Impact assessment of land surface temperature on air pollution and smog formation in major cities of Pakistan using Google Earth engine

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Abstract. Rapid urbanization, industrial expansion, and reliance on fossil fuels cause serious air pollution. Air pollution affects public health, especially in developing countries like Pakistan. Pakistan is among the most affected nations, particularly its major urban centers, which experience recurrent seasonal smog episodes. This study assesses the effectiveness of Sentinel-5P satellite products integrated with Google Earth Engine (GEE) for monitoring spatiotemporal variations of key air pollutants: nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3) in Lahore, Faisalabad, Multan, and Gujranwala from 2018 to 2023. Monthly, seasonal, and annual composites of cloud-filtered Sentinel-5P TROPOMI data were analyzed using GEE, and statistical regression and correlation analyses were applied to examine relationships between pollutant concentrations and land surface temperature (LST). The results reveal pronounced seasonal variability in air pollutant levels, with elevated NO_2 and CO concentrations during winter due to intensified anthropogenic emissions and atmospheric stability, while O_3 concentrations peaked during spring and summer due to enhanced photochemical reactions driven by high temperatures and solar radiation. Quantitatively, wintertime NO_2 concentrations reached approximately 0.009 mol m^{-2}, whereas summer O_3 concentrations peaked at about 0.30 mol m^{-2}. Strong temperature–pollutant relationships were observed in highly urbanized cities such as Lahore and Faisalabad, reflecting the combined effects of dense infrastructure, industrial activity, and urban heat island intensity. Additionally, the COVID-19 lockdown period provided evidence of temporary reductions in pollutant concentrations and LST, highlighting the dominant role of anthropogenic activities in air quality degradation. Overall, the findings demonstrate that Sentinel-5P data, combined with automated cloud-based platforms such as GEE, provides a robust, cost-effective framework for large-scale air quality monitoring. This approach can support informed policymaking, targeted mitigation strategies, and sustainable urban planning to reduce smog intensity and protect public health in Pakistan.

Keywords: Google Earth engine, smog, pollutants, land surface temperature, Sentinel-5P

1. Introduction

Air pollution has become one of the most urgent environmental challenges around the world, especially in developing countries experiencing rapid urban growth. As cities expand, industries grow, and fossil fuel use increases, emissions often exceed what the environment can handle (Mehmood et al., 2021; Wang et al., 2020). In recent years, air pollution has become a major cause of premature death and illness, mainly due to its harmful effects on the lungs and heart (Ialongo et al., 2020). On top of the health risks, polluted air also takes a hefty economic toll lowering worker productivity and driving up healthcare and cleanup costs, costing billions every year (Zhou et al., 2023; Bakaeva & Le, 2022).

One of the most visible and dangerous forms of urban air pollution is smog. There are several types: sulfurous (London-type) smog, winter or “Polish-type” smog dominated by particles, and photochemical smog. In winter, high levels of particulate matter (PM_{10}, $PM_{2.5}$, PM_1) and harmful chemicals like polycyclic aromatic hydrocarbons are common, while photochemical smog forms when sunlight triggers reactions between pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and ozone (O_3) (Naureen et al., 2022). Seasonal smog, especially in winter, has become a regular problem in major cities, raising serious concerns for both public health and the environment (Bilal et al., 2021; Riaz & Hamid, 2018).

Urban centers in developing countries are particularly vulnerable to smog because of dense populations, unplanned city growth, clusters of industry, traffic jams, and shrinking green spaces. These factors not only increase emissions but also change local climates, making conditions that trap pollution and raise city temperatures. Land surface temperature (LST) plays an important role here, affecting how pollutants spread, how quickly chemical reactions happen, and how well the air mixes. Warmer surface temperatures can boost reactions that create ozone, while cold, stable winter air lets pollutants like NO_2 and CO build up (Fuladlu & Altan, 2021). Understanding how temperature and pollution interact is key to explaining seasonal smog and planning effective ways to reduce it.

Pakistan, currently ranked as the second most polluted country in the world, faces major challenges in enforcing environmental laws and using modern air quality monitoring systems (Mehmood et al., 2021). The country struggles with ongoing problems from industrial emissions, more vehicles on the road, burning of biomass, energy shortages, and weak regulations (IQAir, n.d.; Raza et al., 2021). Like many developing countries, Pakistan’s air quality monitoring networks are limited and unevenly distributed, making it hard to get a complete picture of the pollution problem (Anjum et al., 2021). Despite growing awareness, there have been few detailed studies linking long-term changes in air pollutant levels to surface temperatures in Pakistani cities. Winter smog in particular has become a recurring issue in big cities, posing serious threats to public health and the environment (Bilal et al., 2021; Riaz & Hamid, 2018).

The health impacts are alarming. For instance, air pollution causes about 1,250 deaths in Lahore every year (Jahan et al., 2019). Factors like unplanned urbanization, rapid population growth, loss of greenery, and emissions from factories and vehicles have caused pollution levels and emission sources to spike (Ramírez-Aldaba et al., 2025). Lahore, one of Pakistan's largest cities, is growing rapidly and often shrouded in heavy smog. Industrial emissions in cities are a major concern, with poor air quality linked to higher COVID-19 death rates (Bilal et al., 2022). This study focuses on four major urban centers Lahore, Faisalabad, Multan, and Gujranwala. Lahore and Faisalabad, in particular, face heavy contamination from vehicles and industry, while Multan, though less industrialized, still shows high pollution from agriculture and urban growth (Nasar-u-Minallah, 2020).

Ground-based air quality monitoring stations, while valuable, often miss the bigger picture and long-term trends in large urban areas. Satellite remote sensing addresses this gap, offering reliable, regular, and wide-scale data on key pollutants (Wang et al., 2021). Instruments like the TROPOMI sensor on the Sentinel-5P satellite can continuously track pollutants such as NO_2, CO, and O_3, making them ideal for larger-scale air quality assessments (Douros et al., 2022). Google Earth Engine (GEE) is a powerful platform that can handle vast amounts of environmental data and satellite imagery, enabling more efficient, long-term studies. Our analysis of Sentinel-5P satellite data processed in GEE for the years 2018 to 2023 shows concerning levels of pollutants—especially in winter, when smog frequently blankets cities like Lahore, Faisalabad, Multan, and Gujranwala. Heavy industry and dense populations in these areas have significantly worsened air quality, affecting both health and economic productivity. Without enough data and infrastructure, it's difficult to predict pollution accurately or implement effective controls on vehicle and industrial emissions, including biomass burning (Raza et al., 2021). Leveraging GEE's processing power allows us to handle and analyze large datasets for a more detailed understanding of air quality (Kaplan & Avdan, 2020).

This research fills an important gap by combining satellite data on air quality with land surface temperature information to study smog dynamics in Pakistan. The main idea is that changes in surface temperature strongly affect when and where key pollutants become concentrated, making smog worse at certain times. By examining these relationships in Lahore, Faisalabad, Multan, and Gujranwala over a six-year period, this study aims to build a clearer picture of how temperature and pollution interact providing evidence to help design better, data-driven strategies for cleaner air and more sustainable urban development in developing countries.

1.1 Study area

Pakistan located in South Asia, having absolute location approximately between 24°–37° N latitude and 61°–76° E longitude, giving it a strategic location on the map (see Figure 1).

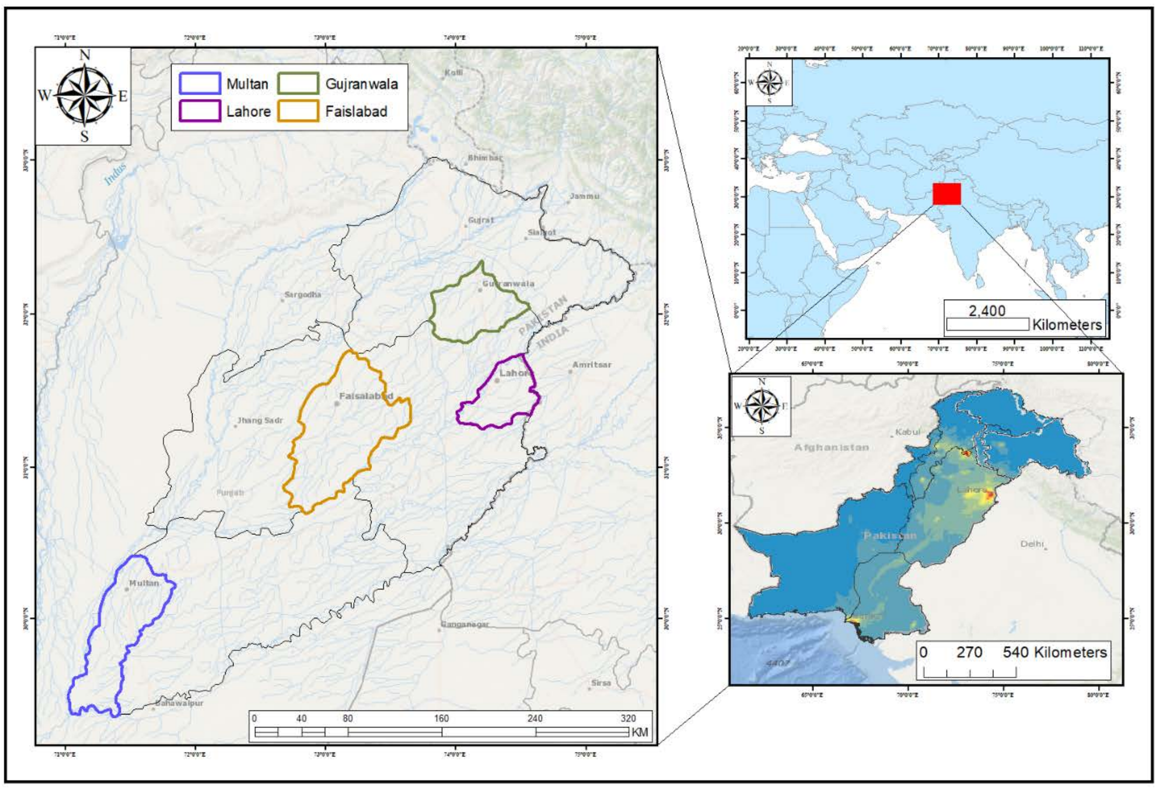

Figure 1. Study Area Map (Gujranwala-Lahore-Faisalabad-Multan)

The country features a wide range of climates—from dry and semi-dry areas to humid, subtropical regions. Rapid population growth, urban sprawl, booming industries, and rising energy use have severely impacted air quality in Pakistan's major cities (Mehmood et al., 2021; Bilal et al., 2021). As a result, Pakistan regularly ranks among the world's most polluted countries (IQAir, n.d.).

This study focuses on four of Punjab's largest cities—Lahore, Gujranwala, Faisalabad, and Multan—all of which have faced frequent smog episodes and consistently high levels of air pollution in recent years (Malhi et al., 2023; Raza et al., 2021). Punjab, the country's most populous and industrialized province, is packed with factories, busy roads, and large urban areas, making it a key region for studying air pollution (Bilal et al., 2021).

Lahore, the provincial capital, is a sprawling metropolis with heavy traffic, a fast-growing population, and intense industrial activity. Its hot, semi-arid climate is marked by cooler winters, where conditions like low wind and temperature inversions often trap pollutants near the ground, causing thick winter smog (Mushtaq et al., 2024; Jahan et al., 2019).

Gujranwala is another major industrial city, home to metal processing, ceramics, food production, and manufacturing industries. The city's rapid industrial growth, growing traffic, and lack of green spaces have led to persistent air quality problems (Bhatti et al., 2021).

Known as Pakistan's "industrial backbone," Faisalabad is famous for its textile industry and other energy-intensive factories. With its semi-arid climate, high industrial emissions, and busy roads, Faisalabad frequently experiences high levels of nitrogen dioxide and carbon monoxide (Zeeshan et al., 2024).

Multan, in southern Punjab, stands out with fewer heavy industries but notable pollution from agriculture, biomass burning, and high land surface temperatures. The city endures extremely hot summers and mild winters, providing a good setting to study how temperature affects air pollution (Khalid et al., 2021).

Together, these four cities capture a range of urban, industrial, and climate conditions—from highly industrialized metro areas to cities with mixed urban and agricultural influences. They also share similar seasonal weather patterns, particularly stable winter conditions that limit the dispersion of pollutants. This makes them ideal for examining how land surface temperature and air pollution interact to drive smog formation in Pakistan (Naureen et al., 2022; Raza et al., 2021).

2. Methodology

In this study, we used satellite technology to explore how land surface temperature (LST) and major air pollutants (NO_2, CO, and O_3) are connected, and how they contribute to smog in

Pakistan's largest cities between 2018 and 2023. Our approach followed four main steps: first, we collected the necessary data; next, we cleaned and organized this information; then, we analyzed pollutant levels and identified pollution hotspots; finally, we estimated land surface temperatures and ran statistical analyses to look for patterns and connections. Figure 2 gives a visual overview of our research process.

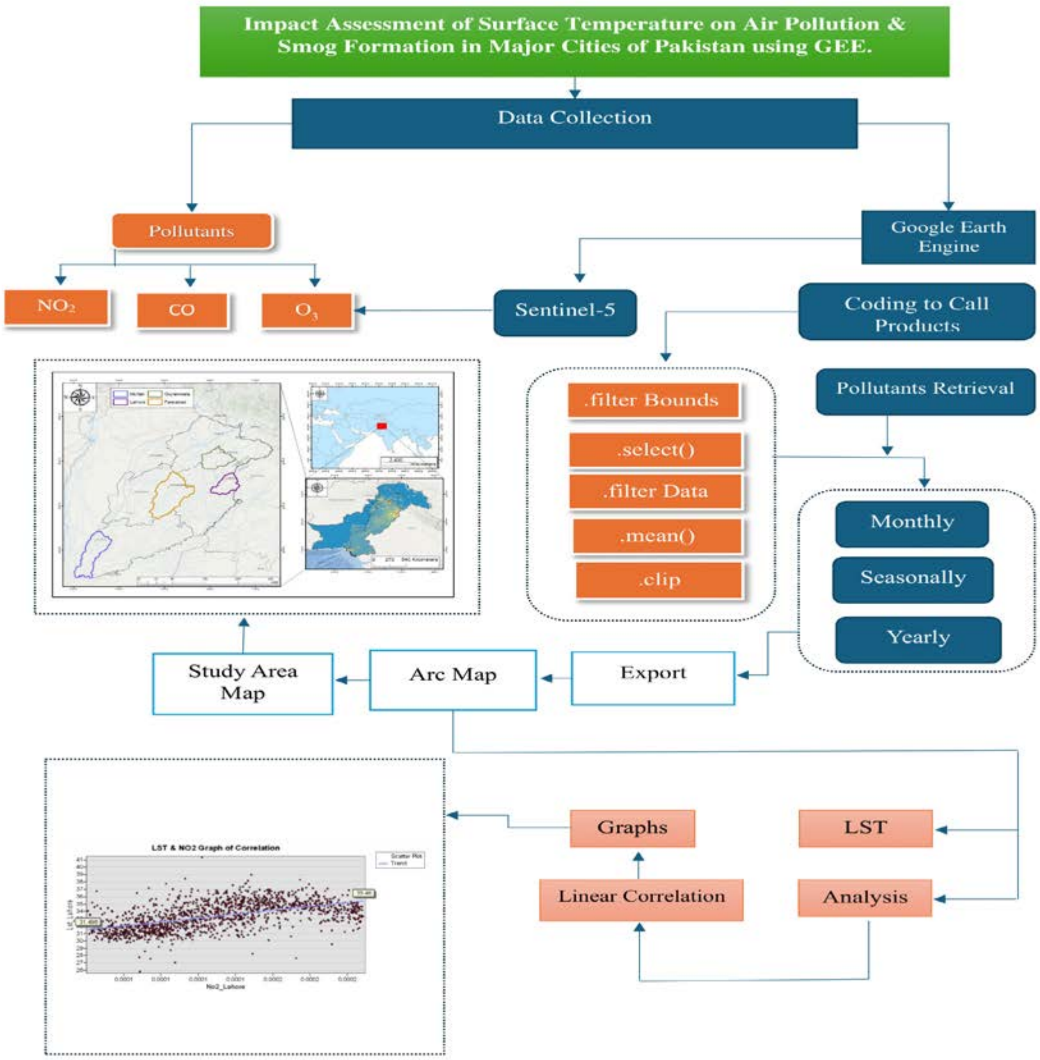

Figure 2. An Overview of Methodology

2.1 Data sources and acquisition

To gather data on air pollution, we used information from the European Space Agency's Sentinel-5P satellite, which carries the Tropospheric Monitoring Instrument (TROPOMI). This satellite gives us daily, detailed global measurements of important air pollutants. For our study, we collected data on nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3) from 2018 to 2023 using the Google Earth Engine platform.

For land surface temperature, we used images from the Landsat-8 satellite, specifically using its Operational Land Imager and Thermal Infrared Sensor (OLI/TIRS). These images, provided by the United States Geological Survey (USGS), allowed us to estimate surface temperatures across our study areas and compare them directly with the pollution data from the satellites.

2.2 Data preprocessing and quality control

We carefully prepared all Sentinel-5P datasets in the Google Earth Engine (GEE) platform to make sure our results were accurate and consistent. This included applying quality assurance checks—using specific quality flags—to filter out any data points affected by clouds or other issues. Only high-quality, reliable pixels were used for our analysis, following well-established methods (Wang et al., 2022). To get a clearer picture of longer-term trends, we grouped the daily Sentinel-5P readings into monthly and seasonal averages. This approach helped smooth out short-term ups and downs and made it easier to spot seasonal patterns. We also adjusted the data to match the spatial resolution of the Landsat land surface temperature (LST) data, making it possible to compare and combine information from both sources in a meaningful way.

2.3 Pollutant characterization and analysis

Our analysis centered on three key pollutants linked to smog: nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3). The details of each pollutant is are provided in Tables 1–3. To understand how these pollutants, change throughout the year, we compared their levels during the study period of 2018-2023.

Table 1. Specifications of NO_2 product

Band Name	**Unit**	**Min**	**Max**	**Description**
NO_2_column_number_density	mol/m^2	−0.0006	0.0096	NO_2 gradient column density ratio
Tropospheric_NO_2_column	mol/m^2	−0.0064	0.0096	Vertical tropospheric column

				of NO_2
Stratospheric_NO_2_column	mol/m^2	8.7×10^{-6}	0.0001	Stratospheric NO_2 vertical column
NO_2_slant_column_number	mol/m^2	−51.4 × 10	0.003908	NO_2 gradient column density
Tropopause pressure	Pa	0.00644	0.009614	Top pause pressure
Absorbing_aerosol_index	Pa	−14.43	10.67	Aerosol index
Cloud fraction	fraction	0	1	Effective cloud fraction

Table 2. Specifications of CO product.

Band Name	Unit	Min	Max	Description
CO_column_number_density	mol/m^2	−297	4.64	CO concentration.
H2O_column_number_density	mol/m^2	−46,536	3.45844×10^7	Water vapor column.
Cloud_height	Meter	−8341	5000	Scattered layer height.
Sensor_altitude	Meter	828,542	856,078	Satellite height according to WGS84 geodetic.
Sensor_azimuth_angle	Degree	−180	180	Satellite azimuth angle, East and North WGS84.
Sensor_zenith_angle	Degree	1	66	WGS84 Satellite elevation angle.
Solar_azimuth_angle	Degree	−180	180	Sun azimuth angle, East and North angle WGS84.
Solar_zenith_angle	Degree	9	80	Apex angle of the satellite is the angle away from the vertical.

Table 3. Specifications of O_3 product.

Band Name	Unit	Min	Max	Description
O_3_column_number_density	mol/m2	0.025	0.3048	O_3 between the surface and the top of the atmosphere.
O_3_effective_temperature	k	19.92	428.11	Mass coefficient of cloudy and clear air.
Cloud fraction	Fraction	0	1	The slope of the O_3 condensation column.
Sensor_azimuth_angle	Degree	−180	180	Satellite azimuth angle, east and north.
Sensor_zenith_angle	Degree	0.098	66.57	WGS84 satellite zenith angle.
Solar_azimuth_angle	Degree	−180	180	Sun azimuth angle, East and North angle WGS84.
Solar_zenith_angle	Degree	8	102	Apex angle of the satellite is the angle away from the vertical.

We used Google Earth Engine (GEE) to detect pollution hotspots areas where pollutant levels stayed higher than the seasonal average year after year. By analyzing monthly data over time, we were able to spot when pollution peaked and how these patterns changed from one year to the next.

2.4 Statistical analysis

To explore how land surface temperature and air pollution are connected, we used correlation and regression analysis. Specifically, we calculated Pearson correlation coefficients to measure how strongly and in which direction seasonal average temperatures and pollutant levels were linked in each city. We also used a robust form of linear regression to minimize the impact of outliers and uneven data. Results were considered statistically significant if they met the 95% confidence level ($p < 0.05$).

We focused our statistical analysis on nitrogen dioxide (NO_2) and ozone (O_3) because their levels are highly affected by temperature and are key players in photochemical smog. Carbon monoxide (CO) was reviewed in a more general way, as its relationship with temperature was weaker and less consistent across different seasons.

2.5 Land surface temperature (LST) estimation

We estimated land surface temperature using thermal infrared data from the Landsat-8 satellite, following standard methods for converting the satellite's raw measurements into temperature values. The process began by converting the top-of-atmosphere (TOA) spectral radiance into what's known as brightness temperature (TB) using established formulas.

Calculation of Brightness Temperature (T_B):

$$T_B = \frac{k_2}{In\left(\frac{k_1}{L}+1\right)} \qquad \textit{Eq. 1}$$

where:

K_1 and K_2 are constants in the thermal band of Landsat-8.

L is the TOA spectral radiance.

$$LST\,(°C) = (ST\_B10 \times 0.00341802) + 149.0 - 273.15 \qquad \textit{Eq. 2}$$

The seasonal and annual averages of land surface temperature (LST) to match up with our air pollution data, making it easier to compare the two. To help visualize and understand the patterns, we used ArcGIS to map out both temperature and pollutant levels across the different areas, allowing us to see how these factors interact and vary from place to place.

3. Results and discussions

In this study, we looked at how key air pollutants NO_2, CO, and O_3 were distributed over time and space in four major Pakistani cities: Lahore, Gujranwala, Faisalabad, and Multan, from 2018 to 2023. By analyzing seasonal and yearly trends, creating maps, and running statistical tests, we explored how changes in land surface temperature are linked to air pollution and smog formation in these urban areas.

3.1 Seasonal and Annual Variability of Air Pollutants (2018–2023)

We found clear seasonal and year-to-year changes in all the pollutants. Ozone (O_3) levels, in particular, showed a steady rise during the warmer months, especially after 2021. This rise is likely due to higher temperatures, stronger sunlight, and an increase in precursor gases like NO_x and volatile organic compounds (VOCs), all of which help ozone form through chemical reactions in the atmosphere. The urban heat island effect and the movement of pollutants from surrounding areas made ozone levels even higher in big cities, particularly Lahore and Faisalabad—a trend seen in other South Asian megacities as well (Hoque et al., 2020; Wang et al., 2020).

Looking at the seasons, ozone was highest in the summer when sunlight and heat speed up its formation. In contrast, levels were lower in winter and during the monsoon because there’s less sunlight and the atmosphere mixes more, which helps disperse the ozone. These trends are shown in Figure 3(a) and Figure 3(b), which map out where ozone is most concentrated and show the annual averages between 2018 and 2023.

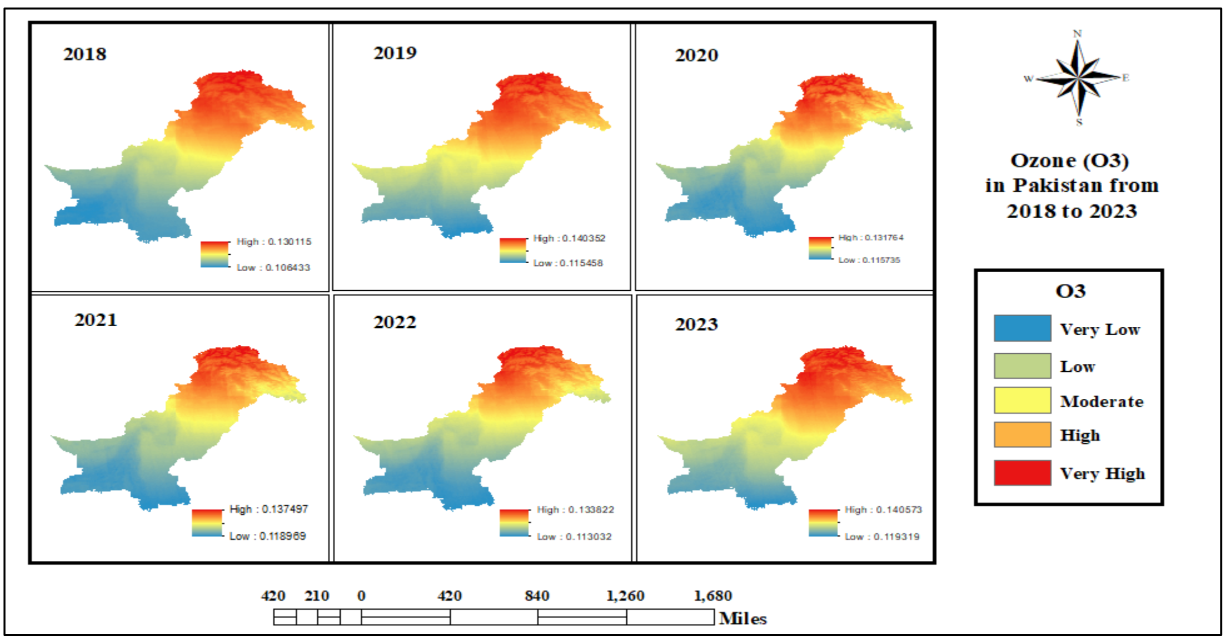

Figure 3 (a). Maps of annual average values for 2018–2023 O_3 in Pakistan (2018-2023)

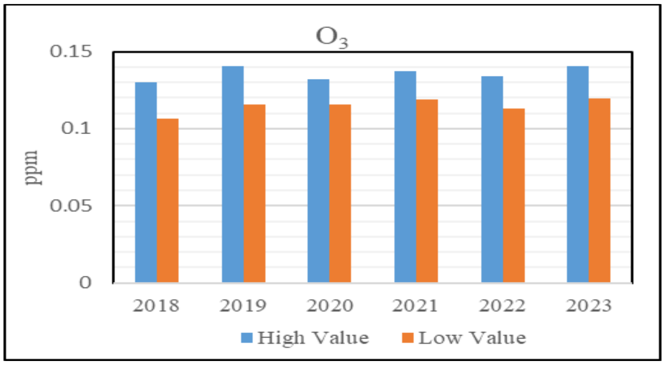

Figure 3 (b). Graphs of annual average values for 2018–2023 O_3 in Pakistan (2018-2023)

Nitrogen dioxide (NO_2) levels varied a lot from place to place, with the highest concentrations found in busy, industrial cities like Lahore and Faisalabad. Looking at yearly trends, NO_2 levels peaked between 2019 and 2021 but then started to decrease after 2022, which may be due to better emission controls and a slowdown in industrial activity. In terms of seasons, NO_2 was more concentrated during the winter. This is mainly because increased fossil fuel use and stable weather conditions trap pollutants near the ground. In contrast, NO_2 levels dropped in the summer and monsoon seasons, thanks to better air mixing and rain, which help clear pollutants from the atmosphere (Karim & Rappenglück, 2023). Figures 4(a) and 4(b) show how NO_2 levels changed across different locations and over time.

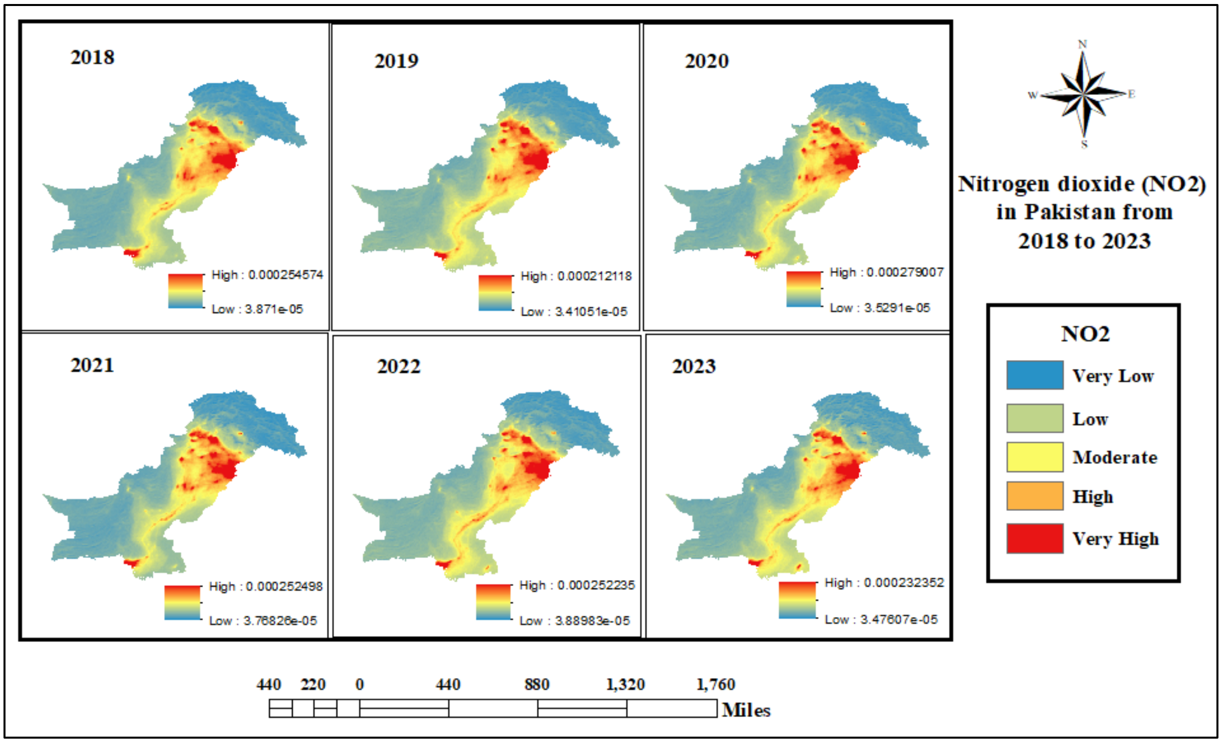

Figure 4 (a). Map of Annual average values of NO_2 in Pakistan (2018-2023)

Figure 4 (b). Graph of Annual average values of NO_2 in Pakistan (2018-2023)

Carbon monoxide (CO) levels remained fairly steady over the years we studied, with only moderate changes from year to year. The highest concentrations appeared between 2021 and 2023, likely due to the economic rebound after COVID-19, more vehicles on the roads, and increased burning of biomass (Wang et al., 2021). Unlike NO_2 and O_3, CO didn't show strong seasonal patterns, which is likely because it stays in the atmosphere longer and comes from more consistent sources throughout the year (Zhou et al., 2021). The variation in CO levels across different areas and times has been shown in Figures 5(a) and 5(b).

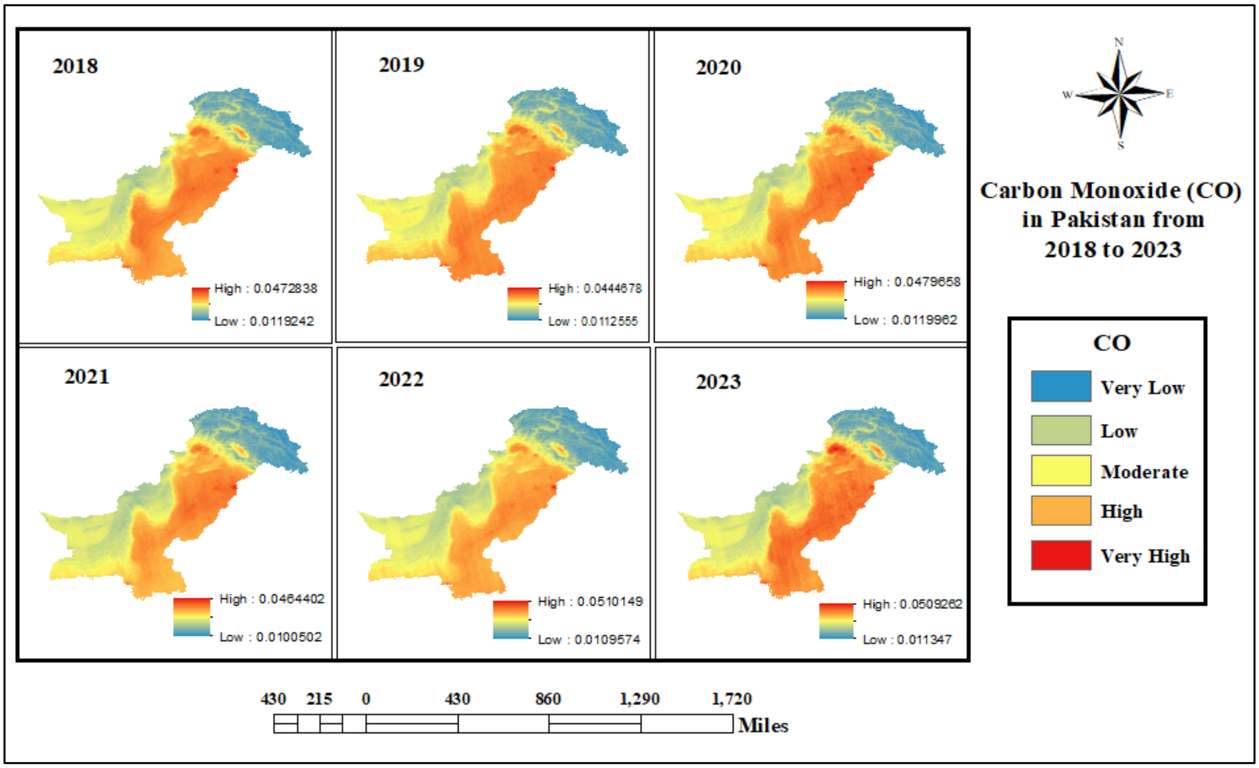

Figure 5(a). Map of annual average values of CO for 2018–2023 in Pakistan

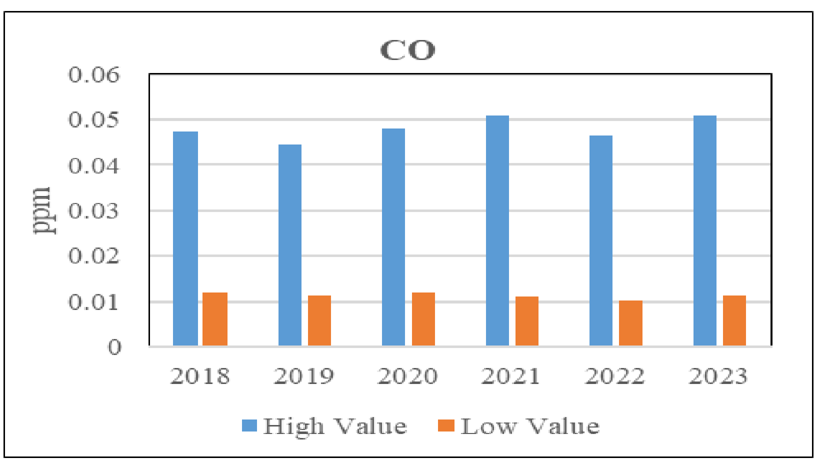

Figure 5(b). Graph of annual average values of CO for 2018–2023 in Pakistan

Overall, these patterns show how weather, rapid urban growth, and different pollution sources all work together to shape air quality in Pakistan's biggest cities.

Table 4. Air Pollutant Summary by City (2018–2023)

City	**Avg CO (mol/m^2)**	**Avg NO^2 (mol/m^2)**	**Avg O^3 (mol/m^2)**
Lahore	0.043292	0.000135	0.128146
Faisalabad	0.040405	0.000085	0.128011
Gujranwala	0.039294	0.000066	0.129268
Multan	0.038432	0.000058	0.126344

Table 4 presents the average levels of carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3) in four major Pakistani cities. Lahore stands out with the highest concentrations of both CO (0.0433 mol/m²) and NO_2 (0.000135 mol/m²), likely because of its heavy traffic, numerous industries, and dense population all of which lead to more pollution from combustion. Faisalabad and Gujranwala show moderate CO levels (0.0404 and 0.0393 mol/m²) and lower NO_2, reflecting their smaller size and slightly less industrial activity compared to Lahore. Multan records the lowest CO (0.0384 mol/m²) and NO_2 (0.000058 mol/m²), consistent with its less crowded and less industrialized environment. Interestingly, ozone (O_3) levels were fairly similar across all four cities. This suggests that ozone is shaped more by broader regional atmospheric conditions and sunlight-driven chemical reactions than by local pollution sources. Overall, these findings highlight how urban growth, traffic, and industry mainly drive CO and NO_2 pollution, while ozone levels tend to be more consistent regionally.

3.2 Relationship between Land Surface Temperature and Air Pollutants

We used autocorrelation analysis to explore how land surface temperature is linked to levels of NO_2 and O_3, two pollutants closely tied to smog, as shown in Table 5. The results showed a clear, statistically significant connection, with R^2 values between 0.45 and 0.72 ($p < 0.05$). This means that temperature changes have a moderate to strong effect on how these pollutants behave.

Table 5. Pollutant-Temperature Statistical Analysis

City	Pollutant	Pearson r	R2	Regression Slope (mol/m2 per ∘C)	Significance (p)	Notes
Lahore	NO2	-0.7892	-0.622	3.00×10−5	0.062	Strong temp sensitivity

Lahore	O3	-0.2343	0.0549	−1.20×10−3	0.655	Weak, descriptive only
Lahore	CO	0.0995	0.0099	2.31×10−4	0.8513	Weak, descriptive only
Faisalabad	NO2	-0.7795	-0.607	1.51×10−5	0.0676	Strong temp sensitivity
Faisalabad	O3	-0.2065	0.0426	−1.09×10−3	0.6947	Weak, descriptive only
Faisalabad	CO	-0.0818	0.0067	−1.94×10−4	0.8775	Weak, descriptive only
Gujranwala	NO2	-0.7741	-0.599	9.31×10−6	0.0708	Strong temp sensitivity
Gujranwala	O3	-0.2828	0.08	−1.30×10−3	0.5871	Weak, descriptive only
Gujranwala	CO	-0.0003	0	−4.84×10−7	0.9996	Weak, descriptive only
Multan	NO2	-0.4852	-0.235	5.26×10−6	0.3293	Moderate relationship
Multan	O3	-0.15	0.0225	−9.92×10−4	0.7767	Weak, descriptive only
Multan	CO	-0.2218	0.0492	−5.01×10−4	0.6728	Weak, descriptive only

The analysis of how outdoor temperature affects air pollution in Lahore, Faisalabad, Gujranwala, and Multan revealed some clear patterns for NO_2, O_3, and CO (see Table 5). NO_2 showed a strong negative relationship with temperature in Lahore (r = -0.79, R^2 = -0.62), Faisalabad (r = -0.78, R^2 = -0.61), and Gujranwala (r = -0.77, R^2 = -0.60), which means that winter low temperatures are closely linked to higher NO_2 levels in these cities. In Multan, this connection was more moderate (r = 0.49, R^2 = 0.24). On the other hand, both ozone (O_3) and carbon monoxide (CO) showed only weak links to temperature in all four cities, with correlation values ranging from -0.28 to 0.10 and low R^2 values, suggesting that their levels don't change much with temperature. Overall, these results indicate that NO_2 is much more sensitive to temperature changes than O_3 and CO. This suggests that strategies to manage NO_2 pollution should take temperature effects into account.

Additionally, Figure 6 illustrates a generally negative correlation between NO_2 concentration and temperature across all cities.

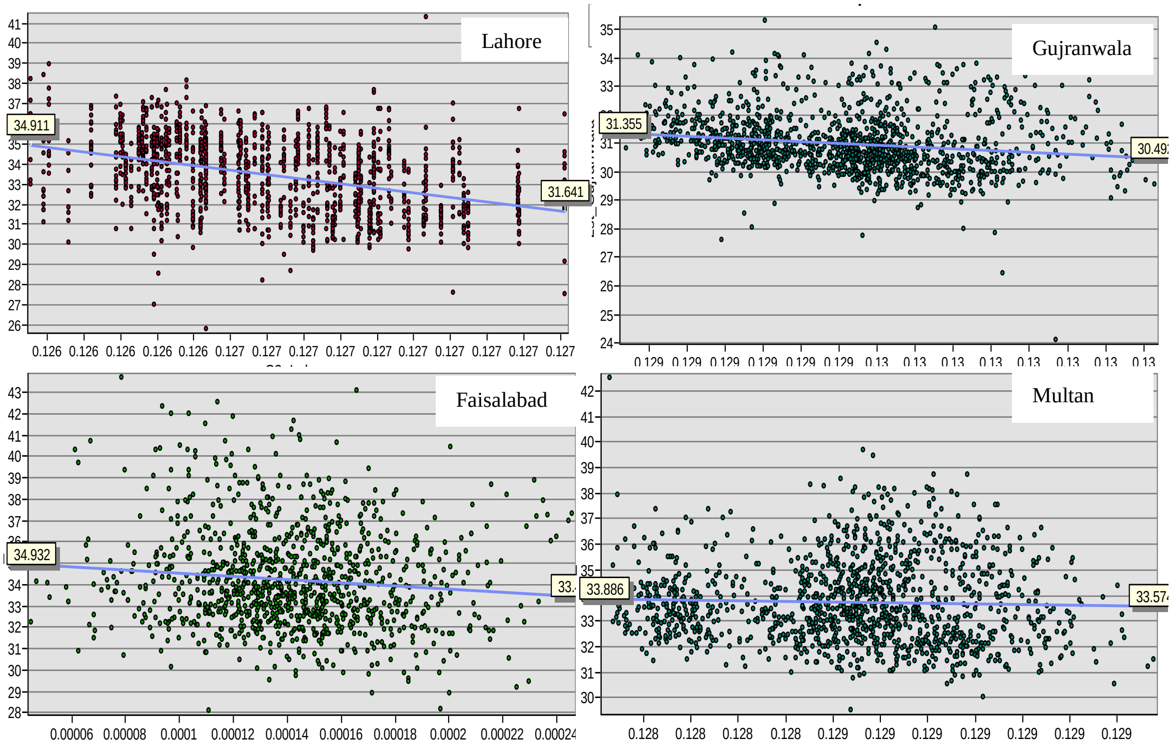

Figure 6. Temperature vs NO2 X-axis = Temperature (°C), Y-axis = NO_2 (mol/m²).

We found that NO_2 levels were higher when temperatures were lower, especially in the winter. During this time, stable weather conditions and increased emissions from heating let pollutants build up in the air. As temperatures rise in the summer, the atmosphere mixes more and pollution can disperse more easily, leading to lower NO_2 levels (Ramírez-Aldaba et al., 2025). This pattern was especially noticeable in Lahore and Faisalabad, where heavy traffic and industrial activity add to the problem.

On the other hand, ozone (O_3) showed the opposite trend. Ozone levels went up as temperatures increased, as shown in Figure 7. This is because warmer temperatures and more sunlight speed up the chemical reactions that create ozone. The effect was particularly strong in Lahore, Gujranwala, and Faisalabad, where dense urban areas and higher emissions provide the right conditions for ozone to form. In Multan, the link between temperature and ozone was weaker, likely because the city has fewer industries and more agricultural land.

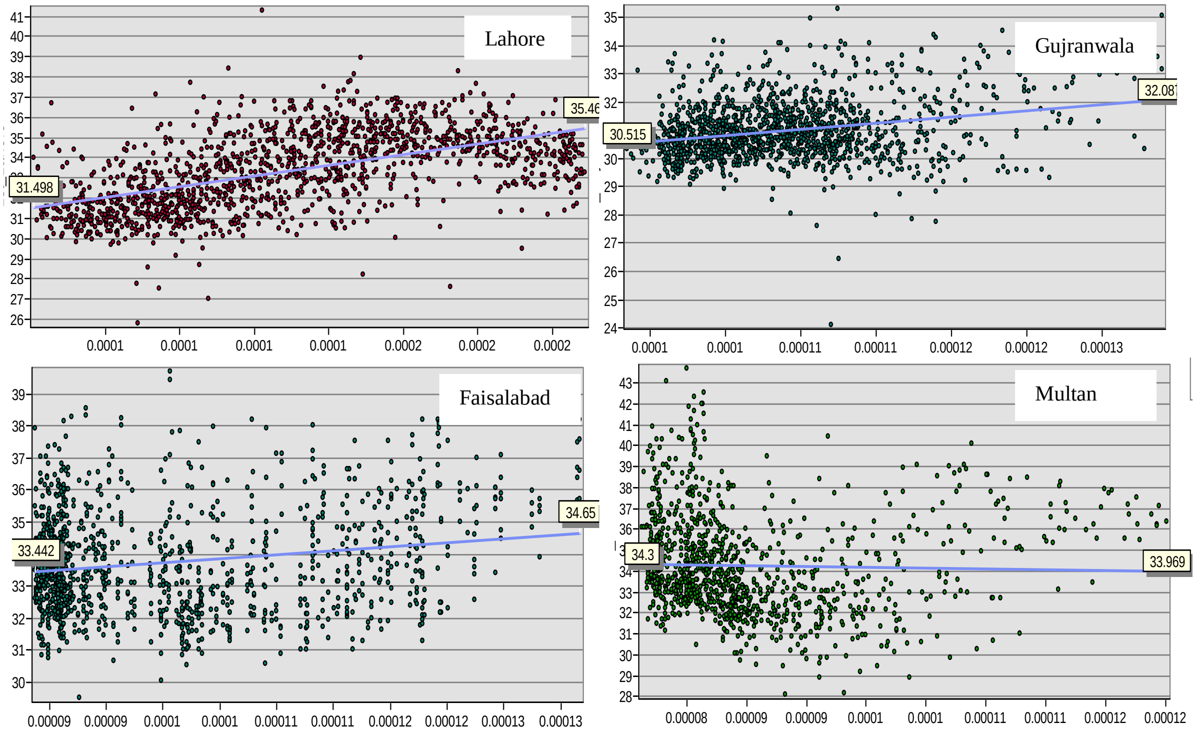

Figure 7. Temperature vs O_3 X-axis = Temperature (°C), Y-axis = O_3 (mol/m²)

These results show that land surface temperature has a big impact on smog-related air pollution, especially when it comes to how ozone forms through chemical reactions in the atmosphere. Higher temperatures don't just speed up these reactions they also make cities warmer overall, which can make smog last longer and become more intense.

3.3 Implications for Smog Formation and Urban Environmental Management

While comparing land surface temperature and pollutant levels together, our study shows that hotter conditions play a big role in making smog worse in Pakistan's largest cities. Pollutants like NO_2 and CO are the main building blocks for smog that intensifies during winters due to lack of atmosphere vertical mixing, while ozone created through chemical reactions that speed up in higher temperatures adds to the problem (Fuladlu & Altan, 2021). This means cities with lots of industry and heavy traffic, especially Lahore and Faisalabad, are more likely to experience frequent and intense smog.

These findings highlight the need for urban planning that tackles both sources of pollution and rising city temperatures. Expanding green spaces, such as urban forests, green roofs, and more vegetation, can help cool city surfaces and clean the air at the same time. It's also important to use data-driven policies to reduce emissions from factories and vehicles in order to manage smog more effectively. The study findings are in line with studies from other fast-growing regions in South and East Asia, which also found a strong connection between temperature and pollution during smog episodes (Hoque et al., 2020; Wang et al., 2020). This research offers local evidence to guide climate-aware air quality policies for Pakistan.

4. Conclusion

1. This study examined how major air pollutants (NO_2, CO, and O_3) vary over time and space and how these changes relate to land surface temperature (LST) in four of Pakistan's largest cities: Lahore, Gujranwala, Faisalabad, and Multan, using Sentinel-5P satellite data and the Google Earth Engine platform from 2018 to 2023.
2. We found clear seasonal patterns in pollutant levels. NO_2 and CO were consistently higher in winter, mainly due to increased industrial and vehicle emissions, combined with stable weather that traps pollutants near the ground and leads to smog. During summer and monsoon seasons, these pollutants dropped as warmer temperatures and more sunlight helped mix and disperse the air. Ozone (O_3), created through chemical reactions in the atmosphere, followed the opposite pattern it peaked in spring and summer, when higher temperatures and strong sunlight speed up its formation.
3. The study also identified a strong link between land surface temperature and pollutant levels, especially in more urbanized and industrial cities like Lahore and Faisalabad. In Multan, where there's less industry and more agricultural land, this link was weaker. This shows that how a city is built, what it's used for, and how much industry it has all play a big role in how severe its air pollution and smog problems are.
4. The COVID-19 lockdown gave us a unique chance to see how quickly air quality and surface temperatures could improve when human activity was reduced, highlighting how much of an impact our daily actions have on urban air pollution.
5. Overall, this research demonstrates the power of using satellite data and advanced analysis tools to improve the relationship between air pollution, temperature, and urban growth in developing countries. It also highlights the urgent need for targeted actions like stricter emission controls, cleaner transportation, and expanding urban green spaces to reduce smog, protect public health, and build climate resilience in Pakistan's major cities.

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