# Spatial and Temporal Variations of Aerosol Optical Depth Using MODIS Data in Google Earth Engine: A Study of Aligarh, India

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***Abstract*—Aerosol Optical Depth (AOD) data from the MODIS MCD19A2 Version 6.1 satellite data collected over the period 2021-2025 and analyzed in Google Earth Engine (GEE) is used in this study to look at the spatial and temporal variability of it over Aligarh, Uttar Pradesh. Daily 1 km resolution satellite data were quality filtered and aggregated into monthly, seasonal and yearly AOD products. Spatial analysis indicated that the mean AOD was 0.04–0.26, with the highest AOD levels (0.22–0.40) being found to the east and in the middle part of the region, and that annual AOD ranged from 0.00–0.40, with higher values (0.22–0.40) to the east and middle parts of the region. The monthly AOD ranged from 0.09 to 0.33 with 0.33 recorded in April 2021 and 0.09 in June-July 2023. The difference between seasonal mean AOD was the highest in winter (0.22) and the lowest in monsoon (0.16), resulting in a seasonal difference of 0.06. Annual mean AOD declined from 0.226 (2021) to 0.161 (2023), increased to 0.206 (2024), and slightly decreased to 0.175 (2025). The monthly anomalies were found to be between −0.084 and +0.068, with more than 80,000 observations inside 0.20–0.25 AOD range, showing the suitability applicability of GEE for long-term monitoring of aerosols and air quality evaluation.**

***Index Terms*—Aerosol Optical Depth (AOD), MODIS MCD19A2, Google Earth Engine (GEE), Spatio-temporal Analysis, Air Quality Monitoring**

## I. INTRODUCTION

The particles that are mixed into the atmosphere and exist as fine solid particles and liquid droplets, known as atmospheric aerosols, are among the most important environmental pollutants impacting air quality, the climate system and human health [1]. These effects affect the Earth radiation budget by scattering and absorbing sun's radiation, affect cloud formation processes, decrease visibility and affect respiratory and cardiovascular diseases [2]. The aerosol emissions have dramatically changed in many developing regions due to rapid urbanization, expanding industries and higher energy use, especially in Indian urban regions [3]. Hence monitoring and evaluation of aerosols has now become a continuous necessity to understand the changes in environment and to maintain sustainable air quality management [4].

Aerosol Optical Depth (AOD), is a parameter widely adopted to measure the amount of aerosol load in the atmosphere measured along the optical line between an object and the observer [5]. It offers important data on the spatial and temporal distribution of the aerosols and is an important parameter to evaluate the environmental impacts of the atmospheric pollution [6]. The use of remotely sensed data from satellites has proved useful forlong-term monitoring of aerosols, as it provides continuous data over a wide geographic area [7]. The Moderate Resolution Imaging Spectroradiometer (MODIS) has become a key satellite sensor in recent years because it is capable of covering the entire globe, revisiting an area on short time scales, and providing reliable AOD retrievals. However, MODIS-derived AOD data products have been widely used to study aerosols, their seasonal variations and trends in different climatic and geographical regions [8].

The growing amount of big satellite data has led to the demand for computational environments that can be used efficiently for processing and analysing geospatial data. Google Earth Engine (GEE), a cloud based geospatial analysis platform, has an integrated environment for accessing, processing, and visualizing petabytes of Earth observation data without needing to access high performance computing resources locally [9]. It also has a large amount of data catalog, parallel processing, and inbuilt geospatial functions to help study ers conduct large scale analyses effectively [10]. GEE's capabilities make it especially suitable for environmental monitoring studies that are based on the MODIS-derived AOD, enabling the fast assessment of aerosol dynamics at a regional and local scale [11].

The complexity of understanding aerosol variability arises from the fact that aerosol concentrations are affected by various factors that can interact, such as seasonal meteorological conditions, temperature, humidity, rainfall, and long-range transport of desert dust as well as urban, industrial, and vehicular pollution and agricultural residue burning [12]. All these factors contribute to the considerable spatial and temporal variation of the aerosol distribution and thus force to study the aerosol characteristics in a region [13]. Aligarh, a fast-growing city in northern India, has seen a rise in urbanization and industrialization, transportation development, and land-use shifts, which can significantly impact local aerosol loading and air quality [14]. Therefore, proper characterization of pollutants over this area requires extensive studies on aerosol behaviour, which would be essential to understanding pollutant dynamics and providing support for effective environmental management [15].

The rest of this paper is organized as follows: The literature review of previous study works is given in Section 2. Previous study works related to aerosol monitoring and MODIS based AOD analysis are presented in Section 2. Section 3 details the study area, datasets and methods employed for the study with Google Earth Engine (GEE). The results of the spatial and temporal analyses and interpretations are discussed in Section 4. Finally, Section 5 concludes the major findings, conclusions and the direction of future study. The Objectives of the Study are as follows:

i. To analyse the spatial distribution and temporal variation of MODIS-derived Aerosol Optical Depth (AOD) over Aligarh, India, using Google Earth Engine.
ii. To evaluate seasonal trends and identify aerosol pollution hotspots associated with urbanization, industrial activities, vehicular emissions, agricultural practices, and dust transport.
iii. To demonstrate the effectiveness of Google Earth Engine as a cloud-based platform for efficient processing and analysis of long-term MODIS satellite datasets.
iv. To provide scientific insights that support air quality management, environmental monitoring, climate studies, and sustainable urban planning in the study region.

## II. LITERATURE REVIEW

This study by Raeisi-Gahrooei et al. (2026) [16] examined temporal and spatial changes in the Leaf Area Index (LAI) and Dust Particulate Matter (DPM) of the Zagros forests of Iran from 2000 to 2025 with the help of MODIS, Landsat and Google Earth Engine (GEE). The results of the study have shown that the LAI ranged between 0.15-0.78, while the DPM concentrations ranged from 0.12-0.65, and there is a strong inverse relation ($R^2 = 0.8134$), supporting the fact that the decrease of LAI is associated with the increase of DPM concentration. Saedpanah et al. (2026) [17] studied the effect of environmental variables on the Aerosol Optical Depth (AOD) of Sanandaj County in the period of 2019 to 2024 by evaluating it using the GTWR model. The model explained 80 % of the variance in AOD (R2=0.80), suggesting that wind speed and LST positively influenced aerosol concentration, while the soil moisture and vegetation density (NDVI) negatively influenced aerosol concentration. Using Landsat-8, MODIS and CHIRPS datasets in GEE, Mehrjou et al. (2026) [18] conducted a study on vegetation–climate interactions in Guilan Province. The study revealed high positive relationships between vegetation and precipitation (R = 0.88–0.92) and negative relationship between LST and vegetation (R = −0.62). The results of the spatial clustering analysis yielded Global Moran's I with a value greater than 0.93 ($p < 0.001$), which indicates ecological sensitivity. Magray et al. (2026) [19] analyzed the glacier albedo variations in the Northwest Himalaya from 2001–2022 from MODIS and Landsat-8 OLI. Mean albedo ranged from 46.2%–55.0% (MODIS) and 52.0%–65.3% (Landsat-8), while the highest seasonal albedo reached 68.8%,

For the year 2020–2024, Goutham et al. 2025 [20] carried out a multi-sensor evaluation of air quality over Andhra Pradesh using the dataset of Sentinel-

5P, MODIS AOD and Landsat-8 processed in GEE. The study ers detected continuing pollution 'hotspots' and found that the concentration of $NO_2$ dropped markedly in the 2020 COVID-19 lockdown period with a gradual recovery. In the Kızılırmak Delta, Dihkan et al. (2025) [21] created an automated algorithm for detecting coastal plumes from Google Earth Engine (GEE) and used satellite imagery of 1750 images, marking the presence of plumes in 110 images with a maximum plume area of 105.32 km2. Garajeh et al. (2024) [22] used machine learning algorithms in GEE to estimate saline storm probability in the Lake Urmia Basin, where SVM model obtained R2 values of 91.12%, 90.45%, 91.78% and 91.65% in 2000, 2010, 2015 and 2022, respectively. Jadhavi et al. [24] retrieved 19-year long archives of air pollutants from Sentinel-5P data in GEE over Gujarat, India, and analyzed them according to seasonal variations. The study results showed the CO concentrations of 0.0295-0.0401 mol/m², the average $SO_2$ concentration of 0.00047 mol/m², the $NO_2$ concentration of 0-0.00021 mol/m², the HCHO concentration of 0.00015-0.00026 mol/m², and the concentration of $CH_4$ of 1780-1940 ppb, with the highest pollution levels occurring in industrialized regions, validating the effectiveness of satellite monitoring in environmental assessment.

While MODIS, Sentinel-5P, Landsat and Google Earth Engine have been previously applied to study Aerosol Optical Depth (AOD) and air quality, limited effort has been dedicated to long-term study of the spatial and temporal distribution of AOD over medium-sized cities of Indo-Gangetic Plain, especially Aligarh, India. Most of the existing study involves short-term assessment or long-term regional studies, which focus on a lack of attention to aerosol variability at the district level, especially on seasonality and annuality. Further, the impact of urbanization, industrial activities, vehicle emissions and agricultural activities on the distribution of AOD is not well studied in Aligarh. Hence, the present study utilizes MODIS AOD data in Google Earth Engine to conduct a comprehensive study over a long time, which is invaluable for air quality management, environmental monitoring, and sustainable urban planning.

## III. RESEARCH METHODOLOGY

The present study uses the remote sensing and cloud computing approach to examine the spatial and temporal variations of “Aerosol Optical Depth (AOD)” over Aligarh district, Uttar Pradesh. “Moderate Resolution Imaging Spectroradiometer (MODIS)” aerosol products available in the “Google Earth Engine (GEE)” platform are used to retrieve aerosol information over the selected study period. Methodology involves delineation of study area, acquisition of satellite data, satellite data preprocessing, retrieval of AOD, spatial analysis, temporal trend analysis, statistical analysis and visualization. While Google Earth Engine also offers cloud-based processing, it can effectively manage large satellite datasets without downloading satellite imagery.

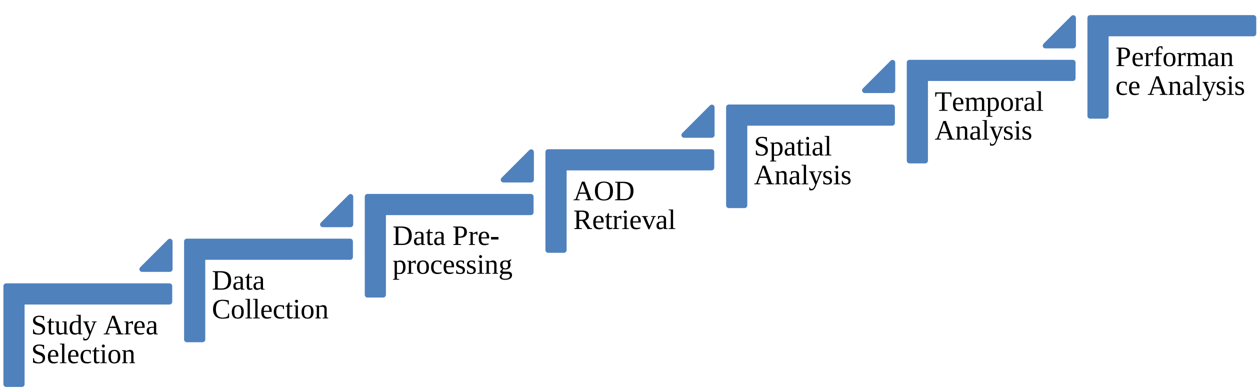


Figure 1: Framework of methodology

3.1Study Area Selection

Aligarh district of Uttar Pradesh, India was chosen as an area for study because of its rapid urbanization, industrial development, increasing transport infrastructure and intensive agriculture activities that are significant contributors to the emissions of aerosols into the atmosphere. The district is located in the Indo-Gangetic Plain and has frequent high concentrations of aerosols due to local sources as well as regional transport. Aligarh is a city where aerosol optical depth (AOD) shows variation across land-use and in the year due to the increasing anthropogenic activities, therefore an ideal city to study its spatial and temporal variations with MODIS satellite data in the Google Earth Engine platform.


Figure 2: Location Map of Aligarh District, Uttar Pradesh, India [24]

3.2Data Collection

The data set used in the study was the MODIS MCD19A2 Aerosol Optical Depth (AOD) Version 6.1 data set available in Google Earth Engine [25]. Aligarh district AOD data with daily time resolution and 1 km spatial resolution was obtained for the study period. Administrative boundary shapefiles were used to define the study area. These datasets ensured that high quality and consistency in spacecraft observations for spatial and temporal analysis of the distribution of aerosols.

3.3Data Pre-processing

The MODIS Aerosol Optical Depth (AOD) data is pre-processed in Google Earth Engine using the quality control filter to guarantee accurate and dependable analyses of the distribution of aerosols over Aligarh district. Filtering based on Period of Study in the image collection was first performed on the image collection.

$$I_t = \{ I_i \mid t_1 \leq t_i \leq t_2 \} \ , \tag{1}$$

where $I_i$ represents an individual MODIS image and $t_1$and $t_2$ denote the start and end dates, respectively. The filtered images were then restricted to the study area using

$$I_r = I_t \cap R \ , \tag{2}$$

where R is the Aligarh district boundary. Quality Assurance (QA) filtering was subsequently applied to retain only reliable AOD observations:

$$AOD_{QA} = \begin{cases} AOD_i \ , \ QA \geq Q_{th} \\ Null \ , \ QA < Q_{th} \end{cases} \tag{3}$$

where is the quality threshold . The processed images were clipped to the district boundary,

$$I_c = I_r \cap B \ , \tag{4}$$

and invalid pixels were removed using ,

$$AOD_{valid} = AOD_i * M, \tag{5}$$

where M is a binary mask (1 = valid pixel, 0 = invalid pixel). These steps produced a consistent and high-quality dataset for subsequent spatial and temporal AOD analysis.

### 3.4 Aerosol Optical Depth Retrieval

The MODIS MCD19A2, Version 6.1, Aerosol Optical Depth (AOD) was obtained from the Google Earth Engine platform. For Aligarh district AOD (Aerosols Optical Depth) at 550nm was extracted from the band of optical_depth_055 after Quality filtering. Average values of AODs were calculated on monthly, seasonal and annual scale for assessing aerosol loading. AOD processed data was used as the main source of data in the process of spatial mapping, temporal trend analysis, and identification of aerosol concentration pattern over the study area.

$$AOD_{mean} = \frac{\sum_{i=1}^{n} AOD_i}{n} \quad (6)$$

where $AOD_i$ is AOD value of ith image, n is Number of observations

### 3.5 Spatial Analysis of Aerosol Distribution

Spatial analysis was performed to analyze the spatial distribution of Aerosol Optical Depth (AOD), in Aligarh district, using Google Earth Engine. Composites of monthly, seasonal, and annual AOD were transformed into thematic AOD maps describing different regions of varying aerosol concentration levels. Hotspot Analysis was conducted to identify areas where aerosol loading is regularly high, such as urban, industrial and transport corridors. The spatial distribution patterns were compared with rural and agricultural areas to understand the impact of land use and anthropogenic activities on the aerosol variability during the study.

### 3.6 Temporal Analysis of Aerosol Variability

The temporal analysis has been carried out to assess the variation of Aerosol Optical Depth (AOD) over Aligarh during different time periods of the MODIS data by using Google Earth Engine. Mean AODs per month, seasons and year were computed to detect short-term variations and long-term trend of the aerosol concentration. The seasonal variation and change from one year to the next were explored with time-series graphs. The periods with higher aerosol loading were also identified under meteorological conditions, agriculture conditions and anthropogenic emissions in order to understand the temporal characteristics of aerosols in the study area.

### 3.7 Performance Evaluation

- Mean

$$\bar{X} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (7)$$

where $\bar{X}$ is Mean AOD

- Standard Deviation

$$SD = \sqrt{\frac{\sum (X_i - \bar{X})^2}{n-1}} \quad (8)$$

where SD is Standard deviation

- Coefficient of Variation

$$CV = \frac{SD}{\bar{X}} * 100 \quad (9)$$

where CV is Coefficient of Variation

- Linear Trend Analysis

$$Y = a + bX \quad (10)$$

- Coefficient of Determination

$$R^2 = 1 - \frac{\sum (Y_i - \widehat{Y})^2}{\sum (Y_i - \overline{Y})^2} \quad (11)$$

where $Y_i$ *is* Observed AOD , $\hat{Y}$ *is* Predicted AOD

- Pearson Correlation

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \quad (12)$$

where r is Correlation coefficient

## IV. RESULTS & ANALYSIS

The spatial distribution of mean and annual Aerosol Optical Depth (AOD) is illustrated in Figure 3 for the study area during 2021–2025. Mean AOD values range from 0.04 to 0.26, while annual AOD varies between 0.00 and 0.40, indicating noticeable spatial and temporal variability in aerosol loading. Higher aerosol concentrations (0.22–0.40) are primarily observed in the central and eastern regions, whereas lower AOD values (0.00–0.10) occur in the western region. These patterns reflect uneven aerosol distribution influenced by regional environmental and atmospheric conditions.

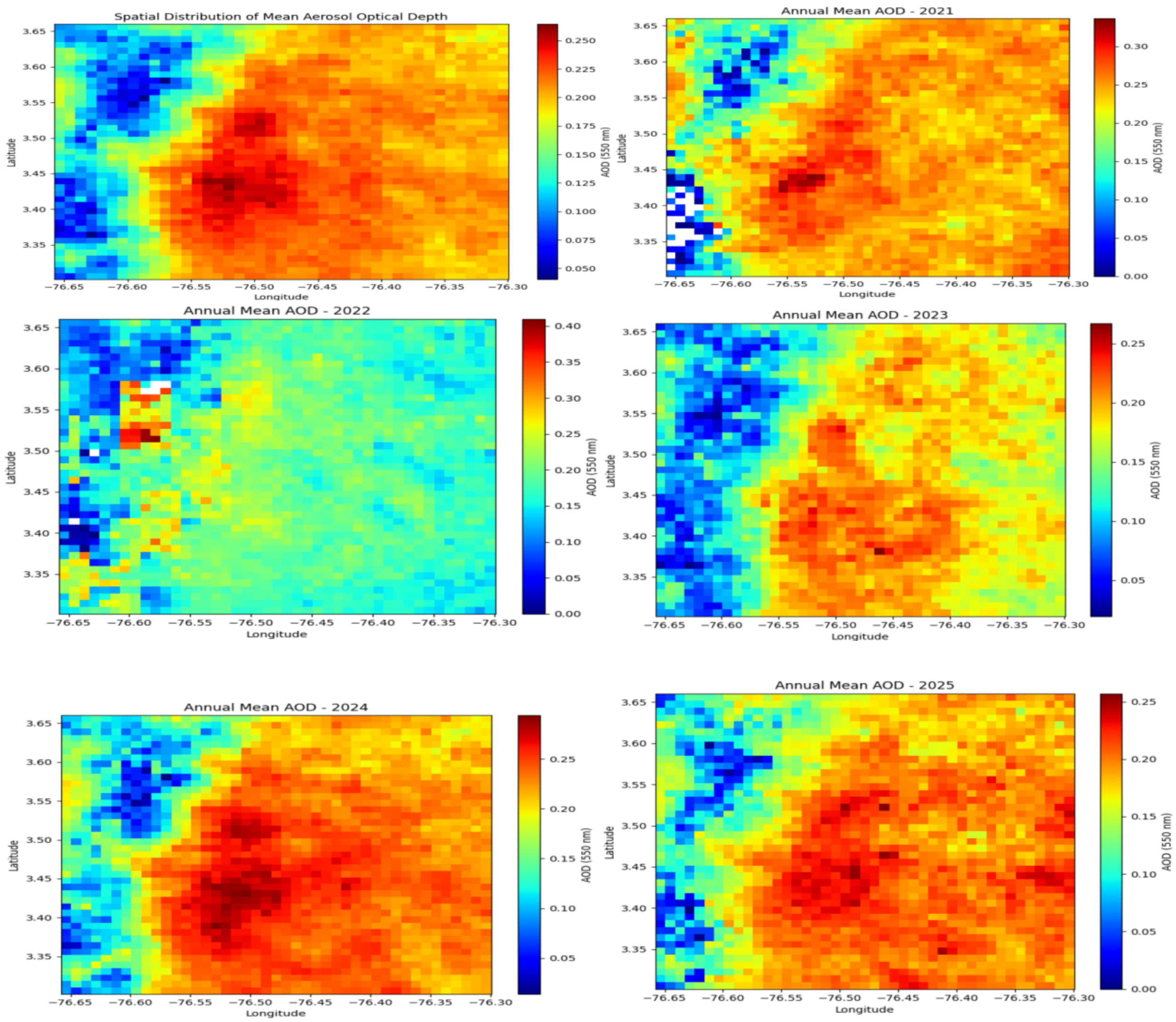


Figure 3: Annual mean and annual AOD (2021 -2025) distribution

The monthly mean Aerosol Optical Depth (AOD) variations for 2021–2025 are shown in Figure 4. The range of AOD values is between about 0.09 and 0.33, with 0.33 the highest in early 2021 and 0.09 lowest in mid-2023. The seasonal fluctuations and temporal variability in aerosol concentrations as observed are moderate (between 0.15 and 0.28).

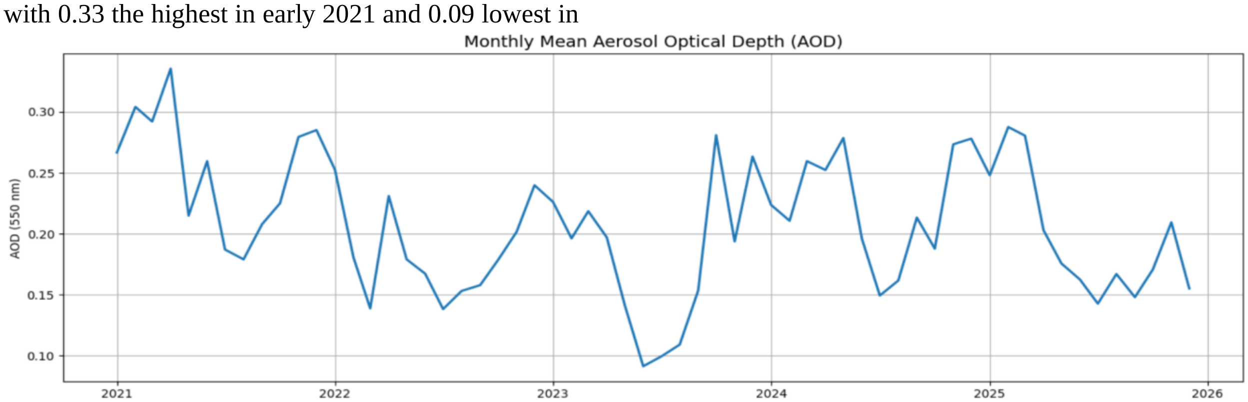


Figure 4: the difference of the monthly mean aerosol optical depth.

Seasonal mean Aerosol Optical Depth (AOD) distribution is shown in Figure 5 over the study area. Mean AOD range is of around 0.16 during Monsoon and 0.22 during Winter. The Pre-Monsoon (0.21) and Post-Monsoon (0.20) have intermediate values. The overall seasonal difference is around 0.06, which means a higher aerosol loading in winter compared to monsoon.

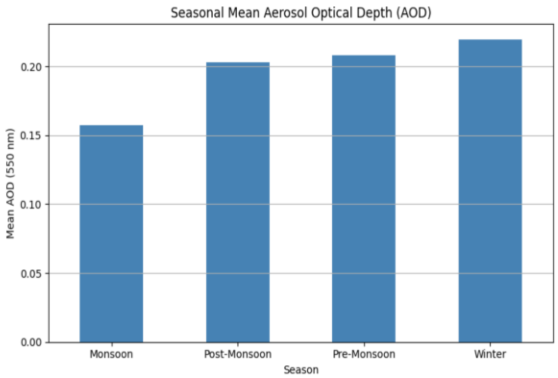


Figure 5: Aerosol Optical Depth (AOD) variation for a season

Figure 6 shows the annual mean Aerosol Optical Depth (AOD) for 2021–2025. Mean AOD decreased from 0.226 in 2021 to 0.161 in 2023, increased to 0.206 in 2024, and declined to 0.175 in 2025. The overall variation is 0.065 which suggests moderate interannual variation in aerosol concentration.

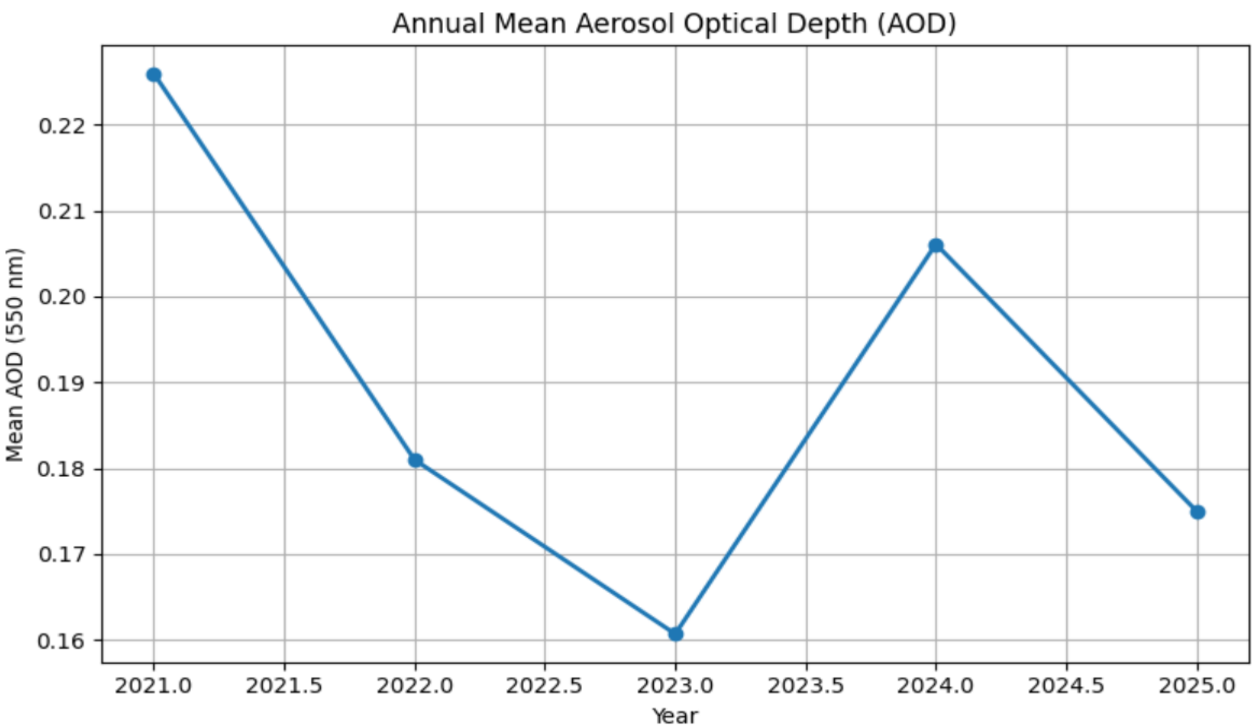


Figure 6: Annual Mean Aerosol Optical Depth .

Figure 7 shows the trend of monthly Aerosol Optical Depth (AOD) from 2021-2025. The monthly AOD ranges from about 0.09 in the beginning to 0.33 at the end and the linear trend decreases from 0.228 to 0.188, which is almost 0.04 in total. This shows that there is a small long-term decrease in the amount of aerosols in the atmosphere, but with a lot of monthly variation.

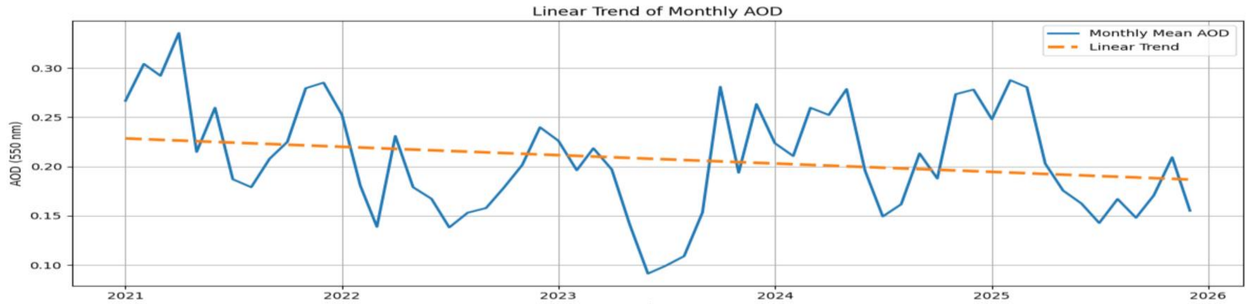


Figure 7: Linear Trend of Monthly Mean AOD

Figure 8 shows the monthly heatmap of Aerosol Optical Depth (AOD) for 2021-2025. The average AOD value is about 0.09 - 0.33. It reaches maximum (0.33) level in April 2021 and minimum (0.09) in June-July 2023. There is also greater seasonal variation in higher AOD, with higher values in March-April and November-December.

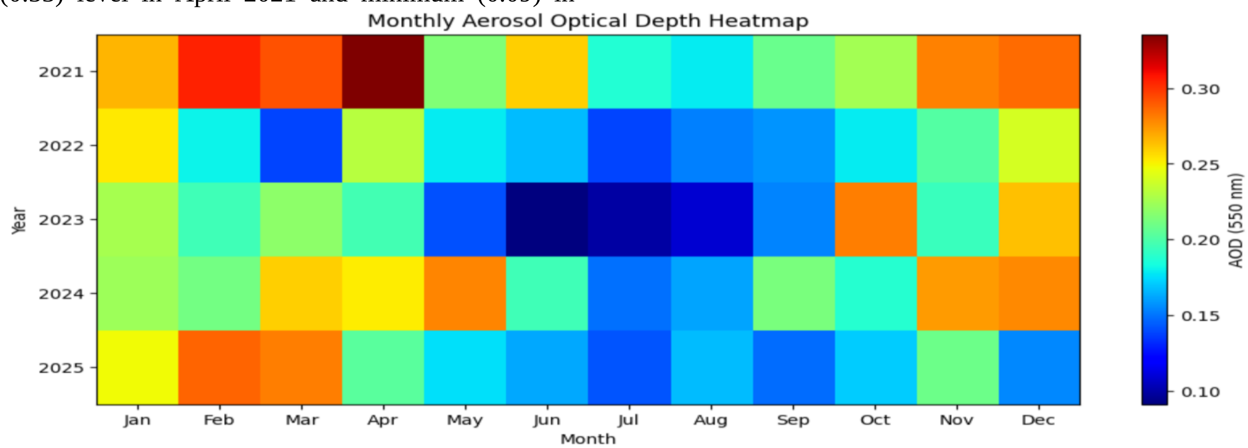


Figure 8: Monthly Aerosol Optical Depth Heatmap Pattern.

The monthly mean Aerosol Optical Depth (AOD) for the period 2021-2025 is shown in figure 9. The mean AOD varies from about 0.143 in July to 0.244 in December and has similar high values in April (0.243). The overall monthly variation is approximately 0.101 which shows that the concentration of aerosols is low during monsoon and high during the winter and pre-monsoon season.

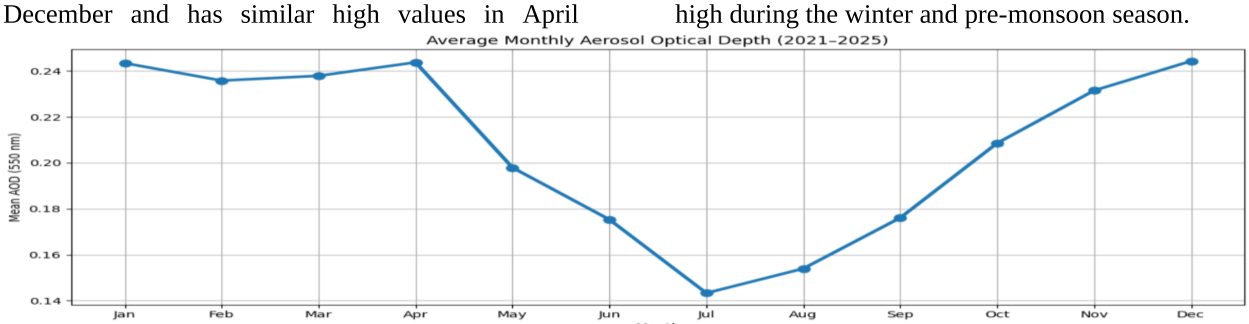


Figure 9: Variability in Aerosol Optical Depth for Average Monthly means.

The figure 10 depicts the seasonal mean variation of the AOD during the 2021–2025 period. The greatest value was observed in 2021 for the winter season (0.324) and the lowest value was observed in 2022 for the monsoon season (0.198). Pre-Monsoon peaked at 0.304 in 2024 and Post-Monsoon at 0.300 in 2023. The interannual variability of overall seasonal AOD was large, ranging from 0.126 (0.324–0.198).

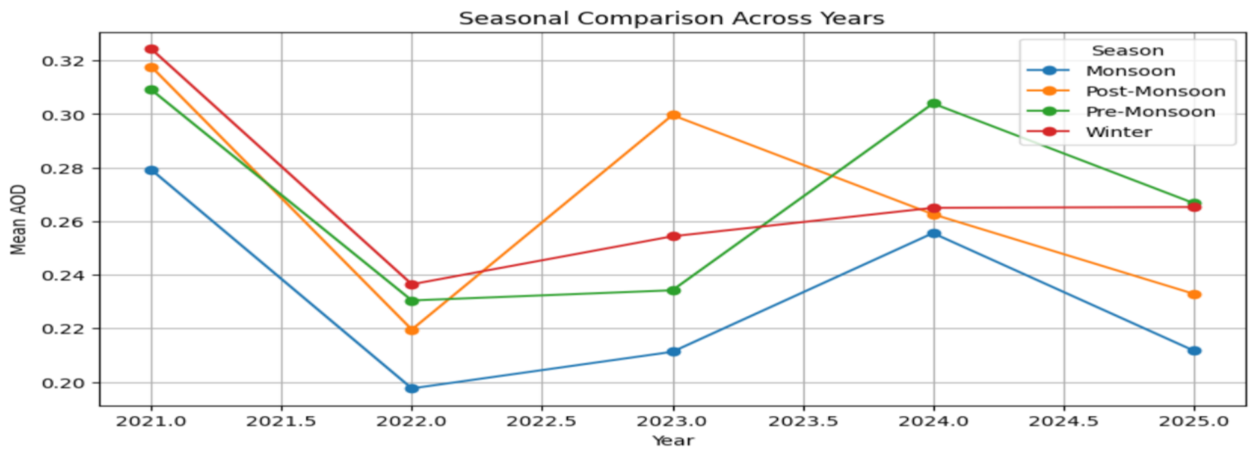


Figure 10: Seasonal mean of the difference in AOD between years.

The figure 11 shows monthly AOD anomaly in the 21st year (2021-2025). The maximum positive anomaly being recorded was +0.068 in 2021 and the minimum was −0.084 in 2023. The anomaly range equals 0.152 (0.068–(−0.084)). There was a significant temporal variation with positive deviations (significant negative deviations) prevailing in 2021 and in early 2025, while 2023 had negative deviations throughout.

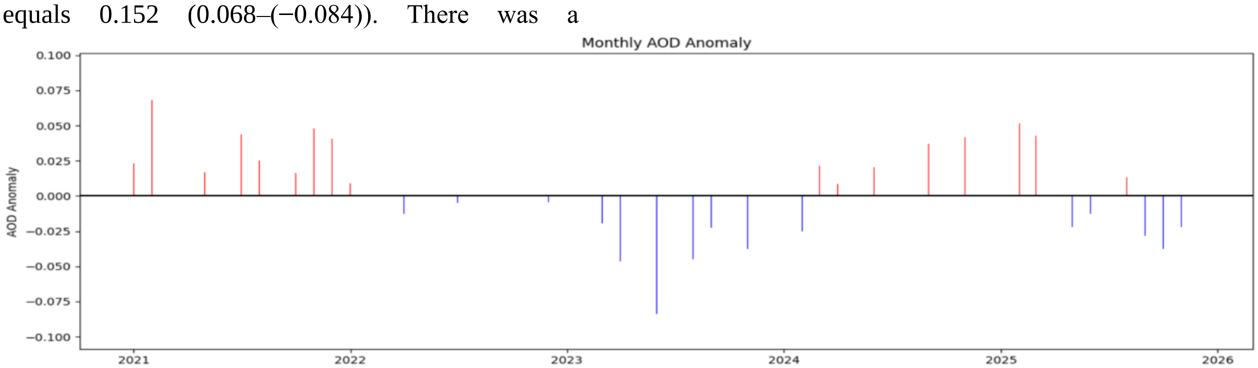


Figure 11: Monthly Aerosol Optical Depth Anomaly Pattern

The figure 12 shows indicates that the range of AOD values is mainly between 0.10 and 0.35, and has more than 80,000 observations around 0.20–0.25. The frequencies drop off rapidly above 0.40 and drop off very slowly above 0.60, that is, the distribution is skewed to the positive side with the majority of the aerosol concentrations being low to moderate.

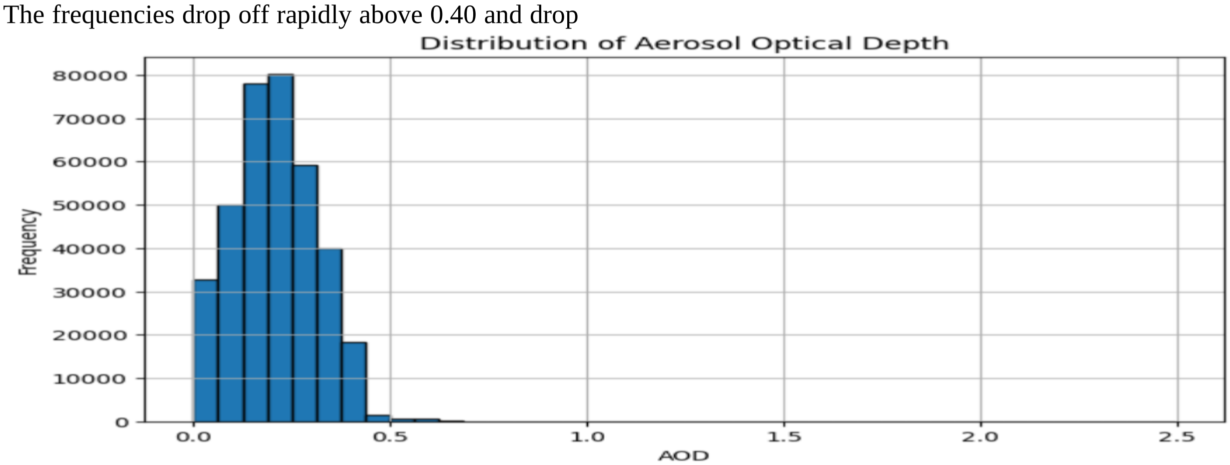


Figure 12: Distribution of AOD

## V. CONCLUSION

The present study has been able to analyze the spatial and temporal variation of Aerosol Optical Depth (AOD) for Aligarh, Uttar Pradesh region with MODIS MCD19A2 version 6.1 data in Google Earth Engine. The spatial analysis revealed mean AOD values ranged from 0.04 to 0.26, while annual AOD ranged from 0.00 to 0.40; the highest concentration of aerosol was found in the central and eastern part of the District. There was moderate temporal variability in the monthly AOD values, ranging from 0.09 to 0.33. The seasonal analysis revealed the highest mean AOD in winter (0.22) and the lowest in the monsoon (0.16) giving the difference in means to 0.06. Annual mean AOD declined from 0.226 (2021) to 0.161 (2023), increased to 0.206 (2024), and slightly decreased to 0.175 (2025), indicating an overall interannual variation of 0.065. The monthly anomalies varied from −0.084 to +0.068, which showed the short-term variations in aerosol loading. The histogram also showed that the data were clustered within the range 0.10-0.35, with the highest frequency around 0.20 - 0.25. The results prove the potential of Google earth engine in long-term efficient monitoring of the aerosols and also give significant scientific evidence for environmental management, sustainable urban development and air quality management in Aligarh.

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