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RESEARCH ARTICLE

ASSESSING THE SEASONAL CORRELATION BETWEEN AOD, LST, NDVI, AND RAINFALL IN SINGRAULI, MADHYA PRADESH, INDIA

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ABSTRACT

Air pollution, particularly from aerosol particles, is a major issue in developing countries like India. Correlating seasonal variations between AOD, LST, NDVI, and rainfall are closely linked to regional air quality changes. This study aims to assess long-term changes in Aerosol Optical Depth (AOD), vegetation index, and land surface temperature in Singrauli, India, and investigate their interactions using remote sensing and GIS methods. This study used Google Earth Engine (GEE) to obtain Multi-Angle Implementation of Atmospheric Correction (MAIAC), a combined Aqua and Terra MODIS product for the year 2024 every month for AOD, NDVI, and LST for Singrauli district. The study found that AOD was lowest during the monsoon season and highest throughout the winter and some months of summer whereas the highest NDVI was obtained in the month after monsoon and some months of winter the lowest NDVI was recorded in the month of summer and LST shows the opposite trend of NDVI means that high LST was recorded in the month of the summer and lowest LST in the month of post-monsoon and winter season. The correlation analysis was performed from the ambient air pollutant data from 4 monitoring sites, NDVI, and LST with AOD. The Particulate matter PM_{10} and $PM_{2.5}$ show a positive correlation with AOD with average R^2 values of 0.4984 and 0.5459 respectively at all 4 locations because particulate matter directly contributes to the concentration of AOD but gaseous pollutants like NO_2 and SO_2 shows the very weak correlation with AOD with R^2 value of 0.1393 and 0.0862 respectively as AOD only consist of particulate matters so these gaseous pollutants didn't contribute much in AOD. Many other factors also influence the AOD and LST in the study area like wind direction, wind speed, relative humidity, and many more. The dominant wind direction in Singrauli throughout the year 2024 is North-West with an average speed of 2-3 m/s.

KEYWORDS

MODIS, NDVI, AOD, Windrose, Ambient Air pollutants, Correlation

1. INTRODUCTION

Human endeavors such as urbanization, and industrialization are linked to the emission of aerosols and trace gas pollution (Fadnavis et al., 2020). Aerosols, with diameters ranging from 0.001 to 10μm, significantly affect human health and Earth's climate at regional and global levels (IPCC., 2007). Aerosols can indirectly change cloud microphysics, lifespan, and thermal emissivity, altering the energy budget (Mermelstein., 2013; Suzuki and Takemura., 2019). Aerosol Optical Depth (AOD) is closely linked to ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and particulate matter ($PM_{2.5}$ and PM_{10}) (Chu et al., 2003; Li et al., 2016; Ratnam et al., 2021). Similar trends were noted in South-East Asia (January-April), Central America (March-May), and central and southern Africa (June-September), the Dead Sea's spring season (March-May) had the highest monthly average, whereas all other seasons had lower AOD values. (Lee et al., 2020; Kadaverugu et al., 2024). Plants absorb and digest pollutants after they are released into the environment, improving air quality by adding oxygen to the atmosphere (Horn and Dasgupta., 2024). Similarly, the Normalized Difference Vegetation Index (NDVI), Land Surface Temperature (LST), and rainfall also vital roles in the concentration of AOD (Polanco-Martinez et al., 2020; Kadaverugu et al., 2021). The correlation analysis between LST and other parameter such as EVI and AOD shows that LST shows direct impact on the EVI or vegetation index more the LST then the vegetation index will be low similarly with AOD LST shows the positive correlation (Badugu et al., 2024). LST and NDV shows strong negative in post-monsoon period and weak negative in winter season (Guha et al., 2022).

In arid and urban areas like Singruali, Madhya Pradesh elevated surface temperatures intensify land dryness and contribute to higher AOD levels due to increased dust and particulate matter. These dynamics play a crucial role in seasonal and regional air quality variations (Raynolds et al., 2013). Rainfall acts as a natural cleansing mechanism for the atmosphere, with seasonal variations playing a key role in regulating aerosol distribution and atmospheric clarity (Fadnavis et al., 2020; Edo et al., 2024). Air quality and environmental dynamics are critical indicators of ecological health and human well-being, particularly in regions with intensive industrial activities. Singrauli, often referred to as the "Energy Capital of India," hosts numerous coal-based power plants, which significantly influence local air quality and environmental parameters. This study aims to analyze the seasonal variations of AOD, LST, NDVI, and rainfall across Singrauli and assess ambient air quality at three locations near power plants for the year 2024. By integrating remote sensing data with ground-based air quality measurements, this research provides a comprehensive understanding of spatiotemporal trends and their potential implications for regional air pollution management, climate resilience, and ecological sustainability. The findings of this study will contribute to environmental monitoring efforts by identifying patterns in air pollution and land surface changes, informing policy measures for

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sustainable industrial operations, and supporting climate adaptation strategies in the region. Understanding the seasonal variations of key atmospheric and terrestrial variables is essential for assessing the environmental impact of these industrial activities and their implications for climate and public health.

2. Material and Methods

2.1 Study area

Singrauli, India, is a key hub of functional coal mining and thermal power plants. Historically, the region was rich in vegetation, with diverse flora, fauna, and various ethnic communities. The district covers 5,672 square kilometres and is situated between latitudes 24° 10' 30" N and longitude 82° 45' 18" E. It consists of three tehsils: Singrauli, Deosar, and Chitrangi, bordered by Uttar Pradesh's Sonebhadra district to the north and northeast, Chhattisgarh's Surguja district to the south and southeast, and Madhya Pradesh's Rewa and Sidhi districts to the west. The central area features hill ranges, with the southern ones rising from 365 to 488 meters above sea level. The data for 2024 were retrieved from the CPCB and MPPCB web portals, covering four ambient air quality monitoring stations in Singrauli: Singrauli Trauma Centre Waidhan, Singrauli Surya Kiran Bhawan Dudhichua, NCL Singrauli, and the NTPC Vindhyanchal station (Figure 1).

2.2 Climate

The district has a hot and humid climate with four seasons: winter, summer, monsoon, and post-monsoon. In the winter, relative humidity ranges between 35% and 63% (Dadhich et al., 2018). The Winter season (December to February) is cooler, while the summer season (March to May) observed temperatures reaching 42.0°C. The average annual rainfall is 108.63mm, with the peak occurring in July and August. Data from the India Meteorological Department (IMD) shows that from April to June, daily temperatures can rise to 40–44°C.

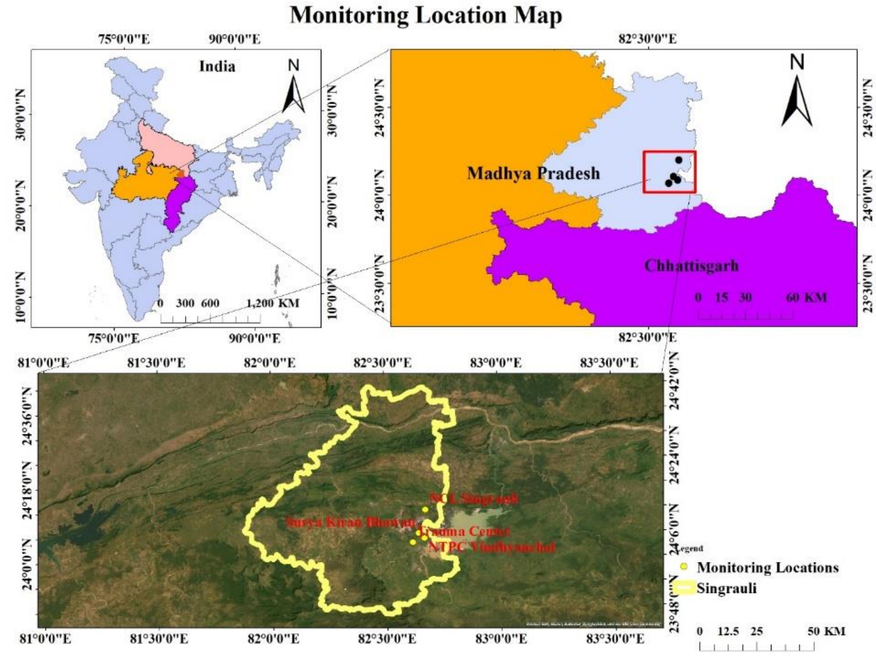

Figure 1: Study area map showing monitoring location

2.3 Wind direction and Wind Direction

A "wind rose" diagram displays the frequency and direction of winds in a certain area over a period of time. Typically, it displays the distribution of wind speeds and directions to help visualize dominating wind patterns and their impact. (Oktavia et al., 2023) Meteorology and environmental studies regularly use this technique to better understand how wind behaviour influences local climate, pollution dispersion, and other atmospheric phenomena. WRPLOT View Software requires seven parameters: year, month, day, hour (00-23), wind speed (m/s), wind direction (degree), and precipitation (mm). The dominant wind direction of the Singrauli is North-West with an average speed of 2-3 m/s as shown in Figure 2

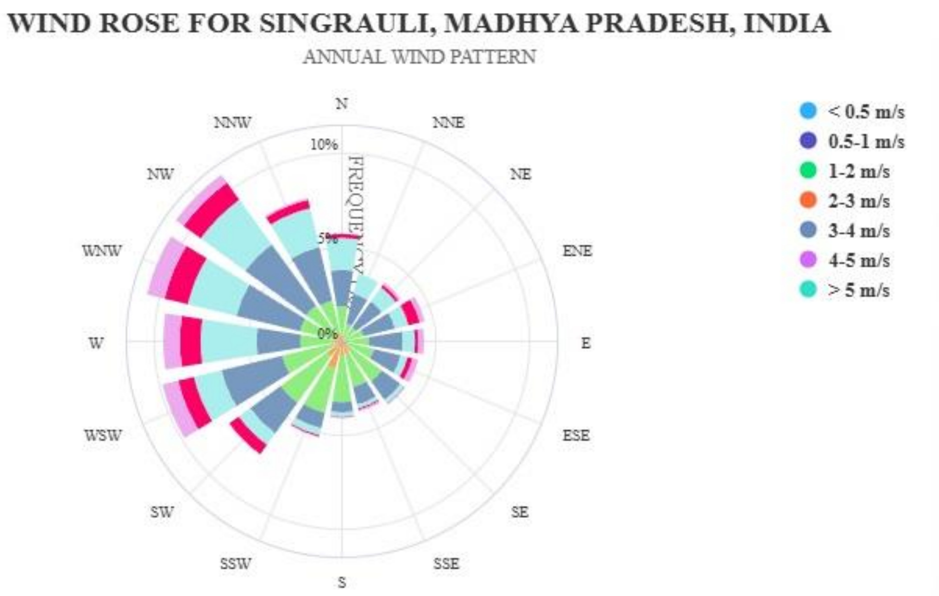

Figure 2: Windrose diagram for the study area

2.4 Satellite Data Collection

The satellite-derived data products viz. MCD19A2.006 MODIS Terra and Aqua daily land AOD, MOD11A1.061 Terra LST and emissivity daily worldwide (Wan et al., 2021; Lyapustin and Wang., 2018). The most recent MODIS LST version, v005, has significantly enhanced spatial coverage, stability, and accuracy when compared to earlier versions (Wan., 2008; MOD13Q1 product, Huete et al., 2002) is used for NDVI, AOD (~1 km), LST (~ 1 km), and NDVI (~250 m), all cataloged in Google Earth Engine (GEE) for the year 2024 on monthly basis.

3. Results

3.1 Aerosol optical depth

The Minimum AOD values were recorded in the rainy season, while the maximum in the winter season which is 0.537 and 0.854 respectively. The monthly average of AOD values revealed minimum concentration during

July and August and maximum in November in the study area The AOD values are also reported to gradually increase over time in almost all regions, primarily due to poor ambient air quality caused by anthropogenic activities which leads to aerosols generation by the transportation and industrial sectors (Prijith et al., 2018). Rain washes away air pollutants from the atmosphere resulting in lower AOD values in monsoon. Cold air hinders vertical mixing resulting in significantly higher AOD values. Similar conclusions were drawn by (Babu et al., 2013). The higher value of AOD was estimated in November month followed by June as shown in Figure 3 and 5 which are 0.95 and 0.88 respectively, The AOD value is maximum in the month of summer and pre monsoon period (Kumar et al., 2016).

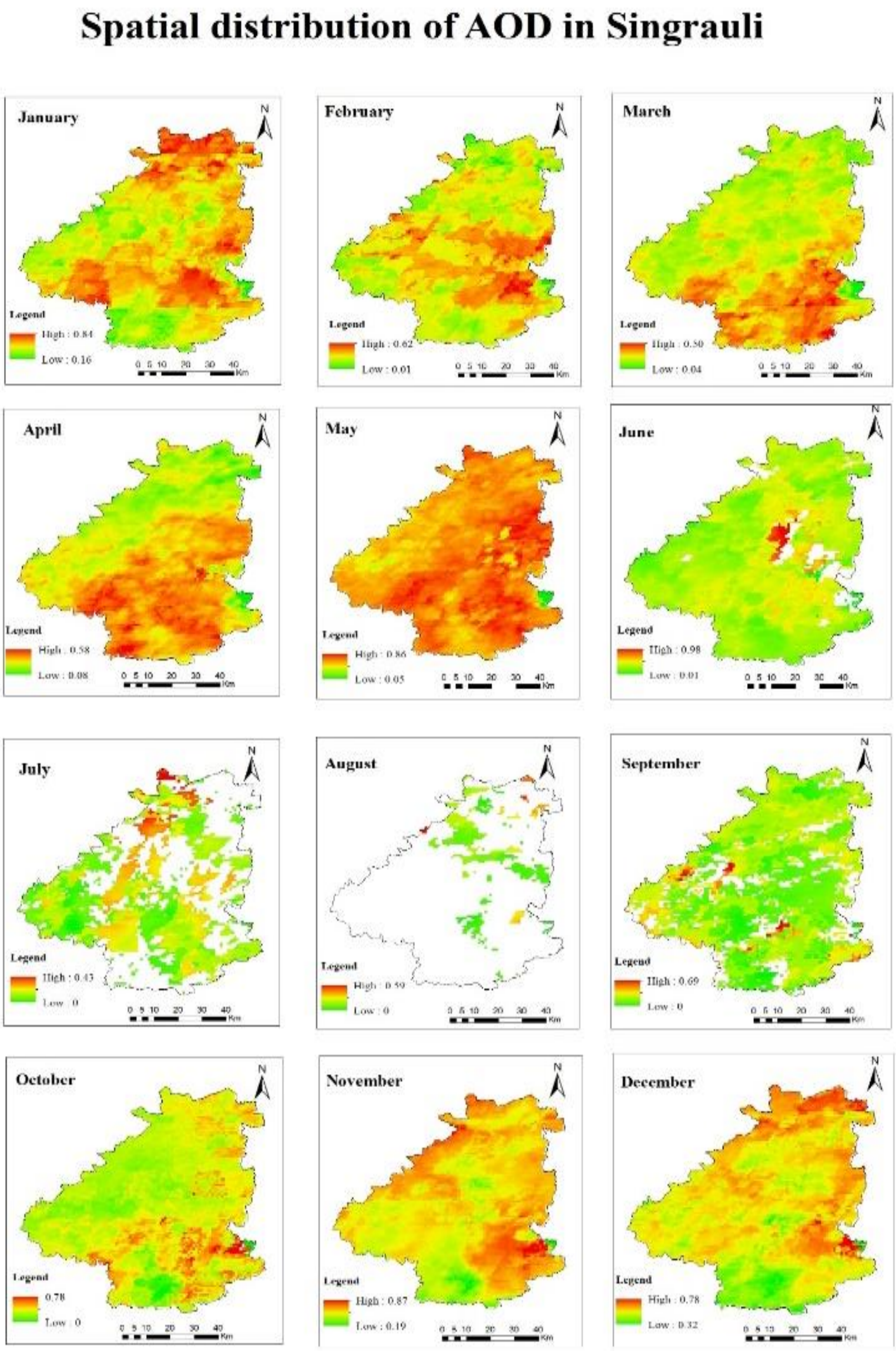

Figure 3: Spatial distribution of AOD in Singrauli district

3.2 Land Surface Temperature (LST)

The product intends to retrieve LST with an error of less than 1 °C (± 0.7 °C standard deviation) in the range of -10 to 50 °C, assuming surface emissivity is known (Wan, 1999; Wan et al., 2004). Validation of the LST algorithm revealed errors of less than 1 °C on homogenous surfaces such as water, crop, and grassland (Wan, 2008; Wan et al., 2004). Found good agreement between ground and MODIS LST, with errors comparable to or smaller than measurement uncertainties in most cases within the 25 to 32 °C range (Coll et al., 2005). The land use and land cover (LULC) of a region also influences the land surface processes that affect LST, primarily through reflection (albedo) of surface net shortwave radiation (SNSR) and through direct obstruction (shade) (Dhole et al., 2023).

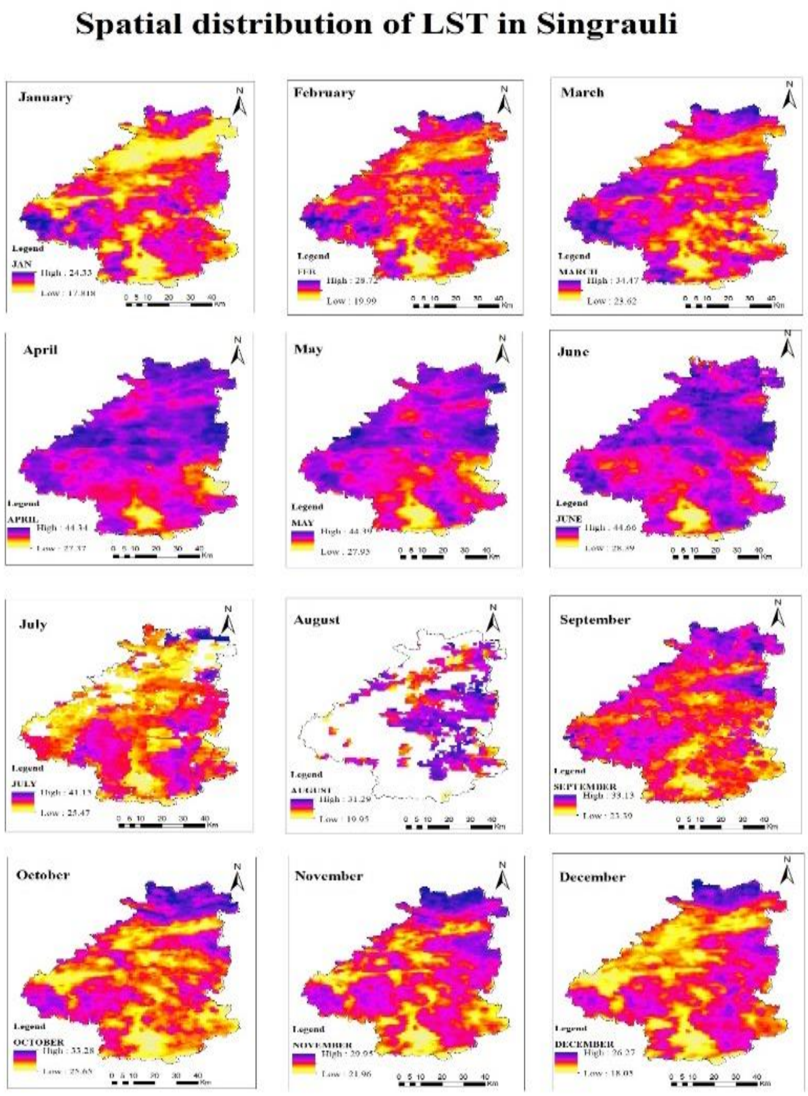

Figure 4: Spatial distribution of LST in Singrauli district

In this study, we used MODIS (Moderate Resolution Imaging Spectroradiometer) LST data to look at seasonal fluctuations in Singrauli, a location heavily influenced by industrial activities, particularly power plants.

The higher value of LST was calculated in May and June shown in Figure 4 and 5 which is 40.52 °C and 39.91 °C respectively, the major reason is due to maximum solar radiance in this month but least LST value was estimated in December and January, but when we compare the LST data with ambient temperature it is more or less shows the difference of 1-2°C (Kumari et al., 2017).

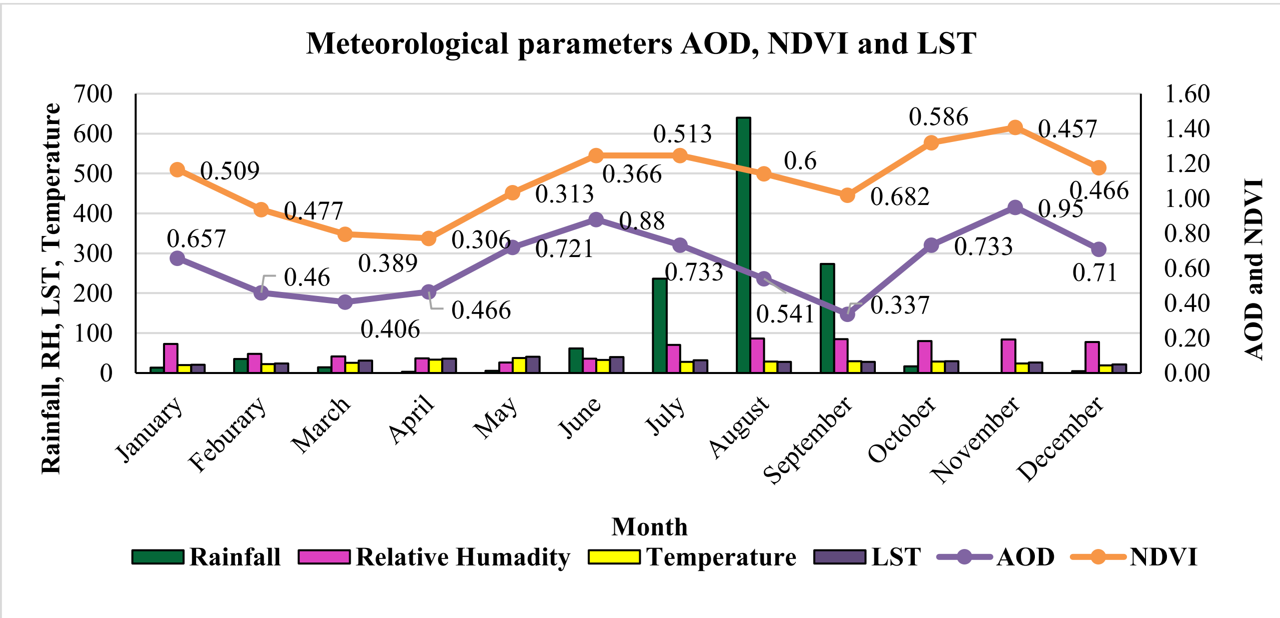

Figure 5: Combo graph of metrological parameters AOD, NDVI, and LST

3.3 Normalized Difference Vegetation Index (NDVI)

A 16-day composite MODIS NDVI dataset with a 250-m resolution, the MOD13Q1 product, was used (Huete et al., 2002). Surface reflectance figures have been adjusted to account for molecular scattering, ozone absorption, and aerosol effects (Vermote et al., 2002). To ensure high-quality NDVI data, firstly removal of cloud-contaminated pixels had been performed before prioritizing near-nadir observations. Because vegetative indices (VI) tend to rise when seen at oblique angles, the MODIS VI compositing approach reduces viewing angle variations. After filtering, the approach compares the two highest NDVI values and chooses the one closest to the nadir view, maintaining consistency during the 16-day composite cycle.

NDVI always ranges from -1 to +1. If there are no green leaves, the value is zero. A zero denotes no vegetation, whereas a value close to +1 (0.8-0.9) suggests the highest density of green leaves conceivable (Kumari et al., 2022). However, the land cover type does not have its specific limit of NDVI values.

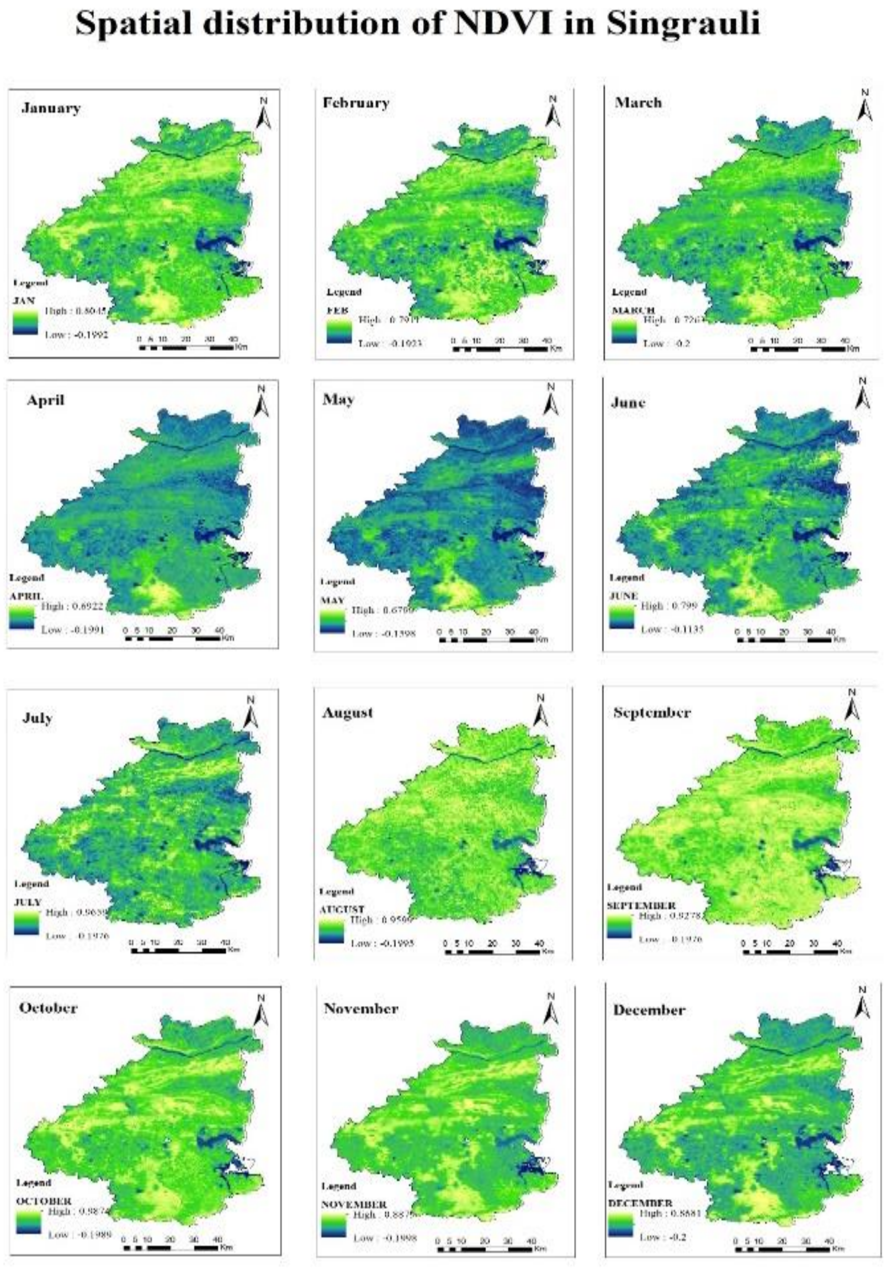

Figure 6: Spatial distribution of NDVI in Singrauli district

NDVI readings in Singrauli are highest in August and September as shown in Figure 5 and 6, owing to the monsoon season, which delivers heavy rains and promotes vegetation growth. The change in NDVI is also significant, due to seasonal changes and its impacts on the vegetation density. NDVI levels rise during the monsoon and fall to their lowest point in the dry seasons (Revadekar et al., 2012; Chakraborty et al., 2018). The arid environment, along with lower soil moisture availability, results in scant vegetation cover, particularly in non-irrigated areas, which leads to less photosynthetic activity and, as a result, lower NDVI values.

3.4 Rainfall

Rainfall was found to have a considerable impact in numerous places in India (Habib et al., 2006). Rainfall was found to be highest in the northeast and lowest in the northwest, the aerosol concentration reduces significantly during peak rainfall in July (Habib et al. 2006; Jain et al., 2016). The change in seasons plays a crucial role in AOD concentration and it can be noticeable over India, with aerosols concentration dominates during the winter and in monsoon seasons, resulting the lower concentration AOD, and coarse mode aerosols and/or growth of fine mode water soluble aerosols during the pre-monsoon and monsoon seasons, resulting in higher AODs (Ramachandran and Cherian, 2008).

The analysis for rainfall is obtained from IMD for Singrauli region and study shows that the maximum rainfall was obtained in the month of July and August and least rainfall was in month of May and June as shown in Figure 7a and rainfall plays a major role in influencing all the other factors which are discussed in this paper like high rainfall leads to lower of AOD as shown in Figure-7b and high rainfall will lead to more healthy vegetation which make NDVI value lies in healthy region. Rainfall also influences other factor like ambient temperature and relative humidity and many more.

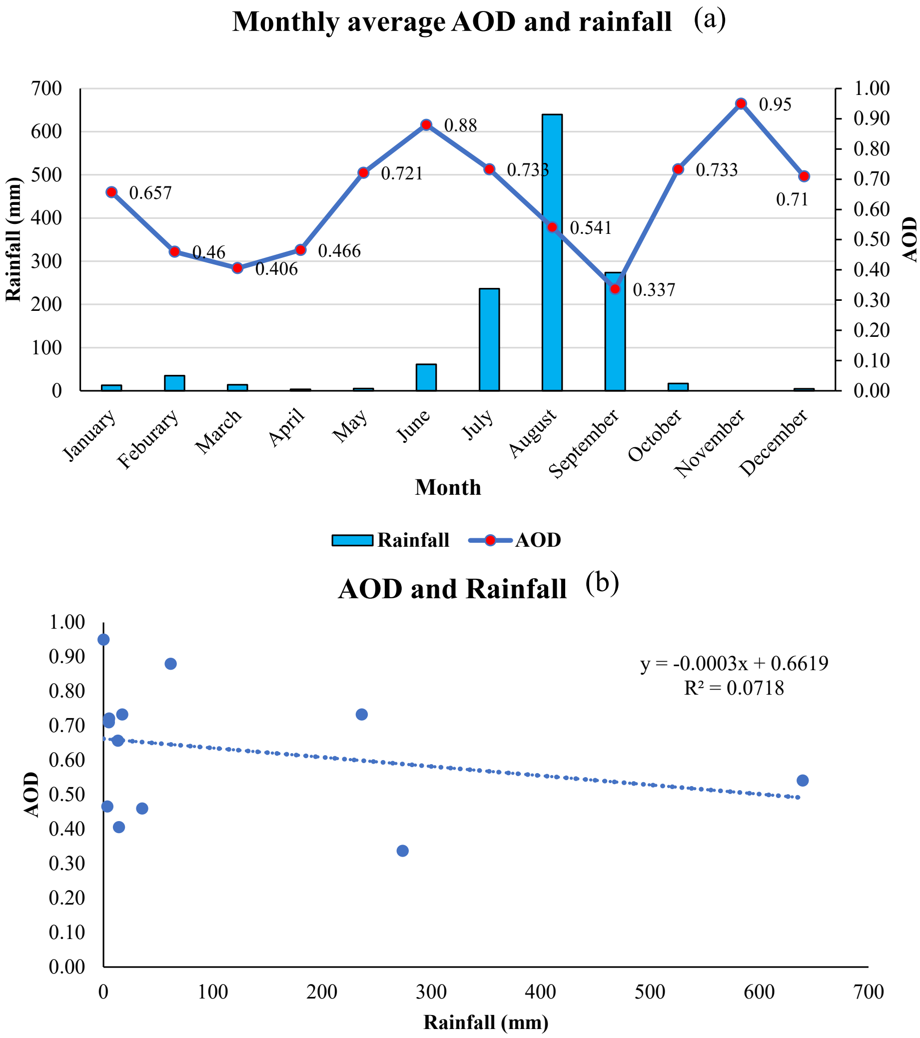

Figure 7: (a) Monthly average of AOD and Rainfall (b) Correlation between AOD and Rainfall NDVI, LST, AOD at monitoring sites

The CPCB and MPPCB has set its Ambient air monitoring site there, the data for Particulate matter and gaseous pollutants were obtained from monitoring sites and further analysed of AOD, NDVI and LST were performed by using GIS tools. Firstly, the monthly mean AOD, NDVI AND LST for all the 4 monitoring locations (Figure 8).

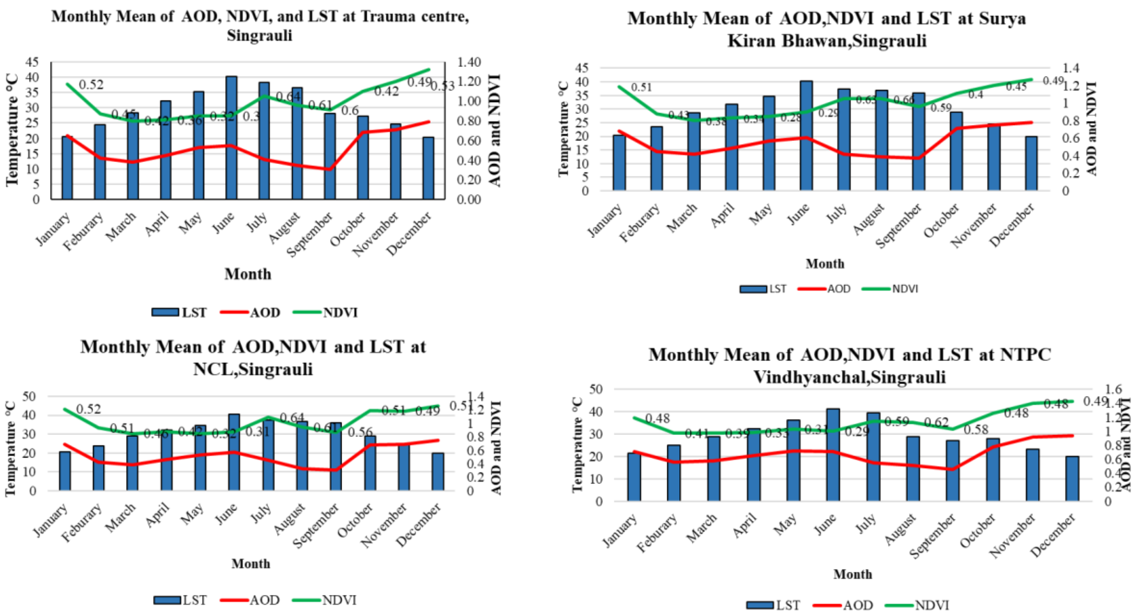

Figure 8: Monthly Mean of AOD, NDVI and LST at all monitoring locations

The following graph shows that the least value of AOD was obtained in the monsoon season and maximum AOD was obtained in the month of winter followed by summer season at all the four sites. The major reason for least AOD was due to heavy rainfall in those location in the month of monsoon and maximum AOD in winter due to burning of fossil fuel for heating purpose and due to phenomena of thermal inversion.

3.5 Correlation of AOD with Particulate matter, Gaseous pollutants, NDVI and LST

Monthly average AOD values for years 2024 revealed minimum concentration during July and August and maximum in November (Figure-7). Rain washes away air pollutants from the atmosphere resulting in lower Maximum AOD values were reported in winters and minimum in summers.

Data from ground air quality stations (PM_{10}, $PM_{2.5}$, SO_2 and NO_2) showed comparable patterns. An overall increase in AOD concentration was observed at all sites. The concentration of AOD decreased in the month of July-September 2024 as compared to other months of 2024 due to other anthropogenic activities and metrological factors.

- District Hospital and Trauma Centre, Waidan, Singrauli, Madhya Pradesh

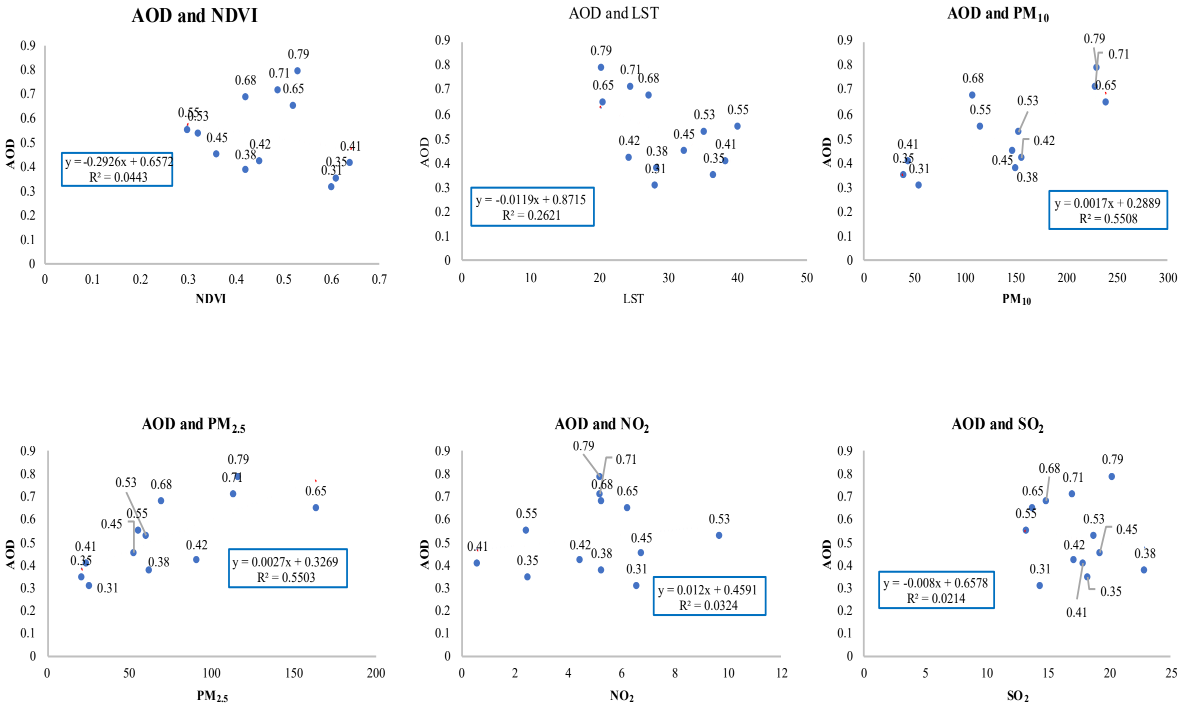

Figure 9: Scatter plots showing the relationship between AOD and NDVI, LST, PM_{10}, $PM_{2.5}$, NO_2, and SO_2 at District Hospital and Trauma Centre, Waidan, Singrauli, Madhya Pradesh

- Surya Kiran Bhawan, Dudhichua, Singrauli, Madhya Pradesh (CPCB)

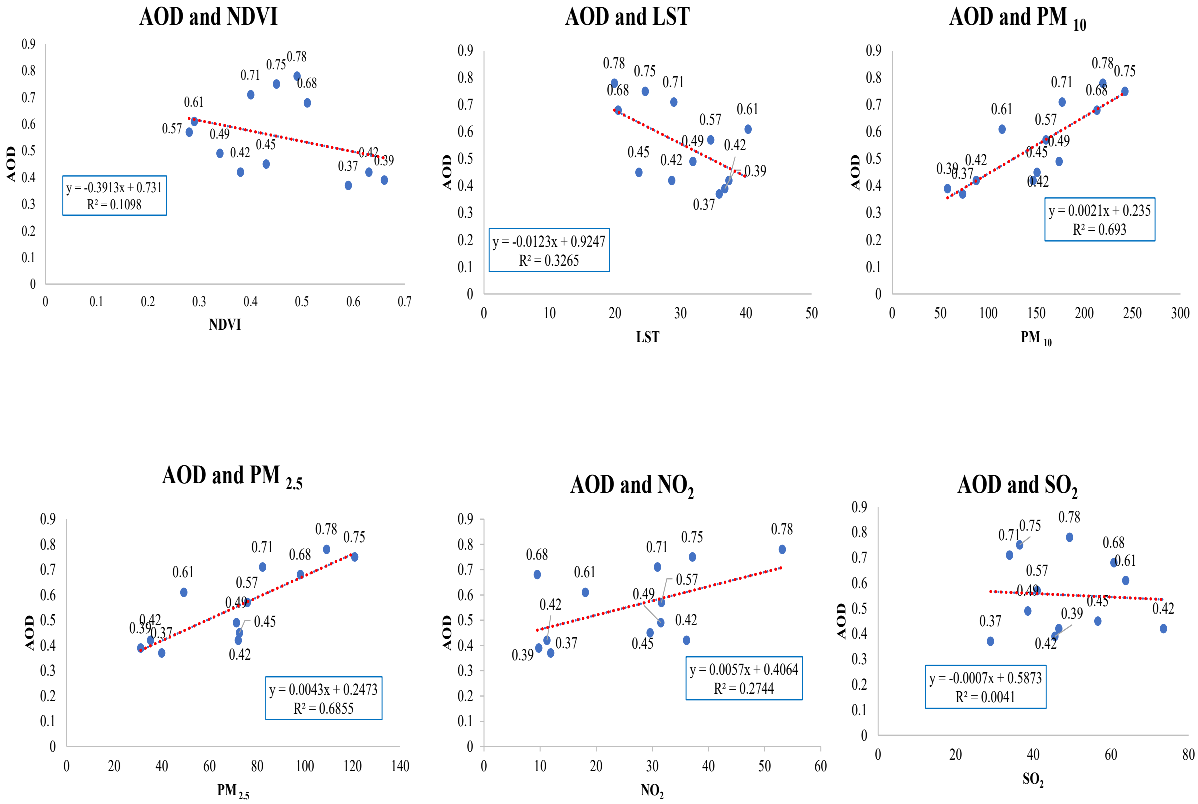

Figure 10: Scatter plots showing the relationship between AOD and NDVI, LST, PM_{10}, $PM_{2.5}$, NO_2, and SO_2 at Surya Kiran Bhawan, Dudhichua, Singrauli, Madhya Pradesh

- Northern Coalfields Limited, Singrauli, Madhya Pradesh

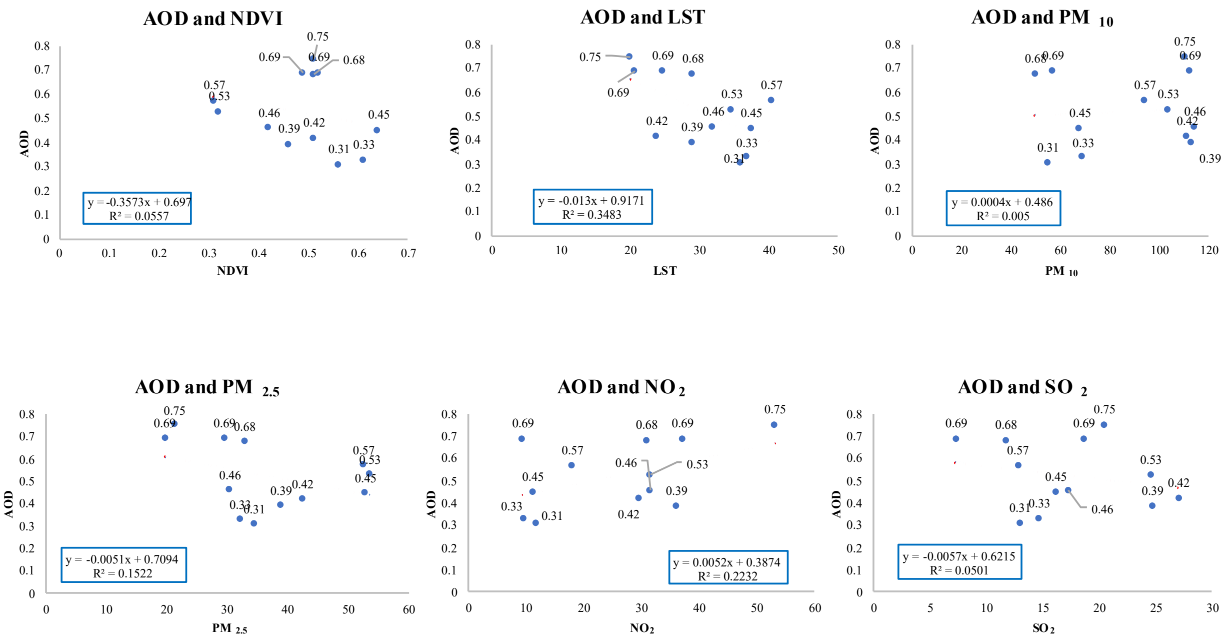

Figure 11: Scatter plots showing the relationship between AOD and NDVI, LST, PM_{10}, $PM_{2.5}$, NO_2, and SO_2 at Northern Coalfields Limited, Singrauli, Madhya Pradesh

- NTPC Vindhyanchal, Singrauli, Madhya Pradesh

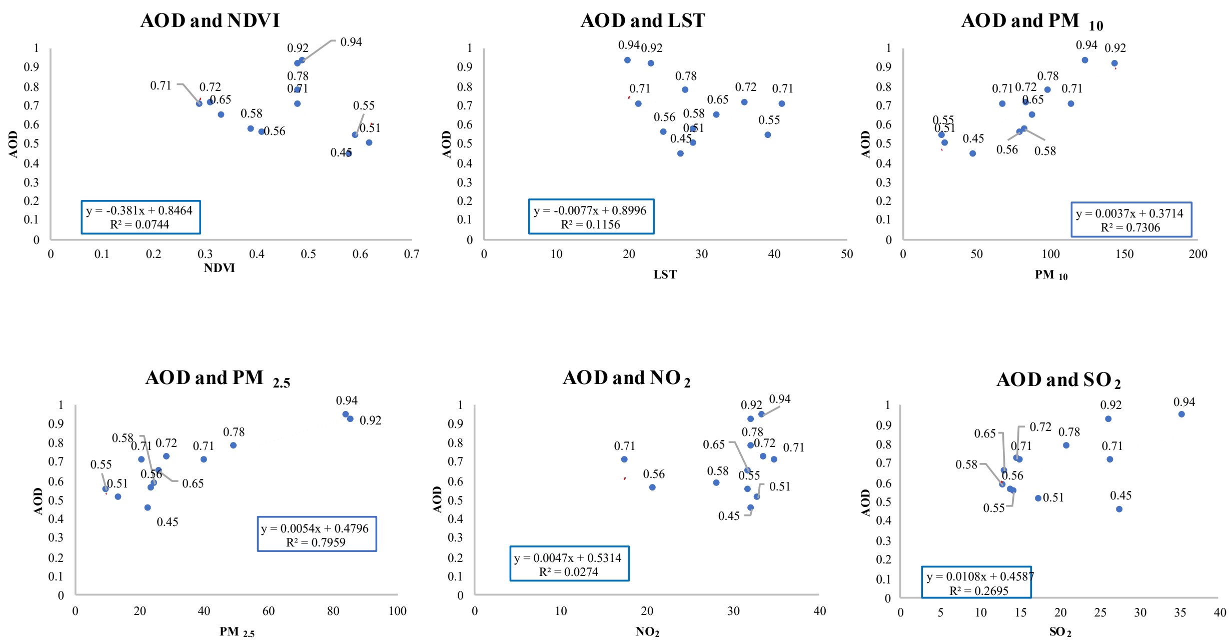

Figure 12: Scatter plots showing the relationship between AOD and NDVI, LST, PM_{10}, $PM_{2.5}$, NO_2, and SO_2 at NTPC Vindhyanchal, Singrauli, Madhya Pradesh

In this study, we calculated the relation between ground station observed data (PM_{10}, $PM_{2.5}$, SO_2 and NO_2) air pollutants, with MODIS AOD, NDVI and LST satellite data. Correlation analysis revealed in (Fig-09 to 12) that the correlation between AOD and NDVI at all the 4 locations shows weak and negative correlation with average R^2 value of 0.0615 means that increase then the value of NDVI get decreased this is mostly due to high concentration of AOD can block the sunlight or influences the intensity of solar light which somehow impact the vegetation health by reducing the availability of the sunlight for plants but there are also other reason which influences the NDVI like rainfall, nutrition for the plants and plant health.

AOD and NDVI shows moderate relationship with average R^2 value of 0.1847 which means that about 18% of variation in LST is explained by AOD. The moderate correlation indicates that AOD has some influence on LST, but on other hand other factors like cloud cover, surface moisture also plays a significant role in influencing the LST in various months.

AOD and Particulate matter (PM_{10}, $PM_{2.5}$) shows positive correlation with an average R^2 value of 0.4984 for PM_{10} and 0.5459 for $PM_{2.5}$, this means that high concentration of particulate matter in atmosphere will directly increase the concentration of AOD in atmosphere. This also makes sense because AOD is an optical measure of aerosols in the atmosphere, and PM_{10} represents larger airborne particulates, which contribute to AOD values. So, the AOD and Particulate matters shows strong positive correlation among themselves.

On other hand gaseous pollutants (NO_2 and SO_2) shows very low predictability and weak positive correlation with AOD with an average R^2 value of 0.1393 for NO_2 and 0.0862 for SO_2, this means that there was very low predictability that AOD depends on these gaseous pollutants, because AOD mostly consist of particulate matter in atmosphere. The concentration of these gaseous pollutants is mostly controlled by the burning of fossil fuels and vehicular emission so these pollutants didn't contribute that much in the concentration of AOD.

4. Discussion

Singrauli's population has been steadily rising as people from different parts of the country move to the city in search of better opportunities and facilities (Nagpal, 2014). This rapid population growth has significantly strained housing and infrastructure, particularly in sectors like mining, power plants, and residential development, gradually transforming the city's landscape. A large number of migrants, drawn by employment prospects, often settle on the outskirts, contributing to urban expansion (Sharma et al., 2009). The eastern region of Singrauli stands out for its more uniform land-use patterns, largely due to the expansion of built-up areas near thermal power plants and surrounding settlements (Bose et al., 1996). The eastern portion of Singrauli has seen significant development, owing primarily to the construction of power stations. With increased human density, several bodies of water are being used for shelter and economic purposes, further altering the city's landscape.

Singrauli has air pollution problem from last few decades, winters are more polluted as compare to summer season and this leads to increase in the concentration of AOD in the study area maximum AOD values were reported in winters and minimum in summers by various researchers across the world (Li and Ramanathan, 2002; Che et al., 2013; Kumar et al., 2014; David et al., 2018; Jia et al., 2020; Kang et al., 2020; Yadav et al., 2022). The major reason is due to the increase in pollution load in November because of the burning of fossil fuels on the other hand in June due to high wind speed the small particles get suspended in the atmosphere which increase the AOD value but least AOD value was estimated in the month of July and August due to rainfall which washes all the pollutants from atmosphere and AOD vale gets low in those months. The maximum AOD was reported in the month of May-June and Nov-Dec because of heavy load of pollution in atmosphere but lowest AOD was recorded in the month of monsoon because rain washes all the atmospheric pollutants which lowers the AOD value and the particulate matter concentration in the study area shows the positive correlation with AOD, the AOD show the positive correlation with $PM_{2.5}$ where the linear regression shows the positive slops which supports the positive correlation with AOD because the particulates matter which have small particulates that directly contribute in the concentration of AOD (Kong et al., 2016; Guo et al., 2009; Jeoung et al., 2014). The R^2 values for the AOD and PM_{10} and $PM_{2.5}$ is 0.4984 and 0.5459 respectively which shows the moderate to strong positive correlation between them, the scatter plot of the correlation between AOD and PM_{10} and $PM_{2.5}$ is shown in Fig-09 to 12.

Similarly, the correlation between gaseous pollutants as NO_2 and SO_2 shows the weak correlation between them because AOD mostly consist of particulates matter in atmosphere and these NO_2 and SO_2 are gaseous pollutants so they will not contribute much in the AOD concentration (Chawala et al., 2023; Lin et al., 2019). The study found that the R^2 values for NO_2, and SO_2 were 0.1393 and 0.0862, respectively, indicating a very weak positive correlation with AOD. These gaseous pollutants have very poor predictability with AOD, which is why they show a weak positive association with AOD in the study area.

Similarly, AOD and NDVI shows the R^2 value of 0.0615 with weak correlation, this indicates that's high AOD negatively impact the vegetation. High AOD reduced the availability of the solar radiance for the plants which impacts the growth of plants and reduce the NDVI value but LST and NDVI show the inverse proportionality trend because as the LST increase the value of NDVI get decreased (Gorgani et al., 2013; Kadaverugu et al., 2024). LST and NDVI share an inverse relationship area with high NDVI (dense vegetation) experience lower LST due to shading and evapotranspiration, which cools the surface (Anbazhagan et al., 2016). Increased soil moisture and good climatic circumstances promote dense forest canopies, agricultural crops, and grasslands, resulting in enhanced chlorophyll activity and strong near-infrared (NIR) reflection. This leads in higher NDVI values, which indicate healthy and lush vegetation. Conversely, the lowest NDVI values are found in May and June, which coincide with the peak summer and pre-monsoon season. During this season, high temperatures and dry circumstances cause water stress, reduced chlorophyll activity, and vegetation senescence, resulting in a drop in NDVI. Conversely, low NDVI (barren or urban areas) leads to higher LST, as these surfaces absorb more heat and lack moisture to regulate temperature.

AOD and LST shows the moderate relationship, but there are also metrological factors which influences the relation between AOD and LST like cloud cover, surface reflectance, soil moisture, anthropogenic activities, settlement area and vegetation cover and many more (Varade et al., 2023).

The study shows the statistical correlation among this all the variables like AOD, NDVI, LST, Rainfall and ambient air pollutants at 4 locations in the study, further in the future we can also this study for comparative analysis of the pollutants are various landscape patterns by building LULC map of the study area for previous year on the and analysis of the decadal changes in the Singrauli district. We can use those decadal change data with the various pollutant's concentrations obtained from satellite imagery and also correlate those data with variable like NDVI, LST for day time and night time

5. Conclusion

The finding of this study emphasized on the significance of estimation of AOD, NDVI and LST from MODIS data and correlate it with metrological factor like rainfall and ambient air pollutants such as $PM_{10,}$ $PM_{2.5}$, NO_2 and SO_2. A significant decline in value of AOD was observed in the month of July to August because this month's receive maximum amount of rainfall in year 2024 and the rainfall washes all the pollutant's which are present in the atmosphere which leads to the lower of AOD concentration in this months, but May to June and November and December have maximum concentration of AOD due to rise in the pollution in these months mostly the particulate matter concentration get increases in this months which leads to increase in concentration of AOD.

The maximum NDVI value is in the range of 0.580-0.682 in the month of August to October because this month's follow the peak of monsoon season which leads to increased soil moisture and support vegetation growth and due to abundant water availability and optimal growing condition plants shows in their healthiest state and that's why plants in this month's shows the maximum value of NDVI, but the least value of NDVI was in range of 0.300-0.389 was observed in the month of March to June because this month's experience high temperature and low soil moisture which causes vegetation stress which leads to shedding of the leaves from tree and the winters crops were also harvested in this month's and the field were left barren this are the major reasons for the lowering of NDVI values in this months. NDVI and LST are inversely proportional because as LST increase the NDVI get decreases.

The maximum LST was observed in the summer season which lies from month of April to early July and the temperature lies in range of 31- 41°C because of intense solar radiation and minimum cloud cover which leads to high surface temperature, low soil moisture due to no rainfall makes land dry which increases the surface heat absorption capacity and increase the LST in these months. Reduced vegetation cover and urban and industrial activities also play role in increasing of LST, but the lower LST value lies in the month of winter starting from October to January lies in the range of 21-28°C because these months are after monsoon seasons which makes land to retains moisture and cool the surface, cooler temperature, lower solar radiation and longer nights results in lower of LST in these months and since NDVI is relatively high in these months (post-monsoon recovery and winter crops), vegetation helps regulate surface temperatures by reducing direct heating of the soil.

The correlation analysis between the variable's like AOD and NDVI share a moderate connection, with an R^2 value of 0.1847, meaning about 18% of LST variations can be attributed to AOD. However, this also suggests that other factors like cloud cover, surface moisture, and land use changes play a bigger role in influencing temperature shifts throughout the year.

AOD and particulate matter are strongly correlated, with R^2 values of 0.4984 for PM_{10} and 0.5459 for $PM_{2.5.}$ This makes sense since AOD measures how much sunlight aerosols in the air scatter and absorb, and PM_{10} and $PM_{2.5}$ are key contributors to this process. Higher PM levels mean more particles in the atmosphere, leading to an increase in AOD. On the other hand, NO_2 and SO_2 show only a weak correlation with AOD, with R^2 values of 0.1393 for NO_2 and 0.0862 for $SO_{2.}$ This suggests that AOD is mainly influenced by particulate pollution rather than gaseous emissions. Since NO_2 and SO_2 come largely from fossil fuel combustion and vehicle emissions, they don't contribute as much to AOD levels compared to particulate matter, which lingers in the air and directly affects visibility and radiation absorption.

Declarations

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Author's Contribution Statement

Bhupendra Kumar: Data collection, analysis, interpretation, conceptual writing

N.C. Gupta: Data collection, analysis, methodology, supervision, review and editing

Neeraj Bohat: Analysis and conceptual writing

Varun Joshi: Review and editing

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Data Availability

The data that support the findings of the study are available from the corresponding author upon reasonable request.

Code Availability

Not applicable

Conflict of Interest

The authors have no competing interests to declare.

Consent of Publication

This manuscript is original and has not been published or submitted for publication elsewhere, and all authors have given their consent for its publication in this journal.,

Consent to Participate

Not applicable

Ethical Responsibilities of Author

The authors confirm that they have read, understood, and complied with the ethical standards and guidelines of this journal.

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