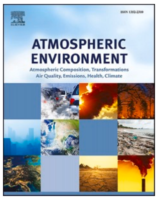
Atmospheric Environment 376 (2026) 122041

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv



Long-term trends in stubble burning in northwestern India and its impact on $PM_{2.5}$ air quality in Delhi

Haoyu Wei [a], Lei Chen [a,*], Jia Zhu [a], Xipeng Jin [a], Yang Yang [a], Hong Liao [a,b]

[a] Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, Jiangsu Collaborative Innovation Centre of Atmospheric Environment and Equipment Technology, School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, China
[b] State Key Laboratory of Climate System Prediction and Risk Management, Nanjing University of Information Science and Technology, Nanjing, China

HIGHLIGHTS

- From 2014 to 2023, the stubble burning season delays by one week, while fire intensity exhibits a decreasing trend.
- The adverse effect of delayed burning season on $PM_{2.5}$ trend may counteract air quality improvements from reduced fire events.
- Unfavorable meteorological conditions (e.g. increase in atmospheric stability) exacerbate $PM_{2.5}$ during post-monsoon season.

ABSTRACT

Stubble burning is widely recognized as a major contributor to severe $PM_{2.5}$ pollution during post-monsoon season in India. In recent years, the pattern of stubble burning in northwestern India has changed significantly, which may alter its impact on Delhi's air quality. Satellite observations show that from 2014 to 2023, the burning season delays by one week, while fire intensity exhibits a decreasing trend. GEOS-Chem simulations reveal that the environmental benefits from reduced burning events ($-1.1\ \mu g\ m^{-3}\ yr^{-1}$) are almost completely offset by the adverse effect of delayed burning season ($+0.9\ \mu g\ m^{-3}\ yr^{-1}$). Although stubble burning is a significant seasonal pollution source, its influence on $PM_{2.5}$ trend has been less pronounced than thought, which is attributed to antagonistic effects of reduced fire events and delayed burning season. Further sensitivity experiment shows observed $PM_{2.5}$ increase in Delhi is primarily resulted from unfavorable meteorological conditions (e.g. the increase in atmospheric stability).

1. Introduction

Post-monsoon air pollution remains a critical environmental challenge across the northwest Indo-Gangetic Plain (IGP) including the capital of India – Delhi (Mangaraj et al., 2025; Pawar et al., 2015). The November 2024 ″India Environmental Air Quality Monthly Report" shows that Delhi is one of the most polluted cities in India (N & Sivalingam, 2024). Large-scale stubble burning is regarded as a major cause of Delhi's poor air quality during post-monsoon season (Bikkina et al., 2019; Bray et al., 2019; Takigawa et al., 2020; Tripathi et al., 2024).

As a traditional agricultural country, India's IGP region commonly uses open burning to dispose of crop residue. This method is considered cost-effective and helps shorten agricultural production cycles (Chandra and Sinha, 2016). In Punjab and Haryana alone, approximately 21.32 million tons and 9.18 million tons of straw are burned annually, resulting in a total $PM_{2.5}$ emission of 141.65 Gg from straw burning (Beig et al., 2020). After the monsoon season, prevailing northwesterly winds transport these smoke particles to Delhi, resulting in significant air pollution (Kumar et al., 2024). The mixture of external pollution from smoke with locally emitted pollutants accumulates under stable atmospheric conditions, making it difficult to disperse and leading to a sharp deterioration in air quality (Mhawish et al., 2022). This leads to 44,000–98,000 premature deaths annually linked to particulate matter from agricultural residue burning (Lan et al., 2022). Rural crop residue burning contributes about 32% of $PM_{2.5}$-related mortality in Delhi during post-monsoon season (Hao et al., 2025).

Many studies have revealed the quantitative contribution of stubble burning on air quality in India during the post-monsoon season. Utilizing Multiple Linear Regression (MLR) and Positive Matrix Factorization (PMF) methods, Pawar and Sinha (2022) identified that paddy residue burning contributed $54 \pm 16.8\ \mu g\ m^{-3}$ to $PM_{2.5}$ at the rural site of Nadampur. Kant et al. (2022) estimated that stubble burning increased $PM_{2.5}$ concentrations in the National Capital Region (NCR) by 23%–26% compared to background levels. Kulkarni et al. (2020), using the WRF-Chem model and FINNv1.5 fire emission inventory, found that the stubble burning contributed approximately 20% of $PM_{2.5}$ concentrations

---

* Corresponding author.
E-mail address: chenlei@nuist.edu.cn (L. Chen).

https://doi.org/10.1016/j.atmosenv.2026.122041
Received 7 December 2025; Received in revised form 19 March 2026; Accepted 20 April 2026

in Delhi during October–November, and 50%–75% during extreme events. Mukherjee et al. (2020) reported that aerosols resulting from stubble burning in the northwestern states contributed over 60% of the surface-layer $PM_{2.5}$ concentration observed in Delhi during one week after Diwali in 2016. Cusworth et al. (2018) combined observations with STILT model simulations from 2012 to 2016 and identified stubble burning as a significant contributor to the elevated $PM_{2.5}$ levels observed during the post-monsoon period. A fire-detection-based approach estimated a 14% contribution to $PM_{2.5}$ concentrations in the Delhi NCR (Mangaraj et al., 2025), while a comprehensive chemical source apportionment study reported that open fires of all kinds (paddy residue burning) contribute approximately 50% (23%) (Awasthi et al., 2024).

In recent years, the pattern of post-monsoon stubble burning in northwestern India has changed significantly. On one hand, groundwater protection policy initially resulted in a delay of the burning period (Ghude et al., 2025; Liu et al., 2021). The lower planet boundary layer height (PBLH) and surface temperature during the delayed burning period may exacerbate the impact of stubble burning on $PM_{2.5}$ levels in Delhi (Liu et al., 2022). However, this impact has been partly offset by the widespread adoption of short-duration rice cultivars such as PR126 (Thakur et al., 2025). This variety matures approximately three to four weeks earlier than traditional cultivars. On the other hand, coordinated efforts between burn bans and mechanized farming practices have led to approximately a 50% reduction in fire counts in Punjab and Haryana from 2015 to 2023 (Mangaraj et al., 2025) and a growing gap between burnt area estimates using Sentinel-2 and active fire counts (Ambulkar et al., 2025). Both the delay of burning season and the decrease in stubble burning events may alter the impact of stubble burning on Delhi's air quality. Furthermore, Delhi's $PM_{2.5}$ pollution is also influenced by local emissions and meteorological conditions (Paulot et al., 2022). For example, the daily heating demand modulates the intensity of small heating fires which contribute 24% of the $PM_{2.5}$ burden during post monsoon season across the entire airshed (Awasthi et al., 2024; Navinya et al., 2023; Pawar and Sinha, 2022). Although existing studies have quantified the impact of stubble burning on Delhi's air quality in a single year, there remains a significant gap in understanding long-term contributions of stubble burning, local emissions, and meteorological conditions on $PM_{2.5}$ trends in Delhi, especially in the evolving environment of the delay of burning season and the decrease in stubble burning.

This study utilizes 375-m resolution Fire Radiative Power (FRP) data from the Suomi NPP satellite's VIIRS sensor to accurately identify the starting and ending dates of the burning season. By integrating the FINNv2.5 fire emission inventory, which combines multiple satellite fire points to capture smaller-scale fires, and employing sensitivity experiments with the GEOS-Chem model, we quantitatively assess the contribution of post-monsoon stubble burning on $PM_{2.5}$ trends in Delhi from 2014 to 2023. The impacts of delayed burning season, and reduced burning intensity are separately shown. Besides, local emission and meteorological conditions on $PM_{2.5}$ trends are also investigated. The findings will provide a scientific basis for formulating and optimizing air pollution control policies in India.

2. Materials and methods

2.1. Fire points and FRP data

To investigate the spatiotemporal distribution characteristics of stubble burning in northwestern India, this study utilizes the 375-m resolution FIRMS active fire product generated by the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the Suomi NPP satellite, launched jointly by NASA and NOAA (https://firms.modaps.eosdis.nasa.gov/). This product enables high-precision monitoring of agricultural fire points through five thermal infrared bands, with a spatial resolution of 375 m. It passes over at local time 13:30 and 01:30 daily, effectively capturing small-scale dispersed stubble burning events. The fire point identification algorithm analyzes surface temperature and solar reflectance changes to eliminate false positives from solar glint and coastal interference, ensuring data reliability (Fu et al., 2020; Schroeder et al., 2014). VIIRS is comprehensively superior to MODIS in technical performance, especially in spatial resolution and radiation performance, which has enabled it to achieve a qualitative leap in the sensitivity, accuracy, and precision of fire detection. FRP is a key parameter indicating energy released per unit time (in megawatts, MW), directly linked to combustion rate and pollutant emission intensity. Based on FRP data, this study further defines the starting and ending date of stubble burning season: the date when cumulative FRP reaches 10% (90%) marks the start (end) of the burning season. This way to define starting and ending date objectively quantifies regional burning peaks in Punjab and Haryana (Saharan et al., 2024; Zhang et al., 2014).

2.2. $PM_{2.5}$ Data

The daily $PM_{2.5}$ concentration data from ground observations is taken from the Central Pollution Control Board (CPCB) online portal (https://cpcb.nic.in/). The CPCB has established a comprehensive Continuous Ambient Air Quality Monitoring Stations (CAAQMS) network across India to monitor major air pollutants, including $PM_{2.5}$. While this network provides valuable and officially recognized air quality data, it has significant limitations in terms of completeness, accuracy, and spatial representativeness. It must be used with great caution in scientific research and often requires data correction and supplementation (Cusworth et al., 2018; Vohra et al., 2025). Therefore, we also utilize the $PM_{2.5}$ observation time series from the U.S. Embassy in New Delhi (https://github.com/dolekhanhdang/Air-Quality-Data-from-U.S.-Embassies) to cross check the reliability of both data. Our comparison reveals substantial differences between the two datasets before year 2018 (Fig. S1). For the period from 2018 to 2023, their Normalized Mean Bias (NMB) remain within 10%. Consequently, only the $PM_{2.5}$ data after year 2018 are reliable and selected for model performance evaluation. In addition, publicly accessible ground-based $PM_{2.5}$ observations reported by Pawar and Sinha (2022) are also used for model evaluation.

2.3. GEOS-chem model

We use the global atmospheric chemistry model GEOS-Chem version 13.3.3 (http://wiki.seas.harvard.edu/geos-chem/index.php?title=GEOS-Chem_versions#13.3) to simulate $PM_{2.5}$ levels in India. Simulations are conducted from 1 October to 30 November (i.e. post-monsoon season) for the years 2014–2023, with a one-month spin-up for each year. The model employs a regional nesting resolution of $0.5^\circ \times 0.625^\circ$ (65°E−105°E, 5°S–45°N) with 47 vertical layers. A coarser resolution simulation at $2^\circ \times 2.5^\circ$ over Asia provids boundary conditions every 3 h for the nested domain. The model is driven by MERRA-2 reanalysis meteorological data. The global anthropogenic emission inventory is Community Emissions Data System (CEDS v2025-04), encompassing the anthropogenic emission of various species including aerosols, aerosol precursors, and reactive compounds (Hoesly et al., 2018).

In terms of fire emissions, this study utilizes the FINN version 2.5 fire emission inventory provided by the National Center for Atmospheric Research (NCAR) (https://rda.ucar.edu/datasets/ds312.9/). This dataset combines satellite-observed active fire information and land cover data with emission factors and fuel load estimates to provide daily updated fire emission data at a 1-km spatial resolution. The FINNv2.5 is an update to the original FINN version 1, significantly improving spatial resolution by using 375-m resolution VIIRS data, allowing for more accurate capture of smaller-scale fire emissions (Wiedinmyer et al., 2023). This improvement has made the dataset particularly effective in estimating fire emissions, especially in northwestern India. Previous global fire emission inventories often underestimated actual emissions in this region, while FINNv2.5 has proven to be one of the most accurate fire inventories available (Liu et al., 2019, 2020).

In northwestern India, there are various types of fire activities during the post-monsoon season, such as stubble burning, open waste burning in landfills, and residential heating (Hakkim et al., 2019). However, the majority of FRP are related to crop stubble burning, while other types account for a smaller proportion (Liu et al., 2018). Therefore, it is both reasonable to use fire emission inventory to quantify agricultural residue burning activities for northwestern India during post-monsoon season.

2.4. *Numerical experiment*

Baseline experiment (BASE) with biomass burning emission, anthropogenic emissions, and meteorological field variable from 2014 to 2023 is designed for model evaluation. BB-Sen experiment with only biomass burning emission variable annually while anthropogenic emission and meteorological field are fixed at 2018 is designed to investigate the impacts of biomass burning emission (i.e. crop stubble burning) on $PM_{2.5}$ trends. To further analyze the relative impacts of combustion intensity and burning date in BB-Sen, two additional experiments are conducted: BB_Intensity-Sen experiment with only the intensity of biomass burning variable annually while burning date, anthropogenic emission, and meteorological field are fixed at 2018; BB_Delay-Sen experiment with only the starting and ending date of biomass burning variable annually while combustion intensity, anthropogenic emission, and meteorological field are fixed at 2018.

Another two sensitivity experiments are conducted to quantify the impacts of anthropogenic emission and meteorological variation on Delhi's $PM_{2.5}$ trends: Ant-Sen experiment with only anthropogenic emission variable annually while meteorological field and biomass burning emission are fixed at 2018; Met-Sen experiment with only meteorological field variable annually while anthropogenic and biomass burning emission are fixed at 2018. The experimental design is provided in tabular form in Supplementary Table S1.

3. Results

3.1. *Model performance*

As shown in Section 2.2, only the observed $PM_{2.5}$ data after year 2018 are reliable and therefore this study only selectes post-monsoon season CPCB monitoring data from 2018 to 2023 for model performance evaluation. The comparison with observational data indicates that the model simulation (BASE) effectively reproduces the $PM_{2.5}$ variations during the post-monsoon season in Delhi. From an interannual perspective (Fig. 1a), simulated $PM_{2.5}$ concentrations show a continuous increase from 2014 to 2018, followed by fluctuations after 2018, consistent with CPCB ground observations. Quantitative assessments reveal a systematic underestimation of simulated $PM_{2.5}$ concentrations compared to observations from 2018 to 2023, with a mean bias (MB) of $-24.1\ \mu g\ m^{-3}$ and a NMB of −14.9%. We also incorporate $PM_{2.5}$ measurements from Pawar and Sinha (2022), which exhibits a similar underestimation (Fig. S2). The MB of AOD between simulations and MODIS observations in Delhi is −0.39, with an NMB of −44.8% (Fig. S3). The underestimation primarily stems from the model's inadequate ability to simulate extreme high values of particulate pollution during the post-monsoon season in Delhi (Jat et al., 2024; Jena et al., 2021; Kumar et al., 2020; Nagar and Sharma, 2022). However, the simulated and observed daily $PM_{2.5}$ concentrations during post-monsoon season exhibit high correlation coefficients, ranging from 0.62 to 0.83 (Fig. 1b–g), which indicates that while the model generally underestimates absolute concentrations, it reliably captures the daily variations.

Fig. S4 exhibits the spatial distribution of AOD. The simulated multi-

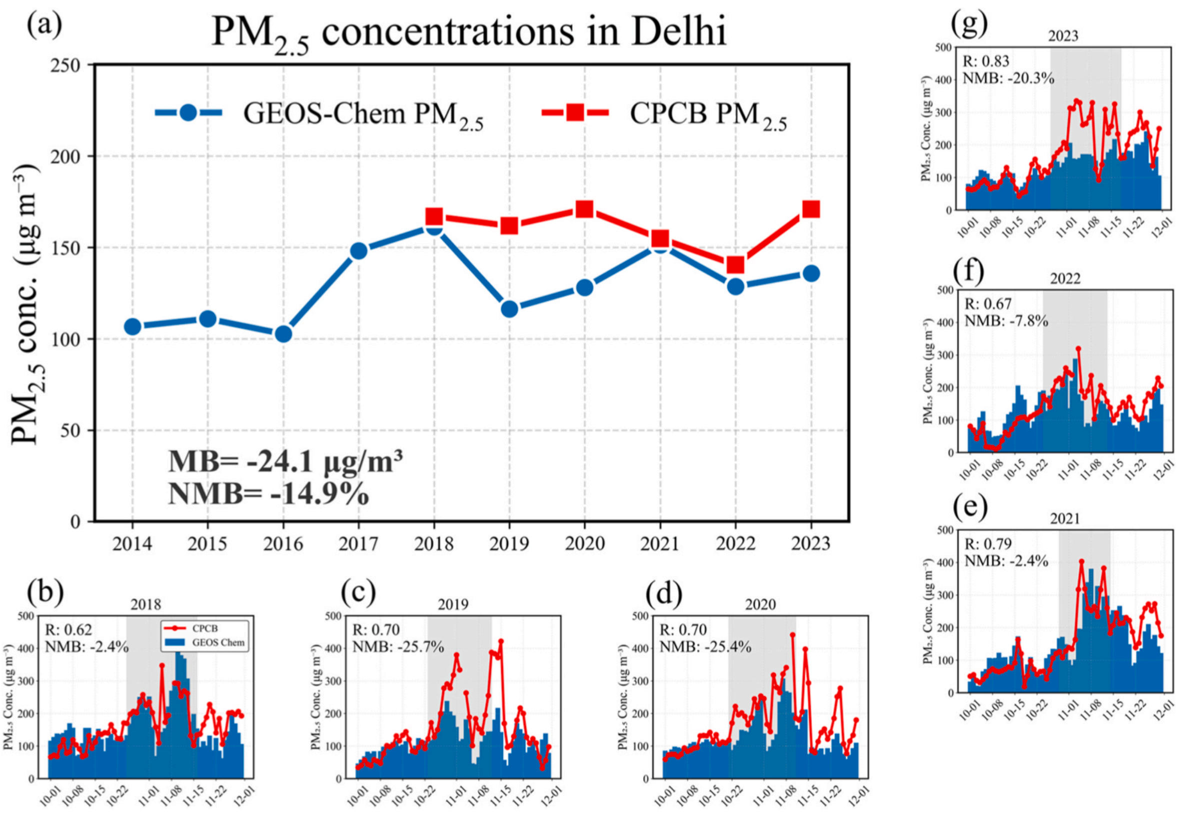


Fig. 1. Comparison of simulated (GEOS-Chem) and observed (CPCB) $PM_{2.5}$ concentrations during post-monsoon season in Delhi. (a) Yearly $PM_{2.5}$ concentrations from 2014 to 2023; (b–g) Daily $PM_{2.5}$ concentrations for 2018–2023. Shaded gray areas indicate the starting and ending dates of the straw stubble burning season. R, MB, and NMB represent correlation coefficient, mean bias, and normalized mean bias, respectively.

year average AOD for India is 0.35, while MODIS AOD is 0.46, indicating an underestimation of 23.9%. Although FINNv2.5 has enhanced its capability to capture small fire events, the emissions inventory for fires may still be underestimated in conditions of cloud cover or smoke obscuration (Kajino et al., 2025). Additionally, the model inadequately characterizes the generation and aging mechanisms of secondary organic aerosols from stubble burning (Zhu et al., 2023). Nevertheless, the spatial distribution patterns of both simulated and observed AOD exhibit a high degree of consistency, with a spatial correlation coefficient of 0.81. Both datasets reveal a significant gradient from south to north, with high values predominantly concentrated in IGP. This distribution is primarily influenced by topographical blocking and cumulative emissions. The Himalayan terrain obstructs airflow coupling with stubble burning (October–November) and urban anthropogenic emissions, leading to sustained aerosol accumulation in the IGP region (Hassan et al., 2023).

3.2. Temporal-spatial characteristics of stubble burning

We first analyze the spatiotemporal characteristics of post-monsoon FRP in India from 2014 to 2023. Fig. 2a shows the spatial distribution of FRP during post-monsoon season across Indian states. Northwestern states in India, especially Punjab and Haryana, account for a significant portion of the total FRP. The Green Revolution turns Punjab and Haryana into India's breadbaskets, producing sufficient rice and wheat for the nation, while also leading to the widespread practice of burning massive crop residue (Kaur and Chauhan, 2024; Kumar et al., 2016; Liu et al., 2021). During the study period, India's average FRP is 594 GW, with Punjab and Haryana contributing 461.3 GW—77.7% of the total FRP (detailed state-level FRP can be found in Table S2). Therefore, fire emissions from Punjab and Haryana serve as an important regional source influencing $PM_{2.5}$ levels in Delhi (Kulkarni et al., 2020). However, it should also be noted that stubble burning in the eastern NCR and within Delhi itself may have a non-negligible impact due to their closer proximity and the potential underestimation of fire activity by satellite-based products in these regions (Awasthi et al., 2024).

Utilizing VIIRS S-NPP 375m active fire data, we obtain daily fire point information, including latitude, longitude, FRP values, and confidence levels. After excluding fire points with low confidence ratings, we accumulate the FRP from all valid fire points within the study area on a daily basis to generate a time series of total FRP. The starting and ending dates of the burning season are defined as the dates when cumulative FRP reaches 10% and 90% of the total FRP during the post-monsoon period. To enhance the robustness and comparability of our results, this study also conducts comparative analyses using multiple threshold sets (5%–95%, 15%–85%, 20%–80%, and 25%–75%) to assess sensitivity in identifying the burning season (Fig. 2b). The stubble burning events mainly occur from mid-late October to early-mid November. We notice a highly notable and robust phenomenon that both the starting date and ending dates of burning season delay by about

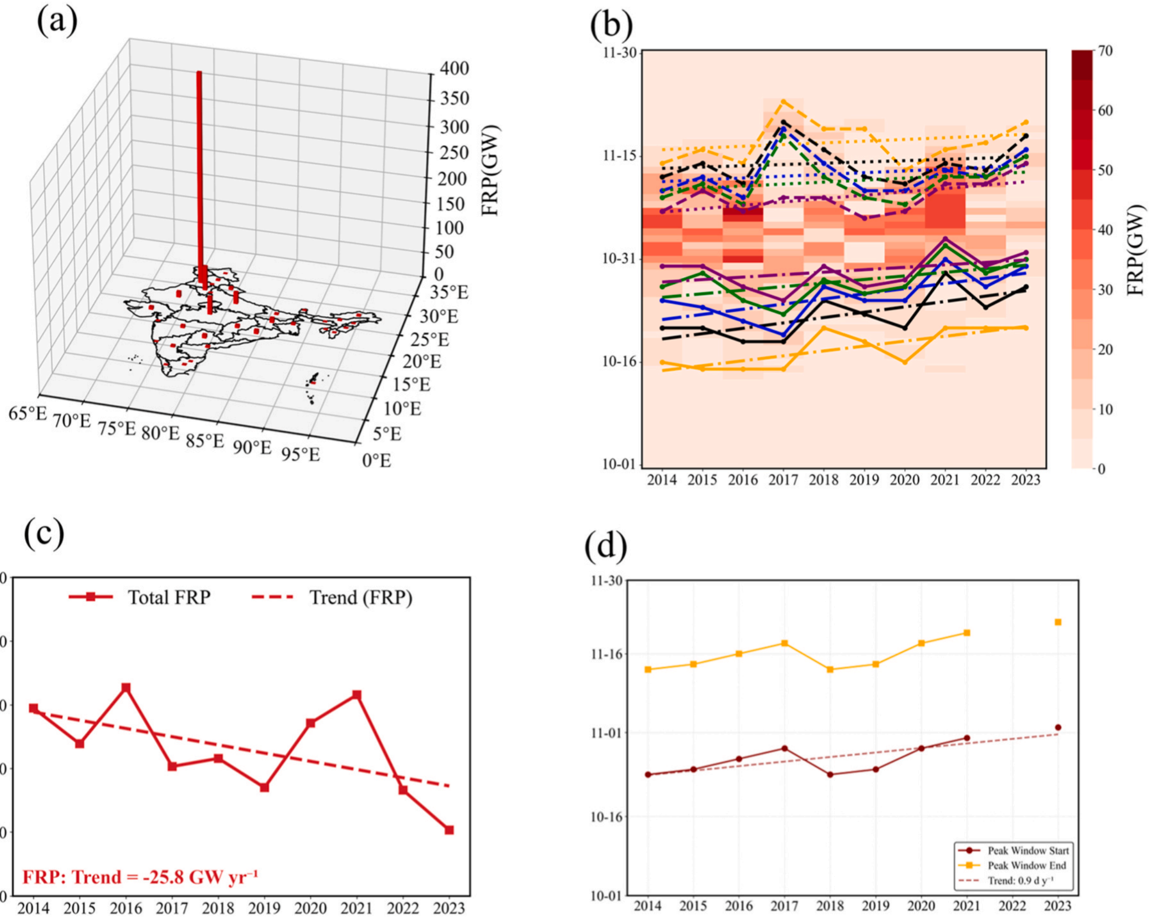


Fig. 2. Spatiotemporal characteristics of stubble burning in India from 2014 to 2023. (a) The FRP across Indian states during post-monsoon averaged from 2014 to 2023. (b) Daily FRP during the post-monsoon period from 2014 to 2023 in Punjab and Haryana. Solid and dashed lines indicate the starting date and ending date of the burning season. Different colors represent varying thresholds for determining these dates (5%, 10%, 15%, 20%, and 25%). (c) Yearly total FRP from 2014 to 2023 in Punjab and Haryana. (d) Yearly starting date and ending date of the burning season based on the peak 21-day CO column data window taken from MOPITT in Punjab and Haryana from 2014 to 2023. The data for year 2022 are excluded due to the substantial amounts of missing value. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

one week ($p < 0.05$) from 2014 to 2023. Initially, the implementation of the Groundwater Conservation Policy by the Indian government in 2009 led to a substantial postponement of burning activities (Ghude et al., 2025). However, in recent years, the frequent delay in the withdrawal of the monsoon has emerged as a potential and critical meteorological driver for the continued shift in the burning season. The India Meteorological Department significantly revised the normal date for the monsoon's withdrawal from Northwest India, shifting it from September 1 to September 17 (Prabhu and Chitale, 2024; Sharma et al., 2025), which further postponed the date of burning activity during post-monsoon season. What's more, this delay primarily characterizes the burning trends of traditional long-duration cultivars, such as PUSA-44, which mature later and concentrate residue burning between late October and November. In contrast, the short-duration cultivar PR-126, which introduced by Punjab Agricultural University in 2016, matures as early as late September. These early burning activities often exhibit lower thermal intensity and are frequently missed by satellite monitoring, particularly fire detection which is easily obscured or avoided during the retreating monsoon period (Ambulkar et al., 2025). The total FRP shows a declining trend of -25.8 GW yr^{-1} during the ten years (Fig. 2c). This drop is linked to a mix of factors, including government-led policies to reduce stubble burning and abnormal rainfall during the harvest season. The Indian government has vigorously promoted the “Happy Seeder” and enhanced the utilization of crop residues, while authorities hold the power to impose environmental compensation fees on farmers who engage in stubble burning (CAQM, 2023, 2024).

It is noted that farmers may delay the burning activity until late afternoon to avoid the overpass times of the satellite sensor (Biswal et al., 2025). Carbon monoxide (CO) is an excellent tracer for smoldering biomass burning and is less sensitive to satellite overpass times compared to thermal hotspots. To provide more robust evidence, we analyze CO column concentration data taken from MOPITT (2014–2023) to validate the burning windows. Fig. 2d also exhibits a highly robust phenomenon that both the starting date and ending dates of burning season delay by about one week ($p < 0.05$) from 2014 to 2023, which supports the conclusion drawn from active fire detection. Besides, we also use harvest calendar to identify the start of the burning season. Following Liu et al. (2021), we retrieve MOD09GA data through Google Earth Engine to calculate Normalized Difference Vegetation Index (NDVI). We identify a specific 14-day window with the minimum NDVI values to characterize the peak burning period and subsequently analyze the 10-year trends of the peak windows. Fig. S5 exhibits a discernible delay in the timing of the 14-day rolling average NDVI minimum.

3.3. Impacts of stubble burning on $PM_{2.5}$ trends in Delhi

As shown in Fig. 2, the FRP shows a decreasing trend while the burning season delays by about one week during 2014–2023, both of which may influence $PM_{2.5}$ trends in Delhi. To distinguish the respective effects of fire intensity and burning season delay, we set up two sensitivity scenarios: one allowing only annual variations in burning intensity (BB_Intensity-Sen) and another permitting only changes in starting and ending dates of burning season (BB_Delay-Sen). The BB-Sen experiment includes both changes.

Fig. 3a shows the $PM_{2.5}$ variations in Delhi owing to variations in fire intensity and burning season delay. The decrease in fire intensity leads to $PM_{2.5}$ decline in Delhi with a trend of $-1.1\ \mu g\ m^{-3}\ yr^{-1}$ during 2014–2023, while the burning season delay results in $PM_{2.5}$ increase with a trend of $+0.9\ \mu g\ m^{-3}\ yr^{-1}$. The delay of burning season is always accompanied by lower PBLH, which is not conducive to the dispersion of $PM_{2.5}$ pollution. This opposite trend highlights the antagonistic effects: the $PM_{2.5}$ pollution exacerbation due to burning season delay significantly undermines potential environmental benefits from reduced fire intensity. When combined effects of fire intensity and burning season

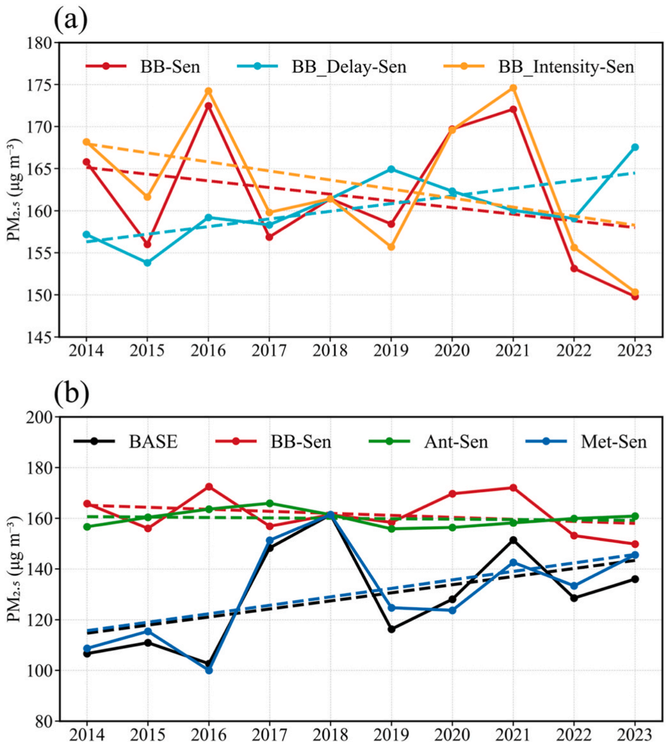


Fig. 3. Impacts of each factor on $PM_{2.5}$ trends in Delhi during post-monsoon season from 2014 to 2023. (a) Yearly variations in $PM_{2.5}$ concentrations driven by respective changes in fire intensity (BB_Intensity-Sen) and burning season delay (BB_Delay-Sen), as well as combined changes (BB-Sen). (b) Yearly variations in $PM_{2.5}$ concentrations owing to respective changes in anthropogenic emission (Ant-Sen), meteorological factors (Met-Sen), biomass burning emission (BB-Sen), and combined changes (BASE).

delay are considered, the $PM_{2.5}$ levels exhibit no statistically significant trend.

3.4. Other factors influencing $PM_{2.5}$ trends in Delhi

Observed $PM_{2.5}$ increase in Delhi (Fig. 1a) can not be totally explained by the impact of stubble burning (Fig. 3a). Therefore, there must be other factors driving $PM_{2.5}$ trends in Delhi. Another two sensitivity experiments are designed to quantify the long-term impacts of anthropogenic emission and meteorological variations on $PM_{2.5}$ concentrations in Delhi. Fig. 3b shows the $PM_{2.5}$ variations in Delhi owing to the respective impact of anthropogenic emission (Ant-Sen), meteorology (Met-Sen), stubble burning (BB-Sen), and combined effects (BASE).

We find that the meteorologically driven $PM_{2.5}$ trend is $+3.3\ \mu g\ m^{-3}\ yr^{-1}$, close to the BASE result ($+3.2\ \mu g\ m^{-3}\ yr^{-1}$), indicating that meteorological conditions play a leading role in regulating post-monsoon $PM_{2.5}$ trends in Delhi. From 2014 to 2023, meteorological factors experience significant changes (Fig. 4). The temperature difference between the surface and 850 hPa exhibits a decreasing trend of $-0.1\ ^{\circ}C\ yr^{-1}$, and the ventilation coefficient shows a decreasing trend of $-67.3\ m^2\ s^{-1}\ yr^{-1}$, both of which reflect an increase in atmospheric stability that suppresses vertical mixing and promotes the accumulation of $PM_{2.5}$ near the surface (Rathore et al., 2025). The relative humidity has risen significantly at a rate of $+3.2\%\ yr^{-1}$, which facilitates the increase in aerosol liquid water content and promotes the formation of secondary aerosols, consequently leading to a substantial rise in total $PM_{2.5}$ concentrations (An et al., 2019; Ervens et al., 2011). This rise is likely driven and amplified by the widespread adoption of short-duration rice cultivars harvested in September which has shifted wheat sowing into the second half of October a timing conducive for high wheat yields (Lobell et al., 2013). This has shifted the first wheat

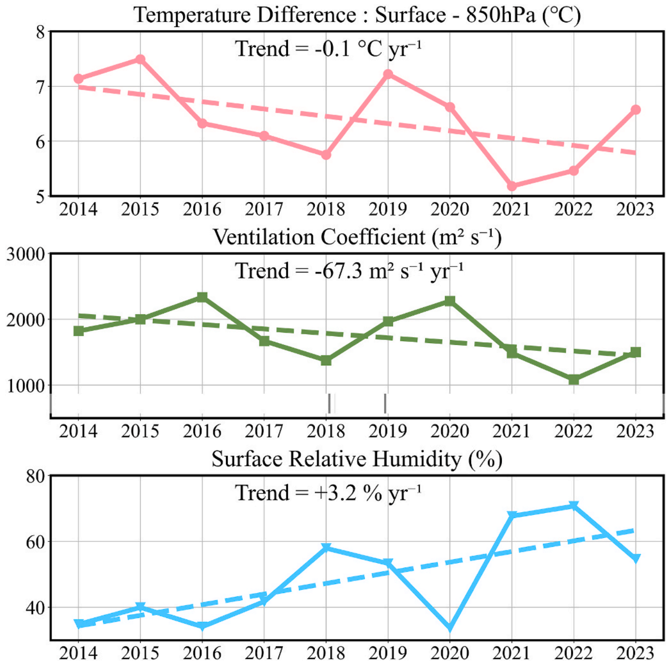


Fig. 4. Yearly temperature difference, ventilation coefficient, and surface relative humidity in Delhi during post-monsoon season from 2014 to 2023.

irrigation (21 days after sowing) into November a time that overlaps with the paddy residue burning of long duration paddy cultivars. Simultaneously, as a strategic adaptation to circumvent satellite monitoring, farmers have recently begun implementing irrigation to cool the soil surface during or immediately after burning. To validate these trends, we also compare the above meteorological trends with ERA5 reanalysis data. As shown in Fig. S6, the temperature difference, the ventilation coefficient, and the relative humidity also exhibit the similar trends.

In contrast, the $PM_{2.5}$ concentration driven by human-made emissions shows a slight decreasing trend of $-0.2\ \mu g\ m^{-3}\ yr^{-1}$. According to the CEDS inventory, the NO, NH_3, and BC emissions have not showed significant decreases from 2014 to 2023; only SO_2 emission decreases significantly (Fig. S7). Despite the implementation of policies such as the National Clean Air Plan (NCAP) and Graded Response Action Plan (GRAP) in recent years (Jha et al., 2025), this study shows that their effectiveness remains limited. According to the high-resolution source apportionment study by Awasthi et al. (2024), biomass burning remains the primary driver of $PM_{2.5}$ pollution in Delhi during the post-monsoon period. CNG vehicles (largely via non-exhaust emissions) and industrial activities account for 11% and 8% of the $PM_{2.5}$ mass loading. Strengthening measures to reduce anthropogenic emissions may be necessary to mitigate Delhi's air pollution (Chutia et al., 2024; Govardhan et al., 2024).

4. Limitations

Although VIIRS has enhanced capabilities for detecting smaller fires, satellite-based fire detection and associated biomass burning emission inventories (e.g., FINNv2.5) still suffer from inherent limitations. These stem from factors including finite satellite overpasses, persistent cloud cover during peak burning periods, farmers' intentional avoidance of satellite detection during residue burning, and irrigation post burning to cool down the thermal anomaly (Biswal et al., 2025; Liu et al., 2019; Pawar and Sinha, 2022), which may cause uncentainties in burning season date and FRP trends. Recently, Kumar et al. (2021) combined district-wise crop yield data with locally measured emission factors for 77 volatile organic compounds (VOCs) to develop a high-resolution (1 km × 1 km) emission inventory for paddy stubble burning in northwest India. Their results revealed substantially higher emissions of key pollutants (e.g., $PM_{2.5}$, 2-furaldehyde, acetaldehyde) compared to traditional inventories. Using such advanced inventories may significantly improve model performance in future studies.

The global CEDS inventory used in this study may not fully capture the rapidly evolving emission landscape in India, particularly the transportation sector. Recent studies have emphasized the scale and importance of these changes. For instance, Mogno et al. (2024) and Hakkim et al. (2022) quantified the emission reduction benefits of fleet replacement strategies under future scenarios. Awasthi et al. (2024) highlighted that current anthropogenic emission inventories failed to accurately reflect real-world conditions. This rapidly changing context underscores the inherent challenges and uncertainties in accurately attributing source contributions. Future studies incorporating updated emission inventories such as RTEII (Hakkim et al., 2021) will be helpful to more accurately assess impacts of different sectors on regional air quality.

Furthermore, the assessment of other factors influencing Delhi's air quality would benefit a lot from including daily heating demand. The contribution of residential heating-related combustion may serve as an important driver for Delhi's air quality during the post-monsoon season (Awasthi et al., 2024; Pawar and Sinha, 2022). More detailed and up to date regional inventory should be used by future model studies to investigate the impact of daily heating demand.

5. Conclusions

Stubble burning is traditionally identified as a major seasonal pollution source, directly contributing to elevated $PM_{2.5}$ concentrations in Delhi during post-monsoon season. In recent years, the pattern of post-monsoon stubble burning in northwestern India has changed significantly, which may alter the impact of stubble burning on Delhi's air quality. Based on satellite observations, this study investigates spatiotemporal characteristics of post-monsoon stubble burning in India from 2014 to 2023, and quantitatively assess its contribution on $PM_{2.5}$ trends in Delhi by using GEOS-Chem model.

Northwestern states in India, especially Punjab and Haryana, account for a significant portion of the total FRP. From 2014 to 2023, the stubble burning season delays by approximately one week, while fire intensity shows a declining trend. These changed patterns are largely associated with a series of policies implemented by the Indian government.

Sensitivity experiments indicate that the delayed burning season leads to an increasing trend in Delhi's $PM_{2.5}$ concentrations at a rate of $+0.9\ \mu g\ m^{-3}\ yr^{-1}$, whereas the decline in burning intensity results in a decreasing trend of $-1.1\ \mu g\ m^{-3}\ yr^{-1}$. This suggests that the two factors exert counteracting effects on Delhi's air quality: the environmental benefits from reduced burning intensity are almost completely offset by the adverse effect of a delayed burning season. When considering both effects, Delhi's $PM_{2.5}$ levels show no statistically significant trend, implying that changes in stubble burning alone cannot account for the observed $PM_{2.5}$ increase during post-monsoon season in Delhi.

Given that anthropogenic emissions and meteorological conditions collectively influence $PM_{2.5}$ concentrations, we further quantify the impacts of local emissions and meteorological variations on Delhi's air quality. The results indicate that meteorological variability is the primary factor driving $PM_{2.5}$ rises with a trend of $+3.3\ \mu g\ m^{-3}\ yr^{-1}$. In contrast, anthropogenic emissions contribute little to Delhi's $PM_{2.5}$ trend. Given that current emission policies have only been partially successful, more strict emission reduction measures should be taken to mitigate Delhi's air pollution.

Overall, although stubble burning is a significant pollution source during post-monsoon for Delhi, its influence on the multi-year trend in $PM_{2.5}$ concentrations has been less pronounced than previously thought, which can be attributed to the antagonistic effects of reduced fire events and delayed burning season. The observed $PM_{2.5}$ increase in Delhi primarily results from unfavorable meteorological conditions.

CRediT authorship contribution statement

Haoyu Wei: Data curation, Investigation, Writing – original draft. **Lei Chen:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Jia Zhu:** Data curation, Funding acquisition, Software, Writing – review & editing. **Xipeng Jin:** Formal analysis, Writing – review & editing. **Yang Yang:** Software, Writing – review & editing. **Hong Liao:** Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (Grants 42305121, 42293323). Constructive comments from three reviewers helped improve the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2026.122041.

Data availability

Fire Points and FRP Data generated by the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the Suomi NPP satellite are available at https://firms.modaps.eosdis.nasa.gov/. The observed $PM_{2.5}$ concentration data from the Central Pollution Control Board (CPCB) can be accessed at https://cpcb.nic.in/. The $PM_{2.5}$ measurements from the U.S. Embassy are accessible at https://github.com/dolekhanhdang/Air-Quality-Data-from-U.S.-Embassies. The FINN version 2.5 fire emission inventory provided by the National Center for Atmospheric Research (NCAR) can be accessed at https://rda.ucar.edu/datasets/ds312.9/. The Community Emissions Data System (CEDS) emission data are available at Zenodo: https://zenodo.org/records/15127477. The MOPITT CO gridded daily means (Near and Thermal Infrared Radiances) V009 can be accessed at https://search.earthdata.nasa.gov/.

References

Ambulkar, R., Govardhan, G., Gavhale, S., Kalita, G., Pande, C., Jat, R., et al., 2025. Crop residue burning in north-western India: emission estimation and uncertainty quantification. J. Geophys. Res. Atmos. 130 (4). https://doi.org/10.1029/2024jd042198.

An, Z., Huang, R.J., Zhang, R., Tie, X., Li, G., Cao, J., et al., 2019. Severe haze in northern China: a synergy of anthropogenic emissions and atmospheric processes. Proc. Natl. Acad. Sci. U. S. A. 116 (18), 8657–8666. https://doi.org/10.1073/pnas.1900125116.

Awasthi, A., Sinha, B., Hakkim, H., Mishra, S., Mummidivarapu, V., Singh, G., et al., 2024. Biomass-burning sources control ambient particulate matter, but traffic and industrial sources control volatile organic compound (VOC) emissions and secondary-pollutant formation during extreme pollution events in Delhi. Atmos. Chem. Phys. 24 (18), 10279–10304. https://doi.org/10.5194/acp-24-10279-2024.

Beig, G., Sahu, S.K., Singh, V., Tikle, S., Sobhana, S.B., Gargeva, P., et al., 2020. Objective evaluation of stubble emission of North India and quantifying its impact on air quality of Delhi. Sci. Total Environ. 709, 136126. https://doi.org/10.1016/j.scitotenv.2019.136126.

Bikkina, S., Andersson, A., Kirillova, E.N., Holmstrand, H., Tiwari, S., Srivastava, A.K., et al., 2019. Air quality in megacity Delhi affected by countryside biomass burning. Nat. Sustain. 2 (3), 200–205. https://doi.org/10.1038/s41893-019-0219-0.

Biswal, A., Takigawa, M., Mangaraj, P., Bisht, J.S.H., Patra, P.K., Matsumi, Y., et al., 2025. Emission time and amount of crop residue burning play critical role on PM2.5 variability during October–November in northwestern India during 2022–2024. Environ. Sci. J. Integr. Environ. Res.: Atmosphere 5 (11), 1211–1229. https://doi.org/10.1039/d5ea00052a.

Bray, C.D., Battye, W.H., Aneja, V.P., 2019. The role of biomass burning agricultural emissions in the indo-gangetic plains on the air quality in New Delhi, India. Atmos. Environ. 218. https://doi.org/10.1016/j.atmosenv.2019.116983.

CAQM, 2023. *Environment (utilisation of crop residue by thermal power plants) rules, 2023* commission for air quality management in National Capital Region and adjoining areas. Retrieved from. https://caqm.nic.in/Index1.aspx?lsid=2&lev=1&lid=2&langid=1.

CAQM, 2024. CAQM in NCR and adjoining area (imposition, collection and utilization of environmental compensation for stubble burning) amendment rules, 2024 Commission for Air Quality Management in National Capital Region and Adjoining Areas Retrieved from. https://caqm.nic.in/Index1.aspx?lsid=2&lev=1&lid=2&langid=1.

Chandra, B.P., Sinha, V., 2016. Contribution of post-harvest agricultural paddy residue fires in the N.W. indo-gangetic plain to ambient carcinogenic benzenoids, toxic isocyanic acid and carbon monoxide. Environ. Int. 88, 187–197. https://doi.org/10.1016/j.envint.2015.12.025.

Chutia, L., Wang, J., Zhang, H., Chen, X., Castro Garcia, L., Janechek, N., 2024. Elucidating the impacts of aerosol radiative effects for mitigating surface O3 and PM2.5 in Delhi, India during crop residue burning period. Atmos. Environ. 339. https://doi.org/10.1016/j.atmosenv.2024.120890.

Cusworth, D.H., Mickley, L.J., Sulprizio, M.P., Liu, T., Marlier, M.E., DeFries, R.S., et al., 2018. Quantifying the influence of agricultural fires in northwest India on urban air pollution in Delhi, India. Environ. Res. Lett. 13 (4). https://doi.org/10.1088/1748-9326/aab303.

Ervens, B., Turpin, B.J., Weber, R.J., 2011. Secondary organic aerosol formation in cloud droplets and aqueous particles (aqSOA): a review of laboratory, field and model studies. Atmos. Chem. Phys. 11 (21), 11069–11102. https://doi.org/10.5194/acp-11-11069-2011.

Fu, Y., Li, R., Wang, X., Bergeron, Y., Valeria, O., Chavardès, R.D., et al., 2020. Fire detection and fire radiative power in forests and low-biomass lands in northeast Asia: MODIS versus VIIRS fire products. Remote Sens. 12 (18). https://doi.org/10.3390/rs12182870.

Ghude, S.D., Kalita, G., Jat, R., Govardhan, G., Debnath, S., Yadav, P.P., et al., 2025. The role of atmospheric feedback and groundwater conservation policies in degrading air quality in Delhi. npj Clean Air 1 (1). https://doi.org/10.1038/s44407-025-00012-x.

Govardhan, G., Ghude, S.D., Kumar, R., Sharma, S., Gunwani, P., Jena, C., et al., 2024. Decision support system version 1.0 (DSS v1.0) for air quality management in Delhi, India. Geosci. Model Dev. (GMD) 17 (7), 2617–2640. https://doi.org/10.5194/gmd-17-2617-2024.

Hakkim, H., Kumar, A., Annadate, S., Sinha, B., Sinha, V., 2021. RTEII: a new high-resolution (0.1° × 0.1°) road transport emission inventory for India of 74 speciated NMVOCs, CO, NOx, NH3, CH4, CO2, PM2.5 reveals massive overestimation of NOx and CO and missing nitromethane emissions by existing inventories. Atmos. Environ. X 11. https://doi.org/10.1016/j.aeaoa.2021.100118.

Hakkim, H., Kumar, A., Sinha, B., Sinha, V., 2022. Air pollution scenario analyses of fleet replacement strategies to accomplish reductions in criteria air pollutants and 74 VOCs over India. Atmos. Environ. X 13. https://doi.org/10.1016/j.aeaoa.2022.100150.

Hakkim, H., Sinha, V., Chandra, B.P., Kumar, A., Mishra, A.K., Sinha, B., et al., 2019. Volatile organic compound measurements point to fog-induced biomass burning feedback to air quality in the megacity of Delhi. Sci. Total Environ. 689, 295–304. https://doi.org/10.1016/j.scitotenv.2019.06.438.

Hao, Y., Strahl, J., Khare, P., Cui, T., Schneider-Beltran, K., Qi, L., et al., 2025. Transported smoke from crop residue burning as the major source of organic aerosol and health risks in northern Indian cities during post-monsoon. Environ. Int. 202, 109583. https://doi.org/10.1016/j.envint.2025.109583.

Hassan, M.A., Mehmood, T., Liu, J., Luo, X., Li, X., Tanveer, M., et al., 2023. A review of particulate pollution over Himalaya region: characteristics and salient factors contributing ambient PM pollution. Atmos. Environ. 294. https://doi.org/10.1016/j.atmosenv.2022.119472.

Hoesly, R.M., Smith, S.J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., et al., 2018. Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the community emissions data system (CEDS). Geosci. Model Dev. (GMD) 11 (1), 369–408. https://doi.org/10.5194/gmd-11-369-2018.

Jat, R., Jena, C., Yadav, P.P., Govardhan, G., Kalita, G., Debnath, S., et al., 2024. Evaluating the sensitivity of fine particulate matter (PM2.5) simulations to chemical mechanism in WRF-chem over Delhi. Atmos. Environ. 323. https://doi.org/10.1016/j.atmosenv.2024.120410.

Jena, C., Ghude, S.D., Kumar, R., Debnath, S., Govardhan, G., Soni, V.K., et al., 2021. Performance of high resolution (400 m) PM(2.5) forecast over Delhi. Sci. Rep. 11 (1), 4104. https://doi.org/10.1038/s41598-021-83467-8.

Jha, N., Pandey, A., Khan, U., Gupta, A., Gour, C.P., 2025. The role of public in mitigating air pollution in Delhi (2004-2024): a critical review. Environ. Claims J. 1–44. https://doi.org/10.1080/10406026.2025.2537092.

Kajino, M., Ishijima, K., Ching, J., Yamaji, K., Ishikawa, R., Kajikawa, T., et al., 2025. Impact of post-monsoon crop residue burning on PM2.5 over northern India: optimizing emissions using a high-density in situ surface observation network. Atmos. Chem. Phys. 25 (13), 7137–7160. https://doi.org/10.5194/acp-25-7137-2025.

Kant, Y., Chauhan, P., Natwariya, A., Kannaujiya, S., Mitra, D., 2022. Long term influence of groundwater preservation policy on stubble burning and air pollution over north-west India. Sci. Rep. 12 (1), 2090. https://doi.org/10.1038/s41598-022-06043-8.

Kaur, S., Chauhan, S., 2024. Dynamics of agricultural transformation in Punjab: crop trends, instability and decomposition analysis. Environ. Monit. Assess. 196 (9). https://doi.org/10.1007/s10661-024-12979-3.

Kulkarni, S.H., Ghude, S.D., Jena, C., Karumuri, R.K., Sinha, B., Sinha, V., et al., 2020. How much does large-scale crop residue burning affect the air quality in Delhi? Environ. Sci. Technol. 54 (8), 4790–4799. https://doi.org/10.1021/acs.est.0c00329.

Kumar, A., Hakkim, H., Sinha, B., Sinha, V., 2021. Gridded 1 km x 1 km emission inventory for paddy stubble burning emissions over north-west India constrained by measured emission factors of 77 VOCs and district-wise crop yield data. Sci. Total Environ. 789, 148064. https://doi.org/10.1016/j.scitotenv.2021.148064.

Kumar, R., Ghude, S.D., Biswas, M., Jena, C., Alessandrini, S., Debnath, S., et al., 2020. Enhancing accuracy of air quality and temperature forecasts during paddy crop residue burning season in Delhi via chemical data assimilation. J. Geophys. Res. Atmos. 125 (17). https://doi.org/10.1029/2020jd033019.

Kumar, R.P., Singh, R., Kumar, P., Kumar, R., Nahid, S., Singh, S.K., Nijjar, C.S., 2024. Aerosol-PM2.5 dynamics: in-situ and satellite observations under the influence of regional crop residue burning in post-monsoon over Delhi-NCR, India. Environ. Res. 255, 119141. https://doi.org/10.1016/j.envres.2024.119141.

Kumar, V., Sarkar, C., Sinha, V., 2016. Influence of post-harvest crop residue fires on surface ozone mixing ratios in the N.W. IGP analyzed using 2 years of continuous in situ trace gas measurements. J. Geophys. Res. Atmos. 121 (7), 3619–3633. https://doi.org/10.1002/2015jd024308.

Lan, R., Eastham, S.D., Liu, T., Norford, L.K., Barrett, S.R.H., 2022. Air quality impacts of crop residue burning in India and mitigation alternatives. Nat. Commun. 13 (1), 6537. https://doi.org/10.1038/s41467-022-34093-z.

Liu, T., Marlier, M.E., DeFries, R.S., Westervelt, D.M., Xia, K.R., Fiore, A.M., et al., 2018. Seasonal impact of regional outdoor biomass burning on air pollution in three Indian cities: delhi, Bengaluru, and Pune. Atmos. Environ. 172, 83–92. https://doi.org/10.1016/j.atmosenv.2017.10.024.

Liu, T., Marlier, M.E., Karambelas, A., Jain, M., Singh, S., Singh, M.K., et al., 2019. Missing emissions from post-monsoon agricultural fires in northwestern India: regional limitations of MODIS burned area and active fire products. Environ. Res. Commun. 1 (1). https://doi.org/10.1088/2515-7620/ab056c.

Liu, T., Mickley, L.J., Gautam, R., Singh, M.K., DeFries, R.S., Marlier, M.E., 2021. Detection of delay in post-monsoon agricultural burning across Punjab, India: potential drivers and consequences for air quality. Environ. Res. Lett. 16 (1). https://doi.org/10.1088/1748-9326/abcc28.

Liu, T., Mickley, L.J., Patel, P.N., Gautam, R., Jain, M., Singh, S., et al., 2022. Cascading delays in the monsoon rice growing season and postmonsoon agricultural fires likely exacerbate air pollution in North India. J. Geophys. Res. Atmos. 127 (24). https://doi.org/10.1029/2022jd036790.

Liu, T., Mickley, L.J., Singh, S., Jain, M., DeFries, R.S., Marlier, M.E., 2020. Crop residue burning practices across North India inferred from household survey data: bridging gaps in satellite observations. Atmos. Environ. X 8. https://doi.org/10.1016/j.aeaoa.2020.100091.

Lobell, D.B., Ortiz-Monasterio, J.I., Sibley, A.M., Sohu, V.S., 2013. Satellite detection of earlier wheat sowing in India and implications for yield trends. Agric. Syst. 115, 137–143. https://doi.org/10.1016/j.agsy.2012.09.003.

M. K, N., Sivalingam, N., 2024. Monthly Ambient Air Quality Snapshot for India: November 2024. Retrieved from Centre for Research on Energy and Clean Air (CREA). https://energyandcleanair.org/india-monthly-ambient-air-quality-snapshot-november-2024/.

Mangaraj, P., Matsumi, Y., Nakayama, T., Biswal, A., Yamaji, K., Araki, H., et al., 2025. Weak coupling of observed surface PM2.5 in Delhi-NCR with rice crop residue burning in Punjab and Haryana. npj Clim. Atmos. Sci. 8 (1). https://doi.org/10.1038/s41612-025-00901-8.

Mhawish, A., Sarangi, C., Babu, P., Kumar, M., Bilal, M., Qiu, Z., 2022. Observational evidence of elevated smoke layers during crop residue burning season over Delhi: potential implications on associated heterogeneous PM2.5 enhancements. Rem. Sens. Environ. 280. https://doi.org/10.1016/j.rse.2022.113167.

Mogno, C., Wallington, T.J., Palmer, P.I., Hakkim, H., Sinha, B., Sinha, V., et al., 2024. Impact of electric and clean-fuel vehicles on future PM2.5 and ozone pollution over Delhi. Environ. Res. Commun. 6 (7). https://doi.org/10.1088/2515-7620/ad507f.

Mukherjee, T., Vinoj, V., Midya, S.K., Puppala, S.P., Adhikary, B., 2020. Numerical simulations of different sectoral contributions to post monsoon pollution over Delhi. Heliyon 6 (3), e03548. https://doi.org/10.1016/j.heliyon.2020.e03548.

Nagar, P.K., Sharma, M., 2022. A hybrid model to improve WRF-chem performance for crop burning emissions of PM2.5 and secondary aerosols in North India. Urban Clim. 41. https://doi.org/10.1016/j.uclim.2022.101084.

Navinya, C., Kapoor, T.S., Anurag, G., Lokhande, P., Sharma, R., Prasad Sv, L., et al., 2023. Heating and lighting: understanding overlooked energy-consumption activities in the Indian residential sector. Environ. Res. Commun. 5 (4). https://doi.org/10.1088/2515-7620/acca6f.

Paulot, F., Naik, V., Horowitz, L.W., 2022. Reduction in near-surface wind speeds with increasing CO2 may worsen winter air quality in the indo-gangetic plain. Geophys. Res. Lett. 49 (18). https://doi.org/10.1029/2022gl099039.

Pawar, H., Garg, S., Kumar, V., Sachan, H., Arya, R., Sarkar, C., et al., 2015. Quantifying the contribution of long-range transport to particulate matter (PM) mass loadings at a suburban site in the north-western Indo-gangetic plain (NW-IGP). Atmos. Chem. Phys. 15 (16), 9501–9520. https://doi.org/10.5194/acp-15-9501-2015.

Pawar, H., Sinha, B., 2022. Residential heating emissions (can) exceed paddy-residue burning emissions in rural northwest India. Atmos. Environ. 269. https://doi.org/10.1016/j.atmosenv.2021.118846.

Prabhu, S., Chitale, V., 2024. Decoding India's changing monsoon patterns: a tehsil-level assessment. Retrieved from New Delhi. https://www.ceew.in/publications/decoding-changing-monsoon-rainfall-patterns-due-to-climate-change-in-india.

Rathore, J., Ganguly, D., Singh, V., Gupta, M., Vazhathara, V.J., Biswal, A., et al., 2025. Characteristics of haze pollution events during biomass burning period at an upwind site of Delhi. J. Geophys. Res. Atmos. 130 (7). https://doi.org/10.1029/2024jd042347.

Saharan, U.S., Kumar, R., Singh, S., Mandal, T.K., Sateesh, M., Verma, S., Srivastava, A., 2024. Hotspot driven air pollution during crop residue burning season in the Indo-gangetic plain, India. Environ. Pollut. 350, 124013. https://doi.org/10.1016/j.envpol.2024.124013.

Schroeder, W., Oliva, P., Giglio, L., Csiszar, I.A., 2014. The new VIIRS 375 m active fire detection data product: algorithm description and initial assessment. Rem. Sens. Environ. 143, 85–96. https://doi.org/10.1016/j.rse.2013.12.008.

Sharma, V., Amarjeet, Singh, G.P., Chakraborty, A., 2025. Variabilities in onset and withdrawal characteristics of Indian summer monsoon after 1998 climate shift: dynamical role of somali jet. Theor. Appl. Climatol. 156 (10). https://doi.org/10.1007/s00704-025-05760-0.

Takigawa, M., Patra, P.K., Matsumi, Y., Dhaka, S.K., Nakayama, T., Yamaji, K., et al., 2020. Can Delhi's pollution be affected by crop fires in the Punjab region? Sola 16 (0), 86–91. https://doi.org/10.2151/sola.2020-015.

Thakur, S., Sidana, B.K., Priscilla, L., Kumar, S., Kaur, S., Mahal, A.K., 2025. Determinants of farmers' adoption of climate-smart agricultural practices and their impact on profitability in Punjab. Econ. Polit. Wkly. 60 (30). https://doi.org/10.71279/epw.v60i30.39487.

Tripathi, S.N., Yadav, S., Sharma, K., 2024. Air pollution from biomass burning in India. Environ. Res. Lett. 19 (7). https://doi.org/10.1088/1748-9326/ad4a90.

Vohra, K., S, M., Chakraborty, A., Shah, H., As, B., Pakki, J., 2025. Urgent issues regarding real-time air quality monitoring data in India: unveiling solutions and implications for policy and health. Atmos. Environ. X 25, 100308. https://doi.org/10.1016/j.aeaoa.2024.100308.

Wiedinmyer, C., Kimura, Y., McDonald-Buller, E.C., Emmons, L.K., Buchholz, R.R., Tang, W., et al., 2023. The fire inventory from NCAR version 2.5: an updated global fire emissions model for climate and chemistry applications. Geosci. Model Dev. (GMD) 16 (13), 3873–3891. https://doi.org/10.5194/gmd-16-3873-2023.

Zhang, X., Kondragunta, S., Roy, D.P., 2014. Interannual variation in biomass burning and fire seasonality derived from geostationary satellite data across the contiguous United States from 1995 to 2011. J. Geophys. Res. Biogeosci. 119 (6), 1147–1162. https://doi.org/10.1002/2013jg002518.

Zhu, H., Martin, R.V., Croft, B., Zhai, S., Li, C., Bindle, L., et al., 2023. Parameterization of size of organic and secondary inorganic aerosol for efficient representation of global aerosol optical properties. Atmos. Chem. Phys. 23 (9), 5023–5042. https://doi.org/10.5194/acp-23-5023-2023.