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Remote Sensing Analysis of Smog-Inducing Aerosol Optical Depth: An Integrated Approach for Air Pollution Mitigation

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ABSTRACT

Aerosol aggravation poses a significant challenge in the administrative Lahore Division of Punjab, Pakistan and contributes greatly to the persistent issue of smog. Since 2017, the division has experienced recurrent episodes of smog pollution, most notably in the months of October and November. In the present study, aerosol optical depth (AOD) has been analyzed alongside three metrological parameters: temperature, humidity and rainfall. These were tracked in October and November of 2018, 2020, and 2022 using remote sensing data and satellite imaging. Additionally, anthropogenic emissions data from automobile exhaust, industries and stubble burning were derived from secondary sources. Ultimately, the study helped piece together the complex environmental picture in Lahore Division in October and November. The results showed that AOD levels not only increased during this time, they were significantly influenced by a full range of metrological variables such as low temperature, high relative humidity, lack of rainfall and emissions from a variety of human activities. It was found that trucks, tractors and buses were among the worst contributors, alongside industry and stubble burning. Therefore, the present study suggests multi sectoral plans to mitigate aerosol levels and combat the smog menace, promoting environmental sustainability in the Lahore Division. A full set of recommendation is included, divided into three categories: industry, transport and agriculture. These are focused on technology, control systems, disposal, incentives, green solutions and more. At all levels, commitment, collaboration, and coordination are absolutely vital.

1. INTRODUCTION

Atmospheric aerosols (Sun et al., 2022; Pervaiz and Shirazi, 2023) are dynamic mixtures of solid and liquid particles (Wang et al., 2023) suspended in the atmosphere (Ali et al., 2022a) having aerodynamic diameter of 0.001 to 100 µm (Bao et al., 2019). Generally, aerosol particles are injected into the ambient air from natural sources (Bahadur et al., 2023) such as desert, road and soil dust (Ali et al., 2020; Xun et al., 2021; Yousefi et al., 2023), wildfires (Yu et al., 2021) and sea salt (Wang et al., 2023). Whereas, anthropogenic aerosols originate from vehicular and industrial emissions, biomass and stubble burning (Jiang et al., 2019; Pervaiz et al., 2023). Aerosols originated from anthropogenic and natural sources vary in types, size, composition (Metangley et al., 2024) and have relationship with meteorological variables such as temperature, rainfall and humidity (Khan et al., 2024; Majeed et al., 2024). Notably, aerosols have a strong ability to absorb and scatter solar radiant energy and also have the ability to alter climate (Hassan et al., 2024), and deteriorate air quality (Wang et al., 2023; Endale et al., 2024). However, uncertainties exist regarding their properties

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reported in the Intergovernmental Panel on Climate Change (IPCC) 5th and the 6th assessment reports (Chen et al., 2022; Metangley et al., 2024). On the other hand other common air pollutants such as $PM_{2.5}$ (Anggraini et al., 2024), carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ground level ozone (O_3) are also associated with the formation of aerosols (Pervaiz et al., 2021; Wang et al., 2023) that increase the concentration level of troposphere aerosols. Therefore, aerosol optical depth (AOD) (Raptis et al., 2020) are used to determine the level of air pollution (Chen et al., 2021; Endale et al., 2024) and help in forecasting atmospheric pollutants (Pang et al., 2018; Waris and Tariq, 2024).

Like other developing countries, Pakistan is also facing severe challenge of air pollution. Especially, 'Lahore' Punjab, Pakistan has drawn significant attention globally because of being affected by smog (Pervaiz and Shirazi, 2023). Several studies have been conducted by the different researchers on Lahore so far. But, evaluation of AOD trend of Lahore Division is still lacking and remains unaddressed where regional smog particularly called as seasonal smog prominently engulfs the division during winter season. Keeping in view this grave concern, there is a dire need to analyze AOD of Lahore Division at local scale for environment development. Therefore, goal of the present study is identification of the key air pollution emitting sources and their contribution in smog formation with the objective to examine aerosol optical depth (AOD) and stubble burning with three meteorological elements i.e., temperature, rainfall and humidity in October and November of 2018 to 2022 using remote sensing data. The specific months i.e., October and November was chosen due to known stubble burning and smog formation months of the study area.

2. METHODOLOGY

2.1 Study site

Lahore Division (Saeed et al., 2019) is geographically located between 31°15′ N to 31°42′ N latitudes and 74°01′ E to 74°39′ E longitudes (Aslam et al., 2022), occupies an area of land about 11,413.5 km^2 (Hassan, 2018) (Figure 1). Administratively, Lahore Division comprises of four districts i.e., Lahore, Sheikhupura, Kasur and Nankana Sahib (Khan et al., 2022). Overall, a huge load of aerosols is contributed in Lahore Division from (i) vehicular and industrial emissions (ii) waste and stubble burning and (iii) fugitive dust.

Lahore Division is the commercial hub of industrial units (Abbas et al., 2022) and well known for its industrial produce and contributes significantly in the country's economy (Rana and Bhatti, 2018). The Division consists of semi-arid to arid climate and divisible into considerable distinct seasons namely spring, summer, autumn, and winter (Fowler and Archer, 2006) including dynamic monsoon season (Chand and Ahmad, 2020). Division is also the hot-spot of intense air pollution which is affected by regional and local transportation of aerosols.

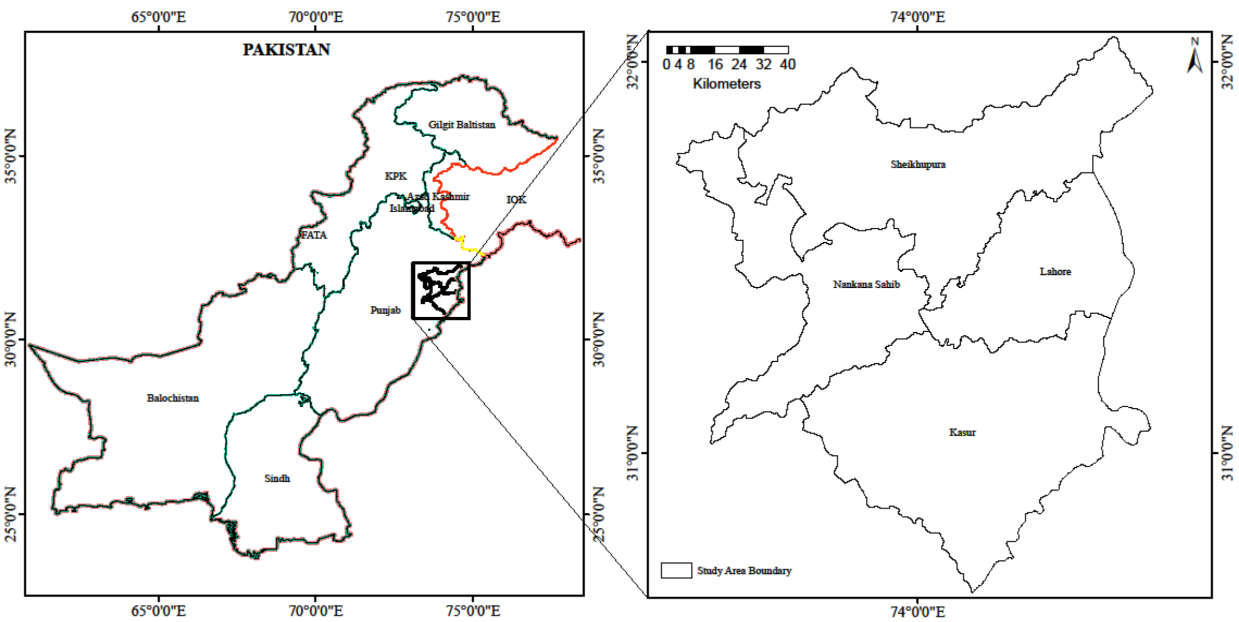

Figure 1. Map of the study area

2.2. Data acquisition

2.2.1 Ancillary data

Multiple studies have reported anthropogenic emissions of smog-causing aerosols (Pervaiz and Shirazi, 2023; Goheer et al., 2024). Therefore, this study focuses on the major contributing sectors that emit air pollutants into the ambient air. These sectors are categorized into three well-known major sources of air pollution i.e., automobiles, industries and agriculture. Data for these sectors were procured from published studies (FAO, 2018), reports (BOS, 2023), the Government of the Punjab, Excise and Taxation Department Pakistan and various published articles.

2.2.1 Remote sensing data

Remote sensing (Raptis et al., 2020) is an advanced approach widely employed for the surveillance and analysis of various environmental phenomena. Various satellite-based sensors are used for this purpose, such as Sentinel-5 Precursor (Sentinel 5P) for aerosol optical depth (AOD) (Zaman et al., 2024) and the Visible Infrared Imaging Radiometer Suite (VIIRS) to examine aerosol concentration and humidity in areas of stubble burning (Shen et al., 2021). Whereas, MERRA-2 (Borhani et al., 2024) is utilized for meteorological variables such as rainfall, humidity and temperature. The data sources, sensors specifications and spatial resolutions derived from these satellites are listed in Table 1.

However, Figure 2 presents an overview of the data acquisitions from different satellites and methods used in the present study categorized into four steps. In step 1, data on AOD; fire anomalies; temperature; rainfall; and relative humidity was derived from satellites. In step 2, the data for the study area was extracted. In steps 3 and 4, emissions data was scaled, as different satellite data with varying spatial resolutions was used. To ensure compatibility and accuracy for analysis, the data was transformed to a uniform resolution of 0.005 meters. This transformation involved converting pixels into points and then applying the Inverse Distance Weighting (IDW) interpolation method to standardize the spatial resolution to 0.005 meters. The map was produced using the following IDW formula:

$$Z_p = \frac{\sum \left(\frac{z_i}{d_i^p}\right)}{\sum \left(\frac{1}{d_i^p}\right)}$$

Table 1. Description of data

Data set name	Sensor	Spatial resolution	Data acquisition year	Months
Aerosol optical depth	Sentinel 5P	10 m	2018, 2020, 2022	October and November
Stubble burning	VIIRS S-NPP	250 m	2018, 2020, 2022	October and November
Temperature	MERRA 2	1 km	2018, 2020, 2022	October and November
Rainfall	MERRA 2	1 km	2018, 2020, 2022	October and November
Relative humidity	MERRA 2	1 km	2018, 2020, 2022	October and November

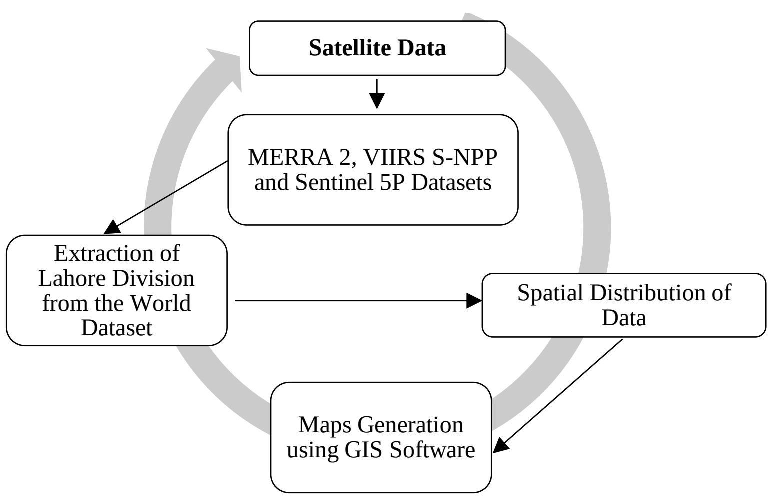

Figure 2. Schematic flowchart of data and methods used in the study

3. RESULTS AND DISCUSSION

3.1 Smog-causing aerosol emission from industry, transport and agriculture sectors

In the Lahore Division (Hassan, 2018), the cities of Lahore, Sheikhupura, and Kasur have a diverse array of industrial units (Paras et al., 2018) encompassing small, medium, and large-scale enterprises. Lahore Division is recognized for its significant industrial output including production of steel, leather, textile, auto parts, marble sheets, chemicals, pharmaceuticals, construction material, and engineering tools and sugar industry (Gilani et al., 2013; Amjad et al., 2019). Lahore Division is a one of the major contributor to deteriorate air by having high concentration of industries that rely on coal. Among all districts of division, Lahore has the largest number of industrial units of Sheikhupura and Kasur. Whereas, Nankana Sahib has more than 1,000 industries. In addition, Lahore Division is well known for its brick kilns (Hamid et al., 2023) furnaces. The large numbers of brick kilns are located in Kasur. However, Lahore and Sheikhupura have more than 200 brick kilns than Nanakana Sahib (Pervaiz et al., 2021). So, the use of fossil fuels and inferior quality of coal used in industrial units and brick kilns are one of the major sources of particulate matter and black carbon emissions (Pervaiz et al., 2022) causing smog.

Various factors of road transport (Muthu et al., 2021) are also linked to air emissions (Wang et al., 2023), encompassing factors like traffic density, traffic flow, congestion, vehicular speed, travel time, vehicle age and fuel characteristics (Pandian et al., 2009; Shrivastava et al., 2013; Khandar and Kosankar, 2014; Gately et al., 2017; Sharmilaa and Ilango, 2022). Moreover, Figure 3 illustrates the view of automobiles percentage in the study area and their contribution to discharge $PM_{2.5}$ emissions which is the most contributing factor in deteriorating ambient air. On comparing results of vehicular registration in the study area, it was noticed that highest population of registered vehicles is motorcycle and least is tractors. However, results of the figure have shown that highest concentration of $PM_{2.5}$ has been emitted by trucks. Similarly auto rickshaws, buses and tractors are also contributing factors to release particulate matter emissions into the ambient air and causing air pollution. Moreover, the previous study conducted by Ali et al. (2022b) supported the findings of the current research that automobiles emissions are one of the major sources of air pollutants.

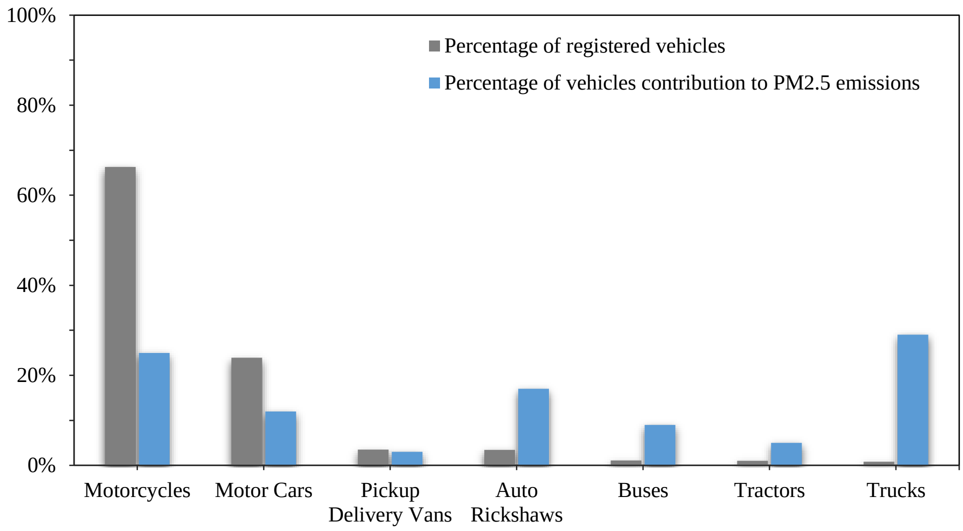

Figure 3. Percentage of registered vehicles and their contribution to $PM_{2.5}$ emissions (Source: Government of the Punjab, Excise and Taxation Department Pakistan 2018)

Furthermore, the Lahore Division claims to be a renowned agriculture sector particularly excelling in the cultivation of rice crops (FAO, 2018; Javed et al., 2023). In addition to this, agricultural processes such as 'slash and burn' (Tang and Yap, 2020) are contributing agents of smog creation (Pierobon et al., 2022), another is rice straw burning (Khalid et al., 2023). Lahore Division is one of the leading division where rice crop (Khan et al., 2021) is grown widely and known to generate high amount of dry residues (Jain et al., 2014). The crop burning emissions are one of the leading causes of smog (Figure 4) based on transportation of regional aerosols (Zeb et al., 2024).

Figure 4. Crop residue burning around Lahore (Shaikh, 2023)

According to the FAO (2018) study, the twelve districts of Punjab are categorized for Basmati Rice growing, namely: Mandi Bahuddin, Sialkot, Gujranwala, Lahore, Gujrat, Hafizabad, Jhang, Okara, Bahawalnagar, Nanka Sahib, Narowal, Sheikhupura and Faisalabad. Three out of the four districts in Lahore Division generate the highest produce of rice (Goheer et al., 2024). However, the breakdown of air pollutants generated from the above source is categorized below (Table 2).

Table 2. Sources of AOD emissions across various sectors

Industry sector	Air pollutants
Steel furnaces / re-rolling mills, paper, and board mills	PM_{10}, $PM_{2.5}$, CO
Brick kilns, fertilizers and pharmaceutical industries	PM_{10}, $PM_{2.5}$, CO, SO_2, NOx
Small resource recovery units, rice, and textile mills	PM_{10}, $PM_{2.5}$
Transport sector	
Motorcycle and motor car	$PM_{2.5}$, HC, CO
Pickup delivery van, auto rickshaw, bus, tractor, truck	$PM_{2.5}$, HC, CO, NOx
Agriculture sector	
Rice straw burning	PM_{10}, $PM_{2.5}$, CO

3.2 AOD trend over Lahore Division in October and November (2018 to 2022)

Lahore, Sheikhupura and Kasur are the industrial and urbanized cities of Lahore Division (Nadeem, 2017; Rana and Bhatti, 2018). Figure 5 has shown the significant variations of AOD in Lahore Division in October and November of 2018 to 2022. Upon comparison of AOD results, it has been noticed that Lahore is the most affected district of Lahore Division where vehicular emissions, industrial soot release into the ambient air and support the findings of the studies conducted by Pervaiz and Shirazi (2023) and Goheer et al. (2024). Furthermore, dust from the southern region of Punjab contributes to Lahore's AOD levels, a phenomenon previously documented in a study by Tariq et al. (2021). Additionally, during stubble burning months (Shabbir et al., 2024) air pollutants get transported in Lahore from India through its shared boundary (Majeed et al., 2024). Hence, AOD caused by stubble burning aerosols (Goheer et al., 2024) coupled with high relative humidity created favorable conditions for the elevation of smog level in Lahore.

3.3 Stubble burning trend over Lahore Division in October and November (2018 to 2022)

According to a 2018 study by FAO, three out of the twelve districts associated with the Lahore Division namely Lahore, Sheikhupura, and Nankana Sahib, are prominently involved in rice cultivation (Younas et al., 2015; Javed et al., 2023). The cultivated rice species in these cities generate a substantial amount of crop residues (Jain et al., 2014). Stubble burning, a common practice, not only releases greenhouse gases but also emits particulate matter into ambient air, typically peaking in the first week of November (Abdurrahman et al., 2020). In the Lahore Division, farmers often prefer stubble burning, believing it enhances soil fertility (Pervaiz et al., 2022). However, incidents of stubble burning have increased with the shift from manual to mechanical harvesting (Sanjay et al., 2021).

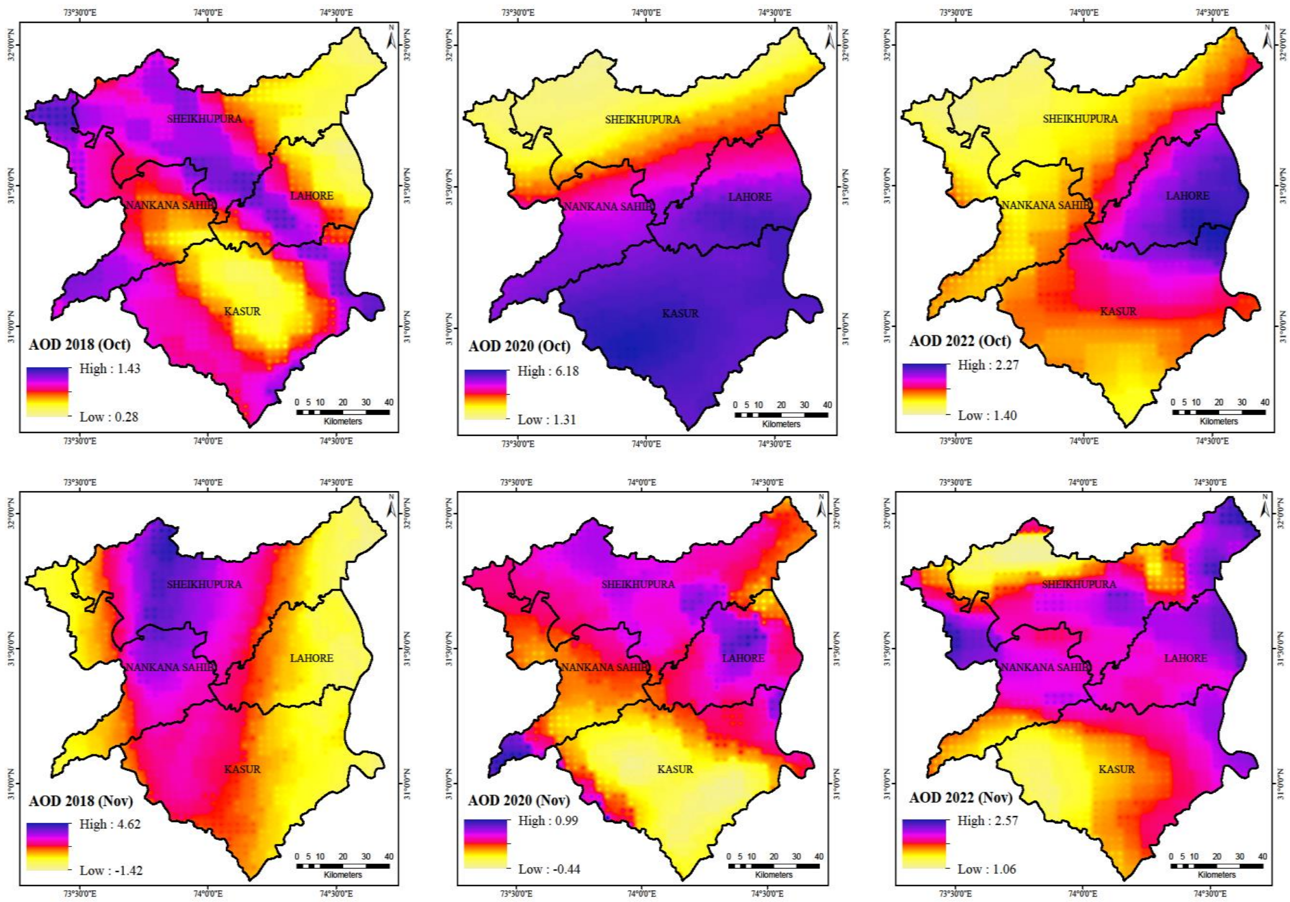

Figure 5. AOD trend over Lahore Division in October and November (2018 to 2022)

However, the results of spatial mapping (Figure 6) reveal the highest extent of stubble burning recorded in Nankana Sahib, a district well-known for its rice crop (Yameen et al., 2019; Shah et al., 2022). Furthermore, emissions from crop burning, when combined with pollutants from vehicular and industrial sources (Gaffney and Marley, 2009; Guo et al., 2024), along with high relative humidity, contribute to the formation of smog (Pervaiz and Shirazi, 2023). Moreover, the study conducted by Kundu et al. (2024) presented the similar findings of our study. In addition to this, our findings of the study also supported by Tariq et al. (2015), Singh (2024), Goheer et al. (2024), and Goenka et al. (2024) who examined that the AOD level increased after crop residue burning in October and November.

3.4 Temperature trend over Lahore Division in October and November (2018 to 2022)

Figure 7 of the study depicts temperature variations in Lahore Division. Notably, Kasur and Sheikhupura have consistently recorded higher temperatures compared to Lahore and Nankana Sahib. A comparative analysis reveals a persistent trend of lower temperature in Lahore from 2018 to 2022. The conjunction of low temperatures in Lahore coupled with high relative humidity significantly impacts air quality emerging as a prominent factor in the formation of smog. This observation aligns with earlier research on Lahore by various authors, reinforcing the current study's findings (Tariq et al., 2021; Pervaiz and Shirazi, 2023) as well as study conducted by Jiang et al. (2024) also reported the findings that low temperature helps to rise the AOD level and deteriorates the quality of air.

3.5 Rainfall trend over Lahore Division in October and November (2018 to 2022)

Meteorological variables, such as rainfall (Kayes et al., 2019; Pervaiz et al., 2022), play a crucial role in mitigating the concentration of air pollutants in the atmosphere. Figure 8 illustrates a consistent low trend of rainfall across most of Lahore Division during the study period. The scarcity of rainfall in October and November proved to be a contributing factor to the heightened levels of Aerosol Optical Depth (AOD) in Lahore, as corroborated by earlier study (Pervaiz et al., 2022). Furthermore, a focused examination of the

2020 spatial data for Kasur highlighted the influential role of low rainfall in elevating AOD levels aligns with the findings of previous studies conducted by Salma et al. (2012) and Kaur et al. (2013). Therefore, Kasur, being a well-known twin city of Lahore, demonstrates similar patterns and by showing the relationship with the meteorological factor i.e., rainfall having influence on air quality in the study area.

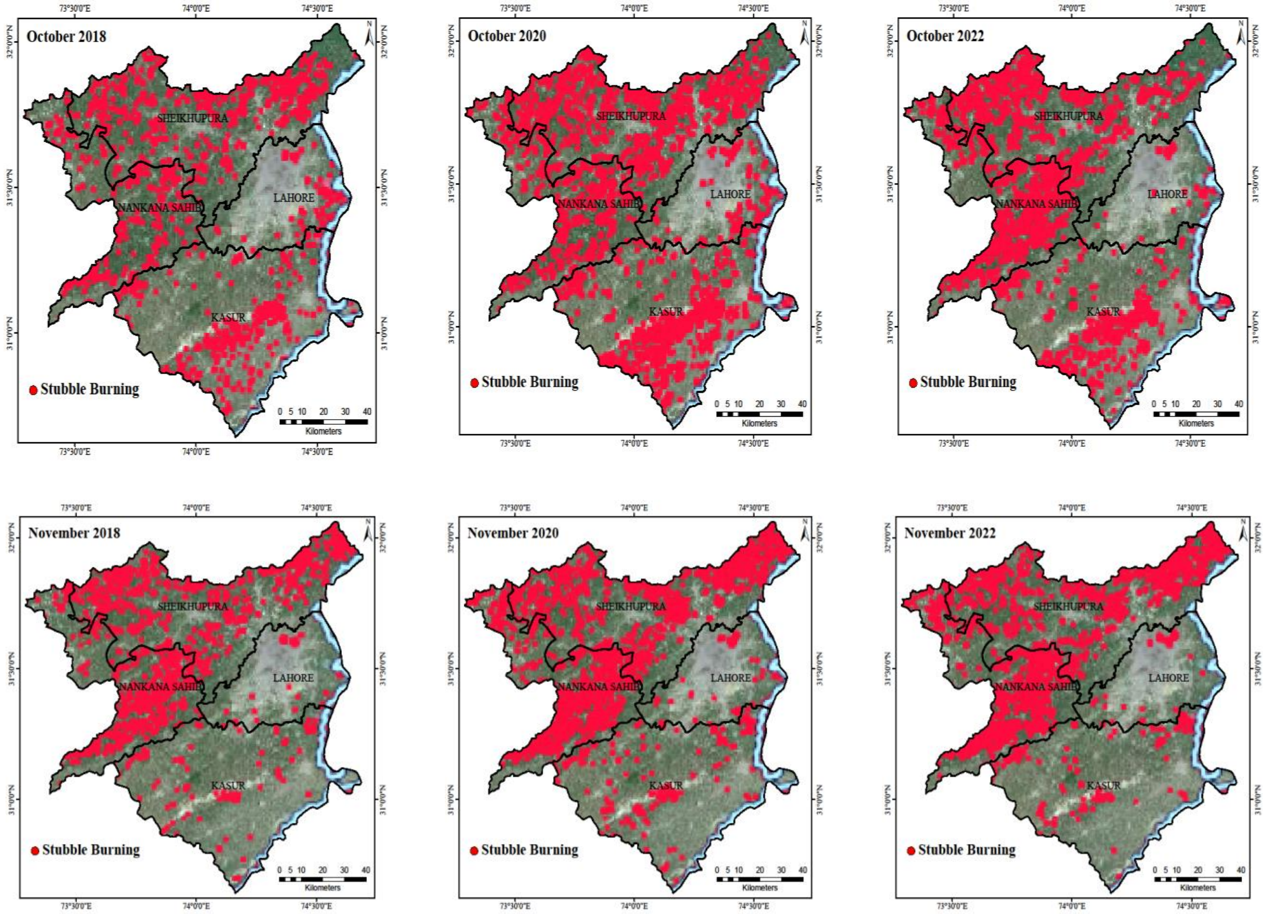

Figure 6. Stubble burning trend over Lahore Division in October and November (2018 to 2022)

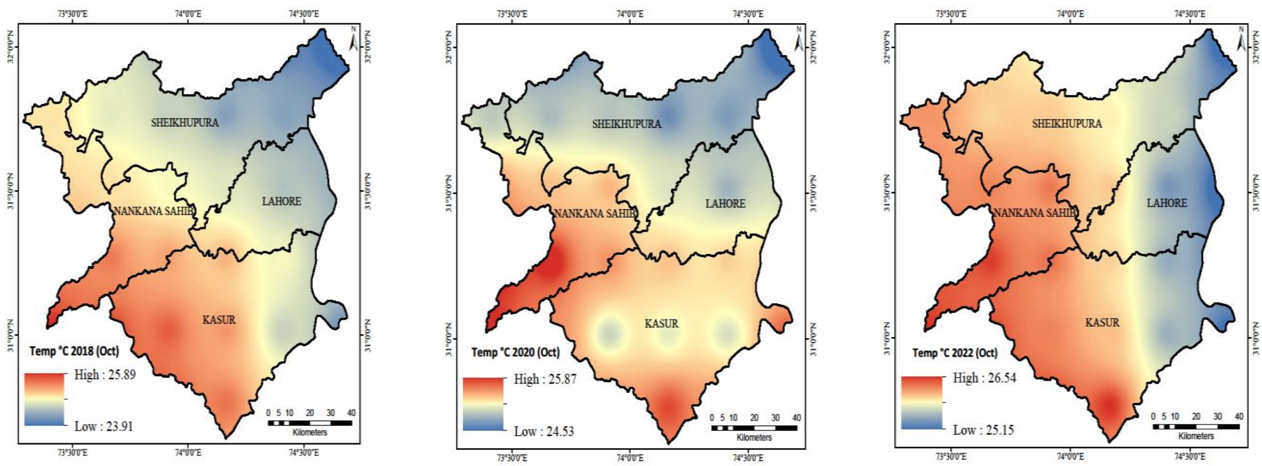

Figure 7. Temperature trend over Lahore Division in October and November (2018 to 2022)

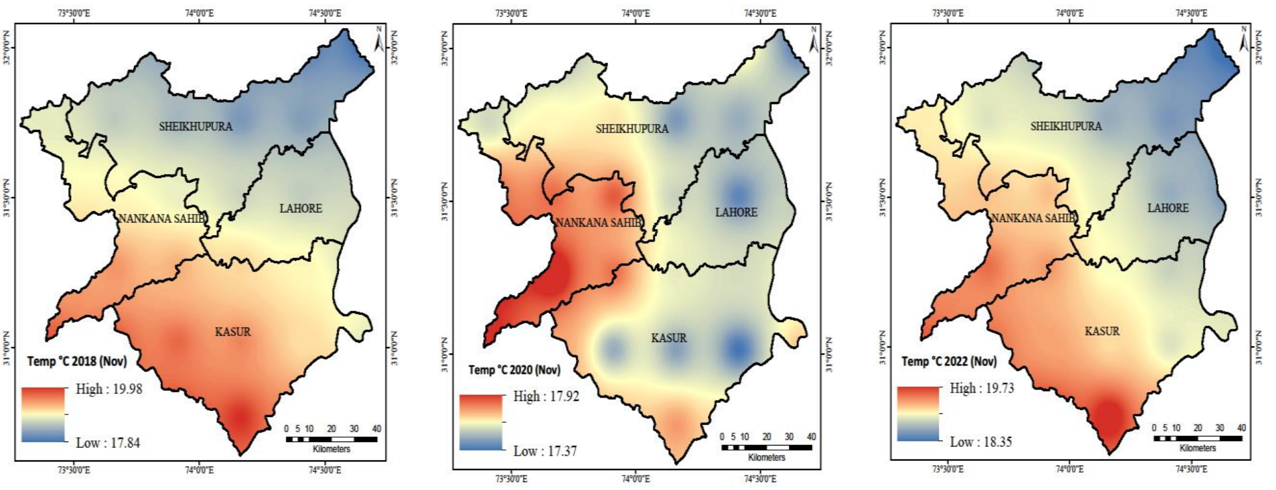

Figure 7. Temperature trend over Lahore Division in October and November (2018 to 2022) (cont.)

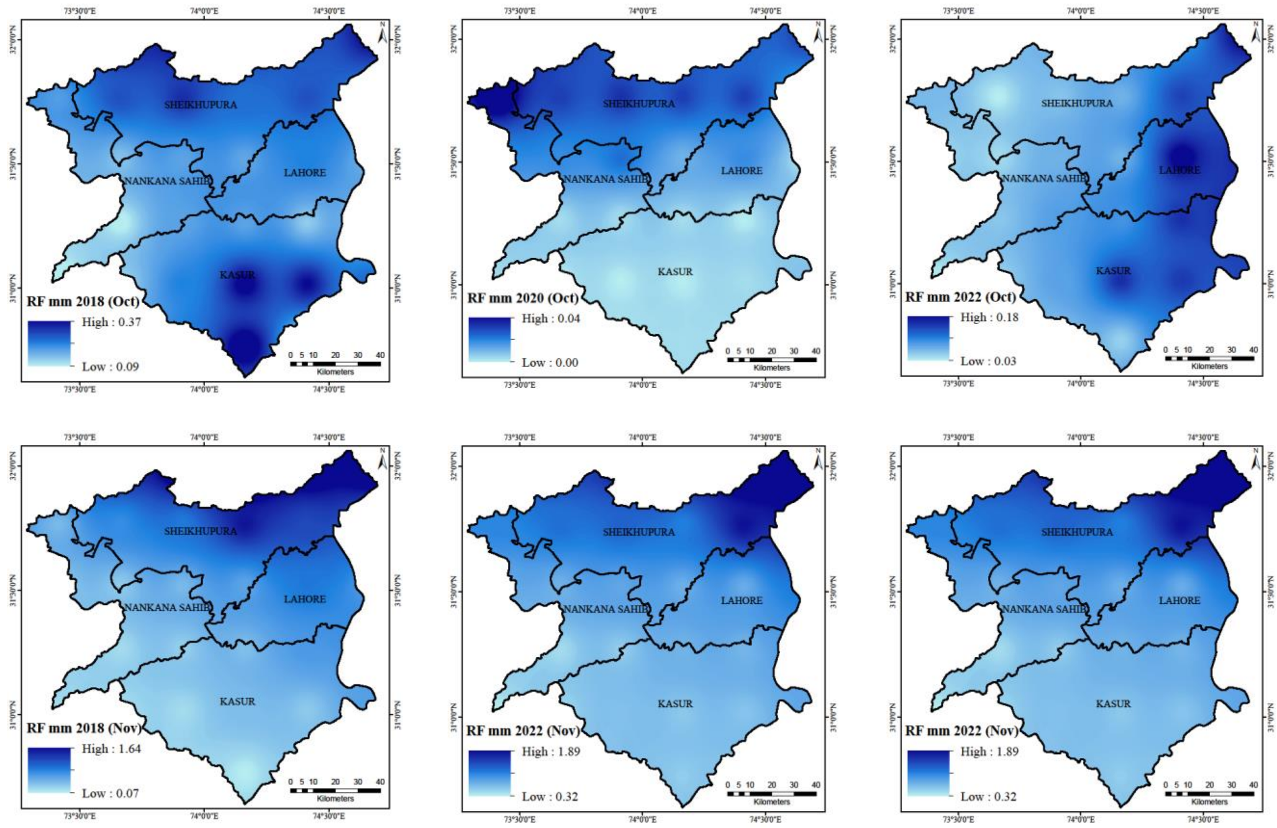

Figure 8. Rainfalltrend over Lahore Division in October and November (2018 to 2022)

3.6. Humidity trend over Lahore Division in October and November (2018 to 2022)

Figure 9 presents the variations in relative humidity in October and November of 2018 to 2022. In October 2018, a notably high trend of relative humidity was observed in Lahore and Sheikhupura and certain parts of Kasur. Similarly, in 2020, elevated relative humidity levels were noted in Lahore, Sheikhupura and central Kasur. However, in 2022, the highest levels of relative humidity were recorded in Lahore and Sheikhupura extending to the northern part of Kasur. In contrast, moderate to low levels of relative humidity were exhibited in Nankana Sahib. Hence, the results show that the high relative humidity levels are a significant contributor by increasing AOD levels into the atmosphere. This meteorological factor contributes to air pollution of Lahore being one of the most affected districts in the Lahore Division. Findings of the present study supported the results of prior study conducted on Lahore (Khan et al., 2021).

However, in support of our study results, studies conducted globally by Shahid et al. (2015), Basharat et al. (2023), Zhu et al. (2024), and Guo et al. (2024) reported the similar findings.

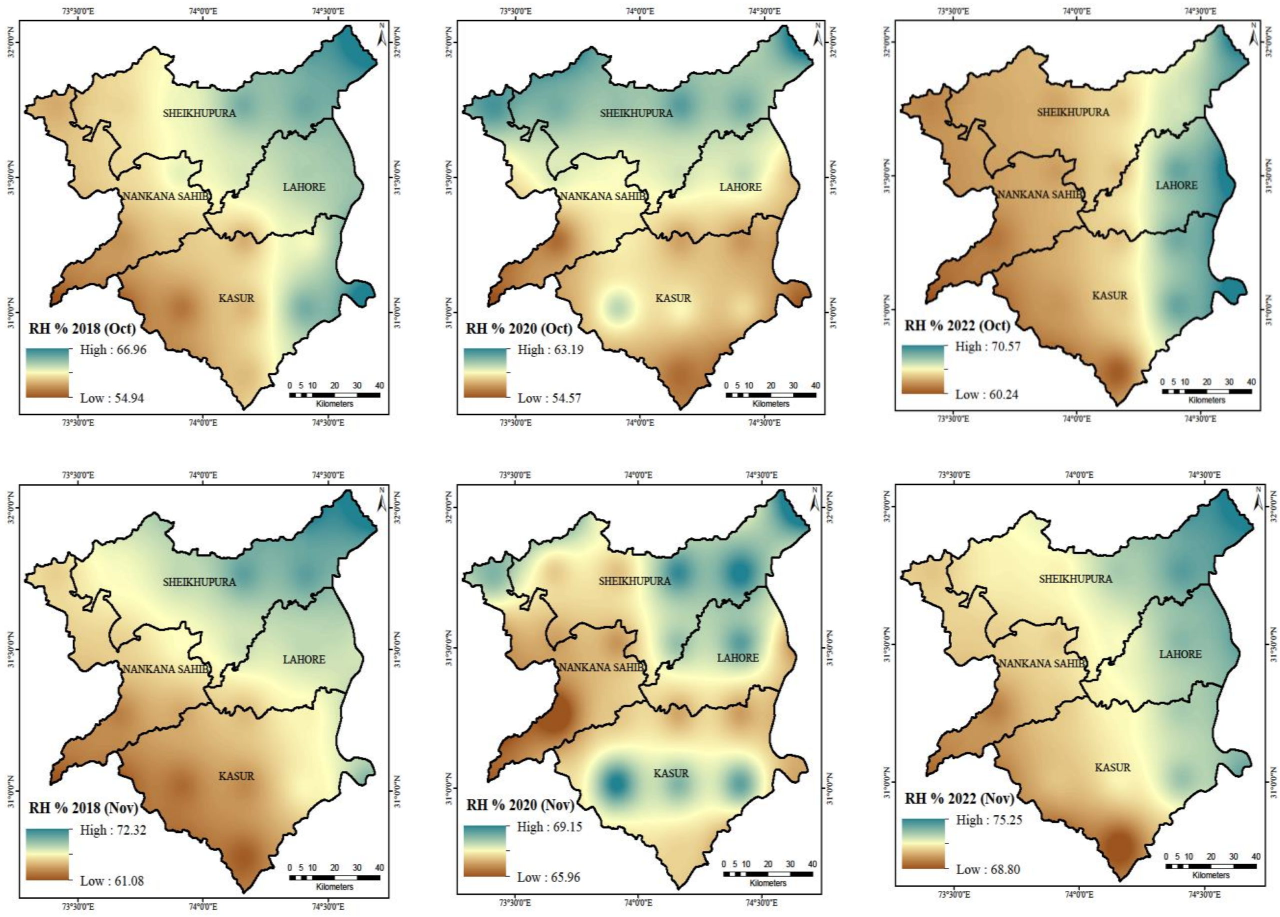

Figure 9. Relative humidity trend over Lahore Division in October and November (2018 to 2022)

4. CONCLUSION AND RECOMMENDATIONS

The government of Punjab has already taken measures to control emissions from road vehicles, crop waste burning, and stationary industrial sources using the Punjab Smog Prevention and Control Rules, 2023. Furthermore, to mitigate air pollution levels, the Punjab Clean Air Policy 2023 (with a phased action plan) has also been notified for clean air. The clean air policy consists of timelines: Short term (<1 year/2023-24), Mid term (1-3 years/2023-26), and Long term (>3 years/2023-30) for the transport, industrial, and agricultural sectors.

However, particular challenges in controlling the generation of anthropogenic aerosols need immediate measures. The current study recorded the highest AOD levels in Sheikhupura, Nankana Sahib, and Lahore in November 2022 compared to October which is known for stubble burning month. Moreover, it is pertinent to note that not only crop residue burning is in practice, but the vegetable and fruit markets in the Lahore Division also contribute significantly to air pollution. These markets burn leftover packing materials at night after delivering goods via high-transport vehicles. These overloaded goods vehicles are another major source of air pollutants by elevating the level of air pollutants.

Considering the study's findings, it becomes evident that a concerted effort is required to address environmental challenges in the context of ongoing economic development. Therefore, sectoral measures for mitigating environmental smog are proposed (Table 3). Implementing these steps requires robust commitment and coordination among government bodies, industries, and citizens to control air pollutants. This collaborative approach is mandatory to ensure the long-term sustainability of a healthier environment in the Lahore Division especially in light of the current study results for the upcoming October and November, 2024.

Table 3. Industrial, transport and agricultural sectoral guide to mitigate environmental smog

Industry sector	Transport sector	Agriculture sector
• Introduction of self-monitoring reporting tools for air emission causing industries • Installation of emission control systems by training cameras using machine learning approaches to monitoring and track industry emission compliance • Adoption of cleaner production technologies • Incentivization of the use of low-emission fossil fuels • Introduction of green industrial zones • Planting ever-green trees as compared to deciduous trees' species, around industrial areas and industrial estates to trap particulate pollutants	• Mandatory vehicular fitness certificates, complying with the Punjab Environmental Quality Standards designed for motor vehicles, required for all public institutes • Reduction of mobility fares to promote train and bus travel for the public • Strict compliance at all entry points of Lahore Division for heavy transport vehicles	• Strict surveillance of vegetable and fruit markets at night • Providing platforms to promote crop waste management practices • Exploring and implementing alternative crop residue disposal methods such as briquetting and waste to energy • Introduction a uniform threshold limit for fire counts using remote sensing data such as for SNPP-VIIRS 7 and MODIS 30%

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