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ARTICLE

Spatiotemporal Variability of Tropospheric NO_2 and Aerosol Optical Depth in Lahore Division

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ABSTRACT

This study examines the spatiotemporal variations of tropospheric Nitrogen dioxide (NO_2) and Aerosol Optical Depth (AOD) over the Lahore Division, utilizing satellite and ground-based data spanning from 2006 to 2023. The findings indicate consistently elevated NO_2 levels, attributed to the dense population, industrial activities, and crop residue burning, with mean values ranging from 3.87 to 6.34 × 10^{15} mole/cm². A seasonal analysis for the period 2021–2023 revealed heightened NO_2 concentrations during winter and autumn, with peaks observed in winter 2022 (4.86–8.09 × 10^{15} mole/cm²) and autumn 2021 (4.18–6.85 × 10^{15} mole/cm²), reflecting post-COVID-19 recovery trends. AOD variations demonstrated higher values in summer and fall (0.5–0.69), predominantly influenced by fine-mode aerosols, with an increasing trend post-COVID-19. The summers of 2021, 2022, and 2023 recorded peak AOD levels (0.68–1.10, 0.75–0.93, and 0.91–1.14, respectively). In 2023, a strong positive correlation (r = 0.02 to 0.19, R = 0.13) suggested an increase in anthropogenic emissions due to urbanization. The changes in NO_2 and AOD patterns from 2019 to 2023 underscore the impact of COVID-19-related restrictions on industrial, commercial, and transportation activities.

Keywords: AOD; Lahore; NO_2; OMI; Pakistan; Remote Sensing; Trace Gases

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1. Introduction

Atmospheric aerosols are one of the important components of Earth's atmosphere; they mostly vary in terms of spatial and temporal variability and play a major role in modifying the planet's energy balance, worldwide precipitation patterns, and large-scale atmospheric circulation patterns [1]. Increased air pollution negatively influences atmospheric quality, creating several issues for ecosystems, biodiversity, human health, and regional climate [2–4]. According to the World Health Organization (WHO, Geneva), 80% of all chronic diseases are respiratory since air pollution is more likely to occur in metro-political areas, which is mainly due to the large presence of polluted atmospheric particles [5–7].

Partial combustion of fossil fuel, crop residue and biomass, vehicle exhaust, natural lighting, and soil emissions are mainly related to the formation of atmospheric nitrogen oxide pollutants ($NOx = NO + NO_2$). This NOx has a significant impact on air quality and is an important factor in ozone formations [8–10]. Changes in seasons, weather, socioeconomic status, and fuel consumption trends are the main causes of regional and temporal variability in tropospheric NO_2 [11–13]. Rising industrial and urbanization rates, lack of health literacy, rapid industry, vehicle emissions, inadequate air quality regulations, outdated equipment, and densely populated areas put developing countries in greater danger [14, 15]. Observations from ground-based stations, instrumented parameters, and satellite remote sensing indicate a widespread increase in NOx levels across various regions of the globe [16–19].

Technological developments in satellite remote sensing of aerosols have made it easier to evaluate the properties of aerosols across a wide region using a large number of repeated measurements. Additionally, the use of remote sensing satellites has the advantage of evaluating the characteristics and spatial distribution of aerosols across a broad region in a single image [20]. The AErosol RObotic NETwork (AERONET), a ground-based aerosol robotic network, is a frequently used network that offers consistent and reliable data regarding aerosol properties [21, 22]. In contrast, AERONET offers a useful way to monitor the characteristics of aerosols in a larger geographic area. Using different methods, the Moderate Imaging Spectroradiometer (MODIS) sensors onboard the Terra and Aqua satellites offer long-term spatiotemporal features of aerosols at regional and global scales.

Aerosol concentrations are increasing, which also affects Pakistan, which is located in northwestern South Asia. Several studies have addressed NO_2 [23–26] in the South Asian region using satellite data and aerosol [27–30] trends, spatiotemporal distributions, and seasonality. Ul-Haq [31] reported an increase in the NO_2– AOD correlation in South Asia with an overall positive trend over different megacities of the region. Previous studies have also indicated that the aerosols in the Lahore region show significant spatial and temporal heterogeneity [32] and that there are greater significant differences in the aerosol's temporal and spatial distribution across South Asia [31, 33] and [34] utilized both ground and satellite-based measurements to examine aerosol optical properties in Pakistan.

Previous studies have indicated that Lahore Division is a hotspot for NO_2 but thorough research has not been conducted on the Lahore Division to examine the variability of tropospheric NO_2 with AOD over the Lahore Division. The current study aimed to investigate the spatial and temporal status of air pollutants such as nitrogen dioxide and aerosol optical depth, retrieved from both satellite and ground-based monitoring data over the Lahore division from 2006 to 2023. The combined study of NO_2 and AOD is crucial for understanding air quality, climate impacts, and health effects in megacities like Lahore.

2. Data and Methodology

2.1. Study Area and Meteorological Conditions at Lahore Division

Lahore Division, located in Punjab, Pakistan, comprises four districts: Lahore, Kasur, Nankana Sahib, and Sheikhupura. Geographically, it spans approximately between latitudes 31°09' N to 31°45' N and longitudes 73°58' E to 74°39' E, with total area of 17,178 km^2 and estimated population of 21 million (https://bos.punjab.gov.pk/). Lahore city is Pakistan's second most populous city, after Karachi. Lahore has four districts, namely, Lahore (31.5090 °N, 74.3674 °E) with population of 14 million, Sheikhupura (31.8046 °N, 73.9818 °E) with population of 4 million, Nan-Kana Sahib (31.4700 °N, 73.7076 °E) with population of 1.5 million, and Kasur (31.1208 °N, 74.4621 °E) with population of 3.5 million, in Punjab province (https://worldpopulationreview.com/). Over the past ten years, Lahore has been listed as one of the world's most polluted cities. The geographical location of the Lahore division is depicted in **Figure 1**, which additionally includes a digital elevation map (DEM) of the entire country. This visual representation provides valuable context for understanding the topography and spatial relationships within the region.

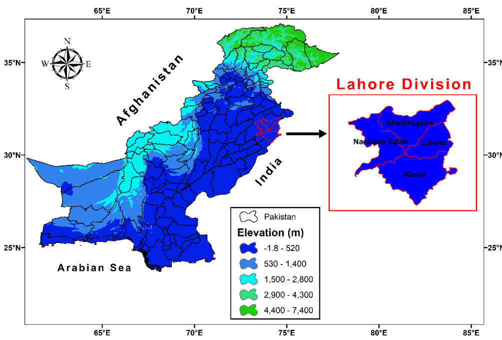


Figure 1. Map showing the location of the study area in red boundary – Lahore Division with digital elevation map (DEM) of Pakistan.

Lahore district has been classified as a hot and semi-arid steppe climate with hot summers, cold winters, and an infrequent but noticeable rainy season (monsoon) [35, 36]. During the monsoon season, the highest rainfall (575 mm) occurs in just two months (July to August), with an annual rainfall of 715 mm year^{-1}. There is a significant variation in low and high- temperatures in the winter (0 °C) and summer (48 °C) seasons [37]. Lahore reveals a marked seasonal warming pattern, with temperatures T_{Max} and T_{Min}, increasing steadily from January to June. A significant escalation in T_{Max} (19.14°C to 41.45°C) and T_{Min} (6.13 °C to 28.84 °C) are observed, accompanied by fluctuations in relative humidity (RH; 62% to 75%) during the spring and summer seasons. These periods are characterized by elevated thermal and humidity regimes, which exert a profound influence on aerosol dynamics and processes [38].

Meteorological data for temperature (T), relative humidity (RH), corrected precipitation (PP), and wind speed (WS) were downloaded from the NASA Data Access Viewer (https://power.larc.nasa.gov/) for the period 2006–2023. The monthly mean variations in T (°C), RH (%), PP (mm/day) and WS (m/s) in different districts of the Lahore Division are shown in **Figure 2**. Lahore experiences significant seasonal variations in temperature (T), relative humidity (RH), and wind speed (WS). In winter (December–February), temperatures average 13–15 °C with moderate humidity of 44–53%. Rainfall is low, under 1 mm/day, peaking in January (1.37 mm/day), and wind speeds are steady at about 1.3–1.4 m/s. In spring (March to May), temperatures rise to 15–16 °C, humidity drops (26–47%), and wind speeds increase, with precipitation around 0.75–1.5 mm/day. Summer (June-August) sees high humidity (58–64%) and peak rainfall in July (7.48 mm/day) due to the monsoon, although temperatures drop slightly to 9–13°C. Autumn (September-November) returns to mid-range temperatures (11–14 °C) and decreasing humidity.

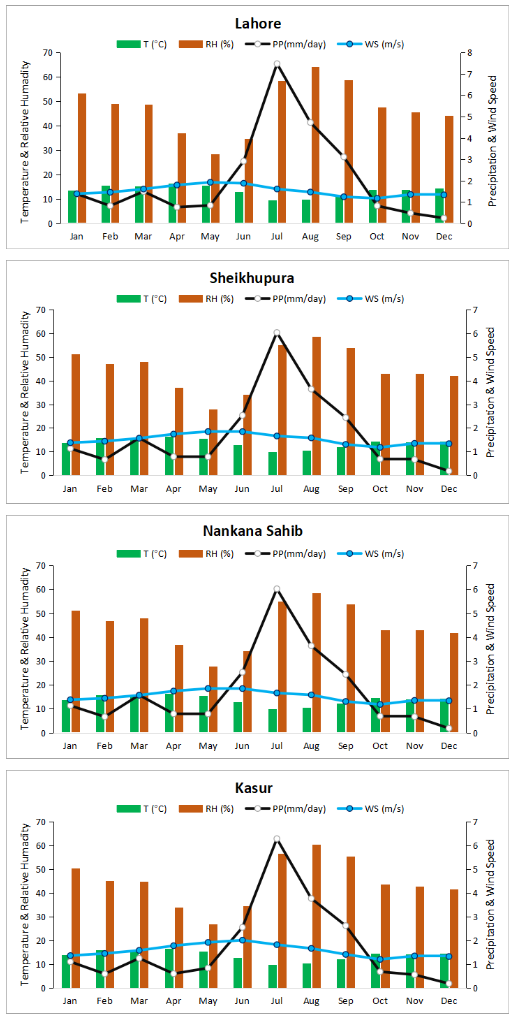


Figure 2. Interannual variations in T (°C), RH (%), PP (mm/day), and WS (m/s) over different cities of the Lahore Division during 2006–2023.

Sheikhupura, Nankana Sahib, and Kasur share similar climate patterns, with mild winters (13–15 °C, 41–51% RH) low precipitation, and a summer monsoon that peaks in July (6 mm/day). Overall, Lahore and the neighboring cities exhibit a semi-arid climate influenced by the monsoon, characterized by moderate winters and warm, humid summers. Each city shows a distinct peak in summer rainfall and humidity, typical of monsoon-influenced climates, with steady seasonal shifts in temperature and wind speed, aligning closely with Lahore's climate patterns [32–34, 38].

2.2. Data Sources and Methodology

To address the spatiotemporal distributions of NO_2 and AOD, remote sensing data from both satellites and surfaces were used for the period 2006–2023. In the current study three different types of data sets were used; (a) Daily, 0.25°, (molecules/cm^2) Nitrogen Dioxide - NO_2 from OMI (Ozone Measuring Instrument), NO_2 Tropospheric Column (30% Cloud Screened) (OMNO2dv003); (b) Monthly, 1 deg, Aerosol optical depth (AOD-550 nm) (Deep Blue, Land-only) MODIS-Terra (MOD08_M3 v6.1), and (c) AOD (500 nm) via AERONET, daily measurements, Level 2.0 Version 3 for the period of Jan 2006 to Dec 2023 as shown in **Table 1**.

Table 1. Data sets used in the current study.

Product	Temporal-Spatial	Source
Nitrogen Dioxide (NO_2),	Daily, 0.25° (molecules/cm^2)	https://giovanni.gsfc.nasa.gov/giovanni/
Aerosol Optical Depth (AOD 550 nm),	Monthly, 1°, Unit less	https://giovanni.gsfc.nasa.gov/giovanni/
Aerosol Optical Depth (500 nm)	Daily measurements, Level 2.0 Version 3, Unit less	https://aeronet.gsfc.nasa.gov/

The broad coverage and excellent resolution of the OMI instrument made it the preferred choice for NO_2 satellite coverage. OMI/Aura features a 0.25° × 0.25° spatial resolution and a broad field of view. The Level-3 daily global gridded (0.25 × 0.25 degree) nitrogen dioxide product (OMNO2d) contains the total column NO_2 and the total tropospheric column NO_2, for all atmospheric conditions and for sky conditions where the cloud fraction is less than 30% [39]. NASA's online user manual provides details of data processing, differential optical absorption spectroscopy (DOAS) analysis, and quality control data for OMI products [40].

Satellite AOD data were accessed via the GIOVANNI of OMI's MODIS/Tera. Coverage for all cloud- and snow-free land areas can be obtained using the MODIS Deep Blue algorithm. We utilized gridded Level 2 monthly, georeferenced and calibrated data at a resolution of 1 km. The aerosol product includes the recently developed "deep-blue" algorithm to obtain aerosol optical thickness in bright land areas [41, 42]. Ground-based AOD data were accessed via AERONET which provides a global database of aerosol optical, radiative, and microphysical properties [22]. The AERONET inversion algorithm excels in aerosol retrievals by harmonizing the comprehensive radiance data – including sun radiance and sky radiance angular distribution at four distinct wavelengths (440, 670, 870, and 1020 nm) – with a radiative transfer model, ensuring superior accuracy and reliability [43]. Lahore and Karachi are the two AERONET stations in Pakistan. We used data for only the Lahore site (**Figure 1**) because Lahore is the main focus of our study.

From the GIOVVANI website, the data was downloaded in GeoTiff and CSV format to analyze it more specifically by making maps and charts. On the other hand, daily AERONET data was used to investigate monthly and seasonal variations in AOD. The aggregation of daily data into monthly and seasonal datasets facilitates a comprehensive understanding of various factors. This approach enables the examination of aerosol concentration patterns and trends on a monthly and seasonal basis, consistent with findings from previous studies [38].

3. Results and Discussion

3.1. Long-Term Annual and Seasonal Variability of NO_2

Spatial-temporal variations in the NO_2 tropospheric column (molecule/cm^2) for different periods are shown by annual and seasonal mean maps in **Figures 3** and **4**, respectively. Annual mean variations from 2006 to 2023 are shown in **Figure 3a−d**, with a mean map (**Figure 3d**) and chart (**Figure 3e**) for the entire studied period. The annual map for the period 2021−2023 was not created because, during this time, the seasonal maps for each year were analyzed. The annual map for the period 2021–2023 was not created because, during this time, the seasonal maps for each year were analyzed. Large spatial variations in NO_2 can be observed with relatively high values in Lahore and its surrounding regions compared to those in other cities of Pakistan. Annual maps every 5 years clearly show that the Lahore division (especially Lahore and Sheikhupura) has consistently high NO_2 levels from 2006 to 2023, with average values of 3.83–6.28 × 10^{15} mole/cm^2 in 2006–2010, 4.34–7.11 × 10^{15} mole/cm^2 in 2011–2015, 3.85–6.31 × 10^{15} mole/cm^2 in 2016–2020, and an overall mean value of 3.87–6.34 × 10^{15} mole/cm^2 during the whole observed period (2006–2023).

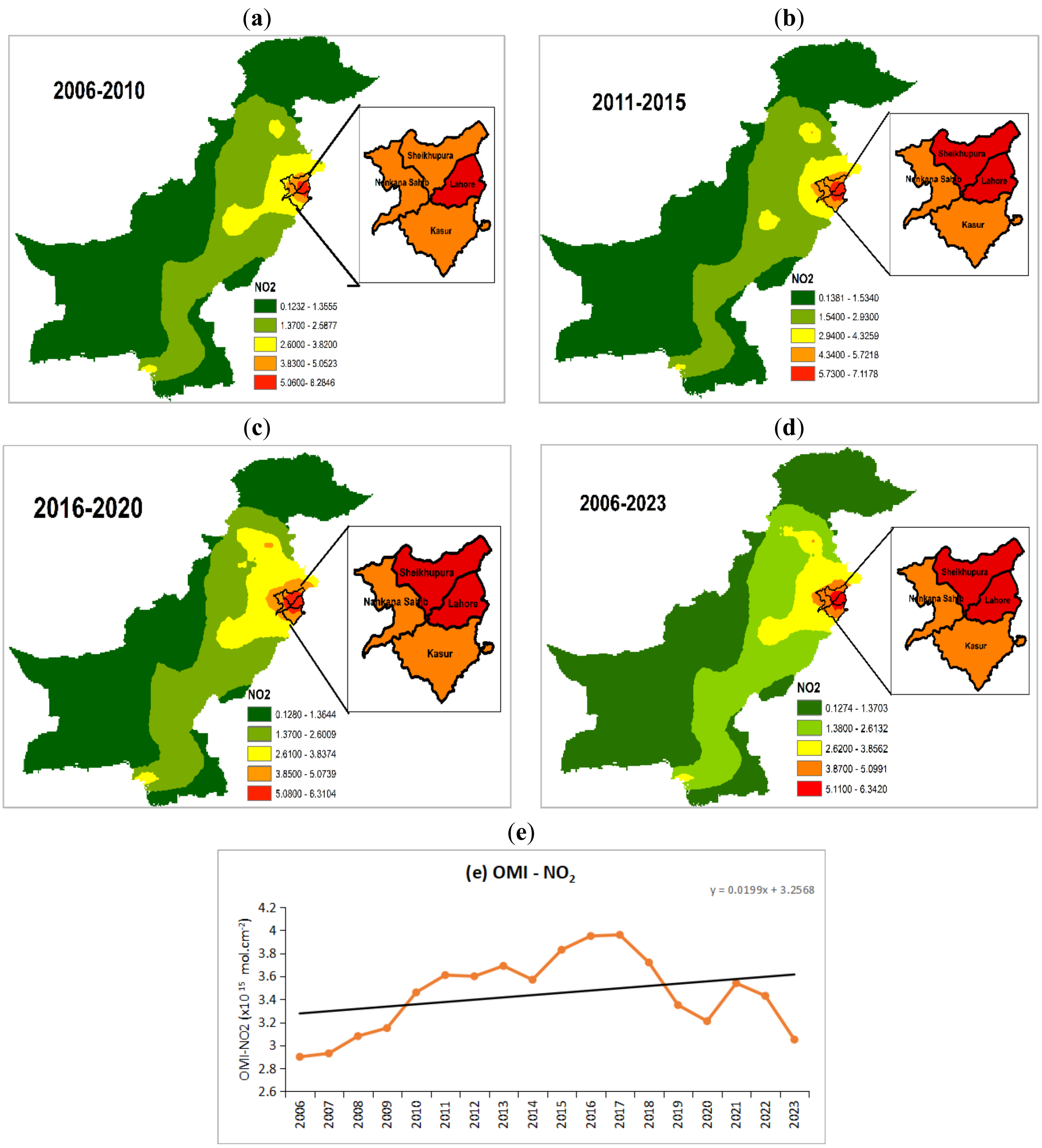


Figure 3. Yearly variations in NO_2 (× 10^{15} molecules/cm^2) obtained from OMI tropospheric column measurements (**a**) from 2006 to 2010, (**b**) from 2011 to 2015, (**c**) from 2016 to 2020, (**d**) mean map from 2006 to 2023, and (**e**) yearly mean variations during 2006–2023. The pop-up in maps indicates Lahore Division.

On average, values are varied between 2.9 and 3.9 × 10^{15} mole/cm^2 with a decreasing trend from 2021 to 2023 which could be attributed to COVID-19 lockdown periods. Seasonal variability in NO_2 (**Figure 4a–c**) for 3 consecutive years, namely 2021, 2022, and 2023, have shown that the Lahore division had relatively higher values of NO_2, especially during the SON (autumn) and DJF (winter) seasons, than did the rest of Pakistan. In 2021, the winter (DJF) season had the highest seasonal mean values (from 4.73 to 7.84 × 10^{15} mole/cm^2) of tropospheric NO_2 followed by autumn (SON) (from 4.18 to 6.85 × 10^{15} mole/cm^2), spring (from 2.98 to 4.96 × 10^{15} mole/cm^2) and summer (from 3.49 to 5.79 × 10^{15} mole/cm^2) seasons. Furthermore, the winter (4.86–8.09 × 10^{15} mole/cm^2) and spring (3.81–6.33 × 10^{15} mole/cm^2) seasons of 2022 have higher concentrations of Tropospheric NO_2 followed by autumn (3.28–5.34 × 10^{15} mole/cm^2) season and have the lowest values in the summer (2.92–4.79 × 10^{15} mole/cm^2) of 2022. However, in 2023, a similar trend was observed for NO_2 values. The winter season had the highest seasonal mean value (4.41–7.32 × 10^{15} mole/cm^2), followed by the autumn (3.00–5.02 × 10^{15} mole/cm^2), summer (2.86–4.72 × 10^{15} mole/cm^2) and spring (2.52–4.41 × 10^{15} mole/cm^2) seasons. These results are higher than reported by [31].

NO_2 concentrations are higher in winter than in summer due to emissions from burning coal, wood, cow dung, and fossil fuels for heating and industrial use, such as sugar mills. In Pakistan, stable atmospheric conditions in winter allow NO_2 to accumulate, while lower solar irradiance inhibits photochemical reactions. Consequently, winter typically sees the peak annual NO_2 levels. In contrast, during the pre-monsoon (dry summer) season, although temperatures rise, NO_2 concentrations decrease. The arrival of the monsoon further reduces NO_2 levels through wet deposition. The lowest concentrations are usually found in spring and summer, driven by high humidity, clean air masses, increased solar radiation, and higher hydroxyl radical (OH) concentrations that promote NO_2 photodissociation [23, 26, 44, 45].

(a)

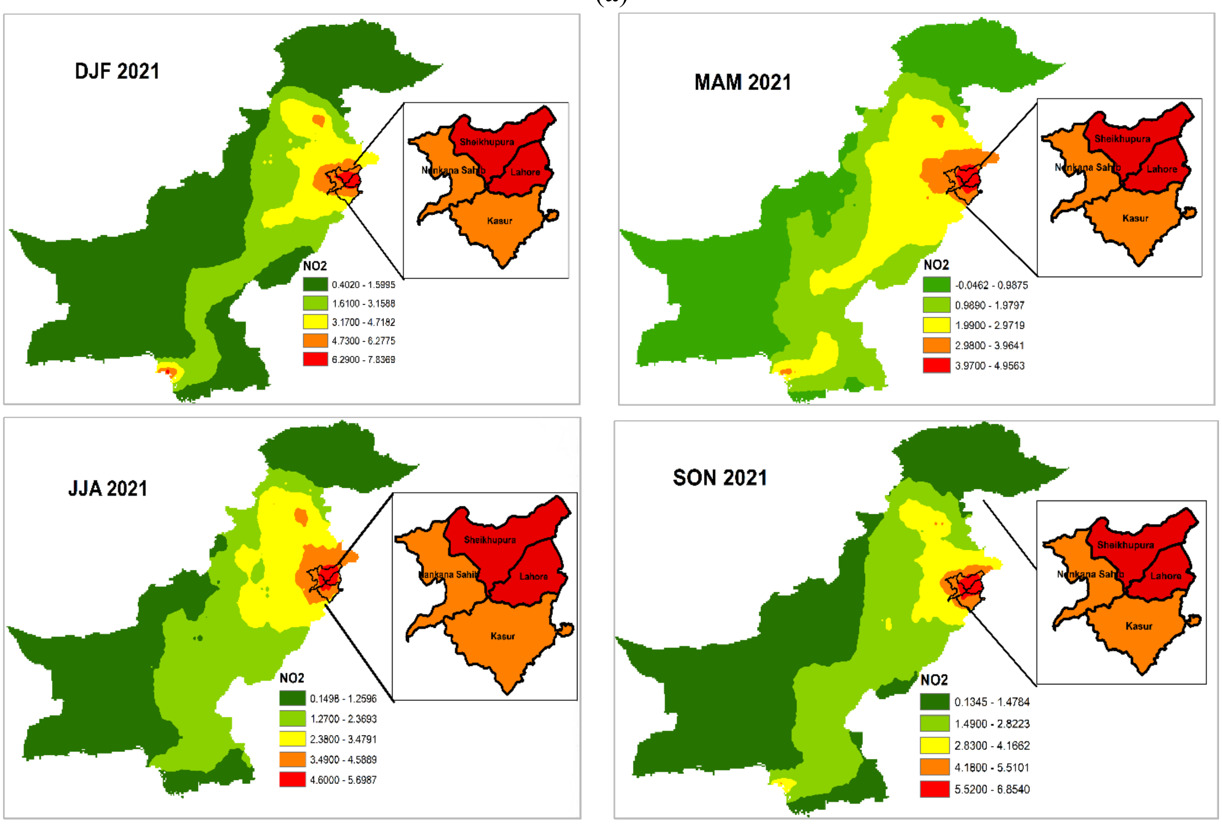
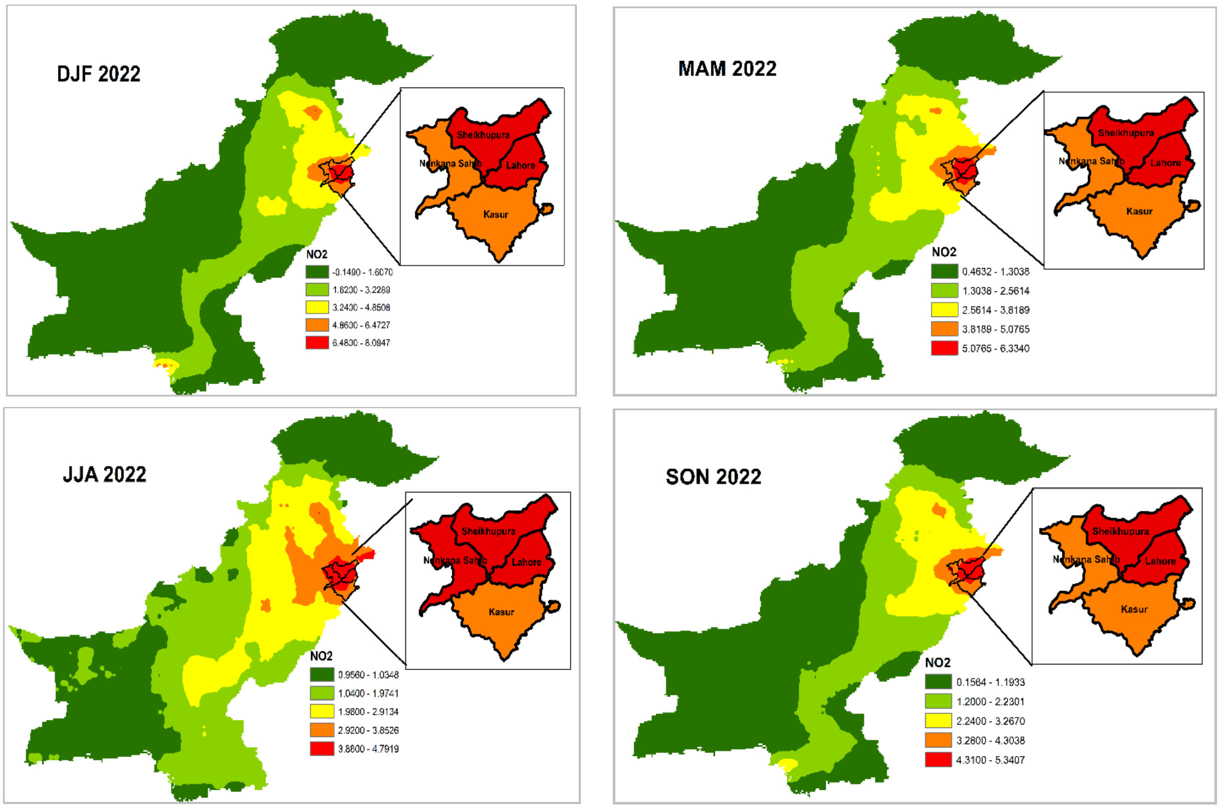


Figure 4. *Cont.*

(**b**)



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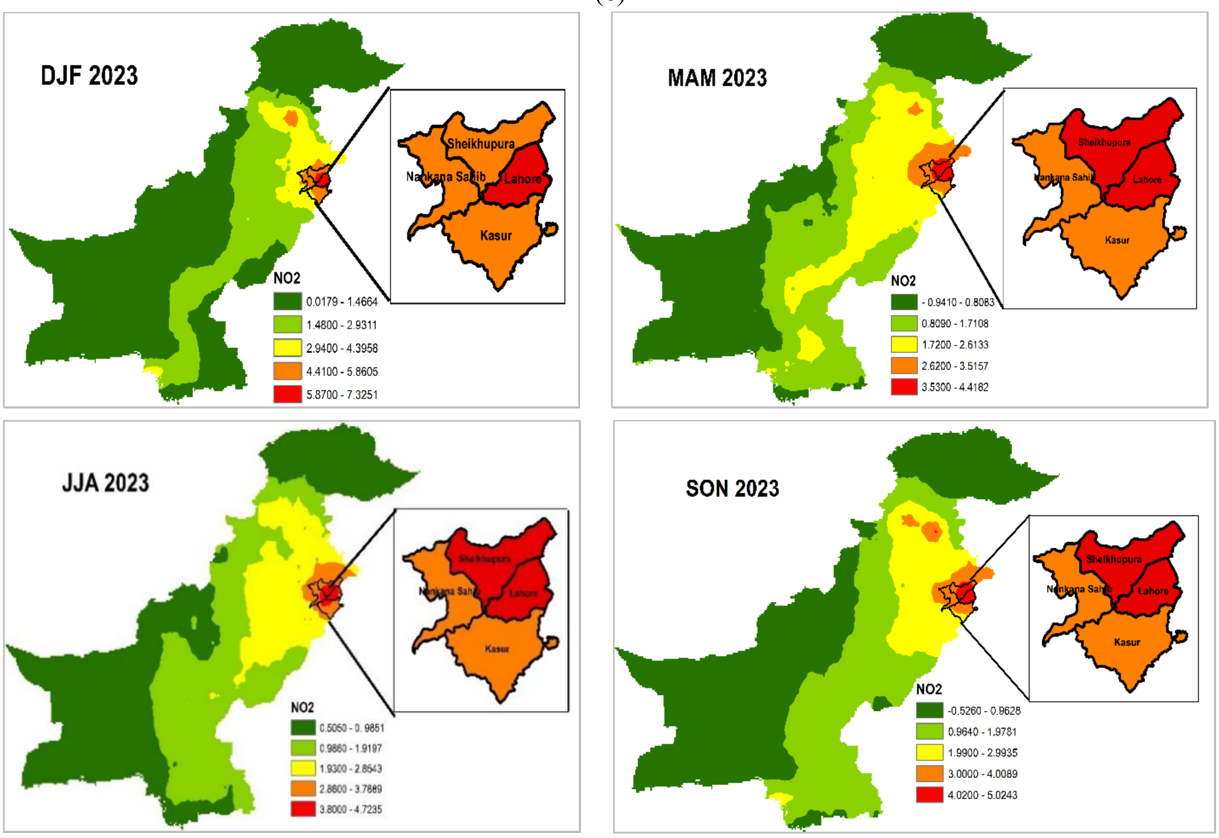


Figure 4. Seasonal variations in NO_2 ($\times 10^{15}$ mole/cm^2) from the OMI tropospheric column measurements for (**a**) 2021, (**b**) 2022, and (**c**) 2023 in winter (DJF), spring (MAM), summer (JJA), and fall (SON), respectively. The pop-up in maps indicates Lahore Division.

3.2. AOD Variability from 2006 to 2023

Figure 5a−e shows the annual mean variability from 2006 to 2023 and **Figure 6a–c** shows seasonal variability from 2021 to 2023 in the MODIS-Tera AOD at 550 nm data. Annual AOD observations have shown that Punjab province, including Lahore Division, has high levels of AOD, especially in the Lahore Division, with an annual mean AOD ranging from 0.54 to 0.67 in 2006–2010, from 0.5 to 0.68 in 2011–2015, and from 0.59 to 0.72 in 2015–2020, with a mean value of 0.59–0.69 during the whole studied period (2006–2023). AOD started to increase just after the end of the complete lockdown (March 2020–May 2021) of COVID-19 in Pakistan, which is supported by the variation of AOD in the seasonal maps (**Figure 6a**) of 2021. Therefore, summer 2021 has a high AOD (0.68–1.10), followed by autumn (0.45−0.75), winter (0.50–0.62), and spring (0.49–0.60). These values vary after 2022 (**Figure 6b**), with AOD ranging from 0.75–0.93, 0.62–0.77, 0.50–0.60, and 0.44–0.57 in summer, autumn, spring, and winter, respectively. The seasonal variability for the year 2023 (**Figure 6c**) showed that the summer (0.91–1.14) and autumn (0.83–1.04) seasons had higher mean AOD values than did in the winter (0.45–0.55) and spring (0.48–0.59) seasons. The MODIS-Tera AOD findings are also supported by AERONET (**Figure 7**) observations during the studied period, which show that the summer (0.85) and autumn (0.80) seasons have relatively high AOD values, while the Angstrom exponent (AE 440/870 nm) has relatively high values in the winter (1.24) and autumn (1.12) seasons, respectively. On average, AOD varies between 0.5 to 0.7 during the study period (**Figure 7**).

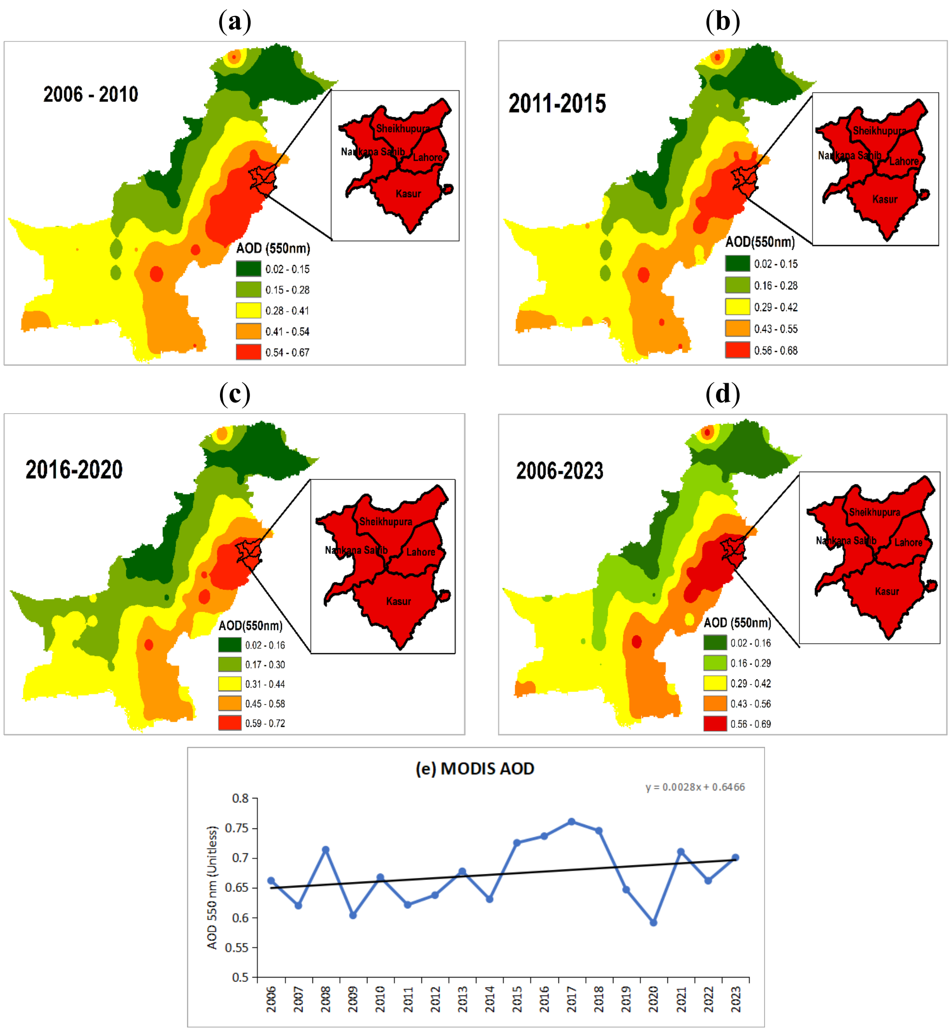
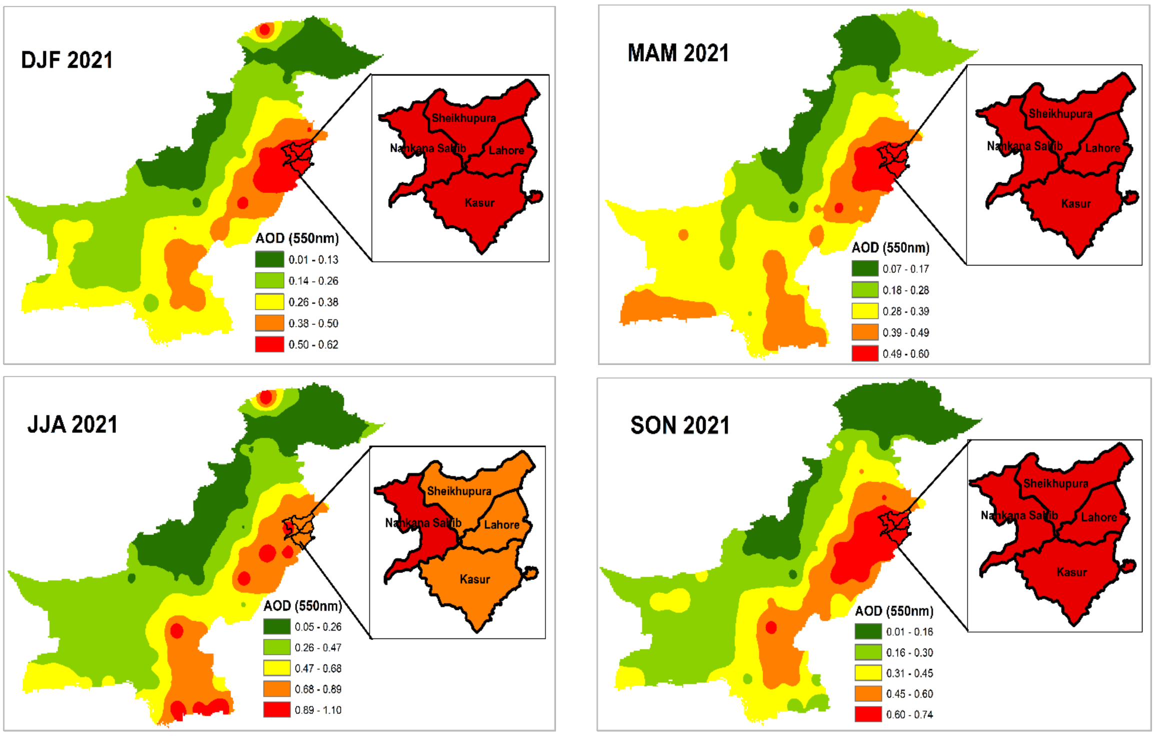


Figure 5. (**a–e**): Annual mean variability from 2006 to 2023 in the MODIS/Tera AOD at 550 nm; (**a**) from 2006 to 2010, (**b**) from 2011 to 2015, (**c**) from 2016 to 2024, with (**d**) time-averaged mean map and (**e**) mean chart during 2006–2023.

(**a**)



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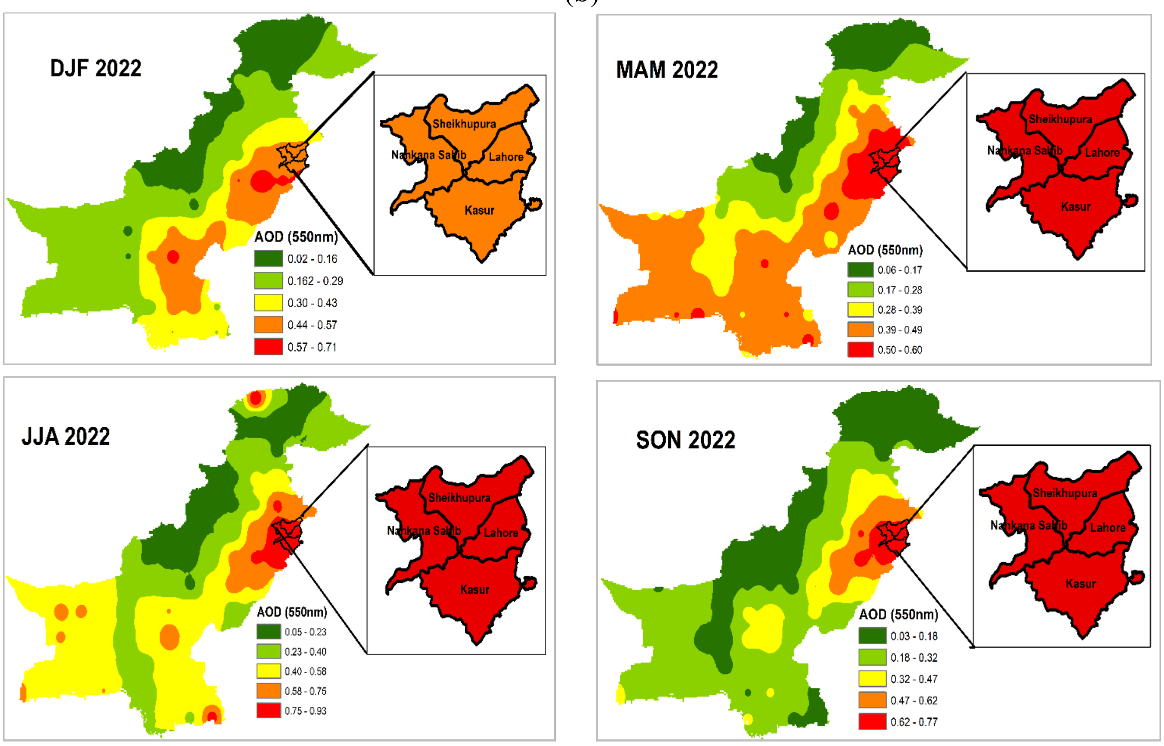

Figure 6. *Cont.*

(c)

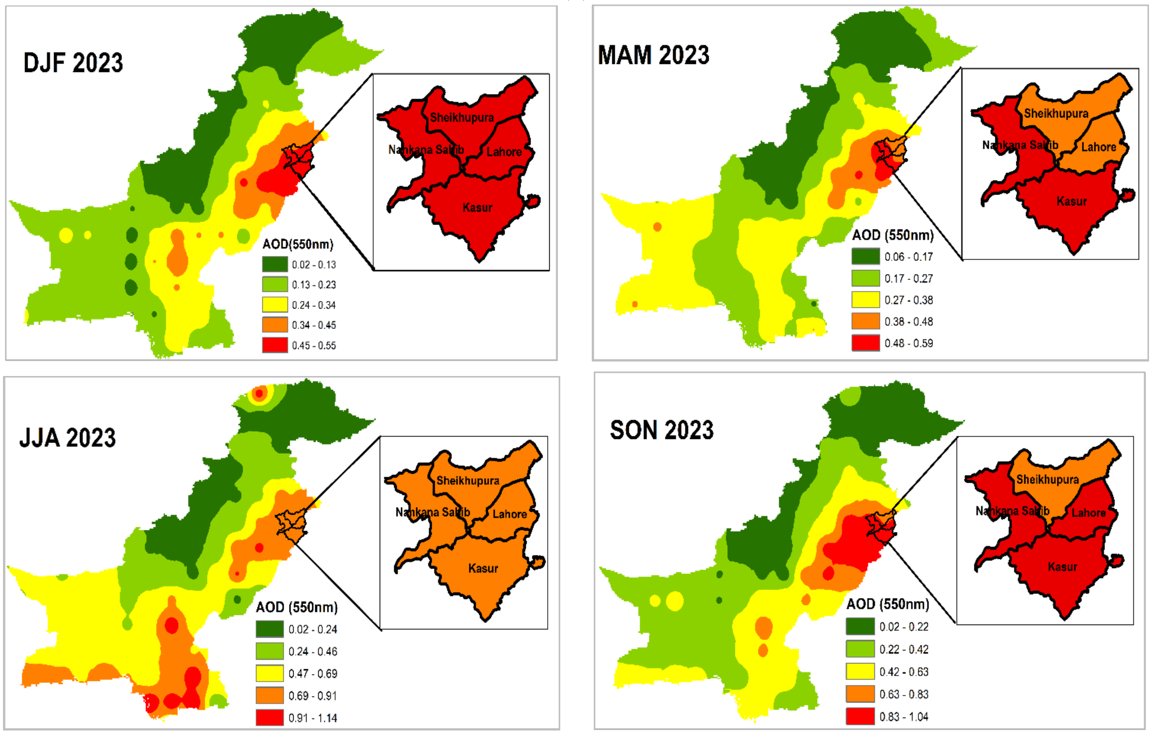

Figure 6. (**a–c**): Spatial and temporal variability of seasonal MODIS/Tera AOD at 550 nm from 2021 to 2023.

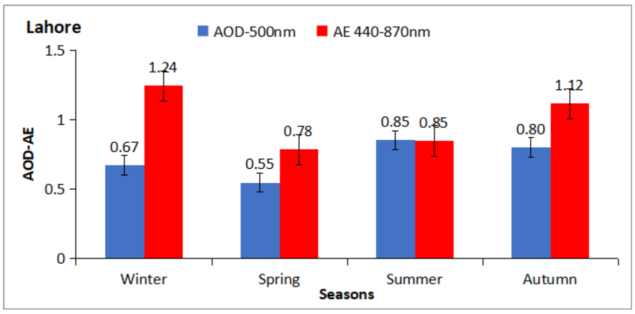

Figure 7. Seasonal AOD 500 nm and AE (440/870 nm) variations from AERONET from 2006 to 2023.

The high AOD values (with low AE) during summer are attributed to fine (coarse)-mode aerosols, originating from the Thar and Rajasthan Deserts, which cause elevated AOD values. Furthermore, the AOD starts to decrease after June due to the onset of monsoon rainfall, which causes the wet deposition of aerosols. Land cover, changes in precipitation, biomass burning, extended periods of elevated temperature [46–48], and hygroscopic growth of aerosol particles [49] can be the leading drivers of the increase in AOD during the summer season in Punjab. These results are higher than reported by [31] and are the extension of previous work.

3.3. NO_2 and AOD Correlations

The yearly NO_2−AOD correlation maps are given in **Figure 8** for the same years (2021, 2022, and 2023) for which the seasonal variations were observed. A significant negative correlation between NO_2 and AOD (to the left of **Figure 8**) was detected for the yearly mean values of $NO_2 - \text{AOD}$ for 2021 (from −0.09 to 0.15) and for 2022 (from −0.22 to 0.07), while a positive correlation was detected for 2023 (from 0.02 to 0.19). The scatter area-averaged (to the right of **Figure 8**) correlation plots for the Lahore Division show a positive correlation value (R = 0.07) in 2021, a negative correlation coefficient value (R = −0.01) in 2022, and a strong positive value (R = 0.13) in 2023. **Figure 9** shows combined (monthly) variations in AOD and NO_2 during the entire study period. Both factors start decreasing from January to March, with an increasing trend from April to June. NO_2 values are observed to be high from November to January, while AOD increases from April to August. The existence of strong spatial correlations in the Lahore Division is the consequence of a large urban area, industrialisation, and intense burning of crop residue in this area with prominent sources of NOx and aerosols [31, 50, 51].

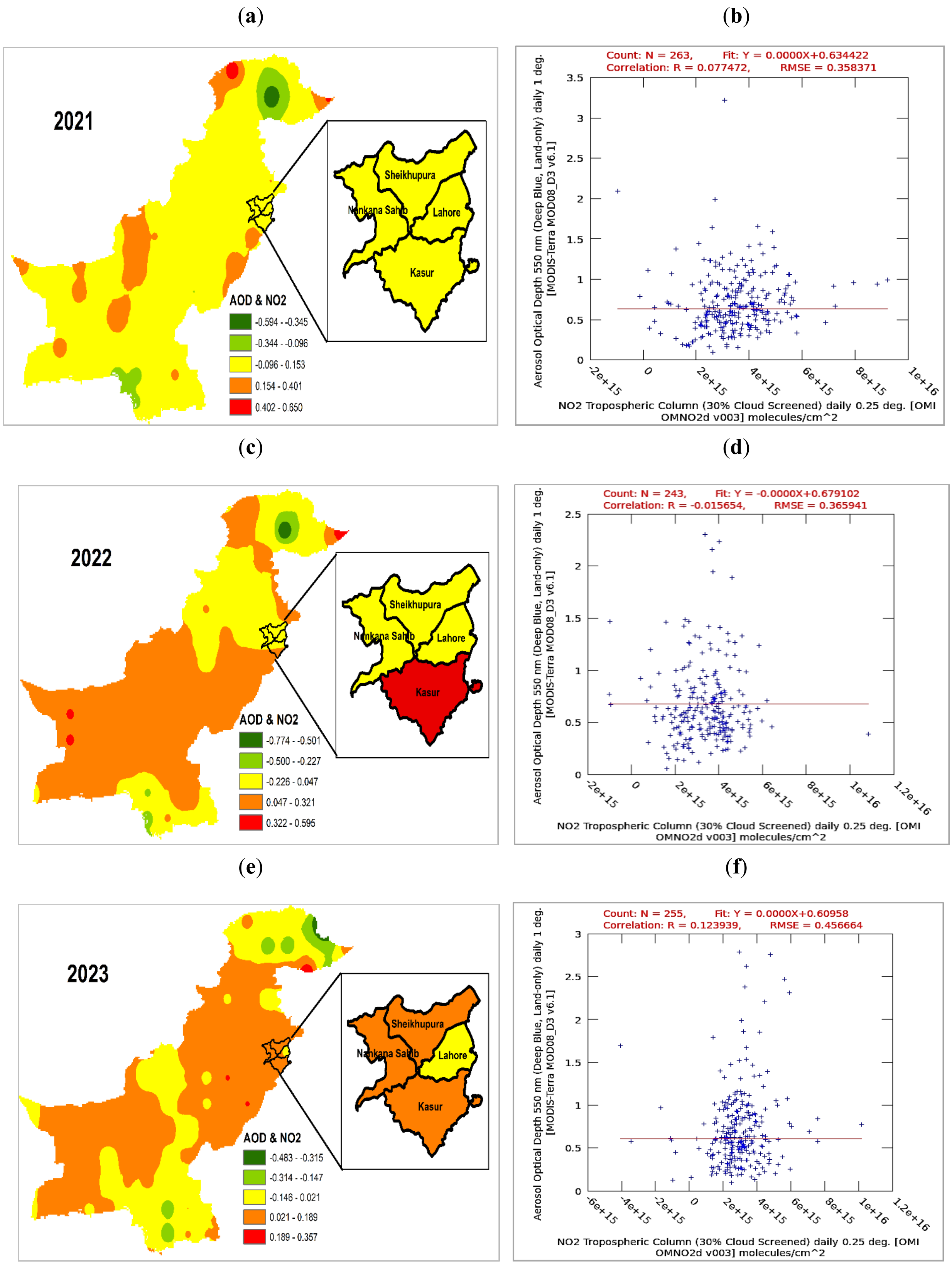

Figure 8. Monthly average variation in NO_2–AOD over the Lahore division during 2006–2023.

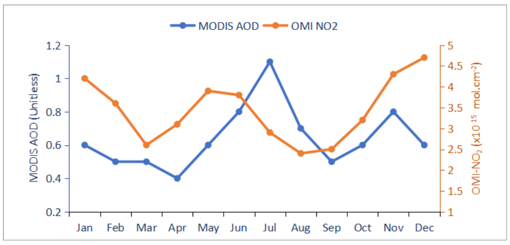

Figure 9. Monthly average variation in NONO$_2$–AOD over the Lahore division during 2006–2023.

4. Conclusions

This article presented spatial-temporal variations in trace gases-aerosol concentrations of NO_2 and AOD from OMI/Aura, MODIS/Tera, and AERONET, from 2006 to 2023. As expected for the Lahore Division, which has a densely populated area, industries, crop residue burnings, and infectiveness in air quality control measures, consistently high tropospheric NO_2 values were recorded with mean values ranging from 3.87 to 6.34 × 10^{15} mole/cm^2 during the entire studied period. Seasonal variations in NO_2 during 2021–2023 revealed that winters and autumns had higher seasonal mean levels of NO_2 than the rest of Pakistan, with the highest values occurring in winter (4.86 − 8.09 × 10^{15} mole/cm^2) of 2022 and autumn (4.18 − 6.85 × 10^{15} mole/cm^2) of 2021, just after the COVID-19 epidemic. Variations in AOD, from both ground and satellite data, during the entire study period indicated that the summer and fall seasons had high (low) AOD (AE) values, with a mean value from 0.5 to 0.69 of AOD, which was attributed to fine (coarse) mode aerosols. More variations in the spatiotemporal behaviour of MODIS/Tera have been recorded since COVID-19. The summers of 2021, 2022, and 2023 had the highest levels of AOD, ranging from 0.68 to 1.10, 0.75 to 0.93, and 0.91 to 1.14, respectively. In 2023, a strong positive correlation (r = 0.02 to 0.19, R = 0.13) was recorded, which is related to high anthropogenic emissions of different aerosols due to rapid urbanization. These general changes in the patterns of NO_2 and AOD during 2019–2023 (including the COVID-19 period) reflect the changes in commuter traffic and transit patterns imposed by the Pakistani government for the implementation of the SOP regulations, which included flexible time limits for commercial and industrial activities, offices and schools. A comprehensive study of the variations of tropospheric NO_2, along with its sources and causes, is essential for future research.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data used in the current study are openly available on NASA's official websites in Giovanni (https://giovanni.gsfc.nasa.gov/giovanni/) and AERONET (https://aeronet.gsfc.nasa.gov/).

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Conflicts of Interest

The authors declare no conflict of interest.

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