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

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Introduction: Assessing atmospheric changes is crucial as population density increases and countries industrialize to meet growing demands. Pakistan is listed among the countries with the most deteriorating air quality globally.

Novelty Statement: This research investigates tropospheric NO_2 patterns in Pakistan from 2005 to 2022 using OMI data. It reveals seasonal variations and anthropogenic impacts, offering valuable insights for air quality policies in developing regions.

Material and Methods: This study analyzed tropospheric nitrogen dioxide (NO_2) patterns using data from the Ozone Monitoring Instrument (OMI) and examined their relationship with meteorological parameters such as rainfall, wind speed, and temperature. The analysis focused on NO_2 pollution patterns at the district level in Pakistan from 2005 to 2022, including major urban centers like Lahore, Faisalabad, and Peshawar.

Results and Discussion: An increasing trend in NO_2 concentrations was observed, with a rise of 9.028 x 10^{15} molecules/cm² in winter. Summer values were lower, around 1.9 x 10^{15} molecules/cm². A notable decrease in NO_2 concentrations occurred in the pre-monsoon months, except in Peshawar, where concentrations fell during spring. The study revealed varied patterns in NO_2 levels in relation to temperature, wind speed, and rainfall over the years. Industrial cities with heavy traffic, large populations, agricultural fires, and fossil fuel combustion exhibited high anthropogenic emission levels in the lower atmosphere.

Conclusion: This study provides regulators with a deeper understanding of anthropogenic emission levels in major cities, helping to identify sources and develop effective air quality management strategies.

Keywords: NO_2; OMI; AURA; Meteorological parameters; Giovanni.

Introduction:

Nitrogen oxides ($NOx = NO2 + NO$) are significant air pollutants that substantially affect the chemical composition of the troposphere. NOx plays a critical role in ozone formation and, consequently, has a major impact on air quality [1]. Air pollution poses severe threats to both human health and the global economy [2], and it is a growing environmental concern in developing South Asian countries like Pakistan. Since 1990, Pakistan has experienced considerable land use and land cover changes (LULCC), urbanization, rapid industrialization, and economic development [3]. Increased NOx levels have been reported globally based on ground measurements, instrumental parameters, and satellite observations [4][5][6][7].

Influences on NO2 Levels:

Tropospheric NO2 concentrations are heavily influenced by human activities and changes in near-surface vegetation [8]. Road traffic is a major contributor to poor air quality in urban areas [9][10], with automobiles increasing nitrogen oxides concentrations through engine combustion [11]. Besides NOx, vehicles also emit significant amounts of CO2, CO, hydrocarbons, particulate matter, and other toxins, impacting environmental health. Another key factor is fossil fuel consumption in thermal power plants [12]. Additionally, emissions from agricultural soils due to extensive nitrogen fertilizer use and biomass burning have raised tropospheric NO2 levels. Aerosol pollution contributes to severe health issues, including cardiovascular disease, asthma, bronchitis, lung disease, lung cancer, respiratory problems, and premature death [13].

Previous Research:

Past studies on the spatial variability of NO2 have used remote sensing data with varying resolutions. Earlier data often had coarser spatial resolution, limiting their ability to capture NO2 gradients, especially in urban areas [14]. Conversely, high-resolution remote sensing data are often aggregated across administrative units, reducing spatial detail through averaging. Long-term NO2 data from satellite missions like the Global Ozone Monitoring Experiment (GOME), the Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY), and the Ozone Monitoring Instrument (OMI) have been utilized for air quality assessments and satellite validation [15][16][17][18]. The Tropospheric Monitoring Instrument (TROPOMI) aboard the European Space Agency's Sentinel-5 Precursor (S5P) satellite provides daily global NO2 measurements with improved spatial resolution (3.6 km × 7.2 km) compared to its predecessors. This study uses NO2 column data from the OMI sensor on the Aura satellite to assess variations in nitrogen dioxide concentrations. OMI data, with a broad spatial coverage of 20 to 30 kilometers, offer insights into large-scale NO2 pollution.

Study Focus:

This study examines long-term trends (2005-2022) of NO2 and weather patterns (temperature, rainfall, wind speed) in Lahore, Faisalabad, and Peshawar, Pakistan's most polluted districts. We analyze how NO2 levels fluctuate monthly and seasonally using district-level statistical analysis and linear regression. The objective is to understand how weather variations influence NO2 concentrations and identify potential links to anthropogenic activities through graphical analysis of peak and low concentration periods. By exploring these trends, we aim to gain insights into the evolution of air quality in these major Pakistani cities and develop targeted strategies for pollution mitigation.

Objective:

The study investigates seasonal changes in NO2 concentrations in Lahore, Faisalabad, and Peshawar, focusing on how weather and human activities affect air pollution levels. It aims to provide policymakers with detailed analyses of NO2 and meteorological conditions in Pakistan's most polluted cities (2005-2022). The findings will help formulate targeted air pollution control measures, guiding air quality management strategies and sustainable development policies to create a healthier environment for Pakistan's citizens.

Material and Methods:

A summary of the methodology is presented in the flow diagram (Figure 1).

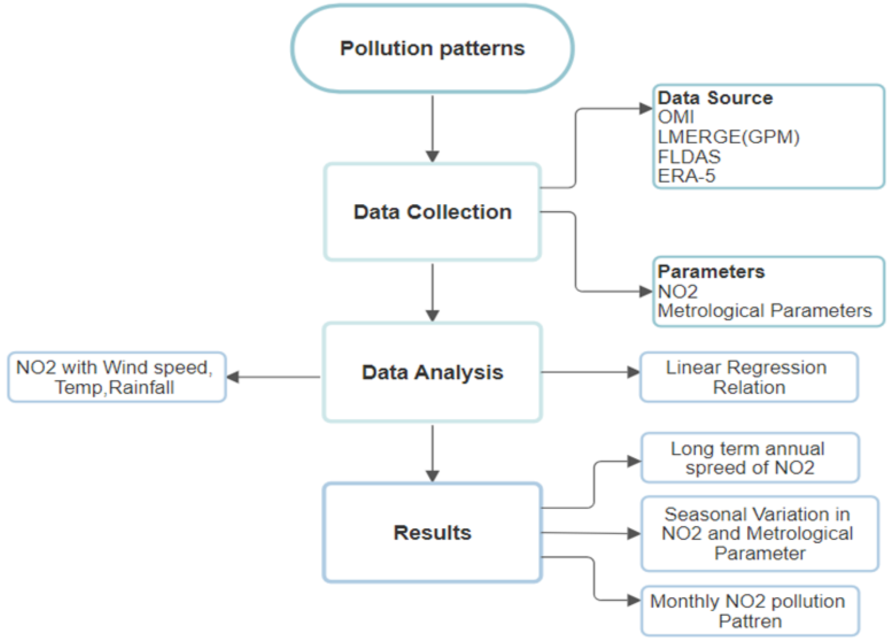

Figure 1: An overview of the methodology applied in this study

Study Area:

Pakistan's increasing urbanization has heightened concerns about air quality, particularly regarding nitrogen dioxide (NO2) pollution. This study explores the long-term relationship between weather patterns and NO2 levels in three major Pakistani cities—Lahore, Faisalabad, and Peshawar—from 2005 to 2022 (as shown in Figure 2). The map visually illustrates Pakistan's national boundaries and the locations of these cities. The study aims to analyze monthly and seasonal variations in NO2 pollution using statistical methods. It will also investigate how weather conditions influence NO2 levels, focusing on periods of maximum and minimum concentrations. Additionally, the study seeks to understand the impact of human activities on NO2 patterns in these cities.

Pakistan, located in South Asia, has a population exceeding 231.4 million and spans an area of 307,304 square miles. It is bordered by China to the north, India to the east, and Iran and Afghanistan to the southwest. The country boasts a 1,046 km coastline along the Arabian Sea to the south. The northern region features K-2, the world's second-highest peak at 8,611 meters, and major glaciers like Siachen (76 km) and Baifo (67 km), which feed into the Indus River. Pakistan's geography includes the Indus Plain, the Northern Range, and hills and plateaus stretching from the Khyber Pass to Baluchistan. The climate is predominantly subtropical and semi-arid, with notable seasonal variations due to monsoons and wind patterns. The southern slopes of the Himalayas and northern hills receive up to 2,000 mm of rainfall annually, whereas the majority of the country receives less than 250 mm. Pakistan experiences four distinct seasons: spring (March to May), summer (June to August), fall (September to November), and winter (December to February), providing a unique context for studying aerosol patterns.

The study focuses on Lahore, Faisalabad, and Peshawar, which represent different aspects of Pakistan's urban spectrum. Lahore (31.52°N, 74.36°E), a densely populated metropolis of 11 million people, is situated near the Ravi River and experiences hot, semi-arid summers with temperatures ranging from 36°C to 46°C [21]. Industrial emissions, vehicular traffic, and nearby agricultural burning contribute to elevated NO2 levels [21]. Faisalabad (31.42°N, 73.08°E), a key industrial hub [22], faces significant air quality challenges due to vehicular emissions. Summer temperatures can soar to 48°C, with a broader seasonal range (-1°C to 48°C) compared to Lahore

[21]. Peshawar (34.31°N, 71.58°E), near the Afghan border, has a cooler climate with winter lows averaging 10°C and summer highs around 40°C [21]. Despite its cooler temperatures, Peshawar contends with air pollution from domestic burning and vehicle emissions. All three cities have experienced substantial population growth between 1998 and 2017, with Lahore increasing by 116%, Faisalabad by 60%, and Peshawar by 101% (Pakistan Bureau of Statistics).

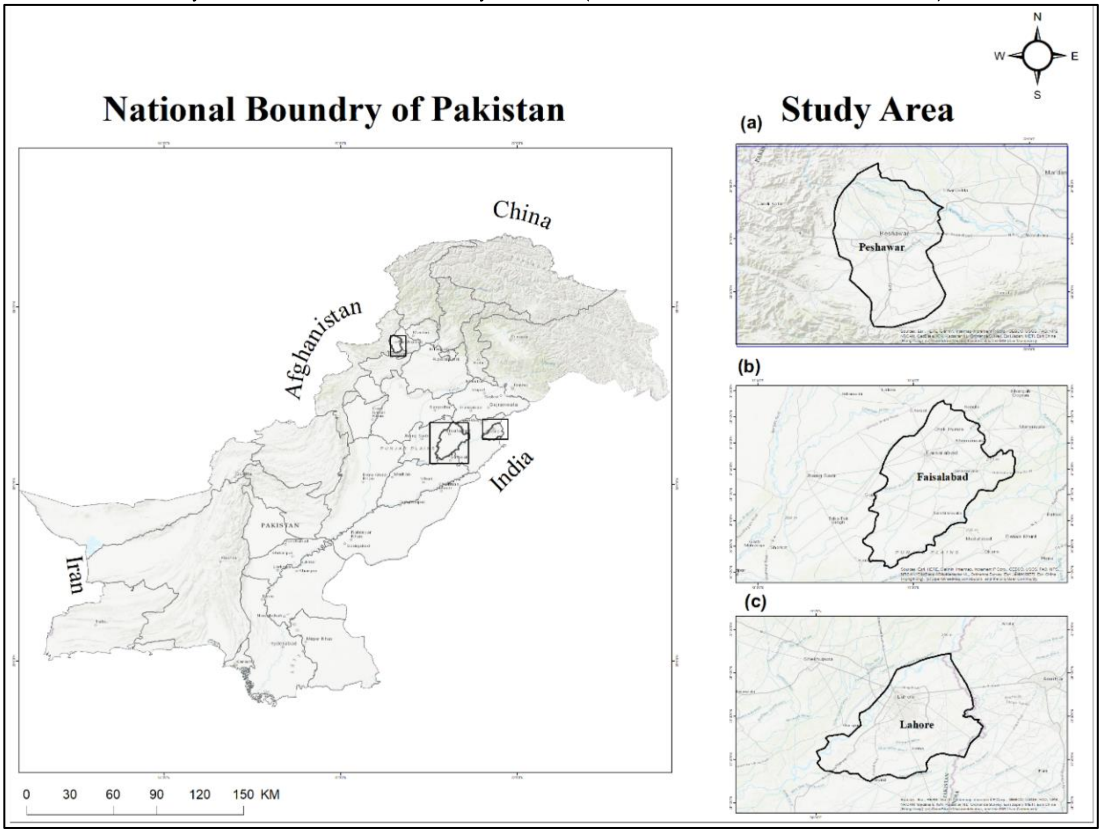

Figure 2: Topographic map showing the administrative divisions of Pakistan and the regions involved in the study. (a) displays data for Peshawar, (b) displays data for Faisalabad, (c) displays data for Lahore.

Data Used:

In this study, we utilized four distinct types of datasets, as detailed 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 (NO2) data from the Ozone Monitoring Instrument (OMI) onboard NASA's AURA satellite, launched in 2004 [23]. The OMI provides high-resolution observations in the ultraviolet and visible spectrum (https://aura.gsfc.nasa.gov/omi.html). We specifically use level 3 NO2 data (OMNO2 003) with less than 30% cloud cover [24]. The OMI data incorporates two key advancements: enhanced techniques for extracting NO2 slant columns using monthly sun irradiance data, and a more precise method for deriving monthly NO2 and temperature profiles [25]. Monthly averaged daily data from 2005 to 2022 were obtained in molecules/cm² from Giovanni (https://giovanni.gsfc.nasa.gov/giovanni/) and converted to CSV format for analysis."

Meteorological Data:

The current study investigated the impact 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 were obtained from the Global Precipitation Measurement (IMERGE) Level 3 product, which offers a spatial resolution of 0.1° x 0.1° and a temporal resolution of 30 minutes. Monthly averaged data, accessible via the GIOVANNI web portal (https://disc.gsfc.nasa.gov/), were used to estimate rainfall rates (mm/day) within the study area. This dataset has been available since the year 2000, using passive remote sensors.

Wind Speed (WS):

Wind speed data were acquired from the FLDAS Land Data Assimilation System model. Monthly averaged wind speed data were retrieved from GIOVANNI to analyze wind patterns across the study region. This dataset has a spatial resolution of 0.1° x 0.1° and a temporal resolution of monthly data, measured in meters per second (m/s), since 1982.

Temperature (T):

Temperature data were sourced from the fifth generation ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis product, available through the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/). This gridded dataset, produced by ECMWF, integrates existing climate data with new observations for enhanced climate assessments and forecasts [26]. It has a spatial resolution of 0.25° x 0.25° and a temporal resolution of monthly data, measured in Kelvin (K), with temperature measurements taken at a height of 2 meters.

Data Analysis:

This study utilizes linear regression analysis to explore the relationships between NO_2 pollution and various meteorological parameters in Lahore, Faisalabad, and Peshawar, Pakistan. Linear regression is a statistical method used to model the linear relationship between a dependent variable (NO_2 concentration) and one or more independent variables (meteorological parameters such as precipitation, wind speed, and temperature) [27]. The coefficient of determination (R^2) is employed to assess the strength and direction of these relationships. Positive R^2 values indicate a positive correlation, while negative values suggest an inverse relationship. The magnitude of R^2 indicates the strength of the association, with values closer to 1 reflecting a stronger connection [28].

Monthly averaged NO_2 data (2005-2022) in molecules/cm^2 were 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, and Peshawar), which were extracted using ArcGIS software (version 10.8) from district shapefiles. For meteorological data, monthly averages of precipitation (P), wind speed (WS), and temperature (T) were gathered from relevant sources and compiled with the NO_2 data into a CSV format suitable for statistical analysis using Microsoft Excel.

The compiled dataset was analyzed using linear regression with 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, and develop trend line equations to represent the linear relationships between NO_2 and the meteorological parameters."

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

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

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

The correlation coefficient (r) is calculated using Equation 2. The coefficient of determination (R^2) is derived by squaring the correlation coefficient, as shown in Equation 3. By analyzing the correlation coefficients (r) and the coefficient of determination (R^2), along with the trend line equations (Equation 1), this study aims to uncover the potential influence of precipitation, wind speed, and temperature on NO2 pollution patterns in the three cities under investigation in Pakistan.

Result:

Long Term Annual Spread of NO_2 on District Level:

Figure 3 illustrates the temporal trends of nitrogen dioxide (NO2) from 2005 to 2015 and from 2016 to 2022 in the Punjab and Khyber Pakhtunkhwa regions covered in this study. The results indicate a notable increase in NO2 levels in Lahore, Faisalabad, and Peshawar, with the highest frequencies observed in these cities. This trend is evident in the average annual NO2 cycles for these regions. Between 2016 and 2022, NO2 emissions were significantly higher compared to the previous decade (2005-2015). The analysis reveals clear differences in pollution patterns between these two periods. The primary sources of anthropogenic NO2 emissions in Pakistan include industrial activities, increased road traffic, high population density, agricultural fires, and fossil fuel combustion.

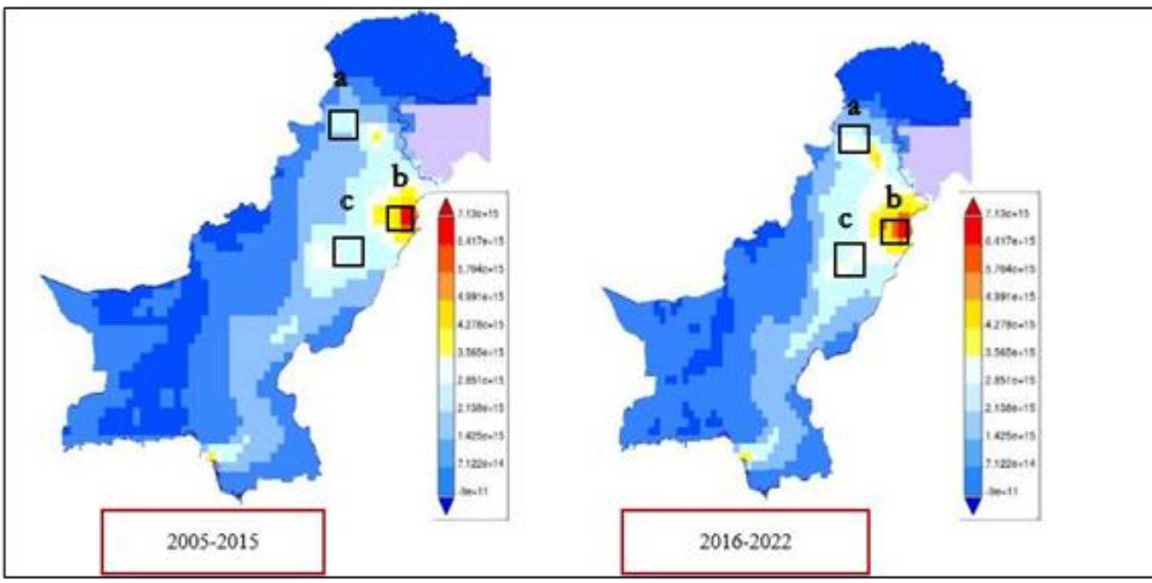

Figure 3: Shows the long term annual averaged NO_2 (molecules/cm2) changes in the districts of Pakistan during the period from 2005-2015 and 2016-2022. Box **a** represent Peshawar, box **b** shows Lahore and box **c** represent Faisalabad (Note: The Purplish color in this map indicates no data values;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

Seasonal Variations in NO_2 and Meteorological Factors:

This study explores the potential impact of meteorological variables on nitrogen dioxide (NO2) pollution patterns in selected regions. The core hypothesis is that examining variables such as precipitation, wind speed, and temperature can offer valuable insights into NO2 emission patterns and their effects on air quality. By establishing relationships between these climatic factors and NO2 concentrations, this study aims to elucidate how meteorological conditions influence air pollution patterns.

NO_2 and Rainfall:

Winter Relationships:

Winters in Pakistan present complex challenges for air quality, particularly concerning nitrogen dioxide (NO2) levels, which can reach hazardous concentrations. Lower temperatures in winter lead to increased use of coal and natural gas for heating in residential and commercial settings, contributing to elevated NO2 emissions [32], [33]. Additionally, winter conditions prolong the atmospheric lifetime of NO2 due to cooler temperatures, reduced sunlight for photolysis (decomposition by sunlight), and stable air conditions with low wind speeds that inhibit pollutant dispersion [34], [35], [36]. Biomass burning for home cooking during winter can further exacerbate NO2 levels in some areas [35], [36]. These factors, combined with a shallower boundary layer, result in pollutants being trapped closer to the surface [37].

A study examining the winter season (December-January-February) from 2005 to 2022 in Lahore, Faisalabad, and Peshawar reveals a negative correlation between precipitation and NO2 concentrations. Higher rainfall (mm) generally leads to lower NO2 pollution levels (molecules/cm²), as precipitation helps remove pollutants from the atmosphere. This trend is supported by the correlation coefficient (R^2) calculated for each city and month. Lahore exhibits 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: $R^2 = 0.169$).

Precipitation patterns vary among the cities. Lahore and Faisalabad experience increased rainfall in January compared to December and February, while Peshawar shows a decrease in December followed by an increase in January. These variations highlight the complexity of the relationship between precipitation and NO2 levels. Although precipitation has a purifying effect, as indicated by the negative correlation, its effectiveness and frequency differ across cities. This variability limits its ability to address the concerning trend of rising NO2 pollution in Pakistani cities during winter.

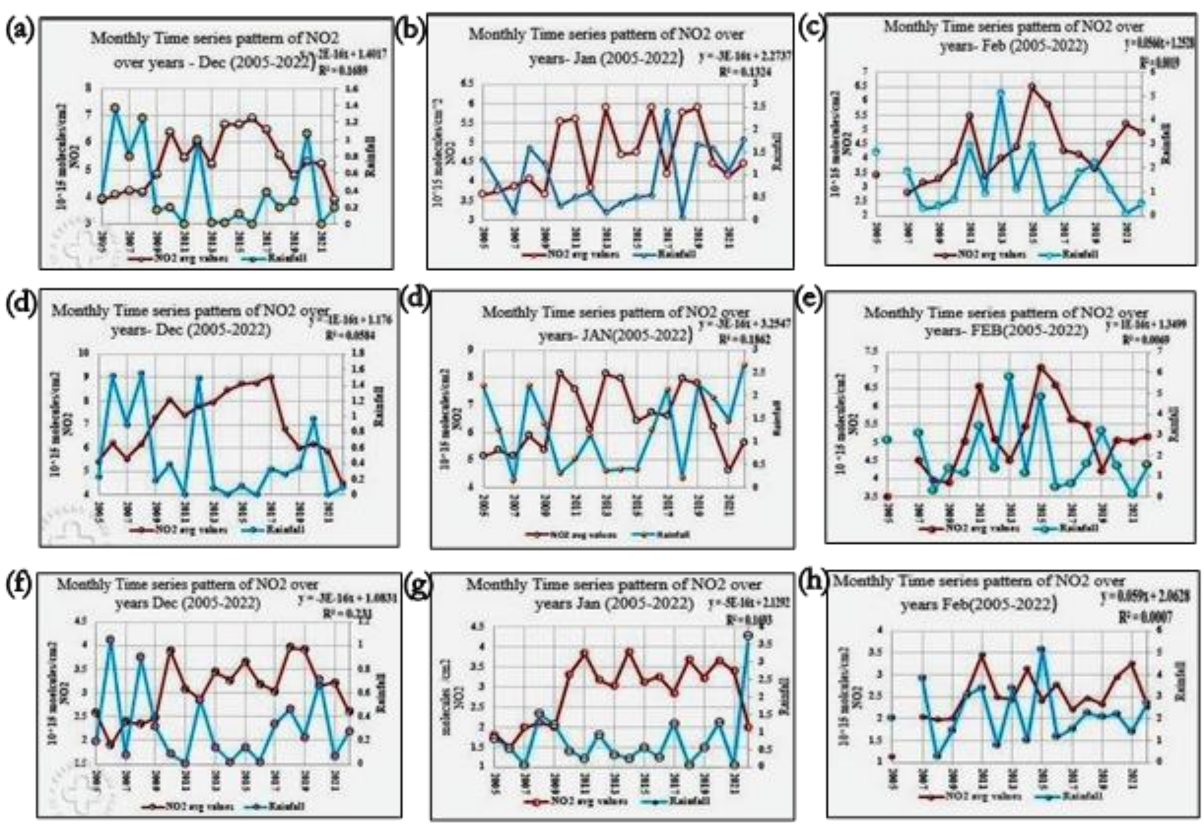

Figure 4: This figure shows the variations in rainfall and Nitrogen Dioxide (NO_2) levels throughout the Winter Season in three Pakistani cities. **(a)** displays data for Faisalabad in December, **(b)** shows Faisalabad data for January, **(c)** represents Faisalabad data for February, **(d)** displays 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 significant challenges for air quality, particularly concerning NO2 levels. Agricultural practices, such as burning wheat residue, release pollutants into the atmosphere, while rising temperatures lead to increased emissions from road traffic, notably from two-stroke engines. Additionally, industrial activity often rebounds from the winter slowdown. An analysis of the relationship between rainfall and NO2 pollution in Lahore, Faisalabad, and Peshawar from March 2005 to March 2022 reveals several notable patterns. Generally, a negative correlation is observed, with higher precipitation (mm) potentially leading to lower NO2 pollution (molecules/cm²) due to the cleansing effect of rainwater. However, the strength of this correlation varies among the cities. Lahore exhibits the weakest correlation, with R^2 values of 0.148 in March, 0.0049 in April, and 0.0058 in May. In contrast, Peshawar shows a stronger negative correlation in March, with an R^2 of 0.34, though this weakens in May (R^2 = 0.0024). Faisalabad, however, shows an inverse relationship in March (R^2 = 0.12) and May (R^2 = 0.0004), suggesting minimal impact of rainfall on NO2 levels in these months. Precipitation patterns also vary among the cities. All three cities experience increased precipitation in March and May, but NO2 emission trends differ. Lahore's NO2 levels decrease in May, while Faisalabad and Peshawar exhibit increased NO2 levels despite the rise in rainfall.

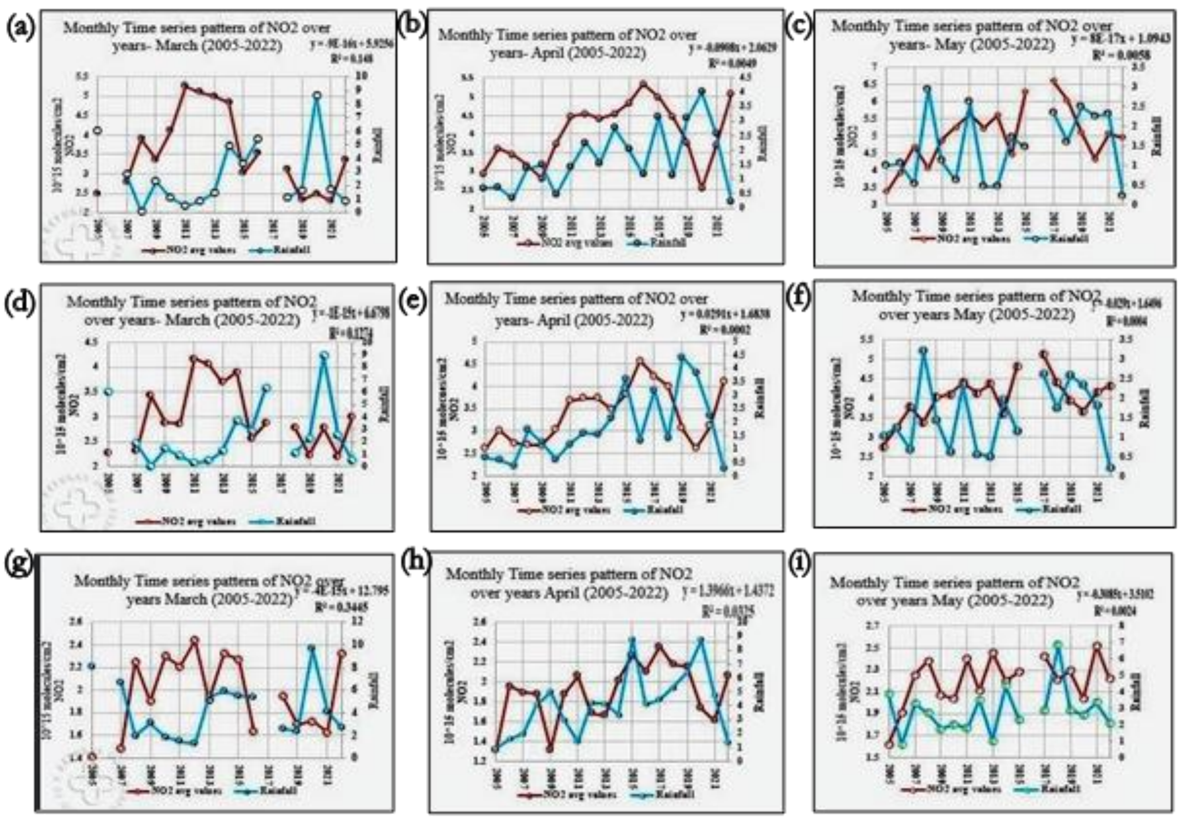

Figure 5: This figure shows the variations in rainfall and Nitrogen Dioxide (NO_2) levels throughout the spring Season in three Pakistani cities. **(a)** displays data for Lahore in March, **(b)** shows Lahore data for April, **(c)** represents Lahore data for May, **(d)** displays data for Faisalabad 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:

During the Summer and Monsoon seasons (June-August), Lahore, Faisalabad, and Peshawar face a complex interaction between rainfall and NO2 pollution. All three cities generally exhibit a weak negative correlation between rainfall and NO2 levels in June and August, indicating some cleansing effect of rainfall. However, the strength of this relationship varies: Peshawar shows a stronger inverse correlation in August ($R^2 = 0.43$) compared to Lahore ($R^2 = 0.07$) and Faisalabad ($R^2 = 0.12$). Interestingly, in July, all three cities display a weak positive or mixed relationship between rainfall and NO2 levels (Lahore: $R^2 = 0.10$, Faisalabad: $R^2 = 0.12$, Peshawar: $R^2 = 0.01$). This may be attributed to increased agricultural burning or industrial activity during this period, which can counteract the potential cleansing effect of rainfall. Despite the overall rising trend in NO2 pollution across these cities during the monsoon, rainfall patterns differ: Lahore and Faisalabad experience reduced rainfall in June and August, while Peshawar only sees a decrease in August. These variations underscore the limitations of relying solely on precipitation for NO2 mitigation and highlight the need for additional strategies, such as stricter emissions regulations and the promotion of cleaner agricultural practices.

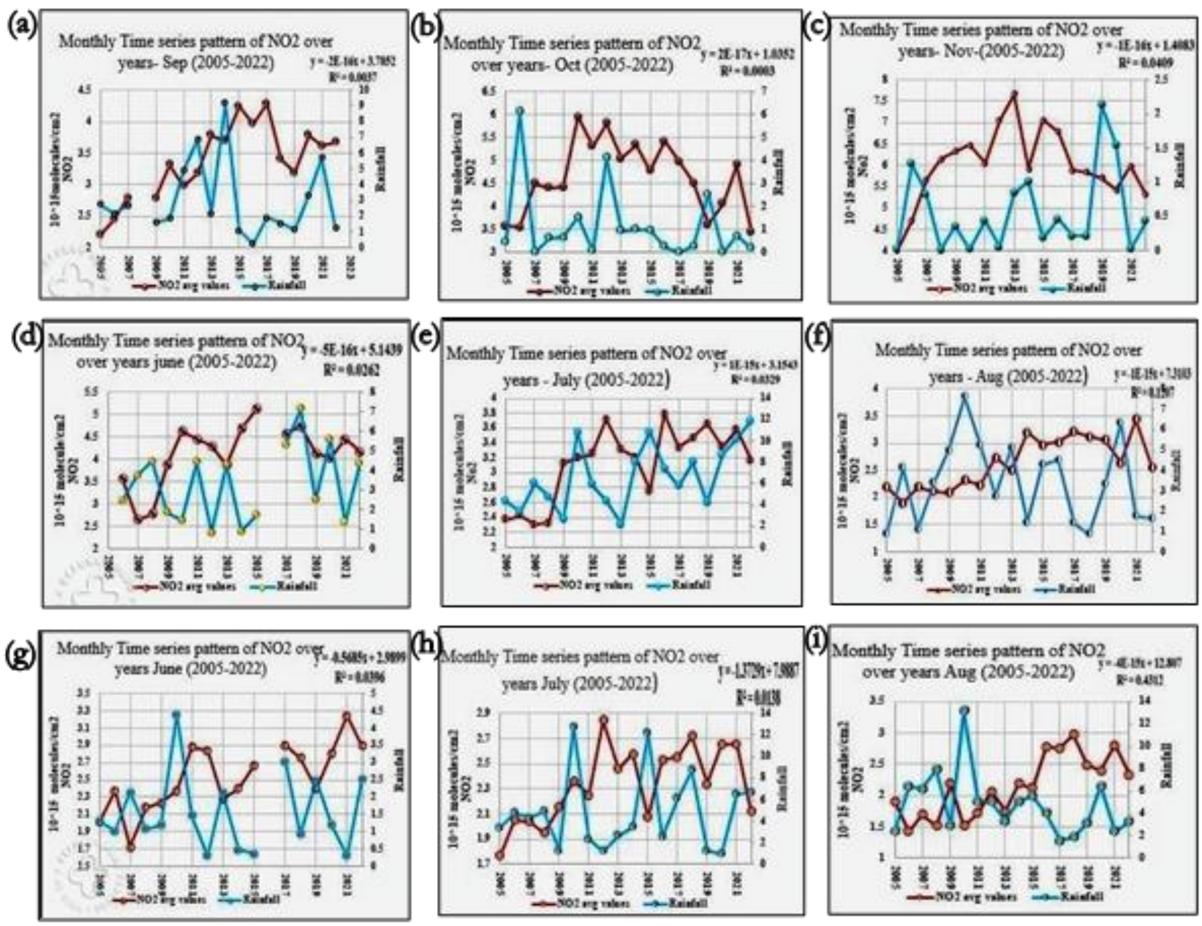

Figure 6: This figure shows the variations in rainfall and Nitrogen Dioxide (NO_2) levels throughout the Summer Season in three Pakistan cities. **(a)** displays data for Lahore in June, **(b)** shows Lahore data for July, **(c)** represents Lahore data for August, **(d)** displays data for Faisalabad 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) reveals a complex interaction between NO2 pollution and precipitation in Lahore, Faisalabad, and Peshawar. Some months exhibit a weak negative correlation between rainfall and NO2 levels, indicating minimal cleansing effects (e.g., October-November in Faisalabad, with $R^2 = 0.0026$-0.024). Overall, the relationship is quite variable. In September, NO2 pollution often increases in all three cities despite reduced rainfall (Lahore: $R^2 = 0.0037$, Faisalabad: $R^2 = 0.16$, Peshawar: $R^2 = 0.003$). This trend may be linked to post-monsoon crop burning, which appears to contribute to higher pollution levels. November shows a weak inverse relationship in Lahore ($R^2 = 0.0409$) and a somewhat stronger inverse relationship in Peshawar ($R^2 = 0.09$) compared to September and October. Precipitation patterns also vary: Lahore and Faisalabad experience reduced rainfall in September and October, while Peshawar sees decreased rainfall only in September. These variations highlight the limitations of relying solely on precipitation for controlling NO2 levels and underscore the need for additional strategies to address the observed increases in NO2 pollution in September and November across these cities, despite minimal rainfall. Autumn weather in Pakistan is generally mild, with lower temperatures and occasional rain.

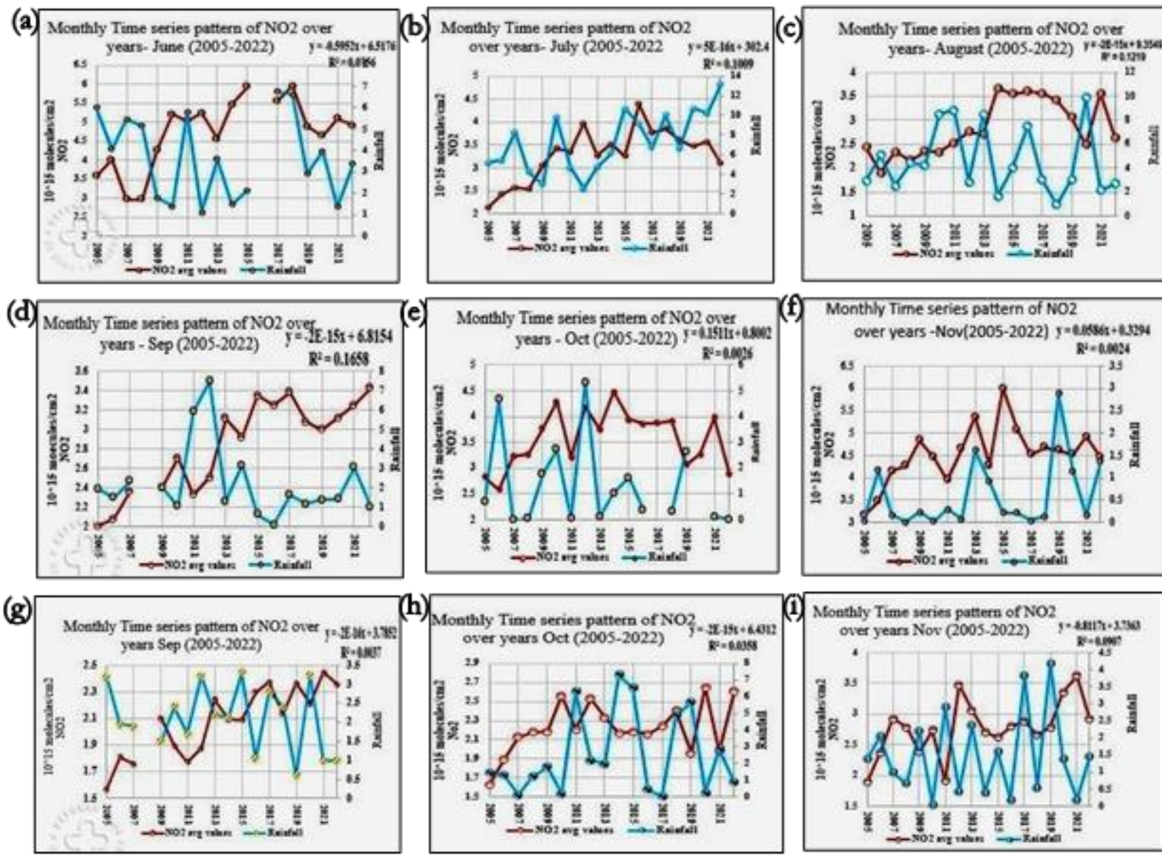

Figure 7: This figure shows the variations in rainfall and Nitrogen Dioxide (NO_2) levels throughout Autumn Season in three Pakistan cities. **(a)** displays data for Lahore in September, **(b)** shows Lahore data for October, **(c)** represents Lahore data for November, **(d)** displays data for Faisalabad 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 NO2 pollution and temperature in Lahore, Faisalabad, and Peshawar during winter (December to February) reveals a nuanced relationship. There is a weak positive correlation between these two variables, though its strength varies by city and month. In Lahore, the greatest impact of temperature on NO2 levels is observed in December ($R^2 = 0.114$), with a weaker positive correlation in February ($R^2 = 0.029$). January, however, shows minimal influence ($R^2 = 0.001$). Faisalabad and Peshawar also experience weak positive correlations throughout the winter, with December and January showing minimal influence and February showing 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 = 0.105, February-R^2 = 0.128). Despite these weak correlations, NO2 pollution consistently rises in all three cities during winter, suggesting that factors other than temperature, such as increased use of coal and natural gas for heating, significantly contribute to elevated winter NO2 emissions.

Spring Relationships:

Spring (March-May) in Lahore, Faisalabad, and Peshawar presents a complex interaction between NO2 pollution and temperature. All three cities show a weak positive correlation between these variables, though the strength varies by month (Lahore: March-R^2 = 0.02, April-R^2 = 0.04, May-R^2 = 0.11; Faisalabad: generally weak positive; Peshawar: March-R^2 = 0.10, April-R^2 = 0.19, May-R^2 = 0.07). Despite this positive correlation, NO2 pollution increases in April and May across all cities (Lahore and Faisalabad) or shows an overall rising trend (Peshawar) since 2005. Although temperatures decline across these months, the positive correlation may indicate that slightly warmer temperatures in March and April facilitate some pollutant dispersion. However, May's weaker association and potential temperature dip could trap NO2 closer to the ground.

Summer Relationships:

The monsoon season (June-August) in Lahore, Faisalabad, and Peshawar reveals a complex relationship between NO2 pollution and temperature. All cities show a generally weak positive correlation during June and August, suggesting some cleansing effect from rainfall. However, the strength of this relationship varies, with Peshawar showing a stronger inverse correlation in August (R^2 = 0.43) compared to Lahore (R^2 = 0.07) and Faisalabad (R^2 = 0.12). July exhibits a weak positive or mixed relationship in all three cities (Lahore: R^2 = 0.10, Faisalabad: R^2 = 0.1207, Peshawar: R^2 = 0.01), possibly due to increased agricultural burning or industrial activity counteracting the cleansing effect of rainfall. NO2 pollution trends upward in all three cities during the monsoon season, despite varying rainfall patterns. Lahore and Faisalabad experience a dip in rainfall in June and August, while Peshawar sees a decrease only in August. This suggests that factors beyond temperature, such as agricultural burning or industrial emissions, likely contribute to the NO2 increase during the monsoon season.

Autumn Relationships:

Autumn (September-November) in Lahore, Faisalabad, and Peshawar presents a varied picture of NO2 pollution and temperature. Some months show a weak negative correlation (October-November in Faisalabad, R^2 = 0.0026-0.024), but overall, the relationship is inconsistent. In September, NO2 pollution often rises despite decreased rainfall (Lahore: R^2 = 0.0037, Faisalabad: R^2 = 0.16, Peshawar: R^2 = 0.003), potentially due to post-monsoon crop burning. November exhibits a weak inverse relationship in Lahore (R^2 = 0.0409) and a stronger inverse relationship in Peshawar (R^2 = 0.09) compared to September and October. Precipitation patterns also vary, with Lahore and Faisalabad experiencing reduced rainfall in September and October, while Peshawar sees decreased rainfall only in September. These variations highlight the limitations of precipitation as the sole means of NO2 control and underscore the need for additional strategies, given the observed increases in NO2 pollution in September and November despite minimal rainfall.

NO2 and Wind Speed:

Winter Relationships:

Winter shows a complex interplay between wind speed and NO2 pollution in all three cities. Despite an overall weak relationship, the direction of the association varies. Lahore exhibits a weak negative relationship in December and February (R^2 = 0.01, 0.0003) but a weak positive relationship 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 relationship in December and January (R^2 = 0.36, 0.16) transitioning to a weak association in February (R^2 = 0.03). Despite variations in wind speed, NO2 pollution increases across all cities during winter, suggesting that factors beyond wind speed, such as emission sources, play a significant role in the winter NO2 surge. Lahore's wind speed remains steady, Faisalabad's decreases in recent years, and Peshawar's decreases in December and January.

Spring Relationships:

The pre-monsoon season (March-May) in Lahore, Faisalabad, and Peshawar shows a complex relationship between wind speed and NO2 pollution. Despite a generally weak relationship, NO2 pollution rises across all three cities during this period. Lahore shows a weak positive association between wind speed and NO2 in some months (R^2 = 0.002-0.05), with increasing wind speeds over the years but limited impact on pollution dispersal. Faisalabad also displays a weak relationship (R^2 = 0.0352) and rising NO2 levels with decreasing 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 NO2 pollution across Lahore, Faisalabad, and Peshawar. Lahore shows a weak positive relationship (June-R^2 = 0.09, July-R^2 = 0.05, August-R^2 = 0.005), with both NO2 pollution and wind speed rising throughout the monsoon months. Faisalabad also exhibits a weak positive relationship (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 NO2 pollution increasing despite declining wind speeds throughout the monsoon season.

Autumn Relationships:

The post-monsoon season (September-November) reveals a complex relationship between wind speed and NO2 pollution across Lahore, Faisalabad, and Peshawar. Despite a rising trend in NO2 pollution throughout this period, the influence of wind speed varies. Lahore shows a weak negative relationship (R^2 = 0.02-0.07) with minor wind speed changes. Faisalabad exhibits a weak positive relationship in September (R^2 = 0.0002) shifting to a weak negative relationship in October and November (R^2 = 0.20, 0.04), despite increasing wind speeds over the years. Peshawar shows a positive but weak correlation with wind speed in October and November (R^2 = 0.0103-0.0128) and a weak negative relationship in September. These variations highlight the need to consider factors beyond wind patterns, with emission sources likely playing a significant role in the NO2 increase during the post-monsoon season.

Monthly NO2 Pollution Patterns (2005-2022):

Lahore, Faisalabad, and Peshawar display distinct seasonal variations in NO2 pollution levels over the period from 2005 to 2022, as analyzed using satellite-based monthly average NO2 concentrations.

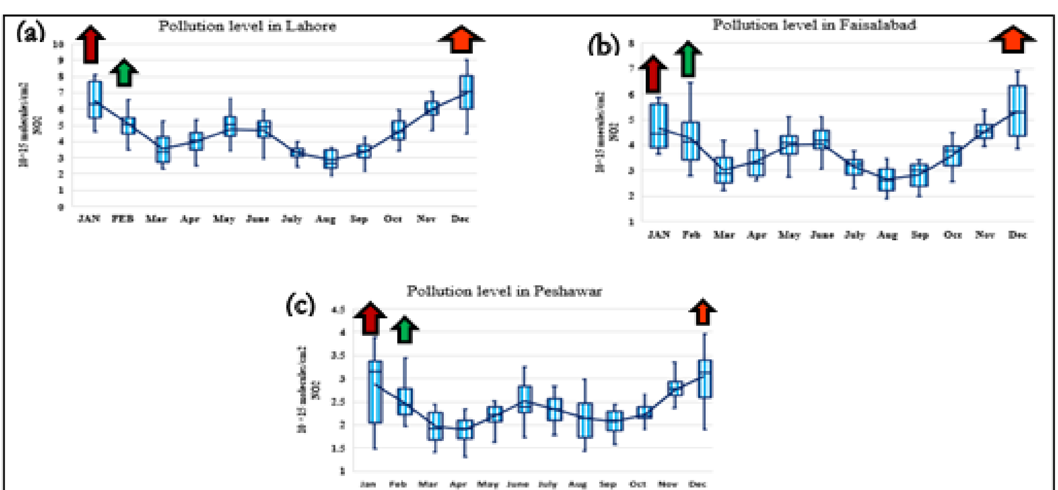

Figure 8: The figure above shows average monthly pollution levels at the local level (thick boxes represent winter months when NO_2 levels are higher). **(a)** represents Lahore, **(b)** shows Faisalabad and **(c)** represents Peshawar

Lahore:

Lahore experiences its highest NO2 concentrations during the winter months, with December peaking at approximately 9.028 x 10^15 molecules/cm², while August records the lowest values at 1.9 x 10^15 molecules/cm². This seasonal pattern indicates elevated pollution levels in winter, likely due to emissions from sources such as animal waste, wood burning for heating and cooking, and coal combustion.

Faisalabad:

Faisalabad, similar to Lahore, shows the highest NO2 concentrations in December (6.80 x 10^15 molecules/cm²) and the lowest in August (1.90 x 10^15 molecules/cm²). This pattern mirrors Lahore's winter peak and monsoon dip, suggesting comparable contributing factors.

Peshawar:

Peshawar's highest NO2 concentrations occur in December (3.95 x 10^15 molecules/cm²), with the lowest levels in April (1.31 x 10^15 molecules/cm²). The winter peak is indicative of increased pollution, likely due to biomass burning and industrial activities.

Identification of Main Anthropogenic Sources:

The primary anthropogenic sources of NO2 emissions in Pakistan include industrial operations, heavy road traffic, dense population centers, agricultural fires, and fossil fuel combustion [38].

Discussions:

Various global studies have utilized satellite-based analyses to examine atmospheric pollution. Instruments such as the Worldwide Ozone Observing Network (GOME), the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), and the Ozone Monitoring Instrument (OMI) on the AURA satellite have assessed regional and local environmental dynamics, reflecting long-term pollution trends.

A previous study investigated NO2 levels in Pakistan's upper atmosphere between 2005 and 2008, revealing a concerning annual increase of 3.29%. This finding aligns with my study's observations and highlights the need for city-specific analyses, as demonstrated by Karachi's variable NO2 levels. The study also noted rising NO2 trends in Islamabad/Rawalpindi, Lahore, and Dera Ghazi Khan, potentially linked to air mass movements and regional atmospheric dynamics [39].

Another study (2005-2014) utilized satellite data to analyze trends in CO, HCHO, NO2, and O3 across Pakistan's Punjab region. It confirmed a significant 28.2% increase in NO2 levels, which supports the historical trend of worsening air quality observed in my research. The study also suggested interactions between these gases, which could impact overall air quality. Future studies could explore how these interactions influence NO2 levels in various regions of Pakistan [27].

Research from 2002-2014 used satellite data to detect increased NO2 emissions linked to fossil fuel burning. The decrease in NO2 levels in Karachi due to reduced industrial activity is consistent with my focus on anthropogenic sources. Both studies underscore the importance of understanding how human activities affect NO2 emissions across different regions [38].

A study covering 2010-2020 investigated the impact of COVID-19 lockdowns on NO2 levels across Asia, including Pakistan. This study, partially overlapping with my research period, found a significant decrease in NO2 concentrations during lockdowns, attributed to reduced human activity, particularly in transportation. This finding complements my research on how reduced traffic influences NO2 levels and highlights the connection between human activities and NO2 emissions. It suggests that strategies to reduce traffic congestion and study the impact of meteorological factors on NO2 could be vital for improving air quality in Pakistani cities [24].

Conclusion:

This study analyzed NO2 pollution variations in Lahore, Faisalabad, and Peshawar between 2005 and 2022, utilizing data from the Ozone Monitoring Instrument (OMI). The research examined the effects of seasonal changes in temperature, rainfall, and wind speed on NO2 levels. Distinct seasonal patterns were identified, with Lahore and Faisalabad showing the lowest NO2 concentrations during the monsoon season (around August) at approximately 1.9 x 10^15 molecules/cm². In contrast, Peshawar's lowest NO2 levels occurred during the pre-monsoon period (March-May), with a minimum of 1.318 x 10^15 molecules/cm².

All three cities experienced a significant increase in NO2 pollution during winter. Lahore recorded the highest concentration in December (9.028 x 10^15 molecules/cm²), 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 NO2, such as industrial activity, traffic volume, and fossil fuel combustion. The study also highlighted the influence of factors like population density and agricultural burning on NO2 levels.

These findings emphasize the need for targeted air quality management strategies, particularly during winter. To address the alarming rise in NO2 pollution and ensure healthier air quality, it is essential to implement stricter regulations, promote cleaner technologies, and reduce human-caused sources such as traffic congestion and industrial emissions.

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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.

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