

Quantifying the Link Between Crop Residue Burning and Air Quality Over Punjab, Pakistan (2004–2024): A Satellite-Based Spatiotemporal Assessment

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Research Article

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Abstract

This study investigates the long-term relationship between crop residue burning and air quality degradation across Punjab, Pakistan, over a twenty-year period (2004–2024). While the practice of open-field residue burning has been a traditional agricultural method in Punjab for decades, the emergence of hazardous smog events, particularly after 2016, has renewed debates regarding the extent of farmers' responsibility for deteriorating air quality. Utilizing Google Earth Engine (GEE), this research analyzed spatiotemporal patterns of burned area using the MODIS MCD64A1.061 Burned Area product and aerosol concentration through the MODIS MCD19A2.061 MAIAC Aerosol Optical Depth (AOD) dataset. Tehsils with burned areas exceeding 65 km² were identified as significant burning hotspots. Correlation analysis between total burned area and maximum AOD values yielded a Pearson correlation coefficient (r) of 0.626 and an R^2 value of 0.3922, indicating a moderate to strong positive relationship between burning intensity and aerosol loading. However, the results also suggest that residue burning explains less than half of the variance in aerosol concentrations, implying the presence of additional factors such as industrial emissions, vehicular pollution, and meteorological conditions. The findings highlight that while agricultural burning remains a significant contributor to poor air quality in Punjab, it is not the sole determinant of smog formation. This study provides critical empirical evidence for balanced, data-driven policymaking and cross-border environmental cooperation.

1 Introduction

Each year, between mid-October and late November, Pakistan's Punjab province enters a period colloquially referred to as the fifth season, a recurring phase of intense smog that blankets the region (Mahmood et al., 2021). This phenomenon poses serious threats to public health, transportation, and agriculture, with particulate concentrations often surpassing the World Health Organization's (WHO) safe limits by several magnitudes (Khokhar et al., 2020). The smog typically coincides with the post-harvest burning of rice residue, a rapid and low-cost method, farmers employ to clear fields before sowing wheat. This practice, while not new, has become the subject of significant environmental and political discourse since 2016, when Punjab began experiencing unprecedented smog events (Ahmad et al., 2022).

Historically, residue burning has been a widespread agronomic technique across South Asia, with documented use for soil rejuvenation dating back to the colonial era (Gupta et al., 2004). The practice intensified in the late 20th century following the mechanization of harvesting and the narrowing of crop rotation windows between rice and wheat (Lohan et al., 2018). While traditional methods have persisted, their environmental implications have grown with urbanization and industrialization, leading to complex air pollution dynamics in the Indo-Gangetic Plain (Cusworth et al., 2021).

Transboundary effects further complicate the issue. Aerosols and fine particulate matter released from crop fires in Indian Punjab can cross borders and affect cities such as Lahore, Gujranwala, and Faisalabad in Pakistan (Jethva et al., 2019). Conversely, localized burning within Pakistan also

contributes to elevated aerosol optical depth (AOD) levels detected across the border. The atmospheric circulation patterns during autumn, marked by weak winds and temperature inversions, trap pollutants near the surface, creating a persistent haze that intensifies the smog crisis (Kulkarni et al., 2020).

However, crop burning is not the sole cause of deteriorating air quality in Punjab. Several studies identify vehicular emissions, industrial discharges, brick kiln operations, and the extensive use of fossil fuels in urban centers as key contributors (Khokhar et al., 2020). Meteorological factors such as low wind speed, high relative humidity, and thermal inversions further exacerbate aerosol accumulation (Guttikunda & Calori, 2013). Therefore, attributing smog solely to farmers' practices risks oversimplifying a multifactorial environmental problem.

This study addresses the need for a scientific, data-driven assessment of the relationship between crop residue burning and air quality over an extended period. By analyzing two decades (2004–2024) of satellite observations, the research aims to quantify whether increased burning corresponds with elevated AOD values and to what extent farmers' activities contribute to air pollution relative to other anthropogenic sources. The findings provide empirical evidence to inform environmental policy, promote sustainable agricultural practices, and foster cooperative regional air quality management between Pakistan and India.

2 Literature Review

2.1 Historical Background of Crop Residue Burning

The practice of burning crop residue is not a recent innovation but a centuries-old method of field preparation. Historical agricultural records from both South Asia and Europe document the use of controlled burning to eliminate pests, renew soil nutrients, and clear stubble efficiently (FAO, 1999). In the context of the Indo-Gangetic Plain, residue burning became increasingly prominent during the Green Revolution of the 1960s and 1970s, when mechanical harvesting technologies shortened the time between rice harvesting and wheat sowing (Gupta et al., 2004). Farmers, facing economic constraints and tight crop cycles, adopted stubble burning as a low-cost and time-efficient alternative to manual or mechanical residue management (Lohan et al., 2018).

In Pakistan's Punjab, where rice-wheat crop rotation dominates, open-field burning was reported as early as the 1980s (Shahid et al., 2015). The problem escalated as rice production expanded and urban populations grew, creating a synergy between agricultural emissions and urban industrial pollution. Despite the longstanding presence of the practice, smog as an identifiable environmental crisis is a relatively modern phenomenon.

2.2 Emergence of Smog in Punjab (Post-2016)

The persistent winter smog in Pakistan's Punjab region emerged as a major environmental concern around 2016, with visibility dropping to near zero in major cities like Lahore and Faisalabad (Mahmood et

al., 2021). According to the Pakistan Environmental Protection Agency (Pak-EPA), the first official *smog emergency* was declared that year due to hazardous particulate concentrations exceeding $400 \mu\text{g}/\text{m}^3$ (Khokhar et al., 2020). Subsequent studies suggested that while residue burning coincided temporally with smog episodes, it could not alone explain the unprecedented severity (Ahmad et al., 2022).

Smog in the region is now understood as a multi-source, meteorologically sustained event. Key contributing factors include industrial and vehicular emissions, transboundary pollution from northern India, and unfavorable weather conditions such as low wind speeds and thermal inversions (Guttikunda & Calori, 2013; Cusworth et al., 2021). Aerosol Optical Depth (AOD) analyses reveal that background aerosol concentrations remain elevated throughout the year, independent of burning seasons, indicating persistent anthropogenic influences (Lyapustin et al., 2018; Jethva et al., 2019).

2.3 The Debate: Farmers' Responsibility or Political Narrative?

The discourse around crop burning in Punjab often frames farmers as the primary culprits behind seasonal air pollution. However, this perception has increasingly been challenged by researchers and policy analysts. Studies by Kulkarni et al. (2020) and Cusworth et al. (2021) found that while stubble fires significantly elevate local aerosol levels, the duration and dispersion of smog are heavily influenced by meteorological stagnation and urban emission sources. Similarly, Shahid et al. (2015) argue that government and media narratives often exaggerate farmers' roles to deflect attention from unregulated industrial and vehicular emissions.

The political dimension of the smog debate is underscored by the transboundary exchange of blame between India and Pakistan. Indian authorities frequently attribute smog to Pakistani burning practices, while Pakistani officials counter that emissions from Indian Punjab and Haryana drift westward due to prevailing winds (Gautam, 2020). In this context, it becomes essential to disentangle political rhetoric from empirical evidence using long-term, data-driven studies, a central motivation for the current research.

2.4 Importance of the Study

Despite widespread public discourse, few studies have quantitatively assessed the relationship between burned area and AOD across Pakistan's Punjab over an extended time frame. Most prior research either focused on single events (e.g., 2016 smog) or regional satellite snapshots (Jethva et al., 2019; Mahmood et al., 2021). By contrast, this study provides a two-decade spatiotemporal assessment (2004–2024) that statistically correlates residue burning intensity with aerosol concentrations.

This work is crucial for three reasons:

- **Policy Relevance:** It offers empirical evidence for policymakers to distinguish between myth, political rhetoric, and actual environmental causation.

- **Scientific Contribution:** It expands longitudinal environmental monitoring for South Asia using high-resolution MODIS datasets.
- **Cross-Border Insight:** It supports cooperative environmental planning between Pakistan and India, as both share the Indo-Gangetic airshed.

2.5 Research Gap

Existing literature reveals a clear methodological and temporal gap. Prior investigations (e.g., Jethva et al., 2019; Kulkarni et al., 2020) concentrated on India's side of the Indo-Gangetic Plain, leaving Pakistan's Punjab understudied. Moreover, most studies examined short-term or single-year data, overlooking interannual variability.

This research fills that void by employing a 20-year dataset (2004–2024) to statistically analyze correlations between burned area and AOD using Google Earth Engine (GEE). The integration of MODIS MCD64A1.061 and MCD19A2.061 datasets provide a robust, high-resolution foundation for evaluating whether crop burning in Punjab significantly contributes to smog or if other anthropogenic sources dominate.

By bridging this gap, the study contributes new, policy-relevant insights into the true drivers of air quality deterioration in Punjab, advancing beyond political rhetoric toward evidence-based environmental governance.

3 Methods and Materials

3.1 Study Area

The study focuses on Punjab, Pakistan, a region situated within the Indo-Gangetic Plain, one of the most densely populated and agriculturally productive zones in South Asia. Punjab lies between latitudes 27°40'N to 34°01'N and longitudes 69°20'E to 75°23'E, covering an approximate area of 205,000 km². The province contributes nearly 60% of Pakistan's total agricultural output, with rice-wheat crop rotation dominating its farming system (Government of Punjab, 2023).

The study identified 24 tehsils with extensive crop residue burning, each exhibiting burned areas exceeding 65 km² during peak post-harvest months (October–November). These tehsils include Ferozewala, Nankana Sahib, Sheikhpura, Daska, Pasrur, Bahawalnagar, Minchinabad, Dera Ghazi Khan, Jaranwala, Gujranwala, Kamoke, Nowshera Virkan, Wazirabad, Hafizabad, Pindi Bhattian, Jhang, Shorkot, Kasur, Lodhran, Narowal, Shakargarh, Depalpur, and Pakpattan.

These locations were mapped using ArcGIS Pro, with spatial visualization supported by MODIS imagery.

3.2 Data Sources

This study utilized two key MODIS (Moderate Resolution Imaging Spectroradiometer) datasets available on Google Earth Engine (GEE):

1. MCD64A1.061 – MODIS Burned Area Monthly Global 500m

This dataset identifies burned surface pixels globally by analyzing spectral reflectance changes in the shortwave and near-infrared bands. It provides monthly composites at a 500-meter resolution and has been extensively validated for global fire mapping (Giglio et al., 2016). In this research, MCD64A1 data were used to extract annual burned area values for Punjab from 2004 to 2024, filtered specifically for October and November, representing the rice residue burning season.

2. MCD19A2.061 – MODIS MAIAC Land Aerosol Optical Depth (AOD) Daily 1km

The MAIAC (Multi-Angle Implementation of Atmospheric Correction) algorithm provides daily AOD retrievals at 1-kilometer resolution (Lyapustin et al., 2018). This dataset corrects for surface brightness and distinguishes between fine and coarse aerosol particles, making it particularly effective over agricultural landscapes where both soil and smoke aerosols coexist (Wei et al., 2020).

The MAIAC AOD product was selected because:

- It offers higher spatial resolution (1 km) compared to standard MODIS AOD (10 km), improving detection of localized pollution events.
- It incorporates bidirectional reflectance distribution function (BRDF) corrections, reducing bias from surface reflectance variations (Lyapustin et al., 2018).
- It performs well over bright land surfaces, which are typical in Punjab's post-harvest fields, enhancing accuracy during stubble-burning months (Sayer et al., 2019).

Thus, MCD19A2.061 represents a robust choice for evaluating aerosol loading associated with agricultural burning.

3.3 Data Processing in Google Earth Engine (GEE)

All satellite data were accessed and processed through Google Earth Engine (GEE), a cloud-based geospatial analysis platform (Gorelick et al., 2017). The analysis workflow involved the following steps:

1. Dataset Import and Filtering

- MCD64A1.061 and MCD19A2.061 datasets were imported into GEE.
- Temporal filters were applied for October 01 to November 30 for each year from 2004 to 2024.

2. Burned Area Computation

- Annual burned area maps were generated using a reducer `.max()` function to identify maximum burned pixels within each year.

- Zonal statistics were applied to calculate total burned area (km²) for each tehsil using Punjab's administrative boundaries.
- Only tehsils exceeding 65 km² of burned area were retained for correlation analysis.

3. Aerosol Optical Depth (AOD) Computation

- Using MCD19A2.061, maximum AOD values were extracted for the same temporal window and spatial boundaries.
- The reducer.max() function ensured that peak aerosol concentrations corresponding to burning periods were captured.

4. Data Export and Statistical Integration

- The processed results were exported as CSV files, containing year, total burned area, and AOD values.
- The datasets were then merged and analyzed statistically using Microsoft Excel for correlation and regression analysis.

3.4 Statistical Analysis

The relationship between burned area and aerosol optical depth was quantified using Pearson's correlation coefficient (r) and coefficient of determination (R^2). The Pearson coefficient measures the strength and direction of a linear relationship between two variables, ranging from -1 (perfect negative correlation) to +1 (perfect positive correlation).

In this study, the computed values were:

- $r = 0.626$, and
- $R^2 = 0.3922$.

A scatter plot was constructed with burned area (independent variable) on the X-axis and AOD (dependent variable) on the Y-axis. The regression equation derived from the trendline quantified the predictive relationship between crop burning intensity and aerosol loading.

These metrics provide the quantitative foundation for interpreting the degree of linkage between agricultural burning and air quality degradation across Punjab, discussed in the next section.

4 Results

4.1 Temporal Patterns of Crop Residue Burning (2004–2024)

The annual analysis of MODIS MCD64A1.061 data revealed substantial variability in burned area across Punjab between 2004 and 2024. The total burned area ranged from a minimum of 65.5 km² in 2006 to a maximum of 1,769.3 km² in 2024, with a 20-year mean of approximately 557.6 km². Early years (2004–2008) showed sporadic burning activity, while the period 2015–2024 exhibited a consistent increase in burned area intensity (Fig. 2). Notably, 2018, 2020, and 2023 marked exceptional peaks, coinciding with reported severe smog episodes across Lahore, Faisalabad, and Sheikhupura (Mahmood et al., 2021).

These findings suggest a steady intensification of agricultural burning over the past decade, particularly in central and northeastern tehsils such as Sheikhupura, Nankana Sahib, Jaranwala, and Hafizabad. Spatial visualization from MODIS data indicates the recurrence of high fire density in these Tehsils during the post-harvest months of October–November, aligning with the rice residue clearing season.

4.2 Aerosol Optical Depth (AOD) Trends

The MODIS MAIAC AOD (MCD19A2.061) dataset exhibited complementary temporal fluctuations with burned area data. AOD values ranged between 3.56 (minimum) and 8.96 (maximum), with a mean of 5.44 (Table 1). The elevated AOD readings typically corresponded to years with higher burned areas, particularly between 2015 and 2024 (Fig. 3).

Four temporal composites (2004–2009, 2010–2014, 2015–2019, 2020–2024) revealed an increasing aerosol load trend, especially in eastern Punjab, encompassing Lahore, Gujranwala, and Kasur districts. The most significant AOD intensification occurred post-2016, coinciding with increased public concern and policy debate surrounding smog events.

4.3 Correlation Between Burned Area and AOD

A scatter plot between annual burned area and AOD values (Fig. 4) revealed a moderate to strong positive correlation. The Pearson correlation coefficient (r) was computed as 0.626, indicating a significant linear association between the two variables. The coefficient of determination (R^2) was 0.3922, implying that approximately 39.2% of the variance in AOD can be statistically explained by crop residue burning.

This suggests that while residue burning substantially contributes to aerosol loading, over 60% of the variability in AOD is influenced by other factors such as industrial emissions, vehicular exhaust, meteorological patterns, and transboundary aerosol transport (Cusworth et al., 2021; Khokhar et al., 2020).

4.4 Statistical Summary

Table 1
Area burned in significantly burned Tehsils and AOD
values over them from 2004 to 2024 with Pearson
Correlation Coefficient Value

Year	Area Burned (Km ²)	Aerosol Optical Depth
2004	205.5990111	5.431
2005	414.6383351	5.25
2006	65.50178364	5.125
2007	168.480009	4.0
2008	239.640148	4.0
2009	167.6589374	5.565
2010	310.33678	5.843
2011	235.0793928	3.564
2012	324.876089	5.303
2013	596.8457402	6.391
2014	247.7317972	4.365
2015	417.007501	6.475
2016	501.8872243	5.224
2017	403.7573208	5.534
2018	1093.130721	4.977
2019	834.0893838	4.59
2020	840.9066783	5.041
2021	1769.327823	7.3
2022	732.2760443	5.763
2023	784.340299	5.603
2024	1356.773365	8.964
		r = 0.626

The consistent increase in both AOD and burned area beyond 2015 suggests that residue burning has increasingly coincided with atmospheric stagnation, thereby exacerbating smog formation.

However, the incomplete overlap between high-AOD and high-burning years indicates that meteorological dynamics (e.g., wind speed, humidity, inversion layers) and non-agricultural emissions

significantly modulate observed air quality outcomes (Ahmad et al., 2022; Guttikunda & Calori, 2013).

4.5 Key Findings

1. Burned area and AOD both increased significantly after 2015, coinciding with the emergence of Punjab's smog crisis.
2. Spatial overlap between burned tehsils and AOD hotspots confirms that agricultural burning contributes locally to air pollution.
3. The Pearson correlation ($r = 0.626$) demonstrates a moderate to strong relationship, validating that stubble burning affects atmospheric aerosol concentration.
4. The $R^2 = 0.3922$ suggests partial causation, meaning crop burning is significant but not the sole driver of smog.
5. Other anthropogenic and meteorological factors explain over half of the variation in AOD, aligning with prior regional studies (Kulkarni et al., 2020; Mahmood et al., 2021).

5 Discussion

5.1 Interpretation of Statistical Findings

The correlation analysis ($r = 0.626$, $R^2 = 0.3922$) reveals a moderate to strong positive relationship between burned area and aerosol optical depth (AOD).

According to statistical interpretation frameworks, a correlation coefficient (r) within the 0.60–0.79 range indicates a significant positive association (Cohen, 1992). Thus, as crop residue burning intensity increases, aerosol concentrations measured via AOD tend to rise proportionally.

However, the R^2 value of 0.3922 implies that only 39% of AOD variability can be attributed to burning activities. This partial explanatory power indicates that residue burning is a major but not exclusive driver of aerosol load in Punjab's atmosphere. The remaining 61% of unexplained variance likely originates from non-agricultural emission sources, including vehicular exhaust, industrial smoke, brick kiln operations, and transboundary transport of aerosols from Indian Punjab (Cusworth et al., 2021; Mahmood et al., 2021).

Therefore, while farmers' burning practices significantly contribute to seasonal spikes in particulate matter, they operate within a broader framework of anthropogenic and meteorological determinants influencing smog formation.

5.2 Comparison with Existing Studies

The current findings are consistent with multiple regional and global studies examining the relationship between crop burning and air pollution. For instance, Kulkarni et al. (2020) reported that stubble fires in northern India increased AOD levels by up to 60% during the post-monsoon period, corroborating the present study's positive correlation. Similarly, Jethva et al. (2019) established that residue burning

accounted for 25–40% of total aerosol loading across the Indo-Gangetic Plain, aligning closely with the $R^2 = 0.39$ derived here. Studies from Pakistan's Punjab also support this linkage. Khokhar et al. (2020) found that AOD peaks coincided with MODIS fire detections, though meteorological stagnation often amplified the persistence of haze. Mahmood et al. (2021) further demonstrated that smog severity correlates with both anthropogenic and natural factors, including temperature inversions and low wind speeds, which trap aerosols near the surface.

In short, the correlation observed in this research falls squarely within the range of previous empirical findings, confirming that while crop residue burning elevates AOD values, it interacts with other pollutants and meteorological processes to produce the observed smog phenomenon.

5.3 Farmers' Responsibility: Scientific vs. Political Perspective

Despite clear scientific evidence linking residue burning to aerosol loading, framing farmers as the sole cause of smog is reductive and politically charged. Historically, this narrative has emerged due to the temporal coincidence between the rice harvesting season (October–November) and peak smog episodes. However, studies (Ahmad et al., 2022; Shahid et al., 2015) indicate that industrial, urban, and cross-border emissions are equally if not more responsible for persistent poor air quality throughout the year.

The political discourse in both India and Pakistan often emphasizes agricultural fires for two reasons: (1) they are visually evident via satellite imagery, and (2) they represent a rural practice that can be regulated more easily than urban industry. Yet, this oversimplification undermines the socio-economic realities of farmers who depend on quick field turnover and lack access to affordable residue management technologies such as the *Happy Seeder* or composting systems (Lohan et al., 2018).

Consequently, while farmers' actions contribute substantially to short-term aerosol spikes, the systemic drivers of smog industrial growth, vehicular expansion, and inadequate emission controls must be acknowledged to frame balanced mitigation strategies.

5.4 The Role of Meteorology and Transboundary Pollution

The persistence of smog cannot be explained solely by local emissions.

The Indo-Gangetic Plain's meteorological characteristics low wind speeds, temperature inversions, and high relative humidity during the post-monsoon months create a stable boundary layer that traps pollutants close to the ground (Guttikunda & Calori, 2013).

This climatic setup transforms short-term pollution events (such as burning) into long-lasting haze conditions.

Additionally, transboundary aerosol transport exacerbates regional pollution.

Research by Cusworth et al. (2021) and Gautam (2020) demonstrated that smoke plumes originating from Indian Punjab and Haryana often drift westward, influencing AOD levels in eastern Pakistani districts. Therefore, smog over Punjab is not a localized issue but a shared atmospheric problem that necessitates cross-border cooperation in emission regulation and monitoring.

5.5 Policy and Environmental Implications

The findings underscore an urgent need for integrated air quality management rather than single-sector blame.

While residue burning contributes to seasonal aerosol peaks, mitigation policies should adopt a multi-source framework addressing:

1. Agricultural practices: Subsidies for residue management machinery (e.g., balers, Happy Seeders), bioenergy utilization, and awareness campaigns.
2. Urban emissions: Stricter vehicular emission standards and industrial zoning reforms.
3. Transboundary cooperation: Joint monitoring programs between India and Pakistan under frameworks similar to ASEAN's transnational haze agreements.

By situating residue burning within a broader environmental system, policymakers can target smog reduction more effectively without disproportionately penalizing rural communities.

5.6 Synthesis of Findings

In synthesis, the research validates the following:

- There exists a statistically significant, moderate-to-strong positive correlation between burned area and AOD.
- Farmers' residue burning is a notable but partial contributor to smog formation.
- Other anthropogenic and meteorological drivers explain most of the long-term air quality deterioration.
- Effective mitigation requires multi-sector, cross-border strategies, not isolated agricultural bans.

This interpretation aligns with the growing consensus in recent environmental research: smog is a systemic crisis, not a singularly caused event.

6 Conclusion and Recommendations

6.1 Conclusion

This study provides a comprehensive, over twenty-year (2004-2024) spatiotemporal assessment of the relationship between crop residue burning and air quality degradation in Punjab, Pakistan.

By integrating satellite-based data from MODIS MCD64A1.061 (Burned Area) and MCD19A2.061 (MAIAC AOD) through Google Earth Engine (GEE), the analysis established a moderate to strong positive

correlation ($r = 0.626$) between burned area and aerosol optical depth (AOD).

This relationship indicates that agricultural residue burning is a significant driver of atmospheric aerosol loading, particularly during the post-harvest months of October and November, but not the sole determinant of Punjab's recurring smog crisis.

The R^2 value (0.3922) suggests that approximately 39% of AOD variance can be attributed to burning activities, leaving over half of the aerosol variability to be explained by non-agricultural sources such as vehicular emissions, industrial discharge, and transboundary aerosol inflow.

This finding aligns with previous research (Cusworth et al., 2021; Mahmood et al., 2021), which similarly emphasized the multi-source nature of air pollution in the Indo-Gangetic Plain.

Thus, attributing smog exclusively to farmers oversimplifies a complex environmental issue with socioeconomic, meteorological, and political dimensions.

Importantly, this study fills a critical gap in existing literature by providing the first two-decade statistical quantification of the burning-AOD relationship specifically for Pakistan's Punjab.

The results advance understanding of how agricultural burning interacts with larger atmospheric systems and provide a scientifically grounded basis for evidence-based policymaking.

6.2 Policy Recommendations

Based on the empirical evidence, several targeted recommendations are proposed to mitigate the impacts of residue burning while maintaining agricultural productivity:

1. Promotion of Sustainable Agricultural Alternatives

- **Mechanized solutions:** The adoption of residue management technologies such as the *Happy Seeder*, *Super Straw Management System (SMS)*, and *Zero-Till Drills* should be incentivized through government subsidies and soft loans (Lohan et al., 2018).
- **Bioenergy utilization:** Establishing decentralized biomass collection centers could convert stubble into bio-briquettes or energy feedstock, turning agricultural waste into economic opportunity.

2. Integrated Air Quality Management

- **Emission control in non-agricultural sectors:** Implementation of stricter vehicular emission standards (Euro-V and above), relocation or retrofitting of brick kilns, and enforcement of industrial air filtration systems.
- **Continuous monitoring:** Integration of satellite and ground-based AOD data into national air quality indices to improve early warning systems and public awareness.

3. Cross-Border and Inter-Provincial Collaboration

- Smog in Punjab is a transboundary phenomenon, influenced by air flows between Indian and Pakistani Punjab.

- Bilateral data sharing agreements, harmonized emission inventories, and joint monitoring frameworks are crucial.
- A South Asian *Clean Air Corridor Initiative* could emulate successful regional collaborations like ASEAN's Transboundary Haze Agreement.

4. Public Awareness and Behavioral Change

- Farmers must be engaged as partners rather than blamed as culprits.
- Awareness campaigns emphasizing the health impacts of smog and training on sustainable residue management can foster community-led adaptation.
- Incorporating environmental education into agricultural extension programs would strengthen local participation in air quality management.

6.3 Future Research Directions

While this study establishes a robust statistical foundation, further research should:

- Integrate meteorological variables (wind speed, humidity, temperature inversion) to model atmospheric retention of aerosols more accurately.
- Utilize higher-resolution sensors (e.g., Sentinel-5P TROPOMI, VIIRS) for sub-district-level emission analysis.
- Conduct seasonal and diurnal studies to distinguish between persistent and episodic aerosol accumulation.
- Expand analysis to health impact assessments, linking AOD variations to respiratory morbidity in Punjab's population.

6.4 Final Remarks

The evidence from this 20-year analysis makes it clear that Punjab's smog crisis cannot be attributed to a single source. Residue burning is undeniably an important contributor to aerosol spikes, but the complex interaction of multiple emission sources and meteorological dynamics underpins the region's persistent air quality deterioration. A balanced, science-based approach combining technological intervention, regulatory reform, and regional cooperation is therefore essential for achieving sustainable air quality improvement.

Declarations

Conflict of Interest The author declares no conflict of interest.

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Figures

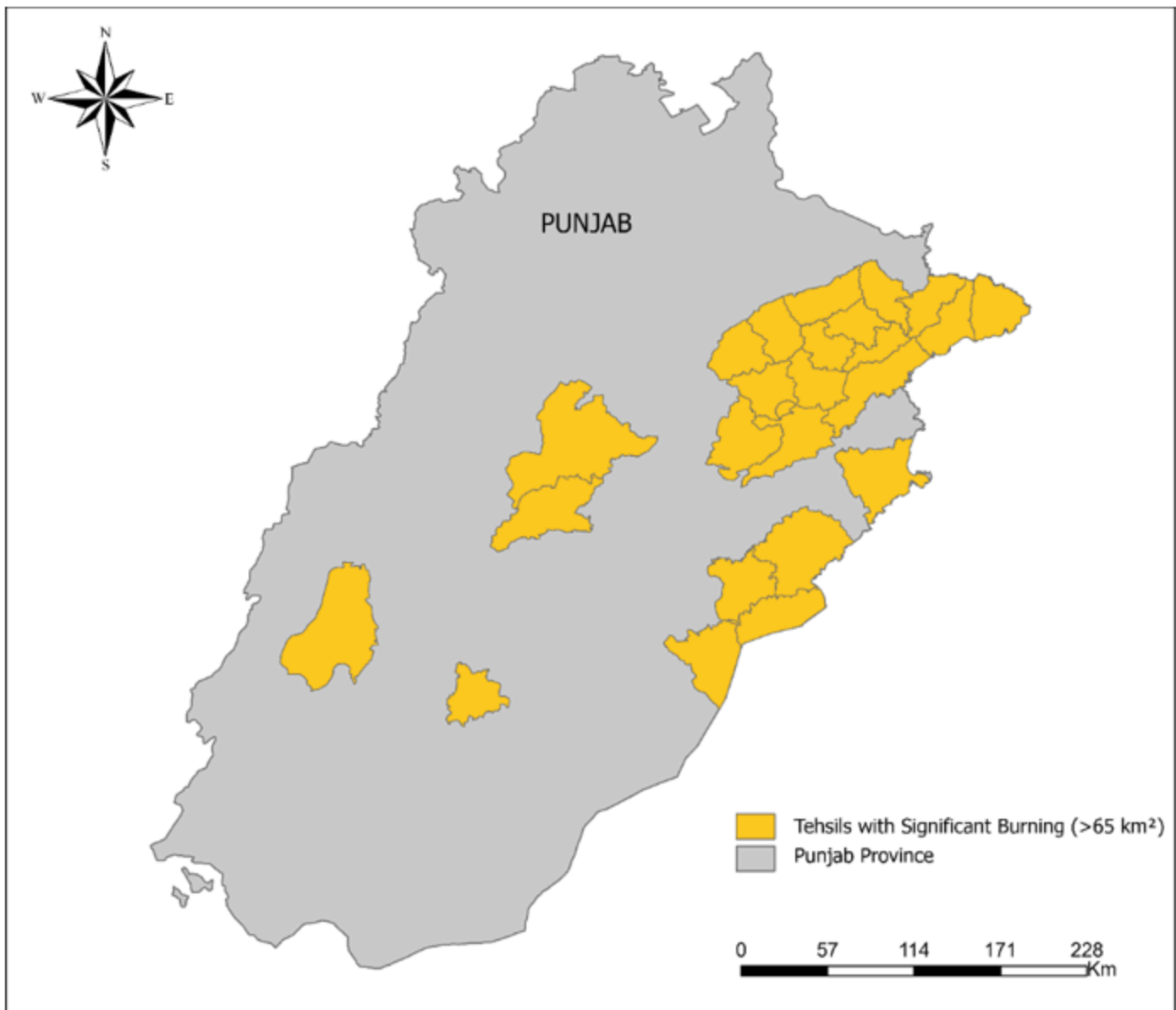


Figure 1

The geographical distribution of the study area, highlighting significantly burned Tehsils across Punjab.

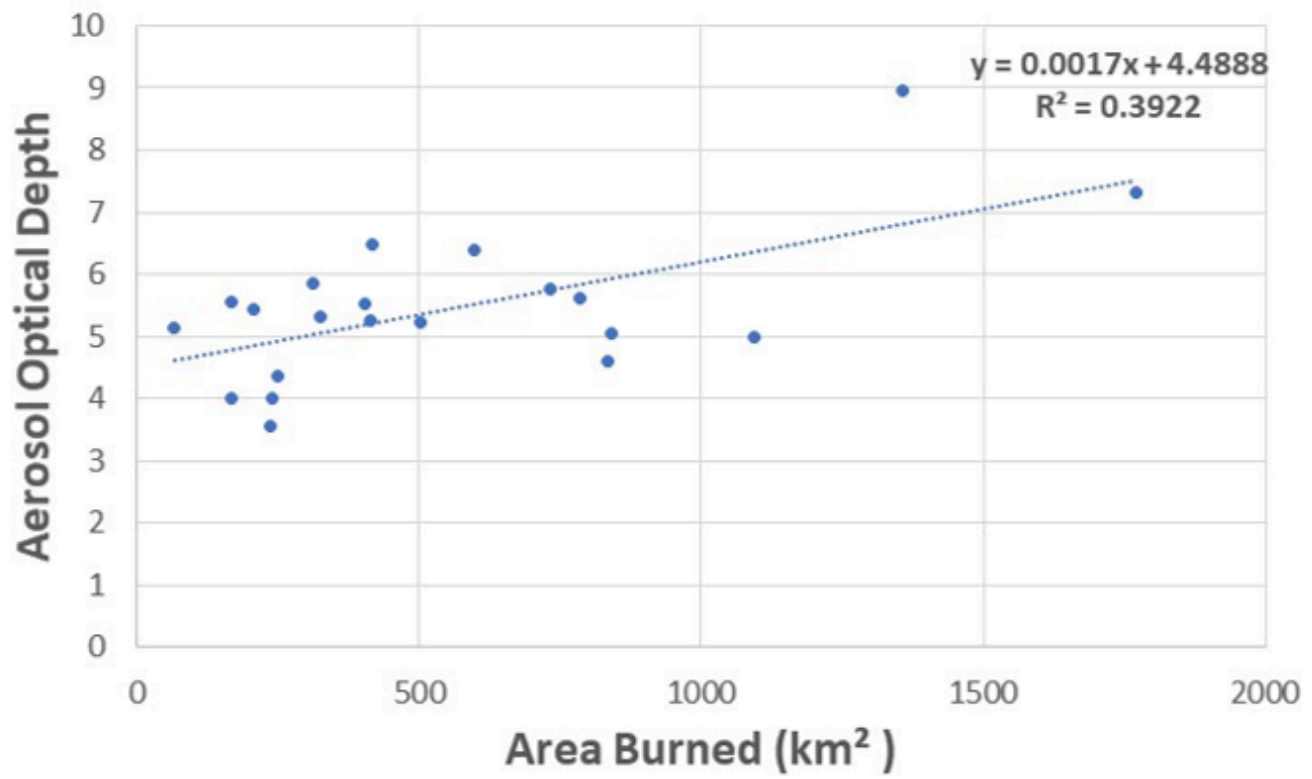


Figure 2

Correlation Between Burned Area and AOD (2004–2024)

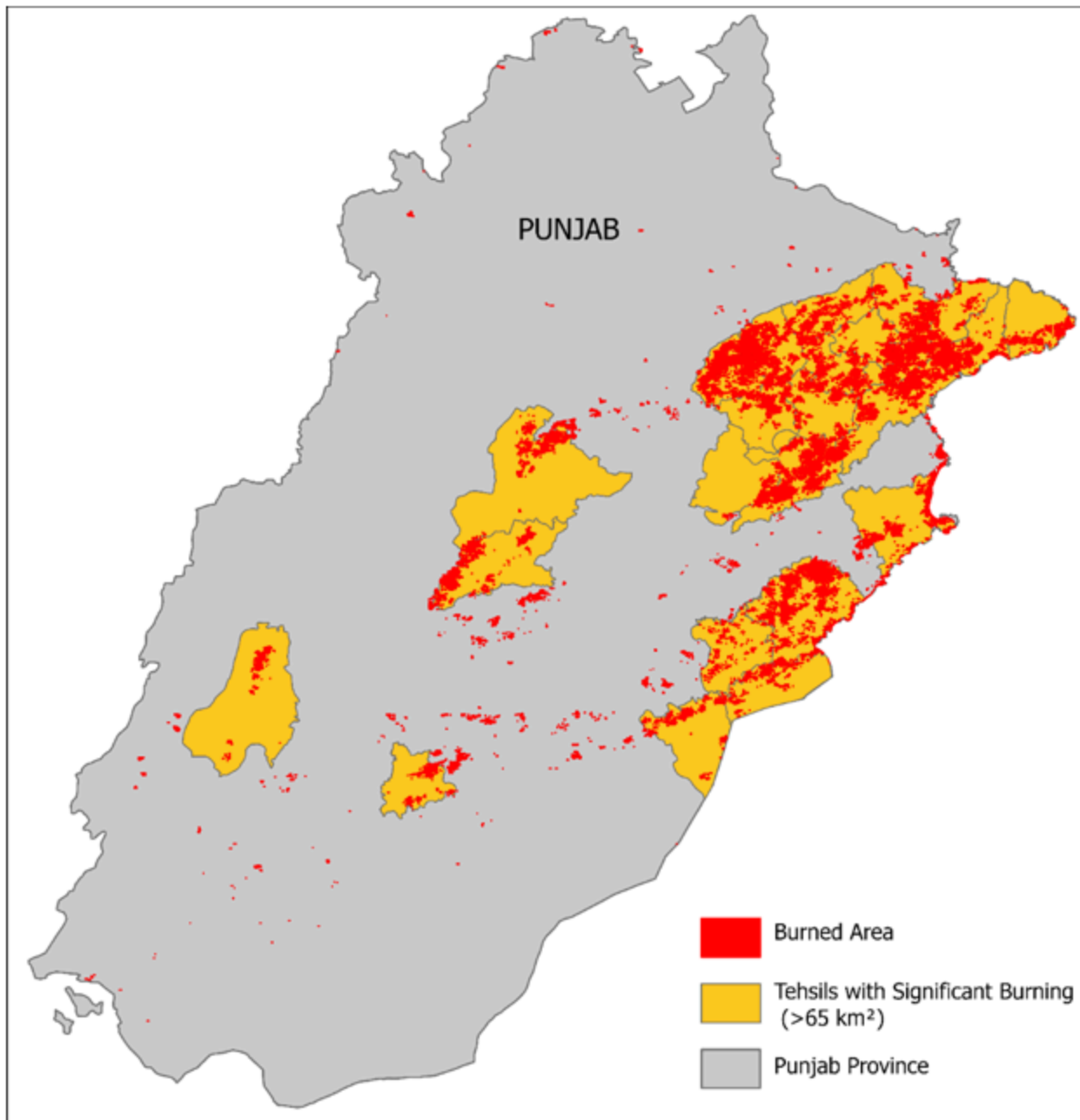


Figure 3

Total Area Burned in Punjab (2004-2024)

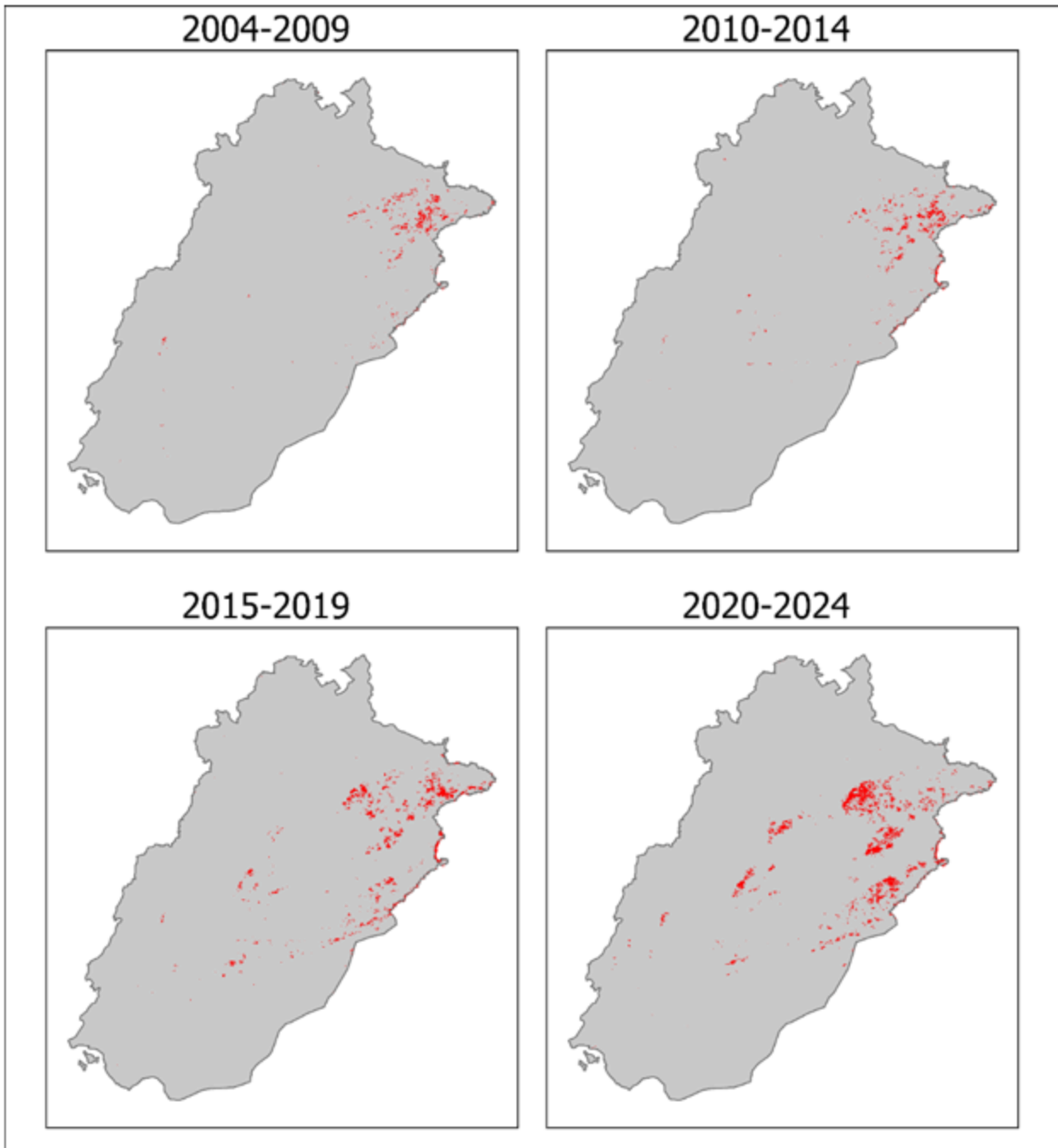


Figure 4

Spatial Distribution of Mean Burned Area by Time Intervals

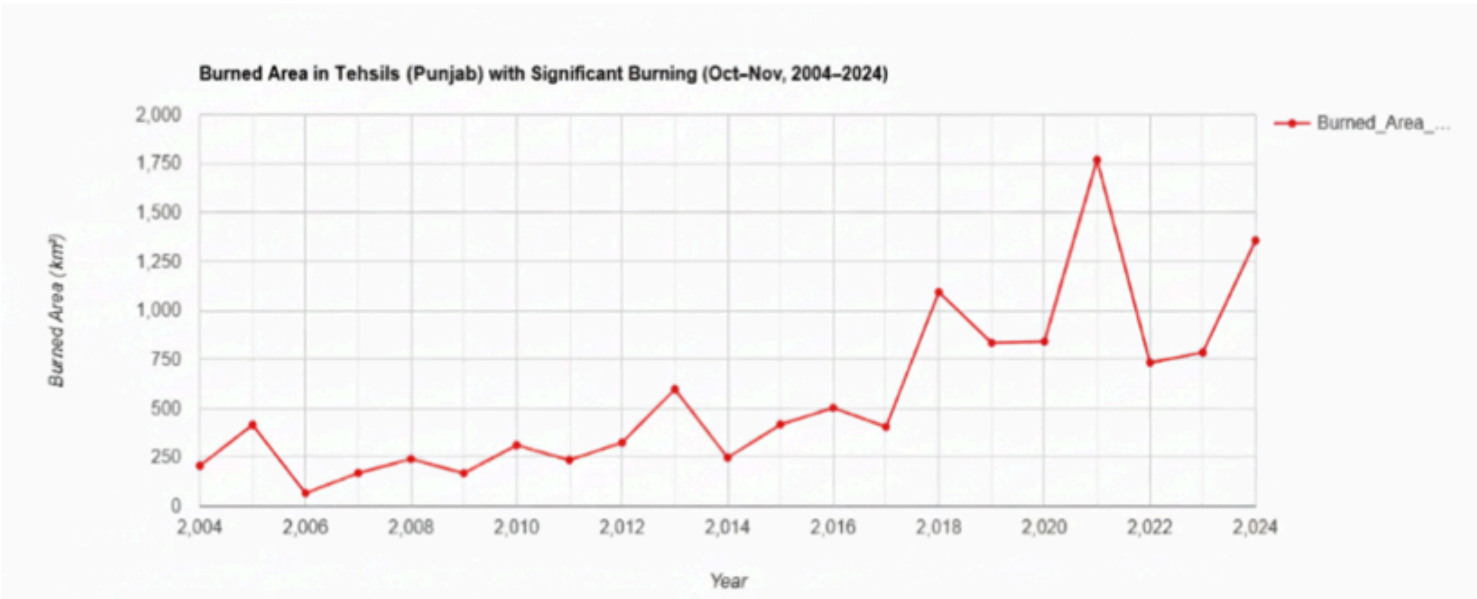


Figure 5

Temporal Trend of Burned Area over Significantly Burned Tehsils (2004–2024)

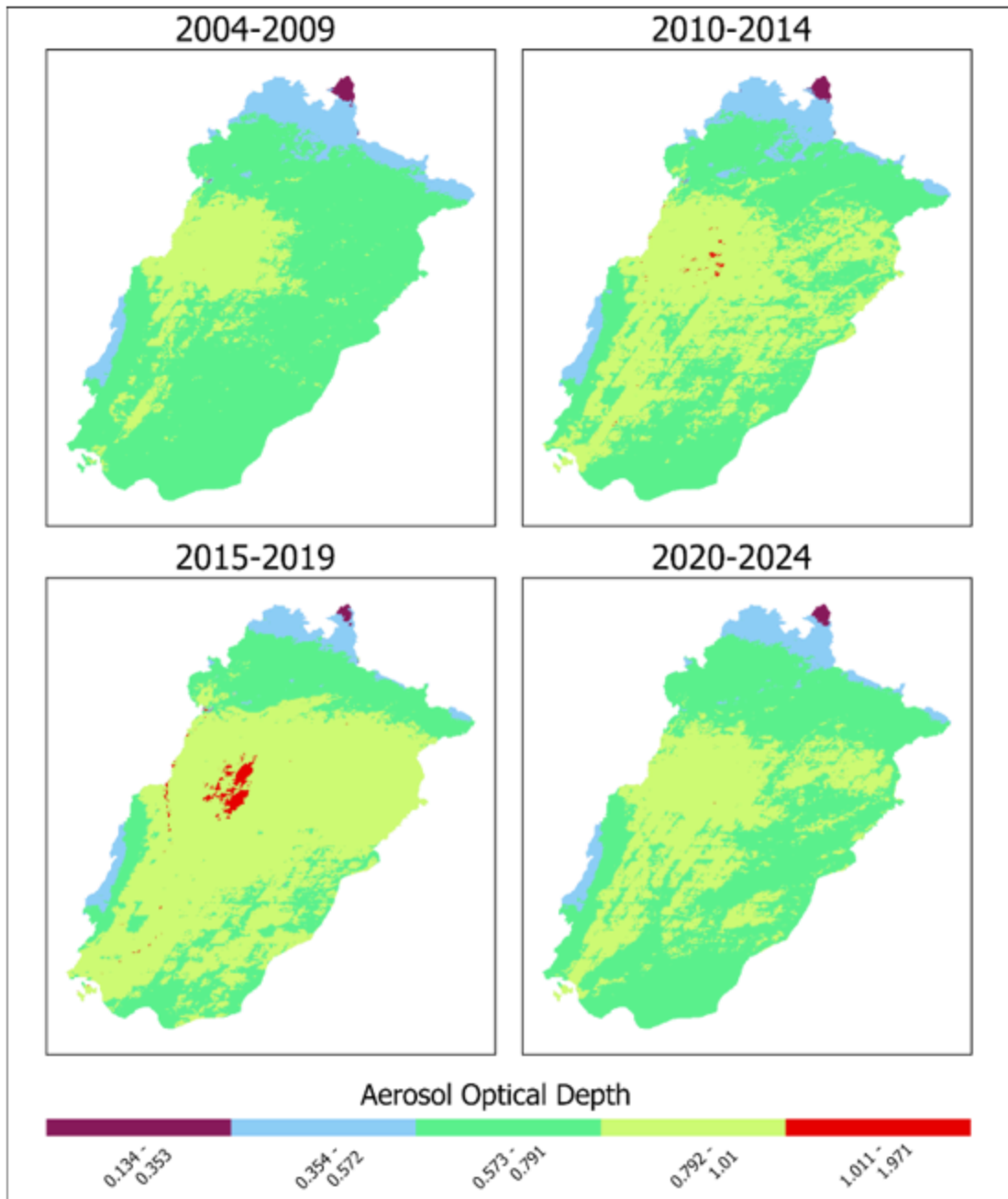


Figure 6

Spatial Distribution of Mean AOD by Time Intervals

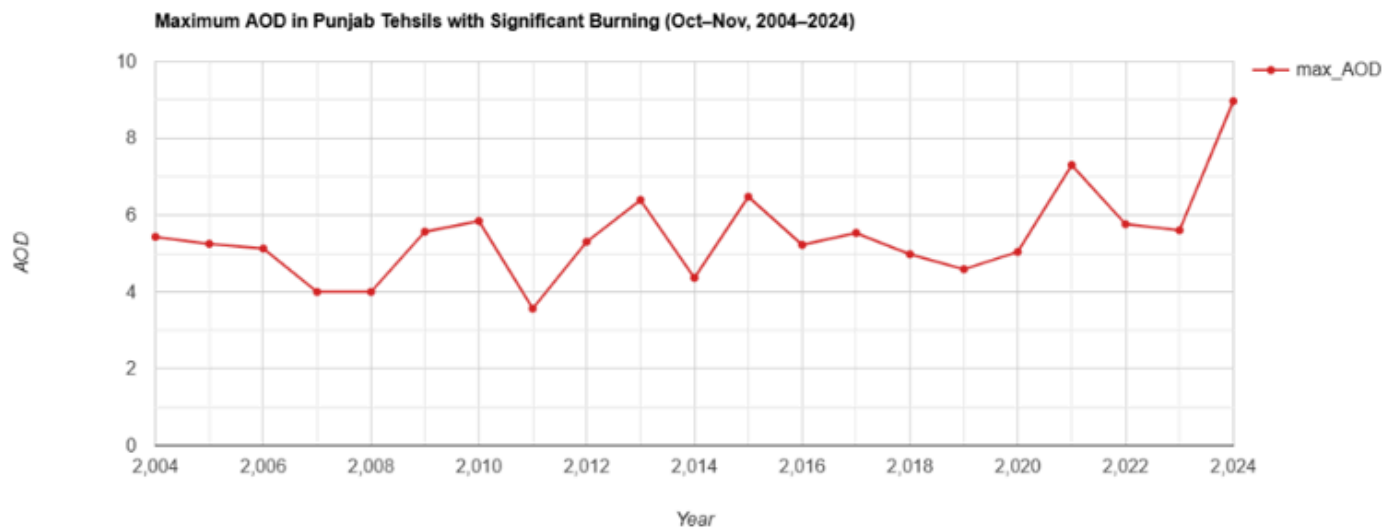


Figure 7

Temporal Trend of AOD over Significantly Burned Tehsils (2004–2024)