

# Spatio-Temporal and Seasonal Analysis of Crop Residue Burning in Punjab and Haryana Using Satellite-Derived Fire Count Data

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**Abstract-** — Agricultural residue burning is a major contributor to seasonal air pollution in northwestern India, significantly affecting air quality across the Indo-Gangetic Plain. This study presents a comprehensive Spatio-temporal and seasonal analysis of crop residue burning in Punjab and Haryana during 2021–2025 using satellite-derived fire count data (MODIS and VIIRS), with a focus on pre-monsoon (Rabi: April–May) and post-monsoon (Kharif: October–November) periods. The results indicate that post-monsoon burning dominates total fire activity, accounting for approximately 70–75% of annual fire counts, with Punjab alone contributing more than 80% of regional fire events. Peak Kharif fire activity exceeded 170,000 events in Punjab, while Haryana recorded comparatively lower counts (~21,000 events). In contrast, Rabi burning remained relatively stable, averaging ~85,000–90,000 fires in Punjab and ~25,000–26,000 fires in Haryana. Temporal trends reveal a substantial decline in Kharif fire counts, with reductions of nearly 90–94% between 2021 and 2025, indicating the effectiveness of policy interventions and residue management technologies. However, Rabi burning exhibited limited reduction, highlighting a critical gap in mitigation strategies. Spatial analysis shows dense clustering of fires in central and northwestern Punjab, whereas Haryana exhibits more dispersed burning patterns. The strong seasonal concentration and magnitude of fire activity confirm that biomass burning remains a dominant driver of particulate pollution. These findings emphasize the need for crop-specific, season-targeted mitigation strategies to achieve sustained improvements in regional air quality.

**Keywords-** Crop residue burning, VIIRS, PM<sub>2.5</sub>, Air pollution, Punjab, Haryana, Seasonal variability

## I. INTRODUCTION

Air pollution has emerged as one of the most pressing environmental and public health challenges of the 21st century, particularly in developing countries such as India, where rapid urbanization, population growth, and agricultural intensification occur simultaneously (Venkataraman et al., 2018; Prabhu et al., 2020). Among the various sources contributing to atmospheric pollution, agricultural residue burning has gained significant attention due to its role in driving seasonal episodes of severe air quality deterioration across the Indo-Gangetic Plain (IGP) (Murari et al., 2020). The northwestern states of Punjab and Haryana, often referred to as the agricultural backbone of India, are central to this issue due to the dominance of the rice–wheat cropping system, which generates large quantities of crop residues within a limited time frame.

The environmental and health implications of air pollution are profound, with fine particulate matter (PM<sub>2.5</sub>) identified as one of the most critical pollutants affecting human health (Bhuvaneshwari et al., 2019). Due to its small size, PM<sub>2.5</sub> can penetrate deep into the respiratory system and enter the bloodstream, leading to respiratory illnesses, cardiovascular

diseases, and premature mortality. India consistently ranks among the countries with the highest exposure to PM<sub>2.5</sub>, and within the country, the Indo-Gangetic Plain represents a major hotspot of air pollution (Sen et al., 2017). While emissions from urban, industrial, and vehicular sources contribute to baseline pollution levels, agricultural residue burning leads to sharp, episodic spikes in particulate matter concentrations, particularly during the pre-monsoon and post-monsoon seasons.

Punjab and Haryana play a critical role in India's agricultural economy, contributing significantly to national food security. Punjab alone contributes a substantial share of rice and wheat to the central grain pool, supported by intensive mechanized farming practices. However, this high productivity comes at an environmental cost, as large quantities of crop residues are generated annually. The use of combine harvesters leaves behind loose straw and stubble, which are difficult and expensive to remove manually. Consequently, farmers often resort to open-field burning as a quick and economically viable method to clear fields for the next cropping cycle (Lan et al., 2022; Ravindra et al., 2019).

The fire activity associated with crop residue burning exhibits a distinct seasonal pattern closely linked to the rice–wheat

cropping cycle. Two primary burning periods are observed: the pre-monsoon (April–May), associated with wheat residue burning, and the post-monsoon (October–November), associated with paddy residue burning. Among these, post-monsoon burning is significantly more intense and widespread due to the large-scale cultivation of rice and the limited time available for field preparation before wheat sowing (A. Kumar et al., 2020; Sarkar et al., 2018). Satellite observations indicate that the majority of fire events occur during the Kharif season, with dense clusters of fires detected across Punjab and parts of Haryana. In contrast, pre-monsoon burning is relatively less intense and more spatially distributed.

Meteorological conditions play a crucial role in determining the impact of residue burning on air quality. During the post-monsoon period, unfavourable atmospheric conditions such as low wind speeds, shallow boundary layer height, temperature inversions, and high humidity contribute to the accumulation of pollutants near the surface (Mhawish et al., 2020). These conditions lead to the formation of dense haze and smog across northern India, particularly affecting urban centres such as Delhi. In contrast, the pre-monsoon season is characterized by stronger winds and higher mixing heights, which facilitate pollutant dispersion and reduce the severity of pollution episodes. As a result, the same level of burning activity has a significantly higher impact on air quality during the post-monsoon period.

Advancements in remote sensing technologies have significantly improved the ability to monitor and analyse crop residue burning. Satellite-based instruments such as the Visible Infrared Imaging Radiometer Suite (VIIRS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) provide high-resolution data on fire counts, enabling researchers to track spatial distribution, temporal trends, and seasonal variability of biomass burning (Cusworth et al., 2018; Liu et al., 2018). These datasets have been widely used to quantify fire activity, identify hotspot regions, and establish relationships between fire events and air pollution levels. Previous studies have demonstrated a strong association between fire counts and elevated PM<sub>2.5</sub> concentrations, confirming the significant contribution of agricultural burning to regional air quality degradation (Rana et al., 2019; Saxena et al., 2021).

Over the past decade, several policy interventions have been implemented to control crop residue burning in Punjab and Haryana. These include financial incentives for farmers, promotion of in-situ residue management technologies such as the Happy Seeder, and stricter enforcement of environmental

regulations. Studies have reported a noticeable decline in fire counts, particularly during the post-monsoon season, suggesting the effectiveness of these measures (S. Kumar et al., 2024). However, the adoption of alternative residue management practices remains uneven, and many farmers continue to rely on burning due to economic constraints and operational challenges. As a result, while Kharif burning has shown a declining trend, Rabi burning remains relatively stable, indicating a persistent gap in mitigation strategies.

Spatial variability further highlights the unequal distribution of burning activity across the region. Punjab consistently emerges as the dominant contributor to crop residue burning, particularly during the Kharif season, due to its extensive paddy cultivation and mechanized farming practices. In contrast, Haryana exhibits comparatively lower fire counts and more dispersed burning patterns, reflecting differences in cropping intensity and residue management practices (Bigi & Ghermandi, 2016). These differences emphasize the need for region-specific and crop-specific approaches to effectively address the issue. The impacts of crop residue burning extend beyond local and regional boundaries, contributing to transboundary air pollution across the Indo-Gangetic Plain. During peak burning periods, pollutants are transported over long distances, significantly affecting air quality in downwind regions such as Delhi-NCR. These pollution episodes pose serious health risks, particularly for vulnerable populations, and contribute to increased morbidity and mortality (A. Kumar et al., 2020; Sen et al., 2017). Additionally, emissions from biomass burning, including black carbon and greenhouse gases, have broader implications for climate change and regional atmospheric processes.

Despite extensive research on crop residue burning, there remains a need for integrated studies that combine spatial, temporal, and seasonal analyses over recent time periods. Many existing studies focus on either short-term observations or large-scale assessments, often lacking detailed inter-annual comparisons and state-level analysis. Furthermore, the evolving trends in burning practices, influenced by policy interventions and technological adoption, require continuous monitoring and evaluation.

In this context, the present study aims to provide a comprehensive Spatio-temporal and seasonal assessment of crop residue burning in Punjab and Haryana during the period 2021–2025. The study utilizes satellite-derived fire count data from MODIS and VIIRS to analyse spatial distribution, temporal trends, and seasonal variability of fire events. The specific objectives are: (i) to examine the spatial distribution of fire counts across Punjab and Haryana, (ii) to analyse

seasonal differences between pre- monsoon and post-monsoon burning periods, (iii) to evaluate temporal trends in fire activity over the study period, and (iv) to assess the implications of biomass burning for regional air quality. The findings are expected to contribute to a deeper understanding of crop residue burning dynamics and support the development of targeted mitigation strategies for improving air quality in the Indo- Gangetic Plain.

## II. STUDY AREA

Punjab and Haryana, located in northwestern India, represent two of the most agriculturally intensive states in the country and play a central role in the issue of crop residue burning. Punjab, widely known as the “breadbasket of India,” lies between 29°30' to 32°32' N latitude and 73°55' to 76°50' E longitude, covering an area of approximately 50,362 km<sup>2</sup>. Haryana, situated to the southeast of Punjab, extends between 27°39' to 30°55' N latitude and 74°28' to 77°36' E longitude, covering an area of about 44,212 km<sup>2</sup>. Both states are part of the Indo- Gangetic Plain (IGP), a region characterized by fertile alluvial soils, flat terrain, and high agricultural productivity. Their geographical location makes them highly relevant for air pollution studies, as the IGP is particularly prone to severe haze and smog episodes due to its meteorological and topographical conditions.

The climate of Punjab and Haryana is predominantly sub-tropical, marked by hot summers (March–June), monsoon rainfall (July–September), and cold winters (December–February). These seasonal variations strongly influence agricultural practices and residue management patterns. Both states follow a rice–wheat cropping system, which became dominant after the Green Revolution of the 1960s. Punjab contributes more than 20% of India’s rice and nearly 30% of its wheat, while Haryana also plays a significant role in national grain production. This intensive cropping system generates enormous quantities of agricultural residue annually, particularly from paddy and wheat crops.

The widespread adoption of mechanized harvesting, especially through combine harvesters, has further intensified the residue management challenge. Unlike manual harvesting, these machines leave behind large quantities of loose straw and standing stubble, particularly in paddy fields, which are difficult to manage without additional labor and cost. As a result, farmers often resort to open-field burning as a quick and economical method for clearing fields in preparation for the next cropping cycle.

Crop residue burning in Punjab and Haryana exhibits a strong seasonal pattern linked to agricultural cycles. Two major burning periods are observed: the pre-monsoon season (April–May), associated with wheat residue burning, and the post-monsoon season (October– November), associated with paddy residue burning. Among these, post-monsoon burning is significantly more intense and widespread, particularly in Punjab, due to the narrow time window between rice harvesting and wheat sowing. In contrast, pre-monsoon burning is relatively less intense, as wheat straw is often utilized as animal fodder. Meteorological conditions play a critical role in amplifying the impact of residue burning on air quality. During the post-monsoon period, unfavourable atmospheric conditions such as low wind speeds, shallow boundary layer height, temperature inversions, and high humidity lead to the accumulation of pollutants near the surface. This results in severe haze and smog episodes across northern India, with pollutants transported to downwind regions such as the Delhi National Capital Region (NCR). Satellite observations consistently show that Punjab records the highest fire activity during this period, while Haryana exhibits comparatively lower and more dispersed burning patterns.

The contrasting burning characteristics of Punjab and Haryana, in terms of intensity, spatial distribution, and seasonal variation, make them ideal case study regions for analysing crop residue burning dynamics. Studying fire activity across these states provides valuable insights into the temporal evolution of burning practices and their implications for regional air quality.

## III. Central Pollution Control Board (CPCB) DATA

The air quality data for particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) used in this study were obtained from the Central Pollution Control Board (CPCB) monitoring network for the period 2021–2025. CPCB, under the Ministry of Environment, Forest and Climate Change (MoEFCC), operates an extensive network of Continuous Ambient Air Quality Monitoring Stations (CAAQMS) and manual monitoring stations across India, providing reliable and high-resolution datasets for air quality assessment.

Particulate matter concentrations were measured using standardized monitoring techniques. Continuous monitoring stations (CAAQMS) utilize advanced instruments such as Beta Attenuation Monitors (BAM) and Tapered Element Oscillating Microbalance (TEOM) to provide hourly

measurements of  $PM_{2.5}$  and  $PM_{10}$  concentrations. In addition, manual monitoring under the National Air Quality Monitoring Programme (NAMP) employs High Volume Samplers (HVS) and Respirable Dust Samplers (RDS) to collect 24-hour integrated samples, ensuring consistency and long-term trend analysis. The integration of these datasets enables detailed temporal and seasonal evaluation of particulate pollution.

In Punjab, CPCB monitoring stations are distributed across major urban and industrial regions, including cities such as Ludhiana, Amritsar, Jalandhar, Patiala, Bathinda, and Mandi Gobindgarh. These locations represent key agricultural and industrial zones and are significantly influenced by crop residue burning activities. Punjab consistently records elevated  $PM_{2.5}$  and  $PM_{10}$  concentrations during the post-monsoon period, particularly in October–November, when large-scale paddy residue burning occurs. The high density of fire events during this period leads to sharp increases in particulate matter concentrations, often exceeding national air quality standards.

In Haryana, CPCB monitoring is conducted in major urban and industrial centers such as Gurugram, Faridabad, Panipat, Karnal, Rohtak, Hisar, and Yamuna Nagar. These stations capture air quality conditions influenced by a combination of local emissions, including vehicular traffic, industrial activities, and agricultural burning. Compared to Punjab, Haryana exhibits relatively lower fire intensity; however, it still experiences significant seasonal variation in  $PM_{2.5}$  and  $PM_{10}$  concentrations, particularly during the Kharif burning period.

The temporal analysis of  $PM_{2.5}$  and  $PM_{10}$  concentrations from 2021 to 2025 reveals a strong seasonal pattern across both states. During the pre-monsoon season (April–May), moderate increases in particulate matter are observed due to wheat residue burning, dust resuspension, and high temperatures. However, these concentrations are generally lower compared to post-monsoon levels due to enhanced atmospheric dispersion.

In contrast, the post-monsoon season (October– November) shows significantly elevated  $PM_{2.5}$  and  $PM_{10}$  concentrations in both Punjab and Haryana. This period coincides with large-scale paddy residue burning and unfavourable meteorological conditions, including low wind speed, shallow boundary layer height, and temperature inversions, which limit pollutant dispersion. As a result, particulate matter concentrations frequently reach peak values during this season, contributing to severe air pollution episodes across the Indo-Gangetic Plain.

Furthermore, inter-annual trends indicate variability in particulate matter concentrations, reflecting changes in burning intensity, meteorological conditions, and policy interventions. A gradual decline in peak pollution levels in recent years suggests the partial effectiveness of mitigation measures; however, persistent seasonal spikes indicate that crop residue burning remains a dominant source of particulate pollution. Overall, CPCB datasets for  $PM_{2.5}$  and  $PM_{10}$  provide a robust basis for analysing the relationship between fire activity and air quality. When integrated with satellite-derived fire count data, these observations enable a comprehensive assessment of the impact of crop residue burning on regional air pollution dynamics in Punjab and Haryana.

#### IV. VIIRS FIRE COUNT SATELLITE OBSERVATION

The Visible Infrared Imaging Radiometer Suite (VIIRS) is a state-of-the-art Earth observation instrument onboard the Suomi National Polar-orbiting Partnership (Suomi- NPP) satellite, launched in 2011, and the NOAA- 20 satellite, launched in 2017. It represents a significant advancement over earlier satellite sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS), offering improved spatial, temporal, and radiometric resolution for monitoring environmental processes, including biomass burning.

One of the most important capabilities of VIIRS is its ability to detect active fires through thermal anomaly detection. The instrument operates across 22 spectral bands, including visible, near-infrared, and thermal infrared wavelengths, which are highly sensitive to the heat signatures produced by burning events. The 375 m spatial resolution of VIIRS fire products provides a substantial improvement over the 1 km resolution of MODIS, allowing for more precise detection of small- scale and fragmented fires typical of agricultural landscapes such as those in Punjab and Haryana.

VIIRS operates on a polar-orbiting platform, completing approximately 14 orbits per day, which enables twice- daily global coverage. This high temporal resolution allows near real-time monitoring of fire activity, making it particularly useful for tracking rapid changes in burning patterns. The fire detection algorithm identifies pixels with elevated thermal signatures, referred to as “hotspots,” which are compiled into fire count datasets. These datasets are widely used to quantify the frequency, spatial distribution, and temporal evolution of biomass burning.

In addition to fire detection, VIIRS provides complementary datasets such as aerosol optical depth (AOD), land surface temperature (LST), vegetation indices, and nighttime lights (Day/Night Band). These datasets enable integrated analysis of fire activity and its environmental impacts. For instance, linking VIIRS fire counts with aerosol measurements can help assess the contribution of crop residue burning to regional air pollution and haze formation.

For agricultural regions like Punjab and Haryana, VIIRS has become an indispensable tool for monitoring crop residue burning during both pre-monsoon and post-monsoon periods. Its high spatial resolution allows accurate detection of fire events occurring in small agricultural fields, while its frequent revisit time ensures consistent temporal coverage. Compared to ground-based reporting, VIIRS provides a more comprehensive, objective, and large-scale dataset, making it highly suitable for long-term trend analysis.

The VIIRS fire count dataset forms the foundation of this study, enabling detailed assessment of spatio-temporal and seasonal variations in crop residue burning. By capturing both the intensity and distribution of fire events, VIIRS data play a crucial role in understanding the dynamics of biomass burning and supporting evidence-based policy interventions aimed at reducing air pollution in northwestern India.

## V. RESULTS AND DISCUSSIONS

### 1. Spatial and Seasonal Distribution of Crop Residue Burning

The spatial and seasonal distribution of crop residue burning across Punjab and Haryana reveals significant variability in both intensity and geographic extent. During the Kharif season (October–November), a markedly higher number of fire events is observed compared to the Rabi season (April–May), with Punjab emerging as the dominant hotspot region. The total fire counts indicate a substantial disparity between the two states, with Punjab recording 174,195 fire incidents (Fig. 1a), whereas Haryana accounts for only 21,418 events (Fig. 1b). This stark difference highlights the disproportionate contribution of Punjab to post-monsoon biomass burning in northwestern India.

The spatial patterns during the Kharif season demonstrate a dense and widespread distribution of fire events across Punjab (Fig. 1a), particularly concentrated in the central and south-western regions. This clustering reflects intensive paddy cultivation and synchronized harvesting practices, which create a narrow window for residue clearance before the

sowing of the next crop. The widespread use of mechanized harvesting further exacerbates residue accumulation, making open-field burning the most feasible option for farmers (Jain et al., 2014; Singh et al., 2018). In contrast, Haryana exhibits a more fragmented and less dense pattern of burning primarily concentrated in the northern districts where paddy cultivation is prevalent. The relatively lower fire counts in Haryana can be attributed to a smaller area under paddy cultivation and comparatively better adoption of alternative residue management techniques. During the Rabi season, a shift in both the magnitude and spatial distribution of fire activity is observed (Fig. 1c–d). Punjab records 89,967 fire incidents, indicating a reduction compared to the Kharif season, while Haryana shows an increase to 26,122 fire events. In Punjab, although burning remains spatially extensive, the density of fire clusters is relatively reduced. This change can be linked to the nature of wheat residue, which is less voluminous and easier to manage compared to paddy straw (Koul et al., 2022). In Haryana, the spatial distribution becomes more uniform during the Rabi season, reflecting the widespread cultivation of wheat across the state. Unlike the localized burning observed during Kharif, Rabi burning is more evenly distributed, indicating a broader geographic spread of residue management practices. A comparative analysis of seasonal patterns highlights that Kharif burning is both more intense and spatially concentrated, whereas Rabi burning is relatively diffuse and moderate in intensity. The higher fire counts during Kharif are primarily driven by agronomic constraints, particularly the limited time available between paddy harvesting and wheat sowing (Singh et al., 2010). In contrast, the relatively flexible cropping schedule during the Rabi season allows for alternative residue management practices, thereby reducing the reliance on burning. The identification of spatial hotspots further emphasizes the concentration of fire activity in agriculturally intensive regions. In Punjab, the central plains and south-western districts consistently emerge as major hotspots, while in Haryana, northern districts dominate during Kharif and a more uniform distribution is observed during Rabi. These hotspots correspond closely with areas characterized by high irrigation intensity, mechanized farming, and intensive cropping systems.

The observed patterns have significant implications for regional air quality. The high density of fire events in Punjab during the Kharif season coincides with severe air pollution episodes across northern India, particularly in the Indo-Gangetic Plain. Previous studies have established a strong linkage between fire counts and particulate matter concentrations, indicating that stubble burning contributes approximately 50–75% increase in PM<sub>2.5</sub> levels during peak burning periods. Furthermore, prevailing north-westerly

winds facilitate the transport of pollutants from Punjab and Haryana towards downwind regions such as Delhi-NCR, intensifying smog conditions (Cusworth et al., 2018; Beig et al., 2020). Overall, the analysis demonstrates that crop residue burning is strongly influenced by crop type, agricultural practices, and seasonal constraints. Punjab remains the primary contributor to large-scale burning, particularly during the Kharif season, while Haryana exhibits moderate but seasonally variable burning patterns. The clear spatial clustering and seasonal trends identified in this study provide critical insights for targeted mitigation strategies and policy interventions aimed at reducing biomass burning and its associated environmental impacts.

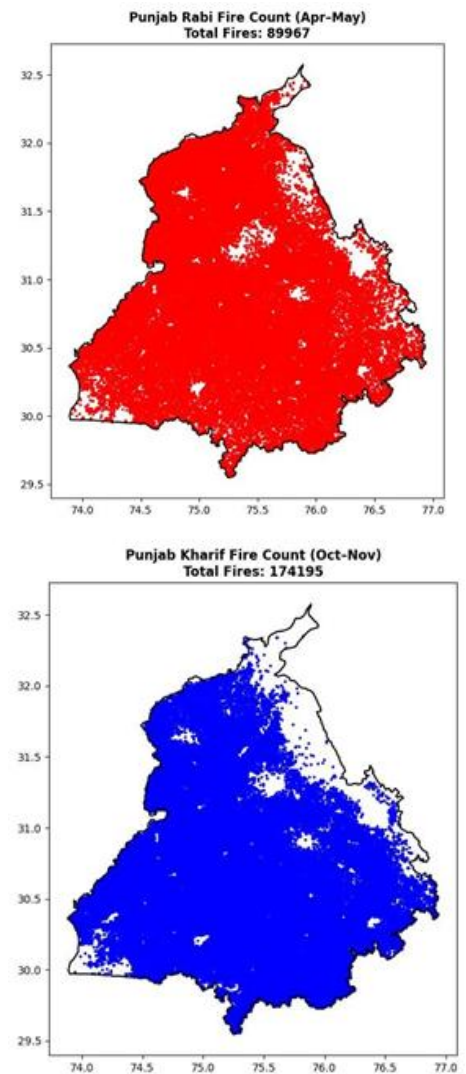


Fig.1a. Punjab area map with fire count

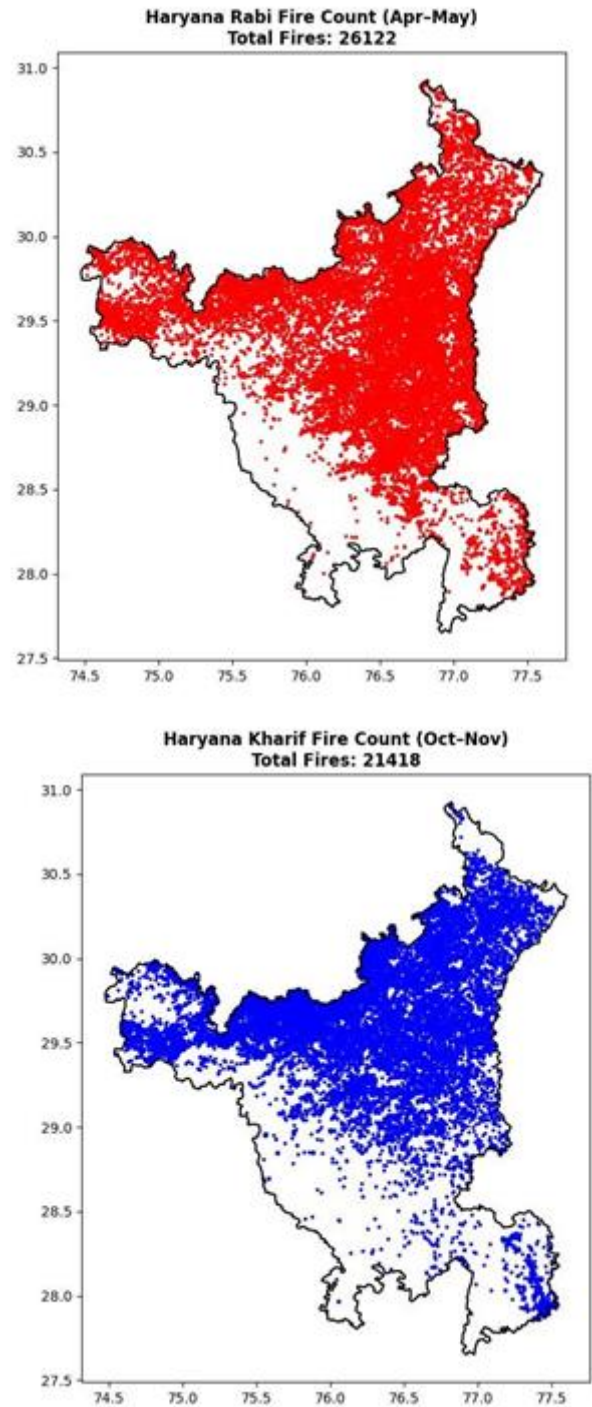


Fig.1b. Haryana area map with fire count

## 2. Temporal Variation of Fire Counts in Punjab and Haryana (Kharif vs Rabi)

The temporal variation of fire counts from 2021 to 2025 across Punjab and Haryana reveals a clear seasonal and inter-annual contrast between Kharif (October–November) and Rabi (April–May) burning patterns (Fig. 2 and Fig. 3). In both states, Kharif burning shows a consistent declining trend over the study period, while Rabi burning remains relatively stable or exhibits moderate variability.

In Punjab, Kharif fire counts show a sharp and continuous decline, decreasing from approximately 77,000 incidents in 2021 to nearly 4,500 incidents in 2025 (Fig. 2). This significant reduction suggests the effectiveness of policy interventions, stricter enforcement measures, and increasing adoption of residue management technologies such as Happy Seeder and in-situ crop residue management practices. In contrast, Rabi fire counts in Punjab remain relatively stable, fluctuating between approximately 15,000 and 19,500 incidents, indicating that wheat residue burning has not experienced a comparable level of reduction.

A similar declining trend in Kharif burning is observed in Haryana, where fire counts decrease from around 10,400 incidents in 2021 to nearly 1,100 incidents in 2025 (Fig. 3). However, the overall magnitude of Kharif burning in Haryana is significantly lower than in Punjab, reflecting differences in cropping intensity and the area under paddy cultivation. Unlike Punjab, Haryana exhibits a more variable pattern in Rabi burning, with fire counts ranging between approximately 4,100 and 6,300 incidents, peaking around 2024 before slightly declining in 2025.

The seasonal comparison highlights a key distinction between the two states. In Punjab, Kharif burning overwhelmingly dominates the fire activity, although its rapid decline indicates a transition towards improved residue management practices. Conversely, Haryana displays a more balanced seasonal contribution, and in recent years (2024–2025), Rabi burning has surpassed Kharif burning, indicating a shift in the dominant burning season. This shift may be attributed to reduced paddy cultivation, improved compliance with Kharif burning regulations, and relatively weaker control measures for Rabi residue management. Overall, the temporal trends suggest that while both states have achieved considerable success in reducing Kharif burning, particularly in Punjab, Rabi burning persists as a relatively under-regulated and stable source of biomass burning. These findings emphasize the need for season-specific and crop-specific management strategies, with increased policy focus on wheat residue

management to ensure comprehensive mitigation of agricultural burning practices.

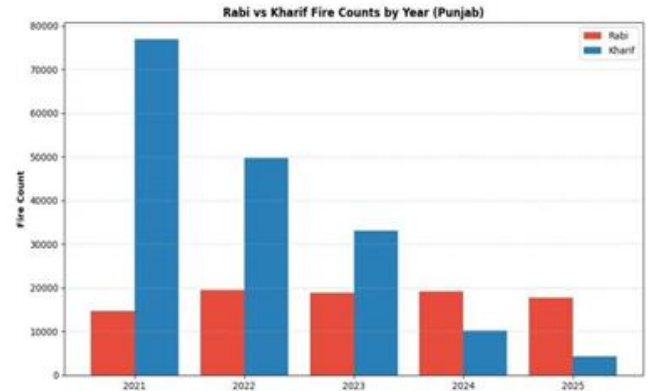


Fig. 2 Rabi Vs Kharif Fire Counts of Punjab by Year

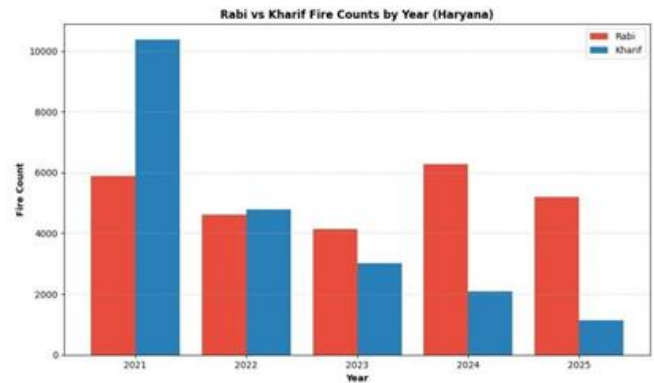


Fig. 3 Rabi Vs Kharif Fire Counts of Haryana by Year

## 3. Monthly Distribution of Fire Counts in Punjab and Haryana (Rabi vs Kharif)

The monthly distribution of fire counts in Punjab and Haryana reveals distinct seasonal peaks corresponding to Rabi (April–May) and Kharif (October–November) burning periods (Fig. 4 and Fig. 5). A clear contrast is observed not only between months but also between the two states in terms of magnitude and intensity of burning. In Haryana (Fig. 4), fire activity during the Rabi season shows a noticeable increase from April (~8,800 fires) to May (~17,500 fires), indicating that residue burning intensifies towards the end of the wheat harvesting period. During the Kharif season, fire counts are relatively moderate, with October recording approximately 10,000 incidents and November showing a slight increase to ~11,400 fires. The gradual rise from October to November suggests a progressive increase in paddy residue burning as harvesting peaks.

In contrast, Punjab (Fig. 5) exhibits significantly higher fire counts in both seasons, with a much sharper increase during peak months. During the Rabi season, fire counts rise dramatically from April (~10,000 fires) to May (~80,000 fires), indicating an intense concentration of burning within a short time window. However, the most prominent feature is observed during the Kharif season, where fire counts increase from approximately 41,000 in October to an extremely high value of ~133,000 in November. This steep rise highlights November as the peak burning month in Punjab, driven by synchronized paddy harvesting and the urgency of field clearance for wheat sowing.

A comparative analysis between the two states shows that Punjab consistently records significantly higher fire counts than Haryana in both seasons, particularly during the Kharif peak in November. While Haryana demonstrates a gradual and moderate increase in fire activity, Punjab exhibits abrupt and highly concentrated burning episodes, especially in May (Rabi) and November (Kharif). This indicates that biomass burning in Punjab is more intensive and temporally compressed, whereas in Haryana it is relatively distributed. The monthly patterns further emphasize that May and November are the critical peak months for residue burning, corresponding to wheat and paddy harvesting periods, respectively. The extremely high fire counts in November, particularly in Punjab, align with severe air pollution episodes in northern India, as large-scale emissions are released within a short duration.

Overall, the monthly analysis confirms that crop residue burning is strongly seasonal and crop-dependent, with Punjab acting as the dominant contributor to peak burning events. The sharp temporal spikes observed in May and November underscore the need for targeted, time-specific mitigation strategies to effectively reduce emissions during these critical periods.

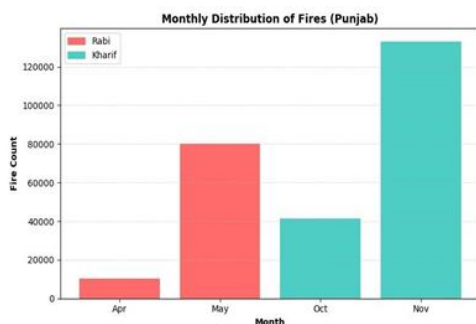


Fig. 4 Punjab Monthly Distribution of Fire Count with Each Season

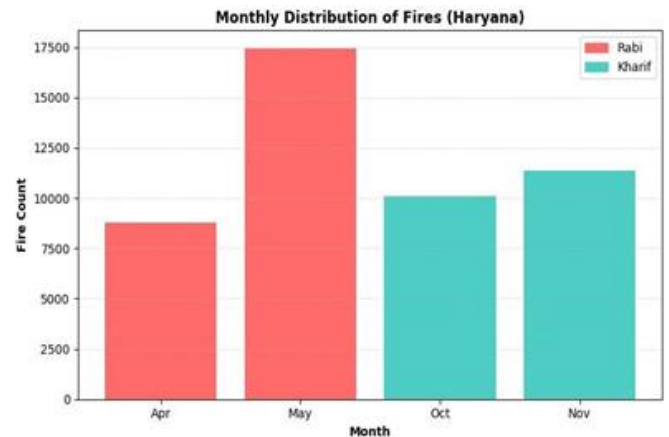


Fig. 5 Haryana Monthly Distribution of Fire Count with Each Season

#### 4. Monthly Spatial Distribution of PM<sub>2.5</sub> and PM<sub>10</sub> in Punjab and Haryana

The monthly spatial distribution of particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) across Punjab and Haryana exhibits strong seasonal variability, with clear quantitative differences across months and regions. In Punjab, PM<sub>10</sub> concentrations range approximately from 135 to 169 µg/m<sup>3</sup>, while PM<sub>2.5</sub> varies between 58 and 86 µg/m<sup>3</sup>. In Haryana, comparatively higher variability is observed, with PM<sub>10</sub> ranging from 130 to 241 µg/m<sup>3</sup> and PM<sub>2.5</sub> from 62 to 136 µg/m<sup>3</sup>, indicating relatively broader pollution spread. During the pre-monsoon (April–May) period, both states show a noticeable increase in particulate matter levels, corresponding to Rabi residue burning. In Punjab, PM<sub>10</sub> concentrations increase to around 150–165 µg/m<sup>3</sup>, while PM<sub>2.5</sub> reaches 70–80 µg/m<sup>3</sup>, particularly in central and eastern districts. In Haryana, the increase is more pronounced, with PM<sub>10</sub> reaching 180–220 µg/m<sup>3</sup> and PM<sub>2.5</sub> exceeding 110–130 µg/m<sup>3</sup>, especially in central and southern regions. The monsoon season (July–September) shows a relative decline in pollution levels in both states, with PM<sub>10</sub> dropping to approximately 140–155 µg/m<sup>3</sup> in Punjab and 150–180 µg/m<sup>3</sup> in Haryana, and PM<sub>2.5</sub> reducing to 60–70 µg/m<sup>3</sup> and 80–100 µg/m<sup>3</sup>, respectively. This reduction can be attributed to precipitation-induced washout and improved atmospheric dispersion. During the post-monsoon (October–November) period, particulate matter concentrations increase sharply, marking the most severe pollution phase. In Punjab, PM<sub>10</sub> reaches values close to 165–170 µg/m<sup>3</sup>, while PM<sub>2.5</sub> rises to 80–85 µg/m<sup>3</sup>, with distinct hotspots in eastern and northeastern regions. In Haryana, even higher concentrations are observed, with PM<sub>10</sub> exceeding 200–240 µg/m<sup>3</sup> and PM<sub>2.5</sub> reaching 120–135 µg/m<sup>3</sup>, particularly in eastern districts, reflecting the combined impact of local burning and transboundary pollution from Punjab. Winter

months (December–February) show moderate pollution levels in both states, with  $PM_{10}$  ranging between  $140\text{--}155\ \mu\text{g}/\text{m}^3$  and  $PM_{2.5}$  between  $60\text{--}75\ \mu\text{g}/\text{m}^3$  in Punjab, while Haryana records slightly higher values due to urban emissions and atmospheric stagnation. Overall, Punjab exhibits more intense and localized pollution hotspots, whereas Haryana shows a wider spatial spread with higher peak concentrations, particularly during burning seasons. The consistent elevation of particulate matter in eastern regions of both states highlights the influence of regional transport within the Indo-Gangetic Plain. These findings confirm that seasonal biomass burning, combined with meteorological factors, plays a dominant role in shaping the spatial distribution of air pollution

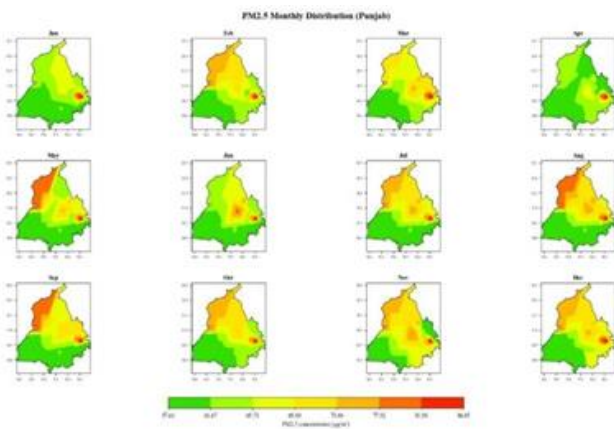


Fig. 6 Monthly spatial distribution of  $PM_{2.5}$  concentrations ( $\mu\text{g}/\text{m}^3$ ) across Punjab showing seasonal variation from January to December

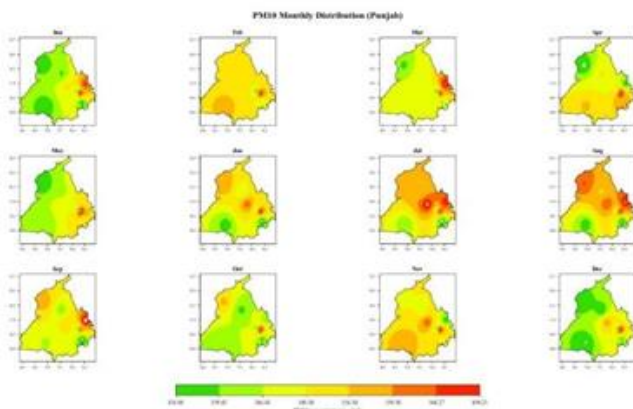


Fig. 7 Monthly spatial distribution of  $PM_{10}$  concentrations ( $\mu\text{g}/\text{m}^3$ ) across Punjab showing seasonal variation from January to December

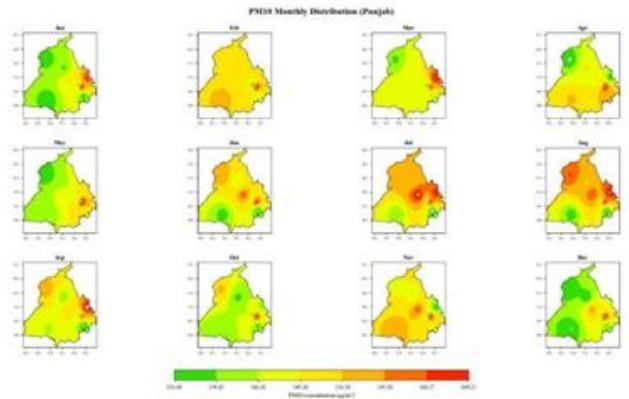


Fig 8. Monthly spatial distribution of  $PM_{2.5}$  concentrations ( $\mu\text{g}/\text{m}^3$ ) across Punjab depicting temporal and spatial pollution patterns.

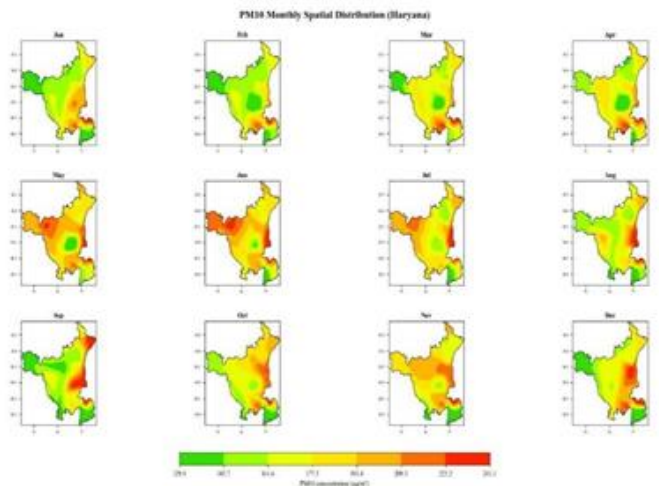


Fig. 9 Monthly spatial distribution of  $PM_{10}$  concentrations ( $\mu\text{g}/\text{m}^3$ ) across Haryana highlighting the impact of seasonal biomass burning.

### 5. Seasonal Variation of Fire Counts and $PM_{2.5}$ – $PM_{10}$ in Punjab and Haryana

The seasonal variation of fire counts and particulate matter concentrations ( $PM_{2.5}$  and  $PM_{10}$ ) across Punjab and Haryana during 2021–2025 reveals a strong temporal association between biomass burning activities and air quality deterioration. In Punjab, fire counts exhibit sharp seasonal peaks, particularly during the Kharif burning period (October–November), where monthly fire counts frequently exceed 400,000– 650,000 events. These peaks are closely aligned with significant increases in  $PM_{10}$  concentrations reaching approximately  $180\text{--}210\ \mu\text{g}/\text{m}^3$ , and  $PM_{2.5}$  levels rising to  $90\text{--}120\ \mu\text{g}/\text{m}^3$ , indicating severe pollution episodes. During the

Rabi burning period (April–May), Punjab shows comparatively moderate fire activity, generally ranging between 100,000–300,000 events, accompanied by  $PM_{10}$  concentrations of around  $140\text{--}170\ \mu\text{g}/\text{m}^3$  and  $PM_{2.5}$  levels of  $60\text{--}90\ \mu\text{g}/\text{m}^3$ . In contrast, monsoon months (July–September) exhibit minimal fire activity, often below 50,000 events, with corresponding reductions in PM concentrations due to enhanced atmospheric dispersion and precipitation effects. Haryana displays similar seasonal trends but with comparatively lower fire intensity. Peak Kharif fire counts in Haryana range between 200,000–650,000 events, while  $PM_{10}$  concentrations reach  $200\text{--}300\ \mu\text{g}/\text{m}^3$ , and  $PM_{2.5}$  rises to  $100\text{--}160\ \mu\text{g}/\text{m}^3$ , particularly in 2021 and 2024. During Rabi burning, fire counts typically vary between 50,000–200,000 events, with  $PM_{10}$  levels around  $160\text{--}220\ \mu\text{g}/\text{m}^3$  and  $PM_{2.5}$  between  $70\text{--}120\ \mu\text{g}/\text{m}^3$ .

A strong temporal synchronization between fire peaks and PM concentration spikes is evident in both states, confirming that biomass burning significantly contributes to particulate pollution. Inter-annual variability indicates a declining trend in fire activity after 2023, particularly during the Kharif season, which is reflected in comparatively reduced PM peaks in subsequent years. However, the persistence of moderate fire activity during the Rabi season suggests incomplete mitigation. Overall, Punjab exhibits more intense and concentrated fire events, whereas Haryana shows lower intensity but broader variability in particulate concentrations, likely influenced by regional transport and urban emissions. These findings confirm that seasonal crop residue burning remains a dominant driver of air pollution in the Indo-Gangetic Plain.

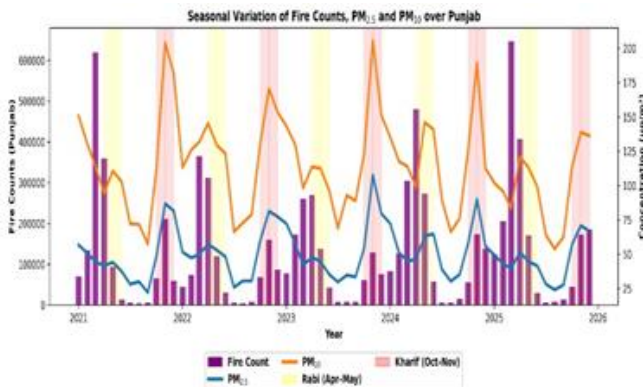


Fig. 10 Seasonal variation of fire counts,  $PM_{2.5}$ , and  $PM_{10}$  concentrations over Punjab (2021–2025)

Positive impact of government initiatives, including the promotion of in-situ residue management technologies such as

the Happy Seeder, financial incentives, and stricter enforcement measures.

However, crop residue burning continues to pose a serious environmental and public health challenge, contributing to severe haze episodes and regional pollution transport, particularly affecting downwind regions such as Delhi-NCR.

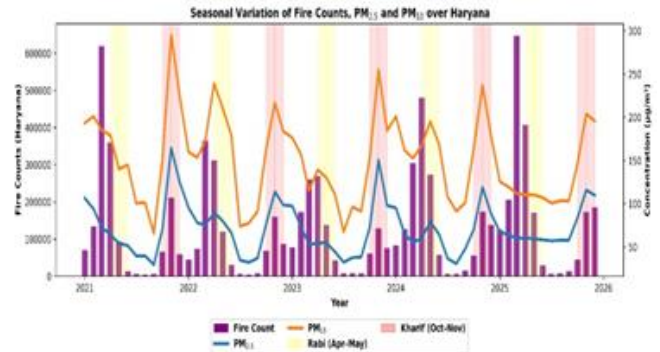


Fig. 11 Seasonal variation of fire counts,  $PM_{2.5}$ , and  $PM_{10}$  concentrations over Haryana (2021–2025)

## VI. CONCLUSION

The comprehensive analysis of crop residue burning across Punjab and Haryana during the study period highlights the persistent and strongly seasonal nature of biomass burning and its significant impact on regional air quality. The findings clearly demonstrate the dominance of Kharif burning associated with rice residue, while Rabi burning linked to wheat residue remains comparatively stable across both states. Although wheat residue burning exhibits limited variability, rice residue burning shows substantial inter-annual fluctuations, with peak fire activity in earlier years followed by a marked decline in recent years, particularly after 2023. This trend reflects the growing influence of policy interventions, technological adoption, and increased awareness among farmers.

- Crop residue burning in Punjab and Haryana exhibits strong seasonal variability, with relatively stable pre-monsoon (wheat) burning and highly variable post-monsoon (rice) burning.
- Post-monsoon (Kharif) burning dominates overall fire activity, contributing approximately 70–75% of total fire counts across the study region.
- Punjab consistently emerges as the primary hotspot of fire activity, contributing more than 75–80% of total fire events, while Haryana exhibits comparatively lower but spatially dispersed burning patterns.

- Wheat residue burning (Rabi season) remains relatively stable, indicating limited effectiveness of mitigation strategies for this crop cycle.
- Rice residue burning (Kharif season) shows a significant declining trend in both states, with reductions exceeding 80–90% between 2021 and 2025, highlighting the success of policy enforcement and technological interventions.
- Monthly analysis identifies May and November as critical peak burning periods, corresponding to wheat and paddy harvesting cycles, respectively.
- Spatial analysis reveals concentrated fire clusters in central and northwestern Punjab, while Haryana shows a more uniform and regionally distributed pattern of burning.
- A strong temporal association between fire counts and particulate matter concentrations (PM<sub>2.5</sub> and PM<sub>10</sub>) confirms that biomass burning is a major driver of seasonal air pollution across the Indo-Gangetic Plain.
- Despite the significant reduction in Kharif burning, persistent Rabi burning indicates a critical gap in current mitigation strategies and policy focus.
- The decline in fire counts in recent years reflects the

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