), whereas a slight increase in CO (Fig. 8), and NH_3 (Fig. 10) concentrations; however, NO_X level were sharply declined (Fig. 7) with more or less no changes in O_3 (Fig. 11) mass concentration during the Diwali days in 2020 and 2021. In 2022, a slight increment was observed in SO_2 and O_3, but NO_X, CO, and NH_3 showed a declining trend during the Diwali days. The average NO_X concentrations during pre-Diwali periods was found to be 137.8 µg/m^3, 81.2 µg/m^3, and 61.1 µg/m^3 in 2020, 2021, and 2022, respectively, which declined to average concentration (NO_X :100 µg/m^3 in 2020, 72.0 µg/m^3 in 2021, 44.3 µg/m^3 in 2022). The surface ozone level was found to vary from 34.4 to 35.9 µg/m^3 in 2020, 34.1 to 30.4 µg/m^3 in 2021, and 35.5 to 39.8 µg/m^3 in 2022 on the Diwali days compared to pre-Diwali days. The mean concentration of CO level changes from pre-Diwali to Diwali as 2.7 to 2.8 mg/m^3, 1.9 to 2.2 mg/m^3, and 1.3 to 1.0 mg/m^3 in 2020, 2021, and 2022, respectively. The average concentration of SO_2 from pre-Diwali to Diwali days increases from 16.9 to 20.0 µg/m^3, 10.3 to 11.6 µg/m^3, and 10.2 to 16.2 µg/m^3 in 2020, 2021, and 2022, respectively, showed a variable

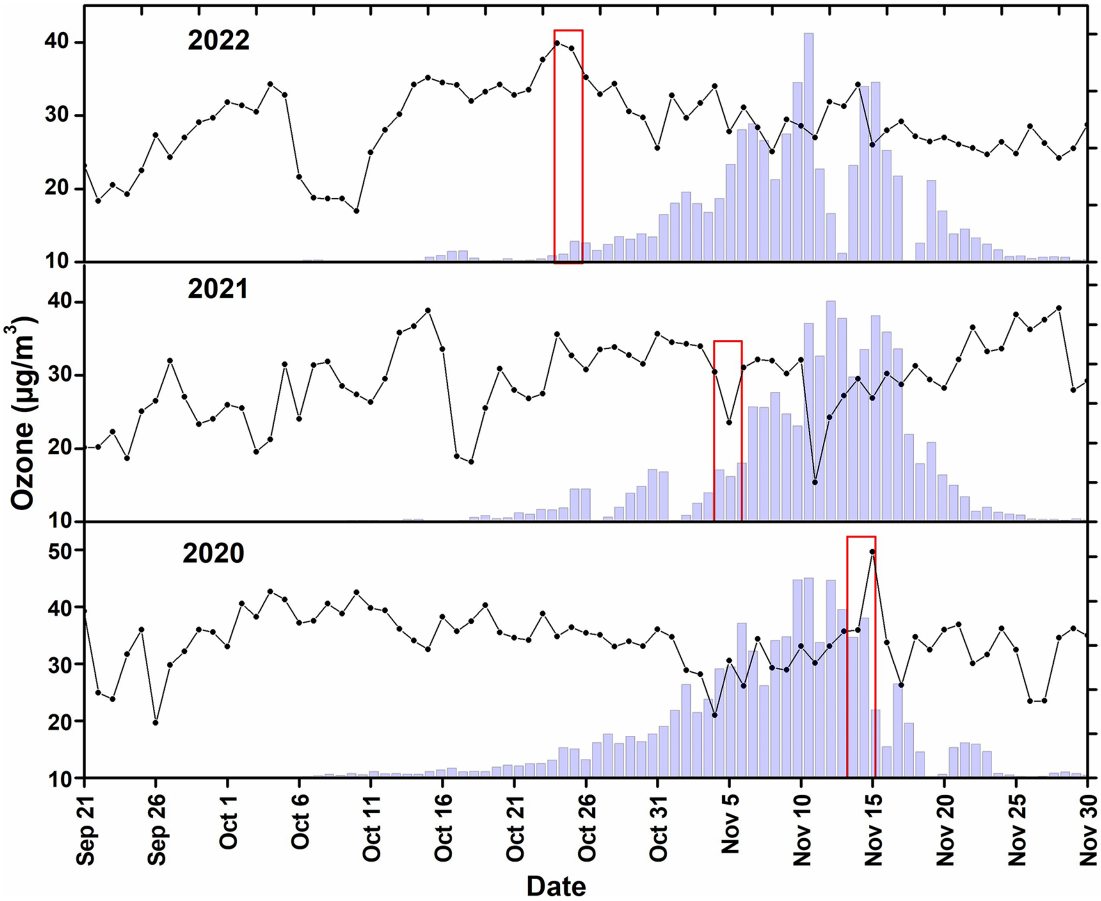

Fig. 11 Graph showing day-to-day variation in number of fire count and corresponding changes in O_3 concentration. Red-coloured rectangle represents the Diwali time in respective years

increment between 10 and 50% (highest in 2022). The average NH_3 level varied 46.7 to 49.3 μg/m^3 and 44.8 to 51.1 μg/m^3 in 2020 and 2021, respectively, with no changes in concentration in 2022 from pre-Diwali to Diwali days.

Conclusion

The present study depicted a significant effect of parali burning and heavy firecracker use during Diwali celebration on particulate matters and gaseous pollutants over Delhi from 2020 to 2022. Daily average particulate matter and gaseous pollutants were fetched from Central Pollution Control Board (CPCB), and daily total fire counts and FRP data were obtained from NASA's Fire Information for Resource Management System (FIRMS). Intense burning across a bigger area is suggested by higher FRP values and higher fire counts around the middle of November in Punjab and Haryana. Daily average particulate matter and gaseous pollutants data during pre-, parali, and post-parali burning time shows that stubble burning contributes 50–75% increase in $PM_{2.5}$ concentration and 40 to 45% increase in PM_{10} concentration in Delhi. Also, a very good positive correlation between particulate matter and most of the gaseous pollutants during stubble burning suggest a strong influence of

Table 1 Pearson's correlation coefficient (*r*) of $PM_{2.5}$, PM_{10}, NOx, NH_3, SO_2, O_3, fire counts, and fire radiative power (FRP) **a** for 2020, **b** for 2021, and **c** for 2022

(A) 2020	***$PM_{2.5}$***	***PM_{10}***	***CO***	***NO_x***	***NH_3***	***O_3***	***SO_2***	***Fire count***	***FRP***
$PM_{2.5}$	1.00								
PM_{10}	0.97	1.00							
CO	0.86	0.89	1.00						
NO_x	0.68	0.77	0.94	1.00					
NH_3	0.85	0.85	0.83	0.69	1.00				
O_3	−0.07	−0.04	−0.12	−0.16	0.01	1.00			
SO_2	0.73	0.79	0.79	0.74	0.78	0.07	1.00		
Fire count (FC)	0.71	0.76	0.64	0.60	0.57	− 0.26	0.49	1.00	
Fire radiative power (FRP)	0.70	0.74	0.62	0.58	0.54	− 0.29	0.46	0.99	1.00
(B) 2021	***$PM_{2.5}$***	***PM_{10}***	***CO***	***NO_x***	***NH_3***	***O_3***	***SO_2***	***Fire count***	***FRP***
$PM_{2.5}$	1.00								
PM_{10}	0.97	1.00							
CO	0.89	0.91	1.00						
NO_x	0.75	0.83	0.95	1.00					
NH_3	0.86	0.89	0.88	0.86	1.00				
O_3	0.25	0.36	0.31	0.33	0.23	1.00			
SO_2	0.82	0.84	0.85	0.78	0.73	0.37	1.00		
Fire count (FC)	0.67	0.66	0.46	0.39	0.51	0.02	0.41	1.00	
Fire radiative power (FRP)	0.68	0.66	0.46	0.37	0.50	0.01	0.40	0.99	1.00
(C) 2022	***$PM_{2.5}$***	***PM_{10}***	***CO***	***NO_x***	***NH_3***	***O_3***	***SO_2***	***Fire count***	***FRP***
$PM_{2.5}$	1.00								
PM_{10}	0.97	1.00							
CO	0.80	0.87	1.00						
NO_x	0.66	0.74	0.90	1.00					
NH_3	0.84	0.86	0.81	0.72	1.00				
O_3	0.40	0.51	0.36	0.27	0.37	1.00			
SO_2	0.60	0.61	0.45	0.48	0.49	0.54	1.00		
Fire count (FC)	0.65	0.60	0.42	0.20	0.55	0.28	0.39	1.00	
Fire radiative power (FRP)	0.65	0.60	0.44	0.21	0.56	0.27	0.40	0.99	1.00

stubble burning on air quality in Delhi, with a time lag of 1 to 2 days. The possible causes of variable response time of pollutants concentration were also studied with the help of HYSPLIT model at an altitude of 500 m above ground level on selected dates representing monthly direction of air masses. The trend of back air mass trajectories indicates a uniform direction of air masses coming from local as well as distant source from the west or north-western regions of India, Pakistan, and Afghanistan with different air mass speed causing variable response (1 to 2 days) of pollutant concentration. Three years satellite-based fire count (FIRMS data) over Punjab and Haryana show highest number of active fire counts in 2021 (80,505) followed by 2020 (75,428) and 2022 (49,194). In all the years considered, ~90% of fire counts were observed in Punjab only with 69,505, 70,430, and 44,401 in 2020, 2021, and 2022, respectively. The time of Diwali celebration coincides with already poor air quality due to parali burning activities in Punjab and Haryana that causes short-term but significant increase in particulate matters ($PM_{2.5}$ and PM_{10}) and gaseous concentration over Delhi. Firecrackers contribute a short-term but considerable increase in particulate matter with ~100% and 55% increment in $PM_{2.5}$ and PM_{10} concentrations.

To mitigate the negative impacts of parali burning and Diwali celebrations on air quality, it is crucial to adopt eco-friendly practices and promote sustainable alternatives. Governments and communities must work together to raise awareness and educate the public on the dangers of air pollution and the benefits of adopting sustainable practices. Conclusively, it is up to all of us to take responsibility and make changes to ensure a cleaner, healthier, and more sustainable future.

Acknowledgements The above study was possible due to the vision, kind support and encouragement from Dr. Aseem Chauhan, Hon`ble Chancellor of Amity University Haryana (AUH), Manesar-Gurugram. The authors are thankful to Hon`ble Vice Chancellor, and Pro-Vice-Chancellor of AUH, Manesar-Gurugram, for their continuous guidance and administrative support. The authors would like to express their sincere gratitude to Central Pollution Control Board (CPCB) for providing data through their website. The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website (https://www.ready.noaa.gov) used in this publication. We acknowledge the use of data and/or imagery from NASA's Fire Information for Resource Management System (FIRMS) (https://earthdata.nasa.gov/firms), part of NASA's Earth Observing System Data and Information System (EOSDIS).

Author contribution Dr. Abul Amir Khan (Principal and Corresponding author): Research idea, conceptualization, methodology, data analysis, writing—original draft. Ms Kalpana Garsa: Data downloading, data analysis, graph preparation, table compilation. Dr. Prakhar Jindal: Writing—review and editing—data analysis, methodology. Prof. P.C.S Devara: Review & editing: all authors read and approved the final manuscript.

Data availability The datasets generated during and/or analysed during the current study are available on CPCB portal (https://app.cpcbccr.com/ccr/#/caaqm-dashboard/caaqm-landing/data), NOAA Air Resources Laboratory (ARL) (https://www.ready.noaa.gov), and NASA's Fire Information for Resource Management System (FIRMS) (https://earthdata.nasa.gov/firms).

Declarations

Ethical approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

Conflict of interest The authors declare no competing interests.

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