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Spatio-Temporal Relationship Between MODIS Fire Activity, Aerosol Loading and $PM_{2.5}$ During the Paddy Residue Burning Season in North-Western India, 2021

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Abstract

The burning of paddy residue is one of the largest seasonal sources of aerosol loading and particulate pollution in north-western India, concentrated in the weeks after the kharif rice harvest. This study focuses on the spatio-temporal link between active fire occurrence, Aerosol Optical Depth (AOD) and ground-level $PM_{2.5}$ across Punjab, Haryana, and the adjoining Rajasthan districts of Hanumangarh and Sri Ganganagar during 2021. Fire activity was tracked using Terra-MODIS cumulative fire frequency (MOD14A1), with Aqua-MODIS included for sensor comparison, columnar aerosol loading came from MODIS MAIAC AOD (MCD19A2), and ground-level pollution came from CPCB station $PM_{2.5}$ records. Data were analysed at monthly, seasonal, district and weekly resolution, with the September–December window examined in most detail. The year had two clear periods of burning. The first was a smaller wheat-residue burning phase during April–May, followed by a much stronger paddy-straw burning phase in October–November. During the later period, Terra cumulative fire frequency, AOD and $PM_{2.5}$ all reached their highest levels. At the weekly scale, fire activity reached its peak in the first week of November, with a cumulative fire frequency of 1,773 and a mean AOD of 1.071. $PM_{2.5}$ reached its highest value one week later, at 173.5 µg/m³ in the second week of November. This one-week difference suggests that aerosols remained in the atmosphere after fire activity had started to decline, with slower dispersion near the ground. The areas with high AOD were also not always located directly over the main fire hotspots, suggesting that smoke was transported away from the fields where burning occurred rather than remaining only around the source areas.Pearson correlation supported these patterns, cumulative fire frequency and AOD were strongly associated ($r = 0.724$, $p = 0.002$, $R^2 = 0.523$), as were cumulative fire frequency and $PM_{2.5}$, though more moderately ($r = 0.560$, $p = 0.024$, $R^2 = 0.314$). AOD and $PM_{2.5}$ tracked each other most closely ($r = 0.900$, $p < 0.001$, $R^2 = 0.811$). Together, the three datasets, satellite fire detection, satellite aerosol retrieval, and ground-based particulate monitoring, give a consistent, weekly-resolved picture of how the 2021 paddy-burning season built up, peaked, and dispersed across the region.

Keywords: *Paddy residue burning, MODIS MAIAC AOD (MCD19A2), Terra-MODIS cumulative fire frequency (MOD14A1), Satellite fire detection.*

1. Introduction

Punjab and Haryana are among India's major food-producing states. The rice–wheat cropping system followed across these states also extends into the irrigated districts of northern Rajasthan. Since the Green Revolution, this region of the Indo-Gangetic Plain has become one of India's major food-grain producing areas. Rice is generally grown during the kharif season, followed by wheat during the rabi season, and this cycle is repeated each year. The system, produces a large amount of crop residue that needs to be cleared within a short period. Farmers usually have only two to three weeks between paddy harvesting and wheat sowing. This leaves limited time to manage the remaining paddy stubble through methods other than burning.

Punjab and Haryana produce nearly 28.1 million tonnes of paddy residue each year, of which more than 42% is burnt in the fields ***(Kumar & Jakhar, 2020***). District-level estimates by ***Chawala and Sandhu (2020***) for Patiala and Ludhiana further show that this is not a rare practice. Paddy residue burning is common across these regions, covers a wide geographical area, and occurs regularly during the post monsoon season. Paddy straw has several possible uses. It can be composted, used as animal fodder, made into mushroom substrate, or supplied to bioenergy plants. However, these options may not be practical for farmers in early November, when machinery costs are high, labour is limited, and the next crop needs to be sown quickly.

When crop residue is burnt instead of being used, the effects can continue beyond the burning season. Repeated burning reduces soil organic matter and affects the microorganisms that help maintain soil fertility. Over time, these changes can accumulate from one season to the next ***(Kumar & Jakhar, 2020)***. This is not simply a technical issue that can be solved by better awareness in fact it is a livelihood decision made under genuine time pressure, which is why community-level training and demonstrations of alternatives such as the Happy Seeder and PUSA decomposer have helped only partially so far, with adoption still well behind the scale of the burning itself ***(Shilla, 2025)***.

Figure 1a: Paddy Cultivation and Paddy Straw Burning: (a) Paddy Crop and (b) Paddy Straw Burning

Source: Author's photographs.

The main concern of this study is the effect of burning on the atmosphere. During the post-monsoon period, open biomass burning releases smoke and fine particles into the air when weather conditions are less favourable for dispersing them. Light winds, a shallow and stable boundary layer, and temperature inversions can keep pollutants close to the ground instead of allowing them to disperse easily. The effects of this pollution extend beyond the fields where burning takes place. In Delhi-NCR, hospitals see a seasonal increase in asthma and COPD cases during the burning period, following a pattern that closely matches the agricultural burning season ***(Singh, 2018)***. Smoke does not respect a state boundary, and a field burning in Punjab by mid-morning can be contributing to Delhi's pollution load by evening***. Govardhan et al. (2023),*** working with the same 2021 season examined here, modelled that transport pathway directly and estimated stubble burning contributed somewhere between 30 and 35% of Delhi's daily particulate load during the peak October–November weeks. ***Saxena et al. (2021)*** report a broadly similar contribution using an independent approach. ***Singh et al. (2023***) reach a comparable estimate as well. ***Vadrevu et al. (2011)*** were already tracking MODIS fire counts against AOD over this same agricultural belt more than a decade ago.

Much of the existing research focuses on the downwind effects of burning, especially the impact of Punjab and Haryana on Delhi's air quality. Less attention has been given to the source regions themselves. In particular, fewer studies have examined whether fire activity, aerosol levels, and ground-level particulate pollution in Punjab and Haryana follow the same pattern on a week-to-week basis during the burning season.

That is the gap this study addresses. By tracking Terra-MODIS cumulative fire frequency, MODIS MAIAC AOD, and CPCB ground-station PM2.5 at weekly resolution across Punjab, Haryana, and the adjoining Rajasthan districts of Hanumangarh and Sri Ganganagar through the 2021 burning season, it asks whether the source region's own air quality data tells the same story its satellites do.

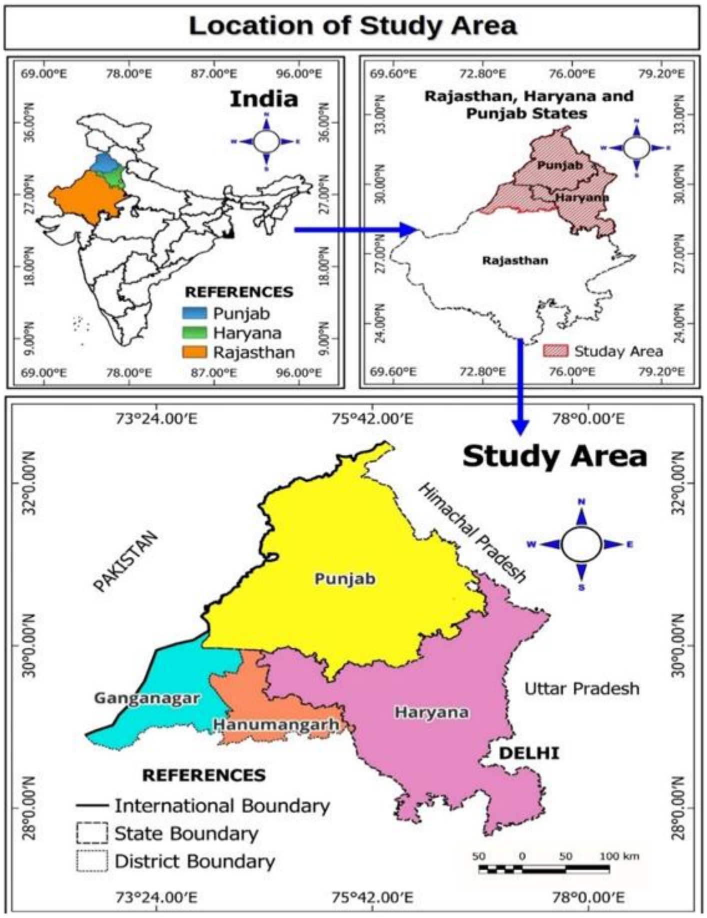
2. Study Area

The study area sits in north-western India, covering Punjab, Haryana, and the adjoining Rajasthan districts of Hanumangarh and Sri Ganganagar, and spans roughly 27°37′ N to 32°32′ N latitude and 72°30′ E to 77°36′ E longitude. Punjab occupies the northern half of that range, between 29°30′ N and 32°32′ N, 73°55′ E to 76°50′ E;

Haryana sits to its south and east, extending from 27°37′ N to 30°35′ N and 74°28′ E to 77°36′ **E** ***(Government of India, n.d.-a; Government of India, n.d.-b).*** Hanumangarh and Sri Ganganagar form the western edge of the study region, part of Rajasthan's irrigated north-western plains rather than its more familiar arid interior ***(KVK Hanumangarh, n.d.; KVK Sri Ganganagar, n.d.)***.

The relief of the study area is mostly uniform, the north-western Indo-Gangetic Plain, flat to gently undulating for the most part. Punjab and Haryana are built on fertile alluvium, Hanumangarh and Sri Ganganagar, are canal-fed semi-arid plains where irrigation rather than rainfall does the heavy lifting. Haryana adds a bit of variation to that flatness, with floodplain tracts along the Yamuna, Ghaggar and Markanda systems and pockets of sandy, undulating ground in its western reaches ***(Government of Haryana, 2020)***. Further west still, Hanumangarh and Sri Ganganagar depend almost entirely on canal networks and semi-arid conditions to sustain agriculture at all ***(ICAR-CRIDA, 2012; KVK Sri Ganganagar, n.d.)***

Figure 2.1. Location Map of the Study Area in North-Western India



The study area has a mainly continental climate, with very hot summers, cool winters, and most rainfall occurring during the south-west monsoon from July to September. Hanumangarh experiences strong seasonal variation, with winter temperatures falling to about 2.1°C and summer temperatures reaching 47.9°C, while Sri Ganganagar also faces extreme summer heat, cold winters, dust storms, and irregular rainfall ***(KVK Hanumangarh, n.d.; KVK Sri Ganganagar, n.d.)***. The soils vary across the region, from fertile alluvial soils in Punjab and Haryana to sandy and loamy soils, floodplain areas, and some salt-affected patches in northern Rajasthan ***(KVK Sri Ganganagar, n.d***.). Together with irrigation, these conditions support intensive rice–wheat farming and contribute to the large amount of crop residue produced in the region.

Rice cultivation rise sharply in Punjab after the Green Revolution and now sits alongside wheat as the state's two defining crops ***(Grover et al., 2016)***. Harvest timing is what actually matters for this study because paddy comes off the fields in October–November whereas wheat goes in during March–April, and due to the short gap between these two successive crops the residue burning happens. In Hanumangarh and Sri Ganganagar, canal irrigation supports farming, with wheat, cotton, mustard, paddy, and fodder grown according to water availability. Hanumangarh depends heavily on its canal systems to support double cropping pattern with rainfed patches lagging well behind in productivity ***(ICAR-CRIDA, 2012)***. Sri Ganganagar tells a similar story, its semi-arid landscape turned genuinely productive almost entirely through irrigation infrastructure ***(KVK Sri Ganganagar, n.d.)***.

These conditions help explain the strong fire activity seen across the study area every October and November. Punjab and Haryana are major food-grain producing states, while Hanumangarh and Sri Ganganagar, although smaller contributors, follow a similar rice–wheat cropping cycle. Mechanised harvesting and the short gap between crops leave large amounts of residue to be cleared within a limited time. This makes the region well suited for studying the relationship between crop burning, aerosol loading, and ground-level air pollution.

3. Research Objectives and Hypotheses

The central aim of this study is to examine how paddy straw burning, aerosol loading and ground-level particulate pollution move together, spatially and temporally, across north-western India during 2021.

That aim breaks down into five specific objectives:

1. Compare Terra and Aqua MODIS cumulative fire frequency at monthly and seasonal scales during 2021, to establish whether the two sensors capture a consistent picture of burning activity.
2. Examine the relationship between Terra-MODIS cumulative fire frequency and MODIS MAIAC AOD at both monthly and weekly resolution.
3. Map the spatial distribution of fire-frequency hotspots and their associated AOD patterns across the study area.
4. Compare satellite-derived fire frequency and AOD against CPCB ground-level $PM_{2.5}$ concentrations for the same period.
5. Statistically test the relationship between weekly cumulative fire frequency, mean AOD and $PM_{2.5}$ using Pearson correlation, significance testing, and R^2.

Three of these objectives converted directly into testable hypotheses:

H1: Terra-MODIS cumulative fire frequency positively correlates with MODIS MAIAC AOD during the 2021 burning season.

H2: Weeks with higher cumulative fire frequency during the paddy-burning period coincide to higher ground-level $PM_{2.5}$ concentrations.

H3: MODIS MAIAC AOD is positively associated with CPCB $PM_{2.5}$, indicating that satellite-derived aerosol loading reflects what is actually happening at ground level during the burning season.

4. Data Sources and Methodology

This study combines satellite-based fire and aerosol data with ground-based air quality observations to examine how paddy straw burning, aerosol loading and particulate pollution moved together over north-western India during 2021. Analysis was carried out at monthly, seasonal, district and weekly scales. Monthly and the seasonal resolution captures the broad annual pattern whereas weekly resolution works on the short-duration build-up and decline that a monthly average would smooth over entirely.

4.1 Satellite Fire Data

Cumulative fire frequency came from the MODIS MOD14A1 (Terra) and MYD14A1 (Aqua) daily fire products, built on the Collection 6 active fire detection algorithm ***(Giglio et al., 2016)***, using the FireMask band with a threshold of FireMask ≥ 7 to retain only nominal, high and very-high confidence detections and exclude low-confidence noise.

Daily fire detections were added for each month, season, or week. Thus, a 1 km pixel detected on several days was counted once for each day. This gives a cumulative fire frequency that reflects both the spread and duration of burning. For example, burning detected at the same location for three days contributes more than burning detected for one day. These values therefore represent fire pixel-day detections, not the number of individual fires.

Terra and Aqua were compared at monthly and seasonal scales before selecting the main dataset. Terra observes the area at about 10:30 local time, while Aqua passes at about 13:30. Aqua recorded much higher fire frequency during the peak burning weeks, possibly because more fires were active or had stronger thermal signals in the afternoon and crossed the FireMask ≥ 7 threshold. The difference between the two sensors also changed with burning intensity. Therefore, Terra was used for the main fire–AOD–$PM_{2.5}$ analysis because it provides a consistent observation time. Aqua was kept only for sensor comparison and was not included in the correlation analysis.

4.2 MODIS MAIAC AOD Data

Aerosol Optical Depth was obtained from the MODIS MAIAC MCD19A2 product (Collection 6), using the Optical Depth 055 band and the standard 0.001 scale factor ***(Lyapustin et al., 2018)***. MAIAC's time-series-based cloud detection and atmospheric correction give it 1 km resolution and better performance in hazy, high-aerosol-load conditions than the older Dark Target algorithm, a relevant property here, given that dense smoke plumes are exactly the scenario in which conventional AOD retrievals tend to degrade.

Mean AOD was calculated at monthly, weekly and district level. For graphical comparison against fire frequency and $PM_{2.5}$ in the same figures, AOD values were multiplied by 100 for visual scaling only whereas all the tables and statistical analysis use the unscaled values.

4.3 CPCB PM2.5 Data

Ground-level $PM_{2.5}$ came from CPCB Continuous Ambient Air Quality Monitoring Station data for 2021 ***(Central Pollution Control Board, 2021)***: 36 station files, 13,140 daily records in total, of which 12,595 valid observations were retained after excluding 545 missing or NA entries.

CPCB data serve here as ground-truth validation for the satellite-derived indicators, the question being not just whether fire activity and AOD moved together, but whether that atmospheric signal was actually reaching the surface as measurable pollution.

4.4 Temporal Aggregation

Monthly data were used to show the overall yearly pattern, while seasonal data helped distinguish the pre-monsoon wheat-residue burning period from the post-monsoon paddy-burning period. Weekly data from September to December 2021 were also used because monthly averages can hide the short period when paddy burning increases, peaks, and then declines.

Each month was divided into four weekly periods. Since September to December have 30 or 31 days, the fourth week contains the remaining 2 or 3 days and is therefore 9 or 10 days long. As a result, its cumulative fire frequency, AOD, and $PM_{2.5}$ values may be higher simply because it covers more days. This was considered when interpreting the weekly results and is also discussed in the limitations.

4.5 District-wise Analysis

Cumulative fire frequency and mean AOD were calculated per district to identify spatial hotspots of residue burning and their related aerosol loading, comparing annual and post-monsoon values to assess whether districts with higher burning activity also showed elevated AOD.

4.6 Spatial Mapping

Weekly maps of Terra cumulative fire frequency and MODIS MAIAC AOD were prepared for September to December 2021. The maps show the main stages of the burning season: September marks the start of paddy residue burning, October shows the build-up, November represents the peak burning and higher aerosol levels, and December shows the decline. They were also used to see whether high AOD remained around fire hotspots or spread into nearby areas, helping to understand the spatial relationship between burning and air pollution.

4.7 Statistical Analysis

Pearson correlation was used to test the strength and direction of association among weekly cumulative fire frequency, mean AOD and mean PM2.5. Three pairs were tested, fire frequency vs. AOD, fire frequency vs. $PM_{2.5}$, and AOD vs. $PM_{2.5}$, with R^2 calculated to express shared variance and significance assessed at the 0.05 level.

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2 \sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

where $X_i$and $Y_i$are the paired weekly values for the two variables under comparison, for instance, weekly cumulative fire frequency and weekly mean AOD, $\bar{X}$and $\bar{Y}$are their respective means, and $n$is the number of weekly observations (n = 16, September–December 2021).

Significance of r was assessed with Student's t-test, $t = r\sqrt{(n-2)/(1-r^2)}$ with degree of freedom df = n − 2 = 14. Because weekly fire, AOD and $PM_{2.5}$ values form a continuous time series rather than independent draws, since each week's conditions are influenced by the week before it, the resulting p-values should be read as indicating a strong linear association rather than as a strict test under the independence assumption classical significance testing relies on.

$$R^2 = r^2$$

R^2 is reported as the proportion of variance in one variable statistically explained by the other under a linear relationship, a description of shared variation, not a claim about which variable drives the other.

In addition to the same-week comparisons above, a one-week lagged Pearson correlation was calculated to test the delay between fire activity and ground-level pollution described in ***Section 5.10***. Weekly cumulative fire frequency and mean AOD in week *t* was correlated against mean $PM_{2.5}$ in week *t+1* (n = 15), using the same formula and significance test described above. Results are reported in ***Section 6.2***.

5. Result and Discussion

5.1 Terra and Aqua MODIS Fire Detection: Sensor Comparison and Selection Rationale

Before examining the fire–aerosol relationship, Terra and Aqua cumulative fire frequency were compared to characterize sensor-wise detection behaviour across the study area in 2021, using monthly and seasonal aggregation ***(Table 5.1).***

Table 5.1: Monthly Terra and Aqua Cumulative Fire Frequency, 2021

Month	Cumulative Terra fire frequency	Cumulative Aqua Fire frequency
January	**11**	**68**
February	**106**	**153**
March	**119**	**111**
April	**865**	**818**
May	**1785**	**1378**
June	**58**	**33**
July	**415**	**53**
August	**35**	**12**

September	**29**	**45**
October	**937**	**6478**
November	**2834**	**26020**
December	**51**	**124**

Both sensors show a similar seasonal pattern. Fire frequency remains low from January to March, increases sharply during April and May due to wheat-residue burning after the rabi harvest, stays low during the monsoon season (June to September), and reaches its highest level in October and November because of post-harvest paddy-residue burning. Although both sensors identify the same timing of fire activity, they differ greatly in the number of fires detected. Terra recorded 937 fire detections in October and 2,834 in November, whereas Aqua recorded 6,478 and 26,020 detections during the same months, with the November total being about nine times higher than Terra.

The difference between Terra and Aqua is mainly related to their different overpass times, not to a problem with the data. Terra passes over the equator at about 10:30 local time, whereas Aqua passes around 13:30, when agricultural burning is often more active ***(Giglio et al., 2006)***. This helps explain why Aqua detected more fires, especially during the peak burning weeks in this study. Studies using both sensors have also found higher fire detection than either sensor alone ***(Hawbaker et al., 2008)***. Thus, the Terra–Aqua difference seen here is consistent with the known behaviour of the two satellites.

Figure 5.1a. Monthly cumulative fire frequency for Terra and Aqua MODIS, full-scale view, showing the dominant Aqua detections during October–November 2021.

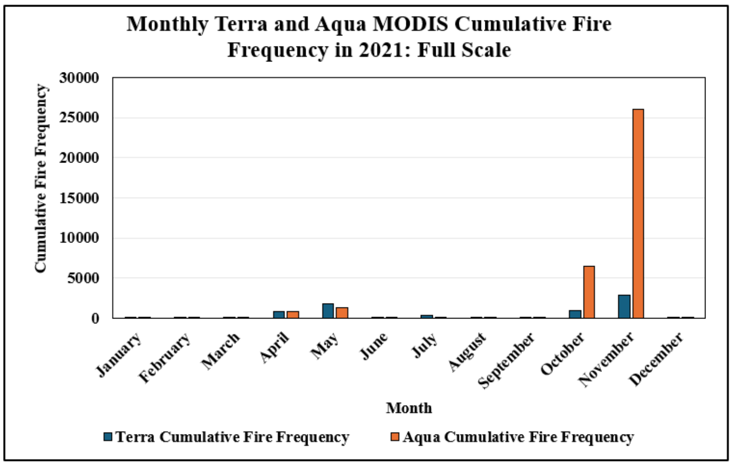
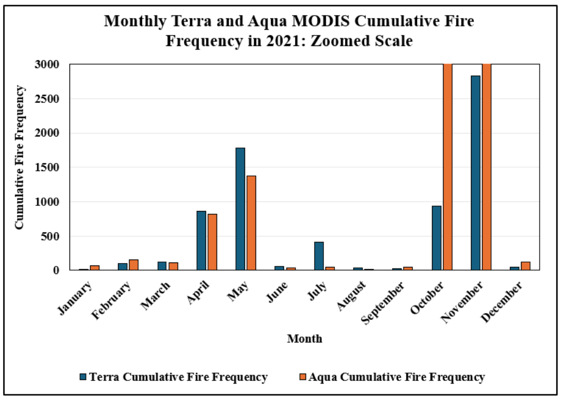


Figure 5.1b. Monthly cumulative fire frequency for Terra and Aqua MODIS, zoomed to a 3,000-pixel ceiling for clearer visibility of the lower-magnitude months.



Both sensors show a similar seasonal pattern. Fire frequency remains low from January to March, increases during April–May with wheat-residue burning after the rabi harvest, stays low during the monsoon period from June to September, and then rises sharply in October–November because of paddy-residue burning ***(Figure 5.1a***).

The main difference is in the number of fires detected. The difference is so large that the smaller monthly values become difficult to see in the full-scale graph, so a zoomed view is also provided ***(Figure 5.1b***). Terra recorded 937 fire-frequency counts in October and 2,834 in November, while Aqua recorded 6,478 and 26,020, respectively. Thus, Aqua's November value was roughly nine times higher than Terra's.

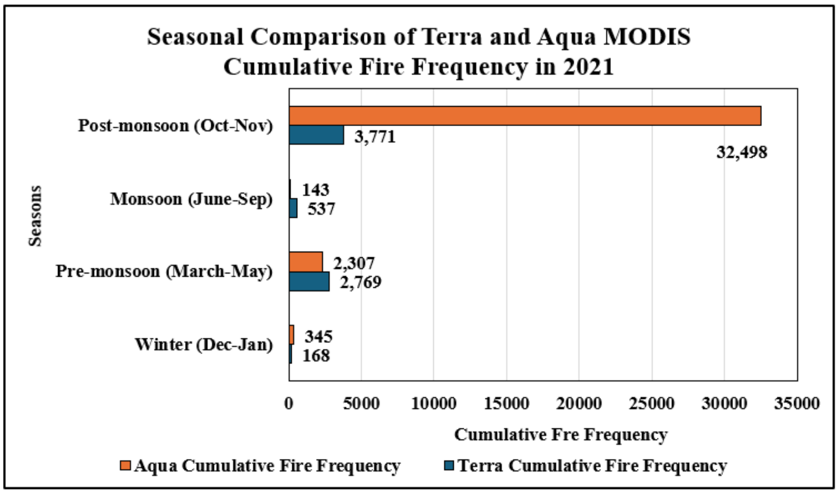
5.2. Seasonal Comparison of Terra and Aqua Cumulative Fire Frequency

Aggregating cumulative fire frequency to seasonal resolution provides a clearer view of which burning phase dominates the annual cycle than monthly comparison alone ***(Table 5.2, Figure 5.2a).***

Table 5.2. Seasonal Terra and Aqua Cumulative Fire Frequency in 2021

Season	Terra Cumulative Fire Frequency	Aqua Cumulative Fire Frequency
Winter (Dec–Jan)	168	345
Pre-monsoon (March–May)	2,769	2,307
Monsoon (June–Sep)	537	143
Post-monsoon (Oct–Nov)	3,771	32,498

Figure 5.2a Seasonal comparison of Terra and Aqua cumulative fire frequency across the study area during 2021.



Fire frequency remains low during winter for both sensors because little residue burning takes place at this time. The monsoon season has the lowest totals overall. Terra recorded 537 fire-frequency counts compared with 143 for Aqua. Since both values are small, this difference is more likely due to the limited fire activity during the season than to a consistent difference between the sensors. It does not change the overall pattern seen in the other results.

The pre-monsoon season shows a different pattern. Terra recorded 2,769 fire-frequency counts compared with 2,307 for Aqua. This difference is real, but it should be interpreted carefully. Peak burning for both wheat and rice residues occurs at around 14:30 local time, so the reversal cannot simply be explained by different burning times ***(Lan et al., 2022)***. Since pre-monsoon burning is much lower than the post-monsoon peak, both sensors may be more affected by factors such as haze, cloud edges, or background temperature. This explanation is tentative and would require daily data to examine in detail.

The post-monsoon season shows the clearest difference between the two sensors. Terra recorded 3,771 fire detections, while Aqua recorded 32,498, nearly nine times higher. This difference is mainly due to their different satellite overpass times, as discussed earlier in Section 5.1. The post-monsoon season alone contributed about

86% of Aqua's annual fire detections and 55% of Terra's annual total. Despite the difference in the number of detections, both sensors clearly identified the post-monsoon season as the main period of fire activity.

The results point to two main burning periods in 2021. A smaller phase occurs during April–May, mainly linked to wheat-residue burning, and both sensors show a similar pattern. The second, much larger phase occurs in October–November with paddy-straw burning, where Terra and Aqua show a clear difference in the number of detections. Since most of the burning takes place in the post-monsoon period, the next part of the analysis concentrates on September–December.

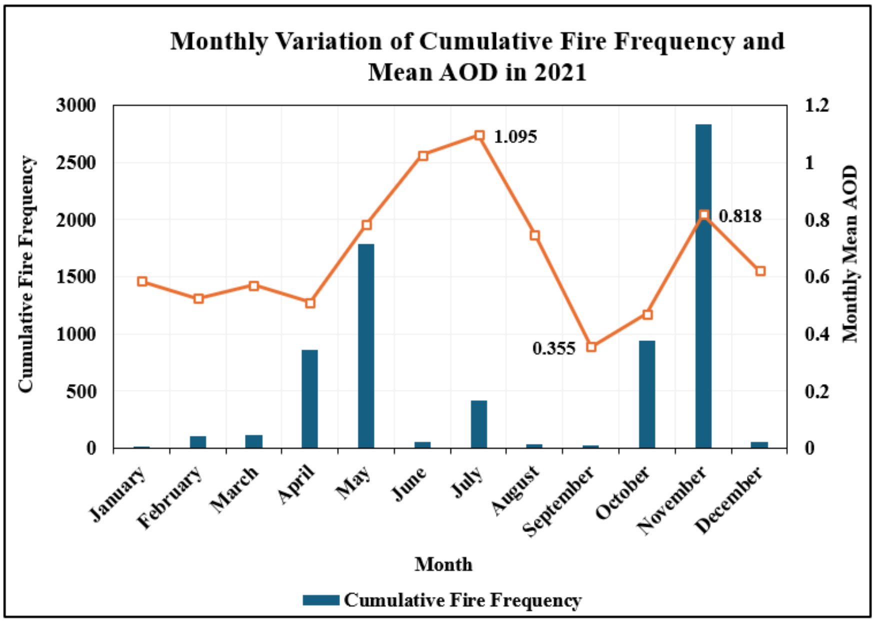
5.3. Temporal Distribution of Monthly Fire Activity and Aerosol Loading in 2021

This section looks at whether months with more burning also had higher aerosol levels. Terra fire frequency and monthly mean AOD are compared for all of 2021 ***(Table 5.3).***

Table 5.3: Monthly Terra Fire Frequency and Mean AOD, 2021

Month	Cumulative Fire Frequency	Monthly Mean AOD
January	11	0.584
February	106	0.524
March	119	0.571
April	865	0.511
May	1785	0.784
June	58	1.026
July	415	1.095
August	35	0.747
September	29	0.355
October	937	0.469
November	2834	0.818
December	51	0.621

Figure 5.3a. Monthly variation of Terra-MODIS Cumulative fire frequency and MODIS MAIAC mean AOD over the study area in 2021



From January to March, both numbers stay low, fire frequency between 11 and 119, AOD flat and unremarkable. Numbers rise up in April and May, when wheat fields get cleared after harvest then fire frequency jumps to 865 and 1,785 and AOD rises with it, from 0.511 to 0.784. Here, fire and AOD move together, roughly as you'd expect.

June and July don't follow that pattern. Fires drop off sharply, but AOD climbs even higher, 1.026 in June, 1.095 in July, the two highest readings of the entire year, in the two months with the least burning. This isn't a strange result specific to this study. During the monsoon, humidity across the Indo-Gangetic Plain is high enough that existing aerosol particles absorb moisture and swell, which raises AOD without any new smoke being added to the air ***(Mhawish et al., 2021)***. Fire frequency does not explain the June and July pattern very well. The higher values during these months are better explained by the increase in humidity.

October and November bring the pattern back. Fire frequency rises from 29 in September to 937 in October to 2,834 in November, and AOD rises alongside it 0.355, 0.469, 0.818. This is the main relationship examined in the rest of the study, and the results show a clear link during the season when it is most relevant.

Two burning phases stand out across the year whereas a smaller one in April–May related to wheat, and a much larger one in October–November tied to paddy straw. The high AOD in June–July is different from both fire activity and the post-monsoon pattern. It is mainly linked to the monsoon conditions rather than burning. Recognising this difference makes the October–November fire–AOD relationship clearer.

5.4 District-Level Fire Hotspots and Aerosol Loading: Punjab

Punjab's fire and aerosol patterns are examined at district level to identify where residue burning concentrates spatially, and whether that concentration lines up with elevated aerosol loading in the same places. District-level cumulative fire frequency and mean AOD are compared across the state's 22 districts, for both the annual period and the post-monsoon season specifically ***(Table 5.4)***.

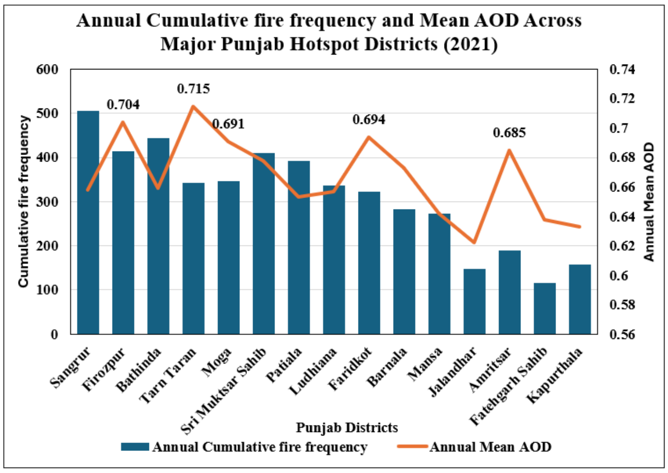
5.4.1 Annual Cumulative Fire Frequency and Mean AOD Across Major Punjab Hotspot Districts (2021)

Table 5.4 sets out the annual and post-monsoon comparison in full.

Table 5.4. Annual and post-monsoon cumulative fire frequency and Mean AOD across Major Punjab Hotspot Districts in 2021

District	Annual Cumulative fire frequency	Annual Mean AOD	Post-Monsoon Cumulative fire frequency	Post-Monsoon Mean AOD
Sangrur	505	0.658	329	0.666
Firozpur	415	0.704	295	0.677
Bathinda	444	0.659	286	0.693
Tarn Taran	342	0.715	282	0.696
Moga	346	0.691	271	0.66
Sri Muktsar Sahib	410	0.678	252	0.727
Patiala	393	0.653	247	0.631
Ludhiana	337	0.657	232	0.636
Faridkot	323	0.694	229	0.694
Barnala	283	0.673	193	0.662
Mansa	273	0.642	171	0.667
Jalandhar	148	0.622	91	0.602
Amritsar	189	0.685	87	0.647
Fatehgarh Sahib	116	0.638	87	0.578
Kapurthala	157	0.633	83	0.61
Fazilka	176	0.669	70	0.699
Sahibzada Ajit Singh Nagar	55	0.532	26	0.427
Gurdaspur	157	0.581	23	0.53
Hoshiarpur	150	0.481	13	0.439
Shahid Bhagat Singh Nagar	45	0.557	10	0.493
Rupnagar	36	0.501	7	0.408
Pathankot	21	0.394	0	0.319

Figure 5.4a. Annual cumulative fire frequency and mean AOD across major Punjab hotspot districts, 2021

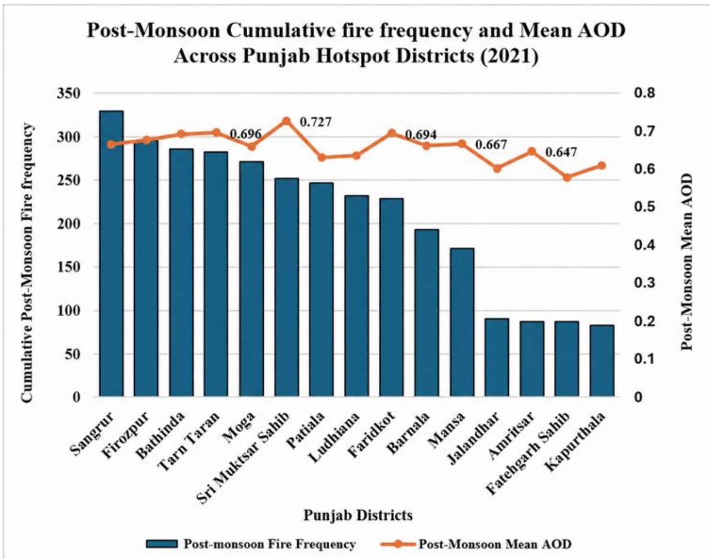


The chart confirms the hotspot cluster already identified in ***(Table 5.4***) Sangrur, Firozpur, Bathinda and their neighbours sit well above the rest of the state on fire frequency. AOD follows the fire pattern only partly. Tarn Taran has the highest annual AOD (0.715) but ranks fourth in fire frequency, while Faridkot has a relatively high AOD (0.694) despite having fewer fires than several other districts. Amritsar shows the clearest difference, with an annual AOD of 0.685 despite its low fire frequency. Its AOD is also higher than nearby Jalandhar (0.622) and Fatehgarh Sahib. Amritsar is Punjab's largest urban centre, and year-round urban and industrial emissions are a possible source of this elevated annual reading, separate from paddy burning. The district also lies close to the India–Pakistan border, within a belt where residue-burning smoke has been documented moving across the boundary in low-altitude plumes ***(Singh & Kaskaoutis, 2014***) though this remains unconfirmed by the present dataset.

5.4.2 Post-Monsoon Cumulative Fire Frequency and Mean AOD Across Major Punjab Hotspot Districts (2021)

The post-monsoon period has the highest paddy-straw burning, making it the most suitable period for examining how closely aerosol levels followed fire activity.

Figure 5.4b. post-monsoon cumulative fire frequency and mean AOD across major Punjab hotspot districts, 2021.



Looking only at the post-monsoon season makes the fire-frequency pattern clearer, while the AOD results change noticeably. Amritsar's earlier spike is no longer present, with its post-monsoon AOD falling to 0.647, which is more in line with its relatively low fire count. Since the higher AOD appears in the annual data but not during the main burning season, the annual value is likely influenced more by other sources than by local paddy burning.

The pattern is also clear in other districts. Sri Muktsar Sahib has the highest post-monsoon AOD (0.727) even though it ranks sixth in fire frequency. Barnala also has a relatively high AOD (0.667) despite having several districts above it in fire frequency. This suggests that smoke movement between nearby districts has a stronger influence on AOD than the fire count within any one district.

5.5 District-Level Fire Hotspots and Aerosol Loading: Haryana

District-level cumulative fire frequency and mean AOD were compared across Haryana's 22 districts, for the full year and the post-monsoon window, following the same approach applied to Punjab in *Section 5.4* ***(Table 5.5)***.

5.5.1 Annual Cumulative Fire Frequency and Mean AOD Across Major Haryana Hotspot Districts (2021)

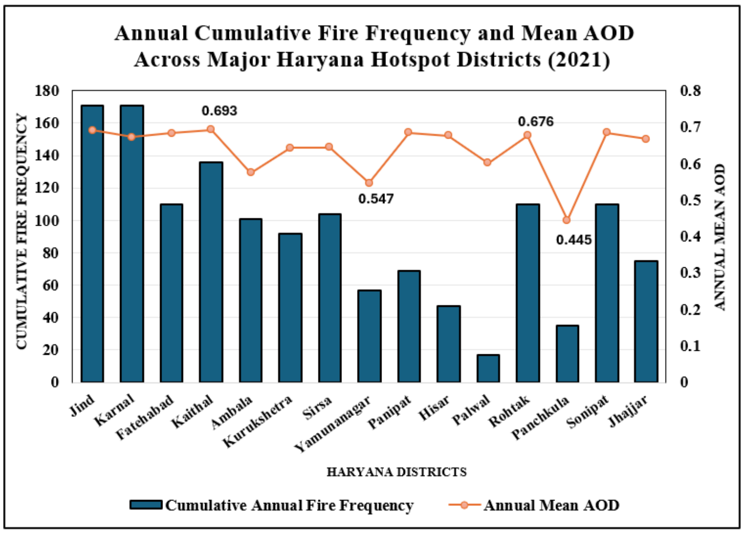
Table 5.5 sets a baseline for how closely fire frequency and AOD track each other across the full year, against which the sharper post-monsoon pattern can be compared.

Table 5.5: Annual and Post-Monsoon Cumulative Fire Frequency and Mean AOD across Haryana Districts, 2021

District	Cumulative Annual Fire Frequency	Annual Mean AOD	Cumulative Post-Monsoon Fire Frequency	Post-Monsoon Mean AOD
Jind	171	0.691	91	0.774
Karnal	171	0.672	68	0.695
Fatehabad	110	0.683	68	0.732
Kaithal	136	0.693	58	0.743
Ambala	101	0.575	51	0.492
Kurukshetra	92	0.643	50	0.609
Sirsa	104	0.645	45	0.667
Yamunanagar	57	0.547	20	0.433
Panipat	69	0.684	19	0.761
Hisar	47	0.677	14	0.79
Palwal	17	0.601	7	0.695
Rohtak	110	0.676	4	0.763
Panchkula	35	0.445	3	0.338
Sonipat	110	0.685	2	0.774
Jhajjar	75	0.667	1	0.759
Bhiwani	19	0.619	1	0.724
Gurugram	6	0.581	0	0.691
Faridabad	2	0.608	0	0.701
Mahendragarh	0	0.573	0	0.679
Rewari	0	0.606	0	0.74
Nuh	4	0.587	0	0.724
Charki Dadri	15	0.622	0	0.738

Jind and Karnal lead the state on annual fire frequency (171 each), with Jind also recording the highest post-monsoon count (91). This northern-central cluster, Jind, Karnal, Kaithal, Fatehabad, forms Haryana's core burning belt, broadly in line with the paddy-intensive districts identified in the wider literature on the state's residue burning.

Figure 5.5a. Annual cumulative fire frequency and mean AOD across major Haryana hotspot districts, 2021.

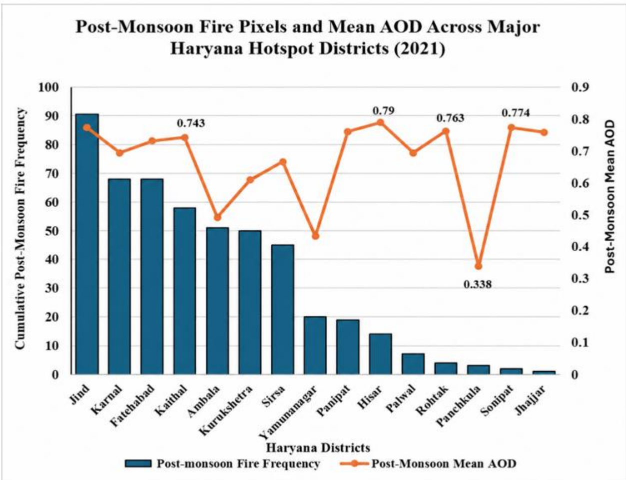


Annual AOD generally follows the fire pattern among the top-ranked districts, with Kaithal, Jind and Sonipat showing both high fire counts and high AOD. Panchkula is the lowest on both measures. The pattern is less clear among the remaining districts.

5.5.2 Post-Monsoon Cumulative Fire Frequency and Mean AOD Across Major Haryana Hotspot Districts (2021)

The post-monsoon window is where Haryana's most striking pattern appears: several districts with almost no local burning still carry AOD comparable to genuine hotspots.

Figure 5.5b. post-monsoon cumulative fire frequency and mean AOD across major Haryana hotspot districts, 2021.



The post-monsoon results show that local fire counts do not always match AOD levels. Rohtak, Sonipat, Jhajjar and Bhiwani recorded four or fewer fire-frequency counts, but their AOD values were still between 0.72 and 0.76, similar to or higher than districts with much more fire activity. The difference is even clearer in Rewari, Mahendragarh, Gurugram, Faridabad, Nuh and Charki Dadri, where none recorded any post-monsoon fire-frequency counts, yet AOD values ranged from 0.68 to 0.74. Rewari is the clearest example, with zero fire counts but an AOD of 0.740, almost the same as Fatehabad, where 68 fire-frequency counts were recorded during the same period.

This pattern does not match what locally generated aerosol loading would look like. It fits a picture of regional transport of smoke originating in Haryana's northern burning belt, and very likely in Punjab's hotspot districts further north again, drifting southward and settling over districts with little or no burning of their own. Several of the affected districts, Gurugram, Faridabad, Nuh, also fall within the National Capital Region, the same downwind zone shown elsewhere to receive a substantial share of its post-monsoon particulate load from upwind stubble burning ***(Govardhan et al., 2023)***. Local NCR emissions may compound the transported signal in these specific districts, though the pattern extends well beyond NCR's boundary into districts like Rewari and Mahendragarh that sit outside it. Panchkula stands at the opposite extreme, recording the lowest post-monsoon AOD in the state (0.338) despite a fire-frequency count in the middle of the state's range, possibly a function of its position in the Shivalik foothills, where terrain likely favours dispersion rather than accumulation.

The Punjab and Haryana results lead to the same overall conclusion. In Punjab, AOD generally increases with fire frequency among the main hotspot districts, while in Haryana, AOD remains high even in districts with zero fire counts. This shows that district-level AOD cannot be treated as a direct measure of local burning. It represents a wider regional pollution pattern, influenced not only by where fires occur but also by the movement of smoke between areas.

5.6 District-Level Fire Frequency and Aerosol Loading: Hanumangarh and Sri Ganganagar (Rajasthan)

Cumulative fire frequency and mean AOD were also examined for the two Rajasthan districts included in the study area, following the same approach applied to Punjab and Haryana ***(Table 5.6).***

Table 5.6: Annual and Post-Monsoon Cumulative Fire Frequency and Mean AOD across Hanumangarh and Sri Ganganagar, 2021

District	Annual Cumulative Fire Frequency	Annual Mean AOD	Post-Monsoon Cumulative Fire Frequency	Post-Monsoon Mean AOD
Sri Ganganagar	81	0.657	7	0.683
Hanumangarh	53	0.625	12	0.636

Fire frequency in both districts is much lower than in Punjab and Haryana. Sri Ganganagar recorded an annual total of 81, which is lower than all but the four lowest-ranked districts in Punjab and below every Haryana district except the near-zero southern cluster. This lower fire activity fits their location at the western edge of the paddy-growing belt, where farming depends heavily on irrigation and includes a wider range of crops than the rice–wheat system found further east.

The two districts show an interesting difference between fire frequency and AOD. Sri Ganganagar has higher annual fire frequency than Hanumangarh (81 versus 53) and also a higher annual AOD (0.657 versus 0.625). In the post-monsoon period, however, the pattern changes. Hanumangarh records more fire frequency than Sri Ganganagar (12 versus 7), but Sri Ganganagar still has the higher AOD (0.683 versus 0.636). Since the fire counts are low and only two districts are being compared, this difference is too small to draw a firm conclusion. It may be due to local burning patterns or simply variation at low fire counts. Still, it supports the broader finding from Punjab and Haryana that AOD does not always follow local fire frequency, suggesting that smoke transport from the larger burning areas to the east also affects these districts.

Because this analysis includes only a few districts and low fire counts, it should be considered as supporting evidence rather than a separate finding. The results match the overall pattern observed across Punjab and Haryana, but the small sample size is not sufficient to draw independent conclusions.

5.7 Comparative Analysis Across Punjab, Haryana and Rajasthan

Bringing the three states together makes clear how unevenly crop residue burning is distributed across the study area, and how that unevenness in fire activity relates or fails to relate to the aerosol loading measured above each state.

Punjab is clearly the main contributor to post-monsoon fire activity in the study area. Most of the recorded fire frequency comes from its central and south-western districts, particularly Sangrur, Firozpur, Bathinda, Tarn Taran and Moga. These areas have intensive paddy cultivation and a short gap between harvesting and wheat sowing, making residue burning a common way to clear fields. Haryana also shows considerable burning, especially around Jind, Karnal, Kaithal and Fatehabad, but its total post-monsoon fire frequency is only about one-sixth of Punjab's. Hanumangarh and Sri Ganganagar record much less activity, about an order of magnitude below Haryana, which fits their location on the western edge of the paddy belt and their more varied cropping pattern.

Fire frequency, in other words, drops off sharply and consistently moving from Punjab through Haryana to Rajasthan but AOD does not fall away nearly as sharply. Haryana's hotspot districts post AOD values comparable to Punjab's Jind's 0.774 and Hisar's 0.790 sit alongside Punjab's own post-monsoon peak of 0.727 in Sri Muktsar Sahib despite Haryana's much lower fire frequency. Haryana's southern districts, including Rewari, Mahendragarh, Gurugram and Faridabad, have almost no recorded fires, yet their AOD remains between 0.68 and 0.74, similar to values seen in major fire hotspots. The same pattern appears in Hanumangarh and Sri Ganganagar, where AOD values of 0.636–0.683 are higher than their low fire counts would suggest. This indicates that AOD is not controlled by local burning alone.

The same pattern is observed at different spatial scales. Punjab has the highest fire activity, while Haryana and Rajasthan, despite having fewer local fires, still experience high aerosol levels. This indicates that AOD is not directly related to the number of local fires. Smoke from the major burning areas in Punjab does not remain confined to those locations and can spread over surrounding districts. The results in ***Sections 5.4 and 5.5*** also show that local fire frequency has only a weak relationship with district-level AOD in Punjab and Haryana. Taken together, the three-state results suggest that the high post-monsoon AOD in 2021 was not caused by local fires alone, smoke moving from the main burning areas also played an important role.

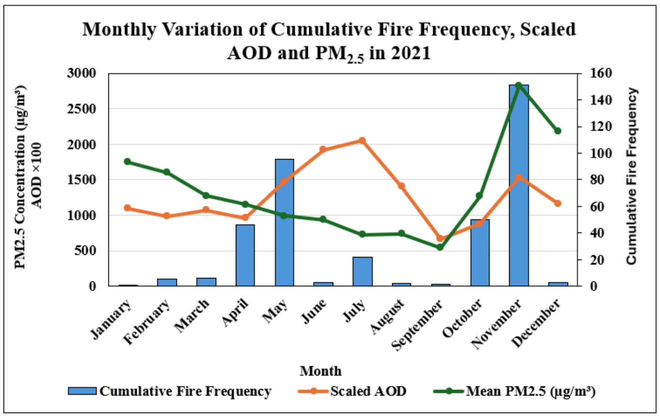
5.8 Monthly Relationship between Fire Frequency, AOD and Ground-Level PM2.5

Terra cumulative fire frequency, monthly mean AOD, and CPCB mean $PM_{2.5}$ were compared across 2021 to see whether satellite-detected fire activity and columnar aerosol loading translate into measurable ground-level pollution. $PM_{2.5}$ values were calculated from 36 CPCB station CSV files, 13,140 daily records in total, of which 12,595 valid observations were retained after excluding 545 missing or NA entries.

Table 5.7: Monthly Terra Cumulative Fire Frequency, Mean AOD and CPCB Mean $PM_{2.5}$, 2021

Month	Cumulative fire frequency	Monthly Mean AOD	Mean $PM_{2.5}$ (µg/m³)
January	11	0.584	93.27
February	106	0.524	85.23
March	119	0.571	67.95
April	865	0.511	61.36
May	1785	0.784	52.71
June	58	1.026	49.92
July	415	1.095	38.69
August	35	0.747	39.39
September	29	0.355	28.82
October	937	0.469	67.48
November	2834	0.818	150.59
December	51	0.621	116.33

Figure 5.8a. Monthly variation of Terra cumulative fire frequency, MODIS MAIAC mean AOD, and CPCB mean $PM_{2.5}$ over the study area in 2021.



(AOD scaled ×100 for graphical comparison only; unscaled values appear in Table 5.7.)

The above ***figure 5.8a*** shows that winter carries a $PM_{2.5}$ burden with no fire signal behind it. January, February and December post mean concentrations of 93.27, 85.23 and 116.33 µg/m³, despite fire frequency sitting near zero in all three months. This is a familiar seasonal pattern across the Indo-Gangetic Plain, where low boundary-layer height and weak dispersion trap pollutants from traffic, heating and industry close to the surface through the cooler months, independent of any agricultural burning.

The pre-monsoon period shows a different pattern. Fire frequency increased sharply in April and May, reaching 865 and 1,785, but $PM_{2.5}$ fell from 61.36 to 52.71 µg/m³ during the same period. Wheat-residue burning was present but it was not strong or concentrated enough to stop the overall decline in background pollution during spring.

The monsoon months show a clear difference between AOD and $PM2_{.5}$. AOD reaches 1.026 in June and 1.095 in July, while $PM_{2.5}$ falls to 49.92 and 38.69 µg/m³. If the high AOD values were caused by higher particulate pollution near the ground, $PM_{2.5}$ would be expected to increase as well. Instead, the two move in opposite directions, suggesting that the high monsoon AOD is mainly linked to humidity-related particle growth rather than a rise in ground-level pollution.

September holds the lowest $PM_{2.5}$ of the year (28.82 µg/m³), alongside the lowest fire frequency and lowest AOD. It is the calm before the season the rest of the paper is built around.

October and November then move together across all three measures at once, fire frequency rises from 937 to 2,834, AOD from 0.469 to 0.818, and PM2.5 from 67.48 to 150.59 µg/m³, the highest reading anywhere in the dataset. This is the clearest match among all three measures during the year and provides strong evidence that paddy-residue burning is linked with ground-level pollution, not just higher aerosol levels in the atmosphere.

December shows that the relationship is more complex than a simple linear pattern. Fire frequency drops by 98% from November to December, but $PM_{2.5}$ falls by only 23%, remaining the second-highest monthly reading of the year at 116.33 µg/m. Pollution continues even after fire activity decreases. This may be due to the persistence of particulate matter in the atmosphere and winter conditions that limit its removal. A similar delayed response is also seen in the weekly analysis that follows.

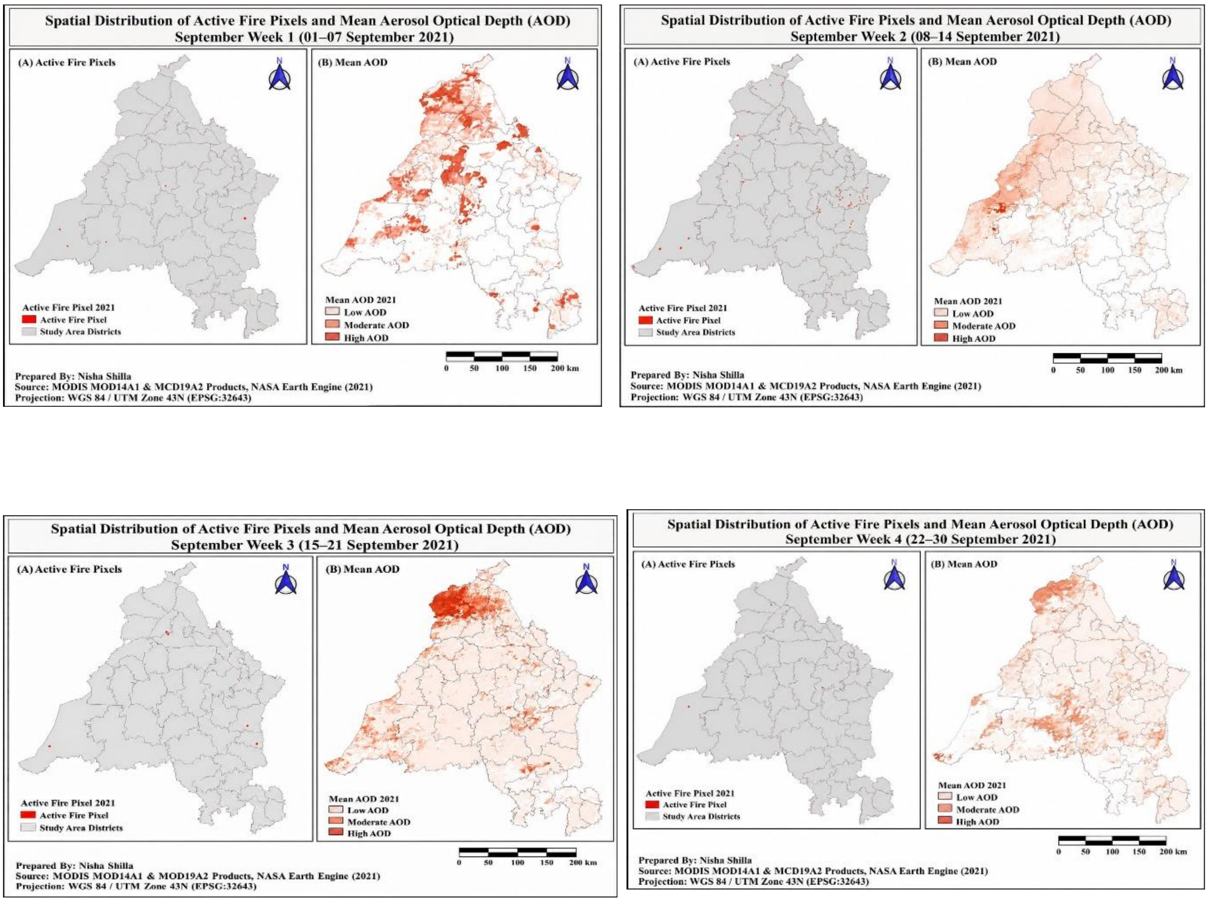
5.9 Weekly Spatial Analysis of Fire Activity and AOD, September–December 2021

Weekly maps of Terra-MODIS fire pixel locations and MODIS MAIAC AOD were produced for September through December 2021 to examine how the spatial relationship between burning and aerosol loading develops, peaks, and disperses across the season ***(Figures 5.9.a–5.9d).***

5.9.1 September: Pre-Burning Background

Fire activity remains very low throughout September, with only a few scattered detections each week and no clear fire hotspot across the study area. AOD, however, is higher in some areas. During weeks 1, 3 and 4, higher AOD is visible over the northern foothill districts, including Gurdaspur and Pathankot, where fire activity is very low according to the district-level data ***(Table 5.4)***. This suggests that the September AOD pattern is more likely related to local terrain and humidity than to agricultural burning. It also shows that AOD and fire activity do not always occur in the same places, and their closer relationship develops during the main burning season.

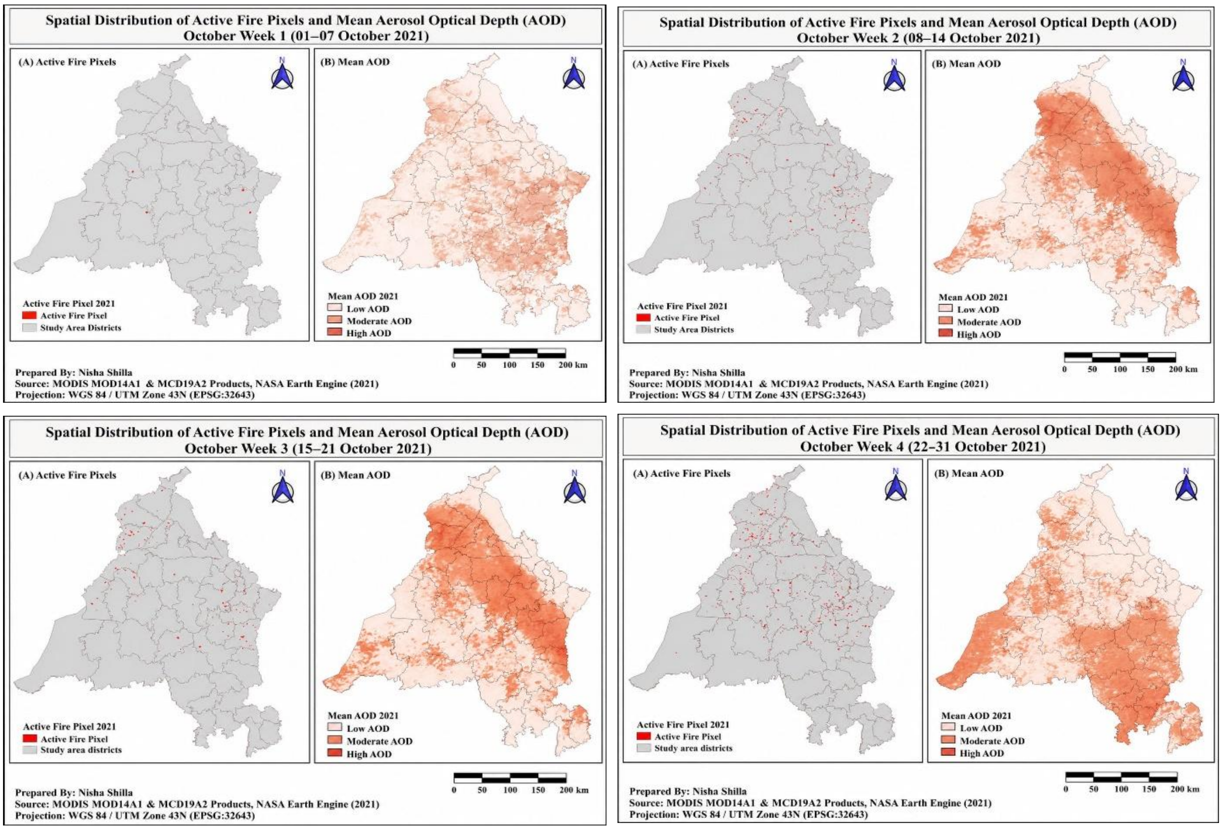
Figure 5.9a. Weekly spatial comparison of Terra-MODIS active fire pixels and MODIS MAIAC AOD during September 2021.



5.9.2 October: Burning Initiation and the Beginning of Transport

Fire detections remain sparse in Weeks 1 and 2 before increasing visibly from Week 3 onward, concentrated in a consistent north-central Punjab cluster that holds its position through Week 4. AOD tracks this cluster only partially. From Week 2 onward, the elevated-AOD zone extends beyond the fire cluster itself, reaching southeast into Haryana. This is the first clear sign, at weekly resolution, of aerosol moving away from its source rather than sitting directly above it.

Figure 5.9b. Weekly spatial comparison of Terra-MODIS active fire pixels and MODIS MAIAC AOD during October 2021

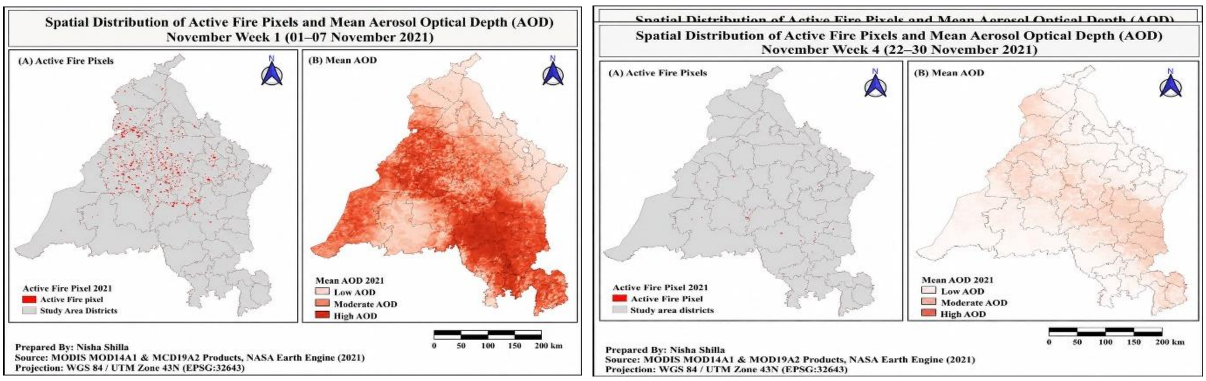


5.9.3 November: Peak Burning and the Fire–AOD Lag

Week 1 shows the highest and most widespread fire activity of the study, mainly across north-central Punjab and nearby parts of Haryana. AOD is already high during this week, but it covers a much larger area, extending into central and southeastern parts of the study region. In Week 2, fire activity starts to fall, while AOD reaches its highest and widest extent of the season, especially across southern Haryana and the districts near the Rajasthan border.

By Weeks 3 and 4, only a few scattered fires remain. AOD also declines, but it continues to cover much of the southwestern study area. The pattern is similar to the one-week lag found in the statistical analysis between fire activity and $PM_{2.5}$ ***(Section 6)***. Fire activity peaks first, followed by higher aerosol and particulate pollution farther downwind, particularly towards Haryana and the Rajasthan border.

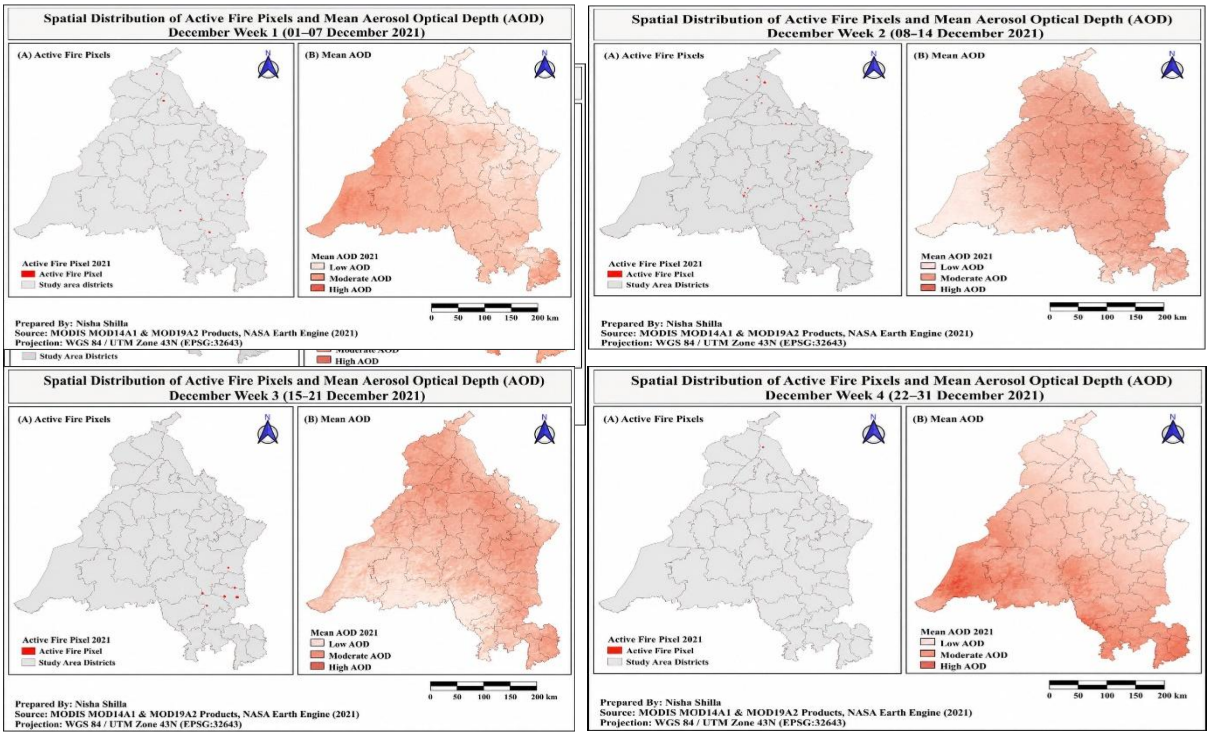
Figure 5.9c. Weekly spatial comparison of Terra-MODIS active fire pixels and MODIS MAIAC AOD during November 2021.



5.9.4 December: Decline and Persistent Regional Haze

Fire activity is largely absent by Week 1 and negligible for the remainder of the month. AOD does not decline at the same rate. Weeks 2 and 3 in particular show a diffuse, moderate-to-high AOD signal spread across nearly the entire study area, with no concentrated source visible on the fire map to account for it. This may be due to aerosol remaining in the atmosphere after the November peak, along with the weaker winter conditions that limit its dispersion, as also seen in the monthly $PM_{2.5}$ results ***(Section 5.8***).

Figure 5.9d. Weekly spatial comparison of Terra-MODIS active fire pixels and MODIS MAIAC AOD during December 2021.



5.10 Weekly Relationship between Fire Frequency, AOD and $PM_{2.5}$, September–December 2021

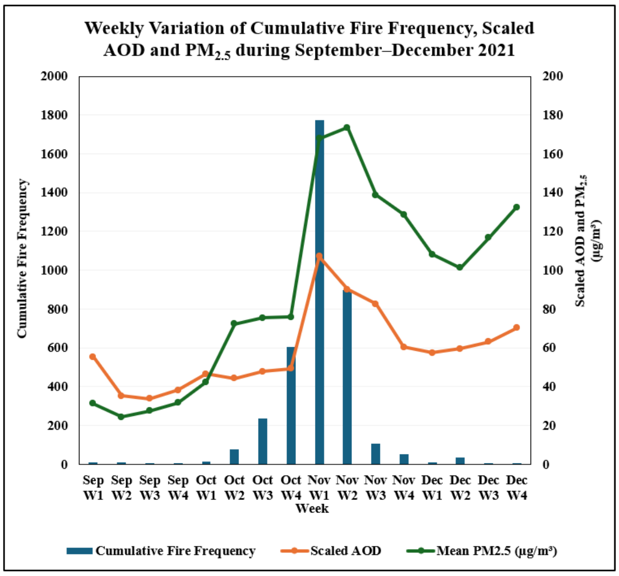
Weekly Terra cumulative fire frequency, mean AOD and CPCB mean $PM_{2.5}$ were compared across the burning season to examine how closely the three measures track each other at finer temporal resolution than the monthly analysis allows ***(Table 5.8, Figure 5.10a)***.

Table 5.8: Weekly Terra Cumulative Fire Frequency, Mean AOD and CPCB Mean $PM_{2.5}$, September–December 2021

Week	Period	Cumulative Fire Frequency	Mean AOD	Mean $PM_{2.5}$ (µg/m³)
Sep W1	01–07 Sep 2021	11	0.552	31.268
Sep W2	08–14 Sep 2021	9	0.352	24.332
Sep W3	15–21 Sep 2021	4	0.337	27.357
Sep W4	22–30 Sep 2021	5	0.382	31.533
Oct W1	01–07 Oct 2021	13	0.464	42.309
Oct W2	08–14 Oct 2021	78	0.441	72.354
Oct W3	15–21 Oct 2021	234	0.478	75.402
Oct W4	22–31 Oct 2021	606	0.492	75.887
Nov W1	01–07 Nov 2021	1773	1.071	167.774
Nov W2	08–14 Nov 2021	899	0.9	173.494
Nov W3	15–21 Nov 2021	106	0.825	138.696

Nov W4	22–30 Nov 2021	51	0.604	128.71
Dec W1	01–07 Dec 2021	8	0.574	108.098
Dec W2	08–14 Dec 2021	34	0.595	101.189
Dec W3	15–21 Dec 2021	7	0.631	116.605
Dec W4	22–31 Dec 2021	2	0.701	132.465

Figure 5.10a. Weekly variation of Terra cumulative fire frequency, scaled MODIS MAIAC AOD, and CPCB mean $PM_{2.5}$, September–December 2021



The ***figure 5.10a*** showing that September marks the baseline period before large-scale crop residue burning. During this month, fire frequency remains low (4–11), AOD ranges from 0.34 to 0.55, and $PM_{2.5}$ concentrations stay between 24 and 32 µg/m³. In October, fire activity increases steadily, with fire frequency rising from 13 in the first week to 606 in the fourth week. During the same period, AOD increases slightly from 0.464 to 0.492, while $PM_{2.5}$ almost doubles from 42 to 76 µg/m³. Fire frequency changes much more rapidly than AOD, suggesting that AOD reflects the combined effect of continuous burning over time rather than the fire count of a single week.

November shows the strongest burning activity and the clearest difference in timing between fire frequency, AOD and $PM_{2.5}$. Fire frequency reaches its highest weekly value in Week 1 at 1,773, while AOD also peaks in Week 1 at 1.071. $PM_{2.5}$ behaves differently and continues to rise into Week 2, reaching 173.494 µg/m³. By then, fire frequency has dropped to 899 and AOD to 0.900. This one-week difference is the clearest lag in the dataset. It also matches the spatial pattern described in ***Section 5.9***, where fires are concentrated in Punjab during Week 1, while higher AOD shifts towards Haryana and the Rajasthan border in Week 2. Together, the results show that smoke can take time to move and accumulate, with higher ground-level pollution appearing later in areas away from the main burning locations.

In Weeks 3 and 4 of November, fire frequency drops sharply to 106 and 51, while $PM_{2.5}$ remains high at 139 and 129 µg/m³, even though it has fallen from the Week 2 peak. These values are still much higher than those recorded in September or early October.

December shows a different pattern. Fire frequency stays very low throughout the month and never rises above 34. $PM_{2.5}$ falls to 101 µg/m³ in Week 2 but then increases to 132 µg/m³ by Week 4. AOD also rises from 0.574 to 0.701 during the month. Since there is almost no fire activity, the increase in AOD and $PM_{2.5}$ towards the end of December is more likely related to winter conditions, including lower temperatures, a shallower boundary layer and weaker dispersion. This is also consistent with the monthly $PM_{2.5}$ pattern discussed in ***Section 5.8.***

6. Statistical Assessment of Weekly Fire–AOD–PM2.5 Relationships, September–December 2021

Following the spatial and temporal patterns established in ***Sections 5.9 and 5.10***, Pearson correlation and Lag correlation was used to quantify the strength and significance of the relationships among weekly cumulative fire frequency, mean AOD and mean $PM_{2.5}$.

Table 6.1: Pearson Correlation, p-value and R^2 for Weekly Fire–AOD–PM2.5 Relationships

Relationship	Pearson *r*	p-value	R^2	Significance
Fire Frequency vs. Mean AOD	0.724	0.002	0.523	Significant
Fire Frequency vs. Mean PM2.5	0.560	0.024	0.314	Significant
Mean AOD vs. Mean PM2.5	0.900	<0.001	0.811	Highly significant

n = 16 weeks; df = 14; significance level = 0.05. Given the autocorrelated nature of weekly time-series data ***(Section 4.7****), these p-values should be read as indicating a strong linear association rather than as a strict independence test.*

Fire frequency has a strong positive relationship with AOD, with a significant correlation ($r = 0.724$, $p = 0.002$). In general, weeks with more burning also had higher aerosol levels. The relationship with $PM_{2.5}$ is also positive and significant, but weaker ($r = 0.560$, $p = 0.024$, $R^2 = 0.314$). This is reasonable because ground-level $PM_{2.5}$ is affected not only by burning but also by dispersion, accumulation and other pollution sources.

The scatter plot ***(Figure 6.1***) shows that much of this relationship comes from the two high-burning weeks in early November. The other fourteen weeks have relatively low fire frequency and show a much weaker pattern with $PM_{2.5}$. Therefore, $r = 0.560$ is a real result for the full dataset, but it is better understood as showing that the weeks with the highest burning also had the highest pollution, rather than as a steady linear increase in $PM_{2.5}$ with every increase in fire activity.

The strongest relationship by a clear margin is between AOD and $PM_{2.5}$ ($r = 0.900$, $p < 0.001$, $R^2 = 0.811$), and unlike the fire-$PM_{2.5}$ relationship, this one holds consistently across the full range of the data rather than depending on a small number of high-leverage weeks (***Figure 6.1***). This is arguably the study's most important statistical result that satellite-derived columnar aerosol loading tracks ground-level particulate pollution closely enough, at weekly resolution, to function as a genuine proxy for it in this region and season.

6.1 Weekly Scatter Relationships between Fire Frequency, AOD and $PM_{2.5}$

Figure 6.1a. Weekly relationship between MODIS MAIAC mean AOD and CPCB mean PM2.5, September–December 2021 ($R^2 = 0.811$).

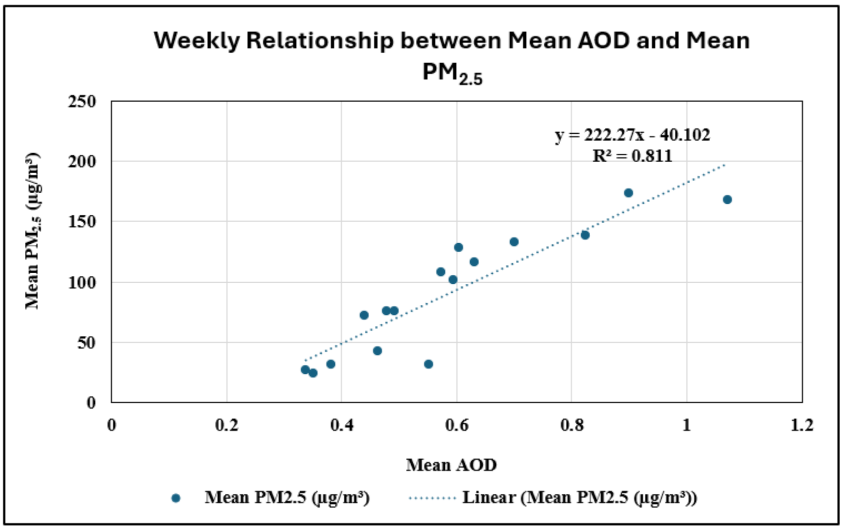


Figure 6.1b. Weekly relationship between Terra cumulative fire frequency and CPCB mean $PM_{2.5}$, September–December 2021 ($R^2 = 0.314$)

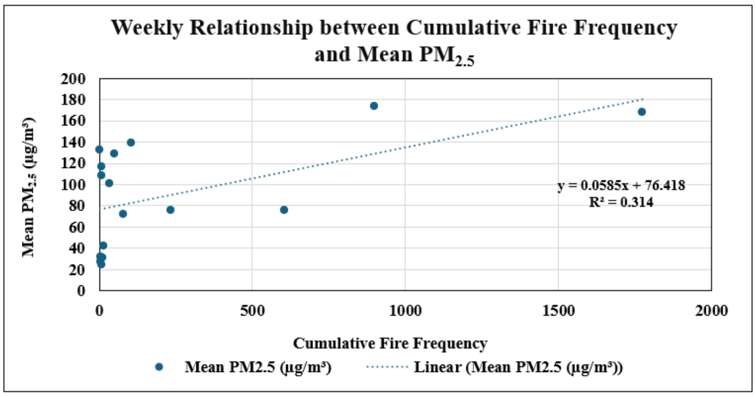
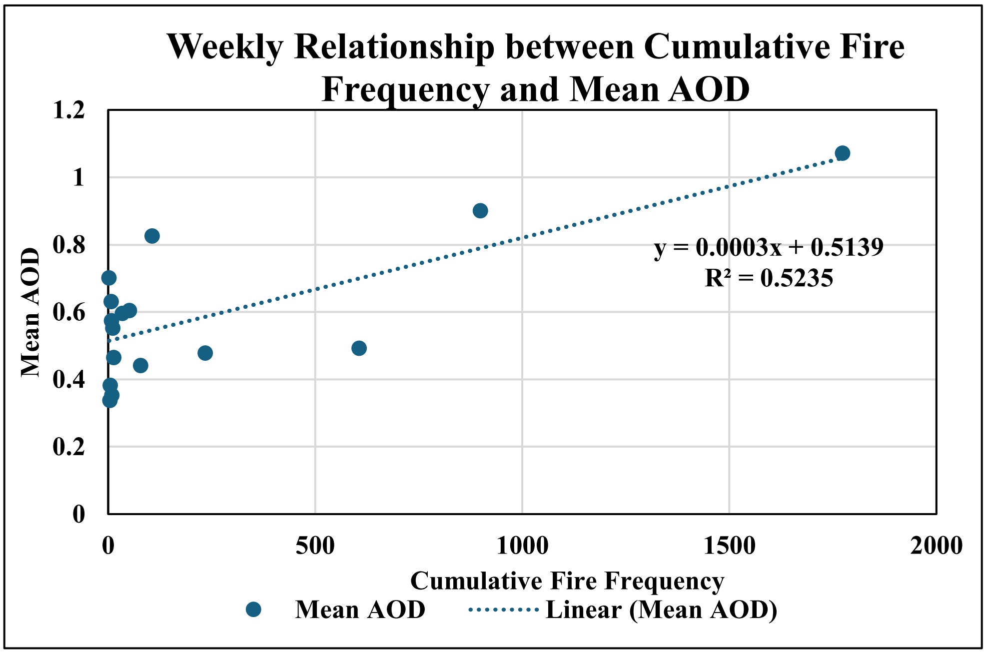


Figure 6.1c. Weekly relationship between Terra cumulative fire frequency and MODIS MAIAC mean AOD, September–December 2021 ($R^2 = 0.523$).



The three scatter plots show the patterns behind the correlation values. The AOD–$PM_{2.5}$ relationship ***(Figure 6.1a)*** is the clearest, with the points following the trendline across most of the AOD range. Fire frequency and AOD ***(Figure 6.1c***) also show a positive pattern, although the points are more spread out. The fire frequency–$PM_{2.5}$ relationship ***(Figure 6.1b)*** is less consistent, with most weeks having low fire frequency but widely different $PM_{2.5}$ values. Its positive trend is also strongly influenced by the two weeks with the highest fire activity. Overall, the three plots suggest that AOD provides the clearest link between satellite fire detections and ground-level $PM_{2.5}$ in this dataset.

6.2 Lag Correlation Analysis

The one-week gap between the fire/AOD peak and the $PM_{2.5}$ peak, described in ***Section 5.10***, was tested directly using a one-week lagged Pearson correlation: fire frequency and AOD in week t was correlated against $PM_{2.5}$ in week t+1 (n = 15).

Table 6.2: Same-Week and One-Week-Lagged Pearson Correlations

Relationship	Same-week r (R^2)	One-week-lag r (R^2)
Fire frequency → $PM_{2.5}$	0.560 (0.314)	0.649 (0.422)
Fire frequency → AOD	0.724 (0.523)	0.698 (0.487)
AOD → $PM_{2,5}$	0.900 (0.811)	0.744 (0.554)

When $PM_{2.5}$ is shifted by one week, its relationship with fire frequency becomes stronger. The R^2 value rises from 0.314 to 0.422, an increase of about 34%. This means that the rise in $PM_{2.5}$ is more closely related to the fire activity of the previous week. Smoke can take time to spread and accumulate near the ground.

The AOD results are different. Its relationship with fire frequency changes only slightly, from R^2 0.523 to 0.487. The AOD–$PM_{2.5}$ relationship becomes weaker after one week, with R^2 falling from 0.811 to 0.554. This suggests that AOD responds more closely to fire activity in the same week, while $PM_{2.5}$ at ground level tends to rise later. The main lag in these results is therefore between fire activity and ground-level $PM_{2.5}$.

7. Conclusion

This study examined the spatio-temporal relationship between paddy straw burning, aerosol loading, and ground-level $PM_{2.5}$ across Punjab, Haryana, and the adjoining Rajasthan districts of Hanumangarh and Sri Ganganagar during 2021, combining Terra-MODIS cumulative fire frequency, MODIS MAIAC AOD, and CPCB $PM_{2.5}$ observations at monthly, seasonal, district and weekly resolution.

Two agricultural burning phases emerge clearly from the annual data, a smaller pre-monsoon wheat-residue phase in April–May and a larger post-monsoon paddy-straw phase in October–November. Terra and Aqua MODIS show the same seasonal pattern but differ greatly in the number of fires detected. This difference is mainly due to their different satellite overpass times, not because of any problem with the data. District-level analysis shows fire activity concentrated heavily in central Punjab, but AOD does not track that concentration precisely. Within Punjab, AOD ranks loosely against fire frequency. In Haryana, some districts have very little local burning but still show AOD values similar to the main hotspots. This, along with the Punjab results, suggests that AOD during the burning season is influenced strongly by smoke transport and not just by fires within the same district.

The weekly analysis adds the temporal detail that a monthly view cannot provide. Fire frequency, AOD and $PM_{2.5}$ all rise sharply into early November, but they do not peak simultaneously, whereas fire frequency and AOD peak in the first week of November, while $PM_{2.5}$ continues climbing into the second week. This lag is supported spatially, as weekly maps show the densest fire activity concentrated over Punjab in the peak week, with the most intense AOD shifting southeast into Haryana and the Rajasthan border districts by the following week. The statistical lag and the spatial displacement are two independent lines of evidence pointing to the same underlying process, smoke accumulating and drifting downwind before registering as peak ground-level pollution.

Pearson correlation supports these patterns without overstating them. Fire frequency correlates significantly with AOD ($r = 0.724$) and, more moderately, with $PM_{2.5}$ ($r = 0.560$), a relationship shown to depend substantially on the two highest-burning weeks of the season rather than holding uniformly across all sixteen weeks. AOD and $PM_{2.5}$ show the strongest and most consistent relationship in the dataset ($r = 0.900$), indicating that satellite-derived aerosol loading is a reliable proxy for ground-level pollution in this region during the burning season.

The results show that paddy straw burning was a major contributor to aerosol and particulate pollution across north-western India in 2021. The effect was not immediate and was not limited to the areas where fires occurred. Smoke moved to other areas, and higher pollution levels appeared later. Weekly fire data, AOD measurements, and ground-level observations helped capture this change. Burning increased through October, reached its highest level in early November, and pollution remained high into December even after fire activity had decreased. This pattern is much less clear when only monthly or seasonal data are used.

8. Limitations of the Study

Sensor overpass timing. Terra's fixed morning overpass and Aqua's afternoon overpass detect different fractions of daily burning activity. Since Aqua recorded substantially more fire activity during peak weeks, the Terra-based fire frequency used in the main analysis likely represents a conservative lower bound on total burning, particularly in early November.

Detection limits for small or short-duration fires. MODIS fire products operate at a regional scale, so small fields or brief burning episodes may fall below detection, meaning fire frequency in this study reflects the broader pattern of burning rather than an exact count of individual events.

Fire pixels as a proxy, not a direct emissions measure. Fire detections indicate the presence of burning at the moment of satellite overpass, not burnt area, residue quantity, or emission volume. The fire-aerosol-$PM_{2.5}$ relationships reported here should be read accordingly, as an association with burning occurrence rather than a direct estimate of total smoke output.

AOD retrieval gaps. Some weekly AOD maps show patchy retrieval, likely related to cloud cover or surface conditions. Spatial interpretation therefore relied on broader weekly and monthly patterns rather than isolated pixel values.

Spatial displacement between AOD and fire hotspots. As ***Sections 5.4, 5.5 and 5.9*** establish directly, elevated AOD frequently extends beyond fire hotspot locations, reflecting atmospheric transport. The fire-AOD relationship in this study is therefore a regional association, not a point-for-point spatial match, and AOD and ground-level $PM_{2.5}$, one a columnar measure and one a surface measure, will not always align exactly for the same reason, shaped further by wind, vertical mixing, humidity and boundary-layer conditions.

Uneven CPCB station coverage. Punjab and Haryana have reasonably dense CPCB monitoring. Hanumangarh and Sri Ganganagar have limited or no station coverage. $PM_{2.5}$ results therefore represent the better-monitored portion of the study area more strongly than the region as a whole.

Meteorological factors considered but not separately modelled. Wind, boundary-layer height, temperature inversion and humidity are discussed qualitatively throughout this study but were not quantified as independent variables, so their individual contribution to the observed patterns cannot be isolated from this dataset alone.

Association, not direct proof of causation. The correlation results demonstrate a strong, statistically significant association between fire activity, AOD and $PM_{2.5}$. However, they do not establish that paddy burning was the only contributor to particulate pollution during this period. Vehicular emissions, industry, dust and other combustion sources possibly also shaped $PM_{2.5}$ levels.

Statistical dependence in the weekly time series. With $n = 16$ consecutive weekly observations, the data are not fully independent draws, which means the reported p-values should be interpreted as indicating a strong linear relationship rather than satisfying the strict independence assumption behind classical significance testing.

Single-year scope. This study focuses on 2021 alone. Burning intensity, weather, and farmer behaviour vary from year to year, so these findings characterise one burning season rather than a general, multi-year pattern. A multi-year weekly analysis would be a natural extension of this work.

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