A Study on Agricultural Fires and Aerosol Optical Depth in Peninsular India

Tharani Kotrike [1], Venkataramana Sridhar [2], Myoor Padmanabhan [3]

[1] CED, GPREC, Kurnool, tharani.ce@gprec.ac.in
[2] Department of Biological Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA
[3] Virginia Tech India, Chennai, India 600095

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Abstract

Agricultural fires are a major contributor to atmospheric pollution and play a significant role in regional climate forcing, accounting for nearly one-fourth of global biomass burning emissions. This study assessed the influence of agricultural burning on Aerosol Optical Depth (AOD) across Peninsular India during two contrasting years—2019 (a dry year) and 2024 (a normal rainfall year), as defined by deviations from long-term precipitation norms by the Indian Meteorological Department. Using VIIRS I-band (375 m) active fire detections and MODIS AOD (550 nm) observations, the study analyzed spatial patterns of fire activity and aerosol loading with high temporal and spatial resolution. Notably, fire counts increased by 9% in 2024 despite it being a wetter year, challenging the assumption that drier conditions necessarily drive more fire events. This unexpected rise in fires was accompanied by a 2–4% increase in AOD, with spatial analysis revealing a strong overlap between fire locations and elevated aerosol levels. These findings suggest that factors beyond rainfall variability—such as shifts in land management, post-harvest residue handling, or atmospheric stagnation—may influence fire dynamics, and that agricultural burning substantially contributes to regional aerosol accumulation regardless of hydrological year type. The study underscores the urgent need for targeted residue management and region-specific emission control strategies in South India.

Introduction

Agricultural fires are a frequent and widespread practice in many parts of India, particularly in Peninsular India, where farmers burn crop residues to prepare fields for subsequent planting cycles. While economically expedient, this practice emits substantial quantities of aerosols and particulate matter into the atmosphere, posing significant risks to environmental quality and public health (Badarinath et al., 2009; Sahu et al., 2016). Biomass burning contributes to air pollution and alters local climate systems through both direct and indirect radiative forcing mechanisms (Gadde et al., 2009; Jethva et al., 2013).

India experiences considerable variability in both seasonal and annual rainfall due to the influence of the southwest and northeast monsoons, with marked interannual fluctuations driven by climate phenomena such as El Niño and the Indian Ocean Dipole (Satish Kumar et al., 2021; Satish Kumar et al., 2023). These variations affect not only agricultural productivity but also land surface conditions and fire susceptibility. In regions like Peninsular India, the post-monsoon season often coincides with peak agricultural fire activity, making it essential to understand how year-to-year changes in precipitation patterns interact with fire emissions and air quality.

Monitoring the atmospheric impact of agricultural fires requires reliable indicators of aerosol loading. Aerosol Optical Depth (AOD) is a widely used metric representing the degree to which aerosols prevent the transmission of sunlight through the atmosphere. Satellite-based AOD retrievals, particularly from sensors such as MODIS, have enabled high-resolution monitoring of aerosol variations associated with biomass burning (Kaufman et al., 2002; Dey et al., 2020). In India, temporal peaks in AOD often coincide with post-harvest burning periods, leading to pronounced regional haze episodes (Beegum et al., 2015; Kumar et al., 2020). Understanding these spatial and seasonal dynamics is critical for evaluating the contribution of agricultural fires to overall aerosol loading and for developing mitigation strategies aligned with India's air quality and climate policy frameworks.

Recent research has demonstrated that fire-induced aerosol dynamics are intricately linked to the broader hydroclimatic variability of South India. For instance, GRACE-based reconstructions of total water storage anomalies across the Godavari, Krishna, Cauvery, and Pennar basins revealed that strong interannual water storage deficits correspond closely to dry-season aerosol build-up and fire occurrence patterns (Satish Kumar et al., 2023). These findings suggest that the same climatic oscillations influencing droughts and groundwater depletion may also govern fire susceptibility and aerosol dispersion. Complementary studies on hydrological drought forecasting in transboundary basins such as the Mekong have further underscored the need for integrated climate–fire–water frameworks to understand cascading environmental impacts (Kang and Sridhar, 2020).

In addition, the variability in post-monsoon rainfall and temperature directly influences residue dryness, ignition potential, and aerosol persistence. Evidence from multi-decadal climate analyses indicates that warming trends and delayed monsoon withdrawal over southern India enhance both the frequency and intensity of agricultural fires (Satish Kumar et al., 2021). The combination of reduced soil moisture, declining water storage, and persistent anthropogenic pressure exacerbates the regional aerosol burden, amplifying feedback loops between surface energy balance and atmospheric stability (Sridhar et al., 2013; Sridhar and Anderson, 2017).

Despite growing attention to the environmental consequences of agricultural burning, the link between fire activity and AOD in Peninsular India remains underexplored, particularly at high spatial and temporal resolution. This study addresses that gap by analyzing satellite-derived MODIS AOD and VIIRS active fire data to investigate how agricultural fires impact aerosol concentrations during a dry year (2019) and a normal rainfall year (2024). The results offer new insights into the relationship between fire events and aerosol loading under varying climatic conditions, providing valuable guidance for policy interventions aimed at promoting sustainable agricultural practices and protecting air quality.

Methodology

Study Area

The study focuses on Peninsular India (Figure 1), encompassing the southern states situated approximately between 8°N and 20°N latitude and 73°E to 85°E longitude. The region is characterized by diverse agro-climatic zones, including coastal plains, interior plateaus, and semi-arid tracts. Agricultural activity in this region is largely influenced by both the southwest (June–September) and northeast (October–December) monsoons. The combination of extensive cropland, post-harvest burning practices, and variable rainfall patterns makes Peninsular India a suitable case for evaluating the linkage between agricultural fires and aerosol loading.

In addition to its agricultural intensity, Peninsular India hosts several rapidly urbanizing centers—such as Hyderabad, Chennai, Bengaluru, and Mumbai—where high aerosol concentrations and modified land surfaces influence both local climate and precipitation dynamics. Studies have shown that variations in Aerosol Optical Depth (AOD) and cloud microphysical properties can significantly affect rainfall distribution, particularly under convective and monsoonal regimes typical of this region (Tharani et al., 2024a). The western coastal belt receives abundant rainfall due to orographic uplift along the Western Ghats, while interior areas such as Telangana, Rayalaseema, and northern Karnataka are semi-arid, receiving less than 800 mm annually and experiencing greater exposure to biomass burning.

Cropping systems across Peninsular India are highly diverse, with rice–rice and rice–maize rotations dominating the coastal deltas of Andhra Pradesh and Tamil Nadu, while rainfed maize, cotton, and pulses are prevalent in Telangana and Karnataka. The widespread cultivation of paddy during the Kharif and Rabi seasons leads to substantial residue generation, and post-harvest stubble burning remains a common practice, particularly in irrigated command areas (Kotrike et al., 2024b). Complementary modeling by Debnath et al. (2020) demonstrated that rainfed rice yields in southern states such as Andhra Pradesh, Tamil Nadu, and Karnataka exhibit considerable spatial variability—averaging 2.1–2.6 t/ha—due to soil moisture limitations and intra-seasonal rainfall fluctuations. The persistence of yield gaps between potential and actual production underscores the agronomic and climatic sensitivity of the region's rice-based systems. Spatial analyses from recent studies have shown that agricultural fires are concentrated near major irrigation projects such as the Godavari, Krishna, and Cauvery basins, where residue accumulation is greatest. This intersection of intensive cultivation, residue burning, and varying rainfall regimes creates an ideal natural laboratory to study how agricultural fires influence aerosol loading and atmospheric processes across Peninsular India.

Data Sources

1. Fire Activity Data

Active fire locations were obtained from the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite. The I-band (375 m) active fire product, designated as VNP14IMGML, was used for the years 2019 and 2024 to represent two contrasting hydrological conditions. Each fire detection record includes the geographic coordinates, acquisition time, brightness temperature, and Fire Radiative Power (FRP, in MW). The VIIRS 375 m product provides high spatial and temporal resolution, enabling the detection of small-scale agricultural fires that are often missed by coarser sensors such as MODIS (1 km).

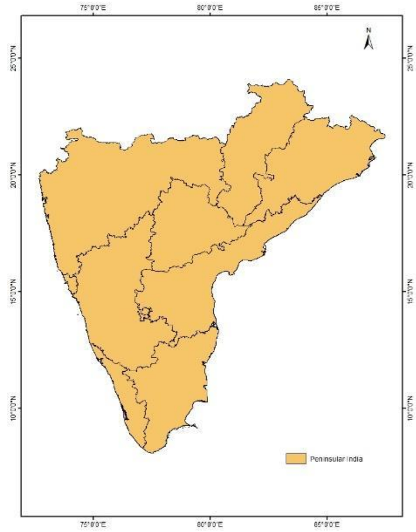

Figure 1: Study Area

Fire data were accessed through the NASA Fire Information for Resource Management System (FIRMS) portal (https://firms.modaps.eosdis.nasa.gov/
). To ensure spatial consistency, duplicate detections and low-confidence pixels were removed based on the confidence attribute (>80%). The fire pixels were then filtered using MODIS Land Cover Type (MCD12Q1) data to isolate those occurring specifically over cropland areas. Fire occurrences in forested or urban zones were excluded to minimize non-agricultural bias.

Monthly and seasonal composites were generated to evaluate spatio-temporal variability in fire frequency and FRP intensity across Peninsular India. Fire counts were aggregated to 0.25° grids to maintain compatibility with rainfall and AOD datasets. Additionally, total FRP per grid was calculated to assess burning energy and intensity. This approach allowed the study to capture both the extent and magnitude of agricultural fires over time.

2. Aerosol Optical Depth (AOD)

Aerosol loading was represented using Moderate Resolution Imaging Spectroradiometer (MODIS)-derived Aerosol Optical Depth (AOD) data at 550 nm wavelength. Monthly mean AOD values were obtained from the MOD08_M3 Collection 6.1 Level-3 global dataset, which provides continuous data at 1° × 1° spatial resolution. The AOD dataset was downloaded from the NASA Earthdata platform (https://earthdata.nasa.gov/).

MODIS AOD retrievals are well-validated across the Indian region and provide consistent measurements for assessing aerosol spatial distribution (Kaufman et al., 2002; Dey et al., 2020). For this study, AOD data were subset for agricultural zones identified using the land-use layer, ensuring that the aerosol signal corresponded directly to burning activity. Monthly AOD anomalies were computed relative to long-term means (2010–2020) to identify deviations associated with major fire episodes.

3. Rainfall Data
The years 2019 and 2024 were categorized as “dry” and “normal,” respectively, based on rainfall anomalies derived from Indian Meteorological Department (IMD) gridded precipitation data (0.25° × 0.25° resolution). Deviations from the long-term (1990–2020) climatological mean were calculated to determine hydrological year types following IMD classification standards. Cumulative monthly rainfall was also compared against seasonal fire peaks to examine the influence of antecedent moisture and vegetation dryness on fire intensity.

In addition, standardized precipitation indices (SPI) were derived to characterize short-term dryness patterns preceding fire events. This multi-parameter approach ensured that rainfall anomalies were robustly quantified and provided a consistent hydrometeorological framework for interpreting fire and aerosol dynamics across Peninsular India.

4. Data Preprocessing and Analysis

All satellite datasets were projected to a common geographic coordinate system (WGS84) and resampled to a 0.5° × 0.5° grid to ensure spatial compatibility between fire, rainfall, and aerosol datasets. The analysis was performed using ArcGIS 10.4 and Python-based geospatial processing libraries. The data integration involved overlay analysis, zonal statistics, and temporal aggregation of monthly AOD and fire frequency to derive composite maps. Quality assurance measures included filtering out low-quality MODIS retrievals (QA < 2) and excluding cloud-contaminated pixels. The final gridded dataset was validated for consistency across both years before statistical evaluation.

Spatial Distribution of AOD
The spatial distribution of annual Aerosol Optical Depth (AOD) for the years 2019 and 2024 is presented in Figure 2. In 2019—a dry year—AOD values across the entire study area remained below 1.0, indicating relatively lower aerosol concentrations and comparatively cleaner atmospheric conditions. In contrast, during 2024—a year classified as normal in terms of rainfall—AOD values reached up to 1.5 in several regions, marking a significant increase in atmospheric aerosol loading.

Notably, the northern parts of the study area, particularly Telangana and northern Karnataka, exhibited a pronounced rise in AOD in 2024 compared to 2019. This spatial contrast suggests that fire activity and associated emissions intensified in these zones, potentially linked to post-harvest residue burning and changing agricultural practices. Overall, nearly 50% of the region experienced elevated AOD levels in 2024. While the entire area recorded AOD values below 1.0 in 2019, by 2024, portions of the eastern coastal zone displayed AOD values exceeding 1.0. This spatial shift highlights a substantial deterioration in air quality, likely influenced by increased biomass burning, reduced atmospheric dispersion, or enhanced regional transport of pollutants from neighbouring states.

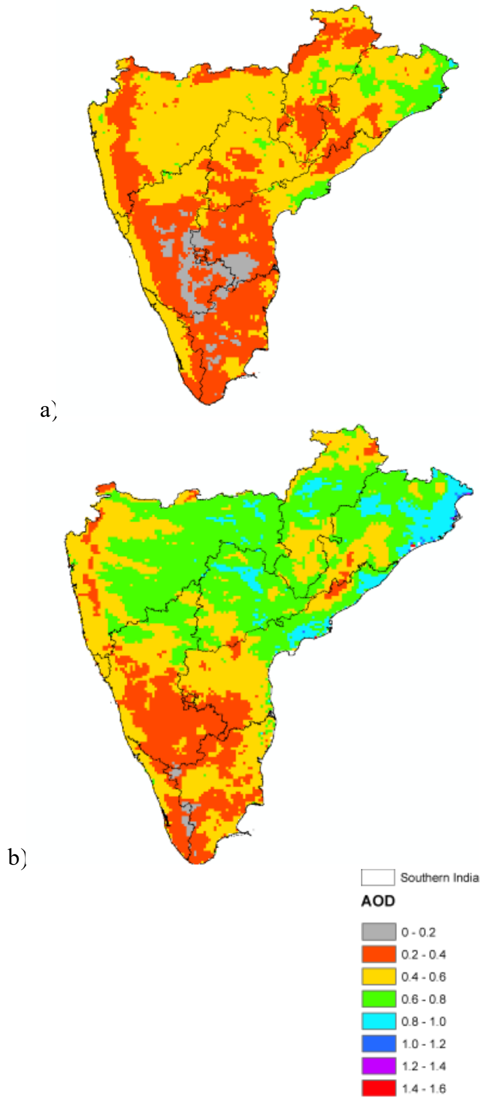

Figure 2: Spatial distribution of annual AOD

Spatial Distribution of Post Monsoon AOD and Fire Counts
During the post-monsoon season of the dry year 2019, a total of 7,909 fire counts were recorded across the study area. Interestingly, in the wet year 2024—despite higher rainfall—the number of fire counts nearly doubled to 16,024. This unexpected increase suggests that atmospheric dryness alone does not account for the frequency of fire events, indicating the influence of other factors such as land management practices or cropping cycles.

The spatial distribution of AOD and fire counts for both years is illustrated in Figure 3. In 2024, AOD values at fire locations predominantly ranged between 0.4 and 0.8, indicating elevated aerosol concentrations. In contrast, during 2019, AOD values at corresponding fire locations mostly remained in the range of 0 to 0.4. This clear spatial correlation suggests that the increase in AOD is strongly associated with the presence and intensity of agricultural fires. The elevated aerosol levels are likely due to the accumulation of smoke and particulate matter released during biomass burning activities. These results reinforce the role of agricultural fires in degrading regional air quality, irrespective of annual rainfall variations.

a)

b)

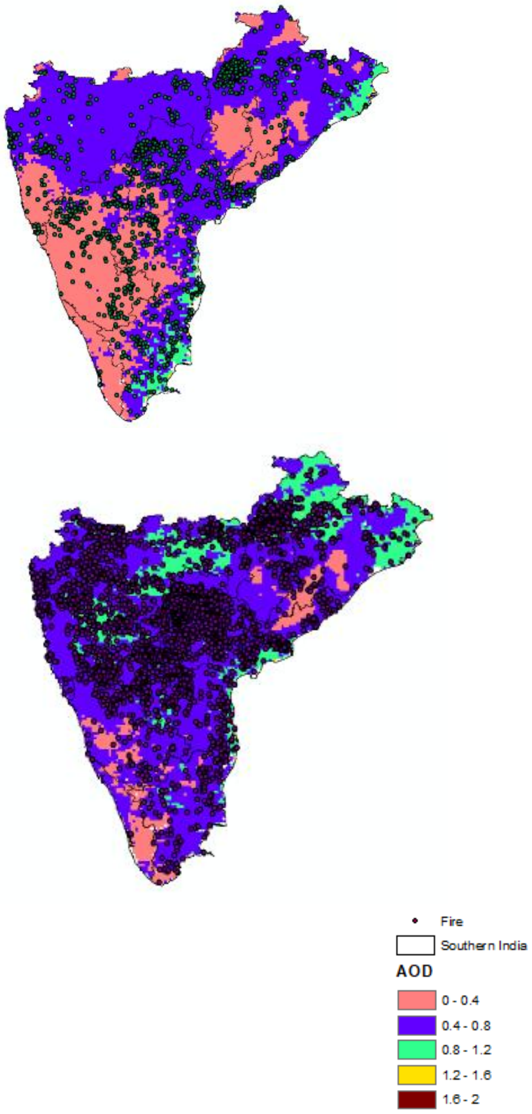

Figure 3: Spatial distribution of post monsoon AOD of a) 2019 b) 2024 (The dots indicate the fire locations)

Fire Radiative Power

The active fire data from the VIIRS band-I product consist of the geographic location and acquisition time of each detected fire activity. The dataset provides the active fire pixel's Fire Radiative Power (FRP, in megawatts) along with the date and hour of burning for every detection. FRP represents the rate of radiant energy released by fire, serving as a quantitative measure of combustion intensity and biomass consumption. It is frequently used as a proxy for estimating fire severity and total carbon emissions from open burning (Sparks et al., 2018).

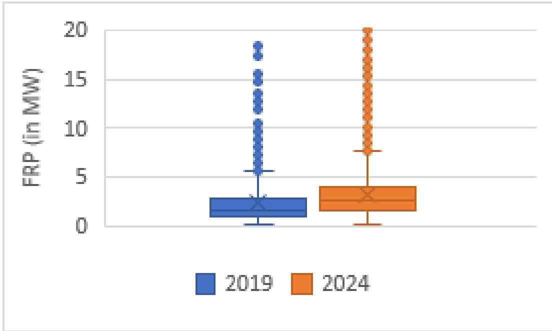

Figure 4: FRP during the post monsoon of 2019 and 2024.

The FRP data were analyzed for the post-monsoon periods of 2019 and 2024, and the results are illustrated in Figure 4. There has been an overall increase in fire intensity in 2024, as evidenced by the higher median FRP compared to 2019. The spatial patterns reveal concentrated fire clusters in northern Telangana, central Karnataka, and parts of coastal Andhra Pradesh, suggesting localized increases in residue burning intensity.

A wider interquartile range (IQR) for 2024 indicates greater variability in FRP values, implying more heterogeneous fire activity across the region. The occurrence of several outliers, particularly in 2024, reflects sporadic high-intensity fire incidents far exceeding normal burning levels. The 2019 distribution, on the other hand, appears more compact and contains fewer extreme values, indicating comparatively moderate and consistent fire events.

The upward shift in both the median and upper quartile values in 2024 suggests a potential increase in the volume of combustible residue, prolonged dry conditions before the burning phase, or a higher frequency of simultaneous fire events. Such patterns underline the growing intensity and irregularity of agricultural fires, emphasizing the need for improved monitoring and sustainable residue management strategies in the region.

Summary and Conclusions

This study investigated the relationship between agricultural fire activity and Aerosol Optical Depth (AOD) across Peninsular India by comparing a dry year (2019) and a normal rainfall year (2024), with a particular focus on the post-monsoon season when biomass burning is most prevalent. Contrary to common assumptions, the results indicate that atmospheric dryness was not the primary driver of fire activity. In fact, fire counts increased significantly in 2024—a year classified as climatically normal—compared to 2019. The post-monsoon fire count nearly doubled from 7,909 in 2019 to 16,024 in 2024, despite higher rainfall, underscoring that factors beyond meteorological dryness, such as land-use patterns, agricultural cycles, and socio-economic drivers, may have a more pronounced role in determining fire incidence.

The spatial analysis further revealed that the increase in fire events corresponded with a noticeable rise in AOD values. In 2019, most fire locations were associated with AOD values in the range of 0.0 to 0.4, indicating relatively lower atmospheric aerosol loading. In contrast, during 2024, fire locations commonly exhibited AOD values between 0.4 and 0.8, with some areas exceeding 1.0, particularly along the eastern coast. This spatial co-location of high fire counts and elevated AOD highlights a strong positive correlation between agricultural burning and atmospheric aerosol concentrations. These aerosols, primarily originating from smoke and other particulate emissions, pose serious risks to public health, visibility, and regional climate processes. A brief study on FRP shows the variability of radiative energy in 2019 and 2024. The mean FRP is higher in 2024 compared to 2019, which aligns with the increase in total fire count, further confirming the intensification of biomass combustion in the region.

The findings suggest that even during a year with adequate monsoon rainfall, agricultural burning can significantly degrade air quality, likely due to persistent or even intensified residue-burning practices following harvests. This pattern calls for a re-examination of fire management strategies that rely solely on climatic indicators such as rainfall anomalies. The decoupling of fire frequency from atmospheric dryness observed in this study implies that policy frameworks must also consider non-climatic factors such as cropping intensity, harvest timing, mechanization, and local land management norms. Moreover, changes in irrigation infrastructure and post-harvest mechanization could be extending the burning window, increasing the probability of overlapping fire events.

From a methodological perspective, this study demonstrates the utility of combining satellite-derived fire count and AOD datasets to detect and interpret the atmospheric impacts of agricultural burning at high spatial and temporal resolution. The approach also highlights the importance of integrating multi-sensor data such as VIIRS fire detections and MODIS AOD products to minimize observational bias. Future refinements could include the use of VIIRS–MODIS fusion data and Sentinel-3 SLSTR observations to better capture smaller and short-lived fire events. To further strengthen the analysis and build a more complete understanding of aerosol dispersion dynamics, future work should incorporate fire radiative power (FRP) and fire size data to assess the energy output of fires and their potential for aerosol emissions.

Additionally, atmospheric transport modeling can provide valuable insights into the spatial reach of these emissions. Models such as HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) and WRF-Chem could be employed to trace smoke plume trajectories and quantify the transboundary movement of pollutants across state and national boundaries. Coupling such models with satellite-based AOD and $PM_{2.5}$ datasets would help establish a cause–effect framework between burning intensity and downstream air-quality deterioration. Incorporating ground-based observations from AERONET or CPCB monitoring stations could also validate satellite-derived estimates and enhance the accuracy of future assessments.

In conclusion, agricultural fires remain a significant and recurring source of aerosol pollution in Peninsular India, regardless of annual rainfall variability. The sharp increase in fire frequency and FRP observed in 2024, despite favourable hydrological conditions, underscores the dominance of anthropogenic and management-related factors over purely climatic controls. The study underscores the urgent need for integrated monitoring systems and multi-sectoral interventions that address both the causes and consequences of open biomass burning. Promoting alternatives such as in-field residue incorporation, bioenergy conversion, and mechanized residue collection could drastically reduce fire occurrences. Furthermore, coordinated policies across agricultural, environmental, and public health agencies are essential to mitigate the adverse impacts of biomass burning on regional air quality, human health, and climate stability. The findings provide a strong scientific basis for developing sustainable land and air-quality management strategies in the region.

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