OPEN ACCESS
International Journal of Innovations in Science & Technology

Assessment of Long-Term Relationship of Tropospheric NO_2 with Meteorological Parameters in Pakistan

Hamza Malik[1], Sawaid Abbas[1,2*], Fatima Naeem[1], Nawai Habib[1], Nosheen Akhter[3]
[1]Smart Sensing for Climate and Development, Center for Geographical Information System, University of the Punjab, Lahore, Pakistan
[2]Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hong Kong SAR
[3]Institute of Geology, University of the Punjab, Lahore, Pakistan
***Correspondence:** sawaid.gis@pu.edu.pk (S.A); sawaid.abbas@connect.polyu.hk

Citation | Malik. H, Abbas. S, Naeem. F, Habib. N, Akhter. N, "Assessment of Long-Term Relationship of Tropospheric NO_2 with Meteorological Parameters for Sustainability in Pakistan", IJIST, Special Issue pp 240-256, June 2024
Received | May 30, 2024 **Revised |** June 05, 2024 **Accepted |** June 08, 2024 **Published |** June 15, 2024.

Introduction: Assessing the atmospheric changes is the main concern with increasing population density over the years within the countries moving towards industrialization to meet their in-house demands. Pakistan is placed in the world's most deteriorating air quality list of countries.
Novelty Statement: This research exclusively explores tropospheric NO_2 patterns in Pakistan from 2005-2022 using OMI data, revealing seasonal variations and anthropogenic effects, providing serious understandings for air quality policy in developing regions.
Material and Methods: This study analyzed the tropospheric Nitrogen Dioxide (NO_2) patterns by using the observations from the Ozone Monitoring Instrument (OMI) and their possible relation with meteorological parameters (rainfall, wind speed, temperature). The analysis assessed the level of tropospheric NO_2 pollution pattern at the district level in Pakistan over the time range of (2005-2022), covering mega urban centers including Lahore, Faisalabad and Peshawar.
Results and Discussion: A rising trend of 9.028 x 10^15 molecules/cm² in NO_2 concentrations was observed in the winter season. Lower values around 1.9 x 10^15 molecules/cm² were observed in the summer season. Interestingly, a dipping concentration of these pollutants was observed in pre-monsoon months, except in Peshawar where the values dipped down during the spring period. Diverse patterns were observed between NO_2 and temperature, wind speed, and rainfall over the years. In the industrial-operated cities with heavy traffic on the roads, a large dense population, agricultural fires, and fossil fuel burning defined the anthropogenic emission levels in the lower layer of the atmosphere in the cities.
Conclusion: This study will allow regulators to comprehend or understand the anthropogenic emission levels in the major cities considering the origin of the emission activities.
Keywords: NO_2; OMI; AURA; Meteorological parameters; Giovanni.

Introduction:

Nitrogen oxides ($NO_x = NO_2 + NO$) are important air pollutants and have a significant impact on the chemical composition of the troposphere. NO_x is particularly important in ozone formation and therefore has a significant impact on air quality. [1]. Air pollution is one of the most serious environmental threats to both human health and the global economy [2]. It is also considered one of the growing environmental problems in South Asian developing countries such as Pakistan. Since 1990, massive land use and land cover change (LULCC), urbanization, rapid industrialization, and economic development have improved in Pakistan[3]. Based on ground, instrumented parameters and satellite observations, increased NOx levels have been reported in many parts of the world[4], [5], [6], [7].

NO_2 concentrations in the troposphere are greatly influenced by human activities and changes in near-surface vegetation cover [8] Road traffic has been identified as a major factor contributing to poor air quality in urban areas[9], [10]. Automobiles greatly contribute to increasing the concentration of nitrogen oxides in cities through the combustion process of their engines [11]. In addition to NO_x, these vehicles emit significant amounts of CO_2, CO, HC, particulate matter and other toxins into the atmosphere, which have serious implications for environmental health. However, a new important factor has emerged: fossil fuel consumption in thermal power plants [12] . However, emissions from agricultural soils from large amounts of nitrogen fertilizers and biomass burning in the region have increased tropospheric NO_2 concentrations. aerosol pollution has negative health effects such as cardiovascular disease, asthma, bronchitis, lung disease, lung cancer, breathing problems and death[13].

Previous studies investigating the spatial variability of NO_2 in the troposphere can be summarized as follows. On the one hand, remote sensing data with partly much coarser spatial resolution were used, which was limited to capturing the strong gradients in NO_2 distribution, especially in urban agglomerations. Or another reference point sauce. On the other hand, high-resolution remote sensing data are aggregated across administrative units, reducing the overall physical spatial resolution through averaging[14]. Tropospheric NO_2 sections from over decade of information gathered by the Worldwide Ozone Observing Examination (GOME), the Filtering Imaging Retention Spectrometer for Environmental Map making (SCIAMACHY), and the Ozone Checking Instrument (OMI) have been utilized for air quality investigations and satellite instrument approvals[15], [16], [17], [18]. The new satellite mission Tropospheric Checking Instrument (TROPOMI) on board the European Space Office (ESA) Sentinel-5 Antecedent (S5P) satellite gives everyday worldwide perceptions of NO_2 sections with a lot better spatial goal (3.6 km × 7.2 km) contrasted with its ancestors. Therefore, the specification of tropospheric NO_2 column derived from the product of OMI sensor on board AURA satellite is utilize to determine the variation in nitrogen dioxide concentration in this study. As OMI data in wide spread usage can understand the contaminant of nitrogen dioxide at large scale of 20 up to 30 kilometers.

This study investigates long-term trends (2005-2022) of nitrogen dioxide (NO_2) and weather patterns (temperature, rainfall, wind speed) in Lahore, Faisalabad, and Peshawar, Pakistan's most polluted districts. We analyze how NO_2 levels fluctuate monthly and seasonally using district-level statistical analysis and linear regression. The goal is to understand how weather variations influence NO_2 concentrations and identify potential links to anthropogenic activities through graphical analysis of peak and low concentration periods. By examining these trends, we can gain valuable insights into the long-term evolution of air quality in these major Pakistani cities, allowing us to develop targeted strategies for air pollution mitigation.

The objective of this study was to investigate seasonal changes in air pollutants in Pakistan, focusing on nitrogen dioxide (NO_2) concentrations in the cities of Lahore, Faisalabad and Peshawar. It aims to empower policy makers by analyzing NO_2 and meteorological conditions in Pakistan's most polluted cities (2005-2022). Research into how weather and human activities affect NO_2 fluctuations will help develop targeted air pollution control measures. This will form the basis of air quality management strategies and sustainable development policies, ultimately creating a healthier and more livable environment for Pakistan's citizens.

Material and Methods:

A brief description of the methodology is illustrated in the flow diagram (Figure 1).

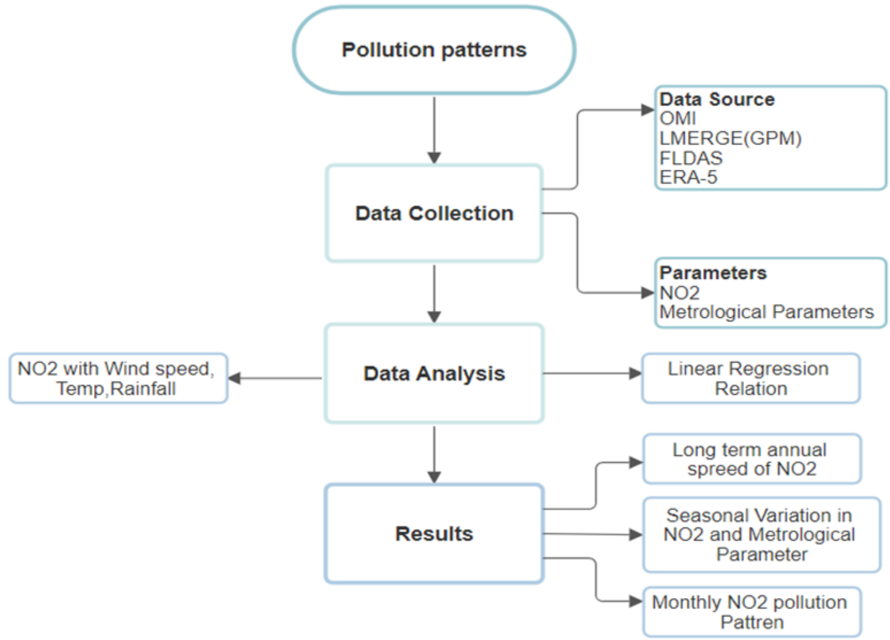

Figure 1: An overview of the methodology applied in this study

Study Area:

Pakistan's growing urbanization has raised concerns about air quality, particularly regarding nitrogen dioxide (NO_2) pollution. This study examined the long-term relationship between weather and climate in three major Pakistan cities from 2005 to 2022: Lahore, Faisalabad, and Peshawar (as show in Figure 2). The map provides a visual representation of Pakistan's national boundaries and the specific locations of these cities within the country. The study aims to determine monthly and seasonal changes in nitrogen dioxide pollution in these regions by using statistical methods. It will also be investigated how weather conditions affect nitrogen dioxide levels, focusing on maximum and minimum periods. Finally, this study aims to understand how human activity affects nitrogen dioxide patterns in these cities.

Pakistan is in South Asia and has a population of over 231.4 million people. Pakistan covers an area of 307,304 square miles and is bordered by China to the north, India to the east, and Iran and Afghanistan to the southwest. The Arabian Coast forms a 1,046 km long coastline in the southern part of the country. The northern region of Pakistan is home to the world's second highest peak, K-2 (8611 m), and the world's largest glaciers (Siachen (76 km) and Baifo (67 km)) that flow into the Indus River. Pakistan consists of the Indus Plain, the Northern Range, and the hills and plateaus extending from the Khyber Pass to Baluchistan. It is a subtropical and semi-arid region. Due to seasonal changes in monsoons and associated winds, the region experiences unusual weather[19]. The southern slopes of the Himalayas and the northern hills of Pakistan receive 2,000 mm of rainfall per year, while the remaining three-quarters of Pakistan receives less than 250 mm. Pakistan's four distinct seasons, spring (March to May), summer (June to August), fall (September to November), and winter (December to February), are a special region to study the spatial and temporal distribution of aerosols pattern [20].

The three areas of interest included in the present study are Lahore, Faisalabad, and Peshawar in Pakistan. Lahore (31.52°N, 74.36°E), Faisalabad (31.42°N, 73.08°E), and Peshawar (34.31°N, 71.58°E) represent Pakistan's urban spectrum. Lahore, a densely populated metropolis (11 million) bordering the Ravi River, experiences hot, semi-arid summers (36-46°C) [21]industrial emissions, vehicular traffic, and nearby agricultural burning significantly elevate NO_2 pollution levels[21]. Faisalabad, a prominent industrial center[22], faces similar challenges with vehicular emissions impacting air quality. Summer temperatures here can reach scorching highs of 48°C, with a wider seasonal range (-1°C to 48°C) compared to Lahore [21]. Peshawar, situated closer to the Afghan border, experiences a cooler climate with winter lows averaging 10°C and summer highs around 40°C[21]. Despite this, Peshawar also struggles with air pollution due to domestic burning and vehicle emissions. All three cities have witnessed significant population growth between 1998 and 2017, with Lahore increasing by 116%, Faisalabad by 60%, and Peshawar by 101% (Pakistan Bureau of Statistics).

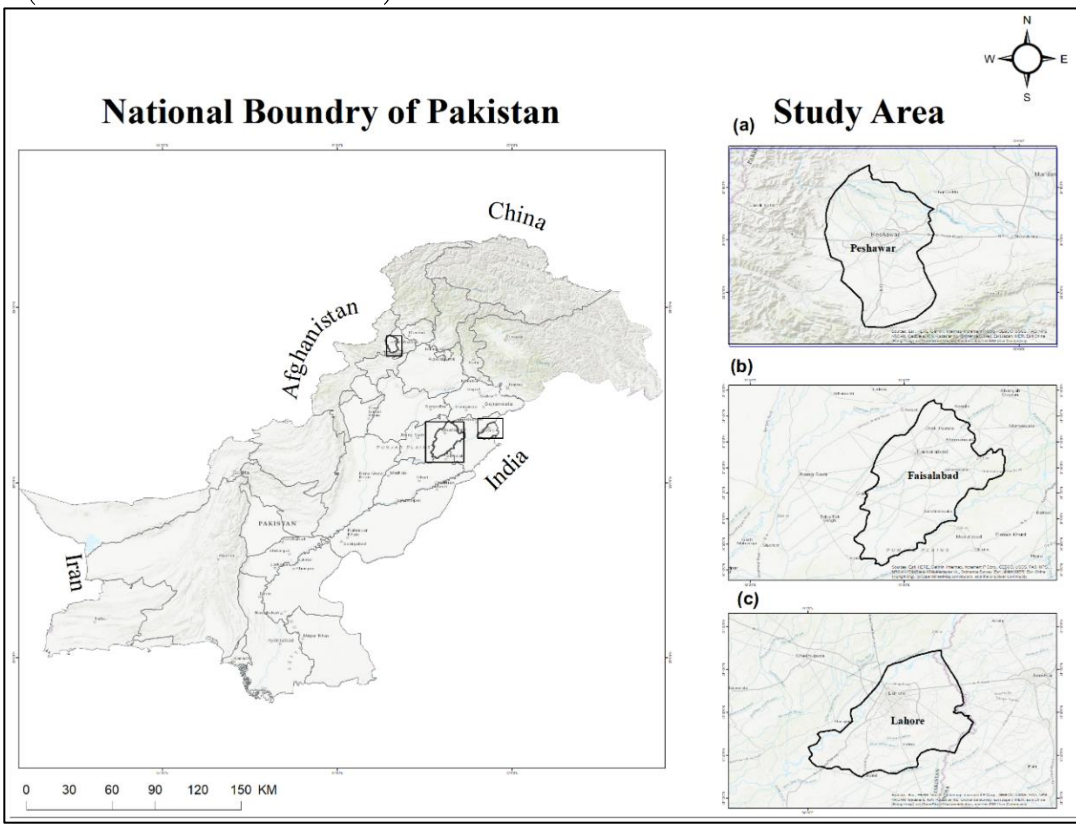

Figure 2: Topographic map showing the administrative divisions of Pakistan and the regions involved in the study. (a) displays data for Peshawar, (b) displays data for Faisalabad, (c) displays data for Lahore.

Data Used:

In the current study, we used four different kinds of data set, as shown in Table 1

Table 1: Detailed information on data used in the current study.

Data Source	Parameter	Units	Spatial Resolution	Temporal Resolution
OMI	NO_2	molecules/cm²	0.25° x 0.25°	Daily
IMERGE(GPM)	Precipitation	mm	0.1° x 0.1°	30 min
FLDAS	Wind Speed	m s^{-1}	0.1° x 0.1°	15 min
ERA-5	Temperature	K	0.25° x 0.25°	Monthly

Nitrogen Dioxide (NO_2) Data:

Our analysis utilizes daily nitrogen dioxide (NO_2) data from the Ozone Monitoring Instrument (OMI) onboard NASA's AURA satellite (launched 2004)[23]OMI data offers high-resolution observations in the ultraviolet and visible spectrum (https://aura.gsfc.nasa.gov/omi.html). We specifically focus on level 3 NO_2 data ($OMNO_2$ 003) with less than 30% cloud cover [24]. The OMI data incorporates two key advancements: improved techniques for extracting NO_2 slant columns using monthly sun irradiance data, and a more accurate method for deriving monthly NO_2 and temperature profiles [25]. Monthly averaged daily data (2005-2022) was obtained in molecules/cm² from Giovanni https://giovanni.gsfc.nasa.gov/giovanni/ and converted to CSV format for analysis.

Meteorological Data:

The current study examined the effects of seasonal fluctuations in three key meteorological parameters: precipitation, wind speed, and temperature, on nitrogen dioxide (NO_2) pollution levels across Lahore, Faisalabad, and Peshawar in Pakistan. Precipitation (P): Daily precipitation data was obtained from the Global Precipitation Measurement (IMERGE) Level 3 product, offering a spatial resolution of 0.1° x 0.1° temporal resolution of 30min precipitation data in millimeters (mm). Monthly averaged data from the GIOVANNI web portal (https://disc.gsfc.nasa.gov/) was used to estimate rainfall rates (mm/day) within the study area. This dataset covers a temporal range since the year 2000 (passive remote sensors). Wind Speed (WS): Wind speed data was acquired from the FLDAS Land Data Assimilation System model. Monthly averaged wind speed data was retrieved from GIOVANNI to analyze wind patterns across the study region over the timeframe of interest. This dataset boasts a spatial resolution of 0.1° x 0.1° and a temporal resolution of monthly precipitation data in meter per second ($m\ s^{-1}$) since 1982. Temperature (T): Temperature data came from the fifth generation ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis product, accessible through the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/). This gridded dataset, generated by the European Centre for Medium-Range Weather Forecasts (ECMWF), incorporates data assimilation techniques to combine existing climate data with new observations for improved climate assessments and forecasts [26]. The data has a spatial resolution of 0.25° x 0.25° and a temporal resolution of monthly data in Kelvin (K). Temperature measurements are retrieved from a height of 2 meters.

Data Analysis:

This study employs linear regression analysis to investigate the relationships between NO_2 pollution and various meteorological parameters in Lahore, Faisalabad, and Peshawar, Pakistan. Linear regression is a statistical technique that models the linear relationship between a dependent variable (in this case, NO_2 concentration) and one or more independent variables (meteorological parameters like precipitation, wind speed, and temperature) [27]. The coefficient of determination (R^2) is utilized to assess the strength and direction of these relationships. Positive R^2 values indicate a positive correlation, while negative values suggest an inverse relationship. Additionally, the magnitude of R^2 reflects the strength of the association, with values closer to 1 signifying a stronger connection [28]. Monthly averaged NO_2 data (2005-2022) in molecules/cm² was obtained from the GIOVANNI online portal (https://giovanni.gsfc.nasa.gov/giovanni/) for the specific latitude and longitude coordinates of each study district (Lahore, Faisalabad, Peshawar) extracted using ArcGIS software (version 10.8) from district shapefiles.

In Meteorological Data Monthly averaged data for precipitation (P), wind speed (WS), and temperature (T) was obtained from relevant sources and compiled alongside the NO_2 data in a CSV format suitable for statistical analysis using Microsoft excel.

The compiled dataset was subjected to linear regression analysis using appropriate statistical software. The analysis aimed to identify statistically significant relationships between NO_2 concentrations and each meteorological parameter (P, WS, T). Determine the strength and direction of these relationships using the R^2 coefficient. Develop trend line equations to depict the linear relationships between NO_2 and the meteorological parameters.

$$\mathbf{y} = ax + b \quad [29] \qquad (1)$$

$$\mathbf{r} = \frac{\mathbf{n}(\sum \mathbf{xy}) - (\sum \mathbf{x})(\sum \mathbf{y})}{\sqrt{\mathbf{n}(\sum \mathbf{x}^2 - (\sum \mathbf{x})^2) \cdot (\mathbf{n} \sum \mathbf{y}^2 - (\sum \mathbf{y})^2)}} \quad [30] \qquad (2)$$

$$\mathbf{R}^2 = \frac{\mathbf{1} - \Sigma(\mathbf{yi} - \acute{y}\mathbf{i})^2}{\Sigma(\mathbf{yi} - \bar{y})^2} \quad [31] \qquad (3)$$

Correlation coefficient (r) is calculated using Equation 2. The coefficient of determination (R^2) is obtained by squaring the correlation coefficient (Equation 3). By analyzing the correlation coefficients (R^2) and trend line equations (Equation 1), this study will unravel the potential influence of precipitation, wind speed, and temperature on NO_2 pollution patterns in the three Pakistan cities under investigation.

Result:

Long Term Annual Spread of NO_2 on District Level:

Figure 3 shows the temporal contribution of nitrogen dioxide from 2005 to 2015 and from 2016 to 2022 in the Punjab and Khyber Pakhtunkhwa regions selected in this study. The results showed that the levels of nitrogen dioxide plumes increased at the highest possible frequency in the cities of Lahore, Faisalabad and Peshawar. This effect can be seen in the average annual time cycle, or NO_2 turnover, of a region. From 2016 to 2022, higher levels of nitrogen dioxide emissions were observed in the cities of Lahore, Faisalabad, and Peshawar, showing a significant increase compared to the pattern of the previous decade (2005-2022). The significant differences between these two periods are clear in the analysis of actual pollution patterns in the cities of Lahore, Faisalabad and Peshawar. The main causes of anthropogenic NO_2 emissions in Pakistan as industrial activities, increased road traffic, high population density, agricultural fires, and fossil fuel combustion.

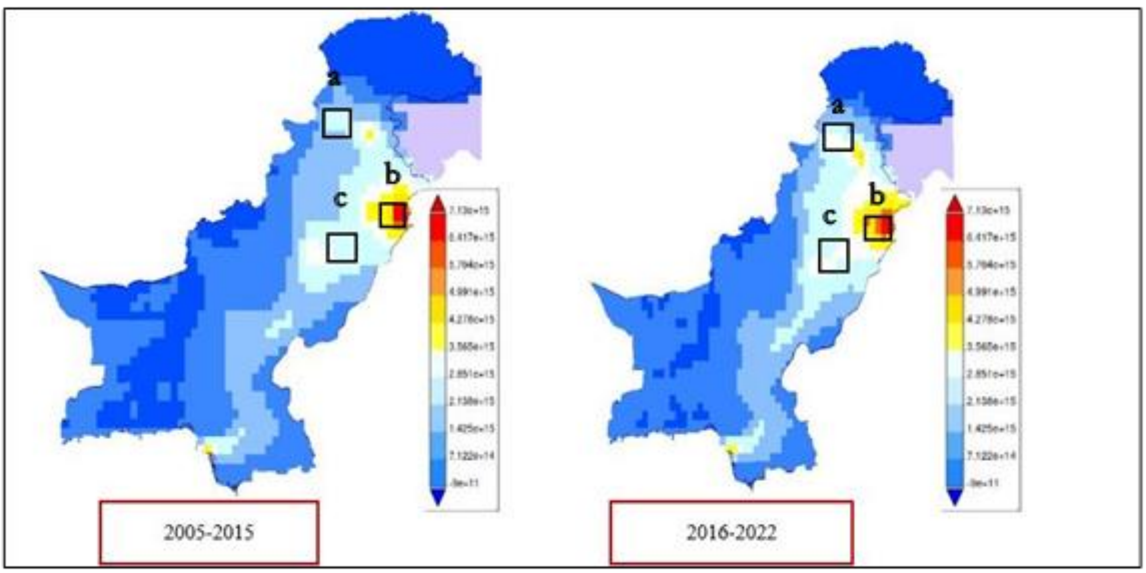

Figure 3: Shows the long term annual averaged NO_2 (molecules/cm2) changes in the districts of Pakistan during the period from 2005-2015 and 2016-2022. Box **a** represent Peshawar, box **b** shows Lahore and box **c** represent Faisalabad (Note: The Purplish color in this map indicates no data values; It has been used to visually complete the entire boundary of Pakistan.)

Seasonal Variations in NO_2 and Meteorological Factors:

This study investigates the potential impact of meteorological variables on nitrogen dioxide (NO_2) pollution patterns in selected regions. The basic premise is that analyzing variables such as precipitation, wind speed and temperature can provide insight into NO_2 emission patterns and the resulting impact on air quality. This study aims to clarify the role of meteorological conditions in shaping air pollution patterns by establishing relationships between climatic factors and NO_2 concentrations.

NO_2 and Rainfall:

Winter Relationships:

Winters in Pakistan pose complex air quality challenges, with a combination of factors causing nitrogen dioxide (NO_2) levels to reach dangerous levels. Lower temperatures lead to increased reliance on coal heating and natural gas, especially in residential and commercial environments, leading to increased NO_2 emissions[32], [33]. Winter conditions also extend the life of NO_2 in the atmosphere due to cooler temperatures, reduced sunlight for photolysis (decomposition by sunlight), and stable air conditions with low winds to prevent dissipation [34], [35], [36] . Burning biomass for home cooking in winter can further increase NO_2 levels in some areas. [35], [36]. In winter, these factors, combined with a shallower boundary layer, trap pollutants near the surface [37].

A study on the winter season (DJF: December-January-February) of Lahore, Faisalabad and Peshawar from 2005 to 2022 shows the relationship between precipitation and NO_2 concentration. There is a negative correlation. Higher rainfall (mm) generally results in lower NO_2 pollution levels (molecules/cm²). This trend, caused by precipitation removing pollutants from the atmosphere, is supported by the correlation coefficient (R^2) calculated for each city and month. Lahore has the weakest negative correlation (December: $R^2 = 0.058$, January: $R^2 = 0.186$) compared to Faisalabad (December: $R^2 = 0.16$, January: $R^2 = 0.13$) and Peshawar (December: $R^2 = 0.231$, January: $R^2 = 0.169$).

However, the precipitation patterns themselves vary. All three cities have increased NO_2 pollution across the DJF, but with different rainfall patterns. Lahore and Faisalabad saw an increase in rainfall in January compared to December and February, while Peshawar decreased in December and then increased in January. This highlights the complexity of relationships. Precipitation has some purifying effect, as shown by the negative correlation, but its effectiveness and frequency vary across cities, limiting its ability to single-handedly address the worrying trend of increasing NO_2 pollution in Pakistani cities during winter.

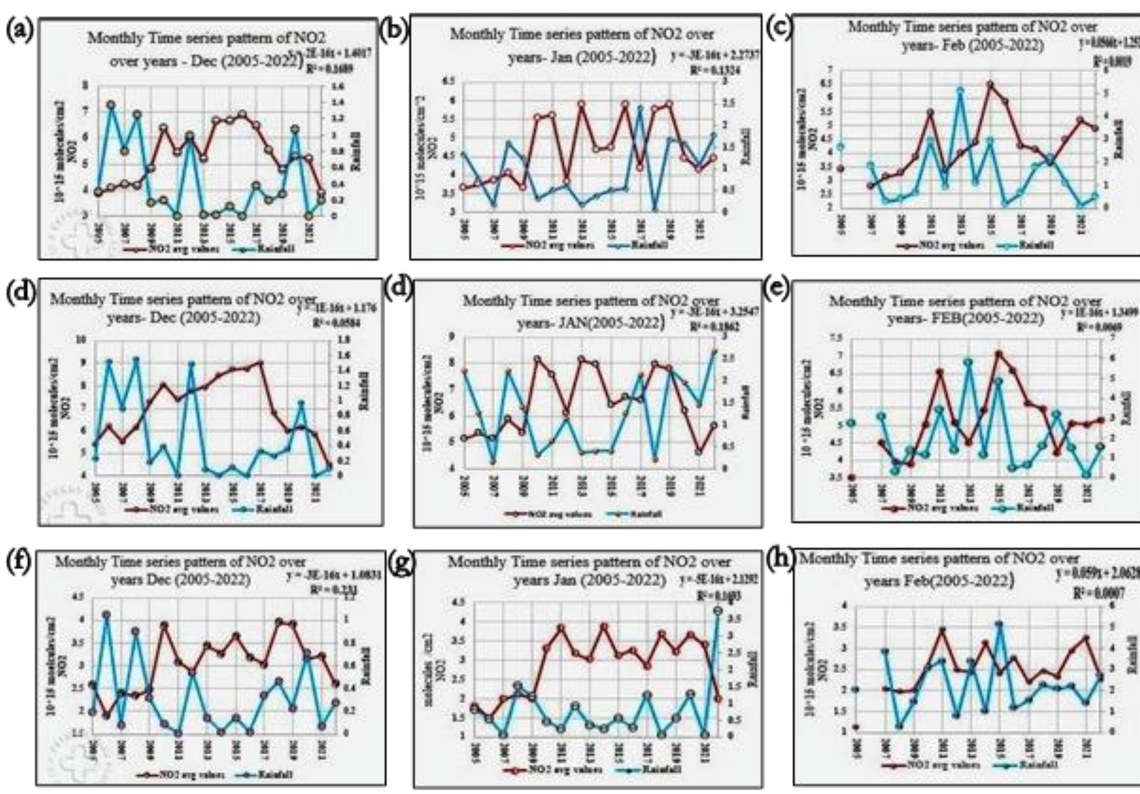

Figure 4: This figure shows the variations in rainfall and Nitrogen Dioxide (NO_2) levels throughout the Winter Season in three Pakistani cities. **(a)** displays data for Faisalabad in December, **(b)** shows Faisalabad data for January, **(c)** represents Faisalabad data for February, **(d)** displays data for Lahore in December, **(e)** shows Lahore data for January, **(f)** represents Lahore data for February, **(g)** displays data for Peshawar in December, **(h)** shows Peshawar data for January, **(i)** represents Peshawar data for February (Note: empty values are missing values in dataset).

Spring Relationships:

Spring in Pakistan presents difficult air quality challenges for NO_2. Agricultural practices such as burning wheat residue release pollutants, and rising temperatures increase emissions from road traffic, especially vehicles with two-stroke engines. Industrial activity can also recover from the winter slump. Spring in Pakistan presents difficult air quality challenges for NO_2. Agricultural practices such as burning wheat residue release pollutants, and rising temperatures increase emissions from road traffic, especially vehicles with two-stroke engines. Industrial activity can also recover from the winter slump. Analysis of the relationship between rainfall and NO_2 pollution in Lahore, Faisalabad and Peshawar (March 2005 to March 2022) revealed several interesting patterns. All three cities show a generally negative correlation, with higher precipitation (mm) potentially leading to lower NO_2 pollution (molecules/cm²) due to rainwater purifying the atmosphere. However, the strength of this correlation is dependent on Lahore showing the weakest correlation (March: R^2=0.148, April: R^2=0.0049, May: R^2=0.0058), while Peshawar shows a stronger negative correlation in March. indicates a relationship (R^2= 0.34). May (R^2=0.0024). Interestingly, Faisalabad shows an inverse relationship in March (R^2=0.12) and May (R^2=0.0004), indicating that rainfall has minimal impact on NO_2 levels. Precipitation patterns themselves also vary. All three cities experienced increased precipitation in March and May, but NO_2 emission trends were different. Lahore's NO_2 levels decrease in May, while Faisalabad and Peshawar have increased NO_2levels despite increased rainfall.

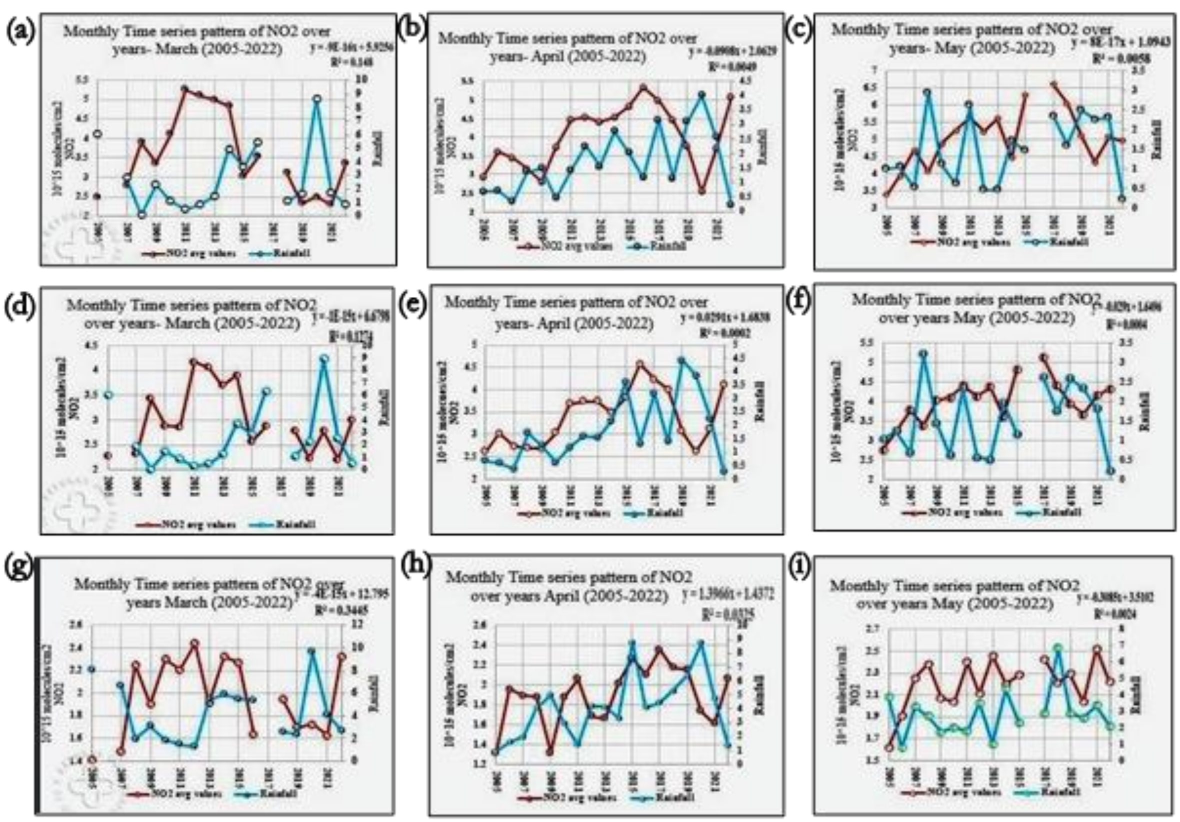

Figure 5: This figure shows the variations in rainfall and Nitrogen Dioxide (NO_2) levels throughout the spring Season in three Pakistani cities. **(a)** displays data for Lahore in March, **(b)** shows Lahore data for April, **(c)** represents Lahore data for May, **(d)** displays data for Faisalabad in March, **(e)** shows Faisalabad data for April, **(f)** represents Faisalabad data for May, **(g)** displays data for Peshawar in March, **(h)** shows Peshawar data for April, **(i)** represents Peshawar data for May (Note: empty values are missing values in dataset).

Summer Relationships:

Summer and Monsoon season (June-August) in Lahore, Faisalabad, and Peshawar presents a complex interplay between rainfall and NO_2 pollution. All three cities exhibit a generally weak negative correlation in June and August, suggesting some cleansing effect from rainfall. However, the strength of this association varies, with Peshawar showing a stronger inverse relationship in August (R^2=0.43) compared to Lahore (R^2=0.07) and Faisalabad (R^2=0.12). Interestingly, July shows a weak positive or mixed relationship in all three cities (Lahore: R^2=0.10, Faisalabad=0.1207, Peshawar: R^2=0.01). This might be due to factors like increased agricultural burning or industrial activity during this month, counteracting the cleansing effect of rainfall. While NO_2 pollution has an overall rising trend across all three cities during the monsoon, rainfall patterns differ. Lahore and Faisalabad see a dip in rainfall in June and August, while Peshawar experiences a decrease in August only. This highlights the limitations of relying solely on precipitation for NO_2 mitigation and highlights the need for additional strategies, such as stricter emissions regulations and promotion of clean agricultural practices.

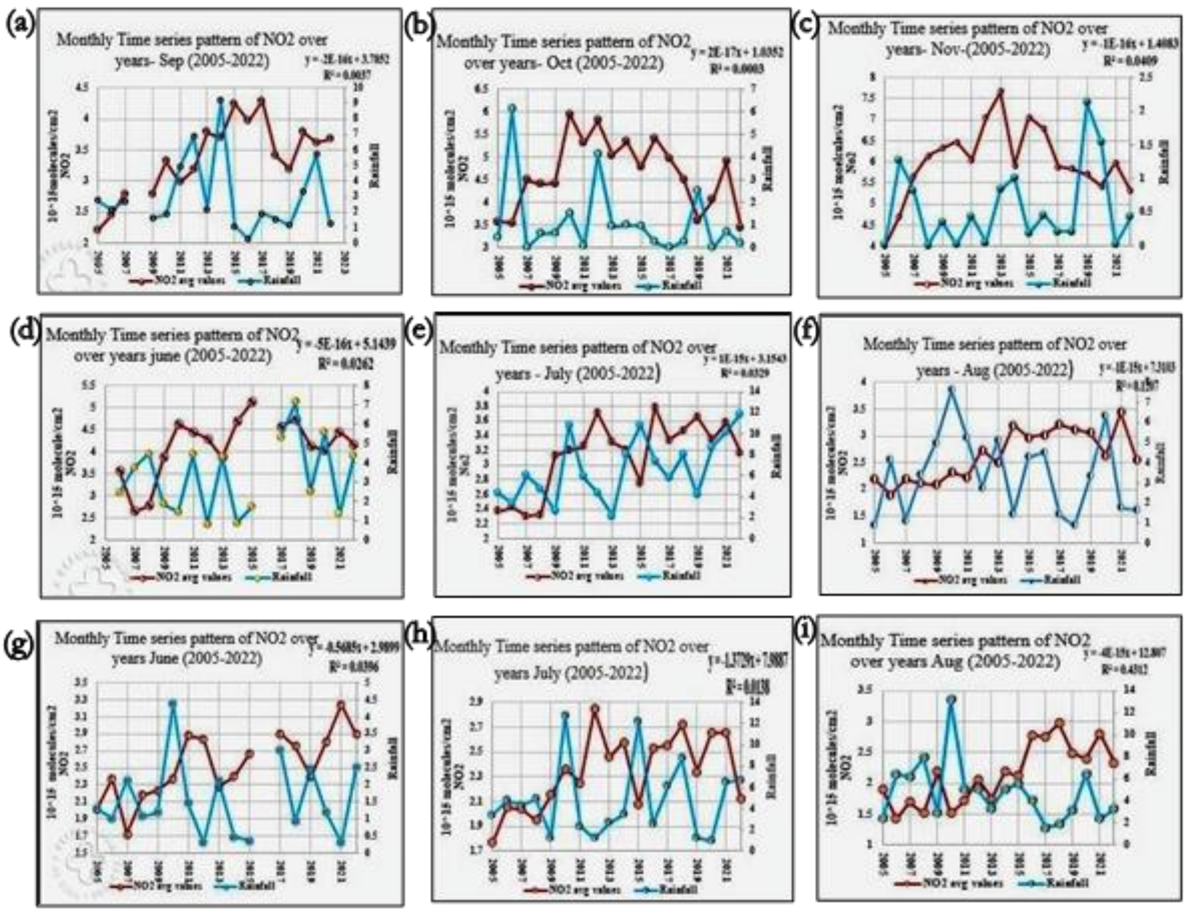

Figure 6: This figure shows the variations in rainfall and Nitrogen Dioxide (NO_2) levels throughout the Summer Season in three Pakistan cities. **(a)** displays data for Lahore in June, **(b)** shows Lahore data for July, **(c)** represents Lahore data for August, **(d)** displays data for Faisalabad in June, **(e)** shows Faisalabad data for July, **(f)** represents Faisalabad data for August, **(g)** displays data for Peshawar in June, **(h)** shows Peshawar data for July **(i)** represents Peshawar data for August (Note: empty values are missing values in dataset).

Autumn Relationships:

Autumn in Pakistan (September to November) presents a complex picture of NO_2 pollution and precipitation in Lahore, Faisalabad and Peshawar. Some months show a weak negative correlation (non-cleansing effect) (October-November in Faisalabad, R^2 = 0.0026-0.024), but the overall relationship is variable. In September, NO_2 pollution often increases in all three cities despite decreased rainfall (Lahore: R^2=0.0037, Faisalabad: R^2=0.16, Peshawar: R^2=0.003), which is like post-monsoon crop burning. This suggests that there is a factor. November in Lahore shows a weak inverse relationship ($R^2 = 0.0409$), while November in Peshawar shows a stronger inverse relationship ($R^2 = 0.09$) compared to September and October. Precipitation patterns also vary. Lahore and Faisalabad see reduced rainfall in September and October, while Peshawar sees reduced rainfall only in September. This highlights the limitations of precipitation as the only means of NO_2 control and highlights the need for additional strategies given the observed increase in NO_2 pollution in September and November in all three cities despite little rain. Fall weather in Pakistan is generally mild with lower temperatures and occasional rain.

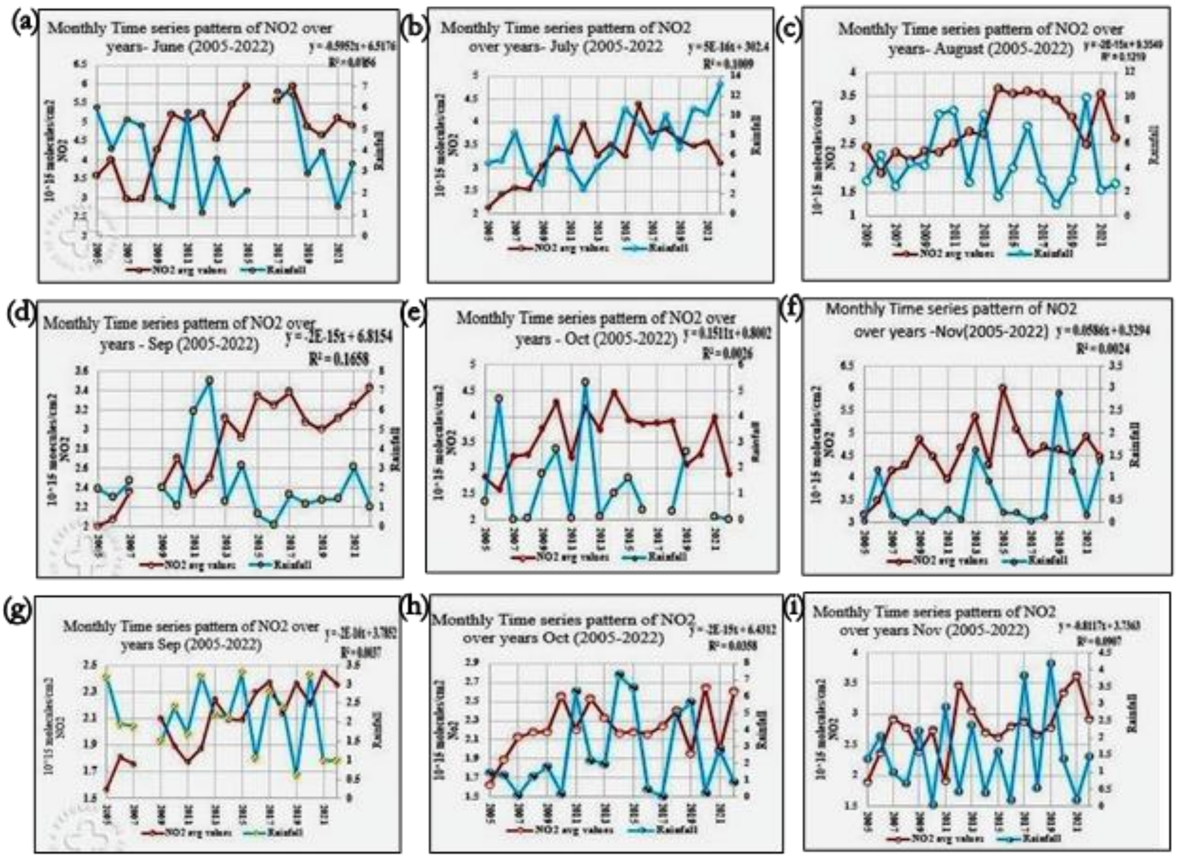

Figure 5: This figure shows the variations in rainfall and Nitrogen Dioxide (NO_2) levels throughout Autumn Season in three Pakistan cities. **(a)** displays data for Lahore in September, **(b)** shows Lahore data for October, **(c)** represents Lahore data for November, **(d)** displays data for Faisalabad in September, **(e)** shows Faisalabad data for October, **(f)** represents Faisalabad data for November, **(g)** displays data for Peshawar in September, **(h)** shows Peshawar data for October **(i)** represents Peshawar data for November (Note: empty values are missing values in dataset).

NO_2 and Temperature:

Winter Relationships:

Analysis of NO_2 pollution and temperature in Lahore, Faisalabad and Peshawar during winter (December to February) shows a complex relationship. There is a weak positive correlation between these two variables, but the strength of this relationship varies by city and month. In Lahore, the greatest effect of temperature was observed in December ($R^2 = 0.114$), with a weak positive correlation remaining in February ($R^2 = 0.029$). However, in January the effect of temperature on NO_2 levels (R^2=0.001) is minimal. Likewise, Faisalabad and Peshawar experience weak positive correlation throughout the winter. December and January show minimal influence and February shows a slightly stronger relationship (Faisalabad: December-R^2=0.04, January-R^2=0.03, February-R^2=0.09; Peshawar): December-R^2=0.04, January-R^2=0.03, February-R^2=0.09;

January-R^2=0.105, February-R^2=0.128). Despite the weak correlation, there are worrying trends. That means NO_2 pollution is steadily increasing in all three cities during the winter. This suggests that factors other than temperature, such as increased reliance on coal and natural gas for heating, are contributing significantly to the surge in winter NO_2 emissions.

Spring Relationships:

Spring (March-May) in Lahore, Faisalabad, and Peshawar reveals a complex interplay between NO_2 pollution and temperature. All three cities exhibit a weak positive correlation between the two variables, but the strength of this association varies across months (Lahore: March-R^2=0.02, April-R^2=0.04, May-R^2=0.11; Faisalabad: weak positive throughout; Peshawar: March-R^2=0.10, April-R^2=0.19, May-R^2=0.07). Interestingly, despite this positive correlation, NO_2 pollution increases in April and May across all cities (Lahore and Faisalabad) or shows an overall rising trend (Peshawar) since 2005. Temperatures dip in all three months across the cities, the positive correlation might indicate slightly warmer temperatures allow for some pollutant movement in March and April. However, May's weaker association and potential temperature dip could trap NO_2 closer to the ground.

Summer Relationships:

The monsoon season (June-August) in Lahore, Faisalabad, and Peshawar presents a multifaceted relationship between NO_2 pollution and temperature. Despite a weak positive correlation across all cities (Lahore: June-R^2=0.02, July-R^2=0.10, August-R^2=0.07; Faisalabad: weak positive throughout; Peshawar: June-R^2=0.0007, July-R^2=0.11, August-R^2=0.13), NO_2 pollution consistently rises in all three locations since 2005. Temperature trends vary: Lahore dips slightly in June and July before rising in August, Faisalabad experiences a dip throughout with an August rise, and Peshawar witnesses a consistent increase across the monsoon months. This suggests factors beyond temperature, such as agricultural burning or industrial emissions, likely contribute to the NO_2 surge during the monsoon season.

Autumn Relationships:

The post-monsoon season and Autumn (September-November) in Lahore, Faisalabad, and Peshawar reveals a weak relationship between NO_2 pollution and temperature. While the strength and direction of this association vary across cities and months, NO_2 pollution consistently rises throughout the period. September shows a weak positive association or weak relationship in Lahore and Faisalabad, while Peshawar exhibits a weak connection. October and November see a shift towards a weak negative relationship in Lahore and Faisalabad.

NO_2 and Wind Speed:

Winter Relationships:

Winter reveals a complex interplay between wind speed and NO_2 pollution in all three cities. Despite an overall weak relationship, the direction of the association varies. Lahore exhibits a weak negative relationship (inverse association) in December and February (R^2=0.01, 0.0003) but a weak positive relation in January (R^2=0.0049). Faisalabad shows a consistent weak inverse relationship throughout winter (R^2=0.03-0.08), while Peshawar has a weak negative relation in December and January (R^2=0.36, 0.16) transitioning to a weak association in February (R^2=0.03). Interestingly, NO_2 pollution shows a rising trend across all cities throughout winter despite variations in wind speed. Lahore's wind speed remains steady, Faisalabad's dips in recent years, and Peshawar's dips in December and January. This suggests factors beyond wind speed, likely emission sources, significantly influence winter's NO_2 surge.

Spring Relationships:

The pre-monsoon season (March-May) across Lahore, Faisalabad, and Peshawar presents a complex interplay between wind speed and NO_2 pollution. Despite a weak relationship (variations include weak positive/negative), NO_2 pollution consistently rises in all three cities throughout this period. While Lahore experiences a weak positive association between wind speed and NO_2 in some months (R^2=0.002-0.05), with wind speed increasing over the years but limited impact on pollution dispersal, Faisalabad also shows a weak relationship (R^2=0.0352) and rising NO_2 pollution with dipping wind speeds in recent years. Peshawar exhibits a similar pattern.

Summer Relationships:

The monsoon season (June-August) reveals a contrasting relationship between wind speed and NO_2 pollution across Lahore, Faisalabad, and Peshawar. Lahore exhibits a weak positive relationship (Lahore: June-R^2=0.09, July-R^2=0.05, August-R^2=0.005) with both NO_2 pollution and wind speed showing a rising trend throughout the monsoon months. Faisalabad also shows a weak positive relationship with specific correlation values of (e.g., June-R^2=0.07, July-R^2=0.12, August-R^2=0.04). Peshawar, however, displays a weak negative relationship (June-R^2=0.06, July-R^2=0.09, August-R^2=0.0008) with NO_2 pollution consistently increasing despite wind speed dipping throughout the monsoon season.

Autumn Relationships:

The post-monsoon season (September-November) presents a multifaceted relationship between wind speed and NO_2 pollution across Lahore, Faisalabad, and Peshawar. Despite a rising trend in NO_2 pollution throughout this period in all three cities, the wind speed's influence varies. Lahore exhibits a weak negative relationship (R^2=0.02-0.07) with slight wind speed changes. Faisalabad shows a weak positive relationship in September (R^2=0.0002) transitioning to a weak negative relationship in October and November (R^2=0.20, 0.04) despite increasing wind speed over the years. Peshawar has a positive but weak correlation with wind speed in October and November (R^2 =0.0103 – 0.0128), but an inverse and weak negative relationship in September. This variation in wind speed's influence highlights the need to consider factors beyond wind patterns. Emission sources likely play a significant role in the NO_2 surge during the post-monsoon season.

Monthly NO_2 Pollution Patterns (2005-2022):

Lahore, Faisalabad, and Peshawar exhibit distinct seasonal variations in their Nitrogen Dioxide (NO_2) pollution levels over the period 2005-2022, as analyzed using satellite-based sensing of monthly average NO2 concentrations.

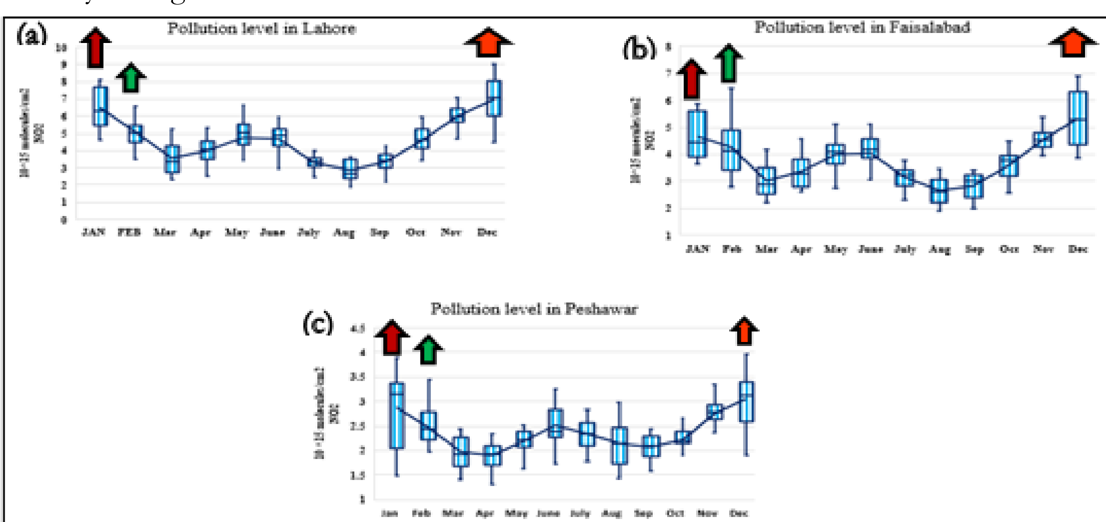

Figure 6: The figure above shows average monthly pollution levels at the local level (thick boxes represent winter months when NO_2 levels are higher). **(a)** represents Lahore, **(b)** shows Faisalabad and **(c)** represents Peshawar

Lahore: The city experiences the highest NO_2 concentrations during winter months, with December peaking at an estimated 9.028 x 10^15 molecules/cm², while August sees the lowest values at 1.9 x 10^15 molecules/cm². This pattern suggests higher pollution levels in winter, potentially due to emissions from animal waste, wood burning for heating and cooking, and coal combustion.

Faisalabad: Like Lahore, Faisalabad observes the highest NO_2 concentrations in December (6.80 x 10^15 molecules/cm²) and the lowest in August (1.90 x 10^15 molecules/cm²). This trend aligns with the winter peak and monsoon season dip observed in Lahore, potentially influenced by similar factors.

Peshawar: Peshawar experiences the highest NO_2 concentrations in December (3.95 x 10^15 molecules/cm²) and the lowest in April (1.31 x 10^15 molecules/cm²). The winter peak suggests higher pollution, likely due to biomass burning and industrial activities.

Identfication of the main anthropogenic sources of NO_2 emissions in Pakistan as being industrial operated , heavy traffic on the roads being seen, a large densely population , agricultural fires, and fossil fuel burning by [38] .

Discussions:

Various studies have been put forward across the world by the researchers to analyzing the atmospheric pollution with the satellite based analysis through Worldwide Ozone Observing Examination (GOME), the Filtering Imaging Retention spectrometer for Environmental Map making (SCIAMACHY), and the Ozone Checking Instrument (OMI) held on AURA satellite across the Europe, America and Asia by to analyze the current dynamics of the regional and local environment which cover the assessments of long term changes of pollution in different years reflecting the pollution patterns.

A previous study examined NO_2 levels in Pakistan upper atmosphere between 2005 and 2008. The research identified a concerning national rise in NO_2 of 3.29% annually. This finding aligns with growing concerns about air quality in Pakistan, mirroring the seasonal trends observed in my study. Interestingly, Karachi displayed both the highest and lowest NO_2 values, suggesting local factors beyond just meteorology play a significant role. This highlights the need for city-specific investigations, which my research addresses by focusing on Lahore, Faisalabad, and Peshawar. Additionally, the study noted increasing NO_2 trends in Islamabad/Rawalpindi, Lahore, and Dera Ghazi Khan. These spatial variations could be linked to air mass movements, prompting further exploration of how regional atmospheric dynamics influence NO_2 concentrations across Pakistan [39].

Click or tap here to enter text.A previous study (2005-2014) engaged satellite data to analyze trends in CO, HCHO, NO_2, and O_3 across Pakistan Punjab region. Their findings confirmed concerns about rising NO_2 levels, showing a significant increase of 28.2%. This aligns with my research focus on NO_2 pollution and highlight the historical trend of worsening air quality. Interestingly, the research suggested interactions between these gases. It hypothesized that NO_2, O_3, and HCHO may contribute to the reduction of CO levels, while NO_2 and CO levels might significantly impact O_3 patterns. This highlights the complex interplay between various pollutants, which my research could acknowledge as a limitation. While focusing on $NO_2$and meteorological factors, future studies can examine how these historical interactions effect overall air quality across Pakistan diverse regions [27].

Previous research in Pakistan (2002-2014) used satellite data to detect increases NO_2 emissions linked with activities such as burning fossil fuels. Interestingly, NO_2 levels in Karachi were decreased due to reduced industrial activity. This is consistent with my research that focus on anthropogenic sources and NO_2 emissions in Pakistan cities. Both studies highlight the importance of understanding how human activities affect NO_2 changes in across different regions [38]. This study (2010-2020) investigated how COVID-19 lockdowns impacted NO_2 levels across Asia, including Pakistan. Their study, partially overlapping with my research period, used satellite data to show a significant decrease in NO_2 concentrations during lockdown years. This decrease is attributed to reduced human activity, especially in transportation. This finding consistent with my investigation of how reduced traffic can influence NO_2 levels in Pakistan cities. Although my study focuses on the role of various meteorological parameters, the observed decrease in NO_2 emissions due to lower traffic during the lockdowns strengthens the connection between human activities and NO_2 emissions. This suggests that strategies aimed at reducing traffic congestion, alongside studying how meteorological factors such as temperature (which may be impacted by reduced traffic) influence NO_2, could be important for improving air quality in Pakistan cities [24].

Conclusion:

This study investigated nitrogen dioxide (NO_2) pollution variations in Lahore, Faisalabad, and Peshawar, Pakistan, between 2005 and 2022. we utilized data from the Ozone Monitoring Instrument (OMI) and examined how seasonal changes in temperature, rainfall, and wind speed affect NO_2 levels.

The study identified distinct seasonal patterns. Interestingly, both Lahore and Faisalabad had the lowest NO_2 concentrations during the monsoon season (around August), with values around 1.9 x 10^15 molecules/cm². In contrast, Peshawar's lowest NO_2 levels occurred during the pre-monsoon period (March-May) with a minimum of 1.318 x 10^15 molecules/cm².

However, all three cities experienced a significant rise in NO_2 pollution during winter. Lahore recorded the highest concentration **(9.028 x 10^15 molecules/cm²)** in December, followed by Faisalabad **(6.80 x 10^15 molecules/cm²)** and Peshawar **(3.95 x 10^15 molecules/cm²).** This trend suggests a strong link between colder months and increased human activities that release NO_2, such as industrial activity, traffic volume, and fossil fuel combustion. The study also highlights the influence of factors like population density and agricultural burning on NO_2 levels.

These findings highlight the need for further investigation into specific emission sources and the development of targeted air quality management strategies, particularly during winter. To tackle the alarming rise in NO_2 pollution and ensure healthy air for everyone, several key actions can be taken. These include setting stricter regulations, encouraging the use of cleaner technologies, and finding ways to reduce human-caused sources like traffic jams and industrial activity.

Acknowledgements:

We would like to express our gratitude to the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) and the Giovanni online visualization tool for providing long-term observation data for precipitation, wind speed, temperature data from Lahore, Faisalabad, Peshawar which was essential for this study. We are also thankful for the satellite-derived nitrogen dioxide, precipitation, wind speed, temperature datasets used in our analysis: NASA's Goddard Space Flight Center for providing access to the Ozone Monitoring Instrument (OMI) NO_2 data onboard the AURA satellite, the Global Precipitation Measurement (GPM) mission for the IMERG data, the National Oceanic and Atmospheric Administration/National Centers for Environmental Prediction (NOAA/NCEP) for the FLDAS wind speed data, and the European Centre for Medium-Range Weather Forecasts (ECMWF) for the ERA-5 temperature data. Their efforts in making these valuable datasets available have significantly contributed to this research.

Author's Contribution:

All the authors had different contributions to this research work and are mentioned here accordingly. This research was supervised by SA; Conceptualization (S.A, H.M), formal analysis (H.M), methodology (H.M and S.A); writing—original draft preparation (H.M, F.N); writing, review and editing (S.A, F.N, N.H, S.M.I). All authors have read and agreed to the published version of the manuscript.

Conflict of Interest: The authors declare they have no conflict of interest in publishing this manuscript in this Journal.

References:

[1] S. N. P. John H. Seinfeld, "Atmospheric chemistry and physics: from air pollution to climate change," Choice Reviews Online, vol. 44, no. 08, pp. 44-4512-44–4512, Apr. 2007, doi: 10.5860/CHOICE.44-4512.

[2] E. Sánchez-Triana, S. Enriquez, J. Afzal, A. Nakawaga, and A. S. Khan, "Executive Summary," in Cleaning Pakistan's Air: Policy Options to Address the Cost of Outdoor Air Pollution, The World Bank, 2014, pp. 1–42. doi: 10.1596/978-1-4648-0235-5_es.

[3] M. Ali, D. Kirikkaleli, R. Sharma, and M. Altuntaş, "The nexus between remittances, natural resources, technological innovation, economic growth, and environmental sustainability in Pakistan," Environmental Science and Pollution Research, vol. 29, no. 50, pp. 75822–75840, Oct. 2022, doi: 10.1007/s11356-022-21228-4.

[4] C. Leue, M. Wenig, T. Wagner, O. Klimm, U. Platt, and B. Jähne, "Quantitative analysis of NOx emissions from Global Ozone Monitoring Experiment satellite image sequences," Journal of Geophysical Research Atmospheres, vol. 106, no. D6, pp. 5493–5505, Mar. 2001, doi: 10.1029/2000JD900572.

[5] A. Richter and J. P. Burrows, "TROPOSPHERIC NO2 FROM GOME MEASUREMENTS," 2002. [Online]. Available: www.eIsevier.com/locatelasr

[6] R. V. Martin, D. J. Jacob, K. Chance, T. P. Kurosu, P. I. Palmer, and M. J. Evans, "Global inventory of nitrogen oxide emissions constrained by space-based observations of NO2 columns," Journal of Geophysical Research: Atmospheres, vol. 108, no. 17, Sep. 2003, doi: 10.1029/2003jd003453.

[7] K. F. Boersma et al., "Near-real time retrieval of tropospheric NO2 from OMI," 2006. [Online]. Available: https://hal.science/hal-00302325

[8] A. Richter, J. P. Burrows, H. Nüß, C. Granier, and U. Niemeier, "Increase in tropospheric nitrogen dioxide over China observed from space," Nature, vol. 437, no. 7055, pp. 129–132, Sep. 2005, doi: 10.1038/nature04092.

[9] D. Mage et al., "Atmospheric Enuironmrnr," 1996.

[10] H. Mayer, "Air pollution in cities," 1999.

[11] L. Emberson, "AIR POLLUTION IMPACTS ON CROPS AND FORESTS: AN INTRODUCTION," 2003, pp. 3–29. doi: 10.1142/9781848161276_0001.

[12] M. Alkon et al., "Water security implications of coal-fired power plants financed through China's Belt and Road Initiative," Energy Policy, vol. 132, pp. 1101–1109, Sep. 2019, doi: 10.1016/j.enpol.2019.06.044.

[13] Z. Wang et al., "Acute health impacts of airborne particles estimated from satellite remote sensing," Environ Int, vol. 51, pp. 150–159, 2013, doi: 10.1016/j.envint.2012.10.011.

[14] I. Müller, T. Erbertseder, and H. Taubenböck, "Tropospheric NO2: Explorative analyses of spatial variability and impact factors," Remote Sens Environ, vol. 270, Mar. 2022, doi: 10.1016/j.rse.2021.112839.

[15] A. Richter and J. P. Burrows, "TROPOSPHERIC NO2 FROM GOME MEASUREMENTS," 2002. [Online]. Available: www.eIsevier.com/locatelasr

[16] A. Richter, J. P. Burrows, H. Nüß, C. Granier, and U. Niemeier, "Increase in tropospheric nitrogen dioxide over China observed from space," Nature, vol. 437, no. 7055, pp. 129–132, Sep. 2005, doi: 10.1038/nature04092.

[17] R. J. van der A et al., "Detection of the trend and seasonal variation in tropospheric NO2 over China," Journal of Geophysical Research Atmospheres, vol. 111, no. 12, Jun. 2006, doi: 10.1029/2005JD006594.

[18] R. J. van der A. et al., "Trends, seasonal variability and dominant NOx source derived from a ten year record of NO2 measured from space," Journal of Geophysical Research Atmospheres, vol. 113, no. 4, Feb. 2008, doi: 10.1029/2007JD009021.

[19] S. K. Satheesh and K. Krishna Moorthy, "Radiative effects of natural aerosols: A review," Atmos Environ, vol. 39, no. 11, pp. 2089–2110, 2005, doi: 10.1016/j.atmosenv.2004.12.029.

[20] F. Sharif, K. Alam, and S. Afsar, "Spatio-Temporal distribution of aerosol and cloud properties over Sindh using MODIS satellite data and a HYSPLIT model," Aerosol Air Qual Res, vol. 15, no. 2, pp. 657–672, 2015, doi: 10.4209/aaqr.2014.09.0200.

[21] G. Ali et al., "Spatiotemporal trends of aerosols over urban regions in Pakistan and their possible links to meteorological parameters," Atmosphere (Basel), vol. 11, no. 3, Mar. 2020, doi: 10.3390/atmos11030306.

[22] M. U. Alvi, F. Chishtie, I. Shahid, T. Mahmud, and R. Hussain, "Traffic -and Industry-Related Air Pollution Exposure Assessment in an Asian Megacity," Clean - Soil, Air, Water, vol. 46, no. 1. Wiley-VCH Verlag, Jan. 01, 2018. doi: 10.1002/clen.201600773.

[23] H. J. Lee and P. Koutrakis, "Daily Ambient NO $_2$ Concentration Predictions Using Satellite Ozone Monitoring Instrument NO $_2$ Data and Land Use Regression," Environ Sci Technol, p. 140204134232009, Feb. 2014, doi: 10.1021/es404845f.

[24] W. Naeem, J. Kim, and Y. G. Lee, "Spatiotemporal Variations in the Air Pollutant NO2 in Some Regions of Pakistan, India, China, and Korea, before and after COVID-19, Based on Ozone Monitoring Instrument Data," Atmosphere (Basel), vol. 13, no. 6, Jun. 2022, doi: 10.3390/atmos13060986.

[25] A. R. Douglass, R. S. Stolarski, S. E. Strahan, and P. S. Connell, "Radicals and reservoirs in the GMI chemistry and transport model: Comparison to measurements," Journal of Geophysical Research D: Atmospheres, vol. 109, no. 16, Aug. 2004, doi: 10.1029/2004JD004632.

[26] K. L. Chan, E. Khorsandi, S. Liu, F. Baier, and P. Valks, "Estimation of surface no2 concentrations over germany from tropomi satellite observations using a machine learning method," Remote Sens (Basel), vol. 13, no. 5, pp. 1–24, Mar. 2021, doi: 10.3390/rs13050969.

[27] N. Zeb, M. F. Khokhar, A. Pozzer, and S. A. Khan, "Exploring the temporal trends and seasonal behaviour of tropospheric trace gases over Pakistan by exploiting satellite observations," Atmos Environ, vol. 198, pp. 279–290, Feb. 2019, doi: 10.1016/j.atmosenv.2018.10.053.

[28] L. Zhang, C. S. Lee, R. Zhang, and L. Chen, "Spatial and temporal evaluation of long term trend (2005–2014) of OMI retrieved NO2 and SO2 concentrations in Henan Province, China," Atmos Environ, vol. 154, pp. 151–166, 2017, doi: 10.1016/j.atmosenv.2016.11.067.

[29] D. Maulud and A. M. Abdulazeez, "A Review on Linear Regression Comprehensive in Machine Learning," Journal of Applied Science and Technology Trends, vol. 1, no. 2, pp. 140–147, Dec. 2020, doi: 10.38094/jastt1457.

[30] H. Yu and A. D. Hutson, "A robust Spearman correlation coefficient permutation test," Commun Stat Theory Methods, vol. 53, no. 6, pp. 2141–2153, Mar. 2024, doi: 10.1080/03610926.2022.2121144.

[31] H. Piepho, "A coefficient of determination (R^2) for generalized linear mixed models," Biometrical Journal, vol. 61, no. 4, pp. 860–872, Jul. 2019, doi: 10.1002/bimj.201800270.

[32] C. Wang, T. Wang, and P. Wang, "The spatial-temporal variation of tropospheric NO2 over China during 2005 to 2018," Atmosphere (Basel), vol. 10, no. 8, Aug. 2019, doi: 10.3390/atmos10080444.

[33] N. Zhao et al., "The potential co-benefits for health, economy and climate by substituting raw coal with waste cooking oil as a winter heating fuel in rural households of northern China," Environ Res, vol. 194, Mar. 2021, doi: 10.1016/j.envres.2020.110683.

[34] Y. Cui et al., "Rapid growth in nitrogen dioxide pollution over Western China, 2005-2013," Atmos Chem Phys, vol. 16, no. 10, pp. 6207–6221, May 2016, doi: 10.5194/acp-16-6207-2016.

[35] I. Uno et al., "Systematic analysis of interannual and seasonal variations of model-simulated tropospheric NO 2 in Asia and comparison with GOME-satellite data," 2007. [Online]. Available: www.atmos-chem-phys.net/7/1671/2007/
[36] A. Richter, J. P. Burrows, H. Nüß, C. Granier, and U. Niemeier, "Increase in tropospheric nitrogen dioxide over China observed from space," Nature, vol. 437, no. 7055, pp. 129–132, Sep. 2005, doi: 10.1038/nature04092.
[37] C. Zheng et al., "Spatial and temporal distribution of NO2 and SO2 in Inner Mongolia urban agglomeration obtained from satellite remote sensing and ground observations," Atmos Environ, vol. 188, pp. 50–59, Sep. 2018, doi: 10.1016/j.atmosenv.2018.06.029.
[38] R. Murtaza, M. F. Khokhar, A. Noreen, S. Atif, and K. R. Hakeem, "Multi-sensor temporal assessment of tropospheric nitrogen dioxide column densities over Pakistan," Environmental Science and Pollution Research, vol. 25, no. 10, pp. 9647–9660, Apr. 2018, doi: 10.1007/s11356-017-1176-7.
[39] Z. ul-Haq, S. Tariq, M. Ali, K. Mahmood, S. A. Batool, and A. D. Rana, "A study of tropospheric NO2 variability over Pakistan using OMI data," Atmos Pollut Res, vol. 5, no. 4, pp. 709–720, Oct. 2014, doi: 10.5094/APR.2014.080.